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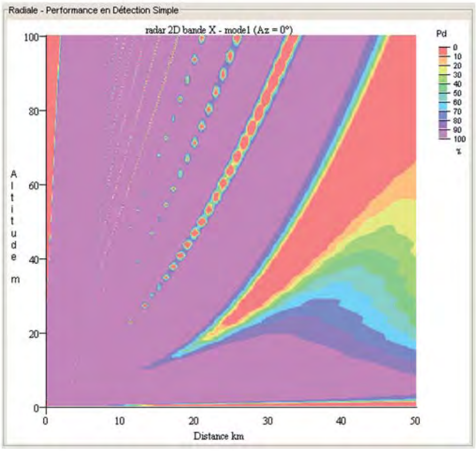

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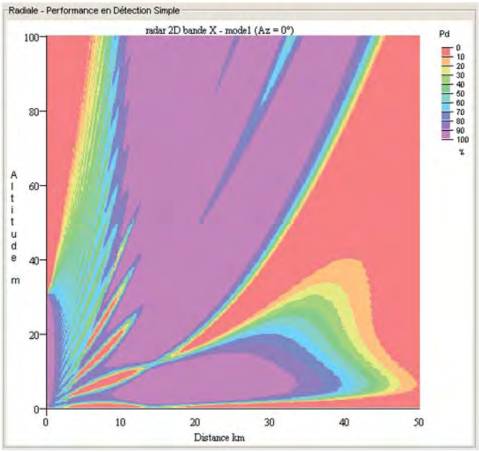

With sea clutter ws=15m/s

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Front cover: Radar coverage diagrams, showing the detection probability in percent, for an X-band radar located near the sea. The combined effects of ducting conditions without (left) and with (right) sea clutter are shown. The color scale spreads from purple (100% detection probability for a target with a radar cross section of 20m^2) to red (0% detection probability). See the paper by Yvonick Hurtaud and Jacques Claverie, pp. 45-52.

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The International Union of Radio Science (URSI) is a foundation Union (1919) of the International Council of Scientific Unions as direct and immediate successor of the Commission Internationale de Télégraphie Sans Fil which dates from 1914.

Editorial

It's Not Too Late for AT-RASC 2015!

Although the official paper-submission deadline for AT-RASC 2015 has passed, it is not too late to share your latest results! Provision will be made to allow submission of "latest results" papers to a special latest-results session for each Commission through February 28, 2015. See the Web site at http://www.at-rasc.com/ for details. Regardless of whether you submit a paper, you need to plan to attend AT-RASC, to be held May 18-22, 2015, in Gran Canaria, Canary Islands. Over 500 papers have already been received, so it is going to be an outstanding first edition of this new triennial flagship URSI conference.

This Issue

Although this is the last issue of 2014, it will reach you in early 2015. I think you'll find it worth the wait: we have a very nice selection of papers.

Our Papers

Passive microwave remote sensing of land surfaces has become an extremely powerful and very valuable tool, particularly for monitoring parameters that affect and are affected by climate change. In his invited paper, Paolo Pampaloni has provided us with a quite comprehensive and easy-to-understand review of this topic. The paper begins with a brief history of satellite-based microwave remote sensing of the Earth. The principles of microwave radiometry are then introduced, and what the microwave radiometer measures and how it makes the measurement are explained. It is explained how radiative transfer theory is used to relate the measured microwave brightness temperature of the land to its geometrical and physical characteristics. The use of this approach in situations where layered media are involved (such as a layer of vegetation over land) is described. The electrical characteristics of liquid water, soil, vegetation, and wet and dry snow are considered, and their impacts on remote-sensing measurements are examined. The structure of a passive microwave remote-sensing system and its various elements is explained in detail. The various models and algorithms used to extract useful data about the land from the quantities measured by the remote-sensing system are reviewed. The practical applications of such remote-sensing systems are then described, including monitoring the water cycle, sensing soil characteristics, monitoring crops, measurements of forests, the measurement of soil moisture in the presence of vegetation, and measurements of snow cover. This article is an excellent introduction to the subject of passive microwave remote sensing of the Earth. It also provides an up-to-date review of what systems are in use, and their methods and capabilities, all presented in a quite easy-to-understand manner.

This invited paper was based on the Commission F tutorial lecture at the URSI GASS in Beijing. The efforts of Roger Lang in bringing us this paper are gratefully acknowledged.

Knowing the time to high precision is one challenge. Being able to accurately distribute that information to different locations – the problem of precise time and frequency transfer – is quite another challenge. D. Matsakis, P. Defraigne, and P. Banerjee address this topic in their paper. More specifically, they address three fully operational systems for accomplishing such transfers: network time protocol, two-way satellite time and frequency transfer, and GPS. They also briefly discuss fiber-optic technology, used on links used for the generation of International Atomic Time, and long-range radio navigation (LORAN). The paper begins with an in-depth look at network time protocol, which is an Internet-based method. The errors associated with this method, and its advantages and problems, are described. The use of global navigation satellite systems (GNSS) for time transfer is then reviewed. The method of establishing a time-transfer standard is discussed. The use of the techniques referred to as common view and all-in-view to account for satellite hardware delays and clock errors, and the effects of propagation and geometry, are examined. The use of the phase measurements that are available with some GNSS receivers to improve time transfer is explained. The potential for improvements due to interoperable GNSS is assessed. After a brief description of LORAN, two-way satellite time and frequency transfer is introduced and explained in detail as offering the potential for the most accurate and precise transfer. A review of fiber-optic time and frequency transfer completes the paper. This paper provides an excellent review of modern time- and frequency-transfer technologies.

The efforts of Yasuhiro Koyama of Commission A in bringing us this paper are gratefully acknowledged.

The littoral, or coastal, areas of bodies of water can present distinctive electromagnetic propagation challenges, particularly for naval systems. How environmental data can be used to predict and visualize such propagation effects is the topic of the invited paper by Yvonick Hurtaud and Jacques Claverie. In particular, the authors describe a software tool, *PREDEM V2*, which was developed to translate geophysical parameters into predictions of naval electromagnetic performance. The paper begins with a review of atmospheric refractivity profiles and the phenomenon of electromagnetic ducting in the atmosphere. The *PREDEM* software is described. The method of using the meterological and atmospheric structure data in *PREDEM* to characterize surface and elevated ducting is explained. The description used for the sea surface, and the modeling of the sea clutter, are described. The paper then reports on a series of campaigns involving complete radar and meteorological measurements that were performed near the French Mediterranean coast to verify and illustrate the use of *PREDEM*. These included measurements using S-band and C-band radars. Illustrations are given showing the impact of the geophysical parameters on the coverage of the radars, and the effects of sea clutter. The paper concludes with a summary of the future developments needed to substantially expand the coverage and utility of the tool. This paper provides an interesting description of a useful tool for relating geophysical data to electromagnetic propagation effects in coastal environments. It also gives a very nice introduction to the major factors affecting propagation in such environments.

Tullio Tanzi (the General Chair of the OCOSS 2013 conference), Jean Isnard, and François Lefeuvre invited this paper on behalf of the *Radio Science Bulletin*. It is a substantially expanded version of the material presented at the OCOSS 2013 conference, and was invited as one of the outstanding papers at the conference. Their efforts are gratefully acknowledged.

John Dellinger's name is commonly associated with sudden ionospheric disturbances (SIDs). Perhaps less well known is the name of Hans Ernst Mögel, who observed and reported on the same phenomenon years prior to Dellinger. In their paper, Fritz Traxler and Kristian Schlegel look at the life and professional contributions of Mögel. The paper begins with a biography of Mögel, tracing his development as both a scientist and engineer. Some most interesting information on Mögel and early German commercial transcontinental radio communication by Transradio AG is then provided. Finally, the history of Mögel's observations and reporting of the disturbances to shortwave radio propagation that are called the Mögel-Dellinger effect are traced. These are compared to the work of Dellinger on what would ultimately be called SIDs. This paper provides interesting insight into the history of some of the more important early discoveries associated with ionospheric propagation.

The paper by William Young, Kate Remley, Christopher Holloway, Galen Koepke, Dennis Camell, John Ladbury, and Colton Dunlap is the second in a three-article series dealing with radio-propagation studies related to public-safety communications. The first paper, "Propagation Measurements Before, During, and After the Collapse of Three Large Public Buildings," appeared in the September 2014 issue of the *Radio Science Bulletin* (pp. 31-47). The third article, "Peer-to-Peer Urban Channel Characteristics for Two Public Safety Frequency Bands," will appear in the March issue. The paper in this issue deals with the characterization of the radiowave propagation environment in urban settings in frequency bands of interest to public safety. The frequency range studied, from 430 MHz to 4.9 GHz, covers most public-safety and cell-phone bands, as well as other bands in wide public use. Propagation was considered in three urban settings: a 57-story high-rise office building, a three-story scientific laboratory, and a six-block urban area. The authors created what they referred to as "radio maps" for these. They carried CW transmitters operating at the various frequencies through the environments, while recording the received signals at several outdoor locations. These measurements differed from previous measurements in several important aspects, and those differences are discussed. A description is given of the experimental aspects, including the choice of frequencies, the transmitters, and the receivers. The environments in which the measurements were made are described. The data are then presented and analyzed. This included estimated cumulative distribution functions for all of the environments at all of the frequencies, as well as an analysis of the measurement uncertainties. Some of the implications of the results for public-safety communications are discussed. This paper is an important contribution to our understanding of public-safety communications.

Our Other Contributions

In his column, Jim Lin reports on current activities in setting radio-frequency exposure limits for humans. Several regulatory and standards-setting bodies are reexamining their current guidelines and standards, and the status of these activities is briefly reviewed. We have reports on several conferences in the field of radio science. There is a summary of the activities of Commission A at its business meetings at the GASS in Beijing. Recent work of the COSPAR/URSI Working Group on the International Reference Ionosphere (IRI) is reported.

Editor-in-Chief of *Radio Science*

I am very pleased to report that Phil Wilkinson, Past President of URSI, was invited by AGU and has accepted the position of Editor-in-Chief of the URSI logo journal, *Radio Science*.

As I noted at the start, this issue will reach you early in 2015. My very best wishes for a most happy, healthy, safe, and prosperous New Year!

Looking at the Earth as a Planet: Passive Microwave Remote Sensing of Land Surfaces

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Abstract

Multi-frequency microwave radiometry from satellites is an excellent tool for providing continuous monitoring of land surfaces, which is crucial in making long-term decisions about land management in terms of water resources, agriculture, forestry, energy, tourism, transportation, etc., as well as in rapid detection of natural and man-made disasters. Microwave radiometers are highly sensitive, stable receivers that measure the thermal emission from observed surfaces. One of the greatest challenges of remote sensing involves inverting the measurements and retrieving the quantities of interest from the observed data. After a short description of the principles of microwave radiometry, the observation instruments, and the techniques, this paper addresses the issue of retrieving the significant quantities of land surfaces, which affect the water cycle and are important indicators of climate change.

1. Introduction

Advanced knowledge and management of the Earth's systems requires the collection of a huge amount of geo-biophysical data, systematically taken at different spatial and temporal scales. These data contribute to studying the significant physical processes that affect our planet, such as the water and carbon cycles, as well as monitoring changes caused by global warming or other factors. Remote sensing from satellites plays a fundamental role in monitoring the Earth's surface on a global scale, utilizing highly sensitive sensors that operate in various spectral bands of electromagnetic waves. Optical sensors can only produce images of the Earth during daylight, and their ability to operate is strongly affected by meteorological conditions. To the contrary, microwave sensors can operate continuously for day/night observations and, depending on the operating frequency, can be used for land observations in virtually all meteorological conditions or for investigating atmospheric parameters. Microwave sensors are also capable of penetrating vegetation, dry snow, and, in some cases, dry soils, as well as exhibiting a high sensitivity to liquid water. Microwave radiometers are highly sensitive, stable receivers, originally developed for radio astronomy and atmospheric research in the 1930s and 1940s. They are able to detect thermal radiation emitted by the Earth's surface and atmosphere. Since this radiation depends on the physical and geometrical properties of the observed bodies, these properties can be retrieved from radiometric measurements through the use of appropriate inversion algorithms. An excellent comprehensive book on microwave remote sensing has recently been published by Ulaby and Long [1].

After the first satellites carrying onboard microwave radiometers for the observation of the Earth's environment were launched by the former Soviet Union and the USA in the late 1960s and early 1970s, a significant milestone in the history of microwave radiometry for remote sensing was achieved by the Scanning Multi-channel Microwave Radiometer (SMMR), a five-frequency instrument launched in 1978 on the Nimbus 7 satellite [2]. The SMMR contributed significantly to the knowledge of sea-ice distribution during the year, and to climatology for the Arctic and Antarctic regions. This experiment was followed by a long series of satellites operated by the Defense Meteorological Satellite Program (DMSP), which carried onboard the Special Sensors Microwave Imager (SMM/I). More recently, two spaceborne multi-frequency microwave radiometers, called the Advanced Microwave Scanning Radiometer, were launched as a cooperation of the US (NASA) and Japanese (JAXA) space agencies, to provide new data for observation of the Earth's surface and atmosphere. These were the Advanced Microwave Scanning Radiometer, AMSR-E, launched in 2002 aboard the NASA Aqua satellite [3], followed by the AMSR-2, launched in 2012 for the Japanese Global Change Observation Mission (GCOM). A third instrument with similar characteristics but with extended polarimetric capabilities, the WindSat Polarimetric Radiometer, was launched by the Naval Research Laboratory (NRL) in 2003 aboard the Coriolis satellite. It was specifically realized to measure the ocean-surface wind vector [4].

The ESA/Soil Moisture and Ocean Salinity (SMOS) mission, based on a single-frequency L-band radiometer, has been operating since November 2009 [5]. Another mission, addressed to the measurement of soil moisture (SMAP), is still in preparation by NASA [6]. In addition to the work involved in preparing these missions and in analyzing the obtained data, the microwave remote-sensing community is deeply committed to improving knowledge in this field by analyzing experimental data collected from satellite, airborne, and ground-based sensors, and in developing more advanced forward models and inversion algorithms.

2. Principles of Microwave Radiometry

Microwave radiometry is based on the measurement of thermal radiation emitted by natural bodies. To study the generation and propagation of this radiation, it is convenient to introduce the concept of specific intensity, $I(r,s)$. For a medium that contains many particles, the emitted power, dP, flowing through an illuminated area, da, at position $\bar{r}$ along direction $\hat{s}$ in the frequency interval $(\nu, \nu + d\nu)$ is given by [7]

$$dP = I(\bar{r},\hat{s})\cos\theta\, da\, d\Omega\, d\nu \ \text{[watts]},$$

where $I(\bar{r},\hat{s})$ is the specific intensity [$\mathrm{wm^{-2}sr^{-1}Hz^{-1}}$], $\bar{r}$ is the position, and $\hat{s}$ is the direction. The power emitted by a blackbody at the thermodynamic temperature T is described by Planck's law. In the microwave region, and in the range of environmental temperatures, Planck's law can be approximated by the Rayleigh Jeans equation:

$$I = \frac{2\nu^2 kT}{c^2} = \frac{2kT}{\lambda^2}, \qquad (1)$$

where I is the specific intensity, k is Boltzman's constant (1.38×10^{-23} $\mathrm{JK^{-1}}$), c is the speed of light, and λ is the wavelength.

The emission from a natural "gray" body in local thermodynamic equilibrium can be written as

$$I = e\frac{2kT}{\lambda^2} = \frac{2kT_b}{\lambda^2}, \qquad (2)$$

where $e(\vartheta,\varphi)$ (with ϑ,φ being the angular coordinates) is the emissivity ($0 < e < 1$), which depends on the observational parameters (frequency, polarization, incidence angle), and on the geometrical and physical characteristics of the emitting medium. The quantity $Tb(\theta,\varphi) = e(\theta,\varphi)T$ is called the *brightness temperature*, and represents a basic quantity of microwave radiometry. We note that a consequence of the energy conservation law and reciprocity is that for a wave impinging on a flat surface of an infinite homogeneous half space in thermodynamic equilibrium, $e = a = l - r$, where a is the absorptivity and r is the reflectivity of the medium. Kirchhoff's law generalizes this concept to the case where there is bistatic scattering due to a rough surface and volume homogeneities.

If a lossless antenna observes a brightness temperature distribution $Tb(\vartheta,\varphi)$, the received power, P, can be written as follows:

$$P = \frac{1}{2}A_r \int_{\nu}^{\nu+\Delta\nu} \iint_{4\pi} \frac{2kT_b(\vartheta,\varphi)}{\lambda^2} F_n(\vartheta,\varphi)\, d\Omega\, d\nu, \qquad (3)$$

where A_r is the effective area of the antenna, $F_n(\vartheta,\varphi)$ is the antenna's normalized radiation pattern, and $T_b(\vartheta,\varphi)$ is the brightness temperature of the energy incident on the antenna.

If $\Delta\nu \ll \nu^2$, we have

$$P \cong kT_b \Delta\nu \frac{A_r}{\lambda^2} \iint_{4\pi} F_n(\vartheta,\varphi)\, d\Omega. \qquad (4)$$

On other hand, the integral of the antenna's radiation pattern is related to the antenna's effective area by the following relation:

$$\iint_{4\pi} F_n(\vartheta,\varphi)\, d\Omega = \Omega_p = \frac{\lambda^2}{A_r}. \qquad (5)$$

Combining Equations (4) and (5) we obtain

$$P = kT_b \Delta\nu. \qquad (6)$$

Equation (6) states that we can express emission through its brightness temperature, T_b. Moreover, we note that that the power delivered to an ideal receiver of bandwidth $\Delta\nu$

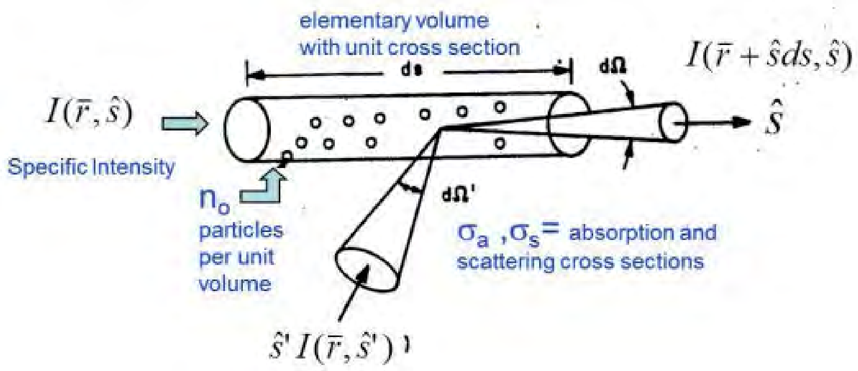

Figure 1. The extinction emission, and scattering processes of radiative transfer.

by a matched load at temperature T_b connected to its input terminal has exactly the same expression as Equation (6). If we substitute for the load an ideal lossless antenna surrounded by a body at uniform temperature T_a ,the power delivered to the receiver can be expressed as

$$P = kT_a \Delta \nu \,, \qquad (7)$$

where

$$T_a = \frac{\iint_0^{4\pi} T_b(\theta,\varphi) F_n(\theta,\varphi)}{\iint_0^{4\pi} F_n(\theta,\varphi)} .$$

For a real antenna, it is necessary to take into account the beam and radiation efficiencies. In this case, the power collected by a radiometer can be expressed by $P = kT_{eq}\Delta\nu$. When the antenna's solid angle, Ω_p , is much smaller than the solid angle subtended by the radiation source, Ω_s , which is the typical case in remote sensing, we can approximate: $T_{eq} \approx T_b$.

2.1 Radiative Transfer Theory

The typical problem of microwave radiometry involves measuring T_b and correlating it to the geometrical and physical characteristics of the observed media. This problem can be solved with various empirical or theoretical methods. The simplest approach in obtaining an expression for T_b of the observed scenes is based on radiative transfer theory (RTT) [7]. This theory assumes no correlation between fields, and it considers the addition of power instead of the addition of fields. Its validity is thus restricted to propagation in those media where scatterers are far from each other with respect to the electromagnetic wavelength, i.e., when there is no interaction among the single-scattering elements. In this theory, the interaction of radiation and matter is described by the two fundamental processes of extinction and emission, which occur simultaneously.

We consider a small elementary cylindrical volume of unit cross section and length ds , filled with n_0 particles per unit volume (Figure 1) as a part of a homogeneous material at uniform temperature, T. Radiation of specific intensity $I(\bar{r},\hat{s})$, incident on the left face and propagating along the s direction, decreases due to scattering and absorption, while it increases due to the thermal emission of particles and due to specific intensity incident from other directions, $\hat{s}'$, and is scattered in direction $\hat{s}$. Considering the balance of the three terms, the variation of the specific intensity, $dI(\bar{r},\hat{s})$, along the cylinder is given by

$$dI(\bar{r},\hat{s}) = -n_0(\sigma_a + \sigma_s) I(\bar{r},\hat{s}) ds$$

$$+ k_a \frac{2KT}{\lambda^2} ds + n_0 ds \int_{4\pi} d\Omega' p(\hat{s},\hat{s}') I(\bar{r},\hat{s}') ,$$

where $p(\hat{s},\hat{s}')$ is the phase function of the particle scattering from direction $\hat{s}$ into direction $\hat{s}'$ (bistatic scattering cross section per unit volume of space), and σ_a and σ_s are respectively the absorption and scattering cross sections of the particles.

This is the radiative transfer equation (RTE), which can be rearranged as follows:

$$\frac{dI(\bar{r},\hat{s})}{ds} = -k_e I(\bar{r},\hat{s}) + k_a \frac{2kT}{\lambda^2} + \int_{4\pi} d\Omega' p(\hat{s},\hat{s}') I(\bar{r},\hat{s}')$$

where $k_e = n_0(\sigma_a + \sigma_s)$ is the extinction coefficient, $k_a = n_0\sigma_a$ is the absorption coefficient, and $\int_{4\pi} d\Omega' p(\hat{s},\hat{s}') = k_s$ is the scattering coefficient.

2.2 Radiation Emitted from a Land Surface

Let us consider the case of a microwave radiometer observing a flat homogeneous medium 1 at temperature T_0, overlaid by a purely absorbing medium 2 at uniform temperature *T*. In this case, the solution of Equation (9) for the upward radiation expressed in brightness temperature T_b is [1,7]

$$T_b = \frac{I_u}{2k/\lambda^2} = T\left(1 - e^{-k_a d \sec \vartheta}\right)$$

$$+ T\left(1 - e^{-k_a d \sec \vartheta}\right) r e^{-k_a d \sec \vartheta} + T_0 (1 - r) e^{-k_a d \sec \vartheta} \quad .(10)$$

The three terms of the second member respectively represent the upward emission of layer 2 of thickness *d*, temperature *T*, and absorption coefficient k_a; the downward emission of the same layer reflected by the surface of medium 1 (of reflectivity *r*) and further attenuated by layer 2 as it propagates upward; and the medium 1 surface emission attenuated by layer 2 (Figure 2). If medium 2 is transparent, $k_a = 0$, and we simply have $T_b = (1 - r) T_0$.

3. Electrical Characteristics of Land Surface Materials

Natural materials of land surfaces are generally heterogeneous mixtures of air and several types of particles. From the electromagnetic point of view, such materials are lossy media characterized by the relative complex dielectric constant (CDC) $\varepsilon = \varepsilon' - i\varepsilon''$, which affects both the absorption and scattering of electromagnetic waves. The power absorption coefficient of a plane wave propagating in these media is $k_a = 2k_0 \left|\operatorname{Im}\sqrt{\varepsilon}\right|$, where k_0 is the wavenumber in free space.

3.1 Liquid Water

The spectrum of the complex dielectric constant of pure water is given by the Debye equation. The relaxation frequency is close to 17 GHz at 20°C, and to 9 GHz at 0°C. A certain quantity of liquid water is almost always included in all land materials, and its presence significantly influences the dielectric characteristics of the mixtures, because its dielectric values are much higher than those of the dry matter.

3.2 Soils

Electromagnetically speaking, soil is described as a dielectric mixture of four components: air, bulk soil, bound water, and free water. Following the pioneering work by Krotikov in 1962 [8], the first studies of the complex dielectric constant of soil involving both experiments and models date back to the early 1980s (e.g., [9]). The most important factor affecting the complex dielectric constant of natural soils in the microwave region is water content. This is due to the contrast between the complex dielectric constant of dry matter and that of liquid water, the molecules of which tend to align their dipole moments along a forcing electric field. In the case of low moisture values, the water molecules are tightly bound to the soil particles, and do not significantly contribute to the complex dielectric constant of the mixture. As the moisture increases above a certain transition level, the added molecules are free to rotate, causing an increase in the mixture's complex dielectric constant. In a comprehensive study of measurements and models performed over a wide frequency range (1 GHz to 18 GHz) for several types of soils, two dielectric mixing models were developed to account for the observed behavior [10, 11]. These models are still frequently used by the microwave remote-sensing community. More recently, important modeling improvements were proposed by Mironov et al. [12, 13] with the Generalized Refractive Mixing Dielectric Model for Moist Soils (GRMDM).

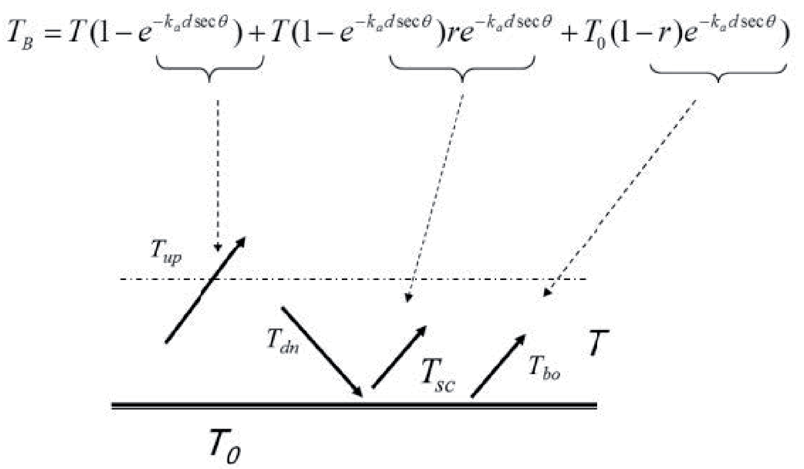

Figure 2. The brightness temperature of radiation emitted by a homogeneous medium at temperature T_0, overlaid by a layer of pure absorbing material at temperature T.

This model is based on the Debye formula, applied for estimating the relaxation spectra related to the bound and free water. A key point in developing the GRMDM was the technique proposed for calculating the conductivities, relaxation times, and static dc complex dielectric constant with the use of regular soil as a function of soil moisture. The comparison of the GRMDM simulated complex dielectric constant (CDC) of a silty clay soil with the results obtained in [10, 11] showed that the GRMDM matched the empirical model fairly well, and estimated data obtained with the semi-empirical model with better accuracy. The dependence of the soil's complex dielectric constant on temperature and the effect of freezing were investigated in [14, 15] by modifying the GRMDM to incorporate the temperature dependence of the Debye parameters (TD GRMDM), and taking into account the phase transformation of the soil water components at the freezing temperature. The validation of this model demonstrated good agreement with the data measured over frequencies from 1.0 GHz to 16 GHz, over moistures from dry to saturation, and over a temperature range from $-30°C$ to +25°C. The standard deviation of the difference between measurements and model predictions was 0.173.

3.3 Vegetation

The complex dielectric constant of vegetation material is strongly determined by the content and salinity of the water present in the plant elements. Ulaby and El Rayes [1, 16] developed an experimental model on the basis of measurements carried out on vegetation material (leaves, stalks, trunks) in the frequency range of 0.2 GHz to 20 GHz. More recently, the dielectric properties of alfalfa plants were investigated by Shrestha et al. [17]. Direct complex dielectric constant measurements of the components of two fir trees were performed by Franchois et al. [18]. A good summary of measurements performed by various authors on different plant elements, together with a great deal of additional interesting information, can be found in Chuklantsev [19].

3.4 Terrestrial Snow

Dry snow is mixture of air and ice crystals. Once snow crystals are deposited on the ground, they are subject to a continuous metamorphism caused by the thermodynamic processes that take place in the medium. If the temperature reaches the melting point, water may partially fill the pore space, and snow becomes a three-phase mixture of air, ice, and water (wet snow).

3.4.1 Dry Snow

In the microwave region, the ε' of ice is independent of temperature and frequency [20], and the same is true for the ε' of dry snow, which is a function only of the snow's density. Data on the complex dielectric constant of snow reported by several investigators in the frequency range from 0.8 GHz to 37 GHz were summarized in [21]. Contrary to the behavior of ε', the imaginary part, ε'', is dependent on both temperature and frequency. However, its value is at least two to three orders of magnitude smaller than ε', and for remote-sensing purposes, is generally neglected, at least up to 37 GHz.

3.4.2 Wet Snow

As the snow temperature increases above a certain level close to zero, the air space starts to be occupied by liquid water. The amount of liquid water in wet snow is given in terms of wetness (the fractional volume of water in snow). In the low range of wetness (the pendular regime), liquid occurs in the form of isolated inclusions in a continuous air space. In the higher range of wetness (the funicular regime), liquid exists in continuous paths covering the ice structure, and air occurs as distinct bubbles. In both cases, the presence of liquid water strongly affects the dielectric constant of the mixture.

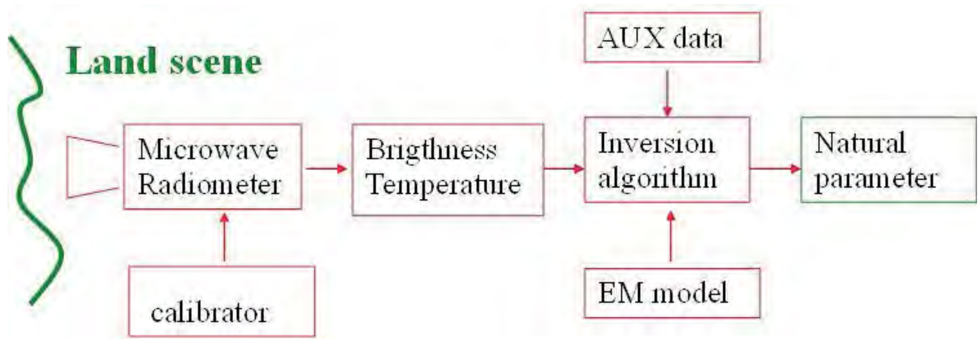

Figure 3. A schematic diagram of a passive remote-sensing system.

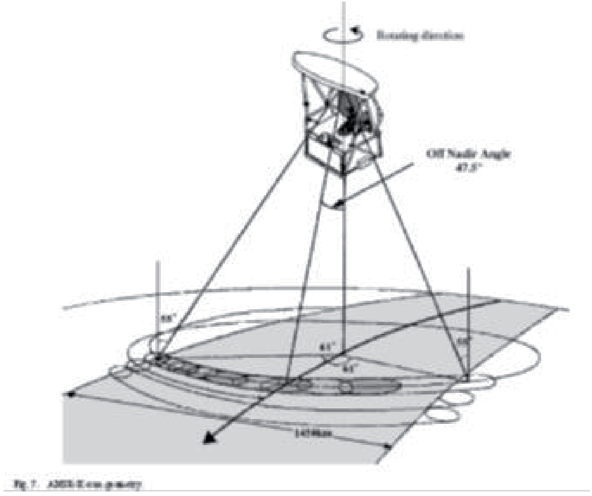

Figure 4. The AMSRE scanning geometry.

4. Structure of a Passive Microwave Remote-Sensing System

Figure 3 shows a scheme for a microwave radiometry system for remote sensing. The calibrated radiometer produces the brightness temperature, T_b, of the observed scene (at one or more frequencies, polarizations, and incidence angles). In turn, T_b must be transformed into the bio-geophysical parameter of interest. This transformation is the core problem of remote sensing, because the radiometer is often simultaneously sensitive to more than one parameter, and there thus is not an univocal relationship between T_b and the quantity to be retrieved. Solving this problem requires further activities: modeling to simulate T_b from natural parameters and to perform sensitivity analysis, developing inversion algorithms to retrieve natural parameters, performing experiments to assess relationships between the measured T_b and the quantity of interest (e.g., soil moisture, plant water content, snow water equivalent), and to validate models and inversion algorithms.

4.1 Microwave Radiometers

A microwave radiometer is basically a highly sensitive receiver, which can be created in various configurations: direct amplification, superheterodyne, etc. (e.g., [1, 22]). Its purpose is to detect the radiation emitted by natural bodies and available to an antenna. The simplest form of a radiometer is the total-power radiometer (TPR), i.e., any receiver that measures the total power from the antenna. The total-power radiometer consists of a pre-detection high-frequency section of gain G with bandwidth $\Delta\nu$, followed by a square-law detector and a low-pass filter with integration time τ. The total power delivered by the antenna at the input of the receiver, taking in account the losses, L $(1 < L < \sqcup)$, in the transmission line at temperature T_0, can be expressed by $P = kT_s\Delta\nu$, where k is Boltzmann's constant, $T_s = T_a/L - (1-1/L)T_0$, and T_a is the antenna temperature. In turn, the receiver contributes a noise temperature T_r due to the thermal noise of its components. The total system noise at the receiver input is hence $p_i = k(T_s + T_r)\Delta\nu = kT_{sys}\Delta\nu$, where T_{sys} is the system noise temperature at the antenna's terminals. It should be noted that both noises have a similar nature, and that most frequently, the antenna noise due to the observation of a scene can be a small increment of the receiver noise. The sensitivity, or the minimum detectable signal, ΔT_{min}, of a total-power radiometer is the signal variation, ΔT, that produces a receiver dc output change equal to the noise output power. It is given by [22]

$$\Delta T_{min} = \frac{T_{sys}}{\sqrt{\Delta\nu\tau}}. \quad (11)$$

Receiver gain instability introduces an additional uncertainty, because the detector cannot distinguish between a variation in signal power, ΔT, from a variation in gain, ΔG. These two variations are statistically independent, and can be combined to establish the actual sensitivity of the total-power radiometer as

$$\Delta T_{min} = T_{sys}\sqrt{\frac{1}{\Delta\nu\tau} + \left(\frac{\Delta G}{G}\right)^2}. \quad (12)$$

The influence of gain fluctuations can be reduced by continuously switching the receiver between the antenna and a reference load or noise source at a frequency high enough to prevent gain variation during a cycle. The output signal is then recovered by using a synchronous demodulator, and becomes independent of the receiver noise temperature because the radiometer actually measures the temperature difference between the signal and the reference load.

Many other techniques have been developed to create instruments best suited for specific applications, taking into account, for example, the need to produce

Frequency (GHz)	Resolution (km^2)
6.9	62×35
10.6	42×24
18.7	22×14
23.8	19×11
36.5	12×7
89	5×3

Table 1. The frequency channels and the corresponding ground resolutions of AMSR2.

images by means of various types of scanning systems. In these cases, the detector integration time, and then the sensitivity, must be compatible with the scanning speed [1, 22]. An improvement of the total-power radiometer, which makes a tradeoff between sensitivity and stability, is the total-power radiometer with frequent calibration. In this system, the antenna is periodically switched between two loads at different temperatures, in order to provide auto-calibration of the radiometer. In order to produce images of a scene of interest from a platform, it is necessary to scan the antenna beam across the track. Scanning can be obtained by mechanically moving the antenna, or by using electronic beam steering . Alternatively, imaging can be obtained using the aperture synthesis approach derived by a radio-astronomical technique, properly adapted for the observation of extended targets.

4.1.1 Scanning Systems

A typical example of a scanning instrument is the Advanced Microwave Scanning Radiometer (AMSR2) of the JAXA GCOM mission, which is the most advanced satellite radiometer designed and used for multipurpose applications (land, ocean, atmosphere) [3]. This instrument is similar to the previous AMSR-E, operated on the NASA Aqua platform from 2002 to 2011 [23] with improved performance. The parabolic antenna of AMSR2, 2 m in diameter, rotates once per 1.5 s, and obtains data over a 1450 km swath (Figure 4). This conical-scan mechanism enables AMSR2 to acquire a set of data with more than 99% coverage of the Earth every two days. AMSR2 has the same frequency channels as AMSRE: the operating frequencies and the corresponding ground resolutions are given in Table 1.

An additional channel at 7.3 GHz (with a resolution of 62 km × 5 km) was added to mitigate the effects of radio-frequency interference (RFI). The WindSat Polarimetric Radiometer [4], launched in 2003 aboard the Coriolis satellite to demonstrate the capabilities of a fully polarimetric radiometer in measuring the ocean-surface wind vector, has characteristics similar to AMSR-E. It is viewed as a successor in technology to SSM/I and AMSR-E, with extended polarimetric capabilities. WindSat data are primarily used to retrieve ocean wind characteristics. However, it is also used by space agencies for producing soil-moisture maps. An inter-comparison of data from AMSR-E and Windsat, recently performed by Das et al. [24], showed a reasonable agreement in the data of both sensors over three selected homogenous sites, as well as over the global landmass, demonstrating the potential of Windsat for land observation, too.

A system that combines an L-band radiometer with a radar, and makes use of a rotating mesh disk antenna that is 6 m in diameter, is under development by NASA for the SMAP mission [6], presently scheduled for early 2015.

4.1.2 Aperture-Synthesis Radiometer

The deployment in space of large moving structures is still problematic. One way to mitigate these limitations is the use of aperture synthesis, which allows a significant reduction of the antenna's collection area by substituting a discrete distribution of small antennas for a continuous surface. In this method, the complex correlation of the output voltages from pairs of antennas is measured at many different baselines. Each baseline produces a sample point in the Fourier transform of the scene, which can be recreated by inverting the transform, after all measurements have been made. An aircraft L-band prototype to demonstrate this concept was developed and tested aboard the NASA P-3 aircraft in June 1988 [25]. This first study opened the doors to the more sophisticated microwave interferometric radiometers with aperture synthesis (MIRAS), developed for the Soil Moisture and Ocean Salinity (SMOS) mission [5]. MIRAS is composed of three deployable arms, connected to a central hub 1.3 m in diameter, with the three arms equally spaced with an angular separation of 120°, extending up to 8 m in diameter. The interferometric measurements result in images from within a hexagon-like field of view about 1000 km across, enabling total coverage of Earth in under three days with a spatial resolution of 50 km.

4.2 Microwave Emission Models

In general, the algorithms developed for retrieving spatial variations of land parameters are based on the inversion of physical or empirical models. A model is basically a relationship linking the observed brightness temperature, T_b, or the emissivity to n surface variables. Empirical models are obtained with field experiments by simultaneous radiometric observations and local measurements of the parameters of interest, carried out with conventional methods. The experimental results are presented in diagrams fitted with more-or-less complicated equations. Physical models are developed by using radiative transfer theory, or more-rigorous approaches based on electromagnetic theory. They can be classified in several ways, considering the two fundamental interaction mechanisms of electromagnetic waves with natural bodies: surface and volume scattering. In general, both mechanisms are simultaneously present, but surface scattering is dominant when the observation regards an almost homogenous medium such as a bare soil, whereas volume scattering takes place in cases of more or less dense mixture of air and other materials, such as vegetation and snow grains. Moreover, if radiation is only (or mostly) scattered by localized scattering centers (discontinuities in surface scattering or single particles in volume scattering), we have *single scattering*. Otherwise, if radiation scatters several times before reaching the receiver, we have *multiple scattering*. In general, in the observation of natural surfaces, multiple scattering is always present. If it is ignored, there is loss of energy, which in most cases is tolerated, considering the benefits achieved in simplifying computations. For practical reasons, semi-empirical models have been frequently developed by combining the two approaches, for example, introducing a measured parameter in a theoretical relationship.

4.2.1 Surface Scattering Model

The emissivity, e, of an infinite half space can be calculated from the reflectivity, r, through Kirchhoff's law ($e = 1 - r$). If the observed medium has a perfectly flat, smooth surface (specular reflection), emission depends only on the dielectric constant of the medium, and is obtained from the Fresnel reflectivity, R. In general, natural soils present a random surface roughness, the impact of which on the emission depends on the statistics of the surface height variations measured in units of the observing wavelength: the autocorrelation function, A_c; the standard deviation of the surface height variation, s; and the surface correlation length, L. According to the Fraunhofer criterion, a surface observed with an incidence angle ϑ can be considered smooth if $s < \lambda / (32 \cos\vartheta)$.

A first simple relationship to characterize the reflectivity of rough surfaces was obtained be introducing an exponential term – a function of s and the incidence angle, ϑ – to correct the Fresnel reflectivity, R, and by disregarding the incoherent component of the scattered field. An improvement to this simple approach was proposed by Wang and Choudhury, who added a second parameter, Q, to take into account the polarization effects [26]. This model is still used in many studies for interpreting experimental data and retrieving the roughness characteristics of surfaces.

On the other hand, a general analytic solution for the scattered field, valid for any type of degree of roughness, is not yet available. Depending on the degree of roughness, the electromagnetic analytical models usually taken into consideration in remote-sensing problems are based on the approximations of small perturbations (SP), Kirchhoff geometrical optics (GO) [1, 7], the integral-equation method (IEM) [27], and the advanced integral-equation method (AIEM) [28]. The limits of the validity of these approaches have not yet been clearly established. An experimental validation has been obtained by comparing model simulations with experimental data obtained on an artificial dielectric surface with the same statistical properties used in the model [29].

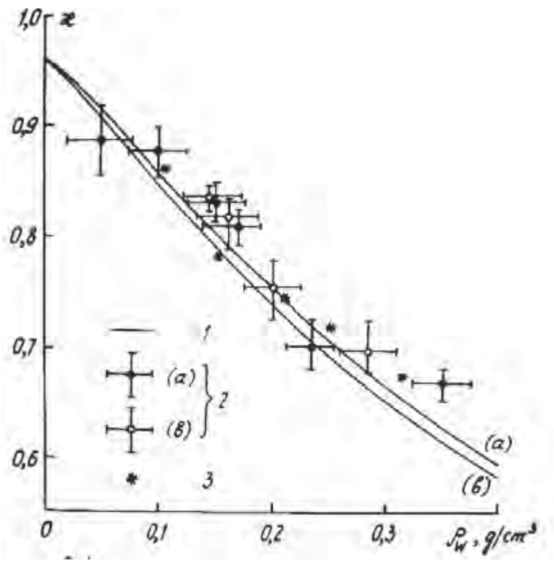

Figure 5. The emissivity of soil as a function of volumetric water content at Ku (a) and L (b) bands. The continuous lines (1) represent computations from Equation (21). The points with error bars (2) represent measurements on natural fields, and the points (3) represent laboratory measurements [40].

4.2.2 Volume Scattering Models

In some natural media, such as vegetation or snow composed of particles immersed in air and overlaying soil, the emitted radiation is scattered by the dielectric discontinuities introduced by the plant elements or snow grains distributed into the medium. In this case of volume scattering, physical models developed for simulating the brightness temperature can be divided into two categories: coherent, where the electromagnetic (EM) theory is rigorously applied by adding the electromagnetic fields; and incoherent, where the addition of powers instead of fields is performed.

For vegetation or snow-covered soils, both surface and volume scattering are present, and modeling of emission is performed by combining the two processes. Assuming that a vegetation layer can be considered a plane parallel absorbing and slightly scattering medium at a constant temperature, T_c, upon the soil surface at temperature T_s the brightness temperature, $T_{bp}(\tau,\mu)$, of the radiation emitted by the canopy at an angle ϑ from the zenith can be written as follows [30]:

$$T_{bp}(\tau,\mu) = (1-\omega)\left(1-e^{-\tau/\mu}\right)T_c$$

$$+\left[(1-R)_p\right]T_s e^{-\tau/\mu} + (1-\omega)\left(1-e^{-\tau/\mu}\right)T_c R_p e^{-\tau/\mu} \quad (13)$$

where p stands for horizontal (H) or vertical (V) polarization; $\mu = \cos\vartheta$, τ (optical depth), and $\omega = k_s/k_e$ (single-scattering albedo) are the parameters that characterize the absorbing and scattering properties of vegetation; and R_p is the soil reflection coefficient for the p polarization. The first term represents the upward emission from the vegetation layer, the second term is the emission from the soil attenuated by the vegetation, and the third term is the downward vegetation emission reflected by the soil and again attenuated by the vegetation. This model, now universally known as the tau-omega model, is largely used in the remote sensing of land surfaces.

An advanced multiple-scattering "discrete element" model, where plant elements are simulated by disks and cylinders, was developed in several steps by Ferrazzoli and his colleagues (e.g., [31]).

Among the various approaches developed to simulate microwave emission from snow cover, three models have particularly attracted the attention of the scientific community. Two of them, the Microwave Emission Model of Layered Snowpacks (MEMSL), developed by Maetzler and Wiesmann [32, 33], and the Helsinki University of Technology (HUT) snow emission model [34], are substantially based on radiative transfer theory and can be included in the category of semi-empirical models. A third model, the Dense Medium Radiative Transfer (DMRT) model, was derived from electromagnetic theory in successive steps by Tsang and his students from 1987 to recent years (e.g., [35, 36]).

The Microwave Emission Model of Layered Snowpacks is based on radiative transfer, and makes use of six-flux theory to describe multiple volume scattering and absorption, including a combination of coherent and incoherent superposition of reflections between layer interfaces. The scattering coefficient is determined empirically from measured snow samples, whereas the absorption coefficient, the effective permittivity, refraction, and reflection at layer interfaces are based on physical models and on measured ice dielectric properties. The Helsinki University of Technology model assumes that scattered energy is mostly concentrated in the forward direction, and ignores scattering in other directions. This corresponds to a Dirac delta function in the phase matrix. Moreover, the frequency dependence of the extinction coefficient is empirically determined. Simulations agreed fairly well with vertically polarized brightness temperature measurements; however, the model poorly reproduced the horizontally polarized component.

As stated in [35], "the basic physical idea of the dense media radiative transfer (DMRT) theory is that because the particles are randomly distributed, the phases of the scattered fields are random so that the products of scattered fields generally average to zero except those terms in the multiple scattering that results in constructive interference." An earlier version of dense media radiative transfer (DMRT) theory was derived for grain sizes smaller than the wavelength and non-sticky particles [37]. The phase matrix was the Rayleigh phase matrix, with a fourth-power frequency dependence of the scattering coefficient. A further step was to combine dense media radiative transfer with the quasi-crystalline approximation (QCA), leading to the QCA/DMRT model. This includes the collective scattering among sticky particles, and uses the pair distribution functions of the Percus-Yevick approximations for non-interpenetrable spheres to simulate the adhesion of ice grains and the formation of aggregates [38]. In such a way, higher-order multipoles beyond the electric dipole are used to account for the aggregate effects resulting in dense Mie scattering. In comparison with the classical radiative transfer theory (independent scattering), the QCA/DMRT model showed a frequency dependence of the scattering coefficient weaker than the fourth power, and a saturation of the extinction at a relatively high volume fraction. Moreover, the phase matrix shows more forward scattering and larger mean cosine than the classical Mie scattering theory.

More recently, Liang et al. [36] developed the multilayer version of the model, and found that it predicted higher polarization differences, and weaker frequency dependence, than the single-layer model. The authors also studied the temporal evolution of T_b from multilayer snow packs by using experimental ground data as input for both multi- and single-layer models. It was found that the results of the multilayer model were in better agreement with the data than the single-layer model.

4.3 Retrieval Algorithms

The complexity of the algorithms to be developed for retrieving land surface parameters greatly depends on the auxiliary information available, and on the direct models selected. The inversion of analytical EM models generally is a complicated procedure. Once the forward models have been validated, retrieval algorithms can be developed that are based on several techniques, and make use of single- or multi-frequency or multi-polarization radiometric measurements. Aside from direct inversions of empirical relationships, the most sophisticated retrieval algorithms are based on the following approaches:

1. The Bayes theorem.
2. Procedures for minimizing the difference between simulated and observed data (cost function), such as the Nelder-Mead iteration.
3. Artificial neural networks.

The method based on the Bayes theorem updates the likelihood of an event, given a previous likelihood estimate and additional evidence. This approach is quite accurate, but it requires a significant computing time due to the complexity of the implemented equations.

The Nelder-Mead algorithm is a direct minimization search method, commonly used in nonlinear regression problems. Computationally, it is quite simple. For the retrieval of land parameters, the inputs to the model are varied until the minimum of an appropriate error function is reached.

The artificial neural network (ANN) techniques are based on the training of the network by means of simulated or measured data. The algorithm frequently chosen for the training phase is the back-propagation (BP) learning rule, an iterative gradient-descent algorithm designed to minimize the mean square error between the desired target vectors and the actual output vectors.

The performance of these three types of algorithms were evaluated by Paloscia et al. [39], who found that the algorithm based on the artificial neural network represented the best compromise in terms of accuracy and computing time.

5. Applications of Microwave Radiometry

5.1 The Water Cycle

The hydrological cycle describes the constant movement of water between the atmosphere and the Earth's surface. In this process, water changes states among liquid, vapor, and ice. The main components of the terrestrial water cycle are soil moisture, i.e., the ground water in the unsaturated zone of land, snow, and vegetation covers. A continuous monitoring of these quantities on a global scale can greatly contribute to understanding the water cycle, and how it is modified by climate changes.

5.2 Emission from Bare Soil

As stated in Section 2, the observed brightness temperature, T_b, of a soil depends on both its emissivity, e, and its temperature, T, according to the equation

$$T_b(\theta,\varphi) = e(\theta,\varphi)T , \qquad (14)$$

where the emissivity is the quantity directly related to the dielectric and geometrical characteristics of soil, that is, the water content, texture, and surface roughness. For a soil modeled as a uniform isotropic semi-infinite medium limited by a plane surface, the emissivity, e, computed for two frequencies at L- and Ku- band as a function of volumetric soil moisture, m_v, is represented in Figure 5, together with experimental data [40].

The effect of texture does not change the slope of the e-m_v curve, but only the intercept with the e axis. Conversely, surface roughness significantly affects the emissivity by reducing the slope as the roughness increases. A frequently used model to describe the effect of roughness is the two-parameter semi-empirical model introduced in [26]. In [41], Coppo et al. proposed to express the emissivity, e, as a function of the height standard deviation, s, normalized to the wavelength, with the equation

$$e = 1 - \mathrm{R}\, e^{-3\sqrt{s/\lambda}} , \qquad (15)$$

where R is the Fresnel reflectivity.

It should be noted that in order to obtain the emissivity from the observed brightness temperature, it is necessary to normalize T_b by the effective radiating temperature of the soil, T_{eff}. In Choudhury et al. [42], T_{eff} was defined as follows:

$$T_{eff} = T_d + C\left(T_{sfc} - T_d\right) , \qquad (16)$$

where T_{sfc} is the observed surface temperature, T_d is the deep soil temperature, and C is an empirically defined weighting function based on the relative contribution of individual layers to the microwave emission at the soil surface. Equation (16), which has been widely used in many field experiments, has been further elaborated for L-band measurements by introducing information on soil permittivity [43] and moisture [44, 45] into the C parameter. A new two-layer scheme that explained the physical meaning of the C parameter was recently introduced by Lv et al. [46]. It was evaluated using in situ soil moisture and temperature measurements.

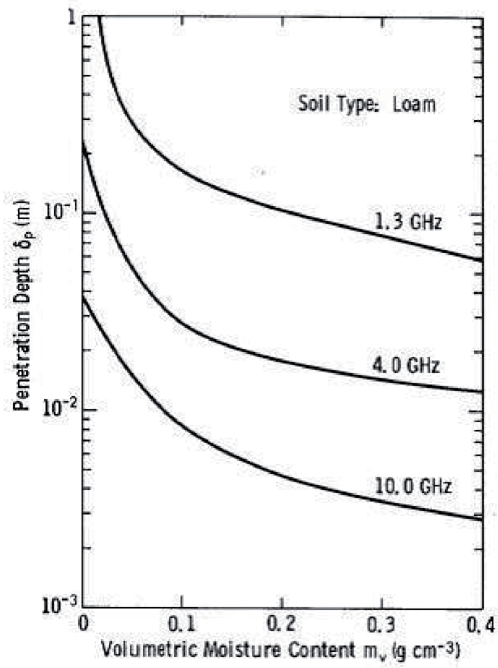

Figure 6. The penetration depth as a function of the volumetric moisture content [1].

The problem of estimating T_{eff} is related to the thickness, δ, of soil actually sensed by a radiometer. This quantity depends on the penetration depth of radiation into the soil, which is inversely proportional to the extinction coefficient, k_e, and depends on the observation frequency, on the soil moisture, and on the temperature profile [1]. For desert dry sand, δ can be of the order of a few meters at L band, whereas for agricultural moist soils, it rarely exceeds a few centimeters [1]. The penetration depth of a loamy soil as a function of volumetric water content is represented in Figure 6.

Normalizing T_b with respect to T_{eff} helps approximate the emissivity of the observed soils, and helps in comparing T_b data obtained with different temperature conditions. In general, for practical reasons, the emissivity is frequently approximated by the normalized brightness temperature, T_n, obtained by dividing the observed T_b by the surface temperature, usually measured with a thermal infrared sensor.

5.3 Remote Sensing of Vegetation

Vegetation is simultaneously a disturbing factor for the estimate of soil moisture as well as a specific target of remote sensing. This is because both crops and forests significantly contribute to the water cycle through the evapotranspiration process.

A vegetation canopy is characterized by several geometrical and physical characteristics, such as the total biomass, the plant density, the sizes and shape of plant elements, the plant water content (PWC in kg/m^2 – i.e., the difference between fresh and dry biomass over a square meter of soil, sometimes called the vegetation water content), and the leaf area index (LAI, in m^2/m^2 – i.e., the total area of leaves present in a square meter of soil).

Thermal radiation from vegetation canopies reaches a maximum in the infrared band, where the emissivity is usually fairly constant and higher than 0.95, and the emission is dominated by surface temperature. On the other hand, in the microwave region, emissivity changes over a wider range, depending on soil and plant moisture. As the water content increases, microwave emissivity decreases, whereas infrared emissivity tends to increase. Due to evapotranspiration, an increase of water in soil and plants is also accompanied by a surface temperature decrease. These combined effects are dimmed in the infrared band, and enhanced in the microwave band [47]. Electromagnetically, a vegetation cover can be treated as a mixture of air and plant elements that absorbs and scatters radiation emitted by the underlying soil, and that in turn emits its own radiation. An excellent exhaustive treatment of microwave radiometry of vegetation was given in the book authored by A. Chuklantsev [19], who considered all the experimental and theoretical aspects of this topic.

5.3.1 Agricultural Crops

Experiments to investigate the feasibility of estimating the physical conditions of vegetated surfaces with microwave radiometers have been performed since the late 1970s [48]. Measurements carried out with different approaches showed that at low frequencies ($<$ 2 GHz to 3 GHz) and small incidence angles, the attenuation of vegetation is generally low, and emission from soil is dominant. As the frequency increases, radiation is emitted from upper layers of vegetation. Therefore, the use of multi-frequency observations allows the assessment of the emissivity characteristics of the entire crop. A study that directly investigated the potential of microwave radiometry in detecting vegetation features was undertaken since 1980 by Pampaloni and Paloscia, using instruments at appropriate frequencies (10 GHz and 36 GHz) to minimize the soil contribution [49]. A great quantity of measurements – taken under different conditions on crops with different development stages – with ground-based sensors, showed that the best incidence angles for vegetation observations were between 40° and 60°. In this range, both soil and sky contributions were minimized. On the basis of these observations and the tau-omega model of Equation (13), the following nonlinear relationship between the optical thickness, τ, and the plant water content of corn and alfalfa was obtained [50]:

$$\tau = \frac{k}{\sqrt{\lambda}} \ln\left(1 + PWC\right), \tag{17}$$

where the plant water content, *PWC*, in kg/m^2, was 0.16 for corn and 0.25 for alfalfa. The standard deviation of the computed values of τ from this model was lower than 0.034 for alfalfa and lower than 0.040 for corn. A similar dependency was obtained for wheat, rye, and alfalfa by Chukhlantsev and Golovachev [51]. These authors also observed that at a constant volume density, the dependence of τ on plant water content was linear. However, since in a real situation, an increase in the water content in a crop takes place due to both the change in crop height and in crop volume density, the link between the optical depth and the water content becomes nonlinear. The relationship between canopy optical thickness, τ, and plant water content, PWC, at low frequencies was investigated in several studies, which in general recommended a linear dependence of τ on plant water content as appropriate in the decimeter wavelength range [52].

The emissivity of well-developed crops in a frequency range between the L and Ka bands was found to have a different spectral behavior for "small leaf" (alfalfa and wheat) and "wide leaf" (corn and sunflower) crops. Indeed, T_n increases with frequency in the first case, and is almost constant for wide-leaf crops. The relatively low emissivity of

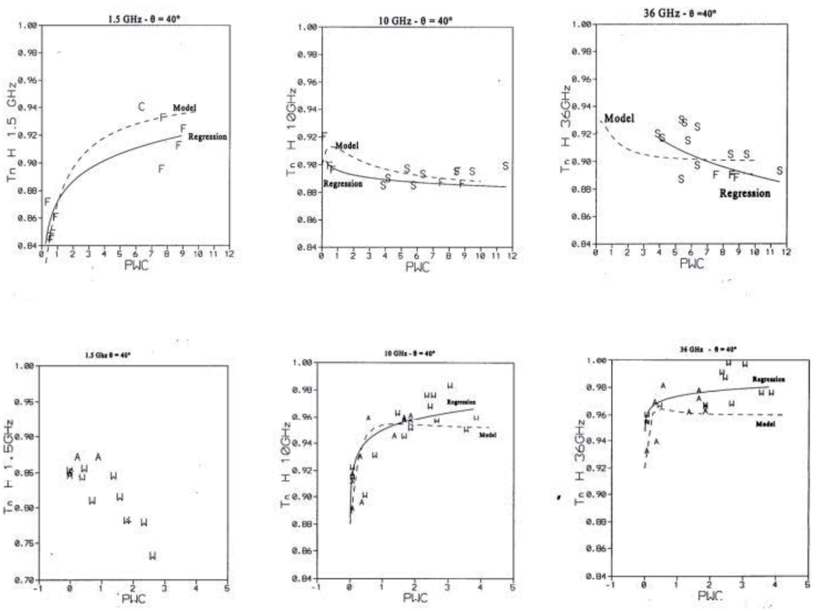

Figure 7. T_n **at H polarization as a function of plant water content for (a) wide and (b) small-leaf crops. The letters represent experimental values (corn: C, sugar beet: S, wheat: W, and alfalfa: A). The continuous lines are regressions, and the dotted lines are simulations obtained with the radiative-transfer theory model of [50].**

corn and sunflower at higher frequencies is due to the increase in the reflectivity of the wider leaves when the wavelength is decreased. The different emission characteristics of the two classes of crops are confirmed by the trends of T_n as a function of vegetation biomass. Figure 7 shows that as the plant water content increases, the T_n of wide-leaf crops increases at L band, and slightly decreases at X and Ka band, whereas the opposite happens for small-leaf crops. This behavior can be explained considering the prevailing effect of absorption (emission) or scattering depending on the relative dimensions of the plants' elements (leaves and stems) in terms of wavelength. The dependence of the relationship between T_n and plant water content on crop type complicates the problem of estimating the crop biomass from single-frequency/polarization radiometric measurements. Fortunately, further information on vegetation biomass can be obtained by using the polarization index (PI) [49], i.e., the difference between the vertical and horizontal components of T_b normalized to their average value. Indeed, the polarized emission from an almost homogeneous and smooth soil is smoothed by the volumetric effect of the vegetation layer. Based on Equation (16), the following simple model to relate the polarization index to the plant water content was derived by Paloscia and Pampaloni [53]:

$$PI\left(PWC,\mu\right) = \frac{PI\left(0,\mu\right)}{\left(1+PWC\right)^{k/\mu\sqrt{\lambda}}} , \qquad (18)$$

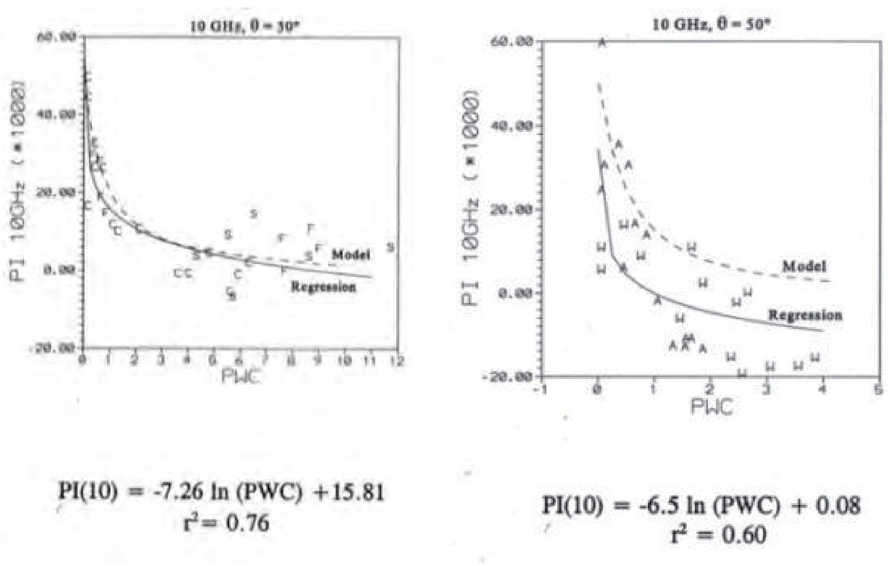

Figure 8. The polarization index at 10 GHz as a function of the plant water content for (a) wide-leaf crops and (b) small-leaf crops.

where $PI(0,\mu)$ represents the polarization index of bare soil, λ is the observation wavelength, and k is a crop factor, independent of wavelength, which was empirically found to be $0.16\ \mathrm{m}^{1/2}$ for corn and $0.25\ \mathrm{m}^{1/2}$ for alfalfa.

Experimental data and model simulations have shown that the trend of polarization index as a function of plant water content decreases for both categories of crops (Figure 8). This makes it possible to establish an inversion approach to retrieve vegetation biomass independently of crop type. Maps of plant water content retrieved from polarization index at X band were obtained by Santi et al. [54] (Figure 9) in the context of an algorithm based on a neural network developed for generating soil moisture and snow-depth maps from AMSRE data.

In addition to the polarization index, the potential of the frequency index, i.e., the difference between T_b at 10 GHz and 36 GHz, was also examined by Paloscia and Pampaloni [55], whilst other indices, derived from the AMSRE channels, have been more recently proposed by Shi et al. [56]. In this work, a microwave vegetation index, MVI, was defined, based on the observation that the brightness temperatures observed at a given polarization with two adjacent AMSR-E frequencies can be described by the following linear function:

$$T_b(f_2) = A(f_1, f_2) + B(f_1, f_2) T_b(f_1), \qquad (19)$$

where the A and B parameters are independent of the underlying soil surface signal, and can be derived directly using dual-frequency and dual-polarization measurements. A is positively correlated to the normalized difference vegetation index (NDVI), which is the most-used indicator of green vegetation, and is affected by the vegetation properties and by the surface physical temperature [57]. B is negatively correlated to the normalized difference vegetation index, and only depends on the vegetation properties. A comparison of the microwave vegetation index with the normalized difference vegetation index measurements derived from MODIS for the year 2003 is shown in Figure 10.

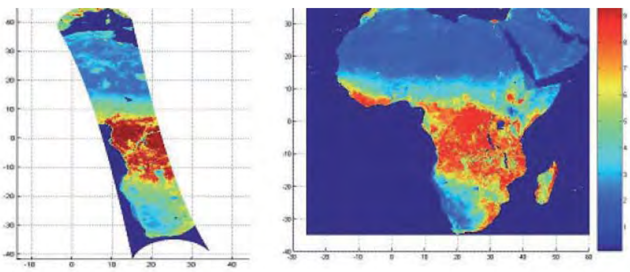

Figure 9. A map of plant water content of a portion of Africa, retrieved from the AMSR-E microwave polarization index at X-band (left), compared pixel-by-pixel with the normalized vegetation index from SPOT 4 [75].

5.3.2 Forests

A review of experimental and theoretical research on microwave emission from forests on a regional and global scale was provided in [58]. Initial results achieved by the scientists of the Russian Academy of Sciences, with airborne sensors in the frequency range of 1 GHz to 36 GHz [48], showed that the emissivity of a dense forest over dry soil was close to unity within the whole of the wavelength range. Airborne campaigns using multi-frequency radiometers were conducted by the Helsinki University of Technology (now Aalto University) of Finland on boreal forests [59]; by IFAC-CNR, Italy, on six broadleaved forests [60]; and by CNES, France, over a coniferous forest [61]. A few studies were also conducted using satellite sensors (e.g., [62, 63]).

The spectra of five forests obtained by aircraft measurements between 1.4 GHz and 10 GHz showed that at the lowest frequency, forests of the same species but with different biomass had significantly different values of T_n, while at the higher frequencies, T_n showed an appreciable sensitivity to forest type [64]. The same data, represented as a function of woody volume (WV) (Figure 11) showed that at the higher frequencies, T_n had a quick saturation followed by an almost flat plateau, with a slight decrease for further increments of biomass. Conversely, at L band, we could see a much more gradual rise, with a saturation at a high value of woody volume that pointed out the best performance of the lower frequencies in estimating forest biomass. These trends, which recall those already observed in agricultural crops, can be interpreted as an initial phase,

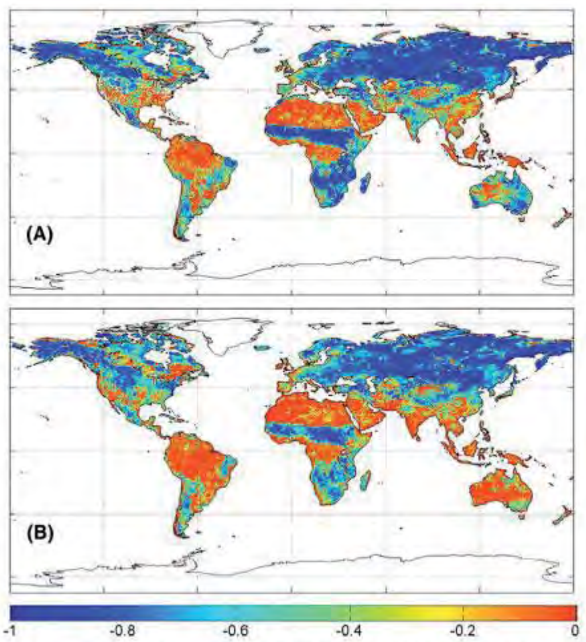

Figure 10. The correlation coefficient between the normalized difference vegetation index and the microwave vegetation index: B(6.9 GHz, 10.6 GHz) in A and B(10.6 GHz, 18.7 GHz) in B, calculated in 2003 [56].

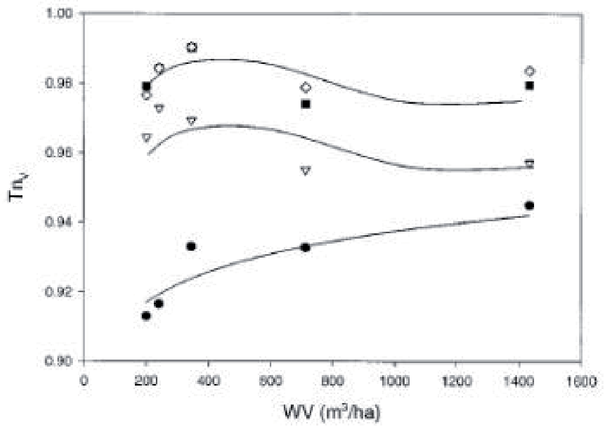

Figure 11. The normalized brightness temperature, T_n, measured at four frequencies as a function of woody volume (WV) (◊ is Ka band, ■ is X band, v is C band, ● is L band). The continuous lines represent regression equations (logarithmic at L band and polynomial at Ka, X, and C bands) [64]

Figure 12. A schematic drawing of the microwave measurements of [70]: (1) downward (soil + trees), (2) downward under crown (soil), (3) upward (trees), (4) sky [65].

where absorption is dominant, and a subsequent stage, where scattering plays a major role. Similar measurements carried out in summer and winter showed no significant difference between the two dates at L band, while at the other frequencies, the highest difference was found for low values of biomass. A sensitivity analysis performed with a discrete element radiative transfer model showed that total emission from trees is mainly due to crowns, and that the main contribution to crown emission is due to primary and medium branches [64].

Measurements of T_n from L to Ka band, H and V polarizations, were performed with ground-based radiometers by Santi et al. [65]. This was done on two forest stands of poplar and pine on different dates and at different incidence and azimuth angles, looking downward (from the tops of trees and from below the crown) and upward (from the soil level) (Figure 12). The frequency spectra of downward-looking measurements from the top showed similar trends in all seasons, with a fairly steep change from the L to the C band, followed by an almost flat behavior up to the Ka band (Figure 13). Measurements in upward directions showed increasing values of T_b as the observation angle increased. In this case, a significant difference was noted between observations of trees with and without leaves, with a most significant effect at the higher frequencies.

The simple tau-omega model (Equation (13)), together with three independent measurements – i.e., downward looking from the top of trees and close to the soil, and upward looking from the soil – made it possible to compute ω, the optical depth, τ, and the soil reflectivity at the L and C bands. The resulting transmissivity confirmed that the effect of leaves is more important at the C band than at the L band. According to these results, it appears that for the observed forest type, some information on soil moisture

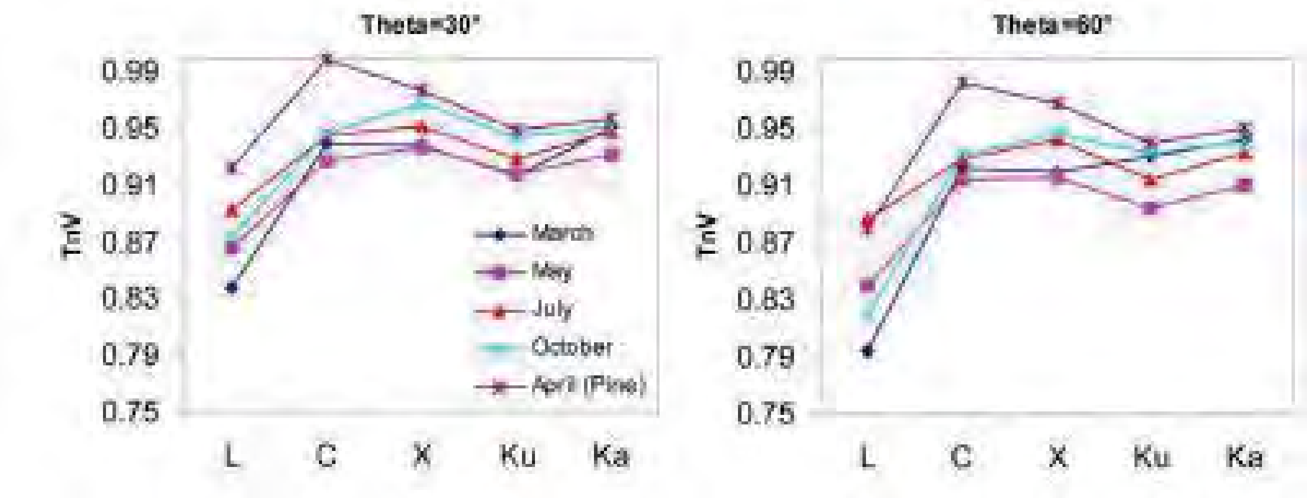

Figure 13. The spectra of downward measurements of T_n (V polarization) obtained on the poplar and pine stands at (left) $\theta = 30°$ and (right) $\theta = 60°$ in March, April, May, July, and October 2006 [65].

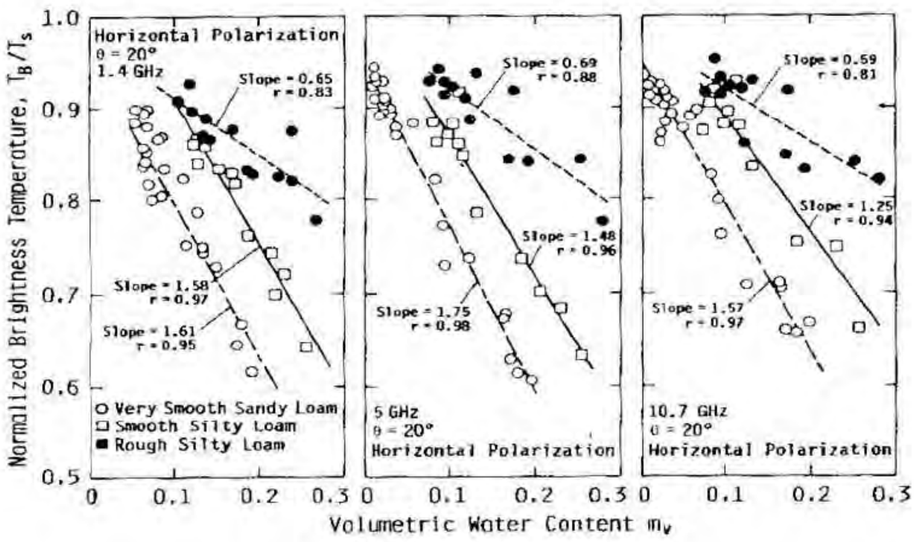

Figure 14. The brightness temperature of bare soil normalized to its thermometric temperature as a function of volumetric water content at three frequencies: (a) 1.4 GHz, (b) 5 GHz, and (c) 10.7 GHz. The data were for three fields with different soil textures and surface roughness values [68].

under defoliated trees can be obtained at both the L and C bands. The transmissivities of deciduous trees at different foliation stages were also measured by Mätzler [66] in a wide frequency range (1 GH to 95 GHz) and Guglielmetti et al. [67] at L band, with similar results.

5.4 Remote Sensing of Soil Moisture of Vegetated Terrains

The research on microwave radiometry of soil moisture content (SMC) began in the late 1960s-early 1970s with the first experiments and theoretical studies carried out in the former Soviet Union and United States (e.g., [49, 68]). Since 1980, a progressive intensification of field experiments as well as of theoretical models has led to a reliable collection of knowledge about the relationships between T_b in a rather wide frequency range and soil characteristics, including texture and surface roughness (e.g., Figure 14). An excellent summary of the early results achieved can be found in [1]. As expected, the highest sensitivity to moisture is in the low range of microwaves, and most attention for practical applications has been given to the protected band for radio astronomy at 1.4 GHz.

The first study on microwave radiometry of soil moisture in Europe was carried out in the summer of 1988 by the Microwave Remote Sensing Group of CNR-IROE, Italy (now CNR-IFAC), under a grant by the European Space Agency [69, 70]. The experiments included surveys with helicopter-borne radiometers at L, X, and Ka bands on agricultural fields. Experimental results at L band, H polarization, and $\theta = 10°$ incidence angle were fitted by

$$T_{nh}(10) = 0.90 - 0.010 m_v \,. \qquad (20)$$

The influence of a vegetation layer on soil emission was first characterized in [40] by a slope-decrease coefficient, β, of the dependence of the brightness temperature as a function of soil moisture, $T_{bs}(m_v)$, that is,

$$\frac{\Delta T_{bsv}}{\Delta m_v} = \beta \frac{\Delta T_{bs}}{\Delta m_v} \,, \qquad (21)$$

where ΔT_{bsv} and ΔT_{bs} are respectively the variations of the brightness temperature of soil and of the "soil/vegetation system" due to soil moisture variations Δm_v. The value of β depends on the vegetation type, its water content, and the observation frequency. A first estimation of β as a function of wavelength for the three types of vegetation taken into consideration can be obtained by using the diagram given by Chukhlantsev in [19] (Figure 15).

In the 1990s, a great deal of experimental research was carried out by several research groups, primarily in the USA, but also in France, Italy, Spain, Switzerland, and The Netherlands. A good summary of the activities carried in the last decade of the past century can be found in the special issue of the *IEEE Transactions on Geoscience and Remote Sensing* published in August 2001. Most of the experiments were conducted in preparation for the launch of the AMSR-E and SMOS missions, which were the first satellite programs to incorporate soil moisture content as a standard product. In the first case, focus was on exploiting the sensitivity of the C-band channel, the lowest frequency available on AMSRE, to soil moisture content, and on the capabilities of multi-frequency observations for improving the retrieval accuracy. In the case of SMOS, specifically designed for soil moisture retrieval, research was mostly focused on the evaluation of spurious parameters affecting L-band emission, including radio-frequency interference. Large airborne experiments, called the Southern Great Plains Hydrology Experiments, were conducted in the USA in 1997 (SGP97) and 1999 (SGP99) to address significant gaps in knowledge and to validate retrieval algorithms. SGP97 was

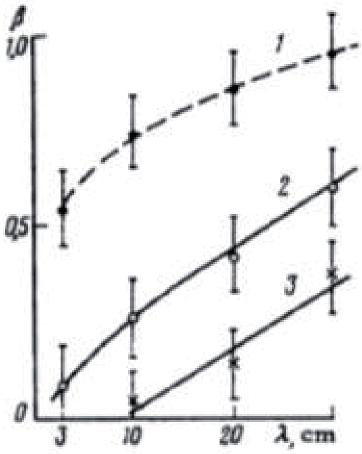

Figure 15. The slope-reduction factor, β of the emissivity-soil moisture function as a function of the wavelength for (1) small-leaf, (2) wide-leaf, and (3) forest [19].

addressed to L-band measurements only, while in SGP99, the Passive and Active L- and S-band airborne sensor (PALS) was used together with the C-band Polarimetric Scanning Radiometer (PSR/C) to provide information on the sensitivities of multi-channel low-frequency measurements to soil moisture content for various vegetation conditions. The 1.41 GHz channel showed the greatest sensitivity, with a retrieval accuracy of 2.3%. However, PSR/C images showed spatial and temporal patterns consistent with meteorological and soil conditions, and indicated the potential of the AMSR-E in providing useful soil moisture information.

Various approaches have been considered for retrieving soil moisture content from the AMSRE frequency channels, which primarily differ in the methods used to correct for the effects of soil texture, roughness, vegetation, and surface temperature. A verified assumption was that over most land areas at the AMSR-E footprint scale, the effects of variability in soil texture and roughness on the observed brightness temperature are small compared to the effect of variability in soil moisture content. The vegetation optical depth can also be approximated as non-time-varying. However, this assumption, together with that of spatial uniformity, must be considered a potential source of error. As summarized by Njoku et al. in [71], soil moisture content retrieval approaches investigated in the early studies related to AMSRE included single-channel retrieval with sequential corrections for soil temperature and plant water content using ancillary data; iterative forward model corrections for soil temperature and plant water content using multi-channel brightness temperatures; and normalization and correction for vegetation temperature and water content using multi-frequency polarization indices. Other methods based on Bayesian iterative inversion of a forward model or neural networks have also been investigated.

A first algorithm implemented by Njoku and Li for NASA [72] used a radiative-transfer model and an iterative least-squares algorithm, based on six radiometric channels. It assumed uniform temperature and moisture over the sensing depths of the frequencies used (using nighttime measurements), and characterized the frequency dependence of the vegetation attenuation factor by using independent measurements from field experiments or analysis of satellite data over terrain of known characteristics. More recently, the NASA algorithm was significantly modified by Njoku and Chan [73]. In this version, called the Normalized Polarization Difference algorithm (NPD), it used normalized polarization ratios (PRs) of the AMSR-E channel brightness temperatures. Soil moisture was computed using the deviation of the polarization ratio at 10.65 GHz from a baseline value. Vegetation and roughness effects were accounted for using polarization ratios at 10.65 GHz and 18.7 GHz in empirical relationships. Baseline values were established from the monthly minima at each grid cell.

The Hydroalgo algorithm, proposed in [74, 75], was based on the sensitivity to moisture of both T_b and the *polarization index* at C band. It used the polarization index at X band to correct for the effect of vegetation. Comparing the values of soil moisture content retrieved from airborne measurements with those measured on the ground, the authors found a correlation coefficient of 0.78, with a standard error of estimate of $SE = 4.31$.

The Land Parameter Retrieval Model (LPRM) [76] is a three-parameter retrieval model (soil moisture, vegetation water content, and soil/canopy temperature) for passive microwave data, based on a microwave radiative-transfer model. It uses the dual-polarized 10.65 GHz data for the retrieval of both surface soil moisture and vegetation water content. The land surface temperature is derived separately from the vertically polarized 36.5 GHz channel. An example of a soil moisture content map generated with the algorithm in [75] from AMSR-E data is shown in Figure 16.

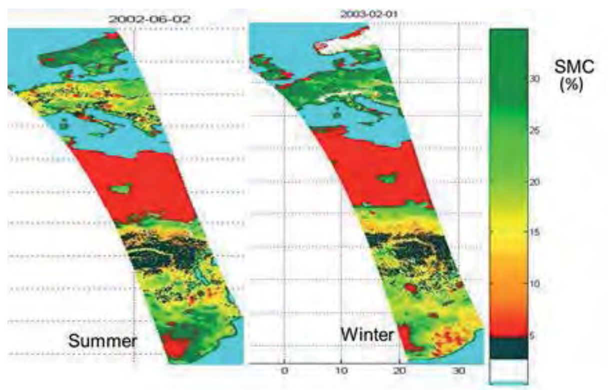

Figure 16. A map of soil moisture (portions of Europe and Africa) obtained in summer (left) and winter (right) with the algorithm described in [75] (brown dark and white areas represent dense vegetation and snow cover, respectively) The volumetric soil moisture content (SMC) scale goes from 0 (black) to 35% (dark green).

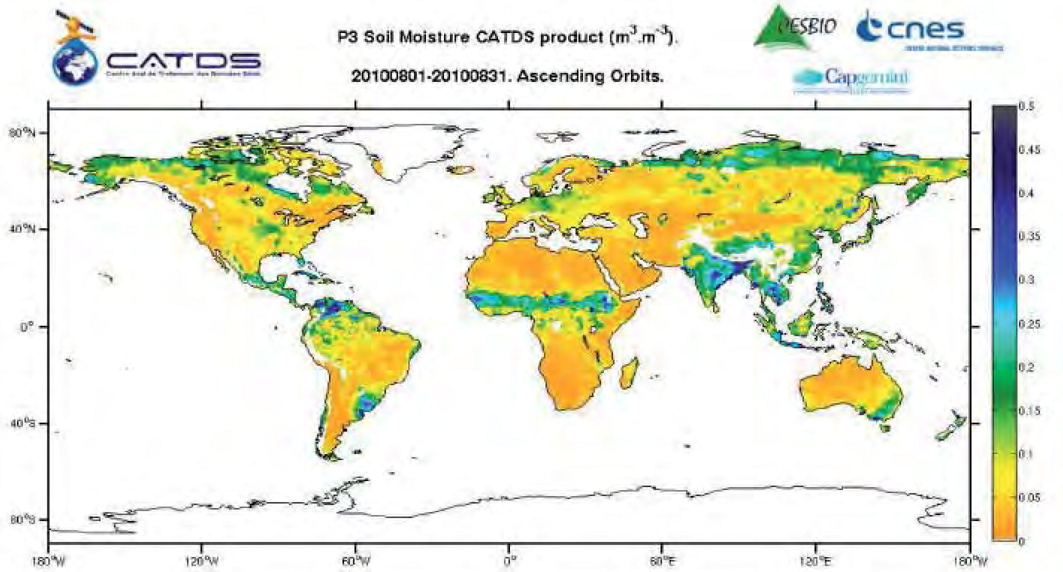

Figure 17. A global map of soil moisture derived from SMOS data for the month of August 2010. The monthly composite/color scale is soil moisture expressed in m^3/m^3 [82].

Despite the fact that several sophisticated models have been developed to characterize emission from vegetation, in almost all these algorithms, the correction for the vegetation effect is performed on the basis of the simple tau-omega model, assuming the relationships between optical depth of vegetation and plant water content given as in [50] or in [52].

The four algorithms – the NASA and JAXA AMSR-E standard products, the Land Parameter Retrieval Model, and a single-channel algorithm (SCA) proposed by Jackson in [77] – were validated in [78] by comparing them with ground data taken on four instrumented watersheds located in different climatic regions of the US. The JAXA algorithm was found to perform better than the NASA algorithm under light-vegetation conditions, although the NASA algorithm remained more reliable for moderate vegetation. However, both algorithms had a quite large bias in all cases. The single-channel algorithm had the lowest overall rmse (lower than the mission requirement of $0.06\ m^3/m^3$) with a small bias. The Land Parameter Retrieval Model had a very large overestimation bias and retrieval errors. Based upon the results presented earlier and the mission requirement for rmse ($< 0.06\ m^3/m^3$), the NASA and single-channel algorithms met or exceeded the specified accuracy. When site-specific corrections were applied, all algorithms had approximately the same error level and correlation.

The theoretical bases of five soil moisture retrieval approaches described in [73, 75-77, 79] were examined in [80] to understand the differences and to develop a suitable approach for improving the algorithm currently used by NASA in producing its operational soil moisture product. The study indicated that the differences among algorithms lie in the specific parameterizations and assumptions of each algorithm. The comparative overview of such approaches was linked to differences found in the soil moisture retrievals, leading to suggestions for improvements and increased reliability in these algorithms.

The SMOS satellite was launched on November 2, 2009, with the goal of delivering global soil moisture content maps with an accuracy of $0.04\ m^3/m^3$. The retrieval algorithm to convert T_b to geophysical products (level 2 data) was implemented on the basis of previous studies performed to evaluate the effects of the spurious parameters (vegetation canopy, soil temperature, and surface roughness) on the sensitivity of microwave emission to soil moisture (e.g., [81]). The algorithm was based on an iterative approach to minimize a cost function, the main component of which was the sum of the squared weighted differences between measured and modeled T_b data, for various incidence angles [82]. An example of the achieved global map is in Figure 17.

A comparison of SMOS operational products with data collected on several sites by hydrological networks suggests that SMOS meets the mission requirement of $0.04\ m^3/m^3$ over specific nominal cases, but differences are observed over many sites.

Many field experiments have been carried out and are still underway to validate the reconstructed brightness temperatures and soil moisture retrievals from AMSR-2 and SMOS by comparing radiometric data with in-situ measurements. Due to the challenge of covering the whole extent of the wide radiometer pixel by ground sampling, several validation strategies have been based on the assumption that local observations are representative of a much larger spatial extent. In the heterogeneous case, where this assumption does not hold, up-scaling (aggregation) and downscaling (disaggregation) approaches, or combinations of the two methods, were used. The analysis of within-pixel variability have shown that errors in the retrieved soil moisture content were generally negligible for a heterogeneous bare soil, and less than 3% of the actual soil moisture for a pixel that is heterogeneous in vegetation and soil moisture.

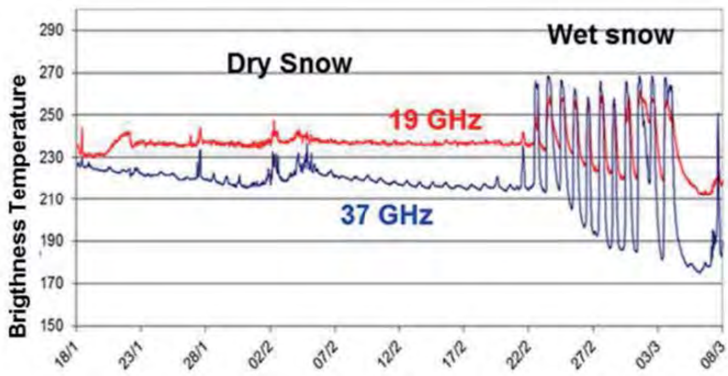

Figure 18. A typical winter-spring trend of T_b for a snow layer in the Alps from mid-January to early March.

5.5 Remote Sensing of Snow Cover

Terrestrial dry snow is a mixture of ice particles and air voids. After a snowfall, the shapes of the ice particles in dry snow are modified by metamorphism because the ice crystals seek equilibrium, for which the ratio of surface area to volume is minimum. A snow cover is thus subjected to continuous evolution, with changes in its characteristics that complicate the interpretation of experimental data.

The sensitivity of microwave emission to snow cover has been pointed out since the early experimental (e.g., [83-85]) and theoretical (e.g., [86]) studies. Experiments carried out by Hofer and Mätzler [84] demonstrated that microwave radiometers can separate three seasonal snow types (winter, spring, and summer). Radiation emitted at the lower frequencies of the microwave band (lower than about 6 GHz to 8 GHz) by soil covered with a shallow layer of dry snow is mostly influenced by the soil conditions below the snow pack. However, at the higher frequencies, the role played by volume scattering increases, and microwave emission becomes sensitive to the presence of snow. Figure 18 shows a typical trend of brightness temperature of a snow cover as a function of time during a winter-spring cycle. As the snow depth increases from mid-January to the end of February, emission decreases with only small fluctuations at Ka band, while it remains almost constant at Ku band. As the diurnal temperature increases above 0°C, it triggers a series of increasing/decreasing cycles of T_b due to snow melting and refreezing, until the final melt of snow. Indeed, if snow melts, the presence of liquid water causes a strong increase in emissivity, especially at high frequencies, and a transition from volume to surface scattering. The average spectra of the brightness temperature show that emission of dry and refrozen snow decreases with frequency, whereas emission from wet snow displays the opposite trend (e.g., [87]). The main factors that affect microwave emission from dry snow are depth (SD), grain size (GS), density (d), and layer stratification. The most interesting

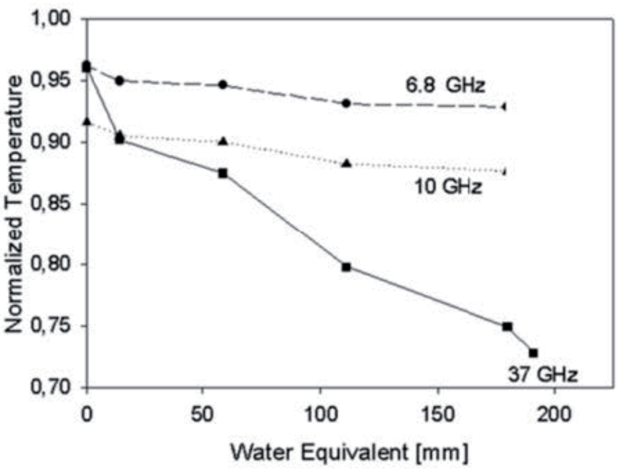

Figure 19. The normalized temperature at 6.8 GHz, 10 GHz, and 37 GHz (at _ $\theta = 40$, H polarization) as a function of the snow water equivalent [87].

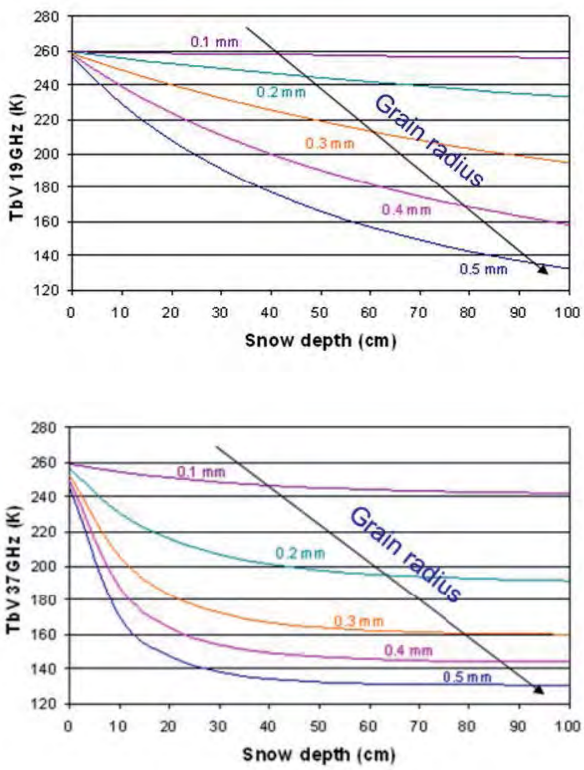

Figure 20. The simulated brightness temperature of dry snow at (a) 19 GHz and (b) 37 GHz as a function of snow depth and grain radius.

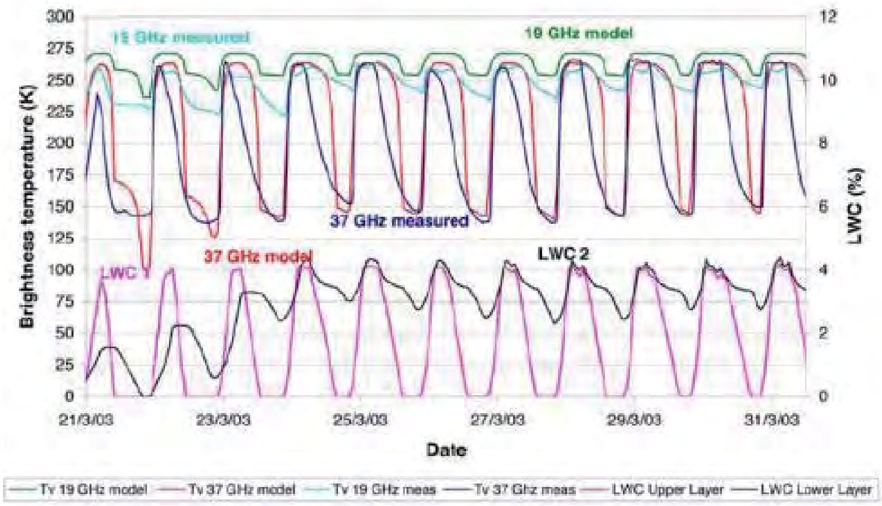

Figure 21. Experimental and simulated brightness temperatures at 19 GHz and 37 GHz (vertical polarization), together with simulated volumetric liquid water content (LWC), of the two snow layers as functions of time [89].

parameter for applications is the snow water equivalent (SWE), equal to the product of snow depth times density. Depending on snow characteristics, the emissivity of dry snow may increase or decrease as snow depth increases, but for most types of natural snow covers, high-frequency emission generally decreases with snow depth and snow water equivalent (Figure 19).

The problem of estimating the effective (weighed average) temperature and the thickness of the layer – which mostly contributes to microwave emission – in order to properly normalize the brightness temperature and assume it to be an equivalent emissivity of the snow pack was addressed by Brogioni et al. [88] with a correlation analysis of the small diurnal fluctuations.

A great utility of the EM models is the possibility of performing sensitivity analyses. For example, Figure 20 shows the sensitivity of T_b to the depth of dry snow for different grain sizes obtained with the DMRT-QCA model.

A temporal sequence of measured and simulated T_b at 19 GHz and 37 GHz of a snow cover during the melting cycles is shown in Figure 21, together with the volumetric liquid water content (LWC), simulated with a hydrological model, which considered the snow cover to be divided into an upper 10 cm layer and the remaining layer below [89]. Electromagnetic simulations were performed with a two-layer model based on the strong fluctuation theory coupled to the smooth soil surface. The increase in T_b during the melting phases was as high as 40 K at 19 GHz, and more than 100 K at 37 GHz, and depended on changes in liquid water content and on snow metamorphism. We could see that in spite of a certain systematic overestimation of T_b at 19 GHz, the model well reproduced the trends of experimental data at both frequencies and the absolute values at 37 GHz. The underestimation of T_b (37 GHz) on the nights of March 21-23 could be explained by taking into account that the hydrological snow pack model is only a two-phase (ice and water) model: it neglects vapor sublimation and condensation. It so happened that the condensation, due to formation of a "firnspiegel" upper layer, impervious to water vapor, observed on the March 20 survey, was such that a thin film of water, able to keep a relatively high brightness at night, too, was neither simulated by the snow pack nor, as a consequence, by the electromagnetic

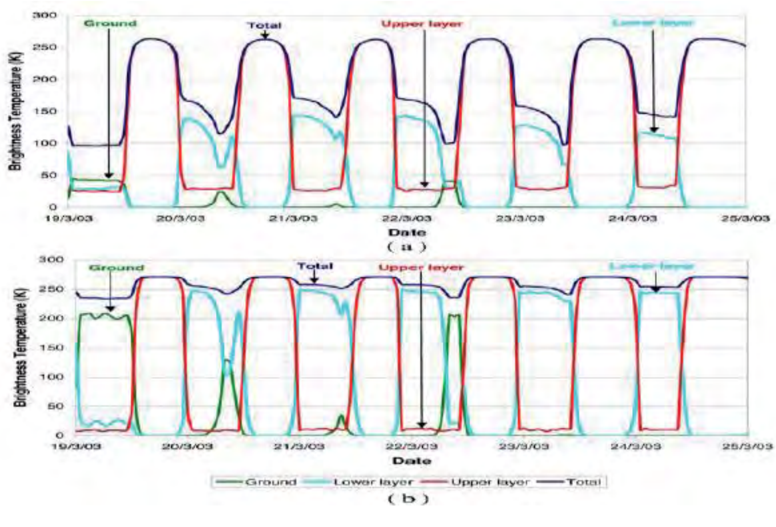

Figure 22. The contributions of emission from soil and from the two snow layers to total brightness temperature: (a) 37 GHz and (b) 19 GHz (red is the upper layer, light blue is the lower layer, green is the ground, dark blue is the total emission) [89].

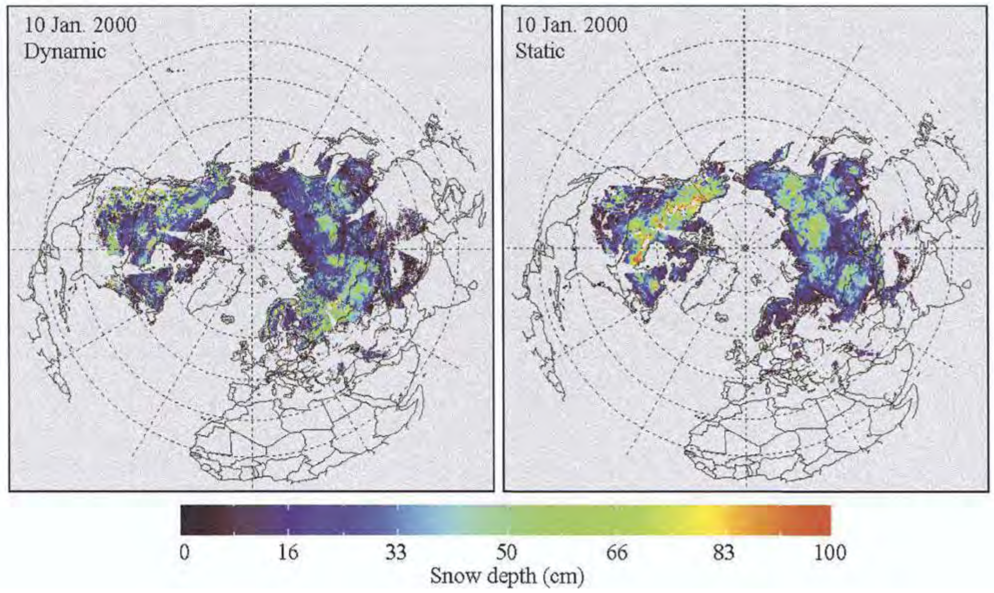

Figure 23. A comparison of the snow depth for January 10, 2001, estimated using the static and dynamic algorithms [92].

model. Model simulation also made it possible to separate the contributions of the upper and lower layers of snow as well as that of soil (Figure 22).

The retrieval of snow depth (SD) or snow-water equivalent of dry snow is mostly based on an empirical combination of two or more frequency and polarization channels available from satellite sensors. The first investigations by Chang et al. [85] pointed out that the frequency index (FI) – i.e., the difference between the low (18 GHz/19 GHz) and high (35 GHz/37 GHz) frequency T_b – can be related to the snow-water equivalent or snow depth. Various combinations of frequency and polarization channels from satellite sensors were correlated to snow-water equivalent by several authors (e.g., [90, 91]). All these approaches generally assumed that the average snow density and grain size did not change over time. However, changes in these quantities can also affect the difference between low- and high-frequency T_b. A dynamic approach to retrieving global snow-depth estimation was presented in Kelly et al. [92]. The algorithm was still based on frequency index, and adjusted the dimensional coefficient (cmK^{-1}) to retrieve snow depth by predicting how the grain size and snow density might vary and affect the emission from a snow pack by using a DMRT model. Compared with static approaches, this dynamic algorithm tended to estimate snow depth with greater root-mean-squared error but lower mean error (Figure 23). A novel approach to improving the accuracy in snow-water equivalent retrieval by assimilating satellite radiometric data and ground-based observations was introduced by Pulliainen [93]. Another method to retrieve the snow depth/snow-water equivalent based on the minimization of simulated and measured (SMM/I) data and optimized to operate by using data from AMSR-E /2 was developed by Santi et al. [41] as a part of a pre-operational algorithm (Hydro-algo), which was also able to produce real-time maps of soil moisture and vegetation biomass.

6. Conclusions

Microwave radiometry has proven to be a good tool for estimating land-surface parameters of the water cycle, and has provided significant contributions toward increasing our knowledge of the Earth as a system. Data from satellite radiometers, singly or combined with other sensor types, are currently used to produce operational or preoperational land products that meet the user requirements as specified by the space agencies after various consultation meetings and working groups. Most efforts were made for the retrieval of soil moisture from AMSR-E/2 and SMOS. Numerous validation and verification studies showed that both sensors can meet the mission requirements of $0.06\ \mathrm{m}^3/\mathrm{m}^3$ and $0.04\ \mathrm{m}^3/\mathrm{m}^3$, respectively, over specific nominal cases. However, differences were observed over many sites, depending on the characteristics of the observed surfaces (vegetation, topography, etc).

Volumetric soil moisture products from AMSR2 in the range 0% to 40%, obtained over global land areas including arid and cold regions, except areas covered by vegetation water content higher than $2\ \mathrm{kg/m}^2$, are distributed by JAXA. The standard accuracy, defined as the mean absolute error of instantaneous observations, is $\pm 10\%$, with a goal of $\pm 5\%$. The Soil Moisture Operational Products System (SMOPS) of NOAA National Environmental Satellite Data and Information Service (NESDIS) delivers global soil moisture maps (%vol/vol) of the surface (top 1 cm to 5 cm) soil layer generated in six-hourly and daily intervals, and mapped with a cylindrical projection on 0.25° × 0.25°

grids. The procedure used first retrieves soil moisture from AMSR2, and then combines its baseline retrievals with those from SMOS and other available satellite sensors to improve the spatial and temporal coverage of the AMSR2 observations.

The European Space Agency (ESA) delivers SMOS soil moisture products online via the Earth Observation Link (EOLI), the ESA client for Earth Observation Catalogue and Ordering Services.

Due to the strong sensitivity of microwave emission to snow grain size, the accuracy of snow depth and snow water equivalent (SWE) retrieval significantly depends on snow type. Global maps of snow depth are distributed by Jaxa on a 30 km grid with a standard accuracy (mean absolute error of instantaneous observations) of ±20 cm. Snow water equivalent maps of the northern and southern hemisphere at 25 km equal-area scalable Earth grids (EASE-grids), produced by the National Ice and Snow Data Center (NSIDC) from AMSR-E data, are available from June 19, 2002 to October 3, 2011 via FTP. NESDIS products from AMSR2 snow cover, snow depth, and snow-water equivalent will be operational in late 2015 or early 2016.

Although the products delivered by the international agencies have reached reasonably good standards, further work needs to be carried out to increase the accuracy and the reliability of the retrieval algorithms in order to fully meet the operational specifications requested in the various applications. The coarse ground resolution of microwave radiometers from satellites limits their use to global observation, although operational services on specific areas can be carried out with airborne sensors. Moreover, several methods to enhance the radiometer's spatial resolution have been proposed in the literature (e.g., [94]). Most of these are based on image-processing techniques or special reconstruction algorithms [95]. These latter aim at retrieving the geophysical parameters on a finer grid by solving a linear inversion problem, similar to that of antenna-pattern deconvolution. The problem belongs to the class of Fredholm integral equations of the first kind, the kernel of which depends on the antenna's gain and on the scanning configuration. Significant improvements in the retrieval of soil moisture are expected by the combination of active and passive instruments of the NASA/SMAP mission.

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Precise Time and Frequency Transfer

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Abstract

This article reviews modern time- and frequency-transfer technologies. The several techniques differ in precision, accuracy, complexity, and cost, and can be considered complementary. The paper discusses the current status and future developments of these techniques.

1. Introduction

In the last few decades, as atomic frequency standards have attained greater precision and accuracy, the precision and accuracy of operational time-transfer modes have improved in parallel. This development was driven by the fact that even a perfect clock would be of little use if its time could not be distributed to users, who have a variety of robustness, accuracy, and precision requirements (RAPRS). In order to assure reliable time to their users, the timing laboratories themselves must meet a more-stringent standard than any of their end-user's requirements. The most demanding requirements come from space systems, notably global navigation satellite systems (GNSS), the end-to-end robustness, accuracy, and precision requirements of which for internal operations and interoperability are currently at the level of one nanosecond. Ground-based navigational systems that serve as backups or supplements would in principle have the same requirements; however, the presence of other sources of error can mask their time-transfer noise. In general, the robustness, accuracy, and precision requirements of satellite communication systems are at the microsecond level, and this is consistent with the ITU frequency specification of 1.E-11. The financial communities have a need for accurate time-stamping and pc synchronization. In the United States, the official specification is effectively one second [1], although some financial brokers have asked for considerably more-accurate synchronization. So as to be able to reliably meet the demands of their users, the timing labs themselves have robustness, accuracy, and precision requirements that would best exceed those of their most critical users by an order of magnitude.

This review concentrates on the status and future of three fully operational systems at this time: network time protocol (NTP); two-way satellite time and frequency transfer (TWSTFT, also known as TWSTT); and GPS (which can be considered as a model for other GNSS systems, such as GLONASS, GALILEO, and BEIDOU). We very briefly discuss fiber-optic technology, which although only operational on links used for the generation of International Atomic Time (TAI) [2], promises the greatest precision of all; and long-range radio navigation (LORAN), which is finding a new value as a backup to GNSS. Although this review attempts to describe the performance of the several techniques at their current level of operational maturity, they are all improving, as will be necessary for future applications such as the evaluation of atomic fountains. Atomic fountains can now achieve operational precisions at the level of 1.E-16 over days if not months [3], and in the next decade, optical frequency standards are expected to be up to two orders of magnitude quieter [4, 5].

2. Network Time Protocol, or NTP

Network time protocol is an Internet-based hierarchal time-transfer technique in which client computers exchange time-labeled packets with servers. Servers receiving their time independently of network time protocol, such as

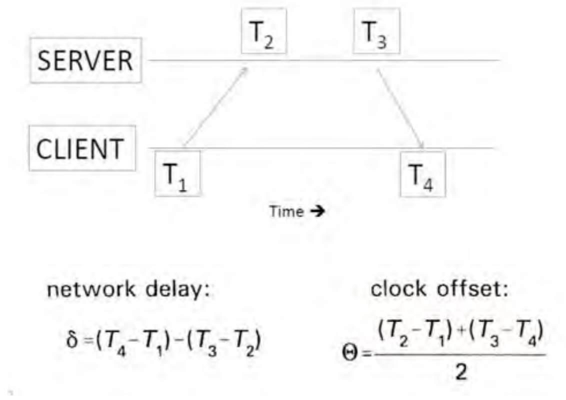

Figure 1. A schematic diagram of network time protocol time transfer. The Ts represent the times of transmission/reception as measured by the local clock, and the formulas show how the time difference and network delay are computed.

from GPS, are termed stratum 1. They distribute time to clients that can themselves be servers: a server receiving time from a set of stratum N receivers would be stratum $N+1$. Internet servers receive billions of requests per day from tens of millions of users, if not hundreds of millions. Along with simply setting the date on computers, network time protocol is widely used in all sorts of networks for such purposes as database management and official time-stamping. Specified by the Internet Engineering Task Force (IETF), computer code and information can be found in www.ntp.org, and the writings of David Mills [6]. Network time protocol is initiated when a client computer sends a small packet to a time server. Minimized through use of universal datum protocol (UDP), the packet contains little more than the client's time when it was generated and the return IP address. Upon receipt of the packet, the server shortly thereafter sends a return packet that contains the original time stamp, along with the server's time when it received the packet, and the time it sent off the return packet. The client records the return packet's time of reception. That is sufficient to estimate the difference between the server and client clocks, and the roundtrip travel time, assuming that the travel-time over the Internet was the same in both directions (Figure 1).

The error budget is dominated by the network travel-time asymmetry, which would be expected to be larger for more-distant servers. Figure 2 shows that nearby servers are slightly more stable in a statistical sense [7]. However, many forms of deviations are not always captured by the statistics, and an example of a transient effect is shown in Figure 3 [7]. Here, the observed difference between a server in St. Louis, Missouri, and one at the US Naval Observatory became bimodal and biased at the level of tens of milliseconds. Three other Washington clients observed variations over the same period, which differed considerably in detail among themselves. Still larger variations, persistent over weeks, have been observed between continents; again, they appeared with different patterns and magnitudes for different clients, who coincidentally had different platforms and versions of the network time protocol installed. Editing data on the basis of excessive roundtrip travel time can identify bad time transfer exchanges. Not always, but in the case of Figure 3, deleting the sections with high round-trip delays would have been useful in removing the bimodal behavior, although a bias would have remained.

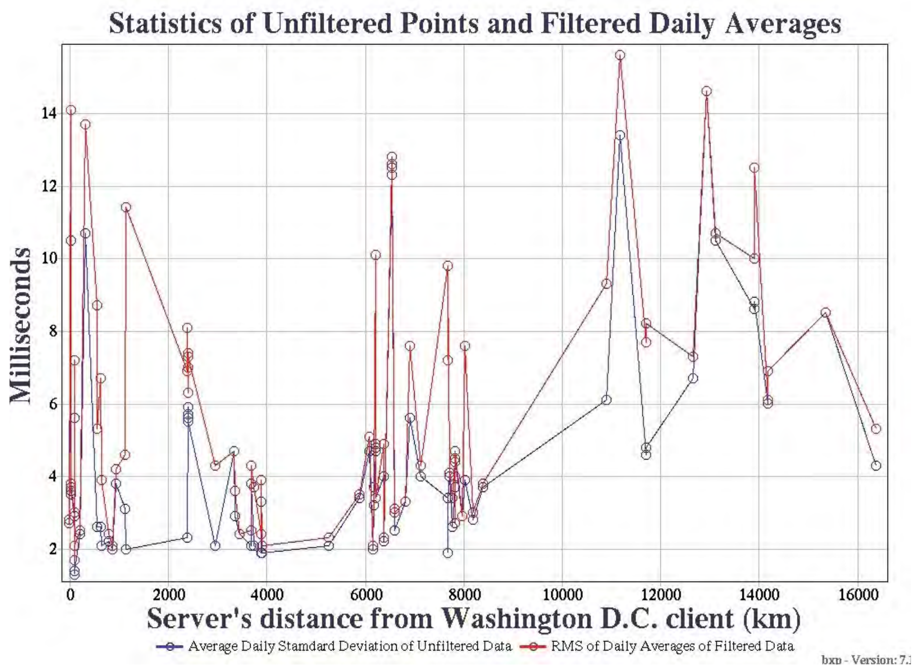

Figure 2. The filtered daily and unfiltered sub-daily standard deviation of network time protocol as seen by a Washington DC client. Pool servers were arbitrarily assigned a distance of 111 km (one degree in latitude).

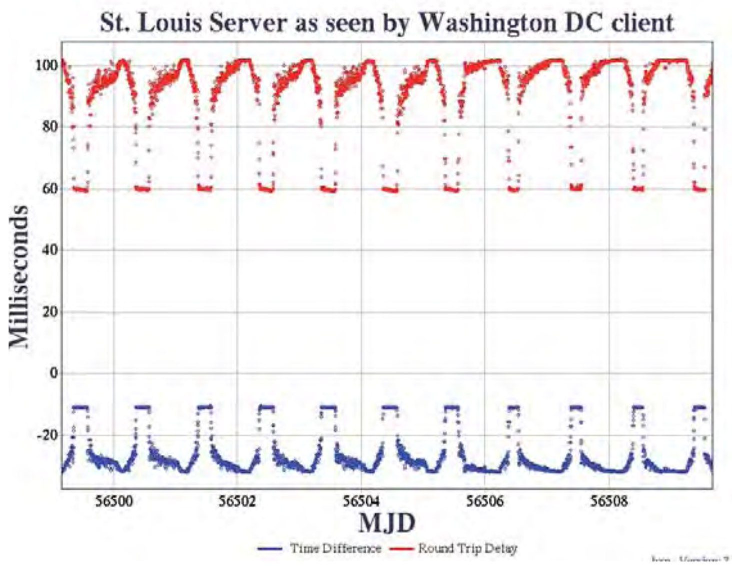

Figure 3. A timing error pattern of a server in St. Louis, Missouri, as seen by a client referenced to UTC (USNO) in Washington, DC [7]. The red upper curve is the round-trip travel time over the Internet; the blue lower curve is the observed timing difference from UTC (USNO). MJD, the modified Julian date, is the number of calendar days since November 18, 1858.

In recent years, a demand has grown for authenticated network time protocol, by which the identity of the server is cryptographically verified. Several laboratories offer this service, occasionally via a for-profit third party. Unfortunately, authentication cannot protect against server failure. Authentication would also still not protect against situations in which an intermediate network component systematically delays packets traveling in one direction. Authentication could become vulnerable to exploitation of cryptographic collisions, enabling a would-be saboteur to rewrite signed time-stamps in an undetectable manner, although the distributed manner in which packets travel over the Internet would offer some protection. It is always recommended that clients always use several redundant servers for an integrity check. Some providers, such as NIST and others listed in www.pool.ntp.org, offer a service that pools servers so that a client randomly points to a variety of nearby servers.

The network time protocol format carries leap-second notifications, for which a table created at NIST has become an industry standard [8]. Unfortunately, every recent implementation of a leap second has resulted in many servers giving false time, sometimes for one day or longer. Conversely, it has been reported by an authoritative but unpublished source that since 2008, on every December 31 and June 30 when a leap second was not in fact called for, some server somewhere in the world erroneously set the leap second indicator [9].

Another widely used network time-transfer method is precise time protocol (PTP). In its full implementation, precise time protocol sends packets to set the time of each component in the network, whereas network time protocol simply passes through the components along the way. Since each component is set to the time of a topologically adjacent unit, network asymmetry is no longer a factor. Furthermore, the instrumental delays associated with each component's asymmetry are modeled, and the error in going from the ports to the logical center of the component is avoided by measuring time at the physical interface. Precise time protocol is designed for controlled local networks, and time-transfer accuracies of tens of nanoseconds can be obtained [10, 11]. However, on the Internet, non-precise-time-protocol-compatible components degrade the accuracy to the same level as network time protocol [11]. To benefit from all the precise time protocol improvements on the decentralized Internet, implementation would also require a means to protect against "spoofers" spreading false time to nearby components.

3. GNSS Time Transfer

Global navigation satellite systems, or GNSS, provide an extremely reliable way of determining the synchronization errors of ground clocks with respect to each other. In the absence of interference, GNSS signals are continuously available, everywhere in the world. After correction for the atmospheric perturbations encountered by the signal, the GNSS measurements will give access to the timing difference between the laboratory ground clocks and the reference time scale conveyed by the atomic clocks onboard the GNSS satellites $\left(t_{local} - ref\right)$. Computing the differences between these quantities collected in two remote sites provides the synchronization between the two remote clocks, and the time evolution of the behavior of the clocks relative to each other. For users unable to afford redundancy or even a ground clock, expenses could be limited to an antenna and a receiver, as shown in Figure 4.

3.1 Time-Transfer Standard

Initially (starting in the eighties) GNSS time transfer was mainly realized using GPS C/A code observations collected by single-channel receivers, and using the satellite positions and clocks provided in the navigation messages

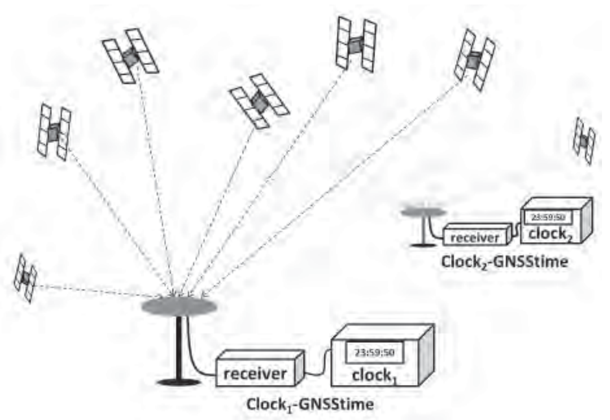

Figure 4. A schematic diagram for GNSS time transfer. The majority of links used in International Atomic Time generation are based upon this configuration. Data from the GNSS receiver, and data comparing the receiver's reference clock to all other laboratory clocks, are digitally uploaded to the BIPM (Bureau International des Poids et Mesures).

[12]. The solutions $(clock_i - ref)$ were collected in dedicated files using the CGGTTS format (for Common GPS GLONASS Time Transfer Standard [13, 14]). These solutions corresponded to a smoothed 13-minute solution for the satellites and epochs appearing in a dedicated tracking schedule provided by the Bureau International des Poids et Mesures (BIPM).Following the improvements of atomic frequency standards in terms of precision and accuracy, the removal of selective availability, and stabilization of the full constellation so that 8/9 satellites were usually available, GPS (or more generally, GNSS) time and frequency transfer underwent major evolutions, both at the algorithmic and hardware levels. Among these was the introduction of multi-channel receivers (e.g., [15]), which increased the number of satellites and correspondingly reduced the noise of clock solutions. Applications requiring the highest precision, such as the computation of International Atomic Time, benefited by correcting the broadcast satellite orbits, satellite clocks, and ionosphere model with the more-precise products computed by the International GNSS Service (IGS) [16, 17]. A variety of troposphere models could be used, and the BIPM uses the hydrostatic Saastamoinen model, which was described in the International Earth Rotation Service (IERS) conventions [18]. The method was later upgraded to benefit from the dual-frequency receivers that observe both GPS frequencies and extract the ionospheric delays to the first order (i.e., 99% of the effect) [19]. The ionosphere-free dual-frequency combination is named P3, and its use led to a factor of two improvement in the stability of the intercontinental time links up to averaging times of 10 days (e.g., [20]). Presently, this approach constitutes the state of the art in GNSS time transfer using only code measurements. The stochastic uncertainty (U_A) is at the level of a few nanoseconds, being limited by the current noise and multipath of the code measurements.

3.2 Common View and All-in-View

The initial Common GPS GLONASS Time Transfer Standard files were produced by single-channel GPS receivers. The time transfer was named "common view" (CV) as it was computed as the differences of the Common GPS GLONASS Time Transfer Standard results collected simultaneously from the same satellite by the two stations:

$$\Delta T = C1 - C2 \quad (1)$$

$$= \frac{1}{N}\sum w_i\left[(G - C_1)_{i1} - (G - C_2)_{i2}\right],$$

where ΔT is the inferred time difference between the clocks C_1 and C_2, and $(G - C_n)_{in}$ is the observed time difference between the GPS time (G) and the reference clock at that site (C_n), as determined from GPS satellite i measurements at site n. This computation is done at each observation epoch, the summation is over the N satellites in common view at both sites, and the assigned weight, w_i is often taken as unity.

All the satellite hardware delays and satellite clock errors are cancelled in this technique; the remaining errors are mainly due to the errors in the corrections applied to the code measurements. When multi-channel receivers began to be implemented in the timing laboratories, common view used a weighted average of those satellites visible at both stations in each 13-minute track of the BIPM schedule. Since the number of simultaneously observed satellites decreases as the baseline increases, the quality of the common view solutions tends to degrade with increasing distance between the stations. Since the exclusion pattern systematically includes certain portions of the sky, systematic errors, such as multipath, would have link-dependent effects not adequately compensated for in calibrations based upon small-baseline full-sky observations. To avoid these problems, the BIPM switched to a technique once termed "melting pot," but now termed "all-in-view" (AV). A clock solution $(clock - ref)$ is computed at each epoch, independently for each station, using all visible satellites, and the difference of the solutions of the two stations is then computed afterwards, as follows:

$$\Delta T = C1 - C2 \quad (2)$$

$$= \frac{1}{N}\sum w_i (G - C_1)_{i1} - \frac{1}{M}\sum w_i (G - C_2)_{i2},$$

where N and M are the numbers of observed satellites at stations 1 and 2. Since the errors from the satellite clock

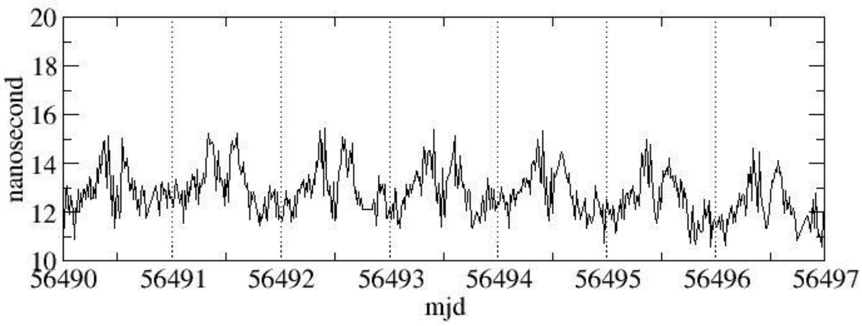

Figure 5. ROA-PTB (the link between the Spanish and German timing laboratories) computed with P3 and all-in-view by the BIPM (available on the BIPM ftp), showing the diurnal repeatability associated with the local environment (multipath plus possible temperature variations).

estimate and the ephemeris estimate do not cancel, as they do in the common-view technique, it is important to use precise ephemerides and clocks, rather than the broadcast navigation messages. Using IGS rapid products [17], the remaining uncertainties due to satellite orbits and clocks appropriately average to well below 100 ps for averaging periods of one day and longer [21, 22]. The references also document the significant superiority of all-in-view with respect to common view for baselines longer than 2000 km. As the baselines approach zero, all-in-view and common view become more equal. In modern GPS data reductions, the use of IGS products improves the data to a level wherein the uncertainties are dominated by multipath on the short term, and instrumental variations on the long term. For this reason, an elevation-dependent weighting is generally adopted in the all-in-view computations, giving more weight to observations at high elevations, i.e., less affected by multipath.

Since time transfer based on the Common GPS GLONASS Time Transfer Standard is a code-only analysis, both all-in-view and common view are significantly affected by multipath of the code signals [23]. Nanosecond-level diurnal variations can appear in the time-transfer solution. This is illustrated in Figure 5, for the link between Spain's timing laboratory ROA and Germany's counterpart (PTB) (about 2000 km). These variations were not due to the clocks. They were the signature of the code multipath (which would not be sinusoidal) and environmental sensitivity in one or both stations (which would usually be somewhat sinusoidal). The geometrical relationship among the satellite, the receiving antenna, and the reflectors that are the cause of multipath reflections has an approximate period of one sidereal day (about 23 h 56 min), so that the amplitude of the multipath signal for each satellite also has this periodicity. However, the pattern can also vary over longer periods, due to weather-induced changes in the reflectivity in the antenna's environment. Systematic geometric effects can often be identified by comparing data as a function of satellite azimuth and elevation, as in [24].

3.3 Carrier Phase

In parallel, some GNSS receivers provide phase measurements of the carrier signal. Thanks to the short wavelength of this signal, the measurement noise and multipath error is about 100 times lower than the noise of the code measurements. For this reason, the potential of GNSS carrier phases for time and frequency transfer was studied and demonstrated by different authors [e.g., 25-27]. With respect to the code measurement, the carrier phase measurement contains an additional unknown ambiguity, which is an integer number of cycles of the carrier. This is constant during a continuous visibility of the satellite, and must be determined from the data. Due to signal-to-noise limitations, the ambiguity is typically determined as a fractional number, but some software provides the option to force the ambiguity to be an integer [28]. Since the phase inherently carries no time information, ambiguity must always shift the phase, and the use of carrier phase data improves only the frequency comparison, not the overall time. The equations for the pseudorange (P) and carrier phases at each frequency i (L) are

$$L = R + c\left(-\tau_s + \tau_r + \tau_t\right) - c\tau_i + N_i\lambda_i + \lambda_i\omega_i + n_{\phi i} \quad (3)$$

$$P = R + c\left(-\tau_s + \tau_r + \tau_t\right) + c\tau_i + c\tau_{di} + n_{Pi} \quad (4)$$

where R is the geometric distance from the antenna to the satellite, τ_s is the satellite clock error, τ_r is the receiver clock error, τ_t is the tropospheric delay, τ_i is the ionosphere delay, N_i is the phase ambiguity, λ_i is the wavelength, ω_i is the windup correction associated with the varying orientation of the satellite with respect to the receiver during this pass, $n_{\phi i}$ is the phase noise, τ_{di} is the instrumental code delay, and n_{Pi} is the code noise.

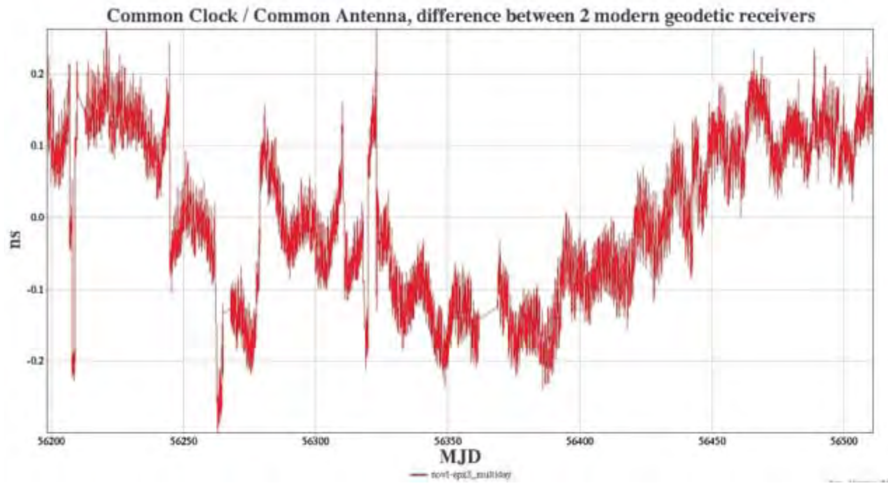

Figure 6. The observed calibration variations between two 21st-century geodetic GPS receivers. The variations may have been due to the electronics supplying the reference signals. Many older-model receivers have shown larger variations, and some somewhat shorter-duration comparisons of modern receivers have shown no discernable long-term variations and peak-to-peak noise < 20 ps.

The main analysis strategy used to combine code and carrier phase measurements for time transfer is the precise point positioning (PPP), as described in [29]. It requires correcting the data to a precision at least equal to that of the carrier phase measurements, using IGS satellite orbits and clock products, as well as Earth tide and ocean loading models [17]. The ionospheric delays are removed through the ionosphere-free combination of dual-frequency measurements, and the tropospheric delay of the dry atmosphere is modeled as in the Common GPS GLONASS Time Transfer Standard results. A fit is made to the data so as to determine and remove the receiver position, receiver clock, carrier phase ambiguities, and the delay due to the highly variable water vapor. While code-only data do not have the precision required to remove the wet delay, in precise point positioning one can either do this by fitting to the amplitude of an elevation-dependent mapping function and, as an option, to an azimuthal sinusoidal wet delay parameter, as well. Fortunately, precise-point-positioning-derived clock values have been shown to be very insensitive to the details of the mapping function employed, although the site clock, zenith troposphere delay, and antenna vertical position are highly correlated [30]. Due to the precision of carrier phase data and the ability to correct those data, precise point positioning can reach a U_A uncertainty of 200 ps for International Atomic Time generation [31], while five-minute points can have standard deviations as low as 15 ps.

The systematic uncertainty (U_B) for precise point positioning time transfer is equivalent to that from the Common GPS GLONASS Time Transfer Standard because the code data are the only observables providing access to the timing information of the clocks. On the one hand, the hardware delays are composed of the GNSS signal delay in the antenna, cable, and receiver, up to the receiver's internal timing measurement point. On the other hand, the time delay between the receiver's internal timing point and the external clock must be allowed for. The first part could be absolutely determined using a GNSS signal simulator, which creates a simulated signal of known time offset to pass through the receiving chain and to be measured. The U_B uncertainty on this kind of calibration is at the level of 1 ns on each frequency [32]. However, it requires specialized equipment that is rarely available. Instead, a relative calibration is usually used, in which a receiving chain is assumed to be absolutely calibrated, and then successively sent to the different laboratories to determine their hardware delays with respect to it. The uncertainty budget of the differential calibration technique is currently officially estimated to be 3.8 ns [33]. Although carefully done individual long-distance relative calibrations with precise point positioning have achieved total uncertainties of the order of 1 ns [34, 35], the BIPM's current policy is to use a conservative 5 ns as the U_B uncertainty for GNSS time transfer. This is under review [36], and any new standard must account for the inability to track system configuration changes at the several laboratories, as well as temporal variations of receiver calibration.

Common-clock observations of parallel GNSS receivers frequently revealed variations at the nanosecond or sub-nanosecond level over months, particularly in older models (Figure 6 and [37]). The use of redundant GNSS systems would enable laboratories to identify units with calibration jumps or drifts or that showed environmental sensitivity; receiver manufacturers have been known to improve their products based upon laboratory feedback (Powers, private communication).

The existence of seasonal calibration issues would be reflected in temperature- or humidity-related diurnal

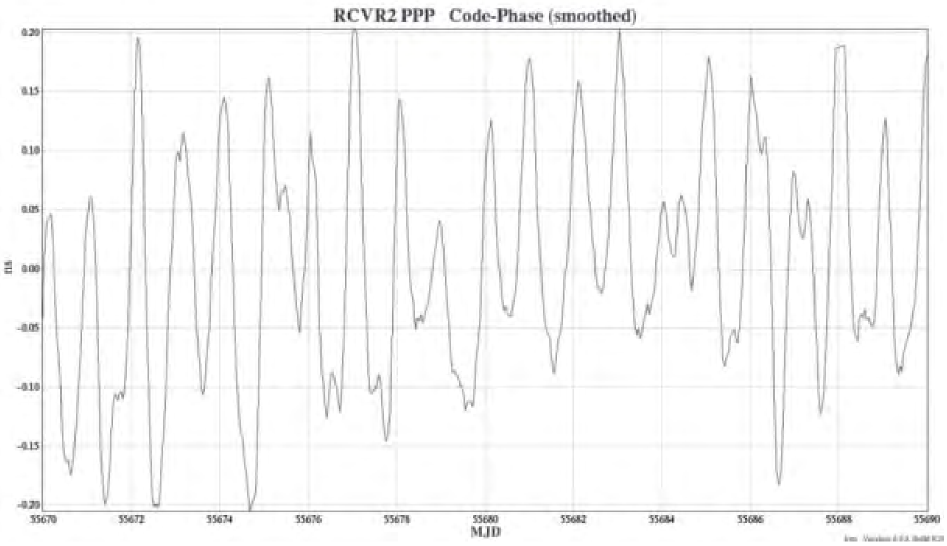

Figure 7. The signature of diurnal variations in the code as revealed in the solution residuals in precise point positioning processing. Such variations could be due to periodic interference, reflections, or expansion of the external cabling. Although often too weak to be seen in un-averaged data, they are suggestive of seasonal calibration variations. Note that the differencing was insensitive to all precise point positioning-derived parameters, except the ambiguities and ionospheric correction. Code residuals would retain sensitivity to all precise point positioning parameters, but any environmental effects that perturb code and phase equally would be absorbed into the clock parameters.

variations in GNSS receiver code data, as well as long-term changes of multipath. Sub-daily precise point positioning solutions are insensitive to daily code fluctuations. However, they can be seen in the solution code residuals (Figure 7 and [38]), along with other effects. These sub-daily code fluctuations are also the cause of the diurnal variations observed in the all-in-view solutions, and illustrated in Figure 5. The combined total of effects to which the code is most sensitive – including but not limited to multipath, interference, environmental dependencies – can lead to discontinuities at the boundaries of independent daily precise point positioning solutions. These are typically sub-nanosecond, and several techniques can reduce them [38-40]. However, the optimal situation is to design a station setup that reduces multipath, and especially the near-field multipath, which is the most problematic for time transfer [41]. One solution is to block reflected signals from entering the antenna. In Figure 8a, shield consisting of an RF absorber was placed below the antenna to prevent reflections from that direction. The impact of this reduced multipath could be seen by ranking all the stations of the IGS, where the station of Figure 8 (named BRUX) was among the three stations having the smallest rms of day boundary jumps [42].

When there are large inconsistencies between the carrier phase and the code, precise point positioning software can respond in predictable but often unexpected ways [43]. For example, Figure 9 shows the precise point positioning solutions for an extreme case, in which the receiver's phase data was apparently frequency offset from the code.

In addition to overall calibration variations, a variety of instrumental effects related to differences in the pre-correlation filtering of GNSS receivers can lead to systematic receiver and satellite-dependent biases at the sub-nanosecond and even nanosecond levels [44-46]. Averaging over different satellites will reduce the errors, but a detailed receiver-dependent analytic treatment is required for highly sub-nanosecond calibrations [47].

Figure 8. A GNSS antenna at the Royal Observatory of Belgium, designed with an underneath RF absorber to prevent near-field multipath.

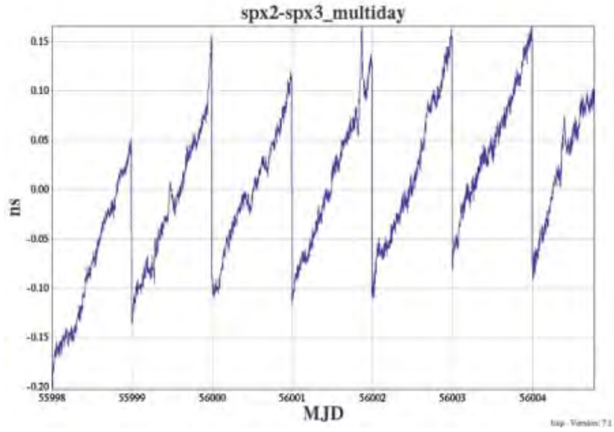

Figure 9. A precise point positioning solution difference between two receivers of the same make, with common clock and common antenna. The sawtooth variations became much smaller after a firmware upgrade, and were presumably due to a frequency offset in the phase data. The use of code data was able to correct this in the daily average, but not the sub-daily differences.

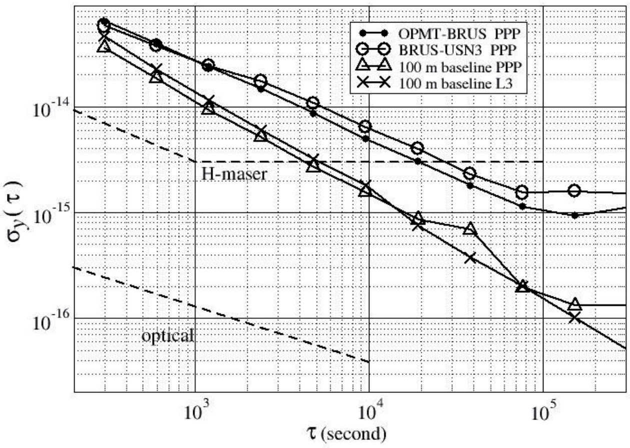

Figure 10. The Allan deviation of precise point positioning solutions compared to those of ground clocks. OMPT, BRUS, and USN3 are the IGS designations for geodetic GPS receivers maintained by the Observatory of Paris, the Royal Observatory of Belgium, and the USNO.

In order to illustrate the present possibilities of GNSS time and frequency transfer, Figure 10 presents the Allan deviations corresponding to some specific baselines. The two curves associated with the 100 m baselines were obtained using two separate receiving chains, both connected to the same H-maser. One curve resulted from the analysis of carrier phase data only (fixing the ambiguities to zero), while the second curve came from a precise point positioning analysis using the software developed by the National Research Council of Canada (NRCAN) on a multi-day basis, in order to avoid the day-to-day discontinuities inherent in daily processing of precise point positioning [39]. The difference between these two curves came from the use of code measurements that degraded the stability at intervals of a few hours, i.e., the classical duration of the satellite visibility on which the ambiguities were constant. Finally, the two last curves of Figure 10 present the Allan deviation of the precise point positioning solutions for the links Brussels-USNO (about 6000 km) and Brussels-Paris (about 300 km). Both provided approximately the same quality. However, the short-term stability was lower than what was expected from the 100-m baseline experiment; the origin of this degraded quality has not yet been identified to date. The H-maser stability curve in the figure shows that H-maser instabilities dominated over periods longer than three hours, so that the curves did not provide information about the performance of the technique. The optical clock stability curves showed that optical clock comparisons would be possible only for GNSS-data averaging times longer than several days, if at all.

3.4 Interoperable GNSS

A large improvement in GNSS capabilities is expected to ensue as new systems go online. By 2020, enough planned regional and global GNSS will have become fully operational so that almost 100 satellites will be globally accessible to users. The variety of signals will provide many opportunities for optimization, and an example of active work in this area was [48]. Figure 11 shows the current status in the Delhi sky for a constellation based upon 31 GPS, 24 GLONASS, four GALILEO, and 12 SBAS satellites augmenting GPS. Interoperability between systems will be particularly useful in cases where visibility is limited; in equatorial regions, ionospheric scintillation could also reduce the number of useful satellites [48]. To achieve full advantage of GNSS, the International Committee on GNSS (ICG) was formed in order to work out issues related to compatibility and interoperability, which are potentially confusing, since only GLONASS's internal reference time follows UTC (and therefore jumps with each leap second). In contrast, GPS and GALILEO times are continuous and 19 seconds offset from International Atomic Time (which has no leap seconds), while BEIDOU time is 33 seconds offset from International Atomic Time. In order to maximize the predictability of the GNSS system's time differences, the ICG requested a more real-time UTC reference, and this was a key motivation for the BIPM's creation of rapid UTC (UTCr).

The combination of measurements from different GNSS constellations for time transfer has several requirements. The receiver's internal reference must be the same for all systems, and the receiver system must be fully calibrated so that the hardware delays at its operating configuration are known for each signal transmitted by each constellation. In some cases, this is complicated by the fact the frequency bands used by different systems do not completely overlap, or the power spectrum inside the band is not the same. Finally, a key requirement concerns the reference of the satellite clock broadcast or corrected values. The user should either know the difference between the reference time scales at each observation epoch, or

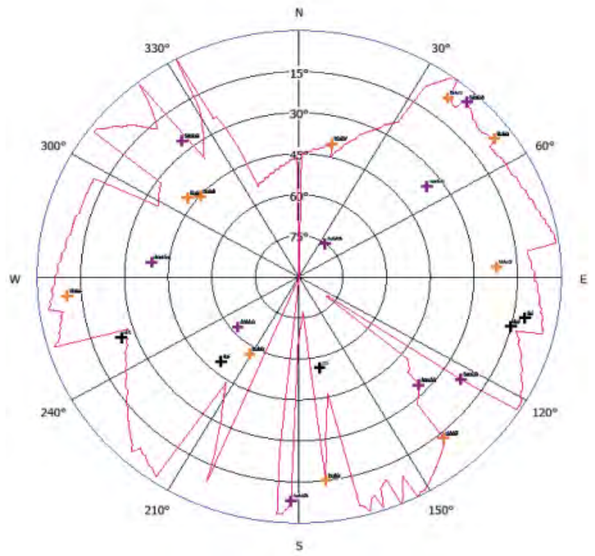

Figure 11. A typical instantaneous satellite pattern, with existing operational GNSS systems. The line segments represent the visibility limits set by nearby structures, the purple crosses refer to GPS Satellite 9, the orange crosses refer to GLONASS Satellite 10, and the black crosses refer to SBAS 5.

introduce this difference as an unknown to be estimated along with the other parameters.

Combined single-reference products are already provided for GPS and GLONASS satellites by some IGS analysis centers, and it is assumed that in the future, such products will also be provided for all GNSS. The combination of simultaneous observations of all these constellations in one global time transfer solution would therefore be possible. A user who fits to a constellation-wide bias could degrade the solution with unnecessary parameters, particularly for the epoch-averaged time-transfer difference. However, one possible benefit would be insensitivity to, and possible detection of, any un-modeled constellation-specific bias within the receiver.

The combination of GPS and GLONASS for time transfer has been studied for the all-in-view technique [49], and in precise point positioning [50]. Because GLONASS uses different carrier frequencies for each satellite, the hardware delays for each satellite-receiver pair must be determined in the clock solution. Since the advantage of increasing the number of observations is counterbalanced by the larger number of unknowns, combining GPS and GLONASS observations does not improve the time accuracy of the solution, although frequency variations are better determined. However, because each GPS, GALILEO, and BEIDOU satellite transmits on the same frequencies as the others in its constellation, their combination will increase the number of observations without increasing the number of unknowns per satellite. A theoretical improvement of a factor of $\sqrt{3}$ would in general be expected from the combination of GPS with the full GALILEO and BEIDOU constellations. The improvement would be still larger in cases of limited satellite availability, due to "dilution-of-precision effects."

Other improvements would be due to better atmospheric corrections, particularly because the frequencies used for the ionospheric correction are further apart for GALILEO. This has been confirmed by observations that the noise in reductions of GALILEO data using the ionosphere-free combinations of E1 with either E5a, E5b, or E5 AltBOC is significantly lower at all elevations than the noise of the ionosphere-free combination of the GPS P(Y)-codes on L1 and L2 [51].

4. LORAN

LORAN was developed for positioning during the second World War. LORAN is less precise than GNSS, due to variable and often un-measurable travel path and delay variations. The precision falls beyond 1000 km due to increased path and delay variations, decreased signal strength, and decreased angular spread of the transmitters. However, LORAN systems are much harder to jam, and could provide an important reliability factor for air and marine navigation. LORAN transmissions are given by chains of synchronized transmitting stations at low (100 KHz) frequencies, so that by observing a pair of stations, the observer can geolocate upon a hyperbolic track. By observing several pairs of tracks, the observer can determine a unique position. Although in its original design LORAN was not capable of delivering time or even time-of-day, in Enhanced LORAN, the hyperbolic solution is not used, since the signal is modified to transmit time information along with real-time corrections to LORAN

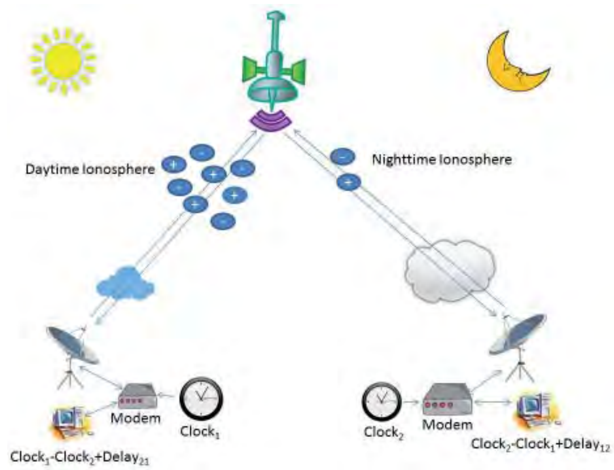

Figure 12. A typical TWSTT (two-way satellite time and frequency transfer) arrangement. Tropospheric cancellation is essentially complete, and the near equality of the uplink and downlink frequencies through each ionosphere leads to considerable cancellation. Satellite motion results in one direction having a slightly longer path length than the opposite direction. Time transfer is achieved by applying calibration and other corrections to the difference between the two modems' measurements of time-of-arrival minus time-of-transmission [53]. For International Atomic Time generation, the data from the modems are uploaded to the BIPM.

Figure 13. A portable two-way satellite time and frequency transfer (TWSTT) station, which is driven to remote sites for the purpose of calibration. The raised antenna ensemble on the taller roof is designed to minimize multipath. The large dish on the roof is capable of providing digital uplink information for GNSS systems, or conducting high-SNR two-way satellite time and frequency transfer observations.

data and the GPS broadcast ephemeris. The totality of these improvements will enable time delivery at the 10 ns level when differential corrections are used close to a transmitter [52]. This accuracy is sufficient for many marine and other applications, and therefore LORAN signals are routinely broadcast in Europe and Asia. Budgetary considerations led to the termination of the American program, although a limited amount of R&D work is still being undertaken in the United States, as well.

V. Two-Way Satellite Time and Frequency Transfer

Two-way satellite time and frequency transfer, or TWSTT, is currently rated by the BIPM as the best calibrated of operational systems contributing to International Atomic Time. To conduct two-way satellite time and frequency transfer, a time-referenced spread-spectrum signal is transmitted to a geostationary satellite, where it is received and re-transmitted at a slightly different frequency to a cooperating user. That user simultaneously transmits a similar signal, which follows the inverse path to the first user (Figure 12).

The basic equations lead to a time difference between the reference clocks, T_i, for sites 1 and 2, as follows:

$$T_1 - T_2 = \frac{(\Delta T_1 - \Delta T_2)}{2} + \frac{(\tau_{1u} - \tau_{1d} - \tau_{2u} + \tau_{2d})}{2} + \frac{(\tau_{1ut} - \tau_{1r} - \tau_{2t} + \tau_{2r})}{2} + S, \qquad (5)$$

where for site i, ΔT_i is the counter reading, τ_{iu} and τ_{id} are the uplink and downlink signal delays including the path through the transponder, τ_{it} and τ_{ir} are the delay differences between the transmitting and receiving parts of the Earth station, and S is the Sagnac effect due to the non-reciprocity of the Earth's rotation.

Because the forward and reverse pathways are similar, many path delays are cancelled when the data at the two ends are differenced to form a timing difference. There remain sub-nanosecond errors in the path delay due to satellite motion, and due to the frequency difference between the upward and downward signals at each site, which lead to different sensitivities to the ionosphere, but these can be modeled [53]. If the satellite uses the same transponder to communicate with the two sites, then its

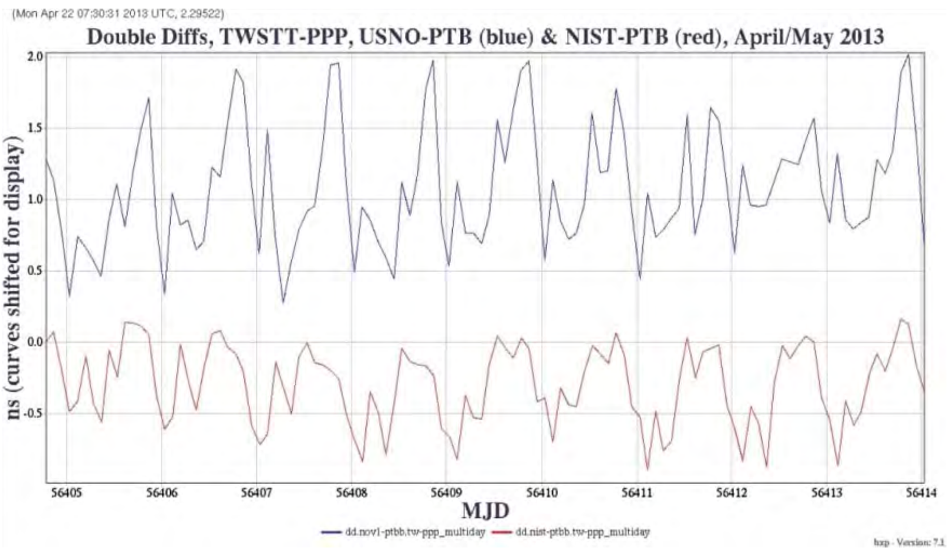

Figure 14. Diurnal signatures in two-way satellite time and frequency transfer between two North American labs and the PTB. To remove clock effects, the data were double-differenced with precise point positioning data. The pattern changed significantly in the following summer.

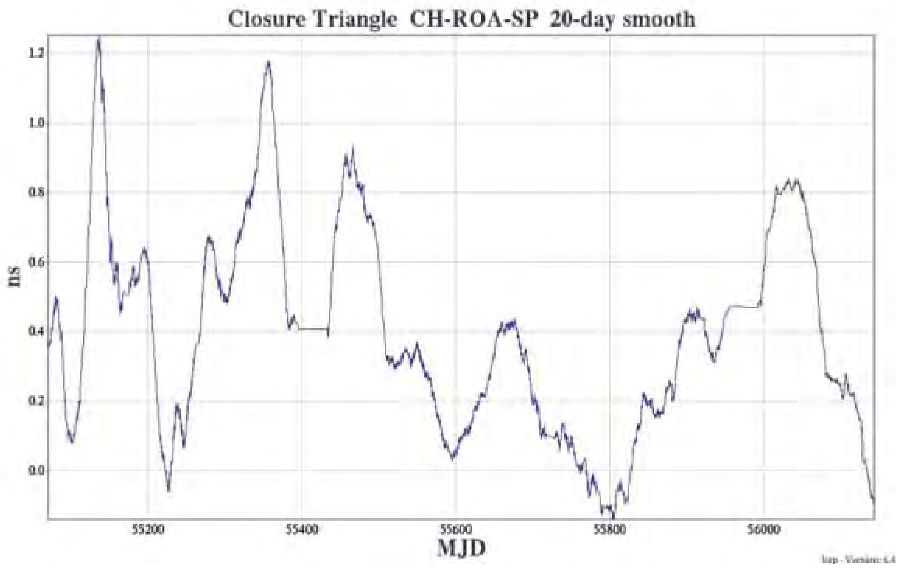

Figure 15. The closure sum of (CH-ROA), (ROA-SP), and (SP-CH). CH, ROA, and SP are the acronyms of the national timing labs of Switzerland, Spain, and Sweden, respectively. Independently of clock variations and all site-based calibration variations, the curve suggested a nanosecond-level limit to individual baseline stabilities.

contribution to the delays cancel, and the relative delay of the transmitting/receiving equipment can be measured by physically transporting a mobile system from one site to another, and conducting observations with the systems to be calibrated (Figure 13).

In most two-way satellite time and frequency transfer data, a lower limit to the short-term precision and the long-term accuracy is revealed by the presence of strong diurnal signatures, often at the nanosecond level (Figure 14). The strength and phase of these can vary with season, frequency, weather, baseline, equipment upgrades, and/or presence of other transmissions. No operationally useful causal relationship has yet been established, although Kalman filtering has been shown to be an effective filter for removing them [private communications from Koppang and from Jaldehag].

Some indications exist from closure studies that the monthly stability of two-way satellite time and frequency transfer calibrations is in general no better than one nanosecond [54]. To understand this, consider a complete set of all two-way satellite time and frequency transfer observations between three sites, whose semi-independent sets of measurements can be made, and their sum is given by

$$S = (A - B) + (B - C) + (C - A), \qquad (6)$$

where A, B, and C are the times of reference clocks from laboratories A, B, and C; and S is the closure sum of the observations. The closure sum would be zero if all baselines were perfectly calibrated. If no site-based calibration was applied, the closure sum should be a constant, but it need not be zero because the observed delay is the average delay over the bandpass, which for each baseline is the product of the individual transmitting/receiving bandpasses [24, 55].

Equation (6) shows that any clock variations or source of error that is site-based (the same for the two baselines that a site is linked with) would not contribute to the closure sum, because the error would appear twice, with opposite sign. For triplets that use a common transponder, all atmospheric and environmental effects would cancel. Triplets that include more than one satellite transponder, such as transatlantic triplets, utilize different frequencies on different transponders, and this would lead to a small sensitivity to un-modeled ionospheric and site-based frequency-dependent variations. For all triplets, including those that employed different satellite transponders, the observed magnitude of the closure sum variations could be assumed to be less than the true calibration variations. Unfortunately, it is not possible from closure sums to know which baseline's calibration varied, but Figure 15 shows nanosecond variations of one European triplet of sites. Similar closure variations have been reported on Asian links, as well [W. H. Tseng, private communication].

Other ways to measure the stability of two-way satellite time and frequency transfer is through the constancy of repeat calibrations, and by double-differencing parallel observations. Two-way satellite time and frequency transfer calibrations are relative calibrations, in which the transportation and labor expenses cost several thousand Euros. Therefore, there have been very few repeat two-way satellite time and frequency transfer calibrations [56, 57]. These have generally been consistent with 1 ns repeatability, although a larger variation was reported in a recent paper [58].

Double-differencing parallel but otherwise independent two-way satellite time and frequency transfer observations provides a means to monitor stabilities. Again, due to the expense, such observation programs are rare. At least two cases of variations exceeding 3 ns over many months have been published [59]; however, as with GPS common clock observations, the possibility of the delay variations being due to a component in the electronic infrastructure supplying the reference signals could not be ruled out.

Considerable effort has gone into the development of satellite simulators, which can enable the possibility of absolute calibration of two-way satellite time and frequency transfer systems. First developed at The Netherland's timing lab, VSL [60, 61], but also designed at the Observatory of Paris (OP) [63] and at at least one commercial entity, these would enable the measurement of the delay of each component, or set of components, of the system. They also would enable the identification of any component responsible for diurnal variations.

It is possible to combine two-way satellite time and frequency transfer with GPS, and the BIPM has created an operational product that uses precise point positioning data in the short-term but two-way satellite time and frequency transfer data for the long-term calibration [63]. While this merger would be vulnerable to any variations in the two-way satellite time and frequency transfer calibration, it retains the precision of precise point positioning, and is being used operationally in some circular-T links.

Two improvements to two-way satellite time and frequency transfer are being rapidly pursued, and show some promise. Observations employing carrier-phase have been shown to provide precisions of 1.E-16 at one day in common-clock short-baseline observations, and 2.E-15 at 1000 sec on the 10,000 km baseline between Japan's and Germany's timing labs (NICT and PTB) baseline (at which point the clock noise masks the performance; however, double-differences with precise point positioning data show relative agreement to 5.E-16 at one day) [64-66]. The noise of carrier phase two-way satellite time and frequency transfer is low enough that effects of satellite motion and differential ionosphere need to be fully removed, which requires the use of ranging data and either IGS products or their equivalents [67-68]. A second improvement to two-way satellite time and frequency transfer under development is termed DPN, for dual pseudo-random noise [69]. This technique employs two narrow (~100 KHz) frequency bands that are widely separated (~ 20 MHz) for uplink and for downlink. The cross-correlation between their combinations yields timing information that is comparable to what would have been received if the full 20 MHz had been utilized. Time deviations (TDEVs) of 10 ps have been obtained at five minutes, and 70 ps at one day, while diurnals have disappeared.

6. Fiber-Optic Time and Frequency Transfer

Fiber-optic frequency transfer is an emergent technology under active development [5, 70]. Although it is usually not possible to calibrate fiber-optic systems over long distances without making justifiable assumptions about path symmetry, time transfer can be either verified or achieved through calibration with the other techniques.

The most common and best-developed method for long-distance fiber transfer can be termed two-way optical transfer (TWOT). Signals are transferred in both directions along a fiber-optic cable, and in one case comparisons with precise point positioning data has shown that the assumption of equal path lengths in each direction was sufficient to calibrate time transfer to the level of 100 ps, and this achieved frequency precision of 3.E-17 at one day [1] over a 480 km link. A demonstration of time transfer with absolute time accuracy of 250 ps and long-term timing stability of 20 ps was reported in [69], based on timestamps carried by the optical phase by modulating a very narrow optical carrier using two-way satellite time transfer modems. A similar technique was used on a 73 km baseline, reaching a time transfer accuracy better than 100 ps [72]. With a pulse-generator on an 80-km baseline, a Chinese effort demonstrated 50 ps time transfer at 1 second and 70 ps at 10,000 seconds [73].

Technique	Precision @5 min	Precision @1 day	Setup Cost	Operating Cost, Non-Labor	Major Improvements Underway
NTP	6 ms	4 ms	$2K	Minimal	PTP (local), pooling (Internet)
GNSS all-in-view (1 GNSS system)	3 ns	250 ps	$5-$20K	Minimal	Combined interoperable GNSS
GNSS PPP (1 GNSS system)	20 ps	100 ps	$10-$20K	Minimal	Multiple signals from multiple GNSS
LORAN	50 ns	100 ns	$5K	Minimal	Enhanced LORAN
TWSTFT (TWSTT)	150 ps	500 ps	$100K	~$100K/year	DPN, carrier-phase, simulators
Fiber-optic	1.E-17 s/s	1.E-19 s/s	$100-$200K	>>$100K/year	Operational use

Table 1. Crude estimates of the current best-practice post-processed operational performance of different techniques, taking advantage of readily available free resources such as IGS products. All quantities are variable by at least a factor of two. Although multiple systems are recommended, the setup costs are estimated for hardware at one system at one laboratory. The operating costs are only for satellite time and fiber-optic rental. Precision over a given time interval is defined in analogy with the Allan deviation, as the rms difference between adjacent data points averaged over that interval, divided by two.

A Japanese link between two optical frequency standards attained frequency precisions of 7.E-17 at 1000 s along a 45-km length at night [74]. European two-way observations over 146 km and 920 km links reached precisions of the order of 5.E-19 over hours and days [75, 76]. An intensive long-term two-way effort involving many European laboratories is in preparation.

SP (Technical Research Institute of Sweden) has developed a low-profile method for passive long-distance – and possibly even trans-oceanic – frequency transfer that was based upon timing the passage of the frame boundaries at the nodes. They reported a precision of a 1100 km in a sub-sea link as 1.E-15 at one day, or 100 ps [77]. One-way two-color transmissions, which compensated for fiber-delay variations by exploiting the frequency-dependent propagation speeds of the two colors, had precisions of 1.E-17 at one day over 6 km distances [78, 79], but the decorrelation of the noise limited the performance over long distances.

Although the expense of renting fiber-optic cables is usually quite high, the technical capabilities of this infant technology are rapidly expanding [80]. They have not reached their theoretical limits, such as in which the noise is proportional to the baseline to the 3/2 power of the distance, and inversely proportional to the frequency [81]. The startup costs for equipment could be as low as $50,000 for the simplest systems, such as the passive system developed by SP, or approach $500,000 for the highest-precision systems. Another potentially expensive cost is creating the connection between the laboratory port and the suitable commercial lines.

7. Conclusion

In this summary, we have made brief note of the advantages of each technique, which are often complementary. Table 1 attempts to describe the performance of the several techniques at their current levels of operational maturity. In order to deliver a reliable product for the user, timing laboratories must take into account all the elements discussed, along with customer capabilities and robustness, accuracy, and precision requirements. However the tradeoffs are made, time and frequency providers must foremost ensure the reliability of their own products. Redundant observations provide the most direct method of verification, as part of a package of both automated and manual quality-control checks. Care must be given at every step of the process, which for International Atomic Time generation is especially important at the systems at the pivot-laboratories that interconnect the time-transfer links of cooperating institutions [24].

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9. Disclaimer

Neither the authors nor the institutions they support can endorse a commercial product. Any identifications would be for technical clarity only, and we caution the reader that the equipment properties described herein may no longer be characteristic of any equipment currently manufactured.

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Geophysical Information Inputs for EM Systems Performance Computation in Littoral Environments

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Editors' Introduction

The following paper was invited as an expanded paper based on a presentation given at the OCOSS 2013 conference, held October 28-31, 2013, in Nice Côte d'Azur, France, a conference sponsored in part by URSI. Tullio Tanzi (the conference General Chair), Jean Isnard, and François Lefeuvre invited this paper on behalf of the *Radio Science Bulletin*, and provided the following introductory comments.

Forecasting the performance of EM systems in a littoral environment drives the engineer to face scientifically and technically interesting but difficult subjects: propagation, clutter, physical properties of the atmosphere, and renewal of meteorological data, including their probabilistic formulation. It is the merit of the authors, Y. Hurtaud, Senior Scientist at the French DoD Research and Development center, and J. Claverie, Professor at St-Cyr Military Academy, to lead the reader through the development of their paper, thanks to their long experience.

Abstract

This paper presents *PREDEM V2*, a decision aid tool dedicated to the French Navy. It can be used for radar applications, but also for various electromagnetic systems that can be sensitive to various propagation effects (refraction, including ducting, sea reflection and scattering, diffraction by the coastline). Many efforts have been made to obtain a complete and accurate four-dimensional (three dimensions plus time) refractivity mapping. Other current works concern the sea surface effects, especially in terms of clutter modeling.

Some of the capabilities of *PREDEM V2* are illustrated, and some promising experimental results are also discussed.

1. Introduction

The performance of electromagnetic systems working in a littoral environment or in the open sea is generally sensitive to the meteorological and oceanographic conditions. The radiation propagation depends on the atmospheric structure, which is characterized by the presence of evaporation ducts, surface-based ducts, or elevated ducts.

In open-sea conditions, the horizontal homogeneity of the geophysical parameters may reasonably be assumed for radar applications. The knowledge of one vertical refractivity profile is sufficient to characterize the electromagnetic propagation for tens of kilometers. In littoral environments, strong horizontal variations can be observed. For instance, the sea temperature (especially the skin temperature used in surface-layer models) decreases as you are moving seaward. The wind speed is also subject to rapid changes, and the sea-breeze circulation is generally associated with the presence of surface ducts. Moreover, the phenomena of diffraction and diffusion due to the presence of the coastline also affect the signal strength. Finally, in the case of radar, sea and terrain clutter can significantly contribute to the received noise.

In order to compute the in situ performance of EM systems (detection range, interception and telecommunication range), it is necessary to take the whole of these effects into account, with suitable spatial and temporal resolutions.

The purpose of the paper is to present the way of taking the geophysical environment into account in the decision-aid tools (DAT) for French Navy applications. The environmental data – coming from various origins according to the type of missions: long-term planning at a strategic level (few months), short-term operational planning (hours or days), operation management (real time) – are exploited following two main axes: presentation of the meteorological context and help to interpret it, and its use for performance computation and visualization of results. This general view is illustrated here by referring to *PREDEM V2*, software dedicated to the prediction of naval electromagnetic performance.

2. Refractivity Profiles and Ducting Situations

As the tropospheric refractive index, denoted as n, is very close to unity, the use of the refractivity, N, is generally preferred. The refractivity is defined by

$$N = 10^6 (n-1) . \quad (1)$$

The refractivity is a function of the following meteorological parameters: the total atmospheric pressure, p (in hPa); the air temperature, T (in K); and the water vapor pressure, e (in hPa); with

$$N = \frac{77.6}{T}\left(p + 4810\frac{e}{T}\right) . \quad (2)$$

Refractivity therefore depends on the height, z, and the function $N(z)$ is referred to as the vertical refractivity profile. Considering long-distance propagation, especially in littoral environments, the horizontal variations of the refractivity also have to be taken into account. The mean statistical behavior of the meteorological vertical profiles results in the definition of a *standard* atmosphere, characterized by

$$\frac{dN}{dz} \approx -39 \text{ N/km} . \quad (3)$$

The lowest values of the vertical refractivity vertical gradient lead to a super-refraction situation. Particularly if

$$\frac{dN}{dz} < -157 \text{ N/km} , \quad (4)$$

ducting situations occur. A part of the transmitted electromagnetic energy may propagate within trapping layers, and reach receivers or targets located beyond the standard electromagnetic horizon. More generally, refraction effects may strongly modify the radar-coverage diagrams compared to what they should be, assuming standard conditions. To visualize the presence of an eventual duct for a given refractivity profile, it is more convenient to use the *modified* refractivity, M, practically defined as

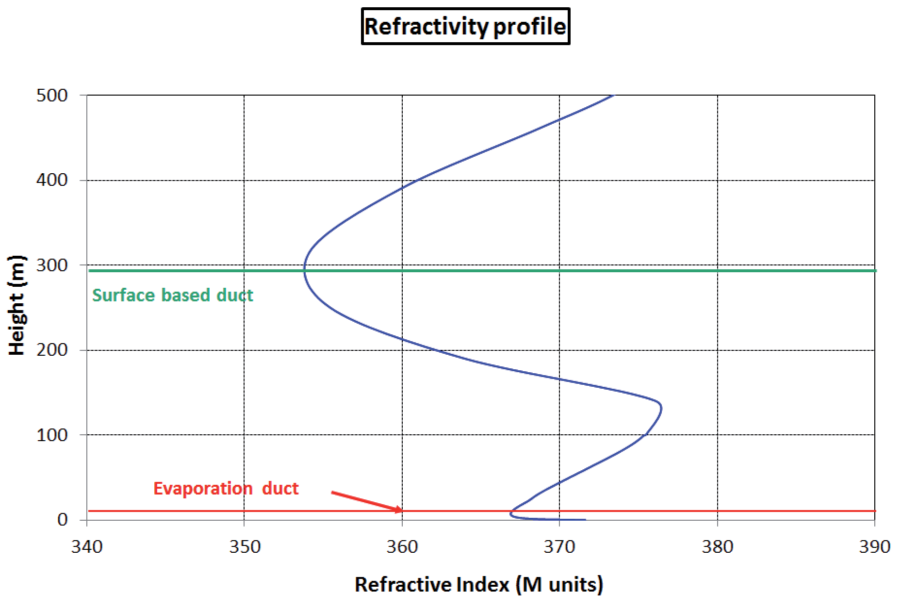

Figure 1. An example of a vertical refractivity profile, characterized by the presence of an evaporation duct and of a surface-based duct.

$$M = N + 0.157z \,. \qquad (5)$$

The ducting condition expressed in Equation (4) thus simply becomes

$$\frac{dM}{dz} < 0 \,. \qquad (6)$$

Above the sea's surface, the rapid decrease of moisture with height explains the existence of a particular type of duct, called an evaporation duct. Evaporation ducts exist most of the time above the seas and the oceans. Their heights may vary from a few meters to a few tens of meters. Due to specific advection phenomena, a dry and hot air mass may cap a wet and cold air mass. This results in the existence of an elevated trapping layer, leading to the existence of a surface-based duct or of an elevated duct. These ducts may have a height of a few hundred meters. The occurrence of such ducts greatly depends on the geographical location. For instance, they are quite infrequent above the North Atlantic, but very common in the Persian Gulf.

Figure 1 is an example of a vertical refractivity profile (in M units). This corresponds to a summer Mediterranean case. In this case, the evaporation duct was overlaid by a strong trapping layer, giving rise to a surface-based duct.

3. A Short Overview of *PREDEM V2*

The *PREDEM* software (*PREDEM* is a French acronym for "*PREDiction de performances des systèmes ElectroMagnétiques*," which can be translated as "*Performance prediction of EM systems*") was developed by CS company under DGA specifications [1, 2]. Version 2 of *PREDEM* is now close to being an operational code. Covering the spectral range from 100 MHz to 20 GHz, its main objective is to provide to the Navy credible prediction of the performance of EM systems, especially for radar detection.

The main outputs of *PREDEM* are presently the following:

- Context visual aids, such as duct-height cartography, vertical profiles of refractivity, emagrams or terrain profiles (ground composition and features)
- Performance predictions (radar coverage, telecommunication ranges,...)
- Decision-aid tools: dual mode (implying, for example, a ship and an aircraft) and determination of the best altitude of the patrol aircraft to detect any target at the sea's surface.

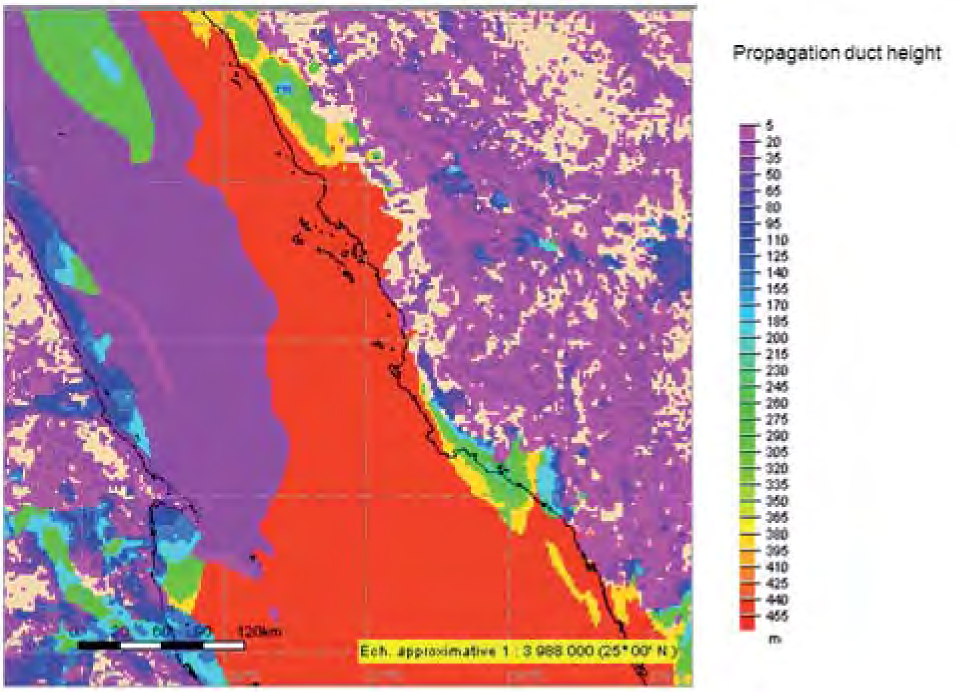

Figure 2. An example of a forecast duct mapping in the Red Sea deduced from the *AROME* numerical weather prediction code. The horizontal resolution here was 2.5 km. Strong surface-based ducts are present above the sea near the eastern coasts and in the south of the area (red color). Meanwhile, an evaporation duct is the main refraction mechanism near the western coasts (purple color).

The propagation code of *PREDEM* is the Advanced Propagation Model (APM), developed by SPAWAR (USA), and based on the Parabolic Equation Method (PEM), including a split-step Fourier resolution scheme. More precisely, this is a hybrid code, using the Parabolic Equation Method only in the regions of strong refractivity gradients or/and at low altitude. At short ranges or above the Parabolic Equation Method domain, other methods, such as flat sea model geometric optics or extended geometric optics, are used.

Compared to the previous version, many improvements have been made to make the code more robust and more operational. We will focus here on the functionalities related to the atmospheric structure and the sea surface. The new capabilities to access two-dimensional sea surface or three-dimensional atmospheric descriptions show the temporal and spatial heterogeneities of the marine boundary layer, and their impacts on the predicted performance of EM systems.

4. Forecast of the Atmospheric Structure

In *PREDEM V2*, the description of the short-term meteorological environment (i.e., the next 24 hours) is compatible with the outputs of the numerical weather prediction (NWP) codes, by way of a GRIB file. The considered parameters are either the atmospheric pressure, the air humidity, and the air temperature, or the modified refractive index, *M*, the vertical gradient of which conditions the atmospheric propagation (see Section 2). The horizontal resolution of the Méteo-France numerical weather prediction code *AROME* is 2.5 km, which allows visualizing the temporal evolution of the atmospheric structure, and rapidly identifying the geographical regions where the propagation is favorable (see Figure 2).

One of the crucial points is the way of merging the evaporation-duct structure with the upper layers. At the present time, the operational numerical weather prediction codes do not consider this structure with enough vertical resolution to be useful for propagation computation. For example, in *AROME*, only two levels (2 m and 20 m) are given. This is the reason why, with the help of Météo-France, we studied a procedure to add a sufficient number of levels to access the vertical profile in a manner fully compatible with the propagation core of *PREDEM V2*. Two methods to merge the evaporation-duct structure with the profile given by the numerical weather prediction *AROME* have been developed, and are illustrated in Figure 3:

- The first method consists of adding five levels below 10 m by running the multi-layer surface scheme *SURFEX/CANOPY*. However, it introduces, for several cases, *M*-index slope discontinuities between 10 m and 20 m, creating artificial propagation effects.

- The second method aims at computing the *M* refractivity profiles by the Marine Surface Boundary Layer (MSBL) code *PIRAM* [3, 4], by taking as the reference point the level at 20 m given by *AROME*. A polynomial blending above 20 m is introduced to fit the *AROME* profile. This method leads to a continuous vertical *M*-profile, respecting the vertical shape of the evaporation duct. Further work is in progress to validate this approach with various sets of data, including those of the *PREDEM* campaigns (summer 2005 and winter 2006 near the French Mediterranean coast).

5. Sea-Surface Effects

5.1 Sea-Surface Description in *PREDEM V2*

The description of the geophysical environment of *PREDEM V2* is completed by a representation of the sea surface that interacts with the electromagnetic propagation. According to the ratio between the rms sea height and the wavelength, the influence of the sea characteristics in terms of roughness on the propagation is slight (VHF-UHF bands) or significant (X, Ku bands). The forward propagation is linked to the sea reflection coefficient, depending on the significant wave height ($H_{1/3}$), whereas the sea clutter depends on $H_{1/3}$, but also on the wave direction.

The main inputs of *PREDEM* for the characterization of the sea surface are then the following:

- Considering the sea homogeneous: Douglas sea state, significant wave height, wind speed, average sea direction

- Considering two-dimensional variations: GRID files issued from sea-wave forecast modeling and/or numerical weather prediction codes, including significant wave height and average direction, sea state, or wind speed.

When the wind speed is taken as the input, the sea surface is considered fully developed by the wind (infinite fetch).

5.2 Modeling of the Sea Clutter

In order to take into account the sea clutter in the radar-performance computation, the Georgia Technical Institute (GIT) model is widely accepted by the radar community. This empirical model [5] computes the apparent reflectivity, σ_0, as a function of radar parameters (frequencies from 1 GHz to 100 GHz, polarization H and V) and of environmental parameters (wind speed, average wave height, look direction relative to wind direction, grazing angle). Due to its large applicability and despite some limitations (discontinuity at 10 GHz, underestimation of sea clutter at low sea states and low grazing angles), the Georgia Technical Institute model was introduced into *PREDEM V2*. In order to

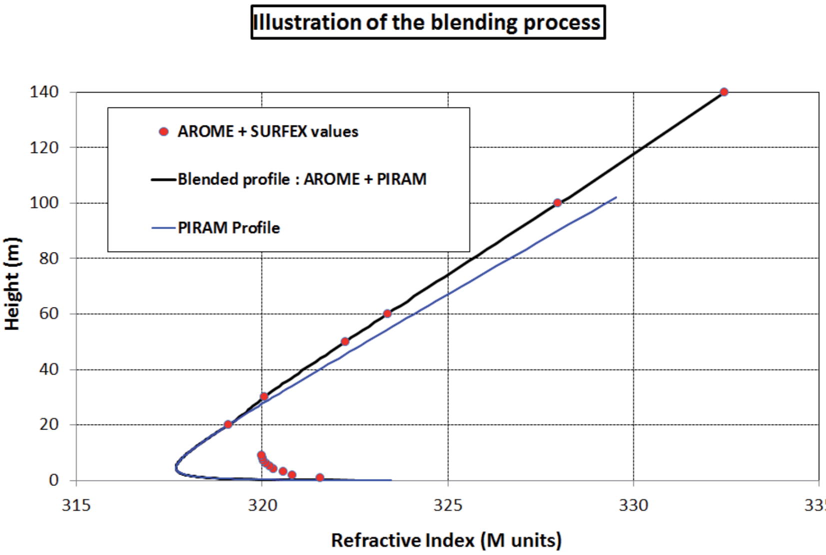

Figure 3. A comparison between *AROME + SURFEX/CANOPY M* profile (red circles) and *PIRAM M* profile (in blue) for an event of the *PREDEM* winter campaign (February 14, 2006, 8:00 am). *PIRAM* was initialized by the *AROME* values at the level of 20 m. The black curve is the resulting blended profile used within *PREDEM* for propagation computations.

compute sea reflectivity in the presence of nonstandard propagation conditions, the coupling between the Parabolic Equation Method and the Georgia Technical Institute model cannot be modeled by a simple product, $\sigma_0 F_{PE}^4$. $\sigma_0 . F_{PE}^4$ Effectively, the interference factor is taken into account by both the Advanced Propagation Model code and the Georgia Technical Institute model. To overcome this problem, one of the functions of the Georgia Technical Institute model, concerning the interference factor, A_i , was modified as follows:

$$A_i^{GIT\,\mathrm{mod}} = A_i^{GIT} \frac{F_{PE}^4(\delta z)}{A_i^{DP}} \tag{7}$$

where A_i^{GIT} A_i^{GIT} is the interference factor of the original Georgia Technical Institute model, F_{PE}^4 is the radar propagation factor given by the Advanced Propagation Model, A_i^{DP} , A_i^{DP} is the radar propagation factor of a double path (direct and reflected paths on a spherical Earth for a standard atmosphere), and δz is the first height considered in the Parabolic Wave Equation resolution.

Recent work on the sea reflectivity has been conducted to propose new empirical models by revisiting the Nathanson set of measurements [6], or by extending physical modeling to low grazing angles. In the frame of a upstream study (MOFREM) driven by DGA MI, ONERA (the French Aerospace Lab) and the Mediterranean Oceanographic Institute (MIO) are developing an extension of the unified model, GOSSA, by combining the small-slope approximation with the Kirchhoff approximation [7]. This new model should include the very-low-grazing-angle case, the effects of wave shadowing and of breaking waves. Furthermore, actual research concerning new formulations of the boundary conditions within the Parabolic Equation Method should lead to avoiding instabilities in the propagation field resolution [8].

6. Experimental and Simulation Results

6.1 The PREDEM Campaigns

In June 2005 and February 2006, complete radar and meteorological measurements were performed near the French Mediterranean coast [1]. S-band and C-band land-based radars, with vertical polarizations, were tracking canonical surface or airborne targets along a constant path with distances up to 100 km. Several times per day, three simultaneous radio soundings were performed along this path. *AROME* and *PIRAM* refractivity profiles were computed for the entire studied periods. Figure 4 shows a representative result of the winter campaign.

For this particular case, the atmospheric structure was similar to that plotted in Figure 3. The evaporation-duct height was around 9 m, and quite constant along the propagation path. As the radar height above the sea level was 35 m and the target height was 75 m, the radio-electrical horizon, assuming a standard atmosphere, should have been around 60 km. The presence of an evaporation duct permitted target detection beyond this standard horizon. Using the radiosondes' (RS) profiles blended with *PIRAM* gave results in good agreement with the radar measurements. However, the modeled refractivity profiles issued from the blending of *AROME* with *PIRAM* also fit the observed data very well.

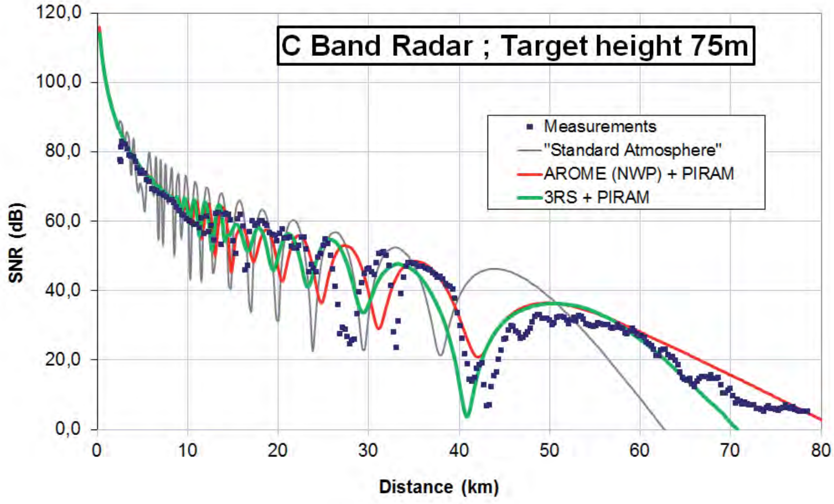

Figure 4. The measured and model results in terms of the signal-to-noise ratio (SNR) for a data set collected on February 14 at 2:00 pm.

6.2 Illustration of the Geophysical Environment's Impact on Radar Coverage

The impact of the environment on radar coverage at centimeter wavelengths is illustrated in this paragraph by using concrete situations encountered in littoral environments. In such environments, the combined effects of the atmospheric structure and the terrain (including the presence of features) significantly modify the radar coverage compared to the standard conditions.

To illustrate the influence of the three-dimensional atmospheric structure, we considered a ship located in the middle of the Red Sea, and equipped with a C-band radar (H polarization). In order to estimate the coverage of this radar, a computation was realized with *PREDEM V2* in the eight directions plotted in Figure 5 (N, NE, E, SE, S, SW, W, and NW).

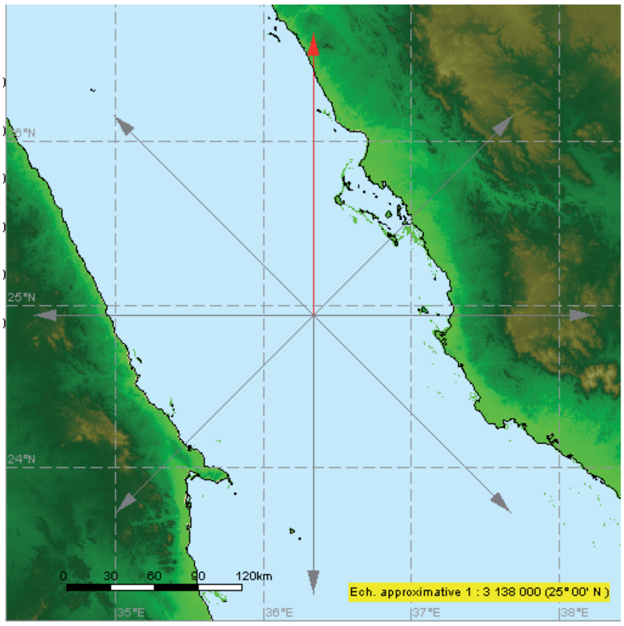

Figure 5. The localization of the on-board C radar in the Red Sea, and an indication of the considered radar directions.

The atmospheric structure was that corresponding to Figure 2. Strong surface-based ducts, with thicknesses of more than 400 m, were present on the eastern and southern parts of the area of interest. The plots on the left (respectively, right) side of Figure 6 present the radar coverage for a bearing W (respectively, NE) up to an altitude of 2000 m and a range of 180 km. The lower curves can be compared with the upper curves, showing the radar coverage diagrams for the same directions, but simply assuming a standard atmosphere. The increase of radar range due to a surface-based duct and an evaporation duct could clearly be seen. Obviously, due to the different duct heights, the changes in the radar-coverage diagrams did not concern the same target heights.

6.3 Clutter Effects

Figure 7 shows the effect of sea clutter on the detection range. This simulated result concerned an X-band radar, with horizontal polarization, located 15 m above the sea surface, and we assumed an evaporation-duct height of 10 m. (At grazing angles, the electromagnetic field polarization has very little influence on the forward reflection coefficient of the sea. However, the sea-clutter level is significantly lower for H polarization than for V polarization.) As for the previous plot, the detection probability was computed for a target having an RCS of $20\ m^2$. The left plot was obtained by considering a flat sea surface (no clutter), while the right plot considered a very rough sea surface (a wind speed of 15 m/s was used as an input of the original Georgia Technical Institute model). A significant decrease of the maximum detection range due to clutter could easily be observed. The impact of the modified Georgia Technical Institute model (Section 5.2) will be studied in the very

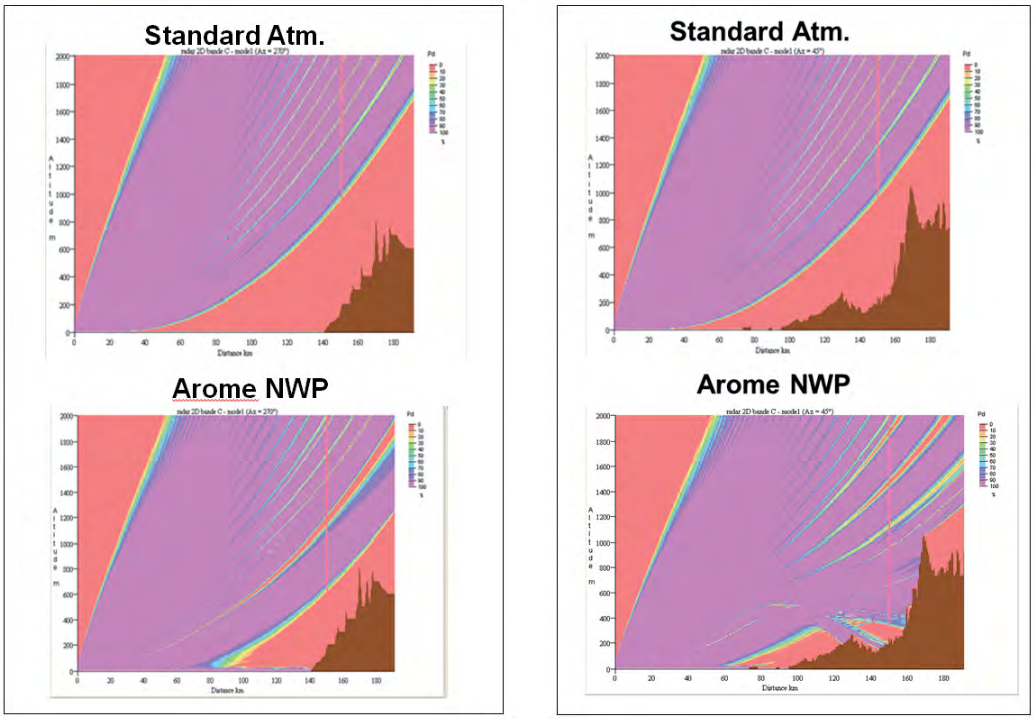

Figure 6. The radar-coverage diagrams for a C-band radar located near the sea in the presence of a forecasted atmospheric structure (lower plots), and for a standard atmosphere (upper plots). The coverage diagrams were drawn with a color scale spread from purple to red (a detection probability between 100% and 0%, computed for a target with an RCS of $20\ m^2$). The red vertical line at 150 km was due to the blind distance of the radar.

near future, and experimental results are needed to validate these simulations.

7. Conclusion

With the introduction of precise geophysical information completed with realistic radar modeling, the credibility of the decision aid tools is significantly increased. However, efforts must be pursued on the following points:

- *Interoperability of the use of weather forecast files*
  The transcription between the meteorological files coming from different sources and the format accepted by the decision-aid tools has to be done by dedicated codes such as *NCOMET*.

- *Clutter modeling*
  Modeling the clutter properties and the interaction with atmospheric propagation in presence of a rough sea and propagation ducting is still an open topic.

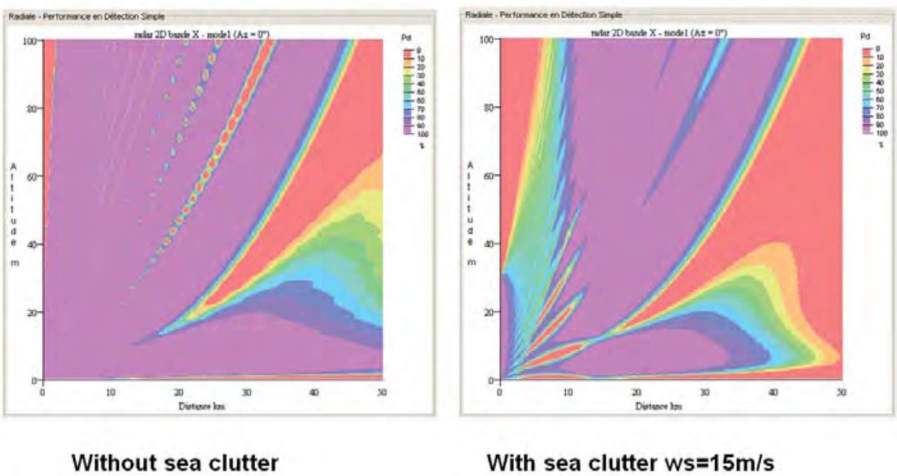

Figure 7. The combined effects of the ducting conditions with sea clutter for an X-band radar. As in Figure 6, the color scale was linked to the detection probability of a given target ($RCS = 20\ m^2$).

- *Global validation of radar performance codes in a littoral environment*
  This needs the installation of important means of measurements, including powerful radars, moving targets, atmospheric soundings, and sea-surface characterization. The analysis of the *PREDEM* campaigns has shown the necessity to have a four-dimensional (three dimensions plus time) refractivity mapping provided by numerical weather prediction codes.

A new experiment, called TAPS, in a tropical environment in the northeast coast of Australia was conducted at the end of 2013, and in the framework of an international cooperation (United Kingdom, United States of America, New Zeeland, Australia, and France). The complete analysis of this new set of experimental data will give us the opportunity to continue to test and improve the atmospheric modeling, especially the blending between the MSBL and the upper atmospheric structure.

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Hans Mögel, Transradio, and the Mögel Dellinger Effect

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Abstract

We sketch the life and scientific and engineering work of Hans Mögel. The article also contains information about early German commercial transcontinental radio communication by Transradio AG. The discovery of the so-called Mögel-Dellinger effect by Hans Mögel and John Howard Dellinger is explained and discussed.

1. The Life of Hans Mögel

Hans Ernst Mögel was born on May 31, 1900 in Leipzig, the son of the engineer Ernst Mögel. In April 1917, he finished his high school education with the "Abitur" at the Realgymnasium in Meißen (Saxonia). Immediately afterwards, he entered the German military as a one-year volunteer for the technical service. After the end of the war in 1918, he started his university education at the "Technische Hochschule" (Technical University) Dresden for electrical engineering (all these details are taken from the curriculum vitae in Mögel's dissertation [1]).

In 1922, he earned his "Diplom" in Electrical Engineering, and started to work as head of the laboratory of the company "Dr. Erich F. Huth GmbH für Funktelegrafie" (wireless telegraphy). He was responsible for the development of transmitters and amplifiers. Already parallel to his university education, he had worked during the vacation time at various technical companies (forging, metalworking, lathing, and woodworking). These practical experiences were very helpful in his later career [1].

Figure 1. Hans Mögel with his wife, Dora, in front of the Moritzburg castle (near Dresden), when just married (1928).

Figure 2. Hans Mögel at the antenna field of the receiving station Beelitz, 1932.

Mögel had a strong interest in research, and he therefore returned to the Technische Hochschule Dresden in 1925. He worked as an assistant of Professor Heinrich Barkhausen (1881-1956), well known for his development of vacuum-tube techniques. During this work, Mögel earned his engineering doctorate with a thesis, "Über die gleichzeitige Erregung zweier Schwingungen in einer Dreielektrodenröhre" ("Simultaneous Excitation of Two Oscillations with the Help of a Three-Element Vacuum Tube" [1]). After completing the corresponding experimental work, he started on November 5, 1926 to work at the "Transradio AG für drahtlosen Überseeverkehr in Berlin" (company for wireless overseas communication), a subsidiary of the well-known German company "Telefunken." He successfully defended his doctorate four months later, on March 5, 1927.

Mögel held the position of "Betriebsphysiker" (operational physicist) for six years. He published many important papers about radiowave propagation, including the famous article on the absorption of radio waves following solar eruptions (see next sections). In 1928, he married Dora Kirste (Figure 1); the couple adopted a son in 1943.

In 1932, he joined the "Reichspostzentralamt" (Imperial Central Post Office). Among his duties were the improvement of the reliability of short-wave radio communication, the planning of transcontinental links, and the enhancement of the amount of transmitted information. He also worked on radiowave propagation forecast as a function of season and solar activity. During this time he was already in contact with a group of scientists and engineers who developed radiowave propagation predictions for the German army, in particular Johannes Plendl (1900-1992), and later also Walter Dieminger (1907-2000) and Karl Rawer (born 1913) [2, 3]. Later, in 1939, these scientists and engineers gathered together with Mögel and other leading experts in HF techniques at the 6. Wissenschaftssitzung der Deutschen Akademie für Luftfahrtforschung (Scientific meeting of the German academy of aviation), which took place in Berlin about half a year before the beginning of WW2 [2].

In 1934, Mögel changed to the Reichsluftfahrtministerium (Imperial Air Force Ministry). As a consultant, and later as group leader with the "Chef des Nachrichten-Verbindungs-Wesen" (chief of communication matters), he was responsible for wireless navigation and air-traffic security. In 1937, he was promoted to a public-servant position with a military rank of "Flieger-Stabsingenieur" (Air Force Engineering Major)[1]. He later joined the corps of engineers of the German air force, and passed through several military ranks. In 1942, he became Oberst-Ingenieur (Colonel Engineer). All through WW2, he was deployed in France, and from 1942-44 he was head of the Luftnachrichten Dienststelle (air force communication service) in Paris. His duties were the organization and operation of radio navigation, and the military ground-based radio and telephone systems. Although no specific details were given in his military records about his duties, a brief entry, "Ausbau des Dezimeternetzes sowie Erprobung der Sender, Navigations- und Ortungsanlagen" (strengthening of the decimeter (wave) network, as well as testing of transmitters, navigation and ranging equipment), indicated that he was probably heavily engaged in the "battle of the beams" between Germany and Great Britain (documented in detail in [3]; see also http://en.wikipedia.org/wiki/Battle_of_the_beams).

In the early morning of April 10, 1944 Mögel died from a heart attack, after a long and exhausting meeting in Paris.

1 In the German Military Archive in Freiburg/Breisgau, the personal files of Mögel are kept, from which all the following information was extracted (files Pers 6/156132 and Pers 6/173916).

Mögel must have been a special person. His military superior, General Martini (1891-1963), head of military communication, characterized him in a promotion statement as "sincere," "good natured," "very conscientious," "tireless hard working," "tactful," with "exceptional knowledge" and "outstanding experience."

2. Mögel and Transradio

The Transradio Aktiengesellschaft was founded on January 26, 1918, jointly by Telefunken, Siemens and Halske AG and the Allgemeine Elektricitäts-Gesellschaft (AEG). The purpose of the company was the operation of installations for wireless communication (telegraphy and telephone) within and outside Germany. The technical installations were first located at Nauen (about 35 km west of Berlin), where Telefunken had operated a wireless research facility since 1906 [4]. In 1911, Telefunken (under Hans Bredow, 1879-1959) had founded the Atlantic Communication Company in New York, and established a station in Sayville on Long Island. The collaboration with the US developed successfully, and on July 23, 1919, the American authorities sent a telegram: "Will you accept commercial business messages from USA?" As a consequence, a commercial business duplex operation was installed, and in 1921, a thirty-year communication treaty was signed. In the following years, Transradio signed similar treaties with Argentina, Brazil, China, and Japan. More details about the early history of Transradio were published by Rotscheid and Quäck [5].

At Nauen in the beginning (1906), spark-gap transmitters, and later, arc converters, were used. In 1913, alternator transmitters with frequency doubling were installed, and continually modernized in subsequent years. They still were in use when Mögel was working with Transradio. The transmission was performed with long waves, in the range of 32 kHz to 48 kHz, because the superior transmission results with short waves was not known at that time. Quäck [6] described the early history of the installations at Nauen. In 1921, a new receiving facility for the transcontinental radio communication was established in Geltow (about 30 km southwest of Berlin). These receivers, as well as the corresponding transmitters in Nauen (and at another location close to Hanover), were controlled via cable from the main operating center in Berlin.

Beginning in 1924, the communication was performed with short waves. In 1930, the whole facility was moved to Beelitz (close to Potsdam, Figure 2), because at Geltow, not enough space was available for the growing need for large antenna arrays. Mögel [7] described the receiving facility in detail. On January 1, 1932, the facilities at Nauen and Geltow were taken over by the "Deutsche Reichspost" (German Imperial Post Office).

Mögel's duties at Transradio comprised:

1. Establishing shortwave propagation forecasts and optimal transmitting frequencies as a function of time of day, season, and geomagnetic and solar activity.

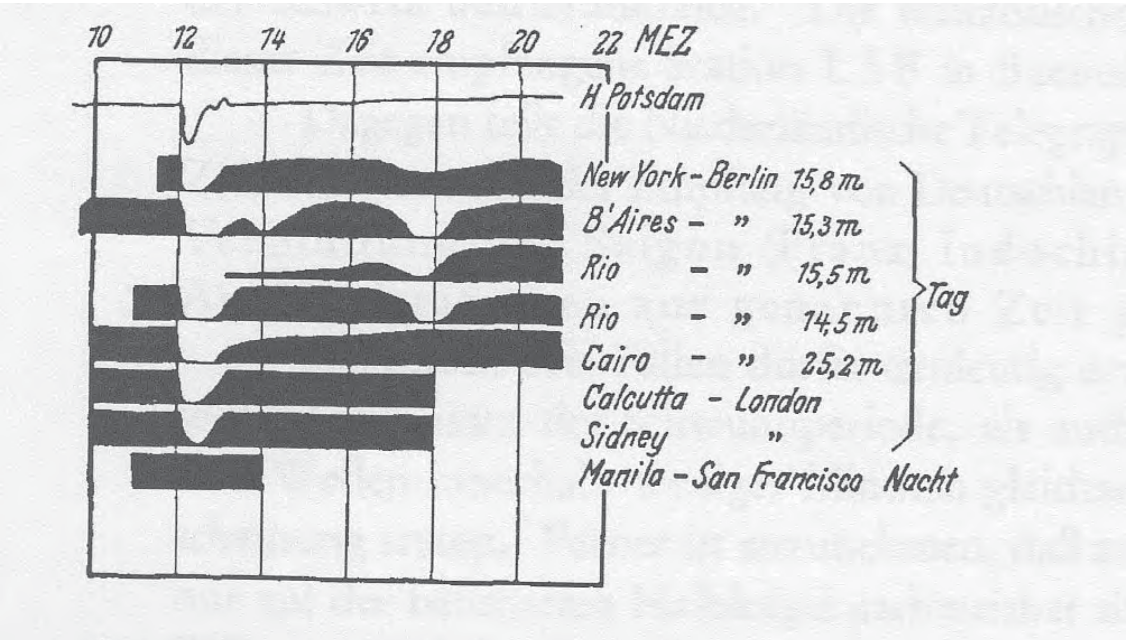

Figure 3. Figure 35 of Mögel's pioneering article [20], showing the SID of October 10, 1928, together with the magnetic H component measured at Geomagnetic Observatory Potsdam. "Tag" indicates the transmission paths on the illuminated part of the globe, "Nacht" is one path on the night side.

2. Development of measures to ensure the fulfillment of international regulations about frequency stability.

3. To document and investigate irregularities and disturbances in the shortwave transmissions.

4. To ensure reliable operation of all services.

These tasks resulted in numerous publications about shortwave transmission techniques. Mögel investigated over two years the audibility of eight transatlantic shortwave communication links, and jointly published the results with his director, Erich Quäck [8]. Some other, more technical papers described the progress in frequency stability (item 2, above). With the help of quartz crystals, Mögel achieved a stability of $\Delta f / f \approx 10^{-4}$ [9], which was later improved by more than an order of magnitude [10]. He also compared the frequency stability of British and German shortwave transmitters [11]. Other subjects investigated were fading [12] and near-field echoes [13]. Mögel summarized his general experiences with shortwave transmission and reception during eight years [14]. After he had left Transradio and while working for the German Postal Service, he published a series of papers about the requirements for facilities in commercial shortwave communication [15-17]. The third part of this series [17] was the last paper Mögel ever published. During his time at the Postal Service, he also performed ionospheric sounding [18, 19].

3. The Mögel-Dellinger Effect

The most interesting papers from the point of view of solar-terrestrial relations showed Mögel's great interest in the investigation and explanation of the relevant geophysical processes, and their influence on shortwave communication. The basic contribution was published in December 1930 [20]. Before, on September 12-13, 1930, he had already presented the corresponding results at the annual meeting of the "Deutsche Geophysikalische Gesellschaft" (German Geophysical Society), in Potsdam. The title of this paper was "Über die Beziehungen zwischen Empfangsstörungen bei Kurzwellen und den Störungen des magnetischen Feldes der Erde" ("About Relationships Between Short-Wave Receiving Disturbances and Disturbance of the Magnetic Field of the Earth"). Consequently, most of the content dealt exactly with these relationships, which he analyzed with the help of data gathered between 1927 and 1930. He compared shortwave reception disturbances with geomagnetic records or indices in a statistical way. Only on the last two pages (out of 18), he described the new phenomenon under the heading "Kurzzeitstörungen" (short-time disturbances). He pointed out that they are fundamentally different from the previously discussed geomagnetically related disturbances, because during these events, the magnetic records show only a very small deviation (he called it bay disturbance). The other fundamental differences were i) the reception field strength decreased within a few minutes to very low levels and remained low for one to two hours; ii) the disturbances occurred only on the sunlit hemisphere (Figure 3). He argued that the disturbances must have been caused by "eine durchdringende vom Erdfeld nicht ablenkbare Strahlenart" (a penetrating radiation not deflected by the Earth magnetic field), and that this radiation ionized the lowest ionospheric layers, since even long waves were affected. In a follow-up of his studies two years later, he mainly discussed the solar-cycle variation of shortwave disturbances [21].

John Howard Dellinger (1886-1962) published his first paper about the same subject in September 1935, under the title, "A New Radio Transmission Phenomenon" [22]. It was a short, one and one-third column publication, were he described the subject only in words, without any illustration. Similarly to Mögel, he pointed out that it was a "semi-world-wide event" (only over the illuminated half of the globe), and "depending apparently on some solar emanation lasting only a few minutes." He had also observed that the phenomenon "occurred in every two solar rotation periods," giving some dates. Interestingly, he did not mention Mögel's observations, but told the reader "the phenomenon was first brought to my attention by a correspondent in France..." in May 1935. After several short publications in various journals (see the bibliography in the following paper), Dellinger published a very detailed study of the phenomenon [23], with many figures and an extensive discussion. In this publication, he probably used for the first time the term "sudden ionospheric disturbance" (SID), which is still in use today. He also realized that SIDs occurred in conjunction with solar flares (not realized by Mögel), and speculated that the phenomenon may be caused by ultraviolet radiation.

Neither Mögel nor Dellinger could establish the correct cause of the SID: solar X-rays emitted during solar flares. They were measured for the first time by Friedman in 1949, using sounding rockets (German V2) [24]. He and his colleagues stated the true cause of SIDs [25]. The slight disturbance of the geomagnetic field observed during a SID is caused by the increase of the E- and D-region conductivity (magnetic crochet).

It is interesting to speculate why Dellinger never mentioned Mögel's work in one of his publications. The most probable reason was that he was not aware of these results, since Mögel published only in a German company journal, the "Telefunken Zeitung," and in the German language. Dellinger should in principle have had access to this journal, since the National Bureau of Standards where Dellinger was employed had a journal exchange with Telefunken. Perhaps Dellinger did not understand German. On the other hand, colleagues must have told him about Mögel's work in later years. However, he always claimed the discovery of SIDs, e.g., in his paper cited above ("The effect was discovered in 1935" [23]), and even at a conference in 1954 (Dieminger, private communication). The priority of Mögel was clearly stated by Appleton [26]. He called Mögel "the pioneer investigator of such matters," but also pointed out that “Such association (fade-out and bright eruptions) has been satisfactorily established only as the result of the work of Dellinger, Jouaust, Fleming, Richardson Newton, McNish, Torreson, Scott and Stanton, and Berkner and Wells.”

Mögel never reacted on Dellinger’s publications and claims.

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Radiowave Propagation in Urban Environments with Application to Public-Safety Communications

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[This is the second article in a three-article series dealing with radio-propagation studies related to public-safety communications. The first article, "Propagation Measurements Before, During, and After the Collapse of Three Large Public Buildings," appeared in the September 2014 issue of the *Radio Science Bulletin* (pp. 31-47). The third article, "Peer-to-Peer Urban Channel Characteristics for Two Public Safety Frequency Bands," will appear in the March issue.]

Abstract

We characterized key elements that pose challenges to public-safety radio communications into and out of large buildings, including the strong attenuation of radio signals caused by losses and scattering in the building materials and structure, and the large signal variability that occurs throughout these large structures. We analyzed measurements of continuous-wave radio signals, and provided the parameters for representative log-normal distributions for six frequency bands, ranging from 430 MHz to 4.9 GHz. The data were collected in experiments in which radio-frequency transmitters were carried throughout large urban structures, and receiving systems were placed outside the structures. In other experiments, the radio transmitters were carried through urban streets, with receivers at locations on the streets within the same urban environment. The transmitters were tuned to frequencies near public-safety and cell-phone bands, as well as those of unlicensed bands.

1. Introduction

Public-safety communication systems must operate in a wide range of radio-frequency (RF) propagation environments, from suburban housing developments to urban streets, and in large, complex structures. When public-safety personnel enter large structures (e.g., apartment and office buildings, sports stadiums, stores, malls, hotels, convention centers, warehouses), communication with individuals on the outside is often impaired. Cell-phone and mobile-radio signal strength is reduced due to attenuation caused by propagation through the building materials, and scattering by the structural components [1-9]. In addition, the large amount of signal variability throughout the structures can impair the ability of the receiver to successfully detect and demodulate the signal. Here, we report on a US National Institute of Standards and Technology (NIST) project to investigate the wireless communication problems faced by public-safety personnel (firefighters, police, and medical personnel) in situations involving large building structures and urban settings. The goal was to create a large body of statistical data in the open literature for improving communication-system development and design. For example, these results are useful for technology-advancement initiatives focused on improving public-safety communications, such as [10-12]. This paper is part of a series covering several aspects of RF propagation for public-safety communications, including imploded buildings, and urban street and building environments. The series of articles provides real-world data and measurement techniques for researchers and practitioners focusing on public-safety communication systems that should benefit the general wireless design community, as well.

The results reported here represent an extension and further refinement of experiments presented in [13,14]. Those described RF propagation measurements in four office buildings, two apartment buildings, a hotel, a grocery store, a shopping mall, a convention center, a sports stadium, and an oil refinery. Those data included narrowband measurements near public-safety and cell-phone bands, as well as industrial, scientific, and medical (ISM), and wireless local-area network (LAN) bands (approximately 50 MHz, 150 MHz, 225 MHz, 450 MHz, 900 MHz, 1.8 GHz, 2.4 GHz, and 4.9 GHz). Here, we present results on frequencies ranging from 430 MHz to 4.9 GHz in three additional, important settings: a 57-story high-rise office building, a three-story scientific laboratory, and a six-block urban area. Empirical cumulative distribution functions (CDFs) were obtained, and subsequently used for parameter estimation of the underlying probability distribution. Unlike our previous studies, data collected in the 750 MHz band were included, as well.

The experiments performed here are referred to as "radio mappings." This involved carrying continuous-wave (CW) transmitters tuned to various frequencies throughout the environment under test, while recording the received signal at sites located at several outdoor locations. In the case of the structures studied, the purpose of the radio-mapping measurements was to investigate how the signals at the different frequencies coupled into the structures, and to determine the field-strength variability throughout the structures. Several previous papers [15-18] have provided results on radio mapping in buildings. Others, such as [19-28], provided results on building penetration for a few of the frequency bands discussed here. Reference [29] outlined a measurement campaign at 2.4 GHz and 5.2 GHz, carried out in support of an overall system-design effort, while [27,28] focused on measurements for public safety. With respect to the breadth of our building-measurement campaign, [30] provided a review of similar radio-propagation measurements up to 1990 within our bands of interest, and also proposed a building-classification scheme. Examples of urban street propagation in some of the frequency bands covered here included [31, 32], which focused on measurements; [33], which provided models of the urban environment; and [34], which presented a modeling approach for the combination of building penetration and outdoor urban propagation.

Our work is different from the aforementioned efforts in several ways: (1) a wider range and number of frequencies were covered per building; (2) multiple types of large building structures were investigated; (3) outdoor urban propagation was measured with both the transmitter and receiver near street level; and (4) the building walk-through paths and receiver-site locations were selected to emulate a public-safety-response scenario. Hence, this work builds upon previous work designed to accurately characterize wireless RF propagation in some key environments by adding much-needed data to building categories 5 (factory buildings with heavy machinery) and 6 (other factory buildings, sports halls, exhibition centers) in [30], by providing propagation data in the 750 MHz band, and by providing statistical estimates of the propagation behavior in urban street and building environments.

2. Experimental Parameters and Equipment

This section covers the frequency bands, transmitter characteristics, and receiver configurations used in the experiments. An overview of these experimental components is important with respect to interpreting the collected data and accompanying analysis.

2.1 Frequency Bands

An overview of the frequencies between 150 MHz and 4.9 GHz, used nationwide (federal, state, and local) by the public-safety community, is given in Table 1. The modulation scheme used by the public-safety community has historically been analog FM, but this is slowly changing to digital, as Project 25 radios come online [10]. The modulation bandwidth in the VHF and UHF bands has been 25 kHz, but due to the need for additional communications channels in an already crowded spectrum, most new public-safety bandwidth allocations are 12.5 kHz. The older bandwidth allocations will gradually be required to move to narrower bandwidths to increase the user density even further. The crowded spectrum and limited available bandwidth are also pushing the move to higher frequency bands, including 750 MHz and 4.9 GHz, in order to support new data-intensive technologies.

Frequency Band (MHz)	Nominal Frequency Used in Measurements	Description
150-174	–	Local police and fire
406-470	430-450	Used by federal officers and others
700-800	750-751	Includes the new public-safety band
800-869	900-908	Primarily urban usage; AMPS or analog systems
1850-1990	1834-1850	PCS or digital systems
2400-2500	2400	Wireless LAN
4940-4990	4960-4900	A recently allocated band with 50 MHz bandwidth for broadband data

Table 1. Public-safety communication frequencies and cellular bands, including nominal frequencies used in the NIST measurements.

Figure 1. A typical transmitter used to generate the CW signal.

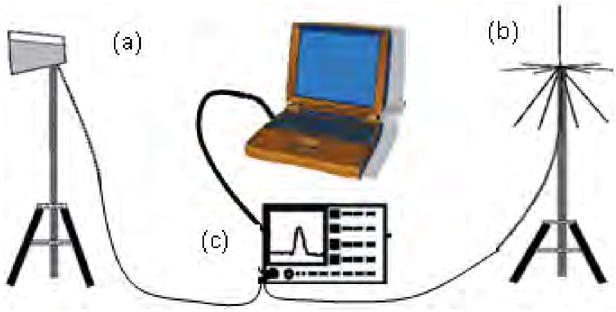

Figure 2. The receiver equipment and setup. The choice of antenna depended on the frequency band: (a) a 1 GHz to 5 GHz horn antenna (or a linear array antenna), and (b) a 50 MHz to 1 GHz discone antenna. (c) The spectrum analyzer was connected to a laptop via a GPIB interface.

As shown in Table 1, frequencies currently used by public-safety and other emergency responders and cellular telephones are typically below 2 GHz. New frequency allocations and systems including higher frequencies (e.g., around 4.9 GHz) will become increasingly important in the future. We chose six frequency bands below 5 GHz, from around 430 MHz to 4.9 GHz. These included three VHF bands typically used for analog FM voice, one band used for multiple technologies (analog FM voice, digital trunked FM, and ISM), one band near the digital cellular-telephone band, and a common wireless LAN band. In designing an experiment to investigate the propagation characteristics into large buildings at these different frequency bands, we chose frequencies very close but not identical to the above bands to minimize interference between our measurements and ongoing usage of those bands. In addition, obtaining frequency authorizations in those bands for our experiments would have been problematic, due to the intense crowding of the spectrum. To circumvent these issues, we received temporary authorization to use frequencies in the US government frequency bands adjacent to these public-safety bands. The second column of Table 1 lists the frequency bands that were used in the experiments. Note also that the distinction between public-safety versus commercial usage is becoming less obvious, as many public-safety products, such as RF-based personal-alert safety systems (RF PASS), are using technology and frequencies in the unlicensed ISM bands.

2.2 Transmitters

The design requirements for the transmitters used in the experiments were that they should (1) transmit at the frequencies listed in Table 1 above, (2) operate continuously for several hours, and (3) be portable. Commercial transmitters in plastic protective cases, such as that depicted in Figure 1, were available for all of the frequency bands. The antennas were electrically short monopoles or "rubber duck" types, with omnidirectional patterns and gains of approximately 0 dBi for the frequency bands up to 1.9 GHz. The 2.4 GHz and 4.9 GHz bands utilized linear-dipole-array antennas with omnidirectional patterns, and gains of between 3 dBi and 5 dBi.

2.3 Receiver

As shown in Figure 2, the receiver consisted of a spectrum analyzer controlled by a graphical programming language. The software ran parallel processes of collecting, processing, and saving the data for additional post-collection processing. The data were continuously read from the spectrum analyzer and stored in data buffers. The software processed these buffers by searching for the power level of the desired CW signal, which was subsequently displayed for the operator. These processed data were then saved (along with the original raw data) on the laptop. The sampling rate of the complete measurement process was the major factor in determining the spatial resolution during radio-mapping experiments and the time resolution for recording the signals. The walking speed of the transmitter operator also factored into the spatial resolution. A narrow frequency band (called the capture bandwidth) around the desired CW signal was measured during each walk (either a walk-through in a building or along the sidewalk in the urban street experiment), which resulted in sampling periods of between 0.2 s and 0.3 s. As the CW sources (i.e., the radios) were carried through the buildings or urban sidewalks, the receiver recorded the capture bandwidth around the CW frequency. The capture bandwidth was typically less than 20 kHz, but wide enough to ensure that the CW signal was measured even if the CW source experienced frequency drift.

Horn antennas, shown in Figure 2a, were used for the 2.4 GHz and 4.9 GHz frequency bands in the experiments at the high-rise building, while linear dipole arrays with gains of 3 dBi to 5 dBi were used in the urban setting and the laboratory building. The horn-antenna gain was 10 dBi, with a beamwidth of approximately 45° at the frequencies of interest. A discone antenna was used for the frequency

Figure 3. The five receiving sites (a through e) for the Denver urban setting measurements, and (f) the transmitter being carried through the Denver streets.

bands below 1 GHz, and it had a gain of 2 dBi and a beamwidth of approximately 45°. Finally, a conical antenna was used for the 1.8 GHz receiving antenna, with a gain of approximately 3 dB. The receiving antenna heights were between 2 m and 4 m.

3. Urban Setting and Building Descriptions

Physical environment features cause scattering and attenuation in RF propagation channels. The brief overview below, with accompanying pictures and maps of the three experimental settings, highlights some of the urban street and building features that may have impacted RF signal reception.

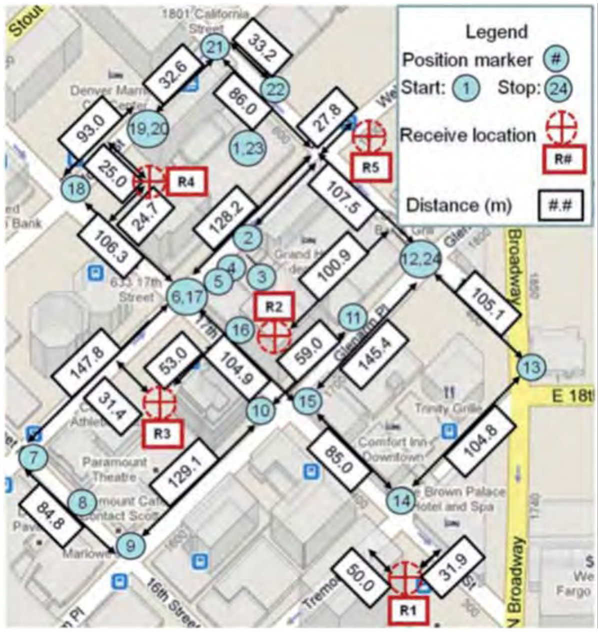

Figure 4. A map of the path walked through the Denver streets. The circled numbers indicate the order of the marked locations traversed. The five receiving locations are indicated, and the distances between key locations are given in meters.

3.1 Urban Setting, Denver, CO

The urban setting studied here covered a four-block section of downtown Denver, Colorado. The Denver urban environment included a mix of multistory buildings, high-rises, parking structures, and parking lots. Brick, concrete, glass, and metal trim made up the exterior of most buildings,

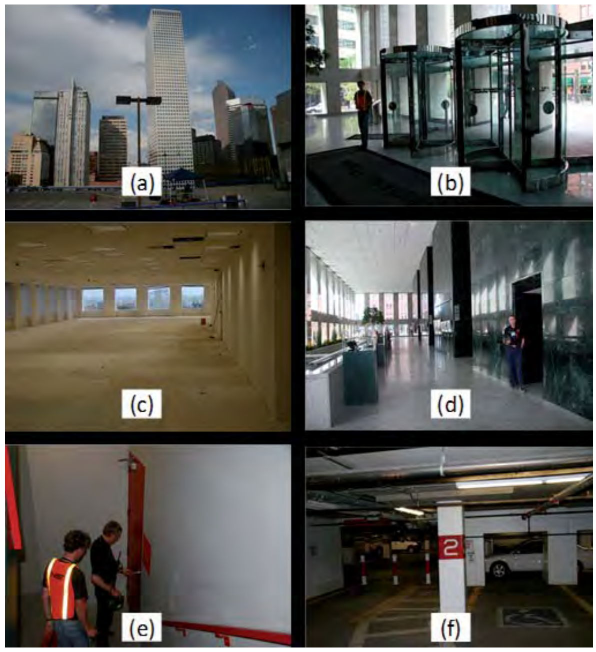

Figure 5. Republic Plaza, Denver, CO: (a) the 57-story building (tallest in the picture); (b) the entrance at 17th Street; (c) a large, open floor, 10th floor; (d) the lobby area on the first floor near the elevators; (e) the stairwell; and (f) the basement.

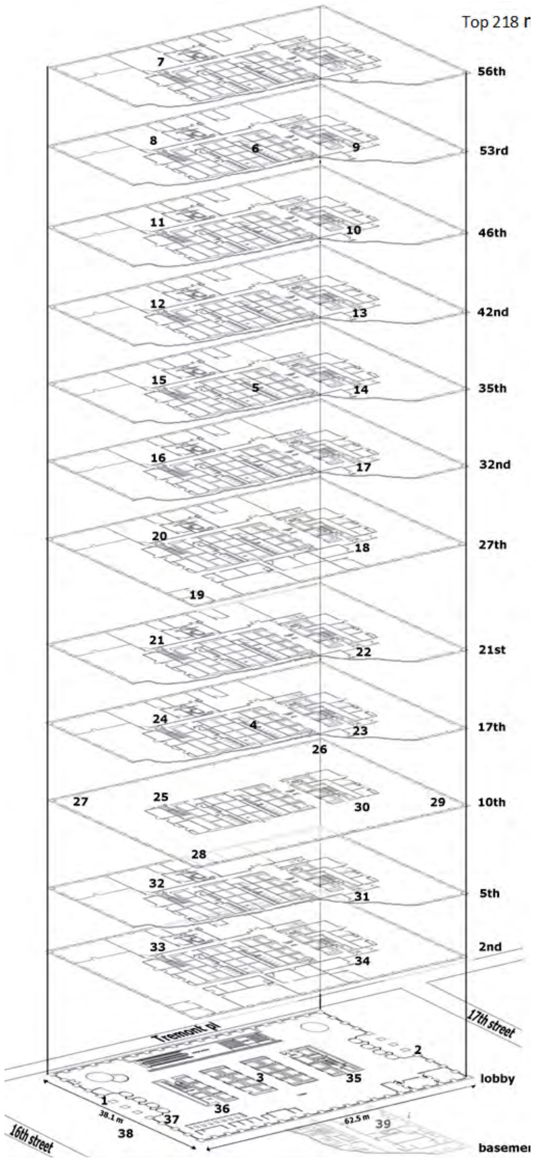

Figure 6. The Republic Plaza 57-story high rise: the numbers indicate the radio-mapping path.

and the parking lots were primarily paved asphalt, with some gravel sections. Figure 3 shows the various building structures in the Denver urban environment, as well as the five receiving sites used during the data-collection process. Figure 4 provides a map of the path traversed with the mobile transmitters. The five receiving sites are shown, as well as some distances between various locations. Numbers in circles indicate key markers in the data-collection process. The path started at Mark 1, and proceeded through all of the markers in order, until ending at Mark 24.

3.2 Republic Plaza, Denver, CO

The Republic Plaza was a 57-story office building in downtown Denver. The construction materials were a typical combination of concrete and steel. The interior building materials were a combination of metal framing, drywall, and trim, with stone finishes in the lobby. The exterior was a combination of glass and metal. Figure 5a illustrates the exterior, and Figures 5b-5f show parts of the interior of the building. Figure 6 shows floor plans for several levels.

In this experiment, the three receiving sites depicted in Figure 7 varied substantially in their distances from the building. Receiving Site 1 was located on the 17th Street side, approximately 10 m from the building; Receiving Site 2 was located on the 16th Street side, approximately 25 m from the building; and Receiving Site 3 was located on the roof of a parking garage, approximately 215 m southwest on Tremont Plaza. These locations were intended to simulate the locations of command vehicles in an emergency-response scenario.

3.3 Building 87, Boulder, CO

The third building was a new science laboratory that was under construction at the NIST campus in Boulder, CO. Measurements were performed at various stages of the construction process. Here, we will focus on the latest data collected when the construction process was approximately 85% to 90% complete. The major building elements were in place for these measurements. This building contained many sophisticated laboratories, and as a consequence, extensive piping, metallic ducting, and other mechanical

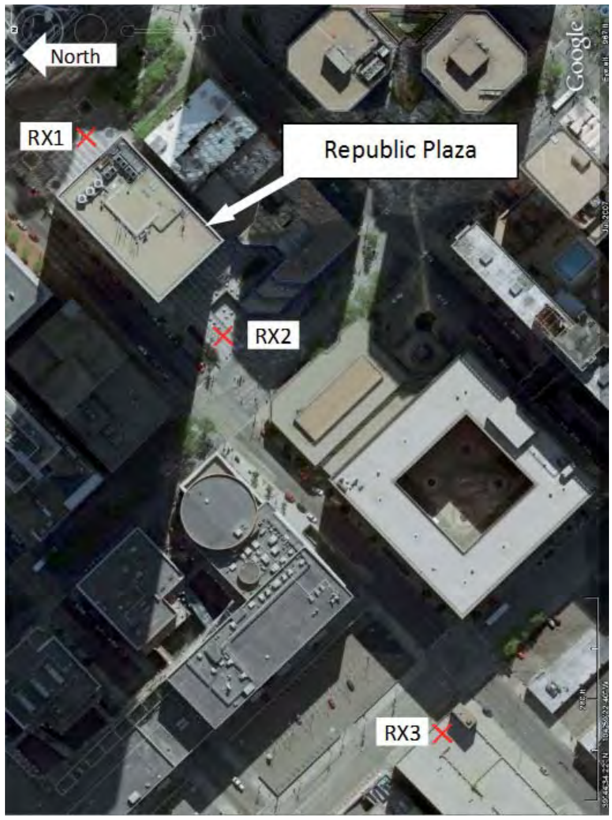

Figure 7. The location of receiving sites at the Republic Plaza building. Note that Receive Site 3 (RX3) was located on the top of a parking garage (© 2009 Google).

Figure 8. Building 87: (a) the south exterior, (b) the north exterior, (c) the main stairwell, (d) the interior wall construction, and (e) some of the extensive mechanical piping found throughout the building.

systems were needed in the building. Figures 8a and 8b show the building's typical exterior finishes of glass, metal trim, and concrete covering a concrete-and-steel building core. The main concrete stairwell is shown in Figure 8c. Typical interior walls of gypsum board on metal-stud framing are shown in Figure 8d, and an example of the extensive mechanical support systems within the building is shown in Figure 8e.

As in the previous data-collection efforts, CW transmitters were carried on a prescribed path within the building while sites outside of the building measured the received power. Figure 9 shows the three-story floor plan, with the numbers indicating the radio-mapping path, and the red circles indicating the orientation of the two receiving sites. (The receiving sites were further from the building than depicted in the figure.)

4. Data Analysis

In post-processing, the software searched for the maximum signal within the capture bandwidth by use of a smaller search bandwidth (less than 10 kHz). This search bandwidth was set even smaller – less than 5 kHz – if an interference source lay within the original capture bandwidth and the desired CW source did not experience significant frequency drift. Because we used CW sources, the maximum value was the received power measured at a given time interval. This allowed the flexibility of removing nearby (in frequency) interference in the original data.

Different radios were used for the various frequencies, with different transmitted power settings. The radios all emitted CW signals, but the radios from 430 MHz to 1.8 GHz transmitted 1 W, while the 2.4 GHz and 4.9 GHz radios transmitted 5 W. To compare received signals, the measured signal power was calibrated for the difference in transmitted power – approximately 7 dB between 1 W and 5 W – by subtracting 7 dB from the measured 2.4 GHz and 4.9 GHz values. These data were also calibrated for receiving and transmitting antenna gains to allow comparison between frequencies. The calibrated power was given by

$$P_{RX}^{cal}\left[\text{dBm}\right] = P_{RX}\left[\text{dBW}\right] - G_{RX}\left[\text{dB}\right]$$

$$-G_{TX}\left[\text{dB}\right] - P_{TX}\left[\text{dBW}\right], \quad (1)$$

where P_{RX}^{cal} is the received power after accounting for the transmitter powers and antenna gains, P_{RX} is the measured received power before calibration, G_{RX} is the gain of the receiving antenna, G_{TX} is the gain of the transmitting antenna, and P_{TX} is the transmitted power. We define the transmitted power relative to a watt, which was 0 dBW and 7 dBW for the 1 W and 5 W transmitters, respectively. To first order, the receiving system (i.e., spectrum analyzer, cables, and receiving antenna) and the antennas on the transmitting radios were assumed to impact the measured power in a manner roughly equivalent to an actual deployed public-safety radio network or other wireless system.

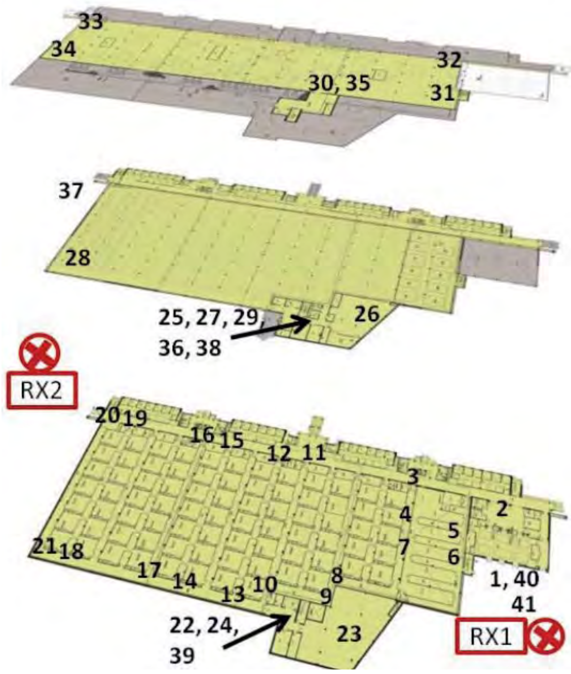

Figure 9. NIST Building 87: The numbers indicate the order of the walked path; multiple numbers indicate a common point in the path. Note that the path from 36 to 37 back to 38 was outside of the building. Both receiving sites were on the ground level, outside the building.

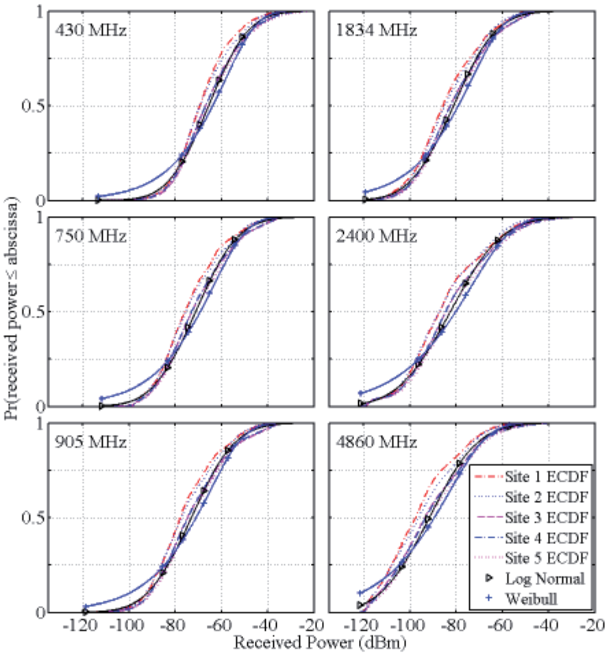

Figure 10. Empirical cumulative distribution functions (ECDF) for the five Denver Urban environment receiving sites. Estimated log-normal and Weibull cumulative distribution functions were based on the combined collected data from all five sites.

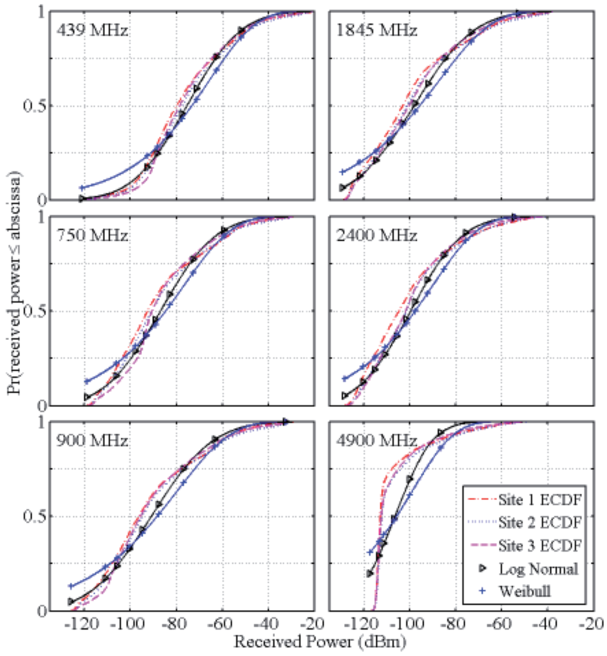

Figure 11. Empirical cumulative distribution functions for the three Republic Plaza receive sites. Estimated log-normal and Weibull cumulative distribution functions are for the combined data from the three sites.

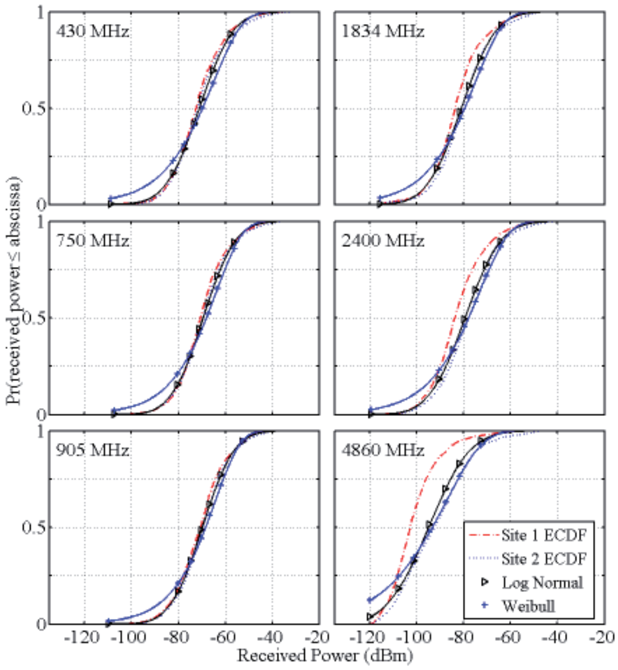

Figure 12. Empirical cumulative distribution functions for the two NIST Building 87 receive sites. Estimated log-normal and Weibull cumulative distribution functions were for the combined data from the two sites.

4.1 Estimated Cumulative Distribution Functions

The calibrated received power data, P_{RX}^{cal}, from all receiving sites were combined for each frequency. A Kaplan-Meier estimate of the cumulative distribution function (CDF) was computed on this aggregate data set with a commercial software package. A Kaplan-Meir or product limit estimation is often used for survivor analysis [35, 36]. The survivor function, $S(x)$, is given by

$$S(x) = 1 - F(x), \tag{2}$$

where $F(x)$ is the cumulative distribution function. The cumulative distribution function is then found from

$$F(x) = 1 - S(x). \tag{3}$$

An estimate of the survivor function thus provides an estimate of the cumulative distribution function. With the variables described in the context of measured power levels, the Kaplan-Meir estimate for Equation (2) is given by

$$S(x) \approx \prod_{k=1}^{n} \left(\frac{m_k - d_k}{m_k} \right), \quad \text{for } x_n \le x < x_{n+1}, \tag{4}$$

where x is the power level P_{RX}^{cal}, k is the index of P_{RX}^{cal} samples in increasing magnitude, m_k is the number of measured power quantities greater than the kth power measurement, and d_k is the number of measured power quantities at the kth power-measurement level.

In these data, the cumulative distribution function provided the probability that the received signal power was below a certain value. The maximum likelihood estimates

Freq. Band (MHz)	Denver Urban		Republic Plaza		Building 87	
	μ (dB)	σ (dB)	μ (dB)	σ (dB)	μ (dB)	σ (dB)
430	–15.12	3.15	–17.37	4.26	–20.29	3.84
750	–16.41	3.38	–20.01	4.36	–19.90	3.59
900	–16.84	3.46	–20.92	4.82	–20.94	4.10
1850	–18.70	3.83	–22.57	4.71	–22.97	3.66
2400	–19.01	4.08	–22.95	4.11	–23.56	3.98
4900	–21.11	3.84	–24.52	2.96	–25.13	3.14

Table 2. Log-normal parameter estimates for the cumulative distribution functions obtained from the combined data collected for the three different environments.

(MLEs) for statistical parameters [37, pp. 260-263], such as the mean, standard deviation, or shape factor, were then computed under the assumption that these data came from gamma, normal, log-normal, or Weibull distributions. The minimum mean-square error between cumulative distribution functions based on the maximum likelihood estimate parameters and the original estimated cumulative distribution functions occurred with the use of the log-normal distribution for all data sets. This was expected, because the log-normal distribution represents the typical power distribution associated with the large-scale fading that is anticipated in office-building and urban environments [38]. In addition, as discussed in [39], the log-normal distribution is well-suited for a variety of data-analysis problems. We include some fundamental properties provided in [39] that are relevant to the data analysis.

The log-normal probability density function is given by

$$p(x;\mu,\sigma) = \frac{1}{\sqrt{2\pi}x\sigma}\exp\left[-\frac{(\ln x-\mu)^2}{2\sigma^2}\right],\ x>0\ .(5)$$

Integrating Equation (5) over $(0,x)$, using the substitution $t=-\frac{\ln x-\mu}{\sigma\sqrt{2}}$ and Equation (7.1.2) in [40], yields the log-normal cumulative distribution function

$$F(x;\mu,\sigma) = \frac{1}{2}\operatorname{erfc}\left[-\frac{\ln x-\mu}{\sigma\sqrt{2}}\right],\ x>0, \qquad (6)$$

where $\operatorname{erfc}(\bullet)$ is the complementary error function, and μ and σ are the mean and standard deviation, respectively, of the natural logarithm of x. In the strict sense, x is the independent variable, but because it is unambiguous here, we use it to represent the random variable, as well [37, pp. 63-73]. The mean is then found by

$$E[x] = e^{\mu+\frac{1}{2}\sigma^2}, \qquad (7)$$

the median value is given by

$$\text{median} = e^{\mu}, \qquad (8)$$

and the standard deviation is found by

$$\text{standard deviation} = e^{\mu+\frac{1}{2}\sigma^2}\sqrt{e^{\sigma 2}-1}\ . \qquad (9)$$

For comparison, the estimated Weibull cumulative distribution function curves based on the combined data for each frequency and environment are also shown. The two-parameter Weibull cumulative distribution function is given by

$$F(x;\alpha,\beta) = 1-\exp\left[\left(-\frac{x}{\alpha}\right)^{\beta}\right],\ \alpha,\beta>0, \qquad (10)$$

where α is the scale factor, and β is the shape factor. The Weibull distribution has been shown to be a useful distribution in similar measurement efforts [41, 42], and is thus considered here.

The empirical cumulative distribution functions, as well as the estimated log-normal and Weibull cumulative distribution functions for the various frequencies, are shown in Figures 10-12. Table 2 provides the maximum-likelihood estimate of the log-normal parameters for the cumulative distribution function of the total data (i.e., the aggregate of multiple receiving sites), at each frequency. Figures 10-12 showed that the general behavior of data from each site compared reasonably well to the estimated log-normal and Weibull curves that were based on the total data. Across all frequencies and receiving-site locations, the mean-square error was smaller for the log-normal fit than for the Weibull fit. In general, the log-normal curves fit the data reasonably well, except for the 4900 MHz frequencies measured in Republic Plaza and NIST Building 87. This was due to the collection of an excessive amount of noise data, which in turn created a step-like behavior in the empirical cumulative distribution functions. The Denver urban-environment measurements showed the same type of behavior as the two buildings, but not as severe a step-like behavior, since the 4900 MHz signal generally experienced much less attenuation outdoors than when it propagated through a building.

4.1 CDF Results

Figures 13-15 show the log-normal cumulative distribution function results based on the aggregate empirical cumulative distribution functions shown in Figures 10-12. These results were obtained by combining all of the data collected from the multiple sites, generating an empirical cumulative distribution function based on the total data set, and then obtaining the log-normal fit to the total data. The estimated values for μ and σ are provided in Table 2.

Power levels at the 0.5 cumulative distribution function values were computed in the following manner:

$$\text{median}\left\{P_{RX}^{cal}\,[\text{dBm}]\right\} = \log_{10}\left(e^{\mu}\right), \qquad (11)$$

where the μ values are listed in Table 2. These median values showed the frequency dependence of the measured attenuation. For example, in the case of the Republic Plaza building (Figure 14) , the received 4.9 GHz signal was greater than –109.7 dBm only 50% of the time, whereas in the case of 750 MHz, the received signal was greater than –94.5 dBm at least 50% of the time. Similarly, in Figure 13, the received 4.9 GHz signal was greater than –91.7 dBm only 50% of the time, but the received 750 MHz signal was greater than –75.0 dBm 50% of the time. For those measurements, the 750 MHz signal was thus attenuated approximately 16 dB less than the 4.9 GHz signal.

Table 3 lists the power level, P_{RX}^{cal} , at the 0.5 level for the various frequencies, based on the curves in Figures 13-15. The 0.5 cumulative distribution function value was selected for comparison because each fitted curve exhibited the best fit to the individual results in the middle region of the curve. The log-normal curves below values of –120 dBm

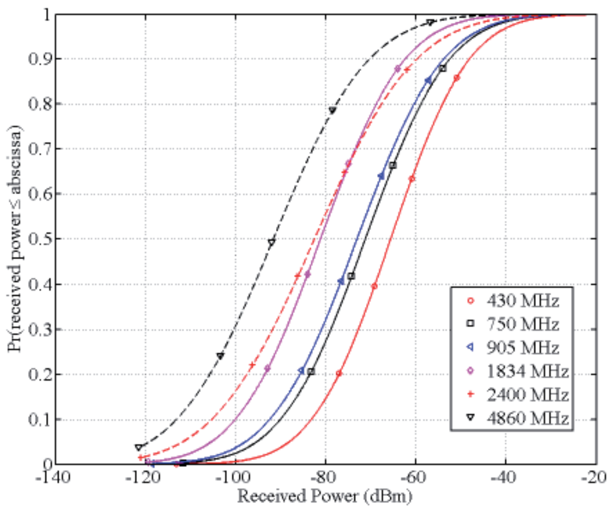

Figure 13. The log-normal cumulative distribution functions determined from the combined data collected at five receiving sites for the Denver Urban environment.

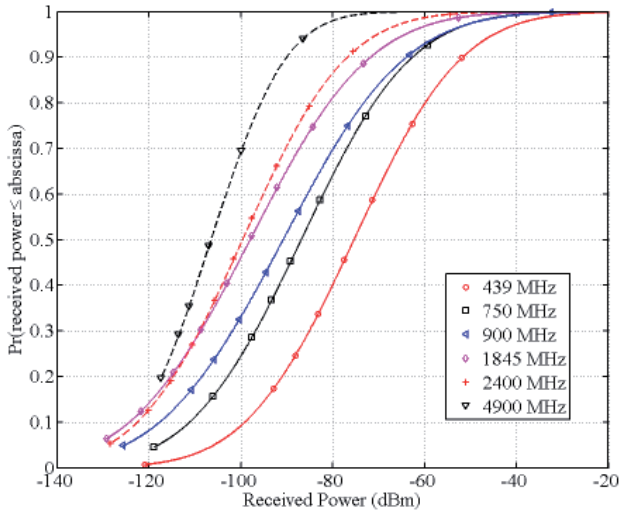

Figure 14. The log-normal cumulative distribution functions determined from the combined data from the three receiving sites for the Republic Plaza building.

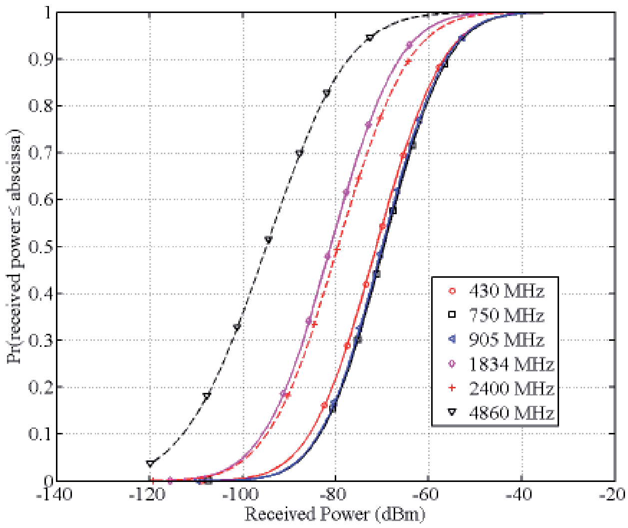

Figure 15. The log-normal cumulative distribution functions determined from the combined data from the two receiving sites for the NIST Building 87 environment.

were not well defined, as this represented the typical noise floor of the measurement system. This was reflected in the truncated tails at higher frequencies in Figures 14 and 15. In general, there was clear frequency dependence, where the higher frequencies experienced greater attenuation. The only discrepancy occurred in the case of NIST Building 87, which indicated a received power level that was 1.5 dB lower at 430 MHz than at 750 MHz. Note that the 0.5 cumulative distribution function values, other than 430 MHz, were within 2.6 dB at a given frequency for the two buildings.

The curves in Figures 13-15 also provided path-loss information about the three environments. Since the curves were based on a 1 W (or 30 dBm) transmission, subtracting 30 dB from the received levels on the abscissa provided the amount of path loss or attenuation experienced by the RF signal. For example, the –80 dBm value on the abscissa corresponded to 110 dB of path loss. Examination of

Freq. Band (MHz)	Denver Urban (dBm)	Republic Plaza (dBm)	Building 87 (dBm)
430	–65.7	–75.4	–88.1
750	–71.3	–86.9	–86.6
900	–73.1	–90.8	–90.9
1850	–81.2	–98.0	–99.8
2400	–82.6	–99.7	–102.3
4900	–91.7	–106.5	–109.1

Table 3. The received power, P_{RX}^{cal}, at the 0.5 probability level.

Figures 13-15 indicated that less than 30% of the 900 MHz signals experienced a path loss greater than 110 dB for the Denver Urban environment, but greater than 65% of the 900 MHz signals experienced 110 dB of path loss in the two buildings. At 2.4 GHz, approximately 58% of the signals experienced a path loss of greater than 110 dB in the Denver Urban environment. However, the two building environments caused greater than 85% of the signals to experience a path loss of 110 dB or more at 2.4 GHz. Clearly, the large buildings created RF propagation conditions that introduced significant path losses, which must be considered in any wireless system design.

Another way to interpret the curves in Figures 13-15 is in terms of how much path loss must be overcome to provide an estimated percentage of coverage in the environment. For example, in the Republic Plaza building, 90% coverage at 900 MHz required overcoming a path loss of approximately 145 dB. At 2.4 GHz, 90% coverage required overcoming a path loss of approximately 155 dB. This is an important consideration in the architecture of a wireless system, and may point system designers to the use of relay radios or multi-hop wireless nodes in order to achieve the necessary coverage for public-safety communications.

Finally, we can also look at the changes in path loss as a function of frequency. Figure 16 provides relative path-loss results based on the median values, relative to the 750 MHz results (430 MHz was not used as the reference, due to the anomalous behavior exhibited in the NIST Building 87 results). Omitting the 430 MHz results, the remaining frequencies indicated a path-loss increase of approximately 7 dB per doubling of frequency.

5. Measurement Uncertainties

Following the convention described in [43], the uncertainties associated with this measurement process could be broken into two categories, Type A (evaluated by statistical means), and Type B (evaluated by non-statistical means). The wireless channel was inherently dynamic with respect to time, frequency, and position, and the data collected were impacted by these parameters. However, the measurement system changed relatively little between data collections. Table 4 describes the various uncertainties associated with the measurement system.

Uncertainties in an estimate of received power for this type of measurement campaign were much higher than those typically quoted in laboratory settings, because the environment was not static. To obtain an uncertainty estimate associated with the measurement process in the field, the transmitter was held at a fixed reference location for approximately 4 s in order to remove the effects of a moving transmitter. Data collected at each site over this 4 s period were normalized by the maximum received signal at that site over that 4 s time period. The standard deviation was then calculated from the combined and normalized data, based on 15 samples from each receiving site (15 samples ≈ 4 s). Uncertainty values are listed in Table 5. Note that the uncertainty analysis was based on data from all received sites, which included both line-of-sight and non-line-of-sight paths to the transmitter. The channel thus may have experienced fluctuation due to objects moving within the channel (as opposed to movement by either the transmitter or the receiver).

6. Conclusions

Emergency responders and public-safety practitioners need confidence that their radio systems will work in

Type	Uncertainty Description	Method of Estimate	Values (dB)
Type A	Accuracy in spectrum analyzer measurements.	Specified by the manufacturer.	< 0.6 Typical
Type A	Data collection system tests, including laptop and spectrum analyzer.	Collected statistical data for a known source over a one day period, in an outdoor environment.	< 0.1
Type A	Measurements from fixed reference positions at the test sites.	Standard deviation of 15 samples. u_{pos}	1.5 to 6.7 (see Table 5)
Type B	Fluctuation of output power from the transmitters.	Observations from bench-top tests.	< 1.5
Type B	Cable changes due to temperature	Observations from previous uncertaintyexperiments.	< 0.2

Table 4. A description of the measurement uncertainties with associated values.

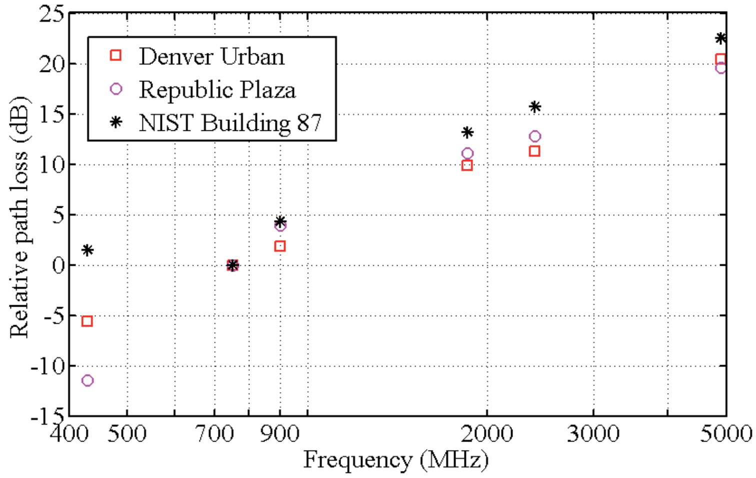

Figure 16. The path loss relative to the 750 MHz band, based on the median values.

urban environments and large structures. Here, we have presented data collected across several key frequency bands in just such environments. The antenna heights and receiving locations were intentionally chosen to mimic the configuration expected in an emergency operation or public-safety activity. The results here provided log-normal cumulative distribution function estimations for frequency bands of interest, ranging from 430 MHz to 4.9 GHz.

Similar frequency dependence in received signal level and distribution was evident in all three measurement scenarios. For the three measurement activities presented here, the difference in 0.5 cumulative-distribution-function values for 750 MHz and 4900 MHz ranged from 19.6 dB to 22.5 dB. Note that the attenuation experienced by the two buildings at the 0.5 cumulative-distribution-function value was within 3 dB for 750 MHz and above. The path-loss calculations for the median results also suggested a 7 dB per octave dependence for these types of propagation scenarios. Finally, the results for the 2.4 GHz and 4.9 GHz bands showed that simply increasing the power from 1 W to 5 W was still insufficient to overcome the significant RF propagation path-loss experienced in large buildings. While these frequencies offer the potential for higher data throughput – as compared to the 750 MHz band, for example – an acceptable level of building coverage may only be achievable with a relay-based or multi-hop wireless architecture.

These observations, along with additional insights from these data, may be useful to designers and operators of public-safety radio systems that must operate in urban environments and large buildings. Future work may include fitting to truncated log-normal distributions to improve the fit with noise-limited data for the higher frequencies.

7. Acknowledgements

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Freq. Band (MHz)	Denver Urban		Republic Plaza		NIST Building 87	
	u_{pos}	u_{tot}	u_{pos}	u_{tot}	u_{pos}	u_{tot}
430	4.3	4.4	1.5	2.1	3.2	3.4
750	3.0	3.2	1.5	2.1	1.9	2.1
900	4.4	4.5	2.2	2.5	3.2	3.4
1850	3.8	3.9	4.5	4.6	3.5	3.7
2400	4.7	4.8	5.7	5.7	6.7	6.7
4900	5.9	5.9	5.5	5.5	3.3	3.5

Table 5. The uncertainty of measurements based on the fixed reference position (u_{pos}), and the total combined (u_{tot}). The values are in dB.

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Report on GASS Commission Business Meetings

COMMISSION A (ELECTROMAGNETIC METROLOGY)

1. Results of Election of Vice Chair and Early Career Representative

Elections were conducted for the positions of Vice Chair and Early Career Representative during Business Meeting 1. The ballots (both mail-in and on-site) were counted by Yasuhiro Koyama. As a result, Patrizia Tavella (INRIM, Italy) and Pedro Miguel Duarte Cruz (NSF, Portugal) were elected as candidates for Vice Chair and Early Career Representative. At the Council Meeting on August 19, both were formally approved as the Vice Chair and the Early Career Representative.

2. Appointment of Associate Editor for *Radio Science Bulletin*

Since the Past Chair, Vice Chair, and Early Career Representative are expected to become the Editors, it was decided to recommend Parameswar Banerjee (Amity University, India), Patrizia Tavella (INRIM, Italy), and Pedro Miguel Duarte Cruz (NSF, Portugal) as Commission Editors. Luk R. Arnaut (University of Nottingham, UK) volunteered to become an Editor, and it was also decided to recommend him as a Commission Editor.

3. Updates/Status of Working Groups

It was proposed to establish a new working group focusing on education and training for metrology. There are many institutes providing such education and training, and it will be very helpful if we can share valuable materials and resources. Since the formal establishment of the new working group will require detailed terms of reference and a list of membership, it was proposed to start from an ad-hoc group with the task of collecting the information on training organized by the various institutes and sharing the information. The name of Bruce Warrington (NMIA, Australia) was suggested as the most appropriate candidate as a Chair of the ad-hoc group.

4. Updates to the Terms of Reference of the Commission

The Terms of Reference of Commission A were reviewed, and the necessity of updating was discussed during Business Meetings 1 and 2. As a result, some changes were proposed, and the draft revised Terms of Reference were presented at the Council meeting. The revisions were approved for the 2014-2017 term. In Business Meeting 3, some additional suggestions were discussed to update the Terms of Reference to reflect the present activities of Commission A. It was understood that the current Terms of Reference are intended to include broader areas, so as to attract more researchers to participate in activities of Commission A. This will be discussed again in the business meetings at the next GASS in 2017. It was asked that participants come prepared to discuss whether further revisions would be useful at that time.

Terms of Reference for Commission A (2014-2017)

The Commission promotes research and development of the field of measurement standards and physical constants, calibration and measurement methodologies, improved quantification of accuracy, traceability, and uncertainty, and the inter-comparison of such. Areas of emphasis are:

1. the development and refinement of new measurement techniques and calibration standards, including antenna techniques

2. primary standards, including those based on quantum phenomena, and the realization and dissemination of time and frequency standards

3. characterization of electromagnetic properties of materials, physical constants, and properties of engineered materials, including nanotechnology

4. methodology of space metrology and electromagnetic dosimetry/measurements for health diagnostics, applications, and biotechnology, including bio-sensing measurements in advanced communication systems and other applications.

The Commission fosters accurate and consistent measurements needed to support research, development and exploitation of electromagnetic technologies across the spectrum and for all Commissions.

5. Proposed Sessions for the Next GASS

For the GASS2017, the following sessions were proposed:

- Complex Isotropic and Anisotropic Magnetodielectrics
- Nonlinear Measurements
- Space Metrology
- SI Units
- Metrology in the THz Region
- Time Scale
- Advanced Time and Frequency Transfer Techniques
- Education and Training in Metrology
- Advances in Sensor Development and Applications
- Mode-Stirred Chambers

As one of the themes for General Lectures at GASS2017, a lecture about the SI units by Terry Quinn, Emeritus Director of the BIPM, was proposed.

6. Proposed Sessions for the AT-RASC

For the AT-RASC2015, the following topics have been provided for Commission A:

Antennas, Bioeffects and Medical Applications, EM-Field Metrology, EMC and EM Pollution, Impulse Radar, Interconnect and Packaging, Materials, Microwave to Sub-Millimeter Measurements/Standards, Millimeter-Wave and Sub-mm Wave Communications, Noise, Planar Structures and Microstrip Circuits, Quantum Metrology and Fundamental Concepts, Time and Frequency, Time Domain Metrology, Techniques for Remote Sensing, Measurements and Calibration in Propagation, Space Plasma Characterization, Material Characterization, RFID, Biological Effects, Signal Enhancement for EM Metrology, Scattering Calibration, References (Bi-Static), Noise Measurement Standards – A Review of Radiometers

It was recognized that the proposals for special sessions are due by October 17, 2014, and ideas for proposals were encouraged.

7. Other Business

The possibility of Commission A again responding to the formal request for opinions from the International Telecommunication Union (ITU) to URSI about the redefinition of Coordinated Universal Time (UTC) was discussed. Although it will be late for inclusion in the background document for the World Radio Conference in 2015, the participants of Business Meeting 3 felt it was a good idea to update the 1999 opinion of Commission A, and to propose that the Council meeting of URSI send it as the opinion of Commission A to the ITU. Some participants (Yasuhiro Koyama, Patrizia Tavella, Felicitas Arias, Demetrios Matsakis, and E. Van Lil) volunteered to update the document as a resolution from the business meeting of URSI Commission A. The document was then submitted at the Council meeting on August 23. The Council decided to forward the document to the Scientific Committee on Frequency Allocations for Radio Astronomy and Space Science (IUCAF) for comments and further action. After some discussion between the representatives of IUCAF and URSI, the document was submitted to ITU-R as an input document.

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Radio-Frequency Radiation Safety and Health

Recent Activities on Radio-Frequency Exposure Guidelines

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Abstract

In addition to a situation where the use of wireless technology is rapidly advancing, a large variety of new radio-frequency exposure scenarios are being introduced into our daily lives. Most existing radio-frequency exposure guidelines and standards were promulgated during the late 1990s. Many guideline- and standard-recommending organizations are engaged at various stages in revisiting their current guidelines and standards, including review of the scientific evidence concerning exposure to radio-frequency electromagnetic fields and the resulting consequences for health, accumulated since the 1990s.

The health and safety of radio-frequency (RF) electromagnetic energy (or radiation) have been under investigation for more than 60 years. In addition, guidelines for limiting human exposure to RF energy have been promulgated for 40 plus years.

The two most widely quoted guidelines and standards are the International Commission on Non-Ionizing Radiation Protection (ICNIRP) guidelines for limiting human exposure, published in 1998 [1], and the Institute of Electrical and Electronic Engineers (IEEE) Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, which was promulgated in 2005 [2]. These guidelines and standards also provide information and advice on specific topics of non-ionizing radiation protection and, in some cases, radiation-protection issues related to specific devices or exposure situations.

Many national entities and territories have adopted versions of these guidelines and standards to help ensure public health and safety pertaining to RF exposure from cellular mobile telephone operations, and a plethora of RF-energy-emitting devices and systems.

In the United States, the Federal Communications Commission (FCC) set the RF exposure limit for mobile phones in 1996 [3]. Establishment of the FCC rules was based on published recommendations from the National Council on Radiation Protection and Measurements (NCRP) and the IEEE, in addition to comments received from federal health and safety agencies. It should be noted that these FCC limits are the only RF exposure safety rules with the power of law in the US.

Clearly, most of these RF exposure guidelines and standards were promulgated during the late 1990s. Except for the separation of the pinna (external ear) from the head by treating it as a part of human-body extremities, the 2005 revised IEEE version was mostly the same as the 1990s versions.

Since then, in addition to a situation where use of wireless technology is rapidly advancing, a large variety of new RF exposure scenarios are being introduced into to our daily lives.

Moreover, it should be noted that there are a number of notable new scientific developments since the 1990's. Specifically, scientific progress made in computational dosimetry has been exceptional. Instead of the homogeneous canonical or geometric models (spheres and cylinders) of human and animal bodies of yore, most – if not all – recent computational exposure and dosimetry studies are based on heterogeneous, realistic anatomical models, using a 1.0 mm voxel resolution or better in biological bodies.

There is also the International Agency for Research on Cancer's (IARC's) classification of RF electromagnetic fields in 2011 as a possible cancer-causing agent to humans [4]. In doing this, the IARC acknowledged published scientific papers reporting increased risks for gliomas (a type of malignant brain cancer) and acoustic neuromas (a non-malignant tumor of the auditory nerve on the side of the brain), among heavy or long-term users of cellular mobile telephones [5]. The IARC is a health research arm of the World Health Organization (WHO).

The scientific community's response to the IARC's classification of RF radiation as a carcinogenic agent was not entirely unanimous. However, the advice still stands today. In addition to the intrinsic and extrinsic limitations of epidemiological methodology as applied to RF electromagnetic fields, uncertainties in measurement of personal exposure and dosimetry (induced fields inside a person's head) remain unresolved.

In any case, as of this writing, the above-mentioned guidelines and standards-recommending organizations (ICNIRP and IEEE) are engaged at various stages in revisiting their current guidelines and standards.

An ICNIRP review of the scientific evidence concerning exposure to RF electromagnetic fields and the resulting consequences for health was published in 2009 [6]. Detailed analysis and discussion of significant investigations published since its 1998 guidelines were examined to assess their implications for health and safety. The review would serve as an important input to the health-risk assessment being undertaken by the World Health Organization [7]. Together, they would provide the basis for a reexamination of ICNIRP guidelines on limiting exposure to RF energy.

In the US, the FCC is working on an update of its safety rules for wireless devices [8, 9].

Only time will tell what the FCC, ICNIRP, or IEEE may possibly do in response to notable new scientific developments since the late 1990s. This would include going forward on whether to change their current RF exposure safety rules, standards, and guidelines or not.

If the FCC does decide to change its current RF exposure safety rules, it would do well to note that since 1998, the scientific progress made in computational dosimetry has been exceptional. Indeed, most recent computational studies are based on heterogeneous, realistic anatomical models using a 1.0 mm voxel resolution or better in biological bodies. Recent studies of the correlation between specific absorption rate (SAR) of RF energy and induced temperature elevation (ΔT) as a function of averaging mass showed that for exposures of 30 s to 60 min, the optimum correlation varied from a mass of 0.5 g to 10 g. There is not a single optimal mass [10, 11]. The optimum actually depends on exposure duration.

Meanwhile, Health Canada's Consumer and Clinical Radiation Protection Bureau has issued, for consultation, a draft safety-code document, intended to replace its previous version. The safety code limits human exposure to RF radiation in the frequency range from 3 kHz to 300 GHz, and specifies the requirements for the safe use of, or exposure to, RF radiation-emitting devices [12].

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Conferences

CONFERENCE REPORTS

INTERNATIONAM CONFERENCE ON MICROWAVE AND PHOTONICS

Dhanbad, India, 13 - 15 December 2013

The first international conference on Microwave and Photonics (ICMAP) was held during December 13-15, 2013, at the Indian School of Mines (ISM), Dhanbad, India. The aim was to bring together researchers, engineers, technicians, manufacturers, and instructors to exchange and share their views, new ideas, and some research results about all aspects of microwaves, photonics and the emerging field of microwave photonics. The conference was organized by the Department of Electronics Engineering, ISM Dhanbad, India, and was technically cosponsored by the International Union of Radio Science (Commissions A, D, E, J, and K); IEEE; IEEE Antennas and Propagation Society; and IEEE Photonics Society. The conference was financially supported by the Indian School of Mines, Dhanbad; Council of Scientific and Industrial Research, Government of India; University Grant Commission, Government of India; Department of Science and Technology, Government of India; Meera Agencies Pvt. Ltd.; Elmax Projects and Services; Fiber Optic Services; ni Logic; Rhode & Schwarz; and JV Micronics.

A total of 191 contributory papers were received, out of which 120 papers were accepted for presentation. In addition, there were ten invited papers and two keynote speeches. These 132 papers were distributed among 17 oral sessions and one poster session. The keynote speech was delivered by Prof. B. M. A. Rahman (UK) and Prof. B. N. Biswas (India). The invited talks were delivered by Prof. Dharmendra Singh (India), Prof. Tadasi Takano (Japan), Prof. Alan Mickelson (USA), Prof. Greg Sun (USA), Prof. Nan-Kuang Chen (Taiwan), Prof. Achanta Venugopal (India), Prof. B. M. A. Rahman (UK), Prof. Y. Lu (China), and Prof. Sudha Mokkapati (Australia).

Out of the 120 accepted papers, 106 papers were presented over three days in parallel sessions. On the second day, an exclusive tour was organized for the participants to visit the attractions at the ISM campus. Interested participants visited the *long wall mine gallery*, the *oval garden*, and some other heritage spots of the campus. A cultural program was also arranged by the ICMAP 2013

Figure 1. The release of the souvenir at the inaugural function of the conference: (l-r) Mukul Kumar Das (Convener, ICMAP 2013); Prof. D. C. Panigrahi (Director, ISM Dhanbad); Prof. A. K. Ghose (Chief Guest); Shri. B. Ramesh Kumar (Guest of Honor); Prof. V. Priye (General Chair, ICMAP 2013); and Dr. S Kumar (Co-Convener, ICMAP 2013).

Figure 2. A group photo of the participants at the front of the Golden Jubilee lecture theater.

Figure 3. The participants visiting the oval garden of ISM Dhanbad.

Figure 4. The Banwan Adibasi Chhau Dance Party performing the cultural program.

Figure 5. The best paper award being delivered to Vintoth Kumar by Shri P. Ranganatheeswar, Deputy Director General (HQ), Directorate General of Mine Safety, Dhanbad, and Chief Guest of the valedictory function.

organizing committee in the evening, where the "Bandwan Adibasi Chhau Dance Party" presented the story of the Goddess Durga as Mahishasura Mardini. The cultural program was followed by a banquet dinner.

A panel discussion was also held on the fourth day, and some recommendations were made. The panel discussion was followed by a valedictory function, where best paper awards were delivered to three participants: one for Commission A, Microwave; one for Commission B, Photonics; and the third for Best Poster. The participants were Mr. Vinoth Kumar for Commission A, Hailu Dessalegn for Commission B, and Mr. Santosh Kumar Choudhary for best poster.

The conference focused on the current status and future trends in the fields of microwave and millimeter-wave technologies, photonics, and microwave photonics. A broad range of high-frequency-related topics, from materials and technologies to circuits, systems, and applications, was covered. It also solicited the exposure of some of the challenging problems in the design, development, testing, and manufacturing work related to the microwave, photonics, and microwave photonics industries for presentation at the conference. Overall, the conference ended with a grand success.

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Report on COSPAR Session on Improved Representation of the Ionosphere

Moscow, Russia, 5 - 6 August 2014

Session C4.1, "Improved Representation of the Ionosphere in Real-Time and Retrospective Mode" of the COSPAR General Assembly, was held in Moscow, Russia, August 5-6, 2014. Session C4.1 was organized by the COSPAR/URSI Working Group on the International Reference Ionosphere (IRI) and was convened by D. Bilitza and T. Gulyaeva. The main focus was on the development of the real-time IRI. However, other IRI-related topics were discussed, as well. The session was well attended, with about 45 participants, and with at times standing room only. Thirty-seven oral and 17 poster presentations were scheduled over a two-day period. Nine oral papers and seven posters were withdrawn, and two additional oral presentations were included in the program. The session was divided into six sections:

1. "Real-Time IRI"
2. "Topside and TEC"
3. "F-Region Mapping"
4. "Comparisons with IRI"
5. "New Inputs for IRI"
6. Posters.

A number of groups are engaged in activities towards the development of a real-time IRI, using different techniques and data sources towards this goal. The University of Massachusetts Lowell (UML) team presented one of the most advanced and mature systems, with their IRI Real Time Assimilative Mapping (IRTAM) technique. This updates the CCIR coefficients for the F-peak density and height with the help of digisonde data from the Global Ionosphere Radio Observatory (GIRO) network. The latest results and validation efforts were reported by I. Galkin and A. Vesnin. At auroral latitudes, Y. Zhang (APL, USA) has succeeded in using TIMED/GUVI and DMSP/SSUSI data to bring auroral-boundary and E-region densities in the IRI to real-time conditions. In the European sector, local and regional assimilative methods are being successfully applied to the IRI using single or regional ionosonde inputs (M. Pezzopane, Italy; H. Haralambous, Cyprus). S. Jun Oh (Korea) reported on a regional HF frequency-prediction service, based on assimilating data from a local ionosonde into the IRI. GPS data are an important data source for real-time monitoring and modeling of the ionosphere (M. Hernandez, Spain; M. Alizadeh, Germany). However, they require tomographic or radio occultation techniques, if information about the altitudinal structure of the ionosphere is required.

Presentations during the IRI session utilized numerous data sources, including measurements by ionosondes/digisondes, incoherent-scatter radars, SuperDARN HF radars (Oinats, Russia), SAURA Doppler radar (Singer and Strelnikova, Germany), TIMED, DMSP, COSMIC, GPS, ISIS, Alouette, ROCSAT-1, Hinotori, Topex, and Jason satellites, and rockets (J. Shi, China). A comprehensive study of EISCAT incoherent-scatter data with the IRI by L. Bjoland (Norway), covering more than two solar cycles, will be an important starting point for improvements of the IRI's parameters at high latitudes. Comparisons of digisonde data from Multan, Pakistan, again showed the need for improvements of the IRI during the extremely low solar-cycle minimum in 2008/2009 (M. Ameen, Pakistan). New models were presented for the upper ion transition height based on Alouette and ISIS topside-sounder data and COSMIC radio-occultation data (V. Truhlik, Czech Republic), and for the ion density around 600 km, based on ROCSAT-1 data (L. Liu, China).

During the IRI business meeting, the working group decided on two important improvements for the next version of the IRI model: (1) as separate options for hmF2, the model by Altadill et al. (Spain) based on digisonde data, and the model by Karpachev et al. (Russia) based on COSMIC radio occultation data; (2) auroral NmE and hmE based on Zhang's (APL, USA) work with TIMED/GUVI and DMSP/SSUSI data. High priority was given to the inclusion of a plasmaspheric extension into the IRI, starting possibly with the IRI-Plas option developed by Gulyaeva (Russia). However, one problem is the still existing uncertainties of the topside profile shape, especially during very low solar activity (Bilitza, USA). The IRI Real-Time effort will continue with developing a scheme for assimilating GIRO digisonde data for the bottomside parameters B0, B1, and D1, into the IRI (Galkin, USA).

Advances in Space Research has agreed to the publication of a special issue on the IRI in real-time and retrospective modes. Oral and poster presenters from session C4.1 were invited to submit their contributions to the special issue. The issue will be open to other IRI-related contributions as well: presentation at the meeting was not a prerequisite for publication in the special issue.

The 2015 IRI Workshop will be held in Bangkok, Thailand, as a COSPAR Capacity Building Workshop. Prasert Kenpankho from the King Mongkut's Institute of Technology Ladkrabang (KMITL) in Bangkok gave a presentation describing the workshop plans and location. The first week will be lectures and seminars for students, and the second week will have the usual IRI Workshop format, with science talks also including presentations by the students about their respective project results from the first week. More information will soon be available on the IRI homepage at http://irimodel.org.

During its business meeting, the IRI Working Group elected its new leadership team for the next four years. David Altadill (Ebro Observatory, Spain) was elected as the new IRI Chair, and Shigeto Watanabe (Hokkaido University, Japan) and Vladimir Truhik (IAP, Czech Republic) were re-elected as Vice Chairs for COSPAR and URSI, respectively. Feza Arikan (Hacettepe University, Turkey) was elected as a new member to the IRI Working Group. The IRI steering committee also includes the former Chairs: L.-A. McKinnell (SANSA, South Africa), B. Reinisch (LDI, USA) and D. Bilitza (GMU, USA).

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The 16th International EME Conference

Brittany, France, 24 - 26 August 2014

The 16th International Earth-Moon-Earth (moon bounce) Conference was held in Brittany, France, on August 24-26, 2014. More than 100 EME enthusiast Hams from 18 countries were registered. More than 20 high-level technical papers were presented. Several workshops allowed everyone to practice power and noise transmission, to learn SDR (software defined radio) and even to perform EME communications using the 13 m antenna PB8. We report hereafter the papers presented in the different sessions: "Propagation," "Components," "Antennas," "Modulation," "Radio Sources," and "Miscellaneous."

Moon-bounce or Earth-Moon-Earth propagation enables non-line-of-sight stations to communicate on VHF, UHF, and SHF by reflecting their signals from the surface of the moon. One of the prerequisites for the use of this opportunity to provide long-distance terrestrial links is the understanding of wave propagation in the environment between the transmitting and the receiving station. After describing the propagation environment, Hervé Sizun reviewed the various aspects of radiowave propagation in the context of EME links (path attenuation, direction of arrival, rotation of the polarization plane, scintillations, radio noise influence, link budget, etc). Al Katz discussed the shift in signal frequency caused by the Doppler shift during moon-bounce communications. He explained the importance of understanding this effect, and gave strategies to improve EME communications when operating both CW and JT EME modes by using knowledge of the Doppler effect due to the movement of the moon. From data obtained from MAP65 decodes, Giorgio Marchi and Flavio Egano made an analysis of QSB (signal fading), showing its dependence not on attenuation, but on focusing or defocusing effects due to ionospheric waves. After defining the algorithms for calculating Faraday rotation from total electron content (TEC) and comparing them to actual MAP65 decodes, they showed how Faraday rotation typically behaves as a function of corresponding station orientation relative to the moon's position (elevation, direction) with respect to the geomagnetic field. The analysis was focused mainly on 144 MHz EME communications, but was applicable to all bands.

Different papers were dedicated to systems (component and subassemblies) that allowed EME communications on different frequency bands (144 MHz, 10 GHz, 24 GHz). Manfred Ploetz gave the mechanical modifications made to an RW1127 TWT system, primary designed for the 10 GHz band to produce 90 W output power, to be used for the 24 GHz band and produce 40 W output power. Mike Watanabe presented a paper by Yoshiro Mataka dedicated to the construction of a 10 GHz EME converter without using an SHF local oscillator. It used a good SHF filter to reject the image signal and improve the radio noise. This converter was developed for 10 GHz-band EMEers in order to be able to listen for Japanese stations. Hans van Alphen presented a 10 GHz EME receiver using a 48 cm-diameter dish, an LNA, a transvertor, and a software-defined radio receiver as intermediate frequency. He also introduced *Spectravue* software to detect the weakest EME signals. The use of such a station requires a good alignment of the antenna to the moon.

Pierre-François Monet showed the possibility of building a solid-state amplifier for the 24 GHz amateur radio band at a very reasonable cost using industrial MMIC devices, and some parts that can be found at a flea market. Many useful references were given. Sam Jewell described his new 144 MHz "Anglian" transverter. Its principal characteristics were an IF of 28 MHz, a noise figure of 1.6 dB to 1.8 dB, a receiver gain of 24 dB to 25 dB, and an output power of 22 dBm. Kits are available to build the Anglian transverter. Paul Wade introduced the ratio of gain to noise temperature (G/T) calculation obtained by *ANTC* software in feed-horn analysis for a parabolic dish. For different types of horns, he provided information to achieve the highest G/T. Comparisons with sun noise measurements made by Tommy Henderson have been realized to verify efficiency calculations. The differences between mesh and solid dishes were studied.

Dave Powis detailed measurements on a small prime-focus dish (2.4 m diameter), fed with a rectangular-waveguide septum transformer feed horn. They were in accordance with the results of simulations reported by Paul Wade. Hannes Fasching described a homebuilt offset 7.3 m diameter dish. Michiaki Watanabe presented different details of various tracking systems and AZ/EL rotators of many Japanese EME stations. Jan van Muijlwijk gave information about the restoration of the big 25 m diameter dish in Dwingeloo. It was officially reopened by Joe Taylor. A moon-bounce wedding was reported. The role of the Dwingeloo dish in rescuing a nano-satellite project was presented. Daniela de Paulis presented her performance-art project of visual SSTV via EME (http://www.opticks.info). An ORPB team (Jean Pierre Blot, Jean Pierre Daniel, André Gilloire, and Lucien Macé) described their future plans to refit the PB8 antenna designed for the C-band traffic in L band (typically, 1150 GHz to 1650 GHz) for new applications including radio astronomy, satellite monitoring, and EME. Simulations using *SRSR* and CST *MWS* software were presented. Several solutions have been tested considering various horn geometries such as conical, corrugated horns, and different feeds to get a low VSWR and axial ratio (cylindrical probes, septum transformer, etc.).

Joe Taylor described the design and construction of a modest 432 MHz EME station for the Princeton University Amateur Radio Club. The specifications were a system noise temperature approaching the state of the art at room temperature; a transmitter power less than 1 kW; an antenna that is small, lightweight, rugged, and easy to point in azimuth and elevation; no Faraday log out; moderate cost; easy to build and maintain; capable of EME QSOs with its own "twin" everywhere in the world, whenever the moon is available. Klaus von der Heide presented new coherent-mode software. It takes into account the Doppler shift and presents a better sensibility to weak EME signal intensities. However, it requires high computational power and a very good signal stability. Alex Artieda described what would be inside the IQ+ IT 144 MHz exciter. He proposed a different way to create a transmitter with the lower impact on the spectrum in terms of image rejection, carrier suppression, undesired signals on the pass-band and sideband noise.

Frank Tonna presented radio-astronomy measurements of the strongest noise sources in the sky, such as Taurus A, Cassiopeia A, Cygnus A, Sagittarius A, Omega and Orion nebula, Tycho Brahé's supernova, Virgo A, and the moon noise. For Venus, only amateur station equipped with 10 GHz high-tech means (solid parabolic dishes with a diameter of at least 4.50 m and ultra-low-noise preamplifier) are likely to be able to detect this weak radiation. Jean-François Lampin showed solar noise measurements at 76 GHz using a receiver based on a LNA MMIC followed by a detector diode. The receiver was placed at the focus of a 12 cm diameter lens antenna pointed toward the sun. The intensity of the solar noise was dependent on season and elevation angle. Sergey Zhutyaev presented some sun, moon, and Jupiter noise measurements at 77 GHz. He pointed out that at this frequency, we need an antenna with an extremely high the reflector-surface accuracy. However, the size of the antenna for EME communications must be at least 2.4 m. It is possible to compensate for surface deviations with a dielectric lens. The antenna gain was approximately 62.5 dBi.

Guy Gervais gave the principal milestones in the history of EME communications spread over the last 60 years, and the evolution of the EME traffic. Sylvain Azarian animated a session dedicated to amateur radio and science: how amateurs can help (possible ways of cooperation between radio amateurs and electronic industry, future topics to develop, etc.). Ghislain Ruy presented the 4M (Manfred Memorial Moon Mission) mission. The 4M spacecraft was launched on October 23, 2014, and has been placed on a lunar transfer trajectory. It carried a transmitter, two experiments, and transmitted basic telemetry data. The reception of the signal is possible by the average amateur satellite station. He asked all OM's from all continents to participate in this experiment. A system based on an Arduino module controlling a transceiver through a CAT or a serial interface was presented by Marc Kleyn. Michel Guillou presented the first transatlantic TV broadcast by satellite link, Andover-Pleumeur Bodou, July 11, 1962, the night that opened a new communication era.

An original CD with all complete lectures and the proceedings can be purchased via the EME2014 Web site: www.eme2014.fr.

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Report on 2014 Spanish URSI Symposium

Valencia, Spain, 3 - 5 September 2014

The 29th edition of the Spanish URSI Symposium was held at Valencia, Spain, from September 3-5, 2014. This symposium was organized by the School of Telecommunications Engineering at the Polytechnic University of Valencia (UPV), Spain, and was chaired by Prof. Alberto Gonzalez-Salvador of this university.

The purpose of this symposium was to meet Spanish young and senior scientists working on the following topics: antennas; biomedical applications, mathematical applications: modeling and simulations; bioelectromagnetism; microwave active circuits and components; microwave passive circuits and components; active components and circuits; mobile and wireless communications; satellite communications; education: new technologies and tools; electromagnetism; photonic and optical communications; metamaterials; new services and security in communications; audio and video signal processing; radar; radiation, scattering, and radio propagation; communication systems; applications and technologies at THz (beyond 74 GHz); and telematics.

The 189 accepted papers were scheduled in 30 technical sessions, which gathered more than 200 participants for fruitful discussions. During the opening ceremony (Figures 1 and 2), the paper entitled "150 Years

Figure 1. (r-l) Alejandro Valero-Nogueira, Alberto González-Salvador, Francisco J. Mora-Mas, Francisco Ares-Pena, and Héctor Esteban-González, at the opening ceremony.

Figure 2. Some of the conference participants during the opening ceremony.

Figure 3. Angel Cardama-Aznar at the opening paper, "150 Years of the Maxwell's Equations."

of the Maxwell's Equations" was presented by Dr. Ángel Cardama-Aznar (Figure 3) of the Polytechnic University of Catalonia (UPC), Spain. The technical program also included two plenary papers: "Satellite Navigation and Galileo Program: Future Opportunities," by D. Javier Benedicto Ruiz and Javier Ventura-Traveset of the European Space Agency (ESA); and "Functional Metastructures," by Prof. Nader Engheta of the University of Pennsylvania (USA).

At the gala dinner, the young scientist best paper awards were given (Figure 4). An international committee had previously evaluated the six best papers among 39 entrants less than thirty-five years old. During the symposium, these young scientists presented their papers in a special season. Finally, the awards committee selected the winner, and three awards for runners-up. These outstanding papers were the following:

Winner

Elena Abdo-Sánchez of the University of Malaga for her paper, "The Complementary Strip-Slot: From the Unit-Cell of Artificial Transmission Lines to the Basic Element of Novel Antennas," coauthored with Jaime Esteban, Teresa M. Martín-Guerrero, Juan E. Page, and Carlos Camacho-Peñalosa.

Figure 4. Elena Abdo-Sánchez (center) receiving the Young Scientist Best Paper Award, together with the finalists.

Abstract: The complementary strip-slot radiating element and its applications are reviewed. The element is a modified version of the conventional microstrip-fed slot that presents very broad matching. Its inherent lattice equivalent circuit, its use as unit-cell of artificial transmission lines, and its utility as radiating element are described. Promising experimental results for prototypes of a phased uniform array, a sequentially-rotated ring array, and a log-periodic array based on the element for microwave frequencies are included.

Awards For Runners-Up

S. Casas-Olmedo of the Autonoma University of Madrid for his paper, "Design Method of Linear Patch Arrays Fed by Waveguide Feeding Networks," coauthored with J. L. Masa-Campos and P. Sanchez-Olivares.

Abstract: A novel method for considering radiating structures independently of their feeding networks is presented. The integration of both parts separately designed suffers a critical misalignment with the theoretical behavior caused by the mutual coupling effects between adjacent elements. This method analyses radiated neat E-field monitors to adjust the whole antenna after joining both independently designed parts. A linearly polarized patch array fed by a rectangular waveguide with internal coupling patches for X band (11 GHz-12 GHz) has been designed to validate the method performance. A double stacked microstrip patch structure with an integrated phase compensation microstrip line has been used as radiating element. The coupling patches inside the waveguide are connected to the external radiating patches by means of metallic probes. The presented method requires changes in the feeding structure as in the radiating elements. Several prototypes have been manufactured and measured: the feeding waveguide structure connectorized, the radiating patches connectorized, the union of both with SMA transitions, and the final integration into the complete antenna. 18.5 dBi gain and 85% efficiency peak values have been experimentally achieved.

G. Rubio-Cidre of the Polytechnic University of Madrid for his paper, "Characterization of a 300 GHz Imaging Radar for Standoff Detection," coauthored with A. Badolato, L. Úbeda-Medina, B. Mencía-Oliva, J. Grajal, A. García-Pino, B. Gonzalez-Valdes, O. Rubiños-López, and J. L. Besada-Sanmartín.

Abstract: A complete characterization of a 300 GHz high-resolution imaging radar with large field of view is carried out in order to optimize its operational parameters. This imaging radar has been designed for standoff detection in security applications. The characterization is focused primarily on the spatial and range resolution. The results show that the imaging radar presents a resolution better than 2 cm. Three-dimensional images revealing a threat hidden under clothing validate the imaging radar performance.

Carlos Molero of the University of Seville for his paper, "Wideband Analytical Circuit Model for 1-D Compound Gratings," coauthored with Raúl Rodríguez-Berral, Francisco Mesa, and Francisco Medina.

Abstract: This work proposes a wideband equivalent circuit to describe the scattering of plane waves by periodic metallic surfaces made of groups of slits (compound gratings). The circuit is rigorously electrical parameters of the model. The predicted responses are in very good agreement with full-wave derived from a simple electromagnetic analysis and analytical expressions are given for all the numerical simulations. The qualitative behavior of the gratings can be easily understood from the topology of the equivalent circuit and the behavior of its elements.

The next edition of the Spanish URSI Symposium will be held at Pamplona, Spain, September 2-4, 2015. It will be organized by the University of Navarre (UPN), Spain.

F. Ares-Pena and J. A. Rodríguez-González
Spanish URSI Member Committee
University of Santiago de Compostela, Spain
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2014 International Conference on Radar

Lille, France, 13 - 17 October 2014

The 2014 International Conference on Radar was held in Lille, France, October 13-17, 2014. Like all such conferences, the 2014 conference illustrated a great diversity of subjects. Among the 33 oral sessions and the three poster sessions, the organizers chose to draw the attention of participants to some special sessions, in which updated subjects were discussed.

As from the start, the plenary session (chaired by François Le Chevalier and Maria Greco, see Figure 1) gave an idea of the extent of the conference, with four speakers. A remarkable survey of metamaterials was given by Sir John Pendry. A deep view of possible improvements of VHF-band radar performance was presented by Wu Jiangi. The sparsity-aware urban radar was the topic of Moeness Amin. The technical challenges for catching the invisible were addressed by Laurent Savy.

Among the manifold subjects, we have only selected a few outstanding topics to illustrate their variety.

Stealth Target Detection

The multi-static properties of targets were well demonstrated by Blyakhman Alexander et al. in "Detection of Unmanned Aerial Vehicles via Multi-Static Forward Scattering Radar with Airborne Transmit Position."

Waveform Diversity

There is no doubt that this theme has been researched for many years. The implementation of diverse waveforms by intelligent antennas will necessitate even more research in particular in the framework of MIMO radars. Among interesting papers, we noted the paper by Gorji Ali and Adve Raviraj, "Waveform Optimization for Random-Phase Radar Signals with PAPR Constraints." Two other sessions, "Waveform Signal Processing" and "Advanced Processing," well completed the previous session.

SIMCLAIRS, which stands for "Studies for Integrated Multifunction Compact Lightweight Airborne Radar Systems," is a program of the European Defense Agency (EDA). Its main objective is to deliver new technologies in the field of unmanned aerial vehicle (UAV) RF payloads, with the combination of SAR/MTI, FOPEN, ESM, and possibly communication. The program aims at extending the concept of multi-functionality using a very wide frequency band. The paper of Ghiotto Antony et al. on "Dual-Mode Power Amplifier Module with In-Band Reconfigurable Output Power for Multi-Functional Radar and Radio Communication Systems" well reflected this standpoint.

Figure 1. The plenary session of the 2014 International Conference on Radar.

Array Beamforming

This is the bread and butter of system designers, to get ever more performance from systems that become more and more complex. An example of this was "Dual Function Radar Communication Time-Modulated Array," by Euzière Jérome et al.

Passive Radar Processing and Passive Radar Systems

To begin with, there is an ambiguity in these terms. Scientifically speaking, the real passive systems are radiometers. In this conference, for the most part, the term passive was used to mean taking advantage of exiting signals, such as TV. A good illustration of the work done in this area was given by Weiss Mathias in "Compressive Sensing for Passive Surveillance Radar Using DAB Signals."

Metamaterials

The "Metamaterials" session focused on their application to agile antennas and radars. The main novelty of the session was the emergence of the concept of a metasurface. The ultimate purpose of this concept is to apply metasurface-by-design techniques to new architectures of electronic beam scanning. In addition, it offers the advantage of optical reconfiguration of the metasurface. The "Disruptive Concept Paper" award was given to one of the articles of the session.

Cognitive Radar and Resource Management

The great difficulty facing the system engineer is to wish to please everybody. The paper by Jeaunneau et al. on "Radar Tasks Scheduling for Multifunction Phased Array Radar with Hard Time Constraints and Priority" is representative of the domain. It would be worthwhile developing it further.

Figure 2. (l-r) Laurent Savy (Technical Chair), Myriam Nouvel (Organizing Chair), and Marc Lesturgie (General Chair).

ISAR is a difficult subject, requiring a deep knowledge of the properties of radar and the physics of targets and their various environments. An interesting paper was given by Brisken Stefan on "Multi-Static ISAR: Chances and Challenges."

Of course, the conference presented many other subjects, such as MIMO radars, weather radar wave vortex, the STAP technique, radar technologies (namely T/R modules),... It is regrettable that there was no session on passive observation of the Earth, nor on the conditions of access of remote sensing to the frequency spectrum, which should have been covered in a session such as "Emerging Radar Applications."

An exhibition by industry took place during the conference. An official reception at the Lille Town Hall, technical visits, and some sightseeing on the Atlantic coast nicely completed the week in Lille.

It goes without saying that the conference was also an ideal opportunity to reward several colleagues during the gala dinner, where the following awards were presented:

Robert Hill Award

In memory of Bob Hill, an award has been created to remember his commitment to the creation of the present cycle of international conferences. He acted not only as a scientist, but also worked in a spirit of international cooperation.

"Characterizing the Doppler Spectra of High Grazing Angle Sea Clutter" by Simon Watts, Luke Rosenberg, and Matthew Ritchie

Best Paper Award

"Mismatched Filter Optimization via Quadratic Convex Programming for Radar Applications" by Olivier Rabaste and Laurent Savy

Disruptive Concept Award

"Blind Spot Mitigation in Phased Array Antenna Using Metamaterials" by Thomas Crépin, Cédric Martel, Benjamin Gabard, Fabrice Boust, Jean-Paul Martinaud, Thierry Dousset, Pablo Rodriguez-Ulibarri, Miguel Beruete, Claudius Loecker, Thomas Bertuch, José Antonio Marcotegui, and Stefano Maci

Best Young Scientist Paper Awards (Three Levels) Young Engineer First (Tie)

"CURACAO, Compact SAR/GMTI First Prototype Development and Tests" by Rémi Baqué, Grégory Bonin, Philippe Dreuillet, and André Barka

"Fast Simulation of a Moving Sea Surface Remotely Sensed by Radar" by Nicolas Pinel, Goulven Monnier, and Julien Houssay

Young Engineer Third

"Two Waveform Design Criteria for Collocated MIMO Radar" by Hongwei Liu, Shenghua Zhou*, Huikai Zang, and Yunhe Cao

Over 450 participants from 30 countries ensured the undeniable success of the conference. It started with 16 tutorials. Its organization rested – as for all such conferences – on a devoted group working well together. It is impossible to mention those who worked on a voluntary basis, but we would like to warmly thank Marc Lesturgie (General Chair), Laurent Savy (Technical Chair), Myriam Nouvel (Organizing Chair) (see Figure 2), Jean-Bernard Choquel (Local Arrangements) and Stéphane Kemkémian (Tutorials).

Jean Isnard
URSI-France, Commission F
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URSI CONFERENCE CALENDAR

January 2015

International Conference on Foundations and Frontiers of Computer, Electrical Engineering: commemorating 150 years of Maxwell's Equations
Hooghly, West Bengal, India, 9-10 January 2015
Contact: Prof. B.N. Biswas, Sir J.C. Bose School of Engineering, Supreme Knowledge Foundation Group of Institutions, 1, Khan Road, Mankundu, Hooghly-712139, West Bengal, India

March 2015

JS2015 – Annual meeting of the French Committee - URSI-France 2015 Scientific Days
"Probing matter with Electromagnetic Waves"
Paris, France, 24-25 March 2015
Contact: Prof. Alain Sibille, Télécom ParisTech, Dept Comelec, 46 rue Barrault, F-75634 Paris Cedex 13, France Phone : +33 01 45 81 70 60, Fax : +33 01 45 80 40 36, E-mail : alain.sibille@telecom-paristech.fr, http://ursi-france.mines-telecom.fr//index.php?id=74

May 2015

URSI AT-RASC 2015 – First URSI Atlantic Radio Science Conference 2015
Gran Canaria, Spain, 18-25 May 2015
Contact: Prof. Peter Van Daele, URSI, Sint-Pietersnieuwstraat 41, B-9000 Gent, Belgium, E-mail: peter.vandaele@intec.ugent.be, http://www.at-rasc.com

September 2015

Metamaterials 2015
Oxford, United Kingdom, 7-10 September 2015
Contact: Prof. Richard W. Ziolkowski, Litton Industries John M. Leonis Distinguished Professor, Electrical and Computer Engineering Professor, College of Optical Sciences, University of Arizona, Tucson, AZ 85721, E-mail: ziolkowski@ece.arizona.edu, http://congress2015.metamorphose-vi.org

IEEE Radio and Antenna Days of the Indian Ocean 2015
Mauritius, 21 - 24 September 2015
Contact: RADIO 2015 Conference Secretariat, Radio Society (reg. no. 13488), Gobinsing Road, Union Park, Mauritius, Email: radio2015@radiosociety.org http://www.radiosociety.org/radio2015

November 2015

COSPAR 2015
2nd Symposium of the Committee on Space Research (COSPAR): Water and Life in the Universe
Foz do Iguacu, Brazil, 9-13 November 2015
Contact: COSPAR Secretariat, 2 place Maurice Quentin, 75039 Paris Cedex 01, France
Tel: +33 1 44 76 75 10, Fax: +33 1 44 76 74 37, E-mail: cospar@cosparhq.cnes.fr
http://cosparbrazil2015.org/

URSI cannot be held responsible for any errors contained in this list of meetings

International Geophysical Calendar 2015

	S	M	T	W	T	F	S	S	M	T	W	T	F	S	
JANUARY					1	2	3				1	2 F	3	4	JULY
	4	5 F	6	7	8	9	10	5	6	7	8	9	10	11	
	11	12	13	14	15 +	16 +	17 +	12	13	(14)	●15 * +	(16) * N +	17 * +	18	
	18 +	19 * +	(20) * N +	●21 * +	(22) +	23 +	24 +	19	20	21	22	23	24	25	
	25 +	26 +	27 +	28 +	29 +	30 +	31 +	26	27	28	29	30	31 F	1	
FEBRUARY	1 +	2 +	3 F +	4 +	5 +	6 +	7 +	2	3	4	5	6	7	8	AUGUST
	8 +	9 +	10 +	11 +	12 +	13 +	14 +	9	10	11	12 *	13 *	14 * N	15	
	15 +	16 +	(17) *	■18 * N	(19) *	20	21	16	17	(18)	■19	(20)	21	22	
	22	23	24	25	26	27	28	23	24	25	26	27	28	29 F	
MARCH	1	2	3	4	5 F	6	7	30	31	1	2	3	4	5	SEPTEMBER
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	15 +	16 +	(17) +	●18 * +	(19) * +	[20] * N	21 +	[13] N	14 *	(15) *	●16 *	(17)	18	19	
	22 +	23 +	24 +	25 +	26 +	27 +	28 +	20	21	22	23	24	25	26	
	29	30	31	1	2	3	4 F	27	28 F	29	30	1	2	3	
APRIL	5	6	7	8	9	10	11	4	5	6	7	8	9	10	OCTOBER
	12	13	(14)	●15 *	(16) *	17 *	18 N	11	12 *	(13) * N	●14 *	(15)	16	17	
	19	20	21	22	23	24	25	18	19	20	21	22	23	24	
	26	27	28	29	30	1	2	25	26	27 F	28	29	30	31	
MAY	3	4 F	5	6	7	8	9	1	2	3	4	5	6	7	NOVEMBER
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	17	18 * N	19 *	20 *	21	22	23	15	16	(17)	■18	(19)	20	21	
	24	25	26	27	28	29	30	22	23	24	25 F	26	27	28	
	31	1	2 F	3	4	5	6	29	30	1	2	3	4	5	
JUNE	7	8	9	10	11	12	13	6	7	8	9 * +	10 * +	11 * N +	12 +	DECEMBER
	14	15 *	(16) * N	●17 *	(18)	19	20	13 +	14	(15)	●16	(17)	18	19	
	21	22	23	24	25	26	27	20	21	22	23	24	25 F	26	
	28	29	30					27	28	29	30	31	1	2	2016 JANUARY
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								10 N	11 *	(12) *	●13 *	(14)	15	16	
								17	18	19	20	21	22	23	
								24 F	25	26	27	28	29	30	
								31							
								S	M	T	W	T	F	S	

N NEW MOON F FULL MOON

(20) Regular World Day (RWD)

●21 Priority Regular World Day (PRWD)

■18 Quarterly World Day (QWD) also a PRWD and RWD

7 Regular Geophysical Day (RGD)

9 10 World Geophysical Interval (WGI)

\+ Incoherent Scatter Coordination Observation Day
(The period Jan 15-Feb 15 is a StratWarm Alert interval with a fallback interval of Feb 10-15. In case of conflicing modes the Solar Eclipse campaign has priority over the Meridional Circle campaign. The period March 13-27 is a Meridional Circle Alert interval based on predictions of magnetic disturbances. Five days notice should be given for both the StratWarm and Meridional Circle Alerts.)

[20] Days of Solar Eclipse: March 20, total; Sept 13, partial

30 31 Airglow and Aurora Period

29* Dark Moon Geophysical Day (DMGD)

This Calendar continues the series begun for the IGY years 1957-58, and is issued annually to recommend dates for solar and geophysical observations, which cannot be carried out continuously. Thus, the amount of observational data in existence tends to be larger on Calendar days. The recommendations on data reduction and especially the flow of data to World Data Centers (WDCs) in many instances emphasize Calendar days. The Calendar is prepared by the International Space Environment Service (ISES) with the advice of spokesmen for the various scientific disciplines.

The Calendar provides links to many international programs, giving an opportunity for scientists to become involved with data monitoring and research efforts. International scientists are encouraged to contact the key people and join the worldwide community effort to understand the Sun-Earth environment.

The definitions of the designated days remain as described on previous Calendars. Universal Time (UT) is the standard time for all world days. Regular Geophysical Days (RGD) are each Wednesday. Regular World Days (RWD) are three consecutive days each month (always Tuesday, Wednesday and Thursday near the middle of the month). Priority Regular World Days (PRWD) are the RWD which fall on Wednesdays. World Geophysical Intervals (WGI) are fourteen consecutive days in each season, beginning on Monday of the selected month, and normally shift from year to year. In 2015 the WGI are February, May, August, and November. Quarterly World Days (QWD) are one day each quarter and are the PRWD which fall in the WGI.
The 2015 FINAL Calendar is available in PDF format.

2015 Solar Eclipses:
There will be a total solar eclipse visible only in the Arctic, with partial phases throughout Europe, on 20 March 2015, and a partial solar eclipse visible only in Antarctica and southernmost Africa on 13 September 2015. Maps are accessible through http://www.eclipses.info, the site for the International Astronomical Union's Working Group on Eclipses.

a. 20 March 2015. A total solar eclipse will start over the northern Atlantic Ocean and proceed north, passing first the Faroe Islands, an autonomous country within Denmark, and then the Svalbard Archipelago, which is controlled by Norway under a 1920 treaty. In the Faroes, which are at the eastern edge of totality, the eclipse will last about 2 m 15 s centered at 9:42 UTC at an altitude of about 20°. The path will be 443 km wide and the Moon will subtend an angle 4% larger than that of the Sun. Iceland will be to the west of the path by about 100 km at its closest point, with 97% of the solar diameter covered at Reykjavik. On the Spitsbergen island of Svalbard, the eclipse will last about 2 m 23 s at an altitude of about 11° but with slightly better weather statistics based on past satellite imaging (available from meteorologist Jay Anderson at http://eclipser.ca). The eclipse will be centered at 10:12 UTC; the path width at that time will be 407 km. The partial phases will be visible throughout Europe as well as from the western half of Asia and northwestern Africa. London will have an 87% eclipse, Paris an 80% eclipse centered at 9:30 UTC in the midst of 2 h 18 min of partials, and Moscow a 65% eclipse at the midst of 2 h 50 m of partials centered on 10:20 UTC. In Africa and extending eastward, the southern limit of the partial eclipse will extend from Guinea on the west through Burkina Faso, southern Nigeria, northern Chad, the midst of Egypt, northern Saudi Arabia, mid- Iraq, northern Iran, southern Turkmenistan, southern Uzbekistan, southern Kyrgyzstan, extreme northwestern China, and western Mongolia. On the western limit, the eclipse will be barely visible in easternmost Newfoundland and Labrador and on St. Pierre et Miquelon.
   Map of total solar eclipse 20 March 2015 (by Fred Espenak).
   Interactive Google map of total solar eclipse 20 March 2015 (by Xavier Jubier)

b. 13 September 2015. A partial eclipse will be visible, with up to 78% coverage, from the side of Antarctica facing northward toward Africa and Asia over to Australia. Only southernmost Africa will see partial phases other than those visible from Antarctica. At 5:43 UTC, 42% of the solar diameter will be covered as seen from Cape Town, South Africa, in the midst of 2 h 5 m of partial phases, at an altitude of 10° in the east. Gabarone, Botswana will have 23% coverage; Windhoek, Namibia, 19% coverage; Harare, Zimbabwe 7% coverage; Lusaka, Zambia, only 2% coverage; and minimal coverage in southernmost Malawi, Mozambique, and Madagascar. The northern limit passes through Reunion Island; Mauritius is north of the limit. The French Southern & Antarctic Lands as well as Heard Island & McDonald Islands will have about 40% coverage with the sun 32° high in the sky. Also in mid-Ocean, Marion Island and Prince Edward Island have about 56% coverage at an altitufde of 25°.
   Map of partial solar eclipse 13 September 2015 (by Fred Espenak)
   Interactive Google map of partial solar eclipse 13 September 2015 (by Xavier Jubier)

We thank Fred Espenak (Arizona) and Xavier Jubier (Paris) for their data and maps. Espenak's new Thousand Year Canon of Solar Eclipses 1501 to 2500 is available from www.astropixels.com/pubs, and is the successor to earlier Canons and the NASA website that he ran. It and other work of Espenak, much of it formerly on the NASA website, is now available at www.EclipseWise.com.
Information assembled by Jay M. Pasachoff, Williams College (Williamstown, Massachusetts), Chair, International Astronomical Union's Working Group on Eclipses, with thanks to Fred Espenak (Arizona; NASA's Goddard Space Flight Center, ret.) and Xavier Jubier (Paris) for their data and maps.

Eclipse References:

- Fred Espenak, Thousand Year Canon of Solar Eclipses 1501 to 2500, 2014 (ISBN-10: 194 1983006); www.astropixels.com/pubs
- Fred Espenak, Five Millennium Canon of Solar Eclipses: -1999 to +3000, 2006 (NASA/TP-2006-214141); http://eclipse.gsfc.nasa.gov; http://eclipse.gsfc.nasa.gov/OH/OH2014.html
- Leon Golub and Jay M. Pasachoff, The Solar Corona, 2nd ed., Cambridge University Press, 2010 (ISBN-10: 052188201X).
- Jay M. Pasachoff and Alex Filippenko, The Cosmos: Astronomy in the New Millennium, 4th ed., Cambridge University Press, 2014 (ISBN-10: 049501303X).
- Leon Golub and Jay M. Pasachoff,Nearest Star: The Surprising Science of Our Sun, 2nd edition, Cambridge University Press, 2014 (ISBN-10: 1107672643).
- Jay M. Pasachoff, The Complete Idiot's Guide to the Sun, Alpha Books,2003 (ISBN-10: 1592570747).

2015 Meteor Showers

(Selected from data compiled by Alastair McBeath for the International Meteor Organization Shower Calendar):

a. Meteor outbursts are unusual showers (often of short duration) from the crossing of relatively recent comet ejecta. Dates are for the year 2015. o February 08, possibility of a fresh outburst for α-Centaurids at 11h28m.
   October 6, possibility of short lived outbursts for the October 5/6 meteors, sometimes called the October Camelopardalids, between 07h10m and 14h30m.
   October-November, possibility for a return of the Taurid 'swarm' of larger particles from about October 29 to November 10.

b. Annual meteor showers liable to have geophysical effects: Dates (based on UT in year 2015) are:

- Dec 28-Jan 12, Jan 04 01h55m, Quadrantids (QUA)
- Jan 28-Feb 21, Feb 08 12h30m, α-Centaurids (ACE)
- Apr 16-Apr 25, Apr 22 23h55m, Lyrids (LYR)1
- Apr 19-May 28, May 06 13h25m, η-Aquariids (ETA)
- May 14-Jun 24, Jun 08 00h, Daytime Arietids (Ari)
- May 20-Jul 05, Jun 10 00h, Daytime ζ-Perseids (Zeta Per)
- Jun 05-Jul 17, Jun 28 23h, Daytime β-Taurids (Beta Tau)2
- Jul 12-Aug 23, Jul 30 (possibly Jul 28-30), Southern δ-Aquariids (SDA)
- Jul 17-Aug 24, Aug 13 06h25m to 08h55m, Perseids (PER)3
- Sep 09-Oct 09, Sep 27 23h (Possibly Sep 29), Daytime Sextantids (Sex)
- Oct 02-Nov 07, Oct 21-22 (possible strong sub-peak Oct 17-18), Orionids (ORI)
- Nov 06-Nov 30, Nov 18 04h05m (possibly Nov 17 21h) Leonids (LEO)
- Dec 04-Dec 17, Dec 14 01h30m - 22h45m, Geminids (GEM)
- Dec 17-Dec 26 Dec 23 02h25m Ursids(URS)

[1] Lyrids (LYR): Esko Lyytinen has suggested that Lyrid rates could be somewhat enhanced in 2015, although from his theoretical modelling, the chances of this seem better - if still uncertain - for 2016 and 2017. The 2015 possibility is heavily dependent on what dust trails other than that established from the one observed return of the shower's parent comet, C/1861 G1 Thatcher, may pass closer to the Earth, something which cannot be modelled. So, there are no predictions for when this may occur (other than probably during the interval the normal maximum should take place), just that meteor rates could be above normal.

[2] Taurid "swarm" return: David Asher has been in touch to say his table suggesting there may be a daytime Taurid "swarm" return in 2015 June is wrong, and that the event will actually be a potential night-time Taurid "swarm" return in 2015 late October to early (perhaps even mid) November instead, so much more likely to be observed from Earth.

[3] Perseids (PER): Jérémie Vaubaillon anticipates from his theoretical modelling that the dust trail from parent comet 109P/Swift-Tuttle's 1862 return should pass closest to the Earth (the separation is about 0.00053 astronomical units) at 18h39m UT on August 12, ahead of the nodal peak (which should still happen as expected too), although its likely activity levels are uncertain. Enhanced rates, if they happen at all from this additional maximum, may persist for several hours.

c. Annual meteor showers which may have geophysical effects: Dates (based on UT in year 2015) are:

- Apr 15-Apr 28, April 24 04h55m, η-Puppids(PPU)
- Jun 22-Jul 02, June 27 21h20m, June Bootids (JBO)
- Aug 28-Sep 05, Sep 1 13h45m, α-Aurigids (AUR)
- Sep05-Sep21, Sep922h15m, Septemberε-Perseids(SPE)
- Oct 06-Oct 10, Oct 9 05h40m, Draconids (DRA)
- Nov 15-Nov 25, Nov 22 04h25m, α-Monocerotids (AMO)

Meteor Shower Websites:

- Shower activity near-real time reports -- International Meteor Organization
- Meteor shower activity forecast from your own location -- Meteor Shower Flux Estimator
- Shower names and data -- IAU Meteor Data Center
- Announcements and reports of meteor outbursts -- IAU Minor Planet Center
- Shower outburst activity forecast -- Institut de Mecanique celeste et de calcul des ephemerides (IMCCE)

Meteor Shower References:

- Handbook for Meteor Observers, edited by Jürgen Rendtel and Rainer Arlt, IMO, 2008.
- A Comprehensive List of Meteor Showers Obtained from 10 Years of Observations with the IMO Video Meteor Network, by Sirko Molau and Jürgen Rendtel (WGN, the Journal of the IMO 37:4, 2009, pp. 98-121).
- Peter Jenniskens, Meteor showers and their parent comets. Cambridge University Press, 2006, 790 pp.

Real Time Space Weather and Earth Effects

The occurrence of unusual solar or geophysical conditions is announced or forecast by ISES through various types of geophysical "Alerts" (which are widely distributed via the internet on a current schedule). Stratospheric warmings (STRATWARM) were also designated for many years. The meteorological telecommunications network coordinated by the World Meteorological Organization (WMO) carries these worldwide Alerts once daily soon after 0400 UT. For definitions of Alerts see ISES URSIgram Codes.

RECOMMENDED SCIENTIFIC PROGRAMS (FINAL EDITION)

(The following material was reviewed in 2014 by the ISES committee with the advice of representatives from the various scientific disciplines and programs represented as suitable for coordinated geophysical programs in 2015.)

Airglow and Aurora Phenomena.

Airglow and auroral observatories operate with their full capacity around the New Moon periods. However, for progress in understanding the mechanism of many phenomena, such as low latitude aurora, the coordinated use of all available techniques, optical and radio, from the ground and in space is required. Thus, for the airglow and aurora 7-day periods on the Calendar, ionosonde, incoherent scatter, special satellite or balloon observations, etc., are especially encouraged. Periods of approximately one weeks' duration centered on the New Moon are proposed for high resolution of ionospheric, auroral and magnetospheric observations at high latitudes during northern winter.

Atmospheric Electricity.

Non-continuous measurements and data reduction for continuous measurements of atmospheric electric current density, field, conductivities, space charges, ion number densities, ionosphere potentials, condensation nuclei, etc.; both at ground as well as with radiosondes, aircraft, rockets; should be done with first priority on the RGD each Wednesday, beginning on 07 January 2015 at 0000 UT, 14 January at 0600 UT, 21 January at 1200 UT, 28 January at 1800 UT, etc. (beginning hour shifts six hours each week, but is always on Wednesday). Minimum program is at the same time on PRWD beginning with 21 January at 1200 UT. Data reduction for continuous measurements should be extended, if possible, to cover at least the full RGD including, in addition, at least 6 hours prior to indicated beginning time. Measurements prohibited by bad weather should be done 24 hours later. Results on sferics and ELF are wanted with first priority for the same hours, short-period measurements centered around minutes 35-50 of the hours indicated. Priority Weeks are the weeks that contain a PRWD; minimum priority weeks are the ones with a QWD. The World Data Centre for Atmospheric Electricity, 7 Karbysheva, St. Petersburg 194018, USSR, is the collection point for data and information on measurements.

Geomagnetic Phenomena.

It has always been a leading principle for geomagnetic observatories that operations should be as continuous as possible and the great majority of stations undertake the same program without regard to the Calendar.

Stations equipped for making magnetic observations, but which cannot carry out such observations and reductions on a continuous schedule are encouraged to carry out such work at least on RWD (and during times of MAGSTORM Alert).

Ionospheric Phenomena:

Special attention is continuing on particular events that cannot be forecast in advance with reasonable certainty. The importance of obtaining full observational coverage is therefore stressed even if it is only possible to analyze the detailed data for the chosen events. In the case of vertical incidence sounding, the need to obtain quarter-hourly ionograms at as many stations as possible is particularly stressed and takes priority over recommendation (a) below when both are not practical.

For the **vertical incidence** (VI) sounding program, the summary recommendations are:

a. All stations should make soundings on the hour and every quarter hour;
b. On RWDs, ionogram soundings should be made at least every quarter hour and preferably every five minutes or more frequently, particularly at high latitudes;
c. All stations are encouraged to make f-plots on RWDs; f-plots should be made for high latitude stations, and for so-called "representative" stations at lower latitudes for all days (i.e., including RWDs and WGIs) (Continuous records of ionospheric parameters are acceptable in place of f-plots at temperate and low latitude stations);
d. Copies of all ionogram scaled parameters, in digital form if possible, be sent to WDCs;
e. Stations in the eclipse zone and its conjugate area should take continuous observations on solar eclipse days and special observations on adjacent days. See also recommendations under Airglow and Aurora Phenomena.

For the 2015 incoherent scatter observation program, every effort should be made to obtain measurements at least on the Incoherent Scatter Coordinated Observation Days, and intensive series should be attempted whenever possible in WGIs, on Dark Moon Geophysical Days (DMGD) or the Airglow and Aurora Periods. The need for collateral VI observations with not more than quarter-hourly spacing at least during all observation periods is stressed.

Special programs include:

- **Sudden Stratospheric Warming (StratWarm)**: Dynamics, electrodynamics, temperature and electron density in the lower and upper thermosphere and ionosphere during sudden stratospheric warming.
  Key objectives:
  To extend studies of stratospheric warming effects to the lower and upper thermosphere and their coupling to the ionosphere;
  To document variations in multiple thermospheric

and ionospheric parameters in response to different stratospheric sudden warming events and determine the mechanisms responsible;
To compare variations in temperatures and winds to the mesospheric response as given by MF and meteor radars and lidars.
Background condition: The observations need to be made before and during the sudden stratospheric warming. A 10-day campaign is requested.
Primary parameters to measure: LTCS mode - electron and ion temperatures from lowest possible altitudes throughout the F-region, zonal and meridional components of the neutral wind in the lower thermosphere (95-140km), ExB drift, F-region meridional wind. Temporal resolution can be sacrificed and data integration period increased in order to obtain data at lower altitudes.
Need for simultaneous data: The idea is to measure how variations in temperatures, electric field and winds associated with sudden stratospheric warming change with latitude and altitude and relate to variations in electron density.
Principal investigator: Larisa P. Goncharenko (MIT Haystack Observatory, USA), lpg@haystack.mit.edu. Larisa is responsible for issuing the alert and will provide five days' notice.
Co-investigators: Jorge Chau (Leibniz-Institute for Atmospheric Physics, Rostock University, Germany), Hanli Liu (NCAR, USA).

- **Gravity Wave Coupling with Winds and Tides**
  Key objectives: Allow the investigation of wave propagation into the thermosphere and potential coupling with winds and tides, as well as studying whether low-altitude generated gravity waves are important for scintillation patches and the generation of TIDs.
  Conditions required: Quiet conditions to restrict contamination from geomagnetic effects. Observations over several contiguous days in January are desired. This request will be satisfied by the StratWarm run.
  Principal investigator: Andrew Kavanagh (British Antarctic Survey, UK), andkav@bas.ac.uk.

- **Solar Eclipse**
  Key objective: To study the ionospheric response to a total solar eclipse.
  Conditions required: The day of the eclipse, 20 March, plus a day or two of quiet conditions on either side of the eclipse. This experiment has priority in case of conflict with the Merino world day run.
  Principal investigators: Owen Roberts (Aberystwyth University, UK), owr6@aber.ac.uk; and Ingemar Häggström (EISCAT Scientific Association), ingemar@eiscat.se.

- **Meridional Circle (Merino)**
  Key objective: To determine the latitudinal variations and their east-west hemispheric differences during solar storms and/or under quiet magnetic conditions.
  Need for simultaneous data: This coordinated observation involves ISR world day participants as well as the Chinese Meridian Project facilities. This major Chinese project provides comprehensive ground-based space weather observing in the Eastern Hemisphere, in particular along the 120E longitude where 15 observatories, including an ISR, distributed from northern China to the South Pole, are established. They are equipped with, among other instruments, ionospheric radio sensors (digisonds, GPS receivers, MF radars, coherent radars, etc) and optical sensors (Lidars, FPIs, all-sky imagers). For this campaign, intensive observational modes will be adopted for most of the instruments.
  Principal investigator: Shunrong Zhang (MIT Haystack Observatory, USA), shunrong@haystack.mit.edu.
  Co-investigators: Guotao Yang and Zhaohui Huang (National Space Science Center, China), and John Foster (MIT Haystack Observatory, USA).
  Time: Four days in the alert period from 13-27 March. Shunrong will be responsible for issuing the alert notice, which will be at least five days in advance of the experiment start. Please note, the Eclipse mode has priority in case of conflict.
  Modes: Synoptic for all radars, except for Millstone Hill where low elevation azimuth scans are preferred.
- **Synoptic**
  Key objectives: Synoptic experiments are intended to emphasize wide coverage of the F region, with some augmented coverage of the topside or E region to fill in areas of the databases that have relatively little data.
  Investigators: Jan Sojka (Utah State University, USA) sojka@usu.edu; and Ian McCrea (Rutherford Appleton Laboratory, UK), ian.mccrea@stfc.ac.uk.

- **Northern Deep Polar Winter Observations**
  Key objectives: Because of the optical conditions near solstice, this is a unique opportunity to capitalize on northern high-latitude measurements by optical instruments. This could be a prime time to study:
  The formation, evolution, and decay of SAPS (Sub-Auroral Polarization Streams) and SED (Storm-Enhanced Densities) by measuring the penetration electric fields at low latitudes, the formation of SAPS electric fields and SED at mid-latitudes, and the motion of enhanced electron densities across the polar cap at high latitudes;
  Meso-scale polar cap phenomena such as patches, reversed flow events, flow channel propagation (Dåbakk);
  The evolution of polar cap aurora and patches (Dahlgren and Semeter);
  Polar cap patch transit, decay rates and large-scale changes within patch structures (Wood); and
  Global trans-polar coupling and sun-aligned arcs (Carlson).
  This period is historically in high demand at the high-latitude ISRs and the facilities will run modes that will satisfy the multiple investigators.

Conditions required: Operating the ISRs for four continuous days centered on the December New Moon should maximize the likelihood of the optical instruments getting good measurements during clear, dark skies.

Principal investigators: Herb Carlson (US Air Force Research Laboratories, USA), herbert.c.carlson@gmail.com; Yvonne Dåbakk (University of Alaska-Fairbanks, USA), y.r.dabakk@fys.uio.no; Hanna Dahlgren (Royal Institute of Technology, KTH, Sweden), hannad@kth.se; K. Oksavik (University of Bergen, Norway), kjellmar.oksavik@uib.no; Joshua Semeter (Boston University, USA), jls@bu.edu; and Alan Wood (Nottingham Trent University, UK), alan.wood@ntu.ac.uk.

Need for simultaneous data: Geomagnetic storms are known to impact the ionosphere on a global scale. Penetration electric fields occur at low latitudes, enhanced SAPS flows occur at mid-latitudes, the plasma flow is enhanced in the polar cap, and dense F-region plasma is transported from lower latitudes into and across the polar cap. Therefore, all radars should be operating at the same time.

- **AO** -- Arecibo Observatory
- **JRO** -- Jicamarca Radio Observatory.
- **Special programs:** Ian McCrea, Rutherford Appleton Laboratory, UK; tel:+44(0)1235 44 6513; Fax:+44(0)1235 44 5848; email: ian.mccrea@stfc.ac.uk, chair of URSI ISWG (Commission G). See the 2015 Incoherent Scatter Coordinated Observation Days (URSI-ISWG) webpage for complete 2015 definitions.
- For the **ionospheric drift** or wind measurement by the various radio techniques, observations are recommended to be concentrated on the weeks including RWDs.
- For **travelling ionosphere disturbances**, propose special periods for coordinated measurements of gravity waves induced by magnetospheric activity, probably on selected PRWDs and RWDs.
- For the **ionospheric absorption program** half-hourly observations are made at least on all RWDs and half-hourly tabulations sent to WDCs. Observations should be continuous on solar eclipse days for stations in the eclipse zone and in its conjugate area. Special efforts should be made to obtain daily absorption measurements at temperate latitude stations during the period of Absorption Winter Anomaly, particularly on days of abnormally high or abnormally low absorption (approximately October-March, Northern Hemisphere; April-September, Southern Hemisphere).
- **For back-scatter and forward scatter programs,** observations should be made and analyzed at least on all RWDs.
- For **synoptic observations of mesospheric (D region)** electron densities, several groups have agreed on using the RGD for the hours around noon.
- For **ELF noise** measurements of earth-ionosphere cavity resonances any special effort should be concentrated during WGIs.

It is recommended that more intensive observations in all programs be considered on days of unusual meteor activity.

Meteorology.

Particular efforts should be made to carry out an intensified program on the RGD -- each Wednesday, UT. A desirable goal would be the scheduling of meteorological rocketsondes, ozone sondes and radiometer sondes on these days, together with maximum-altitude rawinsonde ascents at both 0000 and 1200 UT.

During WGI and STRATWARM Alert Intervals, intensified programs are also desirable, preferably by the implementation of RGD-type programs (see above) on Mondays and Fridays, as well as on Wednesdays.

Global Atmosphere Watch (GAW).

The World Meteorological Organization (WMO) Global Atmosphere Watch (GAW) integrates many monitoring and research activities involving measurement of atmospheric composition, and serves as an early warning system to detect further changes in atmospheric concentrations of greenhouse gases, changes in the ozone layer and in the long range transport of pollutants, including acidity and toxicity of rain as well as of atmospheric burden of aerosols (dirt and dust particles). Contact WMO, 7 bis avenue de la Paix, P.O. Box 2300, CH-1211 Geneva 2, Switzerland or wmo@wmo.int.

Solar Phenomena.

Observatories making specialized studies of solar phenomena, particularly using new or complex techniques, such that continuous observation or reporting is impractical, are requested to make special efforts to provide to WDCs data for solar eclipse days, RWDs and during PROTON/FLARE ALERTS. The attention of those recording solar noise spectra, solar magnetic fields and doing specialized optical studies is particularly drawn to this recommendation.

Variability of the Sun and Its Terrestrial Impact (VarSITI).

Program within the SCOSTEP (Scientific Committee on Solar-Terrestrial Physics): 2014-2018. The VarSITI program will strive for international collaboration in data analysis, modeling, and theory to understand how the solar variability affects Earth. The VarSITI program will have four scientific elements that address solar terrestrial problems keeping the current low solar activity as the common thread: SEE (Solar evolution and Extrema), MiniMax24/ISEST (International Study of Earth-affecting Solar Transients), SPeCIMEN (Specification and Prediction of the Coupled Inner-Magnetospheric Environment), and ROSMIC (Role Of the Sun and the Middle atmosphere/thermosphere/ionosphere In Climate). Contact is Prof. Marianna Shepherd (mshepher@yorku.ca), President of SCOSTEP. Co-chairs are Katya Georgieva (SRTI, Bulgaria) and Kazuo Shiokawa (STEL, Japan).

ILWS (International Living With a Star) International effort to stimulate, strengthen, and coordinate space research to understand the governing processes of the connected Sun-Earth System as an integrated entity. Contact info@ilwsonline.org.

ISWI (International Space Weather Initiative) -- a program of international cooperation to advance space weather science by a combination of instrument deployment, analysis and interpretation of space weather data from the deployed instruments in conjunction with space data, and communicate the results to the public and students. The goal of the ISWI is to develop the scientific insight necessary to understand the science, and to reconstruct and forecast near-Earth space weather. This includes instrumentation, data analysis, modelling, education, training, and public outreach. Contact J. Davila at Joseph.M.Davila@nasa.gov.

Space Research, Interplanetary Phenomena, Cosmic Rays, Aeronomy.

Experimenters should take into account that observational efforts in other disciplines tend to be intensified on the days marked on the Calendar, and schedule balloon and rocket experiments accordingly if there are no other geophysical reasons for choice. In particular it is desirable to make rocket measurements of ionospheric characteristics on the same day at as many locations as possible; where feasible, experimenters should endeavor to launch rockets to monitor at least normal conditions on the Quarterly World Days (QWDs) or on RWDs, since these are also days when there will be maximum support from ground observations. Also, special efforts should be made to assure recording of telemetry on QWDs and Airglow and Aurora Periods of experiments on satellites and of experiments on spacecraft in orbit around the Sun.

Meteor showers.

Of particular interest are both predicted and unexpected showers from the encounter with recent dust ejecta of comets (meteor outbursts). The period of activity, level of activity, and magnitude distributions need to be determined in order to provide ground truth for comet dust ejection and meteoroid stream dynamics models. Individual orbits of meteoroids can also provide insight into the ejection circumstances. If a new (1-2 hour duration) shower is observed due to the crossing of the 1-revolution dust trail of a (yet unknown) Earth threatening long-period comet, observers should pay particular attention to a correct determination of the radiant and time of peak activity in order to facilitate predictions of future encounters. Observations of meteor outbursts should be reported to the I.A.U. Minor Planet Center (mpc@cfa.harvard.edu) and International Meteor Organization (visual@imo.net). The activity curve, mean orbit, and particle size distribution of minor annual showers need to be characterised in order to understand their relationship to the dormant comets among near-Earth objects. Annual shower observations should be reported to national meteor organizations, or directly to the International Meteor Organization. Meteoroid orbits are collected by the IAU Meteor Data Center.

The International Space Environment Service (ISES) is a space weather service organization currently comprised of 16 Regional Warning Centers around the globe, 4 Associate Warning Centers, and one Collaborative Expert Center (European Space Agency). ISES is a Network Member of the International Council for Science World Data System (ICSU-WDS) and collaborates with the World Meteorological Organization (WMO) and other international organizations, including the Committee on Space Research (COSPAR), the International Union of Radio Science (URSI), and the International Union of Geodesy and Geophysics (IUGG). The mission of ISES is to improve, to coordinate, and to deliver operational space weather services. ISES is organized and operated for the benefit of the international space weather user community.

ISES members share data and forecasts among the Regional Warning Centers (RWCs) and provide space weather services to users in their regions. The RWCs provide a broad range of services, including: forecasts, warnings, and alerts of solar, magnetospheric, and ionospheric conditions; extensive space environment data; customer-focused event analyses; and long-range predictions of the solar cycle. While each RWC concentrates on its own region, ISES serves as a forum to share data, to exchange and compare forecasts, to discuss user needs, and to identify the highest priorities for improving services.

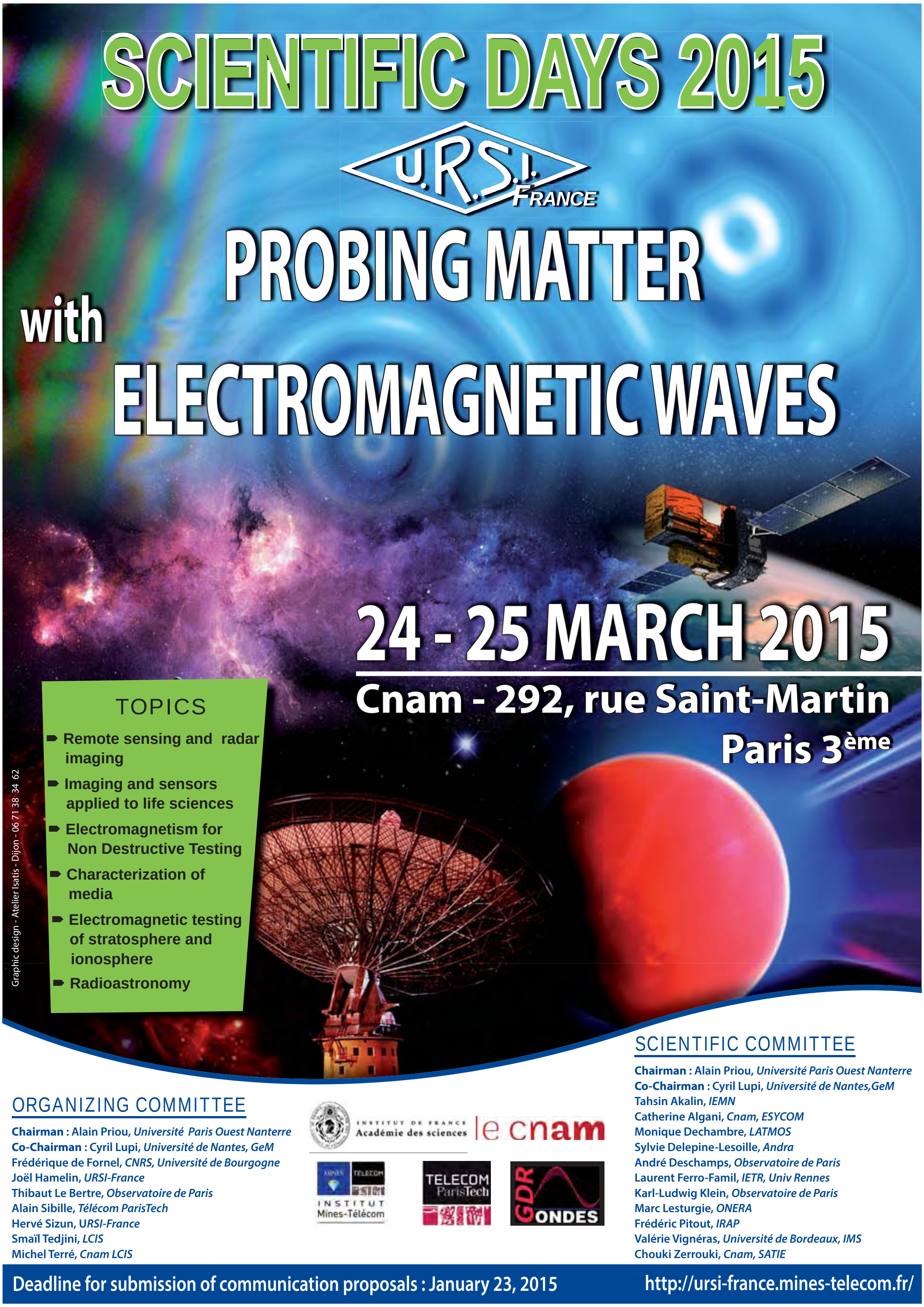
ISES works in close cooperation with the World Meteorological Organization, recognizing the mutual interest in global data acquisition and information exchange, in common application sectors, and in understanding and predicting the coupled Earth-Sun environment.

This Calendar for 2015 has been drawn up by Dr. R. A. D. Fiori of the ISES Steering Committee, in association with spokesmen for the various scientific disciplines in the Scientific Committee on Solar-Terrestrial Physics (SCOSTEP), the International Association of Geomagnetism and Aeronomy (IAGA), URSI and other ICSU organizations. Similar Calendars are issued annually beginning with the IGY, 1957-58, and are published in various widely available scientific publications. PDF versions of the past calendars are available online.

Published for the International Council of Scientific Unions and with financial assistance of UNESCO for many years.

Copies are available upon request to ISES Director, Dr. Terry Onsager, NOAA Space Weather Prediction Center, 325 Broadway, Boulder, CO, 80305, USA, telephone +1-303-497-5713, FAX +1-303-497-3645, e-mail Terry.Onsager@noaa.gov, or ISES Secretary for World Days, Dr. Robyn Fiori, Geomagnetic Laboratory, Natural Resources Canada, 2617 Anderson Road, Ottawa, Ontario, Canada, K1A 0E7, telephone +1-613-837-5137, e-mail Robyn.Fiori@NRCan-RNCan.gc.ca.

Beginning with the 2008 Calendar, all calendars are available only in digital form at http://www.ises-spaceweather.org.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Call for Papers

The National Radio Science Committee of the Academy of Scientific Research and Technology (ASRT) along with MSA University are holding the 32nd National Radio Science Conference during the period 24th – 26th March 2015.

The conference program will consist of invited sessions on selected topics and contributed sessions. The submitted papers must describe original work and cover the activities of the URSI commissions A-K, namely:

A. Electromagnetic metrology
B. Fields and waves
C. Wireless communications and signal processing
D. Electronics and photonics
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F. Wave propagation and remote sensing
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I. Radio astronomy
J. Electromagnetic in biology and medicine

Invited papers describing new trends and state of the art of some of the URSI activities are welcomed. Accepted papers will be published in the conference proceeding conditional upon presentation of the paper and advance registration by at least one of the authors. Presented papers will be included in IEEE Xplore. A special student session will host a limited number of posters presenting B.Sc. graduation projects or Masters' work, with free registration. Best papers and best student papers will be selected by the organizing committee for awards.

Submission Instructions

Prospective authors of papers describing original work are invited to get the standard format and to submit papers electronically through the conference website. The maximum number of pages is 8 per research paper.

Important Dates
Paper Submission deadline: **December 1st, 2014**
Notification of acceptance: **January 19th, 2015**
Camera-ready manuscript: **February 9th, 2015**

Registration Fees (per paper)

Egyptians: LE 500 **Non-Egyptians:** US$ 500

Fees cover attending sessions, proceedings CD, lunches, and coffee breaks for the period of the conference for one of the authors. Non-refundable fees, LE 200 (US$ 200 for non-Egyptians), are paid in advance upon paper submission. The remaining registration fees are paid with the camera ready submission. Extra LE 50 (US$ 50 for non-Egyptians) is added for each additional page.

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