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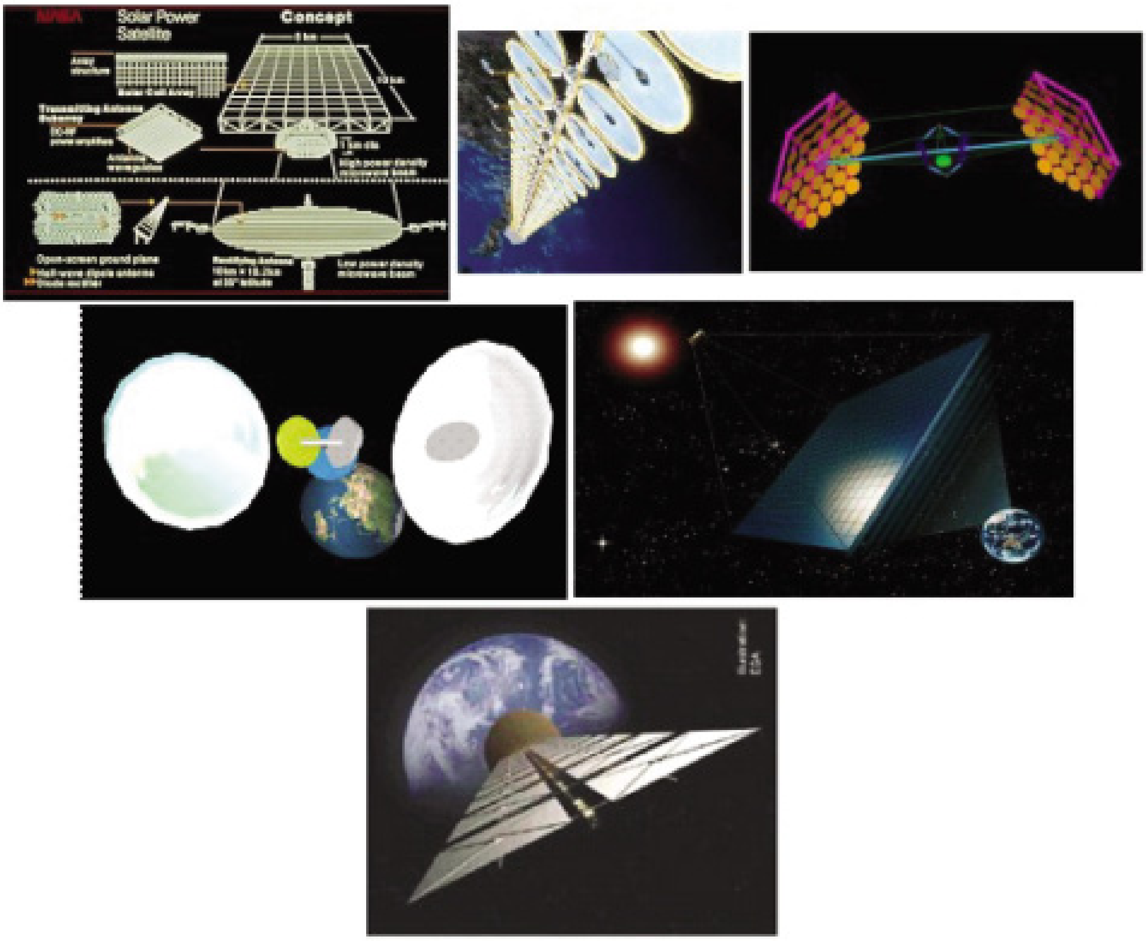
INTERNATIONALE

U.R.S.I.



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# Contents

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*Front cover: An artist's impressions of various current SPS models . See the URSI White Paper on Solar Power Satellite Systems on pp. 12 - 26.*

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# Editorial

We have several special items in this issue.

## Our Papers

Since the last triennium, the URSI Inter-Commission Working Group on SPS and the URSI Board have been working on writing and reviewing an URSI White Paper on Solar Power Satellites. A solar power satellite (SPS) system uses a satellite to capture power from the sun, generate electricity in orbit, and transmit it to the ground using electromagnetic waves. The white paper that appears in this issue is the result of more than three years of work, including input and consultation from the URSI Commissions and Member Committees and the Board. The result is an important document containing a great deal of information, and makes for very interesting reading. It should also be recognized that there are almost certainly scientists active in URSI who may disagree with parts of this white paper. As noted in the White Paper, URSI white papers "are documents issued by URSI scientific experts on controversial subjects involving aspects of radio science. Although under the responsibility of URSI, they do not necessarily reflect all the views of individual URSI Member Committees nor Commissions." More on the nature of URSI white papers and the process associated with generating and reviewing them is given in Appendix 1 of the SPS White Paper. For those interested in more information on solar power satellite systems, the *Report of the URSI Inter-Commission Working Group on SPS*, a document separate from the SPS White Paper, should be available on the URSI Web site (http://www.ursi.org) by the time this issue of the *Bulletin* reaches you.

As noted above, the preparation of this SPS White Paper involved a very large number of URSI radio scientists. The efforts of the members of the Inter-Commission Working Group on SPS and the URSI Board must be particularly acknowledged. Hiroshi Matsumoto and Kozo Hashimoto played leadership roles within the Working Group, and Kristian Schlegel provided leadership within the Board, in bringing this white paper to completion.

Major disturbances to the ionosphere have been observed at mid-latitudes during strong geomagnetic storms. A basic cause of these disturbances is the sub-auroral polarization stream (SAPS). This results from interaction between the magnetosphere and the ionosphere because of increases in the plasmasheet ring currents during storms. The effects driven by the electric fields associated with the SAPS are dramatic, and involve major changes and disruptions in the Earth's plasmasphere. In their invited Commission G *Review*, Anthea Coster and John Foster summarize the experimental evidence for the SAPS and the associated phenomena. They explain how the SAPS is generated, and look at many of the effects caused by it. These can include quite significant consequences, including degradations of GPS sufficient to affect the safety of aircraft landing and navigation, and marine navigation.

Thanks go to M. T. Rietveld of Commission G and, of course, Phil Wilkinson, for helping to coordinate this paper.

There have been dramatic advances in long-haul optical-fiber communications (over hundreds of kilometers to transatlantic distances). Le Nguyen Binh reviews these in his invited paper, based on a presentation made at the WARS2006 (Workshop on the Applications of Radio Science 2006) conference. Part of the advances reviewed in this paper include improvements in modulation techniques. Also included are advances in the ability to compensate for distortion and dispersion effects, including carrying out such compensation using both electronic and photonic means. Experimental demonstrations of such compensation are reported. Also described are experimental demonstrations of the transmission of multiple channels at 40 Gb/s over significant long-haul fiber lengths in practical situations, and the ability for transmission at 40 Gb/s over existing 10 Gb/s systems. Being able to dramatically increase the transmission rate over already-installed systems is particularly interesting, and has significant economic and bandwidth availability implications.

The efforts of Phil Wilkinson and Ray Norris in bringing us this paper are gratefully acknowledged.

Jim Lin looks at a very interesting issue in his Radio-Frequency Radiation Safety and Health column. What is the impact of the source of funding on the published results relating to telecommunications health effects? It turns out that there is evidence suggesting that the source of funding for such research may affect what is published and/or how it is published.

## A New Book

We regularly publish announcements of books authored by URSI radio scientists, and I'm sure we will have such an announcement for this one. However, this is something special. As this issue was going to press, I received a copy of *Electromagnetic Fields, Second Edition*, by Jean Van Bladel (IEEE Press/John Wiley, 2007, ISBN 978-0-471-26388-3). This is a completely rewritten version of the 1964 classic from which many radio scientists learned electromagnetics. "Completely rewritten" does not do the book justice: It contains more than double the material of the original edition (it is 1176 pages), and took more than nine years to write. It has been extensively reviewed: more than 90 authors whose work is quoted reviewed the relevant sections, and major portions of the book were reviewed by more than 15 distinguished radio scientists. The depth and breadth of the material is amazing. It is completely up-to-date, including the impact of modern computational techniques. It is both a textbook, complete with problems, and a valuable reference book. I have by no means read it all, but what I have read is beautifully and clearly written. The book itself is visually striking: it is in an oversize format, with excellent figures and a font size and leading that makes it very easy to read. I predict this will become even more of a classic than was the first edition.

## The XXIX
## General Assembly of URSI

The Coordinating Committee met in Gent, Belgium, in April. We are going to have an excellent General Assembly next year! Around the time you receive this issue, the call for papers should be available via the URSI Web site (http://www.ursi.org). In addition to URSI's traditional support for Young Scientists, there will be a Student Paper Competition. Procedures for applying for both the Young Scientist Awards and the Student Paper Competition will be available on the Web site. The Student Paper Competition will offer some housing support for finalists in the competition to attend the General Assembly, as well as substantial prizes for the winning papers. Please start planning now to contribute to this General Assembly, and to attend.

Ross

***Please note that the Radio Science Bulletin is freely available on the web. From the September 2002 issue onwards, it is possible to download our magazine (in .pdf format) from http://www.ursi.org/RSB.htm***

# XXIX General Assembly of the International Union of Radio Science Union Radio Scientifique Internationale (URSI)

August 07-16, 2008
Hyatt Regency Chicago Hotel on the Riverwalk
151 East Wacker Drive, Chicago, Illinois 60601, USA

## *Call for Papers*

The XXIX General Assembly of the International Union of Radio Science (Union Radio Scientifique Internationale-URSI) will be held at the Hyatt Regency Chicago Hotel in downtown Chicago, Illinois, USA on August 07-16, 2008.

The XXIX General Assembly will have a scientific program organized around the ten Commissions of URSI and consisting of plenary lectures, public lectures, tutorials, invited and contributed papers. In addition, there will be workshops, short courses, special programs for young scientists and graduate students, programs for accompanying persons, and industrial exhibits. More than 1,500 scientists from more than fifty countries are expected to participate in the Assembly. The detailed program, link to electronic submission site, registration form and hotel information will be available on the General Assembly Web site:

**www.ece.uic.edu/2008ursiga**

**Submissions:** All contributions must be submitted electronically via the link provided on the General Assembly Web site. The site will open in July 2007 and will close on January 31, 2008.

**Submission Deadline:** January 31, 2008.

**Authors Notification:** Authors will be notified of the disposition of their submissions by March 31, 2008. Accepted contributions will be scheduled for either oral or poster presentation.

**Contact:** For any questions related to the XXIX General Assembly, please contact the Chair of the Local Organizing Committee:

Prof. P. L. E. Uslenghi
Department of Electrical and Computer Engineering
University of Illinois at Chicago
851 South Morgan Street
Chicago, Illinois 60607-7053, USA
E-mail: uslenghi@uic.edu

## XXIX General Assembly of URSI, Chicago, Illinois, USA – August 07-16, 2008

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| Chair | P. L. E. Uslenghi, *University of Illinois at Chicago*, uslenghi@uic.edu |
| Vice Chair | D. Erricolo, *University of Illinois at Chicago*, erricolo@ece.uic.edu |
| Technical program | J. E. Carlstrom, *University of Chicago*, jc@hyde.uchicago.edu |
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| Poster sessions | D. Erricolo, *University of Illinois at Chicago*, erricolo@ece.uic.edu |
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| | T. T. Y. Wong, *Illinois Institute of Technology*, twong@ece.iit.edu |
| Publications | D. Erricolo, *University of Illinois at Chicago*, erricolo@ece.uic.edu |
| Young scientists | S. C. Hagness, *University of Wisconsin at Madison*, hagness@engr.wisc.edu |
| Graduate students | S. C. Reising, *Colorado State University*, steven.reising@colostate.edu |
| Workshops & short courses | Y. Rahmat-Samii, *University of California at Los Angeles*, rahmat@ee.ucla.edu |
| Exhibits | T. T. Y. Wong, *Illinois Institute of Technology*, twong@ece.iit.edu |
| Fundraising | A. Taflove, *Northwestern University*, taflove@ece.northwestern.edu |
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| Registration | Three Dimensions Meeting Planners, mevegter@verizon.net |
| | or: mevegter@threedimensions.com |
| Social activities | Three Dimensions Meeting Planners, mevegter@verizon.net |
| | Marie Erricolo, Shelly Uslenghi |
| Contact with Intl. URSI | W. R. Stone, *Stoneware Limited*, r.stone@ieee.org |
| Honorary member | S. K. Avery, *University of Colorado at Boulder* |

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**UNION RADIO-SCIENTIFIQUE INTERNATIONALE**

**INTERNATIONAL UNION OF RADIO SCIENCE**

# AWARDS FOR YOUNG SCIENTISTS

## CONDITIONS

A limited number of awards are available to assist young scientists from both developed and developing countries to attend the General Assembly of URSI.

To qualify for an award the applicant:

1. must be less than 35 years old on September 1 of the year of the URSI General Assembly;
2. should have a paper, of which he or she is the principal author, submitted and accepted for oral or poster presentation at a regular session of the General Assembly.

Applicants should also be interested in promoting contacts between developed and developing countries. Applicants from all over the world are welcome, also from regions that do not (yet) belong to URSI. All successful applicants are expected to participate fully in the scientific activities of the General Assembly. They will receive free registration, and financial support for board and lodging at the General Assembly. A basic accommodation is provided by the assembly organizers permitting the Young Scientists from around the world to collaborate and interact. Young scientists may arrange alternative accommodation, but such arrangements are entirely at their own expense. Limited funds will also be available as a contribution to the travel costs of young scientists from developing countries.

All Young Scientists should apply via the web-based form which will appear when they check "Young Scientist paper" at the time they submit their paper. All Young Scientists must submit their paper(s) and this application together with a CV and a list of publications in PDF format to the GA submission Web site.

*Applications will be assessed by the URSI Young Scientist Committee taking account of the national ranking of the application and the technical evaluation of the abstract by the relevant URSI Commission. Awards will be announced on the URSI Web site in April 2008.*

For more information about URSI, the General Assembly and the activities of URSI Commissions, please look at the URSI Web site at: http://www.ursi.org. If the information you are looking for is not on this site, please contact:

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BELGIUM
fax: +32 9 264 42 88
E-mail: info@ursi.org

# APPLICATION FOR AN URSI YOUNG SCIENTIST AWARD

I wish to apply for an award to attend the XXIXth General Assembly of the International Union of Radio Science in Chicago, Illinois, USA, on 9-16 August 2008.

Name: Prof./Dr./Mr./Mrs./Ms. ..........................................................................................................

Family Name First Name Middle Initials

Sex: male / female

Nationality: ..........................................................................................................

Studying/Employed at: ..........................................................................................................

Institution ..........................................................................................................

Department..........................................................................................................

Mailing address: Please send all correspondence to my ☐ business / ☐ home address, i.e.

Street ..........................................................................................................

City and postal code ..........................................................................................................

Province/State ............................................ Country ..................................................................

Fax ............................................................ E-mail ..................................................................

Academic qualifications, with date(s) obtained: ..............................................................................

..........................................................................................................

Title of abstract submitted: ..........................................................................................................

..........................................................................................................

Type of session preferred: ☐ in an oral session ☐ in a poster session

The subject of the paper is relevant to URSI Commission ……….session (leave blank if uncertain).

**I hereby certify that I will be less than 35 years old on September 1, 2008.**

Date:............................ Signed: ..........................................................................................

**For applicants from developing countries only:**
I estimate the cheapest return fare to the URSI meeting is EURO.................................................

# URSI Accounts 2006

As usual, the URSI balance sheet per 31 December 2006 shows the original value of investments, not their actual value. At the advice of the accountants, for investments that have sustained losses, a provision has been made to reflect this loss (partially). However, for investments that have (substantially) increased in value this has not been done. Also, a substantial provision for currency differences was included. This leads to a substantial difference between the market value of investments and the value shown in the balance. The market value of the investments is only slightly lower than the previous year.

The income and expenditure sheet does not yet show the income from the General Assembly 2005, since the share of the fees was received in January of this year. This will, therefore, appear in the 2007 books. As a result, the statement of income and expenditure over 2006 shows a high deficit that is somewhat artificial. Nevertheless, the deficit in income and expenditures over the previous three years is a matter of concern for the Board.

Overall, the state of the URSI finances is sound.

Gert Brussaard
Treasurer

**BALANCE SHEET: 31 DECEMBER 2006**

| **ASSETS** | EURO | EURO |
|---|---|---|
| Dollars | | |
| Merrill Lynch WCMA | 941.06 | |
| Fortis | 1,449.96 | |
| Smith Barney Shearson | 9,810.57 | |
| | | 12,201.59 |
| Euros | | |
| Banque Degroof | 144.76 | |
| Fortis | 153,073.15 | |
| | | 153,217.91 |
| Investments | | |
| Demeter Sicav Shares | 22,681.79 | |
| Rorento Units | 111,414.88 | |
| Aqua Sicav | 63,785.56 | |
| Merrill-Lynch Low Duration (305 units) | 3,268.17 | |
| Massachusetts Investor Fund | 250,011.32 | |
| Provision for (not realised) less value | (26,307.20) | |
| Provision for (not realised) currency differences | (61,801.63) | |
| | 363,052.89 | |
| 684 Rorento units on behalf of van der Pol Fund | 12,414.34 | |
| | | 375,467.23 |
| Short Term Deposito | | 0.00 |
| Petty Cash | | 337.68 |
| **Total Assets** | | 541,224.41 |
| Less Creditors | | |
| IUCAF | 5,951.45 | |
| ISES | 10,657.73 | |
| | | (16,609.18) |
| Balthasar van der Pol Medal Fund | | (12,414.34) |
| **NET TOTAL OF URSI ASSETS** | | **512,200.89** |

| **The net URSI Assets are represented by:** | EURO | EURO |
|---|---|---|
| Closure of Secretariat | | |
| Provision for Closure of Secretariat | | 90,000.00 |
| Scientific Activities Fund | | |
| Scientific Activities in 2007 | 45,000.00 | |
| Publications in 2007 | 40,000.00 | |
| Young Scientists in 2007 | 0.00 | |
| Administration Fund in 2007 | 85,000.00 | |
| I.C.S.U. Dues in 2007 | 3,600.00 | |
| | | 173,600.00 |
| XXIX General Assembly 2008 Fund: | | |
| During 2006-2007-2008 | | 35,000.00 |
| **Total allocated URSI Assets** | | 298,600.00 |
| **Unallocated Reserve Fund** | | 213,600.89 |
| | | **512,200.89** |

**Statement of Income and expenditure for the year ended 31 December 2006**

| **I. INCOME** | EURO | EURO |
|---|---|---|
| Grant from ICSU Fund and US National Academy of Sciences | 0.00 | |
| Allocation from UNESCO to ISCU Grants Programme | 0.00 | |
| UNESCO Contracts | 0.00 | |
| Contributions from National Members | 139,888.00 | |
| Contributions from Other Members | 0.00 | |
| Special Contributions | 0.00 | |
| Contracts | 0.00 | |
| Sales of Publications, Royalties | 0.00 | |
| Sales of scientific materials | 0.00 | |
| Bank Interest | 891.40 | |
| Other Income | 0.00 | |
| **Total Income** | | **140,779.40** |

**II. EXPENDITURE**

| | | |
|---|---|---|
| A1) Scientific Activities | | 29,299.63 |
| General Assembly 2005 | 9,879.23 | |
| Scientific meetings: symposia/colloqiua | 17,847.17 | |
| Working groups/Training courses | 0.00 | |
| Representation at scientific meetings | 1,573.23 | |
| Data Gather/Processing | 0.00 | |
| Research Projects | 0.00 | |
| Grants to Individuals/Organisations | 0.00 | |
| Other | 0.00 | |
| Loss covered by UNESCO Contracts | 0.00 | |

| | EURO | EURO |
|---|---|---|
| A2) Routine Meetings | | 11,062.37 |
| Bureau/Executive committee | 11,062.37 | |
| Other | 0.00 | |
| A3) Publications | | 48,153.34 |
| B) Other Activities | | 5,749.50 |
| Contribution to ICSU | 3,749.50 | |
| Contribution to other ICSU bodies | 2,000.00 | |
| Activities covered by UNESCO Contracts | 0.00 | |
| C) Administrative Expenses | | 112,559.20 |
| Salaries, Related Charges | 67,453.01 | |
| General Office Expenses | 8,180.11 | |
| Office Equipment | 2,640.19 | |
| Accountancy/Audit Fees | 5,777.75 | |
| Bank Charges | 2,200.94 | |
| Loss on Investments | 26,307.20 | |
| **Total Expenditure:** | | **206,824.04** |
| **Excess of Income over Expenditure** | | (66,044.64) |
| Currency translation difference (USD => EURO) - Bank Accounts | | (1,462.90) |
| Currency translation difference (USD => EURO) - Investments | | (22,957.16) |
| Currency translation difference (USD => EURO) - others | | 0.00 |
| Accumulated Balance at 1 January 2006 | | 602,665.59 |
| | | **512,200.89** |

Rates of exchange:

January 1, 2006 $ 1 = 0.8500 EUR
December 31, 2006 $ 1 = 0.7590 EUR

| | EURO |
|---|---|
| Balthasar van der Pol Fund | |
| 684 Rorento Shares: market value on December 31,<br>(Aquisition Value: USD 12.476,17/EUR 12.414,34) | 29,138.40 |
| Market Value of investments on December 31, 2006/2005 | |
| Demeter Sicav | 59,126.10 |
| Rorento Units (1) | 553,800.00 |
| Aqua-Sicav | 82,597.00 |
| M-L Low Duration | 2,311.97 |
| Massachusetts Investor Fund | 162,858.69 |
| | **860,693.77** |

(1) Including the 684 Rorento Shares of the van der Pol Fund

## APPENDIX: Detail of Income and Expenditure

| | EURO | EURO |
|---|---|---|
| **I. INCOME** | | |
| Other Income | | |
| Income General Assembly 2002 | 0.00 | |
| Income General Assembly 2005 | 0.00 | |
| Revenu Taxes | 0.00 | |
| | | 0.00 |
| **II . EXPENDITURE** | | |
| General Assembly 2005 | | |
| Organisation | 8,621.23 | |
| Vanderpol Medal | 0.00 | |
| Expenses officials | 0.00 | |
| Young scientists | 1,258.00 | |
| | | 9,879.23 |
| Symposia/Colloquia/Working Groups: | | |
| Commission A | 0.00 | |
| Commission B | 0.00 | |
| Commission C | 0.00 | |
| Commission D | 0.00 | |
| Commission E | 0.00 | |
| Commission F | 1,000.00 | |
| Commission G | 3,847.17 | |
| Commission H | 7,000.00 | |
| Commission J | 3,000.00 | |
| Commission K | 0.00 | |
| Central Fund | 3,000.00 | |
| | | 17,847.17 |
| Contribution to other ICSU bodies | | |
| UNESCO-ICTP | 0.00 | |
| IUCAF | 2,000.00 | |
| | | 2,000.00 |
| Publications: | | |
| Printing 'The Radio Science Bulletin' | 16,809.46 | |
| Mailing 'The Radio Science Bulletin' | 30,872.31 | |
| Ursi Leaflet | 471.57 | |
| | | 48,153.34 |

# URSI White Paper on Solar Power Satellite (SPS) Systems

## 1. Executive Summary

As a consequence of an ever-increasing world-wide energy demand and of a need for a “clean” energy source, the solar power satellite (SPS) concept has been explored by scientists and engineers in the United States, Japan, and Europe. An SPS constitutes a method of generating electricity from solar energy using satellites and transporting it to the ground via electromagnetic waves. Several candidate systems have been proposed. However, so far no system has been either constructed or tested in space, and it is currently unknown when one might be.

The purpose of this URSI white paper is to provide knowledge about the SPS concept based on evidence, and an open forum for debate on the scientific, technical, and environmental aspects of the SPS concept[1].

In a typical SPS system, solar energy is collected in space by a satellite in a geostationary orbit. The solar energy is converted to direct current by solar cells, and the direct current is in turn used to power microwave generators in the gigahertz frequency (microwave) range. The generators feed a highly directive satellite-borne antenna, which beams the energy to the Earth. On the ground, a rectifying antenna (rectenna) converts the microwave energy from the satellite into direct current, which, after suitable processing, is fed to the terrestrial power grid. A typical SPS unit – with a solar panel area of about 10 km$^2$, a transmitting antenna of about 2 km in diameter, and a rectenna about 4 km in diameter – may yield an electric-power output of about 1 GW. Two critical aspects that have motivated research into SPS systems are the lack of attenuation of the solar flux by the Earth’s atmosphere, and the twenty-four-hour availability of the energy, except around midnight during the equinox periods.

Among the key technologies involved in SPS systems are microwave generation and transmission techniques, wave propagation, antennas, and measurement and calibration techniques. These radio-science issues fall within the scientific domain of the International Union of Radio Science (URSI). URSI’s ten Scientific Commissions (Appendix 2) cover a broad range of aspects involved in an SPS system, ranging from the technical aspects of microwave power generation and transmission to the effects on humans and potential interference with communications, remote-sensing, and radio-astronomy observations.

This has led URSI to organise an open forum for the debate of the radio-science aspects of SPS systems and related technical and environmental issues. The present white paper is intended to draw attention to these aspects of SPS systems. It is not URSI’s intention to advocate solar power satellites as a solution to the world’s increasing energy demands, or to dwell on areas outside of URSI’s scientific domain, such as the whole issue of the space engineering to launch, assemble, and maintain an SPS system in space, the economic justification, and public acceptance. URSI is well aware that if a practical SPS system is feasible, the realisation of such a system is far in the future. Many of the required technologies currently exist, but some of these must be substantially advanced, and others must be created.

Microwave power transmission is an important technology for SPS systems, since its overall efficiency is one of the critical factors that determines the interest in such systems from an economic standpoint. Ideally, almost all energy transmitted from the geostationary orbit should be collected by the rectifying antennas on the ground. In that respect, an overall dc-to-microwave-to-dc power efficiency in excess of 50% is needed (see Section 2.4), which requires the development of suitable microwave power devices. Accurate control of the antenna beam is essential, and measurement and calibration are important issues. Even if these technologies can be successfully developed, there remains the challenging task of combining the outputs of thousands or even millions of elements to form a focused beam. Proper safety measures have to be developed to be certain that the transmitted microwave beam remains within the rectenna’s area. Maintenance of the space systems may be very difficult and expensive in the harsh environment of a geostationary orbit. Ensuring the long-term stability of huge structures in space in the presence of solar radiation pressure and tidal forces is an unsolved problem.

The influence and effects of electromagnetic emissions from an SPS, and, in particular, the microwave power transmission, are radio-science issues that concern URSI. Atmospheric effects on the microwave beam, and linear and non-linear interactions of the microwave beam with the atmosphere, ionosphere, and space plasmas, are among the numerous issues that must be investigated and evaluated. Undesired emissions – such as harmonics, grating lobes, and sidelobes from transmitting antennas and rectennas – must be sufficiently suppressed. This is true not only to avoid wasting power, but also to avoid interference with other radio services and applications and with remote sensing and radio astronomy, in accordance with the provisions of the Radio Regulations of the International Telecommunication Union (ITU). The evaluation of possible effects on human health and the incorporation of appropriate safety measures are essential for legal operation and public acceptance of this power-generation technique.

Finally, this paper identifies specific radio-science issues requiring further studies. It is stressed that only some of these questions can be solved by laboratory work, simulations, and system analysis. Testing of elements of such large systems in space is mandatory before a possible demonstration SPS unit can be considered, and broad international consensus is likely to be required before an SPS demonstration system can be launched.

# 2. Solar Power Satellite Systems

## 2.1 The SPS Concept

A solar power satellite is a very large-area satellite in an appropriate orbit (see Section 2.6), which would function as an electric power plant in space. The satellite would consist of three main parts: a solar-energy collector, to convert solar energy into dc electric power; a dc-to-microwave converter; and a large antenna array, to beam the microwave power to the ground. For the production of 1 GW of dc power, the solar collector would need to have an area of 10 km$^2$, and would consist of either photovoltaic cells or solar thermal turbines. The dc-to-microwave converter could be realised using either a microwave-tube system or a semiconductor system, or a combination of both. For transmitting the power to the ground, frequency bands around 5.8 GHz or 2.45 GHz have been proposed, which are within the microwave radio windows of the atmosphere. The antenna array to transmit the energy to the ground would require a diameter of about 2 km at 2.45 GHz, and its beam direction would have to be controlled to an accuracy of significantly better than 300 m on the Earth, corresponding to 0.0005°, or less than 2 arc seconds (for a geostationary orbit of the satellite).

In addition to the SPS orbiter, a ground-based power-receiving site has to be constructed, consisting of a device to receive and rectify the microwave power beam, i.e. to convert it back to dc electric power. This device is called a rectenna (rectifying antenna). The dimensions of the rectenna site on the ground depend on the microwave frequency and the size of the transmitting antenna. A model system, operating at 2.45 GHz, would use a rectenna site with a diameter of 4 km and a satellite-based transmitting antenna with a diameter of 2 km (see Section 2.4). The peak microwave power-flux density at the rectenna site would then be 300 W/m$^2$, if a Gaussian power profile of the transmitted beam is assumed. The beam-intensity pattern would be nonuniform, with a higher intensity in the centre of the rectenna and a lower intensity at its periphery. For human safety requirements, the maximum-allowable microwave power level has been set to 10 W/m$^2$ in most countries, and the SPS power-flux density would be constructed to satisfy this requirement at the periphery of the rectenna. After suitable power conditioning, the electric output of the rectenna would be delivered to the power network.

The combination of an SPS in orbit and the ground-based rectenna will be called an SPS "unit" in the following. On a global scale, a very large number of 1 GW units may be necessary for a practical SPS system. More details about the SPS concept can be found in [1].

For the sake of completeness, it should be mentioned that besides microwave power transmission, laser power transmission has also very recently been suggested [1, Appendix D.9]. In such a scenario, highly concentrated solar radiation would be injected into the laser medium (direct solar pumping) and transmitted to Earth. On the ground, the laser light would be converted to electricity by photovoltaic cells. It is obvious that such a system would be fundamentally different from a "classical" SPS using microwave power transmission: In space, there would be the light-concentration system and the lasers instead of a photovoltaic-cell array and the transmitting antenna; on the ground, there would be a photovoltaic-cell array instead of the rectenna. Since the technological challenges and problems for such laser-based systems have not yet been sufficiently explored, and since many subcomponents are at a low technology-readiness level, this approach will not be treated in this white paper.

## 2.2 The Aim and Purpose of this White Paper

There are SPS-related issues that are highly controversial. Although several space agencies have pursued SPS studies and research (see the next section), very critical papers have been published that concluded that an SPS is impractical and will never go into operation (e.g., [2]). A more pro-SPS reply to this criticism [3] was based on the economic issues raised in [2]. Among the controversial issues is the question of the space engineering and technology that are necessary for the launch, and the assembly and the maintenance of an SPS system, all of which to a great extent are not yet possible. Other heavily debated issues are related to economic justifications (in comparison with other power sources), are related to the question of whether an SPS can provide a base-load "clean" power system on a global scale, are related to military applications, and are related to public acceptance. All of these issues are beyond URSI's scientific domain and will therefore not be discussed in this white paper. Social issues of an SPS may perhaps be addressed by the International Council for Science (ICSU).

Instead, this white paper will focus on the radio-science aspects of an SPS. Among the key radio-science technologies involved in the SPS concept are microwave generation and transmission techniques, antennas and beam control, and the very challenging task of protecting other services to the levels required by the International Telecommunication Union (ITU). Of the various scientific organisations or unions concerned with international development and applications of these technology areas, URSI has an important role to play, because it covers most aspects of the above-mentioned radio techniques. The scientific competence of URSI's ten Commissions (see Appendix 2) encompasses aspects of microwave power generation (Commissions B, C, and D), antennas (Commission B), calibration (Commission A) and transmission (Commissions G and H), the effects of electromagnetic emissions on humans (Commission K), the potential interference with communications (Commission C and E), remote-sensing (Commissions E and F) and radio-astronomy (Commission J) observations, and, to some extent, solar-cell technology (Commission D). Thus, URSI can provide a continuing forum for development, discussion, and debate on technical issues related to SPS systems.

In keeping with what has been said above, it is not the intention of this document to advocate an SPS as a "clean" solution to the world's increasing power demand (as is argued, for instance, in [1]). However, it is conceivable that an SPS, and, more generally, microwave power transmission, may be used in the future for special purposes. Among such possible scenarios are bringing energy to remote areas on the globe that are difficult to otherwise access, sending energy from spacecraft to spacecraft, or providing energy to the dark side of the moon (in compliance with Recommendation ITU-R RA.479, recognising a shielded zone on the moon). Possible spin-offs from SPS-related research have been considered elsewhere [1, Section 3.6].

A number of the issues related to radio science that are addressed here are also of relevance to the process that the International Telecommunication Union (ITU) has initiated towards an ITU-R Recommendation and/or Report on wireless power transmissions, to be completed by 2010 at the latest [4].

It should be stressed that an SPS is not imminent. Many changes in technology can be expected before an SPS is launched. Major technological problems still have to be solved, even before a demonstration project could be realised. On the other hand, the radio-science aspects of an SPS encompass many interesting scientific, engineering, and technological challenges. To identify, to describe, and to discuss these items is the main aim of this white paper.

## 2.3 The History of SPS Research

The first concept of an SPS system was proposed by P. Glaser in 1968 [5], after a series of experiments on microwave power transmission [6a, 6b]. Following this article, the United States conducted an extensive feasibility study in 1978-1980. The feasibility study was a joint effort of NASA (National Aeronautics and Space Administration) and the Department of Energy. A reference model was proposed in 1979, known as the NASA/DoE reference model (Figure 1, [7]). Research on an SPS was suspended in the US in 1980, due to high estimated costs. Given a pre-set policy to re-evaluate the SPS concept after an appropriate time interval, the Fresh-Look-SPS concepts were published in 1977 as an improved SPS reference system. This included the "Sun Tower" SPS concept (Figure 1, [8]). This is a constellation of medium-scale, gravity-gradient-stabilised, microwave-transmitting space solar power systems. Each satellite resembles a large Earth-pointing sunflower, in which the face of the flower is the transmitting array, and the "leaves" on the stalk are solar collectors. The Sun Tower is assumed to transmit at 5.8 GHz from either a low Earth orbit or a geostationary orbit, and to operate sun-synchronously at a transmitted microwave power level of about 200 MW. NASA stated that due to its extensive modularity, the low-Earth-orbit concept entails the use of relatively small individual system components, which could be developed at a moderate price, ground-tested in existing facilities, and could be demonstrated in a flight environment during a sub-scale test.

An SPS system using mirrors for sunlight concentration on the solar cells, the Integrated Symmetrical Concentrator, was also proposed. It uses 24 or 36 plane mirrors of 500 m diameter for a concentration factor of two or four (Figure 1, [9]).

The European Space Agency (ESA) proposed a Sail Tower SPS (Figure 1, [10]), the design of which is similar to that of NASA's Sun Tower SPS. However, the Sail Tower SPS uses thin-film technology, and an innovative deployment mechanism developed for 150 m × 150 m solar sails. The power generated in the sail modules is transmitted through the central tether to the antenna, where microwaves at 2.45 GHz are generated in mass-produced inexpensive magnetrons. The energy emitted would be 400 MW. In 2003, the Advanced Concepts Team (ACT) of ESA initiated a three-phased, multiyear program related to solar power from space (including laser power-transmission concepts) [11]. In addition, a European Network on Solar Power from Space was established. It provides a forum for all relevant and interested European players in the field of SPS, including industry, academia, and institutions.

Japanese scientists and engineers started their SPS research in the early 1980s. They conducted a series of microwave power-transmission experiments, such as the world's first rocket experiment with powerful microwave transmission in the ionosphere [12, 13], experiments on the ground [14], computer simulations [15], theoretical investigations [16], and system studies for a demonstration experiment [17]. After a conceptual study phase, two Japanese organisations have recently proposed their own models. JAXA (Japan Aerospace Exploration Agency)

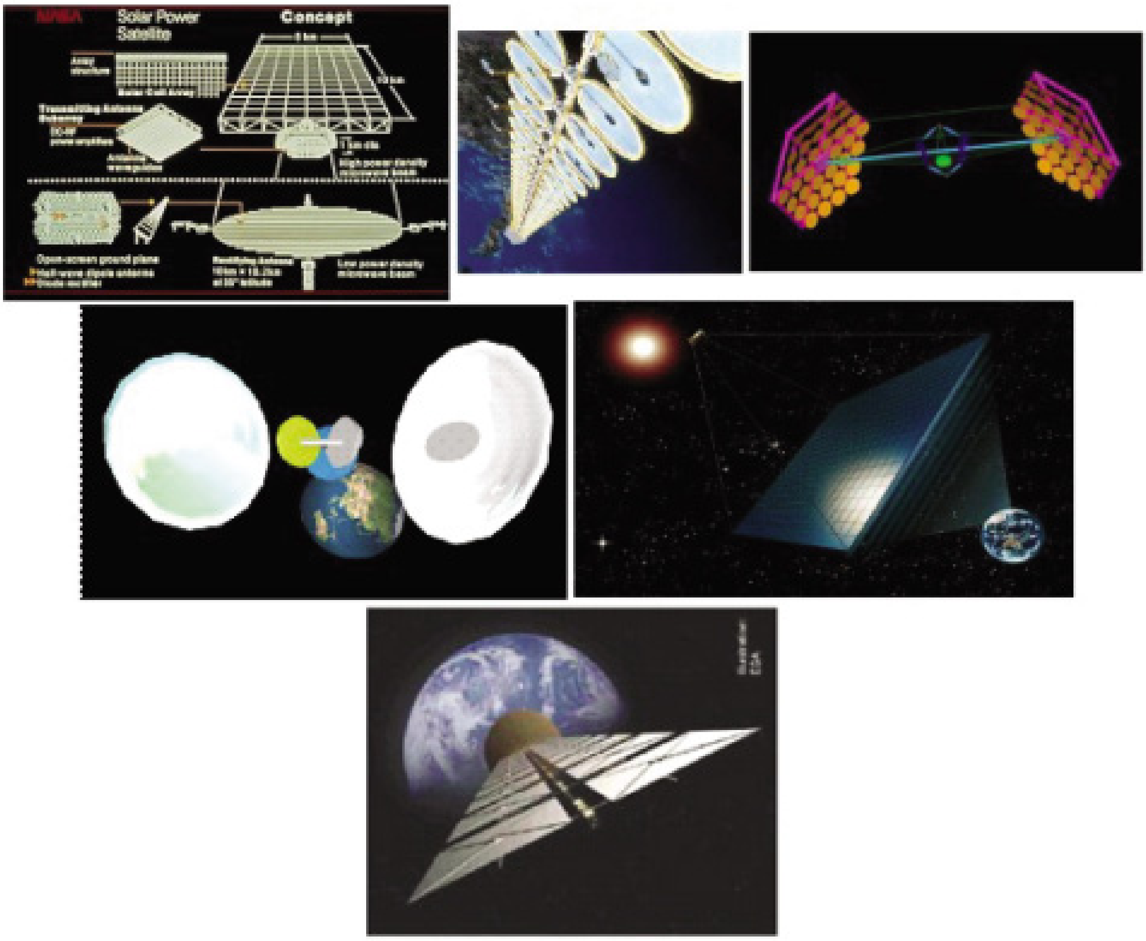

*Figure 1. An artist's impressions of various current SPS models: NASA/DoE SPS Reference Model (top left), Sun Tower (NASA, top centre) [8], Integrated Symmetrical Concentrator (top right) [9], JAXA 2003 Free Flyer Model (middle left) [18], Tethered-SPS (USEF, middle right) [19], and Sail Tower (ESA, bottom) [10].*

proposed an SPS 5.8 GHz/1 GW model (Figure 1, [18]), which is different from the NASA/DoE model. It is based on a formation flight of a rotating mirror system and an integrated panel, composed of a photovoltaic-cell surface on one side and a phased microwave-array antenna on the other side. Formation-flying mirrors are used to eliminate the need for rotary joints. The Institute for Unmanned Space Experiment Free Flyer (USEF) proposed a simpler model (Figure 1, [19]). The USEF model is a tethered SPS, which is composed of an integrated panel similar to JAXA's, but suspended by multi-tether wires emanating from a bus system above the panel.

The leading group in Japan in basic SPS-related research is based at Kyoto University. Many projects on microwave power transmissions have been conducted, and several important papers have been published (e.g., [12-16]). To a large extent, this white paper is based on an extensive review of SPS issues prepared by an URSI Inter-Commission Working Group [1] under the leadership of the Kyoto group.

International collaboration was established at a Japan-US SPS workshop [20], an International Conference on SPS and Microwave Power Transmission [21], by the International Astronautical Congress (IAC) Space Power Committee, and by an URSI Inter-Commission Working Group.

More details about the different proposed models are available in [1].

## 2.4 A Coherent Set of Numerical Values

A set of typical numerical values was extracted from the various concepts of SPS mentioned in the previous section. This set forms the basis of the discussion in this white paper.

Assuming that an SPS unit will generate 1 GW effective power on the ground, the characteristic efficiencies are summarised in Table 1. The figures are given for a 2.45-GHz unit; corresponding values for a 5.8-GHz unit are not fundamentally different. Therefore, in order to generate 1 GW at the ground, one needs to collect about 14 GW in space. Since the solar radiation power flux is equal to

| Quantity | Efficiency | Reference |
|---|---|---|
| Solar-power-to-dc-power efficiency | 13% | [1, Section 2.4.1.2] |
| dc-power-to-RF-power efficiency | 78% | [1, Section 2.4.1.2] |
| RF collection efficiency | 87% | [1, Section 2.4.1.2] |
| RF-power-to-dc-power (rectenna) | 80% | [1, Section 2.3.6,1]<br>(average of 70% and 90%). |
| **Total efficiency** | 7% | |

*Table 1. The efficiencies for SPS processes (for 2.45 GHz).*

1.37 kW/m$^2$, one needs a solar-panel area of approximately 10 km$^2$. The transmitted RF power is $14 \times 0.13 \times 0.78 \approx 1.44$ GW. Taking into account the RF collection efficiency of 87%, the RF power received at the ground level is $P = 1.25$ GW. The efficiency of the microwave power transmission (dc-microwave-dc) is the product of the efficiencies given in lines 2-4 of Table 1, i.e. 54%. (Actually, 54.18% was demonstrated and certified in a NASA laboratory test [22]).

In order to define the rectenna characteristics, a reasonable value for the power flux at the centre of the rectenna system has to be assumed. Different values have been proposed, between 230 W/m$^2$ and 1000 W/m$^2$ [1, Table 2.3.2]. Here, a conservative value of 300 W/m2 (which is less dangerous from a biological point of view: see [1, Section 4.3]) is adopted for the central power flux. Assuming a Gaussian distribution of the power at the ground, and assuming further that the power flux at the edge of the rectenna is equal to 10 W/m$^2$ (for safety reasons, which are discussed in [1, Section 4.3]), after a simple calculation one arrives at a radius of the rectenna of $r_r \approx 2$ km. If $L$ is the altitude of the geostationary orbit ($L = 36000$ km) and if $r_t$ is the radius of the transmitting antenna, one has that approximately $r_r / L = \lambda / (2r_t)$, where $\lambda$ is the RF wavelength ($\lambda = 0.12$ m at 2.45 GHz). Therefore, $r_t = 1080$ m (a more accurate estimate would arrive at 1200 m: see [1, Section 3.1.1]). The assumed sizes are summarised in Table 2.

The last number to be introduced is the desired pointing accuracy of the transmitting antenna. In most projects, one assumes that the allowed displacement of the centre of the beam is a small fraction of the diameter of the rectenna system. In [1, Section 2.1.1], the adopted value of this displacement was 300 m, so that the required pointing accuracy for a geostationary power station is 0.0005°. It should be noted that the above estimate for the rectenna size does not take into account any safety margin due to the pointing accuracy of 300 m.

## 2.5 Economic Issues

As already stated in Section 2.2, economic-related issues are outside of URSI's scientific domain. Some important aspects are therefore touched on only briefly in this section, with some figures quoted from the available literature.

There are four main factors that determine the power-production costs of an SPS system: photovoltaic module efficiency and costs, mass-specific power production (W/kg) of the solar modules and the transmission system, microwave power-transmission efficiency, and launch costs. The target is an efficiency of about 50% for the total microwave power transmission dc-microwave-dc conversion (see Section 3.1), and a specific power output of 1 kW/kg for the whole microwave power-transmission system. The published SPS cost estimates are based on a launch cost of USD150/kg [1, Section 2.1.4]. All these assumptions lead to an estimated energy-generation cost of approximately USD0.1-0.2 per kWh for an SPS system[23]. These estimates remain controversial. For example, present-day launch and space-assembly costs are greater than two orders of magnitude higher than the desired USD150/kg (present-day launch costs are USD10,000/kg [24]). While NASA expects the launch costs to decrease by a factor of 100 by 2025 and by a factor of 1000 by 2040 [25], ESA is less optimistic. In a corresponding ESA report, the energy-generation costs for a 500 GW SPS system were estimated to be USD0.40/kWh, assuming transportation costs of USD1,500/kg, and a mass-specific power production of 0.2 kW/kg [26]. In the same report, it was stated that transportation costs may be reduced to USD200/kg in the future.

| Quantity | Size |
|---|---|
| Solar-cell array | 10 km$^2$ area |
| Transmitting antenna on satellite | 2.4 km diameter (for 2.45 GHz) |
| Rectenna | 4 km diameter (independent of frequency in the above estimate) |

*Table 2. The size of the SPS components being considered.*

A direct comparison of the output power from a space-based solar power unit with that from a terrestrial photovoltaic array with equal area is not straightforward. On one hand, a simple estimate of the energy output yields an advantage of about a factor 2.5 for the SPS. For the SPS system,

> 1.37 kW/m$^2$ solar power flux in space × 0.07 overall SPS efficiency (Table 1) × 24 h = 2.3 kWh/m$^2$/day.

For a terrestrial solar-cell array,

> 5 kWh/m$^2$/day average solar power flux at a sunny place (Arizona [27]) × 0.17 solar cell efficiency = 0.85 kWh/m$^2$/day.

On the other hand, a detailed economic comparison of the costs turns out to be very complicated and dependent on many factors, such as launch costs (see above), SPS concept, power-consumption profile (base-load versus non-base-load power-supply systems), storage technology (for base-load power supply), terrestrial power-transmission system (depending on the location of the terrestrial power plant), energy payback times, and others. ESA conducted several corresponding studies (including also terrestrial solar thermal plants) (e.g., [28, 29]. One of these came to the conclusions that (i) for a base-load power supply, SPS systems above 5 GW and launch costs between USD824 and USD1023/kg would be required for an SPS to be competitive with terrestrial plants; (ii) for non-base-load power supplies, SPS systems above 50 GW and launch costs between USD206 and USD2146/kg would be required for an SPS to reach a competitive level with terrestrial plants [28]. More-detailed results of these comparisons are presented and discussed in [1, Section 2.4.3 and Appendices E.5-E.7].

## 2.6 Key SPS Technologies

The most important key technology concerns the infrastructure to launch, assemble, transport, and maintain the SPS system. Since this topic is beyond URSI's scientific domain, it will not be dealt with here.

The key elements in the dc power generation for the SPS system are the solar cells. Thin-membrane (amorphous) silicon solar cells are expected to be the most suitable type for the SPS system because of their good performance for a given weight, and because of conservation of natural resources, although their conversion efficiency is lower than the figures for Si cells (17.3% [7]) and GaAs cells (20% [7]). Mass-production feasibility is also an important aspect in choosing the most suitable solar-cell type. A sunlight concentrator would enhance the power output. Therefore, two types of power-generation systems have been studied: (a) a massive light-concentration type [9], and (b) a super-light-weight thin-membrane type [30]. An increase of the total power-conversion efficiency is to be greatly desired. However, it should be noted that solar cells in space deteriorate, due to accelerated solar-wind particles and solar radiation. Radiation-hardened cells are already available for long-term space missions, but at considerably higher costs than cells for terrestrial use.

The thermal design and control of the SPS system will also be of importance, particularly if sunlight concentration is applied. One method for thermal control of the generator is blockage of the infrared radiation from the sun, either by effective reflection or by band-elimination filters for infrared radiation.

The radio science and technology of an SPS system, such as the microwave power transmission, microwave power devices, rectennas, and beam control, will be discussed in detail in Section 3.

A very important detail of an SPS is the proper orbit in space. A geostationary orbit has been proposed for most of the systems envisioned so far. However, a more-remote orbit, an L2-halo orbit [31], was also considered. It is generally assumed that the SPS is assembled at a low Earth orbit, with subsequent transportation to a geostationary orbit. Modern SPS concepts rely on robotic assembly and maintenance systems, rather than human astronauts for the assembly task. For transportation, suitable orbit-transfer vehicles have to be developed to transport a very large structure from a lower to a higher orbit. Solar electric-propulsion orbital-transfer vehicles have been suggested for this purpose. Some corresponding prototype propulsion systems, such as a magneto-plasmadynamic thruster, a Hall thruster, and a microwave-discharge ion engine, have been tested ([1, Section 2.3.1.2).

It should also be noted that the selection of the final working orbit of an SPS may have important implications for the antenna design and its characteristics (far-field or Fresnel region).

Other key issues of SPS technology are lifetime and maintenance. The limited lifetime of solar cells has already been mentioned, but a long-term radiation hazard also exists for any solid-state device on the SPS, such as dc-to microwave converters, for instance. In addition, there is the problem of the long-term mechanical stability of the very large structures of the solar panels and the microwave transmitting antenna. The long-term influence of tidal effects and radiation pressure have to be examined. In principle, both effects can deform the structure as well as change its orientation. In particular, the radiation pressure exerts a force that changes continuously in direction with respect to the line joining the satellite and the rectenna. This may pose serious problems concerning the control of the orbit and the orientation of the RF beam. The amplitude of this force is of the order of 100 N for a solar-cell area of 10 km$^2$ (2 × solar radiation power flux × 10 km$^2$/velocity of light). Regarding maintenance, the present-day experiences for low Earth orbits with the Hubble space telescope and the International Space Station indicate that maintaining and servicing a much larger system in a much higher orbit may be very difficult and much more expensive than for low Earth orbits. A completely new approach to space maintenance may be required to maintain assets at geostationary orbit. Currently, progressive replacement is the only viable option.

## 3. SPS Radio Technologies

### 3.1 Microwave Power Transmission

Wireless communication uses radio waves as carriers of information. However, in the microwave power-transmission system, radio waves would be used as carriers of energy. In principle, the energy-carrying microwaves would be monochromatic waves, without any modulation. The microwave power transmission would use power densities at the surface of the transmitting antenna that are three or four orders of magnitude higher than the corresponding levels in wireless-communication systems, and up to 25 orders of magnitude higher than power densities received by the radio-astronomy and remote-sensing services.

The main parameters of the microwave power-transmission system for the SPS system are the frequency, the diameter of the transmitting antenna, the output power (beamed to the Earth), and the maximum power-flux density. In addition to the system parameters described above, the weight per unit power of the microwave devices is also of importance [1, Section 3.2].

Efficiency is very important for the microwave power-transmission system. Assuming the SPS transmitting-antenna-to-rectenna propagation path is optimum, the following efficiencies will be important: dc-to-radio-frequency (RF) conversion, RF-to-dc conversion, and beam-collecting efficiencies. Conversion efficiencies higher than 80% for both RF-dc and dc-RF conversions are necessary to make the cost of the SPS system reasonable (see Section 2.4).

Various types of transmitting antennas have been considered, such as slotted-waveguide antennas, dipole antennas with reflectors, and microstrip antennas. The most suitable antenna type depends on the chosen microwave generator and amplifier, but also on weight. A possible concept seems to be the active integrated antenna technique, combing the dc power generation, microwave conversion, and radiation and control in one multi-layered plate [32].

As mentioned in Section 2.4, the diameter of a transmitting antenna array of a 1 GW SPS system would be about 2 km. The average microwave power-flux density at the array of the SPS would then be about 300 W/m$^2$ on the surface of the transmitting antenna. A phased antenna array is planned for the SPS system, in order to obtain high-efficiency beam collection under the condition of fluctuating SPS attitudes. Depending on the frequency of the microwave power transmission, e.g. 2.45 GHz or 5.8 GHz, the number of antenna elements per square meter would need to be of the order of 100 or 400, where the power delivered by a singe element would be 10 W or 2.5 W, respectively [1, Section 3] . Thus, the total number of elements could be of the order of several hundreds of millions (this number could be substantially reduced if single klystrons of more than 1 kW output power were used to feed one antenna element). Such a large phased array has neither been developed nor constructed up until now, even on Earth. It is uncertain if simple scaling of already realised arrays is possible, or whether it may lead to unexpected problems.

Hence, realising the SPS system will require overcoming many engineering challenges, such as arrays with a dc-RF conversion efficiency higher than 80%, a phase-shifting system with very low root-mean-square errors for accurate beam control, phase synchronisation over millions of elements, and very-low-cost mass production of these elements.

### 3.2 Microwave Power Devices

Many possibilities have been proposed for the microwave generators, such as microwave vacuum tubes (klystrons, magnetrons, travelling-wave tube amplifiers), semiconductor transmitters, and combinations of both technologies. These types of generators have been compared with respect to their efficiency, output power, weight, and emitted harmonics [1, Section 2.3.4.2]. The dc-to-RF conversion efficiency for microwave vacuum tubes can be as high as 65% to 75%; the power of a single tube can be more than 100 kW. For semiconductor transmitters, the best achievable efficiency is 40%, the power from a single transmitter being below 100 W. Better efficiencies may be possible with new devices, such as wide-bandgap devices using GaN, which have significant power output, in particular at microwave frequencies of 2.45 GHz and 5.8 GHz [1, Section 2.3.4.2 (4)].

Compared to semiconductor technologies, a microwave tube has higher efficiency, lower cost, and a smaller power-to-weight ratio (kW/kg), even if one includes the power source, the dc-dc converter, the cooling system, and all the other elements needed to drive the system. Some of the SPS concepts are based on a microwave power transmitter with microwave tubes, such as klystrons and magnetrons. For example, a new concept for a microwave transmitter has been developed. It is called a phase-controlled magnetron, and it satisfies both the requirements of high efficiency and beam controllability [33]. A hybrid tube-semiconductor system is also a possible solution currently under investigation [34].

For the high-efficiency power transmitters, a design that generates a low amount of harmonics, and low-loss phase shifters, are particularly important and would need to be developed. Manufacturability would be one of the important considerations in the implementation of particular technologies for the microwave power-transmission system. Since the SPS requires huge investments, even in electronic parts, the availability of particular materials and the manufacturability need to be examined. From a manufacturing point of view, recent semiconductor technologies could be useful for SPS systems. However, their reliability in space would need to be investigated. For the microwave power-transmission technology, the reduction of the weight per unit of generated power would also be of importance to ensure a reasonable cost for a given performance.

In any case, thousands of microwave tubes or millions of solid-state amplifiers and oscillators have to be phased and controlled, which is a large technical challenge.

## 3.3 Rectennas

The rectenna (located on the Earth) receives the microwave power from the SPS and converts it to dc electricity (e.g., [35]). The rectenna is composed of an RF antenna, a low-pass filter, and a rectifier. It is a purely passive system (apart from a low-power pilot beam: see Section 3.4) and needs no extra power. A low-pass filter is necessary to suppress the microwave radiation that is generated by nonlinearities in the rectifier. Most rectifiers use Schottky diodes. Various rectenna schemes have been proposed, and the maximum conversion efficiencies anticipated so far are 91.4% at 2.45 GHz [36] and 82% at 5.8 GHz [37]. However, the actual rectenna efficiency will also depend on various other factors, such as the microwave input power intensity and the load impedance.

The single elements of the rectenna can be of many types, such as dipoles, Yagi antennas, microstrip antennas, or even parabolic dishes.

The rectenna array, with a typical radius of approximately 2 km, is an important element of the radio technology for which high efficiency is essential. The efficiency depends on the input power, and the input-power flux density is not constant over the entire rectenna site for the SPS system. Further research will be required into rectennas that maintain high efficiency under various input-power conditions. Recently, development has started on a low-power (only 100 μW or less), high-efficiency rectenna system for the perimeter of the rectenna site [38]. Studies and experiments have also been performed for a hybrid technique [39].

## 3.4 Control and Calibration

Another important issue concerning the space-based microwave antenna is the necessarily high precision of the control of the beam direction. This is important for two reasons: to maximise the energy transferred to the Earth; and to limit radiation in undesired directions, in order to avoid adverse effects on existing telecommunications, passive radio-detection systems, and biological systems. This goal may be achieved with the concept of a retrodirective array, in which the rectenna sends a pilot signal to the SPS in order to indicate its position before the power beam is transmitted. This pilot beam is then used to direct the power beam back along exactly the same path as the pilot beam: in the retrodirective direction. The effect of this is to automatically remove perturbations to the direction of the propagating beam, assuming that the perturbing factors along the propagation path do not change during the round-trip transit time. For this to work, retrodirective beam-forming techniques have to be developed in order to suppress sidelobes and to maximise the transmission efficiency. In addition, control measures have to take the delay of commands into account, which is a considerable fraction of a second for an SPS in geostationary orbit.

Emergency procedures should be defined and have to be applied when the beam direction is not contained within the predefined angle of 0.0005°. Ordering an interruption of the RF transmission may be a possible solution, but the detrimental effects that could be caused by a sudden interruption of the dc-to-RF conversion onboard the satellite have to be evaluated, not forgetting that the load to the grid will also need to be managed carefully.

The centre of the microwave beam should be confined to a region within 0.0005° of the centre of the rectenna. This corresponds to less than one-fourth of the 8-arc-seconds half-power beamwidth of a 1000-m-diameter parabolic SPS antenna. Achieving such pointing accuracy and stability would currently pose a major technical challenge. The required beam-control accuracy of the SPS microwave power-transmission system may be achieved using a very large number of power-transmitting antenna elements, and by limiting the total phase errors over the antenna array to a few degrees. Technologies to achieve these goals are presently under study [18]. Beam-collection efficiency is as important as the beam-control accuracy, and the efficiency depends on the power lost in sidelobes and grating lobes.

Measurement and calibration are important issues for the SPS and microwave power-transmission systems, because the SPS's microwave power-transmission system requires accurate beam control with a large phased array. The testing of large SPS antennas presents not only the usual difficulty of making accurate RF measurements over a substantial aperture, but also the unusual problems of devising tests that can accurately predict the performance of the antenna under the harsh mechanical, thermal, and radiation conditions in the space environment. New methods of measurement and calibration would therefore need to be developed. Microwave measurements and calibration would be necessary for the evaluation of power, interference, and spurious emissions from the SPS and rectennas.

The proposed antennas – both the transmitting antenna and the rectenna – are expected to be so large that testing them in their entirety will pose significant challenges. Computer simulations can give accurate predictions of the performance of the antennas in terms of gain, beamwidth, and near sidelobes. However, the transmitting antenna can only be accurately tested once in orbit, and to achieve this, special antenna-measurement and calibration techniques will need to be developed.

# 4. Radio Science Influences and Effects of SPS

## 4.1 Interaction with the Ionosphere and Atmosphere

To a first approximation, it is generally considered that the interaction of the SPS system with the medium – space, ionosphere, and atmosphere – will be negligible. However, as noted in Section 2.6, SPS subsystems may be affected by accelerated solar-wind particles and solar radiation. Space is a harsh environment, with large temperature gradients and ionising radiation (geostationary satellites are in the solar-wind regime during large geomagnetic storms). On the other hand, currents created by SPS may locally affect the medium [40].

Power loss due to normal atmospheric absorption over the distance from a geostationary orbit to the ground is assumed to be below 2%. In abnormal circumstances, significant departures might be expected when, for instance, the beam encounters scintillations in the ionosphere and rain cells in the troposphere, as explained in the following.

Very few groups have worked on the effects of powerful microwaves on the atmosphere and ionosphere, and the few studies presently available refer to potential effects via the heating of ionospheric electrons or via ionisation of the air. The expertise is limited, but it exists. However, at a time where new observations (transient luminous events, terrestrial gamma-ray flashes) raise new questions about energy coupling between the atmosphere and the space environment [41], studies are needed on all phenomena that may influence the atmospheric electrical conductivity and chemical composition.

In the process of SPS construction, large high-power electric propulsion systems would be needed to move the structures from a low Earth orbit to the geostationary orbit. These would inject heavy ions perpendicular to the Earth's magnetic field (around the equator). The injection could strongly disturb the electromagnetic environment surrounding the ion engine in the ionosphere and the magnetosphere, through interaction between the heavy-ion beam and the ambient plasmas. Some of these effects are discussed in [1, Section 4.1.3].

A thorough and systematic theoretical analysis of possible ionospheric effects was published under an ESA contract [42]. This analysis indicated several possible relevant effects, but simultaneously stated that "the natural variability of the ionosphere, as well as the fundamental unpredictability of nonlinear effects certainly limit the accuracy with which the performance of SPS systems and their environmental impact can be estimated."

In principle, radio waves passing through the ionosphere are absorbed due to ohmic heating, i.e., wave energy heats the electrons. This effect is strongest in the ionospheric D and E layers, but the effect is assumed to be small for radio-wave frequencies above 1 GHz, since the heating efficiency varies as the inverse square of the frequency. No ground-based measurements of electron heating by high-power microwaves are available in the GHz range; only theoretical estimates exist for a frequency of 3 GHz [43]. These estimates indicate that an electron-temperature increase from 200 K to 1000 K in the E layer might occur for a power-flux density of 500 W/m$^2$. Test microwave injections from a sounding rocket have been carried out in Japan [12]. Although ohmic-heating effects were not observed, plasma waves were excited by the injected microwaves. This was in agreement with several theoretical predictions that high-power microwaves may produce plasma instabilities in the ionosphere (e.g., [42]). Several types of such instabilities produce secondary electromagnetic waves, which could be a source of interference to other radio services. The instabilities might also result in additional electron heating and density irregularities, which could have an effect on other radio waves propagating through the region. It is uncertain if the SPS microwave power-flux density would be high enough to cause such effects, or whether these effects could affect the SPS microwave transmissions.

Another problem may be defocusing of the microwave power beam, due to naturally occurring electron-density irregularities causing rapid signal-strength fluctuations (scintillations). This could have severe implications for the beam control described in Section 3.4, but, again, it is not known if this effect is important for the envisioned frequency of the SPS microwave beam. Theoretical considerations show that a 2.45-GHz SPS system would be more strongly affected than a 5.8-GHz system [42]. The effects of defocusing and scintillation on natural irregularities will be there for all power densities. What is uncertain is whether the high SPS power densities would enhance the effect through nonlinear interactions and feedback.

Some effects of powerful microwaves on the stratosphere have been studied both theoretically and experimentally [44]. These investigations have been carried out for a quite different purpose, namely to study the effects of ozone-destroying pollutants in the troposphere, and to create an artificial ozone layer in the stratosphere by high-power electromagnetic waves. The field strength necessary for this is much higher than the values that would be used by an SPS. Therefore, such effects on the atmosphere are not expected.

In the troposphere, refraction and scintillation effects on the beam (or even those induced by the high-power beam itself) need to be considered. Also, absorption and diffraction by atmospheric gases, aerosols, (water/ice) clouds, and precipitation must be studied. For instance, Recommendation ITU-R P.619 states the following about interference from an SPS: "Using available data on likely harmonic content, it can be shown that – even at the 4th harmonic – the interfering signal at a distance of 50 km from the rain cell can be comparable with the level of the received signal in the fixed satellite service. At the fundamental frequency, however, direct radiation from the side lobes of the SPS to the terrestrial station will probably exceed the signal due to precipitation scatter." In addition, two other effects have to be taken into account: beam attenuation and beam diffusion due to rain. As an example, for a cloud temperature of 0° C and a path length under rain of 4 km, the absorption at 5.8 GHz is 0.16 dB, 1.2 dB, and 2.8 dB for precipitation rates of 10 mm/h, 50 mm/h, and 100 mm/h, respectively [45]. Although rain rates of 100 mm/h are rare [1], it has to be stated that the last figure corresponds to a power loss of almost 50%. The beam diffusion at a $-30$ dBW level can be as large as 4-6 km in diameter for precipitation rates of 50-100 mm/h [45].

## 4.2 Compatibility with Other Radio Services and Applications

It is assumed that typical SPS systems will use frequency bands around 2.45 GHz or 5.8 GHz. These bands are already allocated in the ITU-R Radio Regulations to a number of radio services (e.g. civilian and military wireless applications), and are also designated for ISM (industry, science, and medical) and applications such as microwave ovens and wireless LANs [46]. It is mandatory that unwanted emissions – such as carrier noise, harmonics, and spurious and out-of-band emissions of the microwave power-transmission beams – are suppressed sufficiently to avoid interference with other radio services and applications, in accordance with the ITU-R Radio Regulations [46]. This is a serious engineering challenge, given the huge disparity between SPS power levels and those of other radio services. Although the intended bandwidth of the SPS emissions is quite narrow – since an essentially monochromatic wave without modulation will be used – spurious and out-of-band emissions generated by microwave power-transmission beams could substantially degrade the performance of other services and applications, even if received only indirectly.

Of particular concern is interference with radio-astronomical observations, which have a protected band (4.9-5.0 GHz) near the envisioned SPS frequencies or their first harmonic. Radio astronomy has historically increased its sensitivity with time, and in the next decade, major initiatives already begun will enhance the sensitivity by 100 fold over existing instruments. All possible measures need to be taken to protect the corresponding observations, since if they cannot be protected, it would not be possible for an SPS to operate legally under the present ITU regulations. Most experts will agree that even a partially operational SPS will constitute a difficult and unwelcome challenge to radio astronomy, and that the coexistence of radio-astronomical observations with an SPS could be extremely difficult. The same applies for measurements by the Earth-exploration satellite services (e.g., a sub-harmonic of 2.45 GHz is close to 1.4 GHz, used for passive sensing of soil moisture and ocean salinity). In 1997, the ITU initiated work towards an ITU-R Recommendation on wireless power transmission [4], which may be relevant to the interference an SPS could cause to other services.

The possibility of spurious emissions related to tube (e.g. magnetron) failure is a serious concern for radio astronomy and many other services. For example, with 10,000 magnetrons of 100 kW output for the microwave transmission, and assuming a mean time to failure of, say, 30 years for these tubes, it is possible that the average failure rate could be one per day at some point in the life cycle.

Furthermore, the passive thermal radiation of the solar cells of a large number of SPS units is expected to make a substantial zone of the sky, centred on the geostationary orbit, unusable for astronomical observations at essentially all frequencies [47]. This would occur even when the microwave transmission of the SPS towards the Earth was not operational.

In addition to this thermal radiation, the huge solar-cell array would act as a broadband antenna for all radio noise created within the SPS (from switching, out-of-band contributions, etc.). Therefore, such RF noise has to be minimised so as not to degrade operations of radio services and applications.

The apparent angular size of a solar-cell array of 10 km$^2$ is close to 1 arc minute (somewhat larger than the angular size of Jupiter), and scattering of unwanted radiation in the atmosphere would substantially extend the affected region. This means that even optical astronomy would be affected in an extended region of the sky, particularly if a large number of SPS units were operational. The substantial loss of observable sky resulting from these wideband emissions (optical, UV, infrared, and radio) needs to be carefully considered.

The requirements of spectral purity (a narrowband signal with very low spurious transmission) and the high efficiency of the transmitter will be opposing constraints. They could be difficult to reconcile, since high-efficiency, high-power transmitters have an inherent problem of non-linearity. This needs to be carefully assessed.

Astronomical Radio Quiet Zones (RQZs) are currently in the process of being implemented in isolated areas in, e.g., Australia, China, and South Africa. This is being done to ensure the regulatory protection of next-generation giant radio telescopes against detrimental manmade radio interference over wide frequency ranges, based on interference threshold levels recommended by the ITU. Currently, regulatory control over the RQZs applies only to ground-based transmissions. However, for the zones to be effective, it is important that they are not exposed to harmful levels of emissions from space. Even when an SPS is operating entirely within its permitted frequency range, with no out-of-band transmissions, the power transmitted within its sidelobes may still be harmful to the operation of broadband radio telescopes in RQZs (and elsewhere). An additional challenge will therefore be to devise solutions to prevent unwanted interference from the SPS into such facilities. These solutions may include aspects of antenna design, location of the SPS, and deployment of mitigation techniques at the radio-astronomy sites.

## 4.3 Microwave Power Transmission Effects on Human Health

A variety of environmental considerations and safety-related factors should continue to receive consideration because of public concerns about radiowave exposure [48]. Above the centre of the rectenna, the SPS power-flux density will be considerably higher than the currently permissible safety levels for human beings. The ICNIRP (International Commission on Non-Ionising Radiation Protection) and Japan both apply limits of 50 W/m2 and 10 W/m$^2$ for 2.45 GHz and 5.8 GHz, respectively [49]. The latter level is equal to the power-flux density at the perimeter of the rectenna site [1, Section 4.3]. The corresponding exposure limits for IEEE standards have recently been revised, and they are now closer to the ICNIRP limits (see [50] for details).

Since established safety limits for microwave exposure are exceeded in an area around and above the rectenna during normal operation of the SPS, access would need to be carefully controlled to ensure that environmental safety and health standards are maintained. Under normal operating conditions, the SPS microwave downlink will need to be monitored continuously to ensure that the tightly tuned phased-array techniques and beam control are functioning correctly. Should there be a loss of control, beam-defocusing techniques to disperse the power would need to be applied.

It should be noted that there are currently insufficient data on specific microwave power-transmission effects on human health, and that standards for this particular application are not sufficiently developed. Taking into consideration the importance of this field, more studies are urgently needed regarding human health and its bioeffects (see also more details in [1, Section 4.3]).

## 5. Radio-Science Issues for Further Studies

The list of issues below is most likely not complete. Depending on the outcome of the questions addressed, other issues may come up. Again, the list is limited to issues of URSI's scientific domain.

- Can the exposure level of the microwave density at the perimeter of the SPS receiving rectenna site be adequately controlled to avoid exceeding the safety level fixed by international standards?

- What is the impact of rectenna operation on (i) biological systems, such as human beings, birds, insects, and plants, etc.; (ii) airborne vehicles, such as airplanes; and (iii) other electric/electronic equipment and telecommunication networks?

- Can SPS operations be made safe by a precise control of the high-power beam using a pilot signal from the Earth, also taking into account the time delay of the signal?

- The influences of atmospheric refraction, beam defocusing, and of absorption and diffraction by atmospheric gases, aerosols, clouds, and precipitation have to be further examined. Are there other effects caused by the SPS power beam on the environment (magnetosphere, ionosphere, troposphere, etc.) that have not yet been explored?

- What is the impact of SPS electromagnetic emissions – both intended and unwanted (harmonics of the microwave frequency, unexpected and harmful radiation resulting from malfunctions) at microwave frequencies and other related frequencies – on telecommunications, remote sensing, navigation satellite systems, and radio-astronomical observations? What actions can be taken to suppress this unwanted emission? Constraints imposed by the Radio Regulations of the International Telecommunication Union must be taken into account.

- How will reflections of sunlight from the huge satellite structure affect optical-astronomical observations, and how will passive thermal emissions affect radio-astronomical observations?

- What potential is there for damage to the SPS system from space weather?

- What are the consequences of long-term exposure to solar-wind particles, and solar radiation of solar cells and other solid-state devices, for the reliability and costs of SPS systems, taking maintenance and possible replacement into account?

- Will an SPS lead to congestion at the geostationary orbit and to interference with communication satellites?

Even if it is beyond URSI's scientific domain, the economics of SPS systems have to be examined by competent organisations, since the cost advantage is a crucial issue for the feasibility of the whole SPS concept.

Only some parts of these questions can be addressed by laboratory work, simulations, or system analyses. Tests of the large structures (solar-cell arrays, transmitting antenna, mirrors) in space are mandatory. After successful testing, launching a pilot SPS unit as an operational demonstrator project – presumably with broad international consensus – may be a suitable way to assess the remaining questions. However, before being considered for launch, even for such a pilot unit, all concerns, such as the impact on communications, radio astronomy, Earth observations, and bio-hazards, must be fully addressed.

## 6. Acknowledgements

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## 8. Appendix 1: URSI White Papers

URSI (International Union of Radio Science) white papers are documents issued by URSI scientific experts on controversial subjects involving aspects of radio science. They may be proposed to the URSI Board of Officers by an URSI Member Committee, an URSI Commission, an URSI Standing Committee, an URSI Working Group, or in response to a request to URSI by another body.

Where the issuance of a white paper is determined to be necessary, the appropriate mechanism for preparing it is agreed to between the URSI Secretariat and the URSI Board of Officers. Once a draft URSI white paper has been prepared, the URSI Secretariat forwards this to the members of the Board of Officers and to the URSI Member Committees and Commissions for review. All comments received by the URSI Secretariat are then either incorporated directly into the white paper, if appropriate, or are forwarded to the author(s) for consideration. The URSI Secretariat acts as a liaison throughout this process. The final version of the URSI white paper is then sent to the members of the URSI Board of Officers for approval. Finally, the white paper is distributed to ICSU, appropriate scientific unions and bodies, and is published in the *Radio Science Bulletin*.

The white paper is the responsibility of URSI. However, it does not necessarily reflect all the views of individual URSI Member Committees nor Commissions.

## 9. Appendix 2: The Ten Scientific Commissions of URSI and their Terms of Reference

### 9.1 Commission A: Electromagnetic Metrology, Electromagnetic Measurements, and Standards

The Commission promotes research and development in the field of measurement standards, in calibration and measurement methodologies, and the intercomparison of such. Areas of emphasis are:

(a) the development and refinement of new measurement techniques;
(b) primary standards, including those based on quantum phenomena;
(c) realization and dissemination of time and frequency standards;
(d) characterization of the electromagnetic properties of materials;
(e) electromagnetic dosimetry.

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

## 9.2 Commission B: Fields and Waves, Electromagnetic Theory and Applications

The interest of Commission B is fields and waves, encompassing theory, analysis, computation, experiments, validation, and applications. Areas of emphasis are:

(a) Time-domain and frequency-domain phenomena;
(b) Scattering and diffraction;
(c) General propagation including waves in specialised media;
(d) Guided waves;
(e) Antennas and radiation;
(f) Inverse scattering and imaging.

The Commission fosters the creation, development, and refinement of analytical, numerical, and measurement techniques to understand these phenomena. It encourages innovation and seeks to apply interdisciplinary concepts and methods.

## 9.3 Commission C: Radio-Communication Systems and Signal Processing

The Commission promotes research and development in:

(a) Radio-communication and telecommunication systems;
(b) Spectrum and medium utilisation;
(c) Information theory, coding, modulation, and detection;
(d) Signal and image processing in the area of radio science.

The design of effective radio-communication systems must include scientific, engineering, and economic considerations. This Commission emphasises research into the scientific aspects, and provides enabling technologies to other areas of radio science.

## 9.4 Commission D: Electronics and Photonics

The Commission promotes research and reviews new developments in:

(a) Electronic devices, circuits, systems, and applications;
(b) Photonic devices, systems, and applications;
(c) Physics, materials, CAD, technology, and reliability of electronic and photonic devices down to nanoscale including quantum devices, with particular reference to radio science and telecommunications.

The Commission deals with devices for generation, detection, storage, and processing of electromagnetic signals together with their applications from the low frequencies to the optical domain.

## 9.5 Commission E: Electromagnetic Noise and Interference

The Commission promotes research and development in:

(a) Terrestrial and planetary noise of natural origin, seismic-associated electromagnetic fields;
(b) Man-made noise;
(c) The composite noise environment;
(d) The effects of noise on system performance;
(e) The lasting effects of natural and intentional emissions on equipment performance;
(f) The scientific basis of noise and interference control, electromagnetic compatibility;
(g) Spectrum management.

## 9.6 Commission F: Wave Propagation and Remote Sensing (Planetary Atmospheres, Surfaces, and Subsurfaces)

The Commission encourages:

(a) The study of all frequencies in a non-ionised environment:
    (i) wave propagation through planetary, neutral atmospheres, and surfaces
    (ii) wave interaction with the planetary surfaces (including land, ocean, and ice), and subsurfaces,
    (iii) characterisation of the environment as it affects wave phenomena;
(b) The application of the results of these studies, particularly in the areas of remote sensing and communications;

(c) The appropriate co-operation with other URSI Commissions and other relevant organisations.

## 9.7 Commission G: Ionospheric Radio and Propagation (Including Ionospheric Communications and Remote Sensing of Ionised Media)

The Commission deals with the study of the ionosphere in order to provide the broad understanding necessary to support space and ground-based radio systems. Specifically, the Commission addresses the following areas:

(a) Global morphology and modelling of the ionosphere;
(b) Ionospheric space-time variations;
(c) Development of tools and networks needed to measure ionospheric properties and trends;
(d) Theory and practice of radio propagation via the ionosphere;
(e) Application of ionospheric information to radio systems.

To achieve these objectives, the Commission co-operates with other URSI Commissions, corresponding bodies of the ICSU family (IUGG, IAU, COSPAR, SCOSTEP, etc.) and other organisations (ITU, IEEE, etc.).

## 9.8 Commission H: Waves in Plasmas (Including Space and Laboratory Plasmas)

The goals of the Commission are:

(a) To study waves in plasmas in the broadest sense, and in particular:
    (i) the generation (i.e. plasma instabilities) and propagation of waves in plasmas,
    (ii) the interaction between these waves, and wave-particle interactions,
    (iii) plasma turbulence and chaos,
    (iv) spacecraft-plasma interaction ;
(b) To encourage the application of these studies, particularly to solar/planetary plasma interactions, space weather, and the exploitation of space as a research laboratory.

## 9.9 Commission J: Radio Astronomy (Including Remote Sensing of Celestial Objects)

(a) The activities of the Commission are concerned with observation and interpretation of all radio emissions and reflections from celestial objects.
(b) Emphasis is placed on:
    (i) the promotion of technical means for making radio-astronomical observations and data analysis,
    (ii) support of activities to protect radio-astronomical observations from harmful interference.

## 9.10 Commission K: Electromagnetics in Biology and Medicine

The Commission is charged with promoting research and development in the following domains:

(a) Physical interaction of *electromagnetic fields** with biological systems;
(b) Biological effects of *electromagnetic fields*;
(c) Mechanisms underlying the effects of *electromagnetic fields*;
(d) Experimental *electromagnetic fields* exposure systems;
(e) Assessment of human exposure to *electromagnetic fields*;
(f) Medical applications of *electromagnetic fields*.

* (*frequency range from static to terahertz*)

More information about URSI can be obtained from its Web pages at http://www.ursi.org.

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[1] URSI (International Union of Radio Science) white papers are documents issued by URSI scientific experts on controversial subjects involving aspects of radio science. Although under the responsibility of URSI, they do not necessarily reflect all the views of individual URSI Member Committees nor Commissions (see Appendix 1).

# Space-Weather Impacts of the Sub-Auroral Polarization Stream

**A. Coster**
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## Abstract

During the strongest geomagnetic storms of the last solar cycle, severe space-weather effects were observed at mid-latitudes. These effects included large-scale enhancements of the total electron content (TEC), steep spatial and temporal gradients in the TEC, and the associated scintillation in phase and amplitude of radio-wave signals. All of these space-weather events can affect the performance of ground and space-based technological systems. An underlying cause of these space-weather disturbances is a phenomenon known as the sub-auroral polarization stream (SAPS), first defined by [1] and characterized by [2]. SAPS is a direct result of magnetosphere-ionosphere (M-I) coupling associated with the enhancement of the storm-time ring current at the inward extent of the plasmasheet. SAPS electric fields erode the outer plasmasphere, producing plasmaspheric plumes, detached plasmas, and large fluxes of cold plasma to the dayside magnetopause. These intense electric fields map between high and low altitudes along the magnetic field. These intense electric fields also drive plasma within the ionosphere, producing plumes of ionization, associated with steep gradients in the TEC, in the pre-midnight and afternoon sectors. This paper reviews the SAPS phenomenon, and describes its associated space-weather effects and their implications.

## 1. Sub-Auroral Polarization Stream

During geomagnetic disturbances, intense storm-time electric fields of magnetospheric origin are observed in regions of low ionospheric conductivity equatorward of auroral electron precipitation. These sub-auroral-disturbance electric fields were defined in a 2002 EOS article [1] as the sub-auroral polarization stream (SAPS). SAPS is an inclusive term for the regions of sunward plasma drift that are observed equatorward and separated from the evening auroral convection cell (e.g., [3]). SAPS is characterized by a strong sunward flow channel that covers a latitudinally-broad region (~3°-5°), and is observed during geomagnetically active times in the dusk-to-dawn sector, a few degrees below the auroral oval. The SAPS fields can extend from the auroral boundary to below 45° latitude, and can last several hours [1].

SAPS encompasses the subset of electric fields known as polarization jets (PJ) [4] or sub-auroral ion drifts (SAIDs) [5, 6]. Sub-auroral ion drifts are confined to latitudinally narrow regions (~1°) of rapid westward ion drift located in the evening sector, centered on the equatorward edge of the diffuse aurora [7]. The features of sub-auroral ion drifts have been detected for many years by satellite ion-drift and electric-field meters [8]. When the sub-auroral ion-drift/polarization-jet structure is observed, it is embedded within the larger SAPS region.

The characteristics of the SAPS channel (latitudinally broad, lasting several hours, spanning the nightside in longitude) differ from those of the polarization-jet/sub-auroral ion-drift feature (latitudinally narrow, lasting 30 minutes to three hours, located in the evening sector). SAPS provides a name and explanation for the larger-scale sunward flow channel that was recognized as a separate feature in earlier studies by [3] and [9]. The new name, SAPS, was needed to convey the characteristics of this larger, more-persistent feature. Once recognized for what it is – a signature of the interactions between the disturbed ring current and the ionosphere – the significance of SAPS for sub-auroral space weather became apparent. SAPS perturbs the ionosphere on an extended spatial-temporal scale, and not as a fleeting, localized intensification (sub-auroral ion drifts/polarization jets).

SAPS forms in the plasmasphere boundary layer (PBL) [10], as pressure gradients at the inner edge of the magnetospheric ring current drive Region-2 field-aligned currents into the evening-sector ionosphere. Large poleward-

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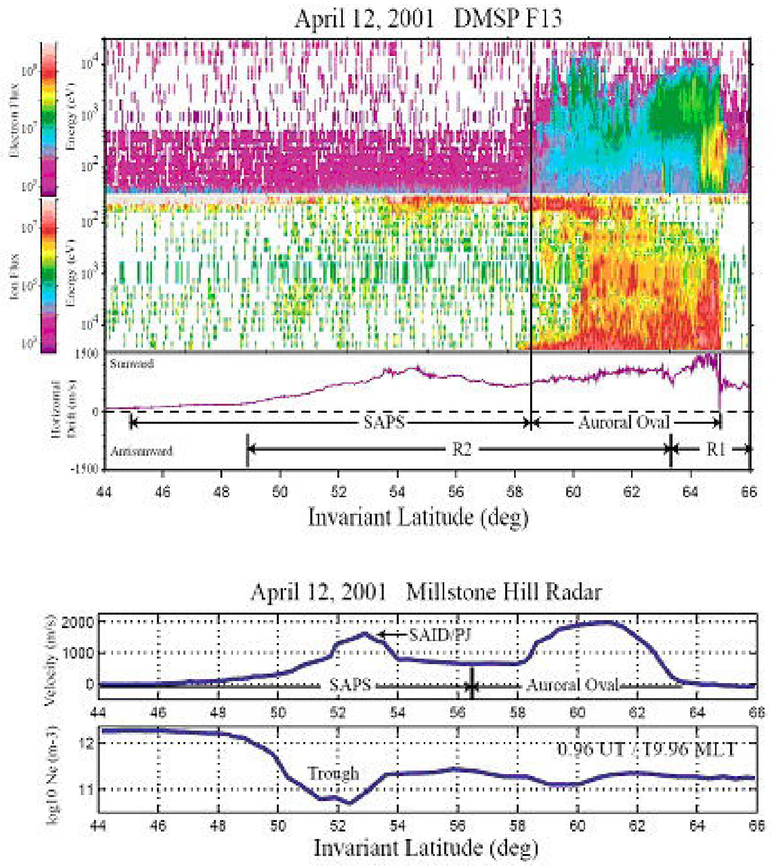

*Figure 1. An Illustration of the SAPS features measured by DMSP and the Millstone Hill Incoherent Scatter Radar( from [1]).*

directed electric fields at ionospheric heights are set up to drive closure currents across the low-conductivity region equatorward of the auroral electron precipitation. The inward extent of the SAPS overlaps and erodes the outer plasmasphere and mid-latitude ionosphere, drawing out the extended plumes of storm-enhanced density (SED) that span the dusk sector and transport plasmaspheric material to the noontime cusp.

Figure 1 illustrates the observed SAPS features as originally described [1]. The top three panels represent the electron flux, the ion flux, and the horizontal drift velocity collected by DMSP satellite F13 at approximately 800 km altitude as it passed near, but to the west, of the Millstone Hill radar, at approximately 1:00 UT (20 MLT) on April 12, 2001. The bottom two panels represent the westward component of the ion drift and the electron density, both at approximately 500 km altitude, observed by the Millstone Hill incoherent-scatter radar (ISR).

Two distinct regions of strong sunward convection can be observed in both the DMSP and the incoherent-scatter radar data. The first region is within the auroral oval, and can be identified by the corresponding high electron and ion flux measurements observed by DMSP. The second region, SAPS, is equatorward of the auroral boundary. The incoherent-scatter radar data clearly show that the second of these regions is approximately coincident with the ionospheric trough.

Incoherent-scatter radar azimuth scans, spanning both auroral and sub-auroral latitudes from two solar cycles (1979-2000), were used to determine the average characteristics of SAPS observed in the North American sector [2]. These observations confirmed the presence of SAPS as a latitudinally-broad and persistent region, which spans the nightside from dusk to the early morning sector for all Kp greater than four. Pre-midnight, the SAPS westward convection lies equatorward of $L = 4$ (60° invariant latitude), spans 3°-5° of latitude, and has an average peak amplitude of greater than 900 m/s. In the pre-dawn sector, the SAPS convection is a region of anti-sunward convection equatorward of $L = 3$ (approximately 55°), spans 3° of latitude, and has an average peak amplitude of 400 m/s.

Some of the recent advances in the modeling and theory of magnetosphere-ionosphere coupling have been aided by the incorporation of SAPS electric fields. Instruments on Cluster measured strong outward components of the electric field in the inner edge of the plasmasheet. This was postulated to result from SAPS [11]. It was shown that SAPS electric fields are needed to correctly model the location of the plasmapause near dusk [12]. The formation of SAPS in the ionosphere was modeled by the Rice Convection Model (RCM) [13], and a Kp-driven magnetospheric model of SAPS was developed [14].

Subsequent work has explored the complex relationship between the broad SAPS channel and sub-auroral ion drifts [15]. Observations of electromagnetic wave structure within fast sub-auroral convection streams were described [16], and small-scale irregularities in the SAPS region were recently observed by the SuperDARN HF radar at Wallops [17]. A model to predict the small-scale structure within the SAPS-driven density trough was developed [18]. Radar observations showed that the discrete features (sub-auroral ion drifts and other intensifications) in the sub-auroral convection electric field moved across the wider SAPS channel with wave-like characteristics [19]. A numerical study of these electric-field oscillations led to the interpretation of the oscillations as an ionospheric footprint of the surface Alfvén waves generated at the equatorial magnetosphere on a steep transverse gradient in the background plasma density associated with the plasmapause [20]. In agreement with [16] and [21], large-amplitude perturbation of the sub-auroral electric field and density oscillation can be associated with the development of the ionospheric feedback instability within the SAPS channel.

## 2. Storm-Enhanced Density

SAPS electric fields are the driving mechanism for a phenomenon known as storm-enhanced density (SED) [22, 23]. Storm-enhanced density can be described as a longitudinally narrow, high-total-electron-content (TEC) plume that is observed in the pre-midnight and afternoon sectors during geomagnetically disturbed conditions [24, 25]. Associated with storm-enhanced density are sharp temporal and spatial TEC gradients, which are the cause of multiple space-weather effects in the mid-latitudes. The space-weather effects associated with storm-enhanced density on radio communication are one of the main reasons that the radio-science community is concerned with SAPS and storm-enhanced density [26-28]. In this section, the relationships of the storm-enhanced-density phenomenon to other significant features in the ionosphere and plasmasphere are presented. In the following section, the space-weather effects of storm-enhanced density will be introduced and their implications for technological systems will be described.

During geomagnetically active time periods, the crests of the Appleton anomaly move further north and south than their normal location. Related to this are regions of enhanced TEC that form in the lower mid-latitudes [23]. In the American sector, where the majority of storm-enhanced density observations have been made to date, values of $\mathrm{TEC} > 200$ TECU have been observed during some $\mathrm{Kp} = 9$ storms [25]. The processes associated with this ionospheric redistribution on low- and mid-latitude field lines have been modeled [29].

The storm-enhanced-density plume is produced when some fraction of plasma from the enhanced TEC (the plasmaspheric bulge) region is stripped away and moved sunward under the $\mathbf{E}\times\mathbf{B}$ force generated by the Earth's magnetic field and the equatorward edge of the strong poleward SAPS field [30]. In general, the enhanced TEC region and the SAPS electric field are present when the storm-enhanced density is formed.

The ionosphere's response to geomagnetic storms has been studied for many years. Matsushita [31] described many facets of storm-enhanced density within the context of the positive phase response of the ionosphere to geomagnetic storms. In the 1970s, Evans [32, 33] postulated the presence of magnetospheric electric fields in the late-afternoon sector to account for the large (100%) increases in electron density frequently observed during storm-time conditions in the mid-latitudes. Mendillo and Klobuchar [34] mapped TEC storm-time effects as a function of latitude and local time with a chain of TEC observing stations. They observed that TEC storm effects grew in magnitude from high to low mid-latitudes. The first identification of a repeatable and spatially distributed storm-enhanced density feature was by Foster [22] in the early 1990s. Foster analyzed incoherent-scatter data from two solar cycles to study the two-dimensional extent of storm-enhanced density and to statistically determine its occurrence at the Millstone Hill location. That study found that although storm-enhanced density is most clearly observed during magnetically disturbed conditions ($\mathrm{Kp} \geq 4$), it can be identified at values of Kp as low as two, based on observations from the Millstone Hill incoherent-scatter-radar database. In 2001, GPS TEC maps were first used to image the storm-enhanced-density feature, providing a time history of the TEC perturbations in two dimensions [35]. Figure 2 illustrates an storm-enhanced-density plume that was observed over the US and Canada on November 20, 2003.

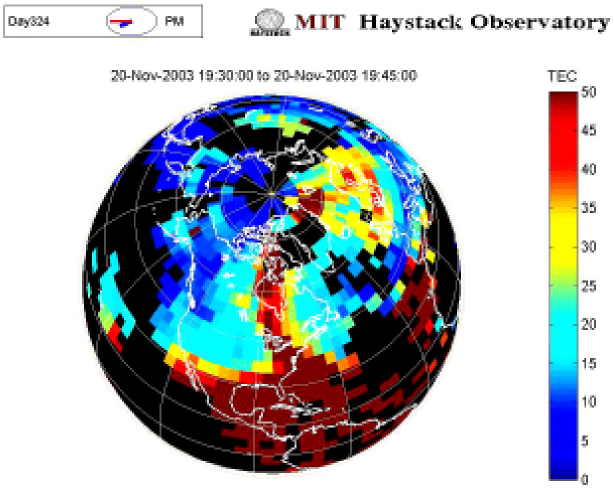

*Figure 2. An example of a GPS TEC map showing a storm-enhanced-density plume extending over the polar cap and into Europe on November 20, 2003, at 19:45 UT.*

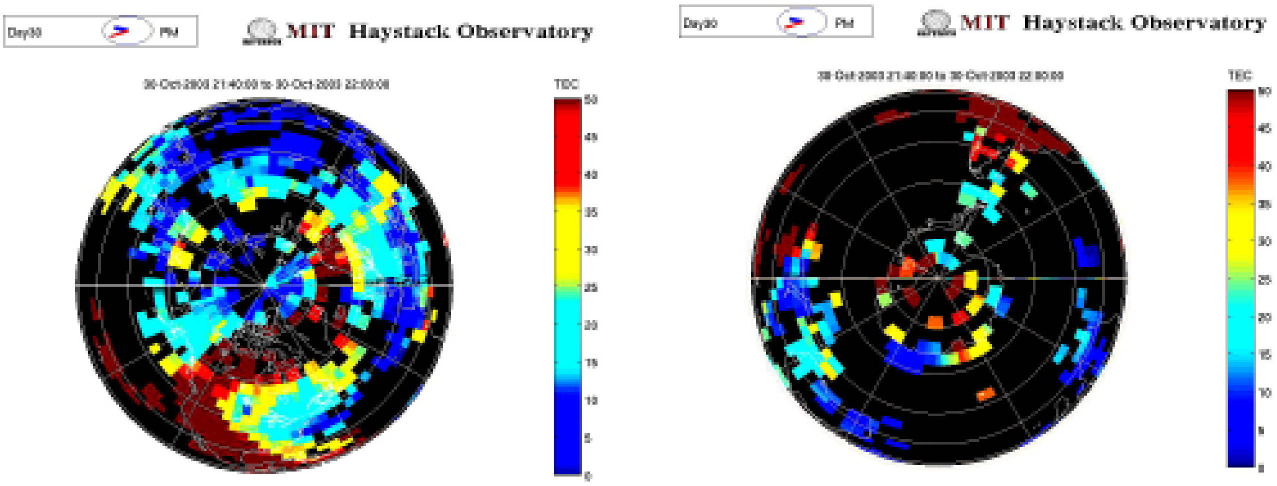

*Figure 3. Storm-enhanced density feeding a tongue of ionization over both the (a) north and (b) south polar regions. This 30 October 2003 storm-enhanced density was observed in both regions at 21:40 UT.*

## 3. New Observations of Magnetospheric-Ionospheric Coupling

The higher spatial- and temporal-resolution observations of storm-enhanced density provided by the GPS maps allowed for new insights into magnetosphere-ionosphere coupling. First, storm-enhanced density (SED) was shown to be the footprint of the plasmaspheric drainage plume observed by the EUV-sensor onboard NASA's Imager for Magnetopause-to-Aurora Global Exploration (IMAGE) Spacecraft [24, 36]. The plasmasphere drainage plume is associated with the storm-time erosion of the plasmasphere boundary layer [10]. The GPS TEC maps thus provided the first ground-based observation of an essentially magnetospheric phenomenon: the erosion of the outer plasmasphere by storm-time electric fields.

Additional studies identified that the predominately F-region plasma in the storm-enhanced density plume is associated with electric fields and velocities of 800 m/s [37]. This velocity translates into an approximate two-hour transit time from the source of the storm-enhanced-density plume at low latitudes to the polar cap at noon, and a plasma flux of approximately $10^{14}$ $m^{-2}s^{-1}$ to the dayside cusp ionosphere. For many of these storms, the F region is lifted to higher altitudes [38]. In fact, for the March 31, 2001, storm, it was reported that greater than 50% of the total TEC, as measured by GPS at the Millstone incoherent-scatter-radar location, was above 800 km, based on a comparison between the GPS and Millstone incoherent-scatter-radar measurement of TEC [25].

Storm-enhanced density appears to be one of the sources for the polar-cap tongue of ionization (TOI) [39]. The tongue of ionization is a continuous stream of dense,

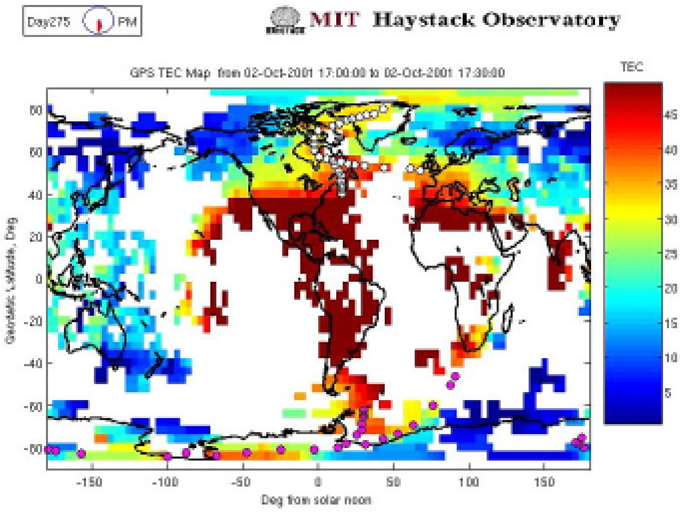

*Figure 4. The storm-enhanced-density feature observed on October 2, 2001, at 17:00 UT in both the northern and southern hemispheres. The conjugate nature of this phenomenon is illustrated with the geomagnetic conjugate points plotted as white circles in the northern hemisphere and magenta circles in the southern hemisphere.*

cold plasma, entrained in the global high-latitude convection pattern. Foster [39] used data from the Millstone Hill, Sondrestrom, and EISCAT radars, combined with GPS TEC data and SuperDARN convection patterns, to show how a storm-enhanced density plume transported plasma from the low latitudes into a polar tongue of ionization. The tongue of ionization as observed by GPS extends through the dayside cusp, across the polar cap to the nightside, in both hemispheres. This last point is illustrated in Figures 3a and 3b (and also to some extent in Figure 4), which show the tongue of ionization observed in both hemispheres. The north polar region has significantly more GPS coverage, allowing for better observation of the tongue of ionization. The high-latitude convection carries the plasma through the dayside cusp and across the polar cap to the nightside north polar region, where it provides a significant enhancement in TEC in the midnight auroral F region.

The storm-enhanced density feature is one of the most significant consequences of SAPS in the ionosphere. Storm-enhanced density is a common feature of geomagnetic storms, and although storm-enhanced density has been primarily observed in North America, observations of storm-enhanced density have been reported in Europe [40] and Japan [41]. There is a suggestion that TEC values associated with storm-enhanced density appear to be higher in the North-American longitude sector than elsewhere, perhaps related to the influence of the South Atlantic Anomaly [42]. In addition, the storm-enhanced-density feature appears to be magnetically conjugate, although there is considerably less data coverage in the southern hemisphere [25, 30]. The conjugate aspects of storm-enhanced density are illustrated in Figure 4, where two storm-enhanced density plumes are shown, one in North America and one in South America. The circles outlining the storm-enhanced density feature in South America shown in Figure 4 are magnetically conjugate to the circles used to outline the storm-enhanced density feature in North America. These storm-enhanced density plumes were observed to form simultaneously.

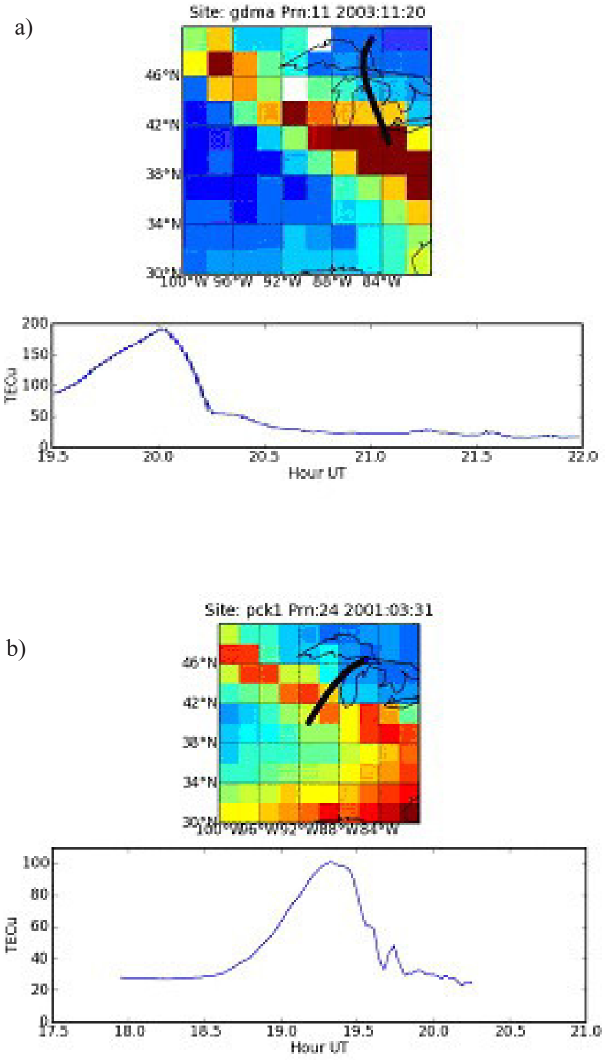

*Figure 5. An illustration of TEC gradients associated with a storm-enhanced-density plume. The top two plots (a) present data from the GDMA site in Grand Marais, MN, and are associated with the November 20, 2003 storm. The bottom two plots (b) present data from the PCK1 in Pickford, MI, and are associated with the March 31, 2001, storm. The top plots in (a) and (b) show the path of the GPS satellite overlying the TEC plume at the midpoint of the satellite pass. The bottom two plots in (a) and (b) show the estimated vertical TEC along the path of the satellite.*

## 4. Space-Weather Impacts

Until recently, the occurrence of space-weather effects and their impact at mid-latitudes had been largely overlooked, as the most common space-weather effects are seen in the high and low latitudes. However, as the uses of space-based technology increase, e.g., GPS, space-weather effects at mid-latitudes become significantly more important to understand and quantify. The GPS maps of TEC clearly illustrate that storm-enhanced density is a recurring phenomenon. The large electron densities, high ion fluxes, and steep temporal and spatial gradients in the TEC associated with storm-enhanced density are the source of some of the most severe space-weather effects in the mid-latitudes.

TEC gradients associated with storm-enhanced density are illustrated in Figures 5a and 5b. This figure presents two different examples of individual GPS satellite tracks crossing through a storm-enhanced density plume. Vertical TEC values, estimated from the line-of-sight TEC measurements along the satellite path, are plotted in the bottom two graphs. The top plot in Figure 5a shows the path of GPS satellite 11 on November 20, 2003. The bottom plot shows the vertical TEC estimates in TEC units ( $1\ \mathrm{TECU} = 10^{-16}\ \mathrm{el/m^2}$ ), which were acquired from the line-of-sight TEC measurements to this satellite from a GPS receiver located in Grand Marais, MN. The TEC started out at approximately 90 TEC units at 19.5 UT, reached a maximum of almost 200 TEC units at 20.0 UT, and then fell to a value less than 50 TECU at 20.3 UT. Data acquired from a different receiver, located in Pickford, MI, are shown in Figure 5b. These TEC measurements were collected on March 31, 2001, and represent vertical TEC measurements from GPS satellite PRN 24. The TEC measurements started out at 30 TECU at 18.5 UT, reached a maximum of 110 TEC at 19.25 UT, and decreased to 40 TECU by 19.75 UT. The TEC gradients associated with storm-enhanced density plumes are not always smooth, and at times can have distinct characteristics, depending on which side of the plume the TEC is measured.

Figures 5a and 5b convolve both the spatial and temporal aspects of the storm-enhanced density phenomenon. From a separate analysis, TEC gradients of 100 TECU per degree were observed during the November 20, 2003, storm. The gradients associated with the March 31, 2003, storm were less, on the order of 40 TECU per degree. To fully analyze the temporal gradients, the motion of the storm-enhanced density plume, in addition to the motion of the GPS satellite, must be considered. However, with respect to a GPS user on the ground, the 100-TECU-per-degree gradients mentioned above have been observed over 10-minute time intervals at some locations during some of the large geomagnetic storms.

TEC gradients associated with storm-enhanced density impact all areas of navigation: air, marine, and land. For instance, the very large 100-TECU-per-degree gradients were observed near many large cities in the northeast and northwest continental US [17]. During some of the recent large geomagnetic storms, storm-enhanced density gradients limited the availability of the Federal Aviation Administration's (FAA) Wide Area Augmentation System (WAAS) for commercial air travel. During October 2003 storms, the Wide Area Augmentation System Precision Approach (PA) service levels were degraded for 15 hours on October 29, 2003, and 11.3 hours on October 30, 2003. The Precision Approach service levels use vertical guidance from the Wide Area Augmentation System, which allows an aircraft to make the final decision to land on its approach to a runway at an altitude as low as 250 ft. (It is worth noting that during this time period, the non-Precision Approach

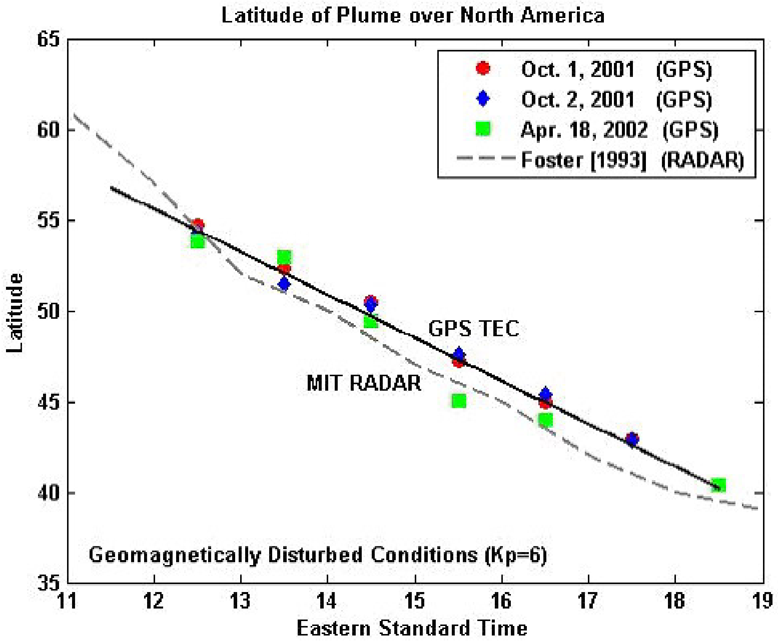

*Figure 6. A comparison of the latitude location of the base of the storm-enhanced-density plume for three SED events under magnetically disturbed conditions,* $\mathrm{Kp} = 6$*. The dashed and solid black lines indicate linear fits to the GPS TEC data. The storm-enhanced-density characterization results using ISR measurements under* $\mathrm{Kp} = 6$ *conditions [22] are plotted with a grey dashed line.*

service levels, which do not depend on GPS, remained unaffected.) It is predicted that the FAA's developing Local Area Augmentation System (LAAS) will also have issues with the short-scale density TEC gradients associated with storm-enhanced density.

Horizontal-positioning errors larger than 20 meters have been observed on differential GPS (DGPS) baselines as short as 150 km, associated with storm-enhanced density events [27]. Horizontal-positioning errors, rather than vertical-positioning errors, have the most consequence for marine navigation. For example, marine users have horizontal positioning requirements of 2-5 meters at a 95% confidence level for safety of navigation in inland waterways. Generally, differential GPS services are used to meet these accuracy requirements [43]. A positive correlation between the larger ionospheric gradients associated with storm-enhanced density and an increase in 95th-percentile differential GPS horizontal position errors has been measured [35].

In addition to the positioning errors associated with large gradients, studies have shown that the storm-enhanced-density phenomenon is one of the major sources of mid-latitude scintillation [44, 45]. The storm-enhanced density plume, the associated density gradients, and the SAPS electric fields provide the conditions necessary in the E and F regions of the ionosphere for the onset of different types of instabilities, and for the generation of a wide range of perturbations in the underlying plasma. A correlation between storm-enhanced density observations and scintillation activity in Canada was observed in a study [46]. In this study, phase-scintillation parameters were measured by specially equipped GPS receivers at different sites in Canada. Scintillations were clearly observed in Calgary and at other sites during time periods that corresponded to the presence of storm-enhanced density in Canada. The presence of L-band scintillations appeared to have an impact on tracking performance for the L-band Wide Area Augmentation System geostationary downlink [44]. In the US, observations [44, 45] have demonstrated that storm-enhanced density and the associated sub-auroral ion drifts can cause debilitating scintillation levels for GPS receivers.

In the future, it is predicted that users of navigation systems will increase their accuracy demands on GPS and differential GPS. Applications that are now being developed include in-vehicle navigation systems, railway control, highway traffic management, emergency response, and commercial aviation. storm-enhanced density and its associated TEC gradients will continue to present challenges to service providers in their quest to improve positioning accuracies with adequate reliability

## 5. Potential for Limited Prediction

In an ideal situation, space-weather predictions of storm-enhanced density and its associated gradients could be derived with several hours lead time to help various communities plan for the effects. This is an extremely challenging task, given our present understanding of geomagnetic storms and storm-enhanced density development. Another option is to monitor the ionospheric gradients in near real time by processing TEC data in real time and implementing a storm-enhanced-density detection algorithm [35]. Measured real-time gradients could be directly interpreted in terms of the possible impact on users. A limited prediction capability could be built by exploiting the general correlation between geomagnetic storms and storm-enhanced density events that has been observed to exist [22, 42]. Foster [22] observed a consistent correlation between the magnetic activity and the latitude location of the storm-enhanced density plume as a function of UT in the American sector. The results are plotted for the case of a Kp of 6 in Figure 6 with a grey dashed line. Colerico [42] reported on a longitude sector comparison for three storm days $(\mathrm{Kp}=6)$ using data from GPS TEC maps. The location of the base of the storm-enhanced density plume, which lies near the ionospheric projection of the plasmapause, was measured from the GPS TEC maps. The observed latitudes of the base of the storm-enhanced density plume are plotted as a function of time (UT) in Figure 6. The latitude locations and their rate of change exhibited consistent behavior and were in excellent agreement with the incoherent-scatter-radar data analysis of the storm-enhanced density base [22]. This level of agreement – between data taken using different measurement techniques and under varying solar cycle conditions – points to the potentially predictive nature of the latitude location of the storm-enhanced density plume base.

## 6. Conclusion

SAPS describes the poleward directed electric field that is present at sub-auroral latitudes during storm-time conditions in the nightside magnetosphere-ionosphere system. It is observed as a strong sunward flow channel that covers a latitudinally-broad and persistent region, spanning the nightside from dusk to the early morning sector for all $\mathrm{Kp}>4$ events [2]. SAPS is significant to radio scientists primarily for its role in the development of storm-enhanced density, a narrow, high-total-electron-content (TEC) plume that is observed in the mid-latitudes in the pre-midnight and afternoon sectors during geomagnetically disturbed conditions [22]. Associated with storm-enhanced density are sharp temporal and spatial TEC gradients that are the cause of severe space-weather effects in the mid-latitudes.

Although considerable knowledge about SAPS and storm-enhanced density has been gained in the last decade, a complete understanding of the complex interaction processes is lacking. For example, questions about the conjugate relationship of storm-enhanced density and SAPS, the longitudinal variation, and the influence of the background ionospheric plasma remain open areas of investigation. The lack of globally distributed measurements has further hindered these investigations. The GPS TEC maps are limited in coverage due to lack of receivers: for example, over the oceans and over large areas of the southern hemisphere. The 2006 launch of the COSMIC/FORMOSAT-3 constellation of six satellites, each equipped with a GPS occultation receiver, may help eliminate the lack of GPS coverage. At this time, measurements of the electric field, a major driving mechanism, are even more limited in the vicinity of the SAPS region. It would be highly desirable to know the electric field at multiple locations and heights in the SAPS region, and along the storm-enhanced-density plume at various stages of its evolution.

As our society becomes more technologically dependent, predicting space-weather effects – especially in the mid-latitudes, where the majority of the world's population resides – becomes increasingly more important for maintaining the required accuracy and integrity of radio-based systems. An understanding of SAPS, one of the main driving forces of mid-latitude space weather, is critical to help forecast and now-cast where and when potentially serious space-weather events may develop.

## 7. Acknowledgement

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# Electronic and Photonic Processing in Advanced Photonic Long-Haul Transmission

**Le Nguyen Binh**

## Abstract

The advancements in electronic integrated-circuit technology and photonics in the last decade have allowed the design and demonstration of ultra-high-bit-rate transmission over advanced optical-fiber transmission lines employing inline optical amplification, as well as electronic compensation and equalization of linear and nonlinear distortion effects. Research and development into novel modulation techniques for achieving effective signal bandwidth and energy distribution per bit in order to extend the transmission reach are also attracting intensive interest. In this paper, we present: (i) A brief overview of optical-fiber communications employing advanced modulation and novel formats, especially the amplitude-and phase-shift keying with both discrete (DPSK, DQPSK, offset DQPSK) and continuous phase shifts (MSK, CPFSK…); (ii) Distortion and dispersion effects due to linear and nonlinear effects, and experimental demonstration of electronic and photonic compensation methodologies; (iii) Practical demonstration of the transmission of multiple channels at 40 Gb/s over several fiber spans of dispersion-managed optical fibers; and (iv) Demonstration of 40 Gb/s over 10 Gb/s wavelength-multiplexed optically amplified long-haul transmission for capacity upgrading.

## 1. Introduction

The staggering successes of low-loss optical fibers, optical amplifiers, and advanced photonic components and ultra-high-speed electronics have allowed the establishment of optically amplified fiber communications. This mode of information transmission is the choice for the delivery of ultra-high-capacity communications for metropolitan areas, and for regional and long-haul information-transport networks [1, 2]. This success has been based exclusively on photonic signal processing for chromatic and polarization-mode dispersion compensation and equalization as the dispersion-management technique. In contrast to other modes of transmission, electronic signal processing was absent from fiber communications for several years, until recent developments in modulation formats [3-5] and equalization techniques [6, 7] for ultra-long-haul transmission systems. The reason for this was due to the fact that the bit rate of fiber transmission systems was above the capabilities of the electronics. In recent years, continuous progress in semiconductor technologies has enabled electronic processing that for the first time matches the transmission rate of optical-fiber systems. This allows designers to benefit from electronic signal processing [8] for improving the system performance concurrently with improved simplicity in transmission structures, e.g., the elimination of the dispersion-compensating modules and associated optical amplifiers [9].

Furthermore, upgrading the transmission capacity in existing fiber-communications backbone infrastructure will be very important in the near future for ultra-broadband Internet [10]. One of the possibilities is to selectively increase the transmission rate to 40 Gb/s over the existing 10 Gb/s on-off-keying (OOK) dense multi-wavelength division-multiplexed (DWDM) optical-communications systems. Due to the properties of the installed fiber, the transmission methods must be highly resilient in the presence of chromatic-dispersion (CD) and polarization-mode dispersion (PMD) impairments. This favors the use of advanced modulation formats, including amplitude, frequency, and phase (such as variants of phase-shift keying), rather than ultra-high-rate time-division-multiplexed (TDM) schemes [11]. This is because the effects of chromatic dispersion and second-order polarization-mode dispersion are proportional to the square of the bit rate.

This paper thus presents (i) A brief overview of the advances in photonic transmission over optically amplified fiber media that would allow the transport of Tb/s; (ii) The

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original physical phenomena of linear and nonlinear distortion effects and their impact on the signal transmission quality; (iii) Pre- and post- compensation/equalization techniques in either the electronic or the photonic domain; and (iv) Demonstration of a hybrid transmission of a long-haul optically amplified and distortion-equalized transmission system at 40 Gb/s in multiple-wavelength multiplexing or over 10Gb/s dense wavelength-division multiplexing.

# 2. Advanced Photonic Modulation

## 2.1 Transmission System Overview

### 2.1.1 A Brief Historical Development

The demands on communication capacity by today's society are unprecedented, and it would be impossible for it to function properly without meeting these demands. Wireless and wire-line communication networks span across cities and continents from hundreds to several thousands of kilometers. This is made possible by the tremendous capacity that can be carried by light waves in a guided medium, the single-mode optical fibers. Several terabits/second can be transported over communication distances of up to 10,000 km using very thin, 125-μm diameter cladding, and a guided core area of only 50 mm$^2$ [12]. This section gives a brief introduction to the historical development of the techniques and optical-communication technology, especially the emergence of photonics and electronics in ultra-long-haul optically amplified transmission.

Over the years since the first demonstration of an optical-fiber communication system in 1976, light-wave sources were modulated directly by the injection and withdrawing of electrons from the lasing cavity. This was done by means of modulating the driving current, which is also biased above the threshold current level of the laser diode. The development and deployment of single-mode optical fibers in the late 1970s allowed the transmission of "mono-mode" optical fields over long distances [13]. Before the invention of optical amplifiers in 1989, the repeater distance was about 60 km for laboratory experiments and 40 km in systems installed in the field with intensity on-off-keying (OOK) modulation. Attempts and intensive research work were conducted in the mid-1980s employing the true coherence nature of light waves, and thence the modulation techniques. Phase-modulation, amplitude-modulation, and frequency-modulation techniques were exploited with homodyne and heterodyne detection in order to improve the signal-to-noise ratio (SNR). Using these modulation formats, the maximum improvement of the SNR was of the order of 6 to 10 dB, compared with OOK direct modulation. Hence, with a fiber loss of 0.2 dB/km in the 1550 nm spectral window, this improvement allowed an extra 30 km. However, conservatively, the deployment would take 20 km extra distance or 60 km repeaterless distance for long-haul transmission systems. This gain in the transmission distance was faced with the requirement that the line width of the laser must be extremely narrow, of the order of a few kHz. There must also be a very stable center frequency of the lasing source, in order to satisfy the detection conditions for either homodyne or heterodyne detection. In particular, the stable frequency and narrow linewidth must be resilient to environmental changes. The practicality of coherent systems would thus not offer any better economic advantage with the extra 20 km of repeaterless distance.

Optical gain or amplification of optical signals in the photonic domain can easily be surpassed with optical gain provided by inline fiber-optical amplifiers. The advent of photonic amplification components, such as the erbium-doped fiber amplifiers (EDFA) or Raman distributed amplifiers [14, 15] and parametric amplifiers, has offered significant optical gain for information-bearing light wave signals, hence eliminating the attenuation limitation in optical-communication systems. Thus, for ultra-long-haul optically amplified communication systems, the problems remain in the compensation of the pulse-broadening effects due to the chromatic dispersion caused by the wavelength dependence of the effective refractive index of the guided mode in the fiber and its waveguide propagation constant. Furthermore, nonlinear effects – such as self phase modulation, four-wave mixing effects, stimulated Raman scattering, and stimulated Brillouin scattering – also deteriorate the distortion and hence increase the error rate of the transmitted signals [16].

The transmission distance has reached thousands of kilometers and, simultaneously, bit rates have been extended to 10 Gb/s, 40 Gb/s, and even 160 Gb/s, with cascaded fiber spans of 80 to 120 km. In these systems, the linear dispersion effects are compensated for by a length of dispersion-compensating fiber with a total dispersion factor that is equal to but of opposite sign from that of the transmission fiber. This dispersion management is very popular in terrestrial and undersea systems. The transmission capacity can be even further increased by multiple-carrier multiplexing of different light wave channels, using dense wavelength-division multiplexing (DWDM) techniques.

The attenuation of these fibers can be easily equalized by optical amplification, and can be boosted for further transmission using booster types of optical amplifiers. The dispersion effect can be further minimized if effective modulation formats are employed. The formats that offer the most efficient bandwidth would suffer the least pulse broadening. The transmission bit rate has matured at 40 Gb/s and is reaching 160 Gb/s per wavelength channel. The development of various modulation formats has also attracted significant attention for effective transmission of wideband information signals over long-transmission optical lines. The multiplexing of several 40 Gb/s signals over the central or short and long wavebands of the low-loss transmittance region of single-mode fibers aggregates to a total capacity of Tb/s. The announcement of the amplification of photonic waves in the photonic domain, with the Nd- and Er-doped fiber amplifiers in 1989, and then extensive development in the 1990s was significant. This photonic amplification process allowed the redesign and restructuring of global optical-transmission systems and networks with total repeaterless transmission distances reaching several thousand of kilometers. This was accomplished with the use of optical amplifiers and dispersion-compensating fibers as the mid-span optical repeaters. Optical amplification can be in form of a lumped Er-doped medium, or via distributed Raman scattering and parametric conversion in the transmission medium under high-power pumping at different wavelength regions.

It would also be more economical to increase the total capacity of the transmission system by multiplexing several information channels carried by the light waves of different frequencies or wavelengths: this is the wavelength-division multiplexing (WDM) technique. The multiplexed optical channels may suffer a number of nonlinear effects via intensity dependent refractive indices and the interactions of light waves in optical fibers. This is not in the scope of this current article. Currently, we have witnessed the demonstration and installation of optical transmission systems at ultra-high speeds, 40 Gb/s and higher with more than 36 multiplexed channels, hence reaching Tb/s total capacity [17, 18]. This is still only a fraction of the possible capacity that the single-mode optical fiber can carry: about 25 Tb/s over the third low-loss window of the S, C, and L bands of silica fiber, around the 1550 nm region.

The major challenging issues for such long-haul and ultra-high capacity transmission systems are modulation techniques that will minimize the linear dispersion effects, that will increase the channel resilience to nonlinear effects, and higher energy concentration in the signal bandwidth. This has led to the emergence of advanced modulation formats to effectively use the available channel separation in the frequency domain, in order to maximize the bit rates of each information-bearing light wave channels.

This section has thus given a brief introduction to photonic signal processing and the role of RF signals in the generation of light-wave carrier-modulated signals for efficient long-haul transmission over optically amplified guided-wave media, and detection techniques. Electronic and photonic technologies are also given for equalization and pre-distortion for compensation.

## 2.2 Transmission Systems

Figure 1a shows a generic dense wavelength-division multiplexing fiber multi-span optically amplified transmission system. In each span, inline optical amplifiers and dispersion-compensating fiber modules are integrated in cascade for pulse-dispersion equalization and for compensation of the propagation loss of carrier-modulated signals. Multiple carrier-modulated channels are multiplexed and de-multiplexed into parallel streams in the photonic domain via an array waveguide grating (AWG) device, in which the principles of spatial interferometry are applied to separate the spectral channels. They are then optically boosted to an appropriate level, typically about 5-10 dBm, for linear transmission that is below the threshold of the nonlinear self phase modulation.

For system engineering and installation, it is preferred that long-haul systems be composed of *modular* spans, which can consist of the transmission fiber plus inline mid-span optical regenerators. The carrier-modulated signals are phase equalized by the dispersion-compensating module (DCM). The dispersion-compensating module has a phase-delay effect that is the reverse of that of the transmission fibers, and hence compensates the distortion of the phases of a group of optical waves. The multi-wavelength optical repeater (MOR) also consists of two lumped or distributed optical amplifiers of either the erbium-doped or Raman-pumped type. The erbium-doped type of amplifier is used to compensate for the transmission loss with a moderate optical power output, in order to avoid the nonlinear self-phase modulation effects of the compensating fibers. Due to the small cross section – and hence the effective mode spot size – of silica-based dispersion-compensating fibers,

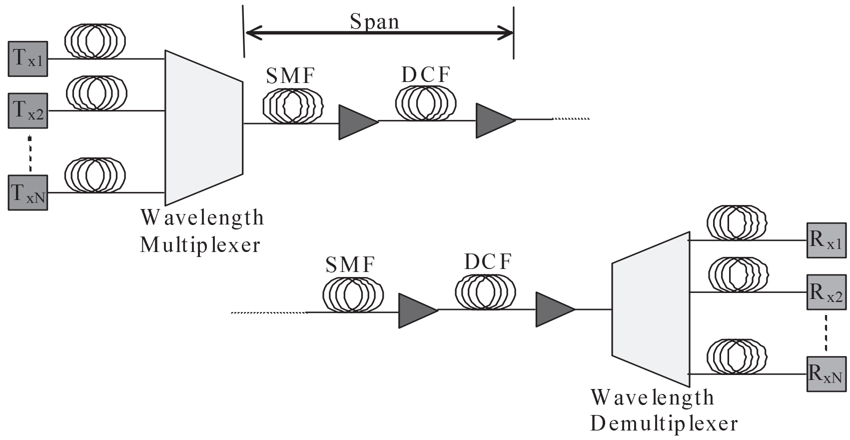


*Figure 1a. A generic inline optically amplified and distortion-compensated transmission system for long-haul multi-span transmission. Legends: MOR = mid-span optical regenerator, Red – Blue: group wavelength channels of longer or shorter spectral regions; DCM = dispersion-compensation module – fiber-based technique; SSMF = standard single mode fiber; AWG = array waveguide gratings for either channel multiplexing or de-multiplexing.*

*Figure 1b. Monash University Siemens TranXpress Wavelength Transport System, bidirectional 8 × 2 × 10 Gb/s, transmission distance 8 × 100 km dispersion-managed (SSMF + DCMs) optically lumped amplified spans.*

their nonlinear power threshold is fairly low, about 0-3 dBm for an optical fiber of 17 mm2 effective area. The second optical amplifier is employed at the outputs of the dispersion-compensating modules to compensate for the optical loss in the compensation fibers, and to boost the total average optical power at the output for transmission to the next fiber span. This complexity of the dispersion-compensating module and the optical amplifiers can be overcome by pre-distortion of the electrical driving signals before modulating the external modulator. A typical commercial optical-fiber transmission system with attenuation and dispersion compensation is shown in Figure 1b. This is described in the next section.

The mismatching of the dispersion compensation of the multi-span distortion and the nonuniformity of the dispersion characteristics of the fibers lead to residual dispersive effects at the end of the transmission system. Hence, dispersion mopping is necessary at this stage for each individual channel before the optical receiver and recovery circuits. Furthermore, the polarization dispersion can also be equalized at this point. Nonlinear effects are also expected. However, there are no photonic components that would exhibit negative nonlinear coefficients to compensate for this nonlinear impact; this is thus compensated for in the electrical domain, normally after the optoelectronic front-end amplifier. Figure 1b shows the Siemens TranXpress Multi-wavelength transport system that can carry 8 × 10 Gb/s wavelength channels in the "blue and red" spectral regions of the low-loss 1550 nm spectral range over 800 km standard single-mode fiber (SMF). It has dispersion-compensating modules with lumped optical amplifiers for each span, as described above. The frequency spacing between wavelength channels is 200 GHz, which can be as narrow as 25 GHz [19] or 50 GHz. This allows the injection of more channels with narrower spacing.

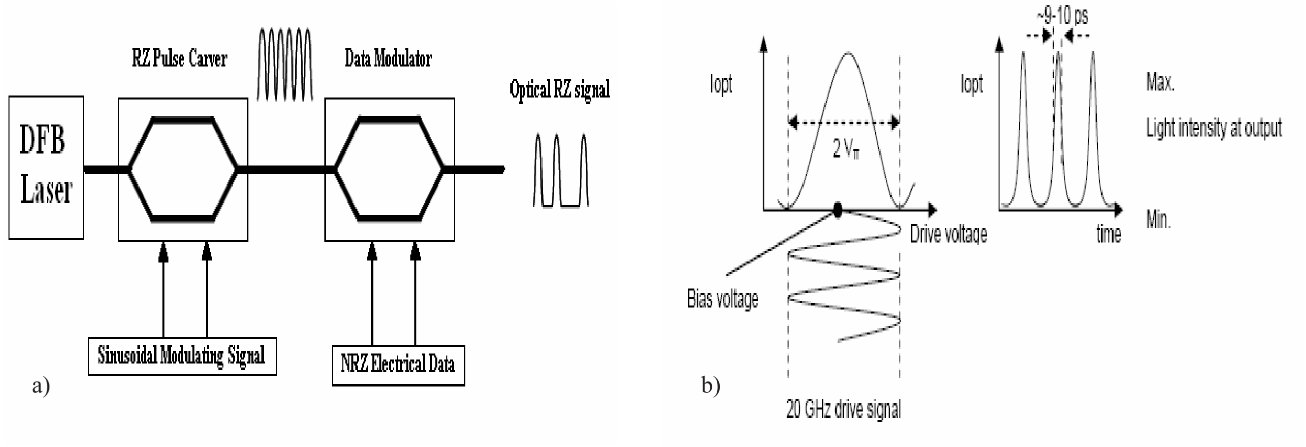
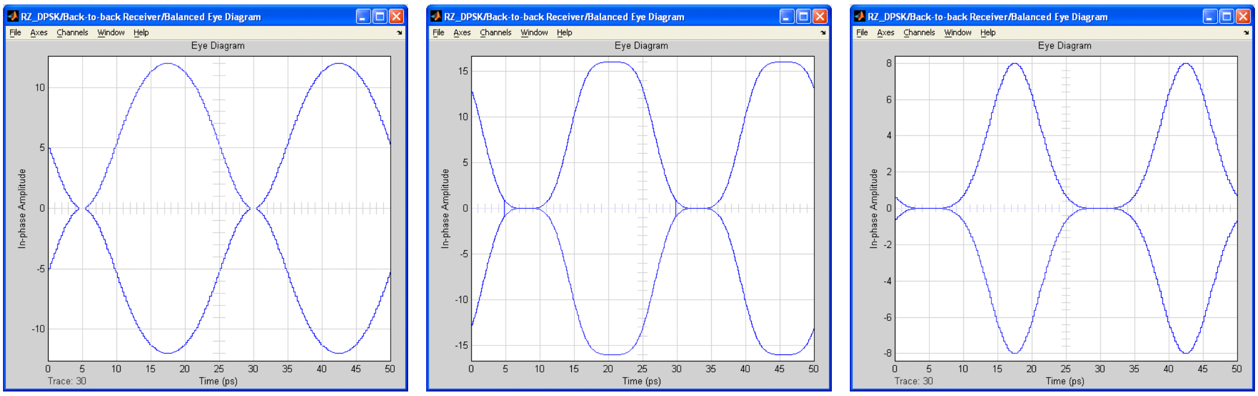


*Figure 2 (a) The modulation of optical signals using different biasing regions of the optical modulators. (b) The optical transfer characteristics of the Mach-Zehnder intensity modulator for modulating the pulse sequence with an electrical RF data sequence. Note: only half of the data rate clock frequency is required for driving the pulse carver if it is biased at the minimum transmission point. The driving voltage is sinusoidal, and hence wide bandwidth is not required.*



a) b) c)

*Figure 3. The eye diagrams of three different return-to-zero modulation formats detected by a back-to-back balanced receiver. From left to right: (a) 67% CSRZ, (b) 50 % RZ, and (c) 33% RZ.*

## 2.3 Photonic Transmitters: Modulation and Line-Code Formats

Line-code formats have been developed and used in wired and wireless communications over the last few decades in order to increase the spectral density and improve the received SNR. Advanced modulation formats have attracted interest in optical transmission. The format can be return-to-zero (RZ). Carrier-suppressed return-to-zero (CSRZ) offers better nonlinear resilience in optical-fiber signal propagation because the power of the carrier is no longer the main contributing factor. The principles of generating the carrier-modulated "clock pulses" and the data modulation are shown in Figure 2. Figure 2a shows the phase modulation of the light wave carrier. As indicated, the phase modulator can be a dual-drive Mach-Zehnder intensity modulator (MZIM), driven by two complementary sinusoidal signals. Figure 2b shows the principle of operation of a Mach-Zehnder intensity modulator and the transfer characteristic. The sinusoidal RF waves are biased at the minimum-transmittance point, with the peak-to-peak amplitude swinging between the two quadrature points. This generates a periodic pulse sequence with a phase shift of the carrier of 0 and $\pi$. The encoded data sequence will then switch the clock pulses on and off accordingly to generate the differential PSK data signals, as shown. The pulse width can be determined by the biasing position of the RF driving signals to give 33%, 50%, or 67% of the bit period, as illustrated in Figure 2b. Figures 3a-3c show the eye diagrams for three different return-to-zero modulation schemes, as detected by the receiver with a back-to-back connection. The phase comparison using a photonic phase comparator or detection of amplitude is described later, and illustrated in Figure 8.

In general, the modulation can be performed with changes of amplitude, phase, or frequency of the carrier, either in binary or multilevel fashion, and continuously or discretely. For phase modulation, any phase transition of the carrier must happen at the transition of the bit period. For

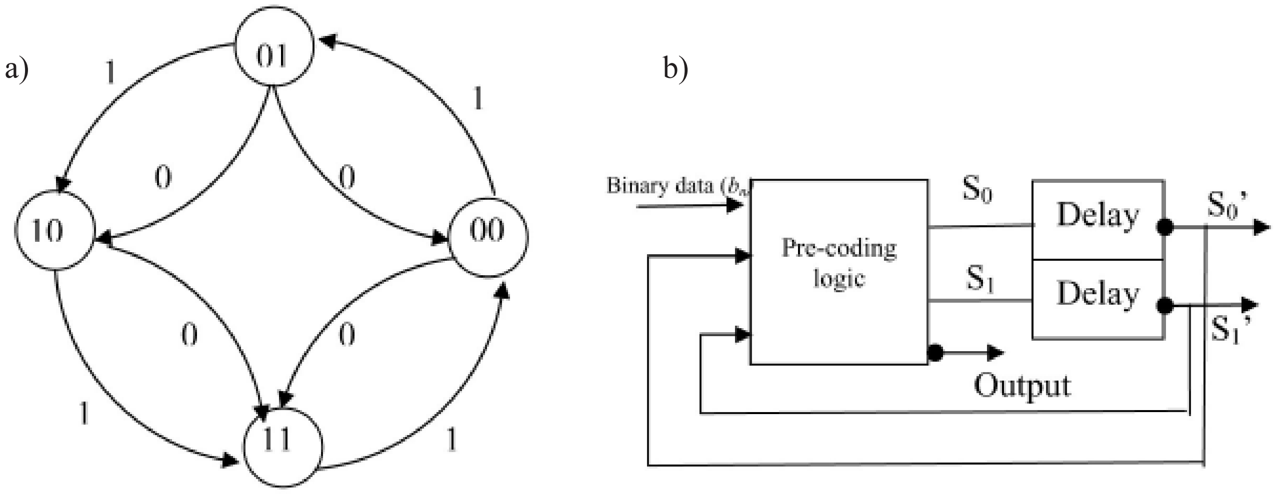
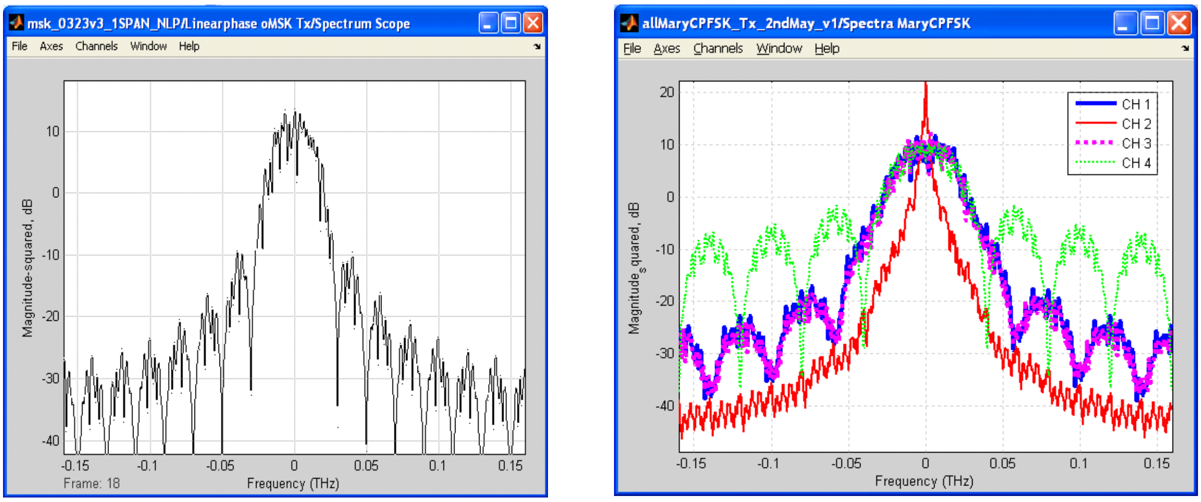


*Figure 4. (a) The logic-state diagram of MSK signal generation; (b) The combinational logic of an electronic MSK precoder.*



a) b)

*Figure 5. Optical spectra: (a) 30 Gb/s binary MSK and (b) M-ary MSK with CH1, CH2, and CH3 of 80 Gb/s optical 4-ary CPFSK signals:* $h = \pm 4/16, \ \pm 15/16$*;* $h = \pm 1/16, \ \pm 3/16$*; and* $h = \pm 1/8, \ \pm 7/8$*; respectively. CH4 shows the spectrum of a conventional 40 Gb/s DPSK signal. All spectra are referenced to the carrier center frequency.*

continuous phase modulation, the change of the phase of the carrier occurs continuously for the duration of the bit period, and continuously between the bits. For example, one of the most popular continuous phase modulations is the minimum-shift keying (MSK), in which the phase change must be $\pi/2$. The phase transitions and the logic states of the even and odd bits are shown in Figure 4a, and the electronic implementation is shown in Figure 4b. The principal advantage of this MSK modulation is the phase continuity and the orthogonality of the even and odd bit sequences. This produces an efficient and narrow bandwidth of the signal spectrum, and is thus more resilient to fiber impairments due to dispersion and nonlinearity. The spectrum of this modulation scheme is shown in Figure 5a, while those of the M-ary (four-level MSK) are shown in Figure 5b, with various phase transition levels of $h = \pm 4/16, \ \pm 15/16$; $h = \pm 1/16, \ \pm 3/16$; and $h = \pm 1/8, \ \pm 7/8$ [20]. Furthermore, the optical spectra of 40 Gb/s continuous-phase frequency-shift keying (CPFSK) is also included, for comparison.

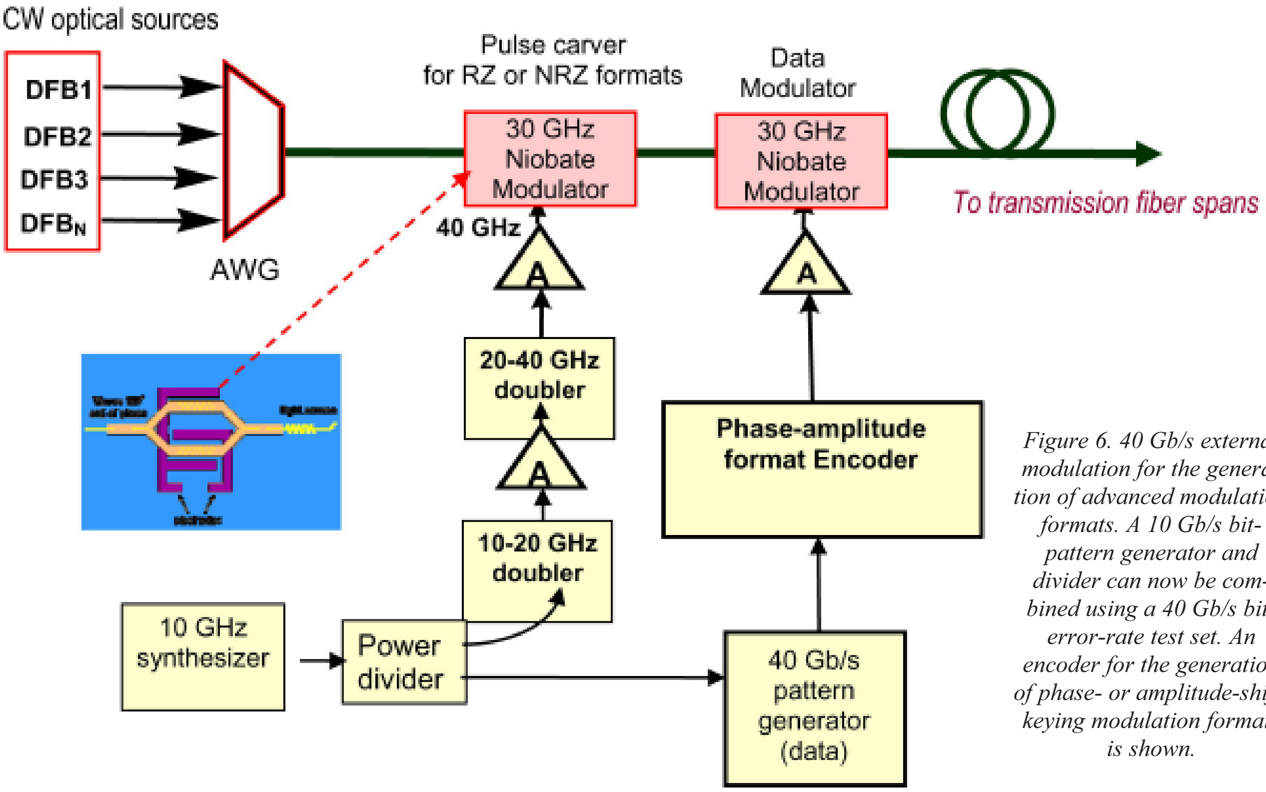


*Figure 6. 40 Gb/s external modulation for the generation of advanced modulation formats. A 10 Gb/s bit-pattern generator and divider can now be combined using a 40 Gb/s bit-error-rate test set. An encoder for the generation of phase- or amplitude-shift-keying modulation formats is shown.*

The implementation of photonic transmitters for processing of the modulation and line-code formats is shown in Figure 6. Two optical Mach-Zehnder intensity modulators are used to generate the clock pulse and data encoded sequences, as mentioned above. The electrical-to-optical bandwidth of these modulators for 40 Gb/s operation would need to be about 30 GHz, due to the $\cos^2$ profile characteristic of the interference of two interferometric beams [21, 22]. The synthesizer is driven incorporating a bias T, which would place the RF signals at the specific biasing point on the transfer curve. The amplitude of the RF waves would be adjusted by the gain and attenuation factor of the RF amplifiers. The sinusoidal behavior of the driving signals for clock-pulse generation makes a resonant type Mach-Zehnder intensity modulator applicable, so that the driving voltage can be reduced down to a very low level, possibly less than a volt.

Naturally, due the high-speed operation of the modulation, direct modulation of the driving current of a laser source is not possible. This would broaden the linewidth of the laser; normally, a distributed feedback laser has a line width of about 100 kHz under continuous-wave operation. CW light waves are then modulated via electro-optic modulators with a structure that follows a Mach-Zehnder type of interferometric structure (MZIM). Both single- and dual-drive electrode structures can be used, in which traveling-wave electrodes are placed across the optical waveguide branches of an optical interferometric structure, as shown in the insert of Figure 6. This figure illustrates the practical implementation of the driving signals for the optical modulators. The phase modulation of light waves propagating through these arms generates destructive or constructive interference at the output, and thence amplitude or phase modulation. The dc biasing applied to these electrodes is also critical to the phase difference of the modulated light waves. For example, a bias difference of $\pi$ would set the suppression of the carrier at the output of the modulator, as shown in Figure 6b. The pulse formats, return-to-zero (RZ) or non-return-to-zero (NRZ), can be generated by using a pulse carver, which would periodically switch the light waves on and off, as indicated in Figure 2. The electrical data sequence can be either amplitude or phase encoded, and then applied to an external data modulator. Normally, due to the $\cos^2$ profile of the modulator, the bandwidth of the modulator would assume about 70% of the bit rate for a return-to-zero format. The amplitude of the electrical signals compared with $V_\pi$ (the voltage at which the phase shift is 180°) of the Mach-Zehnder intensity modulator would determine the phase difference of the modulated sequence. Figure 7a shows the optical spectra of various advanced amplitude and phase modulation and non-return-to-zero or return-to-zero formats at a bit rate of 40 Gb/s. Indeed, only one Mach-Zehnder intensity modulator dual drive is required to generate all possible amplitude and phase modulations. As described above for return-to-zero and carrier-suppressed return-to-zero modulation, it would require an additional pulse carver to generate the return-to-zero-format pulse sequences. It is noted that whenever phase modulation of the optical carrier is required, this operation must be implemented in the photonic domain. Otherwise, the signals must be converted back to the electronic domain so that signal processing can be performed. Therefore, for any phase or phase-difference modulation of optical channels, the encoding is done in the electronic domain. They are then used to manipulate the phase of the light waves via traveling-wave electrodes, and thence the electro-optic effects or electro-absorption in solid-state, polymer, or semiconductor integrated waveguides. The advantages and disadvantages of different cuts of the electro-optical and electro-absorption modulators are tabulated in Table 1.

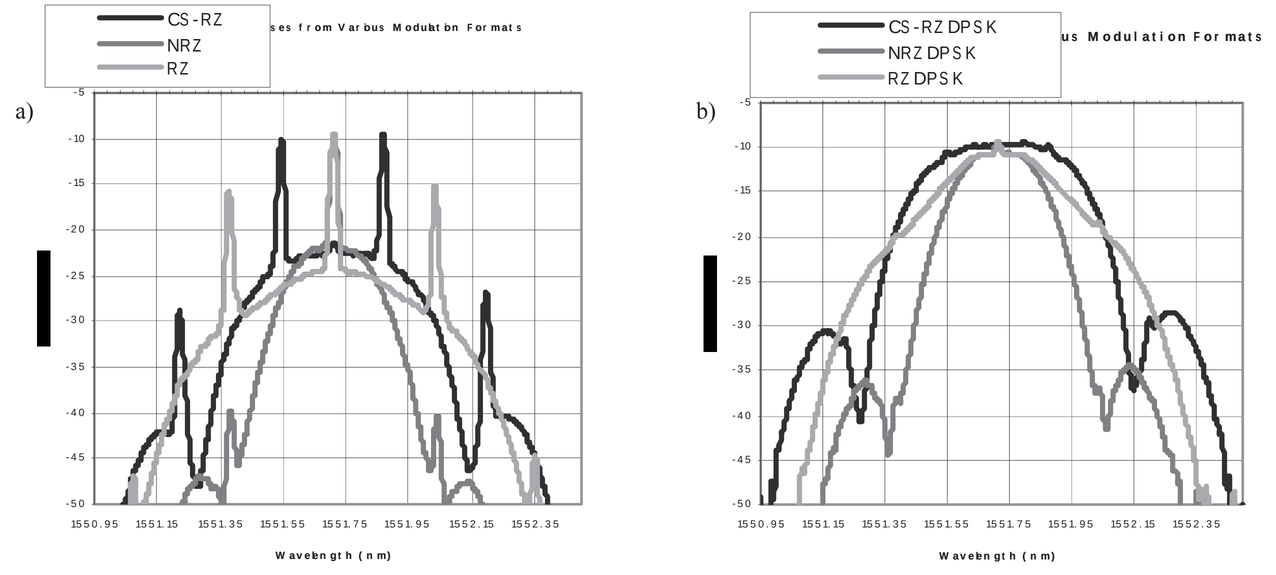


*Figure 7. The optical spectra of 40 Gb/s CS-RZ DPSK, NRZ DPSK, and RZ DPSK, with a base rate of 40 Gb/s. The spectra of ASK RZ modulated signals for (a) amplitude modulation and (b) phase-shift-keying modulation.*

| Configuration | Advantage | Disadvantage | Application |
|---|---|---|---|
| Z-cut | – lower and well behaved chirp than EA modulator<br>– lower $V_\pi$ | – chirped (unchirped only by balanced dual drive)<br>– more DC drift than X-cut<br>– single drive not for PSK | Traditionally use for RZ and NRZ (balanced driven) |
| X-cut | – intrinsically balanced - chirp free<br>– no need to align the delay (phase) of 2 signals | – electro-optical efficiency lower than Z-cut<br>– higher driving voltage | Suitable for modulation required absolute chirp free |
| EA modulator | – linear and low driving voltage | – high chirp and dynamically changing with bias<br>– high insertion loss | Cannot be used for PSK |

*Table 1. A summary of the advantages, disadvantages, and application of X-cut, Z-cut, and EA modulators.*

It is critical that the optical power contained in the carrier can be minimized, and that the bandwidth of the modulated signals can be optimized, to minimize the total transmission-distortion effect. The measured optical spectra of different modulation formats are shown in Figure 7. The carrier exists in the amplitude-modulation return-to-zero and non-return-to-zero formats, but not in carrier-suppressed return-to-zero. In phase-shift keying, the energy of the signals is concentrated and higher than in the amplitude counterparts. To this end, the carrier-suppressed return-to-zero format and phase-shift keying offer better transmission performance.

## 2.4 Fibers for Transmission and Dispersion Compensation

The transmission and dispersion fibers can be of types such as standard ITU G. 652, ITU G655 non-zero dispersion shifted fibers (NDSF), or matched dispersion and dispersion-slope fibers, such as the Corning Vascade types, etc. [23]. Standard single-mode fibers (SSMF) are usually found in installed systems, usually laid in the late 1980s and the 1990s. A dispersion factor ranging from 3 ps/nm/km to 16.8 ps/nm/km for these fibers is specified. A transmission loss of about 0.2 dB/km in the C band of silica fibers and the sensitivity of lumped optical amplifiers lead to span lengths of 80 km to 120 km. These span lengths can be extended to 160 km if Raman distributed amplification is used. The optical fibers act as an optical low-pass filter with a transfer function that is purely a phase modulation component as a function of the square of the frequency difference of the optical pass band and the carrier frequency. This frequency-dependent phase-variation term is critical for phase or phase-difference modulation formats. These phase distortions can be equalized by using dispersion-compensating fibers with dispersion factors and slopes that can be matched to those of the transmission fibers. The use of dispersion-compensating fibers requires two optical amplifiers, one after the transmission fiber and the other after the dispersion-compensating fiber so as to boost the optical power for further transmission. These two amplifiers contribute to the total transmission noise, due to additional amplified stimulated-emission noise in each optical amplifier. This noise accumulates over several cascaded spans, and hence limits the total transmission reach. Thus, if the dispersion effects can be reduced by pre-distortion at the transmitter, post-compensation at the receiver, or a shared combination of pre- and post- compensation, the structure of the photonic transmission system can be significantly simplified. These electronic compensating techniques will be addressed in a later section.

The transmission of light wave signals is restricted to below the nonlinear threshold of the self-phase modulation and other effects, such as four-wave mixing, cross-phase modulation, stimulated Raman scattering, and stimulated Brillouin scattering, which have been treated in detail over the years [24].

## 2.5 Photonic Phase Comparator and Balanced Receiver

An optical receiver normally consists of a high-speed photodetector followed by an electronic amplifier, and then a main amplifier, clock recovery, and sampling circuits, for the case of amplitude-shift-keying modulation. A balanced receiver with a dual photodetector pair connected back-to-back, acting as a push-pull current generator, could also be used for a phase-shift-keying system.

For the DPSK or DQPSK modulation formats, or for non-return-to-zero, or return-to-zero, or carrier-suppressed return-to-zero, it is necessary that a photonic delay interferometer in integrated optic form be used to compare the phases of the carrier contained in two consecutive bits, as shown in Figure 8. Both the constructive and destructive ports are then fed into a differentially balanced high-speed photodiode pair, connected back-to-back, so that the differential phase is translated into an amplitude evolution. It is possible to construct the delay difference for a data sequence operating at 40 Gb/s or even 160 Gb/s. The delay can be tunable by using the thermal effect to compensate for any fabrication or environmental errors. Typical eye diagrams, detected using balanced receivers, are shown in Figure 12.

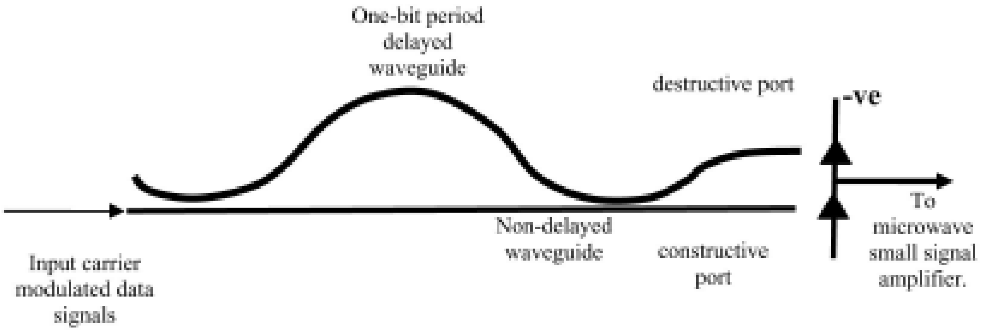


*Figure 8. A planar view of an integrated optic Mach-Zehnder delayed interferometer for phase comparison and differential optoelectronic detection.*

## 3. Equalization

The complexity of the design of optically amplified long-haul fiber transmission with two optical amplifiers in association with the dispersion-compensating module can be eliminated if a novel compensating technique can be implemented in the electronic domain, rather than in the photonic domain. Continuous progress in semiconductor technologies has enabled electronic processing to match the information speed of optical-fiber systems for the first time. This gives the opportunity for fiber-system designers to benefit from electronic signal processing and design systems the performance of which would exceed systems without electronic processing at lower cost. The demonstration of such electronic pre-distortion for compensation [25, 26] is shown in Figure 10, in which the amplitude of electrical signals was distorted before modulating the phase of the light waves. This phase distortion is equivalent to the dispersion of the light waves after propagating over a transmission distance. A recent demonstration indicated that it is possible to compensate over 10,000 km of standard single-mode fiber for a 10 Gb/s return-to-zero-DPSK channel[27]. This significantly simplifies the transmission configuration, especially the elimination of at least one lumped optical amplifier, and hence the associated amplified simulated emission noise. Furthermore, if Corning Vascade fibers, made of positive and negative fibers of approximately identical effective area, were used, then the transmission distance would be extended much longer than 10,000 km for 10 Gb/s (more than 1000 km for 40 Gb/s). It would be limited only by the total amplification of stimulated-emission noise of the inline optical amplifiers.

We note that the principal difference between the processing in the photonic and electronic domains is that we deal with the optical field of the light waves, rather than the electronic current/voltage, which are converted from the optical intensity of the received signals. A photonic dispersion compensator can be in the form of a resonator, operating at a particular wavelength at which the group delay can be matched to that of the dispersion of the system [28, 29].

## 3.1 Equalization of Polarization Mode Dispersion

As described above, the progress of photonic signal processing for long-haul transmission has been quite significant. Signal distortion can be compensated for in the linear region by using dispersion-compensating techniques via negative-dispersion fibers. Other dispersion effects,

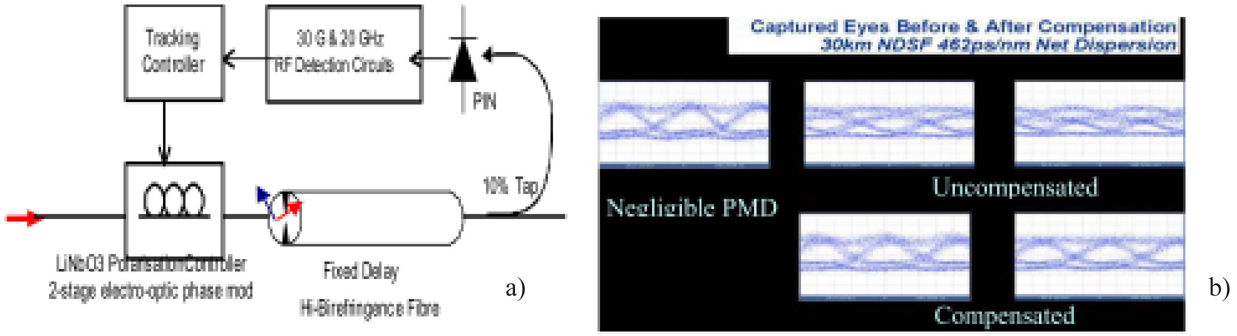


*Figure 9. Electronic-photonic processing for the equalization of polarization-mode dispersion in field-installed transmission fibers: (a) a schematic diagram of the compensator; (b) the uncompensated and compensated eye diagrams.*

such as polarization-dispersion effects, can also be evaluated and compensated for with optical delay lines and control feedback in the electronic domain, as shown in Figure 9a. The polarization states of the modulated input electromagnetic light waves are rotated according to the electronic detection of the fundamental frequency of the signals, which is tapped and detected from the optical signals. The optical delay line, a high-birefringence optical fiber, has a very large difference in the polarized-mode propagation constants. Hence, equalization of the delay difference of the two modes of the linearly polarized modes of the transmission standard single-mode fiber occurs. A length of about 20-30 m of this hi-birefringence fiber is sufficient to equalize the residual polarization-mode dispersion for nearly 1000 km of a standard single-mode fiber link. Figure 9b shows the eye diagram as detected for 30 km of uncompensated nonzero-dispersion-shifted fiber (NDSF) transmission with polarization-mode dispersion. The compensated eye diagram shows the effectiveness of the polarization rotator and the feedback control based on the detection of the peak of the signals at a certain band of the modulated signals.

## 3.2 Electronic Dispersion Compensation

The elimination of optical-dispersion-compensating modules from a network by electronic means has several advantages: (i) reduction of first-installed cost by the elimination of optical compensators and supporting amplifiers; (ii) simplification of deployment and reconfiguration, because each channel discovers and optimizes its own dispersion; and (iii) reduction of linear channel impairments caused by optical filters.

Dispersion of the complex signal envelope of light wave propagation through long-haul optical guided media is a linear operation on the optical electric field. As a consequence, its direct effects can be removed by linear filtering proportional to the complex field. In contradistinction, present-day commercial transmission is overwhelmingly based on intensity-modulated direct detection (IM/DD). This limits the range of the electrical-domain dispersion compensation, since the action of direct detection introduces a squaring function into the channel [30], making it highly nonlinear and much less susceptible to linear-equalization remedies. On the other hand, advanced modulation formats are based mainly on the electric field of the light-wave signal. The equalization of the light-wave signals can be carried out by (i) pre-distortion of the electrical signals before driving the optical modulator, or (ii) equalization at the receiving end, or (iii) shared equalization using a combination of these two methods.

Pre-distortion of the data signals prior to modulating the Mach-Zehnder intensity modulator, so as to compensate for the propagation dispersion, is of much interest in order to reduce the use of optical amplifiers and dispersion-compensating modules. The high sampling rate of an electronic system can be incorporated with the digital signal processing to produce the real and imaginary parts of the baseband signals. This can be implemented as shown in Figure 10. The data at baseband is first pre-coded according to the line code and modulation. It is then processed digitally in the digital signal processor (DSP), and then split into a real and imaginary parallel data sequence. This is then converted to the analog domain, and used to drive the dual electrodes of the Mach-Zehnder intensity modulator. It is assumed that the transfer characteristics of the fibers are known. In the linear region, the fiber acts as a low-pass filter with a parabolic phase characteristic [12]. It is very

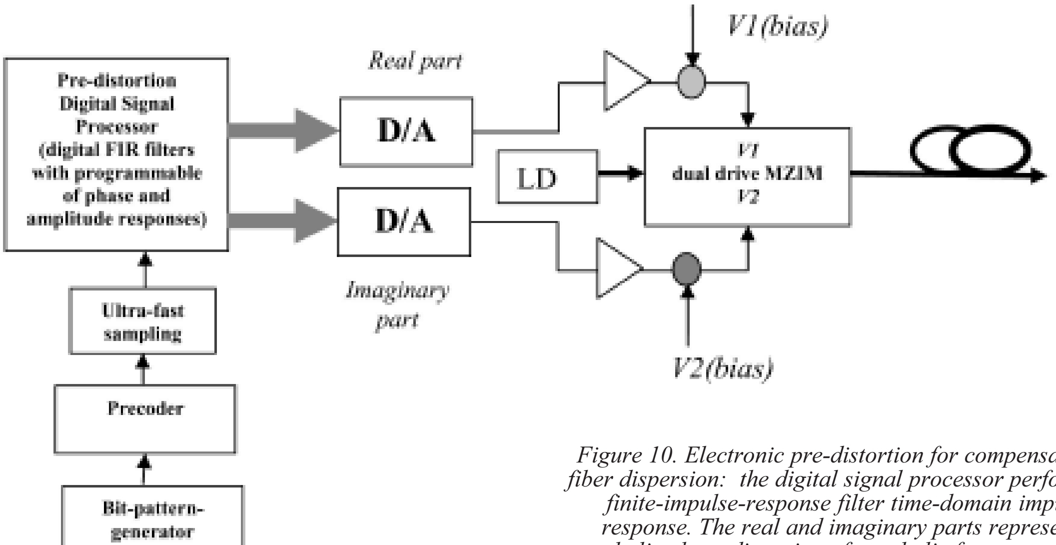


*Figure 10. Electronic pre-distortion for compensation of fiber dispersion: the digital signal processor performs the finite-impulse-response filter time-domain impulse response. The real and imaginary parts represent a parabolic phase distortion of parabolic frequency dependence opposite to that of a single-mode fiber transmission line (adapted from [6])*

| Techniques | Photonic/Electronic Domain | Performance | Quantity |
|---|---|---|---|
| Dispersion Compensating fibers[35] | Photonic | good | Chromatic dispersion – linear effect |
| Fiber Bragg grating [36] | Photonic | Good but uncertain at edge of the roll off | Chromatic and pre-distortion |
| Optical resonators (etalon, ring resonance …)[37] | Photonic | High dispersion factor – stable | Chromatic dispersion |
| Optical feed-forward equalizer (transversal filter) [38] | Photonic | Very good | Chromatic and polarization dispersion |
| Pre-distortion [39,40] | Photonic, *electronic* or combined | Very good and stable | Chromatic, linear and nonlinear dispersion effects |
| Decision feedback equalizer (nonlinear)[41, 42] | *Electronic* | Good – required high speed feedback decision circuit | All effects (L,NL and PMD) |
| Maximum likelihood sequence estimator[43,44] | *Electronic* | Complex receiver, good | All effects |

*Table 2. Electronic and photonic equalization techniques.*

straightforward to pre-distort the phase of the complex envelop of the baseband sequence by alternating the imaginary parts of the digitally processed signals. Recently, electrical equalization was demonstrated with over 60,000 ps/nm of chromatic dispersion over 3840 km of non-dispersion-shifted fiber at a bit rate of 10 Gb/s using non-return-to-zero on-off keying [31, 32].

The simulation of duobinary modulation formats with an electrical pre-equalization scheme was demonstrate to extend the reach of 10 Gb/s signals (with a BER $<10^{-15}$) that were transmitted over 400 km of standard single-mode fiber. The proposed scheme is based on pre-distorting the duobinary or di-phase signal using two half-period-spaced finite-impulse-response (FIR) filters [33, 34].

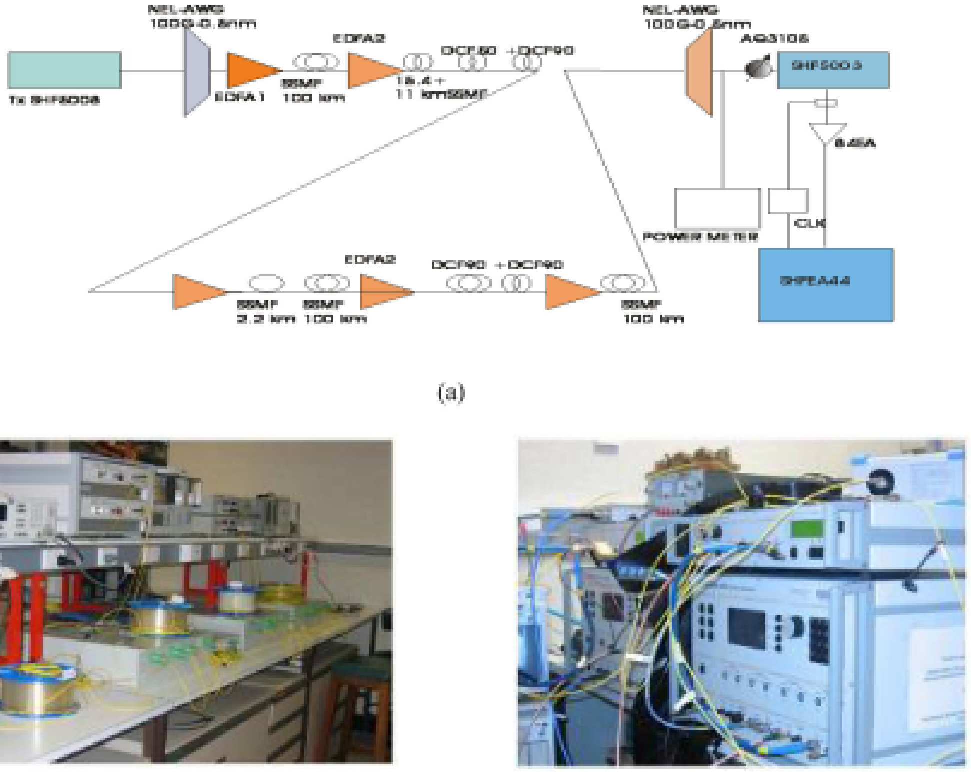
In general, the electronic decision can be implemented for arbitrary dispersion effects whether they are of the linear or nonlinear type. The maximum-likelihood sequence estimation (MLSE) can be associated with the phase locus or trellis of the modulated signals. All signal paths of the phase trellis are used to select the best path and, hence, the maximum optical signal-to-noise ratio (OSNR) can be achieved. An overview of electronic and photonic equalization techniques is given in Table 2. The maximum-likelihood sequence estimation technique is also included, as this is one of the best techniques for maximizing the optical SNR or minimizing the BER.

# 4. Modulation Formats for 40 Gb/s and 10 Gb/s Hybrid Transmission

## 4.1 Transmission Test Bed

Due to the economics of high-speed optical networks, the upgrading of existing installed 10 Gb/s with only a certain few wavelength channels to 40 Gb/s may be required. We thus investigated the possibility and engineering of the transmission of 40 Gb/s channels over a 10 Gb/s dense-wavelength-multiplexed optically amplified transmission system.

The optically amplified fiber transmission setup is shown in Figure 11a. A tunable laser source was coupled with the SHF-5003 optical transmitter to modulate the light wave channels. Various formats, such as return-to-zero, carrier-suppressed return-to-zero, non-return-to-zero, return-to-zero DPSK, and return-to-zero DQPSK, could be generated. Array waveguide gratings with ITU- standard wavelength grids were inserted at the transmitter and receiver sites. Optical amplifiers were employed as pre-amplification subsystems and boosters at the front and post ends, respectively, of the dispersion-compensating module, to compensate for transmission-and compensating-fiber losses, and to boost the power of optical channels so as to keep the transmission system uniform over the spans of the transmission link. Differential or intensity receivers were used at the receiving end, before being inserted into the error analyzer. The average optical power was measured via a 1:10 coupler at the input of the receiver. Thus, all optical receiver sensitivities had to be increased accordingly. The transmitter consisted of two cascaded interferometric optical modulators. One served as the pulse carver, and the other was for data switching. A carrier-suppressed return-to-zero format could thus be created by biasing the pulse carver at its minimum transmission point. If it was biased at maximum transmission, the generated data sequence operated at a carrier-max state. DPSK and DQPSK formats could also be generated by integrating an electrical pre-coder and then amplifying to an appropriate level, so as to swing the data pulses over the biasing state with a phase difference of 0 and $\pi$. An optical attenuator was used to adjust the optical power entering the receiver to evaluate the receiver sensitivity. Several types of optical filters could be inserted, such as (i) an NEL array waveguide grating (AWG) multiplexer/de-multiplexer filter with a 0.45 nm 3 dB bandwidth (BW) and 100 GHz spacing; (ii) a Piri AWG multiplexer/de-multiplexer filter, 0.5 nm (3 dB bandwidth), 200 GHz spacing; (iii) an FBG of 0.55 nm pass



(a)

(b)

(c)

*Figure 11. A demonstration of an optical transmission system set up for 40 Gb/s with advanced modulation format: a total fiber length of 320 km and an effective 328 km dispersion compensation. (a) A schematic diagram of the transmission system; (b) the hardware se up for the optically amplified and dispersion-compensated fiber transmission line; (c) the transmitter and receiver (SHF 5300 and 5800 [13]), plus the SHF bit-pattern generator and error analyzer (right).*

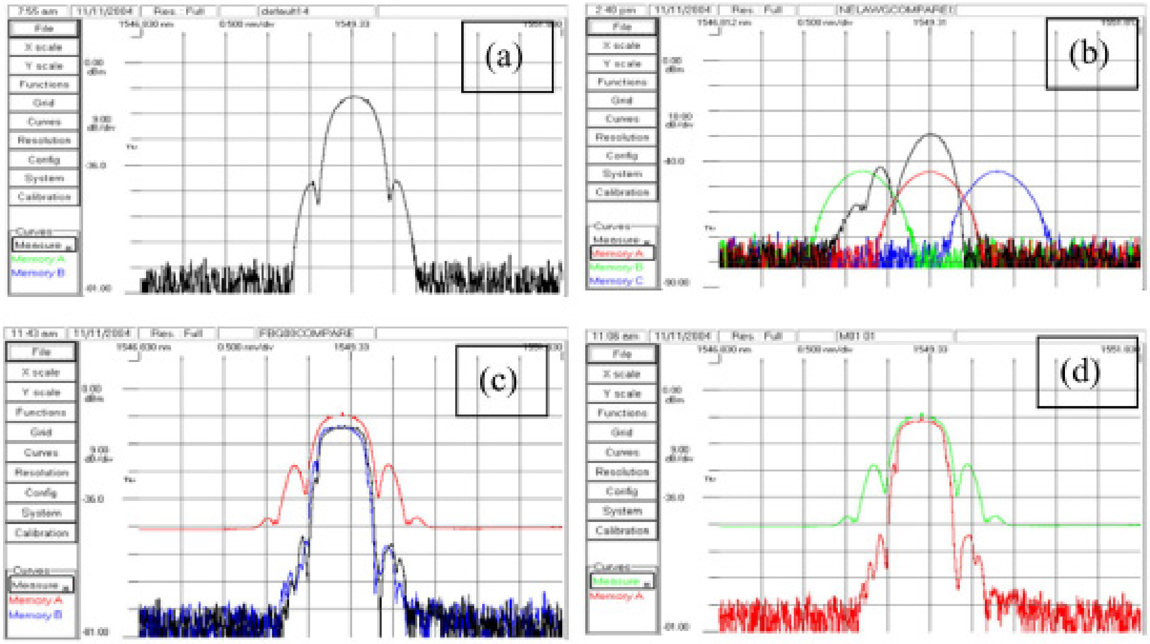


*Figure 12. The optical pass bands of array waveguide grating (AWG) filters: (a, top left corner) the signal spectrum of a channel; (b, right top): the optical pass band of the multiplexed output of the AWG; note the parabolic pass band characteristics and the "black" curve of the output spectra of a wavelength channel; (c) the signal spectrum and its output of the AWG; (d) the same as (c) but for a different wavelength region.*

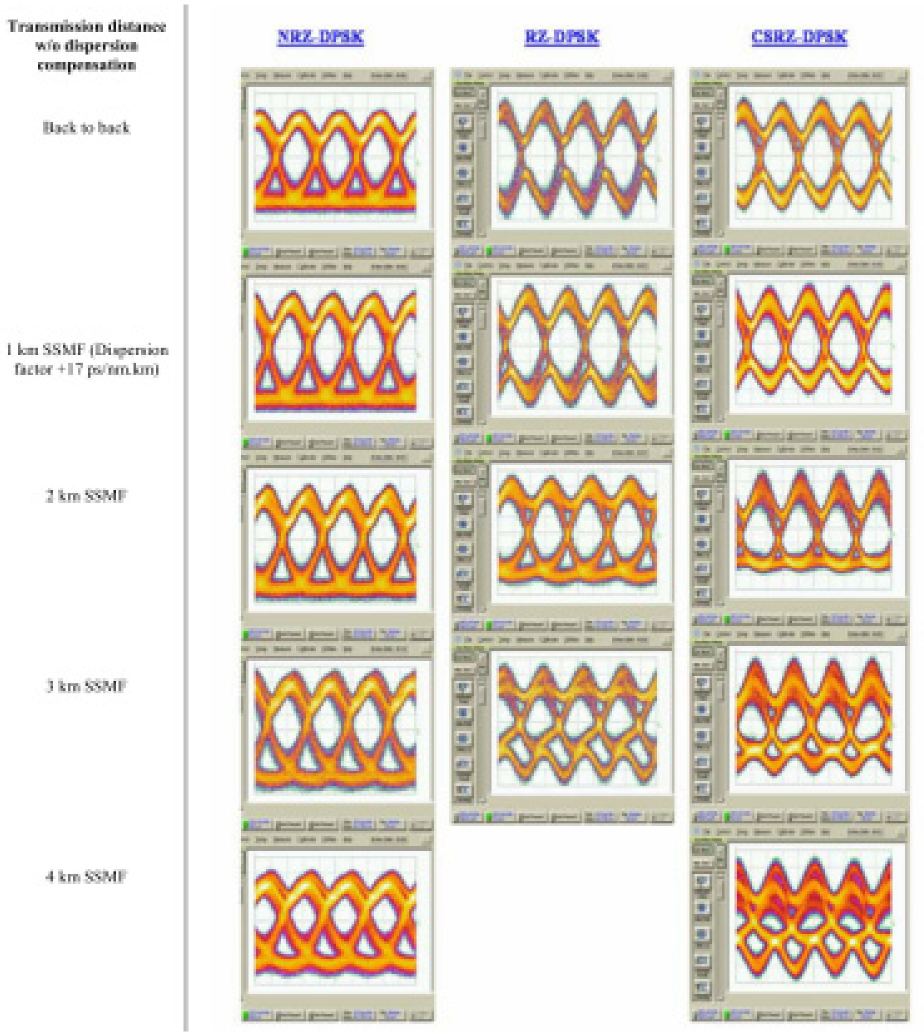


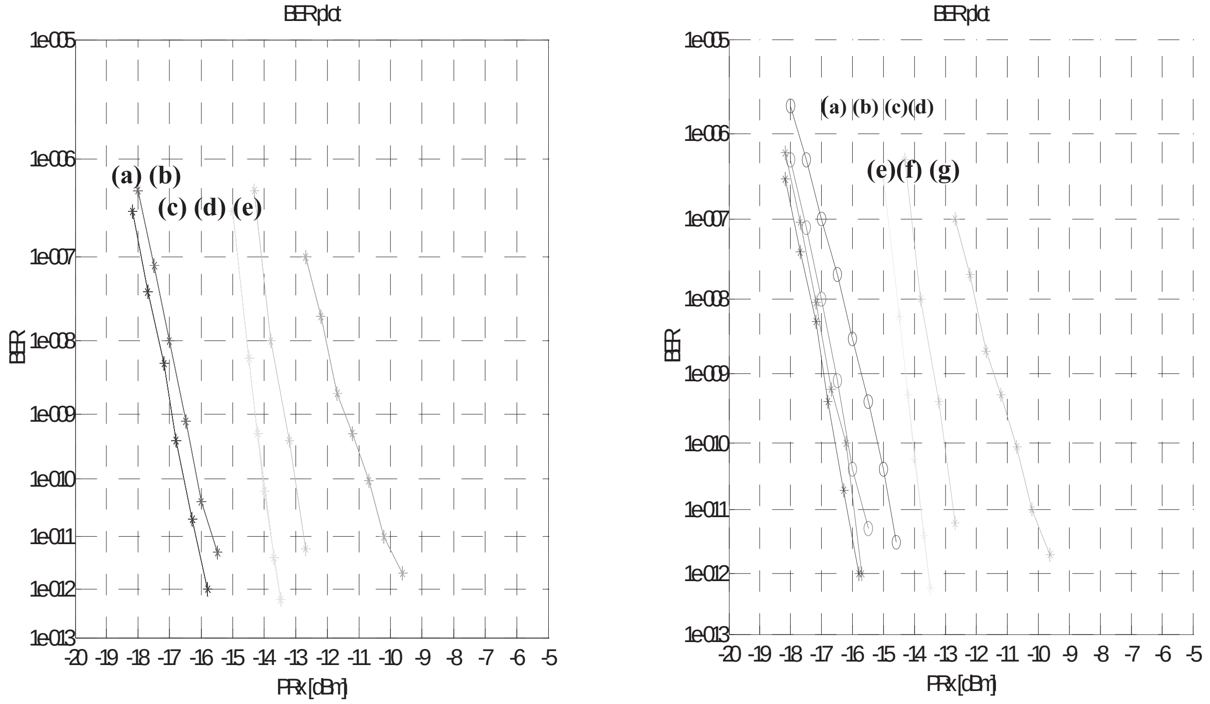
*Figure 13. The detected eye diagrams of DPSK modulation formats, RZ and CSRZ.*

band; (iv) an AWG 8 channel de-multiplexer with 0.35 nm pass band; (v) a JDS tunable filter of 1.3 nm pass band; (vi) and a Santec 0.5 nm BW wideband roll-off. These were inserted into the transmission system wherever appropriate.

Initially, the impact of the optical filtering characteristics of the multiplexer were evaluated with a back-to-back transmission setup. The sampling clock was set directly from the auxiliary clock output of the 231-1 pattern generator. Although two array waveguide gratings could be used as multiplexers and de-multiplexers, we used only one array waveguide grating at either the transmitter or receiver sites. The other filter could be substituted for by a thin-film multilayer optical filter. Two optical filters, acting as a multiplexer and a de-multiplexer at the transmitting and receiving ends, were then used to evaluate their impacts on 40 Gb/s channels. We observed insignificant degradation of the BER, as shown in Figure 14. Note that the sensitivity must be read 10 dB down from the scale given in these figures, due to the 1:10 coupling ratio.

Typical eye diagrams, detected for the differential phase-shift keying formats, are shown in Figure 13. The decision threshold could be set at an optimum level to achieve the best bit-error rate (BER) that could be measured by the SHF 44EA error analyzer. The transmission distance was set so that the dispersion tolerance of the transmission formats could be characterized. Thus, back-to-back and up to 4 km transmission through various lengths of standard single-mode fiber could be achieved. The BERs, plotted against the receiver sensitivity as obtained for various modulation formats such as ASK, DPSK, and DQPSK, with return-to-zero, non-return-to-zero, or carrier-suppressed return-to-zero, are shown in Figure 14. The sensitivities did not change significantly under the influence of the 0.5 nm optical filter on the 40 Gb/s channels operating under different modulation formats. The Gaussian-like or $\cos^2$ profile of the pulses generated at the output of both optical modulators, and the parabolic pass-band properties of the array waveguide grating could tolerate wider signal spectra. We did not observe any degradation of the BER as a function of the sensitivity for the cases of wideband optical filters (1.2 nm) and 0.5 nm optical filtering of the multiplexer.

The transmission was then conducted with a total transmission length of the standard single-mode fiber (SSMF) of 320 km, and an effective dispersion-



a) b)

*Figure 14. (a) The BER as a function of the received optical power (at the power meter, with a 1:10 coupler before the receiver). Curves: "blue" (a) CSRZ-DPSK; "red"(b) RZ DPSK; "yellow" (c) CSRZ- ASK; "cyan" (d) RZ-ASK; "green" (e) NRZ ASK. (b) The BER as a function of the received optical power (at the power meter, with a 1:10 coupler before the receiver). Curves: (a) "blue x" CSRZ-DPSK (one NELAWG); (b) "red - cross" RZ DPSK (one NELAWG); (g) "green" NRZ ASK (one NELAWG); (e) "yellow" CSRZ-ASK (one NELAWG); (f) "c" RZ-ASK (one NELAWG); only one optical filter NEL AWG was used; (b) "Red o" CSRZ DPSK two AWGs; (c) "blue o" RZ-DPSK with two AWGs.*

compensating length of 328 km of standard single-mode fiber. That meant that there was an effective 8 km standard single-mode fiber mismatch of dispersion in the 1550 nm spectral window. The BER as a function of the receiver sensitivity for the return-to-zero DPSK and carrier-suppressed return-to-zero DPSK formats was obtained as shown in Figures 15a and 15b, respectively. The optical filters used as multiplexers had typical pass bands of 1.2 nm and 0.5 nm. No degradation of the receiver sensitivity was observed for different pass-band filters. A 4 dB improvement in the receiver sensitivity was observed for carrier-suppressed return-to-zero DPSK compared to that of return-to-zero DPSK, due to an enhancement in the total energy contained in the pulse sequence with a suppression of the carrier of the carrier-suppressed return-to-zero DPSK.

## 4.2 Impacts of Adjacent 10 Gb/s on 40 Gb/s Channels, and Vice Versa

320 km transmission was also conducted, to assess the performance of 10 Gb/s non-return-to-zero ASK and carrier-suppressed non-return-to-zero DPSK 40 Gb/s channels. The transmission of adjacent and non-adjacent channels was demonstrated and evaluated with a 100 GHz array-waveguide-grating multiplexer and a 1.2 nm tunable filter at the input of the receiver. An insignificant power penalty was observed when an adjacent 40 Gb/s channel was co-transmitted. A transmission system was set up with a 320 km standard single-mode fiber and a dispersion-

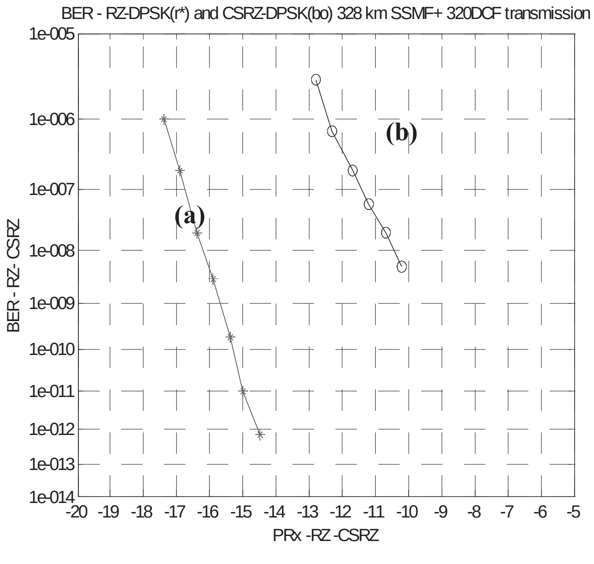


*Figure 15. A 328 km standard single-mode fiber and DCM320 (320 km effective compensating length) compensating fibers were used in the transmission system. (a) CS-RZ DPSK modulation format (red curve); (b) RZ-DPSK modulation format.*

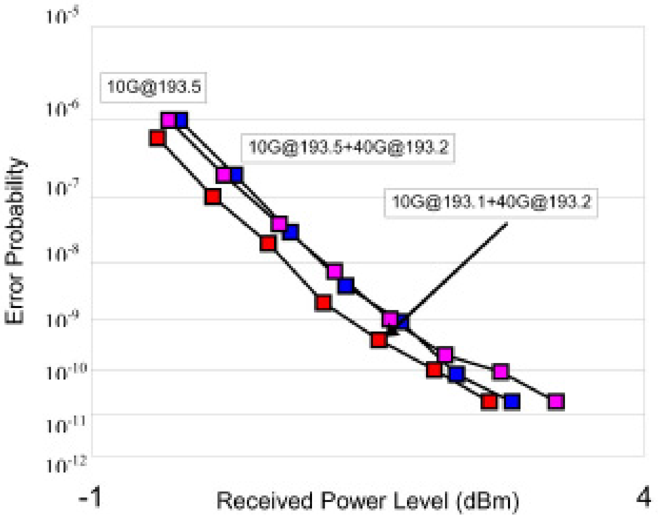


*Figure 16. The impact of a 320 km 40 Gb/s transmission on a 10 Gb/s channel: the BER as a function of the receiver sensitivity (dBm). This shows the effects of a 40 Gb/s (CS_RZ DPSK) with 10 Gb/s (NRZ-ASK) channel simultaneously transmitted for NRZ ASK and CS-RZ DPSK formats. The blue dots are for a 1.2 nm thin-film filter and the red dots are for a 0.5 nm AWG filter (de-multiplexer with 100 GHz spacing).*

compensating module with two 100 GHz array waveguide gratings used as multiplexers and a receiver filter, to measure the impact of an adjacent carrier-suppressed return-to-zero DPSK 40 Gb/s channel on 10 Gb/s non-return-to-zero ASK performance. No significant sensitivity degradation of the 10 Gb/s dense-wavelength-division multiplexing channels was noted when 40 Gb/s channels, adjacent or non-adjacent, were co-transmitted, as seen in Figure 16.

## 5. Concluding Remarks

Optical transmission with advanced-modulation-format channels has been presented using photonic and electronic processing techniques. We have also demonstrated transmission of 40 Gb/s channels over an optical-fiber communication system with optical characteristics that are similar to those of standard 10 Gb/s dense-wavelength-division-multiplexing channels. The filtering properties of the multiplexers and de-multiplexers did not significantly affect the transmission performance in terms of BER and receiver sensitivity. We also measured the transmission quality of both 40 Gb/s and 10 Gb/s channels, and observed no degradation of either channel by the other. Indeed, the use of optical filters can also be incorporated with the frequency-discrimination technique for phase detection of DPSK channels [6]. In this case, a narrowband optical filter will reduce the amplified noise and, hence, simplify the receiver structure.

We have also reported some recent advanced techniques of electronic signal processing for pre-distortion of the electrical signals prior to the modulation of the phases of the light waves propagating through an external modulator. This makes it possible to compensate for extremely long-distance transmission without resorting to the use of dispersion-compensating fibers, and hence results in a significant simplification of the transmission system structure.

Transmission of 40 Gb/s channels will be demonstrated over a commercial 10 Gb/s dense-wavelength-division-multiplexing Siemens TranXpress System, including a polarization-mode dispersion emulation, so as to prove the effectiveness of advanced modulation formats over a practical system. Once this is proven, demonstration of the transmission will be implemented over an installed long-haul transmission system, for example, the Sydney-Melbourne optically amplified fiber terrestrial link. The impact of the self-phase-modulation nonlinear effects will also be investigated.

Furthermore, efficient binary and M-ary modulation techniques, such as minimum-shift keying (MSK) and continuous-phase frequency-shift keying (CPFSK), are under investigations by us, and their transmission performance over long-haul transmission will be reported in the future.

We expect that the convergence between electronic processing speeds and photonic processing will open new fields of research and interaction between these two fields, which are the principal focuses of the activities of Commission D of URSI.

## 6. Acknowledgement

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# Radio-Frequency Radiation Safety and Health

James C. Lin

## *Mobile Telecommunication Health-Effect Research Outcomes and Sources of Funding**

## Abstract

A recent systematic review of the outcome of experimental studies reported in scientific journals and sources of funding for the reported research suggests that the evaluation of results from existing and future studies of the health effects of microwave radiation from wireless communication should take sponsorship into account.

From time to time, there have been anecdotal or media accounts suggesting there is reason to suspect that sponsors of cell-phone or wireless radio-frequency (RF) radiation safety research may suppress publication of scientific results that are adverse to the sponsors, such as the wireless industry and military establishments. Some have speculated that the cell-phone manufacturers, for their interest, often seem bound and dogged to frustrate and refute any suggestion that their products might be harmful to human health. Of course, the manufacturers are constantly offering new designs, improved services, and ever-increasing numbers of minutes, which can't help but encourage subscribers to use cell phones more and more frequently. However, I'm convinced that cell-phone manufacturers are not deliberately making their products addictive, although the end result might seem not too different, at times.

A recent article on a systematic review of the outcome of experimental studies reported in scientific journals and sources of funding for the reported research suggested that the evaluation of results from existing and future studies of the health effects of microwave radiation from wireless communication should take sponsorship into account [1]. The study included papers published in English, German, or French, through February 2005 (between 1995 and 2005). It included original articles reporting studies of the effects of controlled laboratory exposure with RF radiation on human-health-related outcomes, which included electroencephalogram (EEG) recordings, assessments of cognitive or cardiovascular function, hormone levels, and subjective well-being and symptoms. Data on sources of funding were independently extracted from the papers, as reported by the authors. The quality of the reported studies was assessed by study design and analysis in terms of blindness and randomization, exposure setting and dosimetry, and appropriate statistical analysis. The primary criterion was the reporting of at least one statistically significant ( $p < 0.05$ ) association between cell-phone RF exposure and a health-related outcome. Logistic regression models were used to assess whether the source of funding was associated with the reporting of at least one significant effect in the paper.

Among 59 relevant studies, published in 31 journals, 12 (20%) were exclusively funded by the telecommunications industry, 11 (19%) were funded by public agencies or charities, 14 (24%) had mixed funding (including industry and industry-independent sources), and the source of funding was not reported in 22 (37%) studies. Five (8%) studies had authors with industry affiliation. The median study participant size was 20.

The results showed that studies exclusively funded by industry were less likely to report statistically significant results: the odds ratio (OR) for reporting at least one significant finding was 0.11, compared to studies funded by public agencies or charities ( $\mathrm{OR} = 1.00$ is the reference). This finding was not altered after adjusting for the number of outcomes reported, study design and quality, exposure characteristics, or outcomes. Similar results were obtained for results reported in the abstracts or in the conclusions of

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the abstracts. Also, among the 59 studies, 11 (19%) had a title reporting an effect, 11 (19%) had a title reporting no effect, and 37 (63%) had a neutral title. Note that a majority (68%) of the studies evaluated showed biological effects, although at present it is unclear whether the biological effects translated into relevant health hazards.

A potential limitation of this study's finding is that the statistically significant association ignores the extent of reported biological effects. However, the same indication was obtained when the authors' conclusions in the abstracts were analyzed. Nevertheless, the report showed that studies exclusively funded by industry were nine times less likely to report statistically significant effects on a range of endpoints that may be relevant to health.

Although the recent article on cell phones is the first published study to examine the sponsorship issue in the context of exposure to cell-phone RF electromagnetic fields, publications on the correlation between industry sponsorship and associated outcomes that favor the sponsor's product are not new. The influence of the tobacco industry on the research it funded has been well documented [2]. A meta-analysis revealed that studies sponsored by the pharmaceutical industry were about four times less likely to have clinical outcomes unfavorable to the sponsor's drug than studies with other sources of funding [3]. Possible explanations for the association between the source of funding and research results in the context of drug research sponsored by the pharmaceutical industry include the type of outcomes targeted, the selective publication of studies that produced results that fit the sponsor's agenda, the sponsor's influence on the design of the study, and the protocol for the exposure [3-5].

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# Conferences

## CONFERENCE ANNOUNCEMENTS

### INTERNATIONAL CONFERENCE ON RADIO SCIENCE (ICRS 2008)

Om Niwas, Jodhpur, India, 25 - 29 February 2008

The 4th International Conference on Radio Science, which will be held in Jodhpur, India, from 25 to 29 February 2008, is organised by the International Centre for Radio Science and sponsored by the Departments of Govt. of India and Rajasthan, the International Union of Radio Science (URSI) and the IEEE-GRS Society (IEEE-GRSS), USA.

The ICRS has a registered office at Jodhpur and has collaborative programmes with Research Institution as well as Universities. ICRS has worked for projects for Defence Research and Development Organization. ICRS have completed Seven DRDO projects related to material properties measurements, measurements of electrical properties of natural earth materials (Soil, Snow etc) and studies of radar systems. Over the past 9 years, ICRS has been organizing annual conferences on the related topics. It has already organized five National conferences and three International conferences.

During this conference, an exhibition will be organized. Educational Institutions and Scientific Organizations from the field of Radio Science and Companies and Industries related to this field & publishers are invited to display their projects and products. The request for participation should reach by 15th November 2007.

#### Topics

URSI Commissions
- Electromagnetic Metrology : Commission A
- Fields and Waves : Commission B
- Radio Communication Systems and Signal Processing: Commission C
- Electronics and Photonics : Commission D
- Electromagnetic Noise and Interference: CommissionE
- Wave Propagation and Remote Sensing : CommissionF
- Ionospheric Radio and Propagation : Commission G
- Waves in Plasmas : Commission H
- Radio Astronomy : Commission J
- Electromagnetics in Biology & Medicine : Commission K

and also
- Antenna arrays and Antenna pattern synthesis.
- Dielectric property measurement.
- Expert systems for antenna design and smart antenna.
- Microstrip antenna and wideband antenna
- Microwave and millimeter wave device and circuits.
- Microwave measurements.
- Radar Cross section.
- Microwave remote sensing of land, Ocean and atmosphere.
- Passive and active microwave sensors including radiometer and radar systems.
- Data products generations for different applications.
- Antenna measurement using planar Near Field facility compact antenna test facility.
- Microwave Tubes
- Microwave Systems
- Terahertz Application
- Digital Signal Processing

#### Deadlines

15 September 2007: Submission of Summary (500 words)
15 October 2007: Acceptance of Summary:
15 December 2007: Submission of Full paper

#### Workshops

Two workshops will be organised as parallel sessions:
- Workshop I on Asymptotic and Numerical Techniques for RCS and Antenna Analysis
- Workshop II on Microwave Remote Sensing

For further details please visit our website www.radioscience.org, www.icrsju.org

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# NATO Advanced Research Workshop: Metamaterials for Secure Information and Communication Technologies

Marrakesh, Morocco, 7 - 10 May 2008

Metamaterials represent a truly multidisciplinary research area spanning the bridge from basic theoretical and experimental research at universities to industrial production of a diverse spectrum of electrical, microwave, infrared and optical materials and devices. The meeting will cover a broad scope of topics ranging from the fundamental electromagnetic theory of metamaterials to novel types of microwave and optical devices and components. Special attention will be given to applications of these innovative materials in secure wireless and optical communication systems, high-speed circuits, optical sensing, nanoscale imaging and cloaking.

The workshop program will include invited talks, contributed oral and poster presentations. META'08 will be the foremost place to learn about the most important developments in the field of Metamaterials.

## Topics

META'08 topics include, but are not limited to:

- Fundamental and applied aspects of waves in structured, periodic and disordered metamaterials.
- Electromagnetic properties of complex materials including photonic and plasmonic band gap materials, negative-index materials and novel composites with unusual electromagnetic properties.
- Modelling, fabrication and characterization of complex materials and surfaces.
- Metamaterials technologies and applications.

## Deadlines

30 June 2007: First Call for Papers
15 October 2007: Second Call for Papers
22 December 2007: Deadline for Submission of abstracts
28 January 2008: Notification of acceptance
3 March 2008: Submission of final manuscript and registration

## Paper Submission

Authors MUST submit camera-ready papers up to 2 A4 pages including figures by 22th December, 2007, via the conference website. The paper format and submission guideline can be found at: http://meta.lgep.supelec.fr/submission.html

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# URSI CONFERENCE CALENDAR

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

## June 2007

**MSMW'07 - Sixth International Kharkov Symposium on Physics and Engineering of Microwaves, Millimeter and Submillimetre Waces + TeraTech'07**
*Kharkov, Ukraine, 25-30 June 2007*
cf. Announcement in the Radio Science Bulletin of March 2007, p. 56.
Contact : MSMW'07, IRE NASU, Ul. Proskury 12, Kharkov, 61085, Ukraine, Phone: +38 (057) 3150006 , Fax: +38 (057) 3152105, E-mail: msmw07@ire.kharkov.ua, http://www.ire.kharkov.ua/MSMW07/index.html

**EMC'07 - International Symposium on Electromagnetic Compatibility and EM Ecology**
*St. Petersburg, Russia, 26-29 June 2007*
cf. Announcement in the Radio Science Bulletin of September 2006, p. 50.
Contact : Discone-Centre Ltd., St. Petersburg State Electrotechnical University - LETI, Tel. +7 812-234-4840, Fax +7 812-234-4681, E-mail : discone@mail.wplus.net , Web : www.eltech.ru/emc

## July 2007

**IRI/COST296 Workshop on Ionosphere Modeling, Forcing and Telecommunications**
*Prague, Czech Republic, 10-14 July 2007*
Contact : Dr. Jan Lastovicka, Institute of Atmospheric Physics, Acad. Sci. Czech Republic, Bocni II, 1401a,

14131 Prague 4, Czech Republic, Fax +420 2727 63745, jla@ufa.cas.cz

**URSI CNC/USNC North American Radio Science Meeting**
*Ottawa, ON, Canada, 22-26 July 2007*
Contact : Dr. Yahia M.M. Antar, (CNC Chair), Email: antar-y@rmc.ca , Dr. George Uslenghi, (USNC Chair), Email: uslenghi@uic.edu, Web : http://ursi2007.ee.umanitoba.ca

**EMTS 2007 - URSI Commission B EMT-Symposium**
*Ottawa, ON, Canada, 26-28 July 2007*
cf. Announcement in the Radio Science Bulletin of December 2006, p. 77.
Contact : Prof. Lot Shafai, Chair Commission B, Dept. of Electrical and Computer Engineering, University of Manitoba, 75 Chancellors Circle, Winnipeg, MB, Canada R3T 5V6, Fax (204) 269 - 0381, E-mail : shafai@ee.umanitoba.ca , Web : http://emts2007.ee.umanitoba.ca

**International Symposium on Signals, Systems, and Electronics (ISSSE 2007)**
*Montreal, Canada, 30 July - 2 August 2007*
cf. Announcement in the Radio Science Bulletin of December 2006, 78.
Contact: Prof. Ke Wu, Director of Poly-Grames Research Center, Ecole Polytechnique, C. P. 6079, Succ. Centre-Ville, Montreal, Quebec, Canada H3C 3A7, Tel: +1 (514) 340-4711 ext. 5991, Fax: +1 (514) 340-5892, E-mail: ke.wu@polymtl.ca or ke.wu@ieee.org

## August 2007

**Rarotonga Energetic Particle Workshop 2007**
*Rarotonga (Cook Islands), 5-10 August 2007*
Contact : Dr. Craig J. Rodger, Department of Physics, University of Otago, P.O. Box 56, Dunedin, New Zealand, Fax +64 3 479 0964, crodger@physics.otago.ac.nz , Web : http://www.physics.otago.ac.nz/space/REPW2007_Home_Page.htm

**ISAP 2007 - International Symposium on Antennas and Propagation**
*Niigata, Japan, 20-24 August 2007*
Contact : Yoshihiko Konishi (Publicity Chair), Mitsubishi Electric Corporation, 5-1-1 Ofuna, Kamakura, 247-8501 Japan, E-mail : isap-2007@mail.ieice.org, Web : http://www.isap07.org

## September 2007

**International Symposium on Radio Systems and Space Plasma**
*Sofia, Bulgaria, on 2-5 September 2007*
cf. Announcement in the Radio Science Bulletin of December 2006, p. 79.
Contact : Prof. B. Shishkov, Head of Telecommunication Dept., Institute of Mathematics & Informatics, Bulgarian Academy of Sciences, Acad. G. Bonchev Str., Bl. 8, Sofia 1113, Bulgaria, fax: ++359 2 971 3649, e-mail: bshishkov@math.bas.bg, Web : http://www.math.bas.bg/isrssp/

**International Conference on Electromagnetics in Advanced Applications (ICEAA 07)**
*Torino, Italy, 17 - 21 September 2007*
cf. Announcement in the Radio Science Bulletin of December 2006, p. 79.
Contact: Prof. Roberto D. Graglia, Chair of ICEAA Organizing Committee, Dipartimento di Elettronica, Politecnico di Torino, Corso Duca degli Abruzzi, 24, 10129 Torino, Italy, E-mail: roberto.graglia@polito.it or Prof. Piergiorgio L. E. Uslenghi, Chair of ICEAA Scientific Committee, Department of ECE (MC 154), University of Illinois at Chicago, 851 South Morgan Street, Chicago, IL 60607, USA, E-mail: uslenghi@uic.edu.

**EMC Zürich 2007**
*München, Germany, 24-28 September 2007*
Contact : Prof. Dr. P. Russer, Symposium President, TU Munich, Germany and Prof. Dr. R. Vahldieck, General Chairman, ETH Zürich, IFH, Switzerland, Tel: +41 44 632 2951, Fax: +41 44 632 1198 , e-mail: info@emczurich.ethz.ch , http://www.emc-zurich.ch/

## October 2007

**From Planets to Dark Energy: the Modern Radio Universe**
*Manchester, UK, 1-5 October 2007*
cf. Announcement in the Radio Science Bulletin of December 2006, p. 80.
Contact : Prof. Ph. Diamond, Jodrell Bank Observatory, University of Manchester, Macclesfield, Cheshire SK11 9DL, UK, fax +44 1477-572618, E-mail : pdiamond@jb.man.ac.uk , majordomo@jb.man.ac.uk , Web : http://www.jb.man.ac.uk/mru2007/

**Scientific and Fundamental Aspects of the Galileo Programme**
*Toulouse, France, 2-4 October 2007*
cf. Announcement in the Radio Science Bulletin of December 2006, p. 81.
Contact : Dr. Bertram Arbesser-Rastburg, ESA-ESTEC, TEC-EEP, Postbus 299, NL-2200 AG Noordwijk, the Netherlands, fax +31 71 565-4999, Organisation Committee: Martine.Segur@anae.fr, Scientific Committee: Clovis.de.Matos@esa.int, Web : www.congrex.nl/07a06

**Metamaterials 2007 - The First International Congress on Advanced Electromagnetic Materials for Microwaves and Optics**
*Rome, Italy, 22-26 October 2007*
cf. Announcement in the Radio Science Bulletin of December 2006, p. 81.

Contact : Dr. Said Zouhdi, Electrical Engineering, University Pierre et Marie Curie, Paris, France + Laboratoire de Genie Electrique de Paris LGEP-Supelec, Fax : + 33 1 69 41 83 18, E-mail : sz@ccr.jussieu.fr

**11th URSI Commission F Triennial Open Symposium on Radio Wave Propagation and Remote Sensing**
*Rio de Janeiro, Brazil, 30 October - 2 November 2007*
cf. Announcement in the Radio Science Bulletin of March 2007, p. 57.
Contact : Dr. Emanoel Costa, CETUC-PUC/Rio, Brazil (Chair, Propagation), Luciano Vieira Dutra, INPE, Brazil (Chair, Remote Sensing), Web: http://wwwusers.rdc.puc-rio.br/ursif/

## November 2007

**APSAR 2007 - Asia-Pacific Conference on Synthetic Aperture Radar**
*Huangshan city, Anhui province, China, 5-10 November 2007*
Contact : Mr. Mengqi Zhou, Chinese Institute of Electronics, P.O. Box 165, 100036 Beijing, China, Phone : +86 10-6816 0825, Fax : +86 10-6828 3458, E-mail : mqzhou@public.bta.net.cn , Web: http://www.cie-china.org/APSAR2007/index.htm

**EuCAP 2007 - The Second European Conference on Antennas and Propagation**
*Edinburgh, United Kingdom, 11-16 November 2007*
Contact : The Institution of Engineering and Technology, Paul Newell / Simon Blows / Emily Woodman, Event Services, Michael Faraday House, Six Hills Way, Stevenage, Hertfordshire SG1 2AY, UK, Tel: +44 1438 765648/ 765653, Fax: +44 1438 765659, Email: eucap@ietevents.org, http://www.eucap2007.org/

## December 2007

**APMC 2007 - 2007 Asia-Pacific Microwave Conference**
*Bangkok, Thailand, 11-14 December 2007*
cf. Announcement in the Radio Science Bulletin of September 2006, p. 51.
Contact : Dr. Chuwong Phongcharoenpanich, General Secretary of APMC 2007, King Mongkut's Institute of Technology Ladkrabang, Bangkok 10520, Thailand, E-mail:kpchuwon@kmitl.ac.th, Web:http://www.apmc2007.org/

## February 2008

**ICRS 2008 - International Conference on Radio Science**
*Jodhpur, India, 25-29 February 2008*
cf. Announcement in the Radio Science Bulletin of June 2007, p. 56.
Contact : Prof. O.P.N. Calla, Director ICRS, OM-NIWAS, A-23 Shastri Nagar, Jodhpur 342003, Rajasthan, India, Fax +91 291-2626166, E-mail : opncalla@yahoo.co.in , E-mail : http://radioscience.org/default.html

## May 2008

**IES2008 - 12th International Ionospheric Effects Symposium**
*Alexandria, Virginia, USA, 6-8 May 2008*
Contact : JMG Associates Ltd., IES Symposium Managers, 8310 Lilac Lane, Alexandria VA 22308, USA, Fax: +1-703-360-3954, Web : http://www.ies2008.com/index.html

**Metamaterials for Secure Information and Communication Technologies**
*Marrakesh, Morocco, 7 - 10 May 2008*
cf. Announcement in the Radio Science Bulletin of June 2007, p. 57.
Contact: Prof. Saïd Zouhdi, Laboratoire de Génie Electrique de Paris (LGEP-Supélec), Plateau de Moulon, 91192 Gif-Sur-Yvette Cedex, France, Tel: +33 1 69851660, Fax: +33 169418318, Email: said.zouhdi@supelec.fr, Web site: http://meta.lgep.supelec.fr

## July 2008

**COSPAR 2008 - 37th Scientific Assembly of the Committee on Space Research and Associated Events "50th Anniversary Assembly"**
*Montreal, Canada, 13 - 20 July 2008*
cf. Announcement in the Radio Science Bulletin of March 2007, p. 58.
Contact : COSPAR Secretariat, c/o CNES, 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, Web : http://www.cospar2008.org

**EUROEM 2008 - European Electromagnetics**
*Lausanne, Switzerland, 21-25 July 2008*
Contact : EUROEM'08, EPFL-STI- LRE, Station 11, CH-1015 Lausanne, Switzerland, Tel : +41-21-693 26 20, Fax : +41-21-693 46 62, E-mail: information@euroem.org, Web : http://www.euroem.org

## August 2008

**URSI GA08 - XXIXth URSI General Assembly**
*Chicago, IL, USA, 9-16 August 2008*
Contact : URSI Secretariat, c/o INTEC, Ghent University, Sint-Pietersnieuwstraat 41, B-9000 Ghent, Belgium, Tel. : +32 9 264 3320, Fax : +32 9 264 4288, E-mail : info@ursi.org

*An up-to-date version of this Conference Calendar, with links to various conference web sites can be found at www.ursi.org/Calandar of supported meetings*

# News from the URSI Community

## NEWS FROM A MEMBER COMMITTEE

### TURKEY

### Computational Electromagnetics Workshop (CEM’07)

Izmir, Turkey, 30 - 31 August 2007

Bilkent University Computational Electromagnetics Research Center (BiLCEM.) is organizing an international workshop on August 30-31, 2007, in the beautiful Aegean city of Izmir, Turkey, to discuss recent progress in the area of computational electromagnetics. Details of the workshop, such as travel, hotel, and social program, will be announced at the following web link as they become available: **http://www.cem.bilkent.edu.tr/CEM07.html**

### Topics

**Methods**

- Fast solvers
- Integral equations
- Iterative solvers and preconditioning
- Parallel computing
- Frequency-domain methods
- Time-domain methods
- Direct solvers
- Recursive solvers
- Optimization methods
- FDTD methods
- FEM methods
- High-frequency methods
- Hybrid methods

**Applications**

- Large-scale problems
- Scattering and RCS
- Antennas
- Radars
- Metamaterials
- Optics
- Imaging
- Remote sensing
- Inverse problems
- Biomedical applications
- Wireless and propagation
- EMC/EMI
- Chips, packages, and interconnects

### Important Dates

| | |
|---|---|
| June 25, 2007: | Submission of one-page abstracts |
| July 2, 2007: | Notification of acceptance |
| July 9, 2007: | Registration deadline |
| July 30, 2007: | Submission of summaries |

### Contact

Please direct your questions and inquiries to Prof. Levent Gürel, Director of BiLCEM.: lgurel@bilkent.edu.tr

## BOOK PUBLISHED BY AN URSI RADIOSCIENTIST

### Electromagnetic Fields, 2nd Edition

By Jean Van Bladel, Wiley IEEE Press, 2007, 1176 pp, Hardcover,
ISBN-13: 978-0-471-26388-3

This definitive text and reference on electromagnetic fields has been updated and expanded to twice its original content. It incorporates the latest methods, theory, formulations, and applications that relate to today’s technologies. With an emphasis on basic principles and a focus on electromagnetic formulation and analysis, Electromagnetic Fields, Second Edition includes:

1. Detailed discussions of electrostatic fields, potential theory, propagation in waveguides and unbounded space, scattering by obstacles, penetration through apertures, and field behavior at high and low frequencies
2. Many analytical developments suitable for exploitation by the numerical analyst, including the popular method of moments

3. Comprehensive discussion of singularities of sources and fields with delineations of field properties at edges and at sector and cone vertices
4. Extensive appendices and an extensive carefully compiled set of references

With descriptions of methods for solving problems and with many applications of theory to electromagnetic engineering, this is a valuable resource for students, professors, and practicing engineers. It is also a comprehensive textbook for graduate-level courses in various aspects of electromagnetic theory.

## Abouth the Author

Jean Van Bladel is an eminent researcher and educator in fundamental electromagnetic theory and its application to electrical engineering. He is a fellow of the IEEE and was awarded the Heinrich Hertz Gold Medal of IEEE in 1995. He has been an Honorary President of the International Union of Radio Science since 1999, and was their Secretary General from 1979 to 1993. Dr. Van Bladel received his Ph.D. in Electrical Engineering from the University of Wisconsin. After a few years with the Philips Company, he taught at Washington University (St. Louis), the University of Wisconsin and, from 1964 to 1987 at Ghent University, where he is currently Professor Emeritus.

# In Memoriam

## ROGER GENDRIN
## 1932 - 2007

Dr Roger Gendrin, Commission H Chair from 1975 to 1977, and rewarded by a John Howard Dellinger medal in 1987, passed away on April 21st 2007. He was 76 years old. He was one of the pioneer in space plasma physics and marked several generations of researchers working in this domain.

Roger Gendrin started his scientific career in the sixties by developing search coil magnetometers and implementing them in two conjugated stations: Sogra (in Russia) and Kerguelen islands (Indian Ocean). From measurements performed in both stations he shown how to derive properties of the magnetospheric plasma crossed by ULF waves. In parallel he made very significant contributions to the theory of Wave Particle Interactions (WPI's). In the seventies he plaid a key role in the definition and acceptation by ESA, of the GEOS spacecraft and took the lead of the wave consortium. In that respect he strongly contributed to the constitution of a strong European Solar System community. His contribution to the "Study of waves of natural origin propagating in the surroundings of the Earth, and their influence on the behaviour of the magnetosphere" was acknowledged by the URSI John Howard Dellinger medal. In view of his prominent role as a scientist and as an efficient organiser, he was elected President of IAGA for the period 1987 – 1991.

Roger Gendrin has been the director of CRPE, now called CETP (Centre d'étude des Environnements Terrestres et Planétaires), for 4 years. Together with Professors Maha Ashour Abdalla (UCLA) and Hiroshi Matsumoto (Univ. of Kyoto), he took an active part in the development of numerical simulation, by organizing a series of international schools. No doubt that this initiative had an important impact in the fast expansion of this tool for studying space plasmas. Before retirement he headed IFRTP, the French Institute for polar studies, thereby being in charge of the coordination of studies conducted in Kerguelen Islands, where here he made his first experiments about 30 years before.

Even after retiring he continued to be dedicated to science. In the early two thousands he chaired the ESA Space Weather Working Team (SWWT) in charge of following first European initiatives on Space Weather. More recently he strongly contributed to the reviewing phases of the URSI white paper on Solar Power Satellites.

Roger was a character, difficult to convince but always ready to discuss. He was very involved in ethics, rights and responsibilities issues. We deeply miss this original scientist who was very demanding but so friendly and generous.

We convey our greatest sympathy to his wife Janine and his children and grandchildren.

Dr. Alain Roux
Email: alain.roux@cetp.ipsl.fr

# The Journal of Atmospheric and Solar-Terrestrial Physics

## SPECIAL OFFER TO URSI RADIOSCIENTISTS

AIMS AND SCOPE

The *Journal of Atmospheric and Terrestrial Physics* (JASTP) first appeared in print in 1951, at the very start of what is termed the "Space Age". The first papers grappled with such novel subjects as the Earth's ionosphere and photographic studies of the aurora. Since that early, seminal work, the Journal has continuously evolved and expanded its scope in concert with - and in support of - the exciting evolution of a dynamic, rapidly growing field of scientific endeavour: the Earth and Space Sciences. At its Golden Anniversary, the now re-named *Journal of Atmospheric and Solar-Terrestrial Physics* (JASTP) continues its development as the premier international journal dedicated to the physics of the Earth's atmospheric and space environment, especially the highly varied and highly variable physical phenomena that occur in this natural laboratory and the processes that couple them. The *Journal of Atmospheric and Solar-Terrestrial Physics* is an international journal concerned with the inter-disciplinary science of the Sun-Earth connection, defined very broadly. The journal referees and publishes original research papers, using rigorous standards of review, and focusing on the following: The results of experiments and their interpretations, and results of theoretical or modelling studies; Papers dealing with remote sensing carried out from the ground or space and with in situ studies made from rockets or from satellites orbiting the Earth; and, Plans for future research, often carried out within programs of international scope. The Journal also encourages papers involving: large scale collaborations, especially those with an international perspective; rapid communications; papers dealing with novel techniques or methodologies; commissioned review papers on topical subjects; and, special issues arising from chosen scientific symposia or workshops. The journal covers the physical processes operating in the troposphere, stratosphere, mesosphere, thermosphere, ionosphere, magnetosphere, the Sun, interplanetary medium, and heliosphere. Phenomena occurring in other "spheres", solar influences on climate, and supporting laboratory measurements are also considered. The journal deals especially with the coupling between the different regions. Solar flares, coronal mass ejections, and other energetic events on the Sun create interesting and important perturbations in the near-Earth space environment. The physics of this subject, now termed "space weather", is central to the Journal of Atmospheric and Solar-Terrestrial Physics and the journal welcomes papers that lead in the direction of a predictive understanding of the coupled system. Regarding the upper atmosphere, the subjects of aeronomy, geomagnetism and geoelectricity, auroral phenomena, radio wave propagation, and plasma instabilities, are examples within the broad field of solar-terrestrial physics which emphasise the energy exchange between the solar wind, the magnetospheric and ionosphericplasmas, and the neutral gas. In the lower atmosphere, topics covered range from mesoscale to global scale dynamics, to atmospheric electricity, lightning and its effects, and to anthropogenic changes. Helpful, novel schematic diagrams are encouraged. Short animations and ancillary data sets can also be accommodated. Prospective authors should review the *Instructions to Authors* at the back of each issue.

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# Information for authors

### Content

The *Radio Science Bulletin* is published four times per year by the Radio Science Press on behalf of URSI, the International Union of Radio Science. The content of the *Bulletin* falls into three categories: peer-reviewed scientific papers, correspondence items (short technical notes, letters to the editor, reports on meetings, and reviews), and general and administrative information issued by the URSI Secretariat. Scientific papers may be invited (such as papers in the *Reviews of Radio Science* series, from the Commissions of URSI) or contributed. Papers may include original contributions, but should preferably also be of a sufficiently tutorial or review nature to be of interest to a wide range of radio scientists. The *Radio Science Bulletin* is indexed and abstracted by INSPEC.

Scientific papers are subjected to peer review. The content should be original and should not duplicate information or material that has been previously published (if use is made of previously published material, this must be identified to the Editor at the time of submission). Submission of a manuscript constitutes an implicit statement by the author(s) that it has not been submitted, accepted for publication, published, or copyrighted elsewhere, unless stated differently by the author(s) at time of submission. Accepted material will not be returned unless requested by the author(s) at time of submission.

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Material submitted for publication in the scientific section of the *Bulletin* should be addressed to the Editor, whereas administrative material is handled directly with the Secretariat. Submission in electronic format according to the instructions below is preferred. There are typically no page charges for contributions following the guidelines. No free reprints are provided.

### Style and Format

There are no set limits on the length of papers, but they typically range from three to 15 published pages including figures. The official languages of URSI are French and English: contributions in either language are acceptable. No specific style for the manuscript is required as the final layout of the material is done by the URSI Secretariat. Manuscripts should generally be prepared in one column for printing on one side of the paper, with as little use of automatic formatting features of word processors as possible. A complete style guide for the *Reviews of Radio Science* can be downloaded from http://www.ips.gov.au/IPSHosted/NCRS/reviews/. The style instructions in this can be followed for all other *Bulletin* contributions, as well. The name, affiliation, address, telephone and fax numbers, and e-mail address for all authors must be included with all submissions.

All papers accepted for publication are subject to editing to provide uniformity of style and clarity of language. The publication schedule does not usually permit providing galleys to the author.

Figure captions should be on a separate page in proper style; see the above guide or any issue for examples. All lettering on figures must be of sufficient size to be at least 9 pt in size after reduction to column width. Each illustration should be identified on the back or at the bottom of the sheet with the figure number and name of author(s). If possible, the figures should also be provided in electronic format. TIF is preferred, although other formats are possible as well: please contact the Editor. Electronic versions of figures *must* be of sufficient resolution to permit good quality in print. As a rough guideline, when sized to column width, line art should have a minimum resolution of 300 dpi; color photographs should have a minimum resolution of 150 dpi with a color depth of 24 bits. 72 dpi images intended for the Web are generally *not* acceptable. Contact the Editor for further information.

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A version of Microsoft *Word* is the preferred format for submissions. Submissions in versions of $T_EX$ can be accepted in some circumstances: please contact the Editor before submitting. *A paper copy of all electronic submissions must be mailed to the Editor, including originals of all figures.* Please do *not* include figures in the same file as the text of a contribution. Electronic files can be send to the Editor in three ways: (1) By sending a floppy diskette or CD-R; (2) By attachment to an e-mail message to the Editor (the maximum size for attachments *after* MIME encoding is about 7 MB); (3) By e-mailing the Editor instructions for downloading the material from an ftp site.

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The review process usually requires about three months. Authors may be asked to modify the manuscript if it is not accepted in its original form. The elapsed time between receipt of a manuscript and publication is usually less than twelve months.

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