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GPS-based verticality approximation of an experimental fully-airborne VLF antenna

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Abstract

Verticality, a parameter calculated as a difference between the positions of the upper and lower ends of a long, aerostat- or aircraft-supported antenna, divided by the antenna's length, is an important parameter describing the spatial form of the very low frequency (VLF) antenna, crucial for the assessment of its operation efficiency. In this paper, a fully-airborne (not anchored) VLF test antenna is analyzed in the terms of its verticality during the ascending phase of its flight, including flight in the proximity of the stratospheric jet stream. The unsynchronized GPS data from the antenna's proximities are used to determine the verticality with defined accuracy. The limits of this method are shown, with the possible ameliorations in order to refine the data collection and expand the range of their usefulness towards the overall antenna design.

1 1. Introduction. Airborne VLF antennas and their verticality

Antenna systems involving airborne technology have been considered as an alternative for large VLF terrestrial antenna systems since the 1920s [1], potentially providing a significant reduction of installation costs, elongation of the vertical part of the antenna and, if sufficiently high altitudes are reached, practical stealth properties of the transmitting system. These airborne systems can be divided into three main groups: airplane-trailed antennas, aerostat-lifted antennas anchored on ground and fully-airborne aerostat-lifted antennas.

The first group allows the deployment of antennas reaching several thousands of meters of length, yet their verticality is dependent on the path followed by the trailing aircraft, the aircraft's velocity (minimal approximately 300 km/h) and the efficiency of the drought's operation (a small parachute-like device on the end of the antenna); such VLF antenna deployment methods are widely investigated today [2]. The second group, investigated in the 1980s and 1990s [3, 4], is a practical substitution of terrestrial mechanical supporting structures (towers, masts) with an aerostat; the antenna length may also reach thousands of meters, while preserving the properties of a terrestrial structure regarding the positioning of the transmitter - with the static electrification of the wire being one of the main issues for such systems [4]. The third group consists of a specially redesigned stratospheric balloon missions, lifting up long vertical antennas equipped with transmitters to the maximum altitude of ~30000 m, being able to provide both very long antenna dimensions and the practical stealth of such stratospheric system [5, 6].

The value of antenna verticality for all these groups - a parameter calculated as the difference between the positions of the upper and lower ends of the antenna, divided by its total length - is an important indication of the antenna's spatial form, which is a main factor affecting its performance as a radiator (as vertical antennas at VLF range produce stronger electric fields [7]), and therefore allowing the evaluation of the antenna's mechanical properties. It is dependent on the antenna flight conditions (wind, flight path etc.) and the design of the antenna wire, producing a specific aerodynamic drag. The parameters used to determine the verticality - the overall shape of the airborne wire, or the recorded positions of the antenna's extremities - can be investigated optically (both from above the antenna and from the ground) or by using a global navigation satellite system (GNSS), delivering data on the evolving positions of the antenna's extremities, which are then used to reconstruct the form of the wire in space and its changes in time. The employment of the second determination method also remain compliant with the safety requirements for a fully-airborne long-antenna aerostatic mission, providing a constant radio signal transmission from the entire flight train as a collision avoidance method, despite the fact that the flight train might range over more than one flight level [6].

In this paper, a fully-airborne VLF test antenna is analyzed in the terms of its verticality during the entire stratospheric flight, with the use of the GNSS system indications of the positioning of its extremities, with the flight path involving an interaction with time-evolving jet stream in the lower stratospheric region.

2 Experimental system and flight description

The fully-airborne VLF antenna system (no active VLF transmitter onboard) deployed on 12th September 2020, delivered numerous data on the electrical phenomena to which the antenna wire is subjected during flight [8, 9] and the operation/procedures of the launch and landing (detailed antenna description in [8]; total length of approximately 144 m). The upper end of the antenna - the flight train's main gondola - was equipped with a AVRT5 Automated Package Reporting System transmitter, operating on 144 MHz, delivering housekeeping data and a GPS-based position with altitude; the lower end of the antenna had a Vaisala RS41-SGP radiosonde attached, reprogrammed to transmit at 437.6 MHz with 4FSK modulation the transmitter's GPS-based position and the altitude.

The mission successfully passed through a storm front and reached the maximum altitude of 20326 m a.s.l. The AVRT5 transmitter worked with no disruptions, the RS41-SGP transmitter ceased operation shortly before the mission's apogee due to the temperature-linked failure of its power supply. Figure 1 presents the altitude vs. position data from both transmitters for the mission’s ascend phase, with the position expressed as a change in the guiding radius ΔR, calculated as the difference between the current guiding radius and the guiding radius in the beginning of the measurements (the radius calculated as a square root of the sum of squared longitude and latitude values expressed in meters [10]). At around 18 km of altitude the upper- and lower curves tend to converge (the vertical part of the curves in Figure 1), which indicates the entering of the zone of stratospheric winds associated with the jet stream [11] - an omniplanetary tubular whirlwind-like structure, characterized by a fast wind zone in its central part and significant spatial evolution (form changing) in time. This convergence however does not necessarily indicate the full verticality of the lifted antenna system - Figure 2 presents the jet stream region indications enlarged.

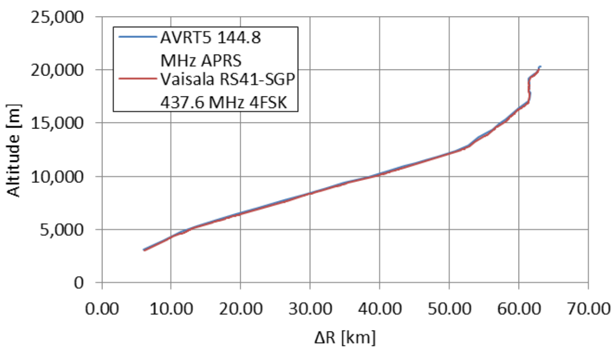

Figure 1. Altitude vs. guiding radius/position data for both transmitters affixed to the 144-m-long fully-airborne VLF antenna.

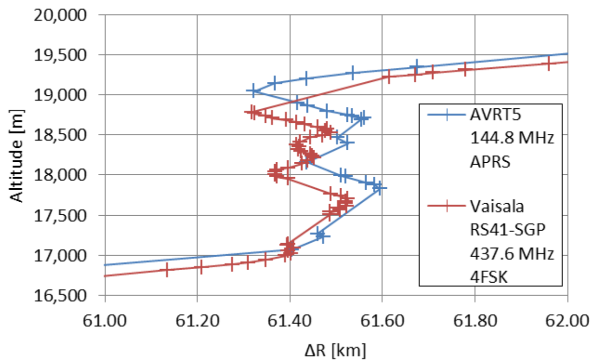

Figure 2. Altitude vs. guding radius/position of the fully-airborne VLF antenna flight train in the proximity of the jet stream.

3 Verticality approximation

As mentioned in the first paragraph, the verticality (expressed in %) is calculated as the difference between the positions of the antenna's extremities, divided by its total length. For accurate measurements, this parameter shall not exceed 100% + the measurement tolerance – otherwise, the extremities' positions are either not synchronized, or some of the positions are missing and the comparison can be expressed as an approximation only. In the case of the analyzed flight train, the lower transmitter did not deliver time stamps in its household data, which permitted a data synchronization based on the guiding radius only. Figure 1 clearly shows an acceptable offset of the data, which can be effectively used for verticality analysis; Figure 2 shows that the jet stream data points are positioned with much wider gaps between them, exceeding the actual length of the antenna (144 m).

To analyze the verticality in this region, the curves (data point groups forming them) were divided into parts approximated by Matlab curve fitting tool (polynomial, with the highest levels of polynomials for non-error fits). These approximations enabled the estimation of the altitudes as continuous functions (regardless of the number of the recorded data points), which were necessary for the verticality calculation, shown in Figure 3. Below the jet stream region, the verticality quickly rises (above the storm front) and approaches 100% twice; inside the jet stream region the differences between the received and non-time synchronized data produced overranged results, which indicate intense movements of the antenna, but with no reasonable accuracy.

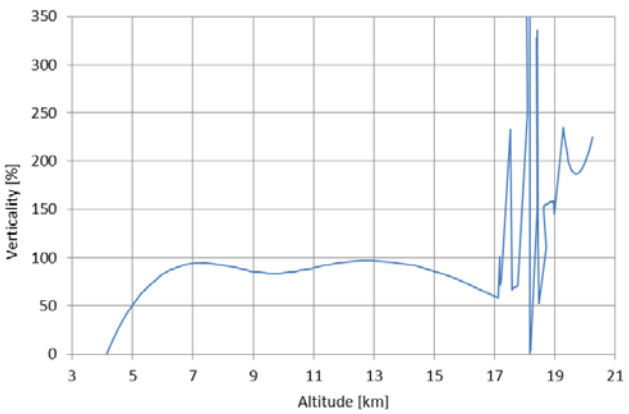

Figure 3. The calculated verticality parameter as a function of altitude for the considered fully-airborne VLF antenna mission.

For the reasonable results, the accuracy for the new-generation (after 2010s) GPS system is 3 m in the horizontal plane [12] and 15 m in the vertical plane [13], which gives a total verticality accuracy in these results of ±10.62 %.

4 Conclusions

The fully-airborne stratospheric VLF test antenna system was analyzed using experimental in-flight GPS data, approximated by continuous curves to deliver best-fitted functions used for the definition of the verticality parameter. The rapid changes of antenna position in the jest steam region around 18 km of altitude resulted in a severe dilution of positioning due to low amount of received data (the GPS transmitters operated continuously), distorting the calculated verticality. The verticality values obtained in the presented method (unsynchronized GPS indications) present best results for a stable flight, with the jest stream-affected flight requiring the employment of another position reporting system, e.g. using an inertial measurement unit (IMU) with GPS-based time synchronization. An accurate definition of verticality, apart from being an input to the analysis of operation of a fully functional VLF transmitting system, would also provide important data on the accelerations to which the antenna and its components are subjected, which is crucial for the improvements of the antenna's mechanical design.

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