TIME SERIES DATA IN GEOPHYSICS/SPACE PHYSICS

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ABSTRACT

Most geophysical and space physics data have time as one of the key variables in the data acquisition and subsequent analysis. Generally, in order to achieve physical understanding of these data, it is necessary to carry out comprehensive time series analyses. This paper outlines briefly the driving sources that produce time variability in many space and geophysical systems. It then discusses time series analyses of several selected data sets that describe the evolution of physical systems ranging from the sun through the interplanetary medium to the surface of Earth.

1. INTRODUCTION

No aspect of the Earth and its environment within the solar system is constant in time. The geology of the planet continually changes through such internal processes as earthquakes and volcanism. The surface topography is modified by variations in rain, wind and tropical storms. The dark splotches on the surface of the sun (now known as sunspots), discovered by Galileo shortly after his invention of the telescope, have an eleven year cycle of intensity. Even the total illumination of the sun (the solar "constant") is now known to change by a fraction of a percent over a sunspot cycle, and perhaps by even larger percentages over many tens or hundreds of years. The possible scale of such solar variabilities for producing changes in Earth's climate and weather is being actively investigated at present.

In addition to these time variations in readily familiar geophysical settings, there is a large variety of other solar-originating variabilities that can influence the earth's environment [1]. These originate because of magnetic activity within the sun and on its surface (as evidenced most visibly by the occurrence of sunspots). As schematically depicted in Figure 1, the sun emits charged particle radiation (primarily protons and electrons) in addition to light (photons) into the interplanetary medium. The energies of these particles (called plasmas) range from a few keV in the case of the solar wind to many tens of MeV in the case of particles emitted in association with solar flares and with coronal mass ejections (see below).

The solar wind, produced by the outward expansion of the solar corona (the hot, few million degree temperature, outer atmosphere of the sun familiar from solar eclipse photos) fills the entire solar system as far as has been measured to date (about fifty times the earth-sun distance). At Earth's orbit, the solar wind density is about ten electrons and protons per cubic centimeter, and can vary significantly with the intensity of magnetic activity on the sun.

The higher energy solar particles, while several factors of ten less in terms of average number density, originate from solar flares and from acceleration of lower energy particles by shock waves in the interplanetary medium. Some of the largest of these shocks are associated with coronal mass ejections, whose origins are just as their name would imply: large amounts of mass (order 10^{13}kg) suddenly ejected from the solar corona into the interplanetary medium.

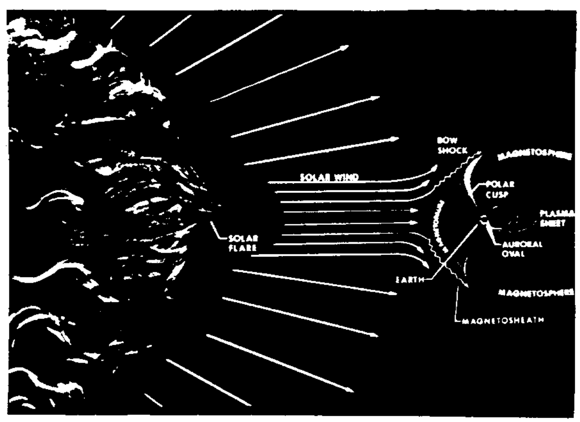

Fig. 1 Solar-terrestrial environment

2. TIME VARIABILITY

The interactions of all of these solar emissions – the solar wind, coronal mass ejections, and energetic solar particles – with the magnetic field of the Earth produces a very dynamic and highly time-variable space environment around Earth. Most importantly, the solar wind flow forms the earth's magnetic field into a long, invisible, comet-shaped object (the magnetosphere; Figure 2) that contains charged particles (plasmas) of a wide range of energies and intensities, including the Van Allen belts of trapped

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electrons and protons. The time variabilities of the solar emissions produce large changes in the trapped particles and current systems of the magnetosphere, changes that are not only of scientific interest, but also of considerable practical importance as they can detrimentally affect satellite systems in orbit around the earth and some technological systems that are deployed on Earth [2]. A few selected examples of space and geophysical time series and their natures are given in the following sections.

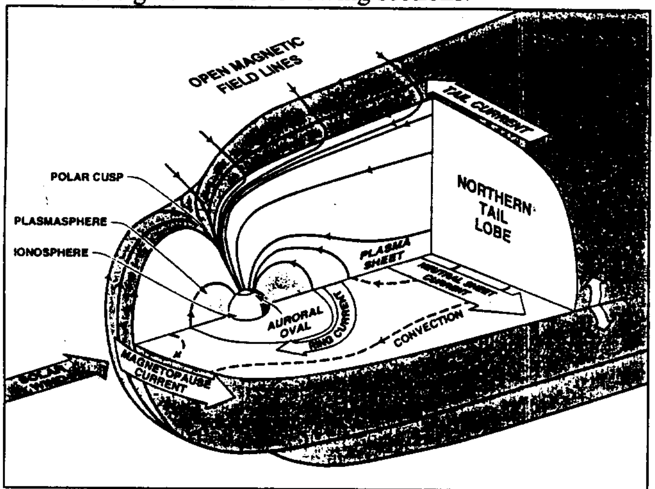

Fig. 2 Earth's magnetosphere

2.1. GEOMAGNETIC FIELD FLUCTUATIONS

Time variations in the magnetosphere current systems, including the ionosphere currents, produce changes in the magnetic field intensity measured in the magnetosphere as well as that measured at the Earth's surface. The spectra of geomagnetic field fluctuations are red, as is seen in the power spectra of Figure 3. These spectra are for magnetic field fluctuations averaged over a one month interval for data acquired with two different instruments at Arrival Heights (McMurdo Station), Antarctica [3]. They have a distribution varying approximately as f^{-2} over the ten decade range shown. In addition to the variability with time of the amplitudes and frequency dependence of such spectra, they also vary significantly with geomagnetic latitude.

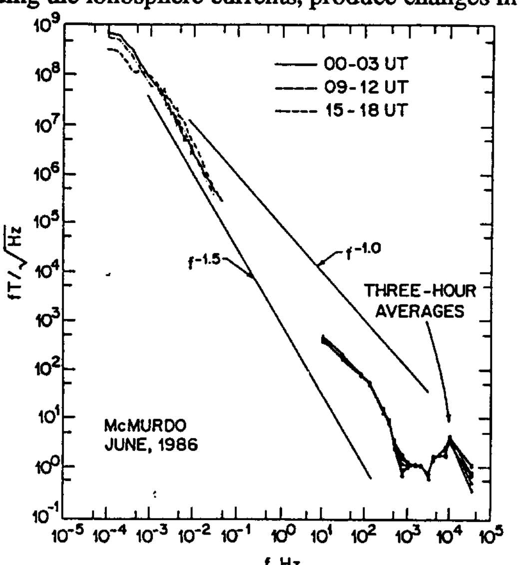

Fig. 3 Magnetic field power spectrum.

2.2. EARTH CURRENTS AND GEOMAGNETIC FLUCTUATIONS

The fluctuating magnetic field intensities at Earth's surface induce electrical currents to flow within the conducting Earth. If conductors such as communications cables, electrical power lines, or pipe lines are deployed on the Earth's surface, the Earth currents will tend to flow within the conductors rather than in the Earth itself. If these Earth currents become too large, as they can become at times under unusual geophysical conditions, they can damage the conducting systems through which they are flowing. For

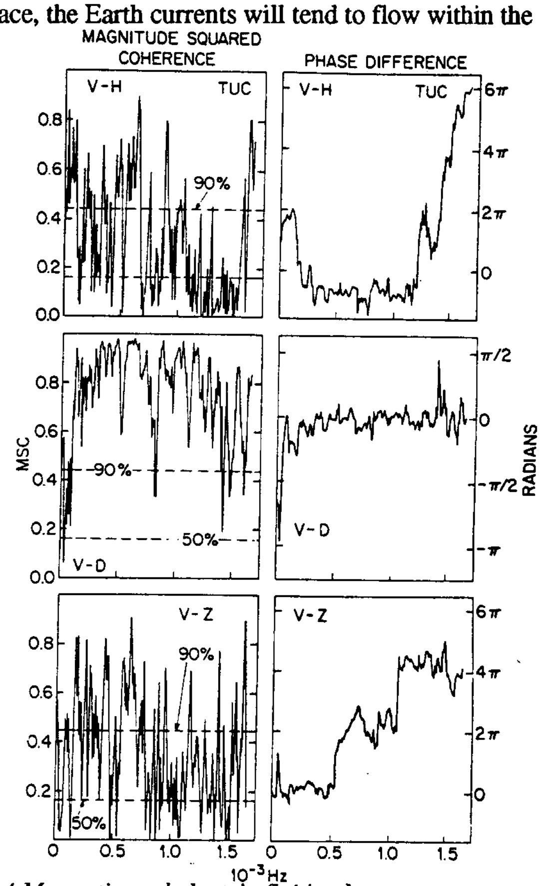

Fig. 4 Magnetic and electric field coherences

example, the power grid in the province of Quebec was disrupted during a geomagnetic disturbance in March 1989. These Earth currents can be measured and analyzed together with measurements of the magnetic field variations to determine the (complex) transfer functions between the two physical quantities. The determined transfer functions can be used with inverse mathematical techniques to provide information and models of the conductivity structure of the Earth beneath the site where the measurements were made [e.g., 4].

Shown in Figure 4 are the coherences between the three orthogonal components of the geomagnetic field and the Earth currents measured in an approximately 300km length of telecommunications cable running off-shore from Tuckerton, NJ. The cable run is approximately west-east. The magnetic field data were acquired at Tuckerton.

The coherences in Figure 4 are found to be quite high between the west-east component of the magnetic field and the cable current measurements. This high coherence is in a direction orthogonal to that expected for such a cable orientation, and implies a conducting structure in the Earth that "channels" induced electrical currents parallel to the ocean coast (approximately north-south orientation) rather than perpendicular to the coast [5] as would be expected under conventional arguments.

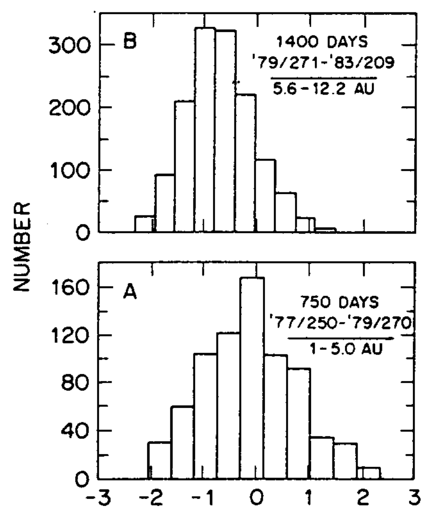

Fig. 5 Count rate distributions

3. INTERPLANETARY CHARGED PARTICLE DATA

As briefly described in the Introduction, the sun emits into interplanetary space charged particles that cover a wide range of energies. These particles can be accelerated to higher energies by the shock waves that propagate away from the sun through the solar system. The emission, acceleration, and propagation processes all involve time scales that are variable.

3.1. LOG-NORMAL PARTICLE COUNT RATES

A study reported [6] the statistical occurrence distributions of the logarithms of the count rates of the fluxes of several proton energies that were measured in the outer solar system by an instrument on the Voyager spacecraft. Shown in Figure 5 are these distributions for daily average count rates for about 0.5 MeV protons measured during the Voyager spacecraft transit between the Earth and Jupiter (lower panel) and for the distance between Jupiter and Saturn (upper panel). Both distributions show that the count rates are distributed approximately as log-normals.

Together with the f^{-2} power spectra that characterized these particle count rates, as shown in [6], these log-normal distributions were attributed to the net acceleration of such interplanetary ions being a product of random probabilities occurring in a step-like fashion in association with interplanetary shock waves produced by solar disturbances [6]. While a systematic study of the statistical distributions of a wide range of geophysical variables has not yet been carried out, it does appear to be the case that many have log-normal distributions.

3.2. POWER SPECTRUM OF PARTICLE COUNT RATES

The availability of long, nearly uninterrupted, intervals of charged particle data obtained by the Ulysses spacecraft as it ascended to high southern solar latitudes (the first spacecraft to leave the ecliptic plane) was used for a study of the frequency content of the particle count rates [7]. A number of investigations of the data were made, including spectral studies of the counting rates of different particle species (electrons, protons, helium ions) in several energy channels (from a few tens to a few hundred of keV).

Plotted in Figure 6 is a power spectrum of interplanetary particle count rate fluctuations in the frequency range 0.5 – 50 μHz. The data were analyzed using prolate window techniques and fast Fourier transforms [8, 9]. The data are from the HI-SCALE instrument on Ulysses. The individual lines shown in the spectrum correspond to frequencies that were observed above the 95% confidence level in three or more of the particle channels that were analyzed and that were coincident in frequency to within 0.2 μHz around each frequency value. The "background" of the spectrum, shown as the solid line connecting the lower edges of the spectral peaks, corresponds to the expected value of the F-test in noise. Essentially the entire spectrum is dominated by individual spectral lines, most of which in this frequency range have been identified in [7] as possible evidence of solar g-modes.

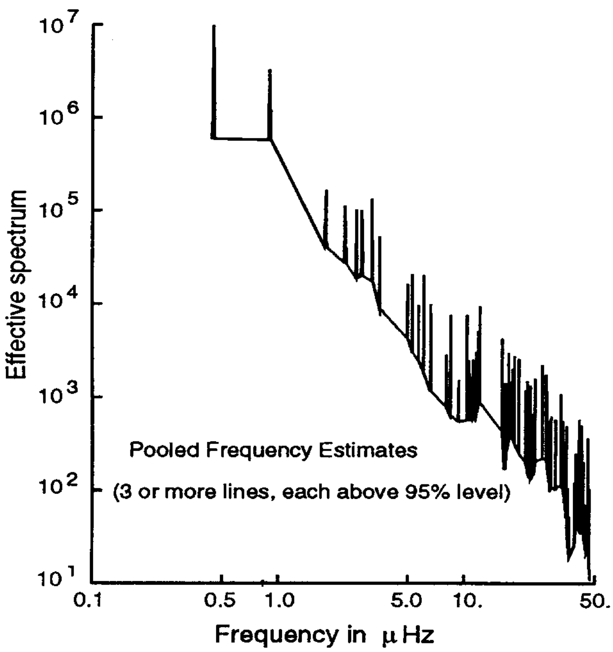

Fig. 6 Solar particle spectrum

4. IMPLICATIONS

As mentioned above, the fluctuations in the solar and interplanetary conditions give rise to time variations in geophysical and space parameters that are of intrinsic scientific interest as well as of importance for practical concerns related to the successful operations of technologies deployed in space and on the Earth [2]. The importance of the time series analysis of many of these parameters is that such analyses can potentially provide understandings of the occurrence of harmful geophysical and space conditions as well as the possible predictions of such conditions. Accurate predictive capabilities are yet in the future; their achievement holds the potential for eventual large practical pay-offs for this basic research.

5. SUMMARY

The geophysics and space physics examples in this paper, while limited in number, illustrate the wide range of areas where modern time series analysis methods lead to advances in understanding. An area that warrants more work and where major insights can be expected is using the results of time series analysis for the prediction of geophysics and space environments that can impact physical systems.

6. ACKNOWLEDGMENTS

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7. REFERENCES

[1] L.J.Lanzerotti, "Solar-terrestrial physics", in Encyclopedia of Physical Science and Technology, Academic Publ., vol. 12, p. 834, 1987.

[2] L.J.Lanzerotti, "Impacts of solar-terrestrial processes on technological systems", in Proc. 1992 STEP Symposium, Pergamon Press, Oxford, p.547, 1994.

[3] L.J.Lanzerotti, R.A.Langel, and A.D.Chave, "Geoelectromagnetism", in Encyclopedia of Applied Physics, VCH Publ., vol.7, p.109, 1993.

[4] L.J.Lanzerotti, D.J.Thomson, A. Meloni, L. V. Medford, and C. G. Maclennan, "Electromagnetic study of the Atlantic continental margin using a section of a transatlantic cable", J.Geophys.Res., 91, 7417, 1986.

[5] I. I. Rokyanski, Geomagnetic Investigation of the Earth's Crust and Mantle, Springer-Verlag, New York, 1983.

[6] L.J.Lanzerotti, R.E.Gold, D.J.Thomson, R.E.Decker, C.G.Maclennan, and S.M.Krimigis, "Statistical properties of shock-accelerated ions in the outer heliosphere", Astrophys.J., vol. 380, L93, 1991.

[7] D.J.Thomson, C.G.Maclennan, and L.J.Lanzerotti, "Time series analysis of interplanetary particle data: Evidence for solar g-modes", Nature, submitted, 1994.

[8] D.J.Thomson, "Quadratic-inverse spectrum estimates: applications to paleoclimatology", Phil. Trans. R. Soc. Lond. A 332, 539-597, 1990.

[9] D.J.Thomson, "An overview of multiple-window and quadratic-inverse spectrum estimation methods", Proc. ICASSP 94, VI-185 to VI-194, 1994.