

Goniopolarimetry: Space-borne Radio Astronomy with Imaging Capabilities

Goniopolarimetrie: Imagerie en radioastronomie spatiale

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Abstract—The principles of space-based low frequency radio astronomy (below 50 MHz) are briefly introduced. As the wavelength range considered does not allow the use of focusing systems, goniopolarimetric (or direction-finding) techniques have been developed. These inversion techniques provide the direction of the wave vector, the polarization state and the flux of the observed electromagnetic wave. In case of spatially extended sources, we can also infer the order of magnitude of the apparent source size. These techniques are presented, and their limitations are discussed. An example from a recent study illustrate the techniques and capabilities.

Index Terms—Radioastronomy, Space Physics, Goniopolarimetry, Auroral-Physics / Radioastronomie, Physique Spatiale, Goniopolarimétrie, Physique Aurorale

I. INTRODUCTION

The frequency band of interest for low-frequency radio astronomy ranges from a few kilohertz to several tens of megahertz. (see Figure 1a for planetary radio emissions). In this frequency range, the corpuscular description is never used, the electromagnetic wave description is used instead. The sampled wave quantities are then the electric and/or magnetic field components. Space-based radio instrumentation and interplanetary missions, such as the *Voyager*, *Galileo* or *Cassini* missions, are required due to several constraints: (i) radio emissions below 10 MHz cannot be observed from the surface because of the Earth's ionosphere cutoff; (ii) low-frequency emissions of the outer planets cannot be observed from the orbit of Earth, because of the solar wind plasma frequency cutoff, (see Figure 1b); (iii) the space environment of Earth is polluted by man-made radio interferences above 10 MHz.

The angular resolution of a classical telescope, with a “dish” reflector concentrating radio waves onto an array of antennas that will record the image formed at the focal plane of the telescope, is defined by λ/D , where λ is the wavelength of observation and D the aperture size of the telescope. The size required for such a telescope (≈ 1 to 10^4 km for $\lambda/D \ll 1$) is totally unrealistic for space-based observations. Hence, simple electric dipoles with a length L of a few meters (or tens of meters) are usually used. They have a poor intrinsic angular resolution ($\lambda/L \approx 1$). Goniopolarimetric (GP) techniques (allowing retrieval of flux, polarization state and direction of arrival of an observed electromagnetic wave) have therefore been developed in order to achieve angular resolution from measurements recorded with these antennas.

In this paper, we will present the antennas and receivers used for space-based radio astronomy, discussing the specific requirements for GP analysis. They are illustrated by a recent study: source location of the Saturn Kilometric Radiation with *Cassini* data [6].

II. INSTRUMENTATION

Two key elements of a radio instrument are the antenna and the receiver. The antenna is the sensing device: it transforms the electromagnetic fluctuations of the medium surrounding the spacecraft into voltage fluctuations that can be measured by the receiver. The receiver is the measuring device: it converts the voltage at the antenna feeds into a set of parameters (spectral flux density, amplitude, phase...) that are recorded by a data processing unit (DPU).

The classical space-based instrumentation constraints apply: low mass, low power consumption, small size, reliability, robustness to vibration and radiation. Following recent technological developments, e.g., miniaturization with application specific integrated circuits (ASICs), it is possible to build versatile low-noise radio receivers with very low mass and low power consumption. However, the main limitation still lies in the electrical sensors. They must be light and their length usually implies that they have to be deployed after launch. Hence, their deployment mechanisms have also to be light and reliable.

Depending on the primary objectives of the mission, the spacecraft can be either spinning (plasma, particles and fields science objectives) or 3-axes stabilized (imaging science objectives). The radio science objectives together with the spacecraft attitude will drive the characteristics of the antenna (length, orientation, type, etc.) mounted on the spacecraft and those of the associated radio receiver.

We thus use electric wire antennas that can be either a monopole or a dipole. In case of a monopole, the instantaneous voltage is probed between the antenna and the spacecraft body, while in the case of a dipole, the differential voltage is probed between the two poles of the antenna. Considering the spacecraft as an infinite conductive plane, the monopole and spacecraft body system would be strictly equivalent to a dipole antenna. In reality the spacecraft is smaller than the monopole length and is not planar. The beaming pattern of the effective antenna will thus be altered from that of the physical antenna.

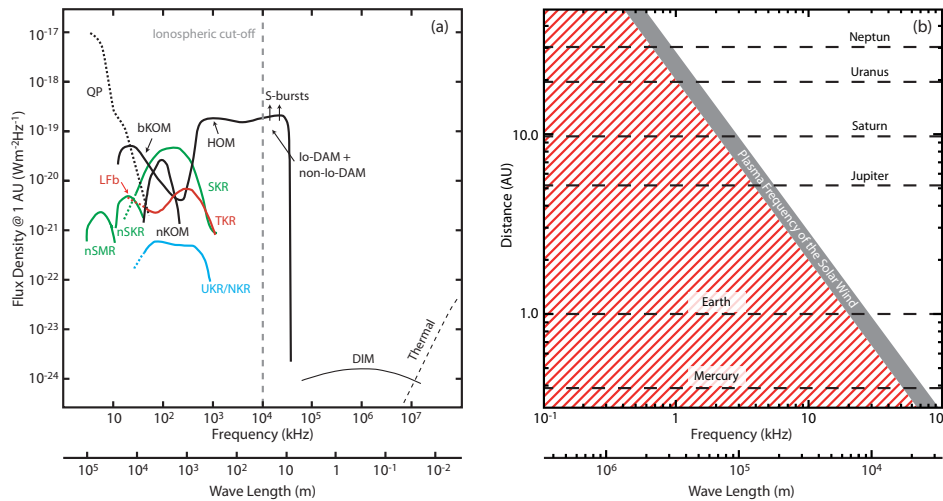


Fig. 1. **(a)** Typical spectra for planetary radio emissions in the solar system. The radio emissions from Jupiter are in black (nKOM: narrowband Kilometric Radiation; bKOM: broadband Kilometric Radiation; QP: Quasi-Periodic bursts; HOM: Hectometric Radiation; S-bursts: short (or millisecond) bursts; Io-DAM: Io-controlled Decametric Radiation; non-Io-DAM: non-Io-controlled Decametric Radiation; DIM: Decimetric Radiation; Thermal: black body thermal radiation); from Saturn in green (nSMR: narrowband Saturn Myriametric Radiation; nSKR: narrowband Saturn Kilometric Radiation; SKR: Saturn Kilometric Radiation); from Earth in red (LFB: Low-Frequency bursts; TKR (or AKR): Terrestrial (or Auroral) Kilometric Radiation); and from Uranus and Neptune in blue (UKR/NKR: Uranus/Neptun Kilometric Radiation). The vertical grey dashed line represents the Earth ionospheric cut-off. Figure adapted from [1], updated with [2], [3], [4]. **(b)** Typical range (grey area) of the plasma frequency in the solar wind with respect to the distance from the Sun. The grey area vertical thickness represents the typical interval of the variation of the plasma frequency in the solar wind. As the plasma frequency is a low frequency cut-off for free-space propagating electromagnetic waves, radio waves cannot propagate in the red hatched area. Figure adapted from [5].

The radio receiver may have several input channels. A single-channel receiver can only measure the power received by the connected antenna. Dual-channel receivers can use the signals provided by two antennas simultaneously. Such receivers provide spectral power series for both antennas and, depending on the receiver's design, cross-correlation series of the signals measured on each antenna. The *Cassini*/RPWS/HFR and *STEREO*/Waves receivers include such cross-correlation measurements.

The antenna calibration consists of determining the antenna beaming pattern. There are three ways to calibrate an antenna response: (i) rheometric analysis, consisting in measuring the electrostatic response of a small model of the spacecraft and its antennas when placed in a tank filled with a dielectric medium [?]; (ii) wire-grid electromagnetic modelling [?]; (iii) inflight measurement of the antenna response with known radio sources [?], [8]. When using a wire monopole in the quasistatic range, the calibration simply provides the effective length (including the gain and attenuation due to the base capacitance) and direction of the equivalent electric dipole.

The receiver calibration provides the parameters required to convert the recorded parameters into the wave parameters probed by the antennas. It thus provides the gain of each of its channels for any operating mode. When the receiver provides cross-correlation measurements, the phase shift between the different channels of the receiver has to be calibrated, too.

In the quasi-static frequency range, the voltage induced by an incoming electromagnetic wave is $V_{el} = \vec{h} \cdot \vec{E}$, where \vec{h} is the effective antenna vector and $\vec{E} = \vec{E}_0 e^{i\omega t}$ is the electric field of the wave. A GP radio receiver measures a series of correlation values $P_{ij} = \langle V_i V_j^* \rangle$. A transverse electromagnetic plane wave (i.e., emitted by a point radio source at infinity)

is characterized by its Stokes parameters (S the flux, Q , U , the linear polarization degrees, and V the circular polarization degree) and the wave vector \vec{k} direction which is defined by its colatitude θ and azimuth ϕ in a given frame. A model for the voltage correlation P_{ij} expression can be found in [7] or in [8] in case of a point source and in [9] in case of an extended source.

There are two possible ways to achieve GP on spaceborne radio receivers: (i) spin demodulation GP on a spinning spacecraft, like *Geotail*, *Wind* and *Ulysses*; and (ii) instantaneous GP on 3-axes stabilized spacecraft, like *Cassini* and *STEREO*. Each of these GP techniques may provide the direction of arrival of the wave, flux, polarization and the angular size of the source. At the time of writing, inversions providing the size of the source exist for spin demodulation GP, while the development of such inversions is in progress in the *STEREO*/Waves team for 3-axes stabilized spacecraft. These inversions will be based on the model-expression of the measurements in case of an extended source [9].

Several sources of uncertainty may alter or bias the GP measurements and results. Some sources of error such as the signal-to-noise ratio and digitization noise, depend on the receiver setup. The electromagnetic environment also induces noise: galactic background emission (resulting from the free-free interactions of the electrons in the galactic magnetic field), local plasma noise and photoelectron noise, and interference lines from the spacecraft. The source variability, its apparent size and the fact that we can observe several sources at the same time, may also induce errors in the results (see Fig. 2). Complete discussions of these uncertainty sources may be found in [8], [7], [9].

As the antennas measure the electric field of electromagnetic

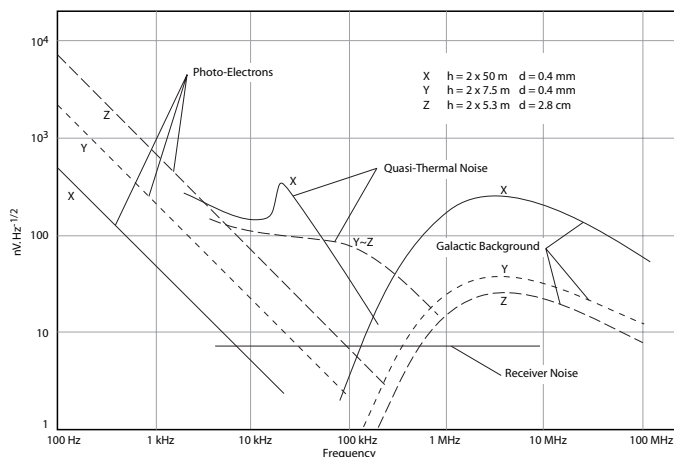


Fig. 2. Noise sources and noise levels for space-based radio receivers. Interference lines due to other instruments or from power converters can add to the displayed spectra. The noise spectra are traditionally given as a square root of a spectral power, i.e., in units of $1 \text{ nV Hz}^{-\frac{1}{2}}$. The noise levels are provided for various antenna characteristics (h is the antenna length and d its diameter). Type X antennas correspond to *Wind* antennas, for instance. Figure adapted from [10].

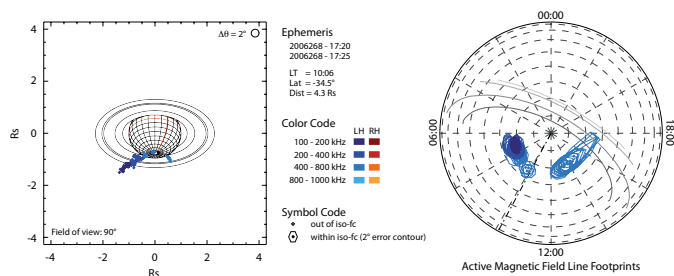


Fig. 3. SKR source localization with *Cassini*/RPWS/HFR data on day 2006-268, between 17:20 and 17:25, spacecraft event time. The *Cassini* spacecraft was located at 10:06 LT, in the southern hemisphere (-34.5° southern latitude), and at 4.3 Saturn radii from the center of the planet. Left panel: computed directions of arrival as seen from *Cassini*. Right panel: footprints of the magnetic field lines supporting the radio sources. On that panel, the mixed lines represent the LT of *Cassini*, and the grey curves delimit the visible portion of the $f = f_c$ iso-surface, for each of the four frequency ranges. Left-handed radio emissions are observed (blue) from 100 kHz to 800 kHz. No right-handed (red) emission is observed. This figure is adapted from [6].

waves passing in the vicinity of the spacecraft, GP techniques only measure the local direction of the wave vector. When propagation effects occur between the source and the spacecraft, e.g., refraction and diffusion, modeling of the ray path between the source and the spacecraft is necessary. Particular care is needed when the local plasma frequency along the path of the wave is close to the wave frequency.

Careful data selection is essential in order to obtain accurate GP measurements. In the case of *Cassini*/RPWS/HFR, the selection criteria for a typical accuracy are given in [8].

III. EXAMPLE OF A GP RESULT: SATURN KILOMETRIC RADIATION SOURCE LOCATION

Many papers have been published using the GP techniques described in the previous sections. A recent study [6] is highlighted here: the source location of the Saturn kilometric radiation using GP data provided by *Cassini*/RPWS/HFR.

The *Cassini* spacecraft has orbited Saturn since July 2004, exploring various orbital distances, latitudes and local times (LT). During the 24 hours of data presented in that study, the radio receiver was operating in two-antenna mode. In order to

find the source location, several assumptions were made: (i) the observed radio waves were circular polarized; (ii) straight propagation between the source and the spacecraft; (iii) an emission process is proposed which implies that the wave is emitted at the local electron cyclotron frequency f_c . With these assumptions, the source is located where the straight line defined by the direction of arrival intersects the $f = f_c$ iso-surface, which is computed using a planetary magnetic field model. Once the source is located, it is possible to compute the footprint location of the active magnetic field line. Figure 3 shows an example of GP results and source localization.

IV. CONCLUSION

The GP techniques allow radio astronomers to rebuild the wave parameters from space-based radio instruments, despite the poor angular resolution of electric antennas. From the example presented above, it is clear that the GP techniques provide a very powerful tool that can yield the flux density of the observed radio wave, its polarization state, the direction of the wave vector, and possibly the size of the source. Thanks to careful data selection, it is possible to make radio emission maps (see left panel of Figure 3). The main advantage of this imaging technique is that it is possible to build a posteriori any maps with selection on time, frequency, polarization, etc. These imaging capabilities are not possible with classical imaging instruments. The main drawback is that it is usually necessary to make assumptions about the wave (or source) parameters in order to invert GP measurements. However, it is clear from the study of Saturn presented above that GP results can be strongly enhanced when coupled with physical models.

REFERENCES

- [1] P. Zarka, "The auroral radio emissions from planetary magnetospheres: What do we know, What don't we know, what do we learn from them?" *Adv. Space. Res.*, vol. 12, no. 8, pp. 99–115, 1992.
- [2] P. Zarka, B. Cecconi, and W. S. Kurth, "Jupiter's low-frequency radio spectrum from Cassini/Radio and Plasma Wave Science (RPWS) absolute flux density measurements," *J. Geophys. Res.*, vol. 109, p. A09S15, 2004.
- [3] L. Lamy, P. Zarka, B. Cecconi, R. Prangé, and plus 2 authors, "Saturn Kilometric Radiation: average and statistical properties," *J. Geophys. Res.*, vol. 113, p. A07201, 2008.
- [4] L. Lamy, P. Zarka, B. Cecconi, and R. Prangé, "Diurnal modulation of AKR discovered by Cassini/RPWS," *Geophys. Res. Lett.*, 2008.
- [5] P. Zarka, "Radio Emissions from the Planets and their Moons," in *Radio Astronomy at Long Wavelengths*, ser. Geophysical Monograph, R. G. Stone, K. W. Weiler, M. L. Goldstein, and J.-L. Bougeret, Eds. Washington DC: AGU, 2000, vol. 119, pp. 167–178.
- [6] B. Cecconi, L. Lamy, P. Zarka, R. Prangé, and plus 2 authors, "Goniopolarimetric study of the Rev 29 perikrone using the Cassini/RPWS/HFR radio receiver," *J. Geophys. Res.*, 2009.
- [7] A. Lecacheux, "Direction Finding of a Radiosource of Unknown Polarization with Short Electric Antennas on a Spacecraft," *Astron. Astrophys.*, vol. 70, pp. 701–706, 1978.
- [8] B. Cecconi and P. Zarka, "Direction finding and antenna calibration through analytical inversion of radio measurements performed using a system of 2 or 3 electric dipole antennas," *Radio Sci.*, vol. 40, p. RS3003, may 2005.
- [9] B. Cecconi, "Influence of an extended source on Goniopolarimetry (or Direction Finding) with Cassini and STEREO radio receivers," *Radio Sci.*, vol. 42, no. RS2003, 2007.
- [10] R. Manning, "Instrumentation For Space-Based Low Frequency Radio Astronomy," in *Radio Astronomy at Long Wavelengths*, ser. Geophysical Monograph, R. G. Stone, K. W. Weiler, M. L. Goldstein, and J.-L. Bougeret, Eds. Washington DC: AGU, 2000, vol. 119, pp. 329–337.