SPECTRAL FEATURES OF JOVIAN HECTOMETRIC EMISSION OBSERVED BY GALILEO AND WIND SPACECRAFT

M. Y. Boudjada*, P. H. M. Galopeau†, and H. O. Rucker*

Abstract

The combination of Wind/WAVES and PWS/Galileo observations enables the study of the Jovian hectometric emissions in the frequency range from 300 kHz up to 13.8 MHz. The Wind satellite is close to Earth whereas Galileo spacecraft is orbiting within the Jovian magnetosphere. Despite the distance between the Wind satellite and Jupiter (more than 4 AU) the HOM emissions are detected by the Wind/WAVES experiment. We consider the HOM spectral features taking into consideration the geometric configurations of Jupiter, Galileo and Wind spacecraft. Part of the HOM beam is observed at the Earth and only for specific longitudes. The analysis of the spectral arcs, and their corresponding polarisations, allow us to discuss some common features of hectometric and decametric emissions.

1 Introduction

Jupiter is known as the most powerful emitter of non–thermal radio waves in our Solar system. It is composed of three low frequency components: decameter–wave radiation (DAM), hectometer–wave radiation (HOM) and kilometer–wave radiation (KOM). These emissions emanate from several distinct locations in the magnetosphere and are intensity–modulated by the planetary 10–hour rotation period.

The HOM emission is generally agreed to be emitted from high Jovian magnetic latitudes at frequencies close to or just above the local gyrofrequency [Ladreiter and Leblanc, 1989]. The polarization measurements from Voyager observations [Ortega–Molina and Lecacheux, 1991] indicate that the emission is predominantly right–hand polarized when observed from the Jovian Northern hemisphere and left–hand when observed from Southern hemisphere. The radiation is beamed into a hollow cone which is only received when the cone orientation is towards the observer. The periodic variations of HOM in terms

*Space Research Institute, Austrian Academy of Sciences, Schmiedlstrasse 6, A–8042 Graz, Austria
†Centre d'Étude des Environnements Terrestre et Planétaires, F–78140 Vélizy, France

of central meridian longitude (CML) are due to the varying jovicentric declination of the observer within one Jovian rotation.

The spectral HOM pattern has the following characteristics: (a) the lower frequency is observed down to 40 kHz and generally closer to 300 kHz when the upper frequency is about 3 MHz but sometimes about 5 and 7 MHz [Barrow and Desch, 1989], (b) the emission occurs nearly at each Jovian rotation with a gap range around 200° CML, (c) the latitudinal beaming is the consequence of the emission pattern and propagation effects through the Io torus.

Recent observations of the Unified Radio and Plasma Wave experiment (URAP) and Plasma Wave Instrument (PWS) on board Ulysses and Galileo spacecraft confirm the previous observations obtained from the Voyager spacecraft. They reveal new features of the Jovian hectometric emission, notably the presence of a sinusoidal–shaped "band" of a less intense emission within between 500 kHz and 3 MHz at all longitudes [Lecacheux et al., 1980; Higgins et al., 1995]. Such an intensity attenuation presents two peaks per rotation, the first at CML $\sim$ 50° and the second one at CML $\sim$ 185° attributed to a radiation emanating from Southern and Northern hemisphere sources, respectively. Such bands are interpreted as a coherent scattering effect due to field–aligned density irregularities close to the Io L–shell [Gurnett et al., 1998] or as a caustic effect [Higgins et al., 1999]. Direction finding using spin modulation of radio wave data has mainly been used by URAP and PWS experiments. The Ulysses data reveal that the HOM source location is in the Jovian auroral region [Ladreiter et al., 1994b] or near the foot of the magnetic field lines in the range $3 \leq L \leq 10$ [Reiner et al., 1993b; Menietti and Reiner, 1996]. From Galileo observations, the HOM emission seems to be related with either the plasma torus or magnetic flux tubes in the wake of Io.

In the following we attempt to describe the Jovian hectometric beam observed by WAVES and PWS experiments on board Wind and Galileo spacecraft. In the next section we consider events observed during particular geometric configurations, i.e. the planet Jupiter and both satellites. This allows us to analyse and to discuss the features of the HOM beam in section 3 and 4, respectively.

2 Particular geometric configurations

We select the observation data where Jupiter, Galileo and Wind spacecraft are quasi–aligned. We focus on closest approach dates to check on the corresponding dynamic spectra the possibility to get simultaneous events observed by both spacecraft. This is mainly the case at the perigee when the Galileo spacecraft is very close to the planet. As a first step we combine the dynamic spectra of Wind data, i.e. RAD1 and RAD2 observations, which allows us to localize the beaming of the hectometric emission in the frequency range from 300 kHz to more than 6 MHz. In the second step the previous dynamic spectra are compared to the same one recorded by the PWS experiment. In the following we describe the main characteristics of each experiments.

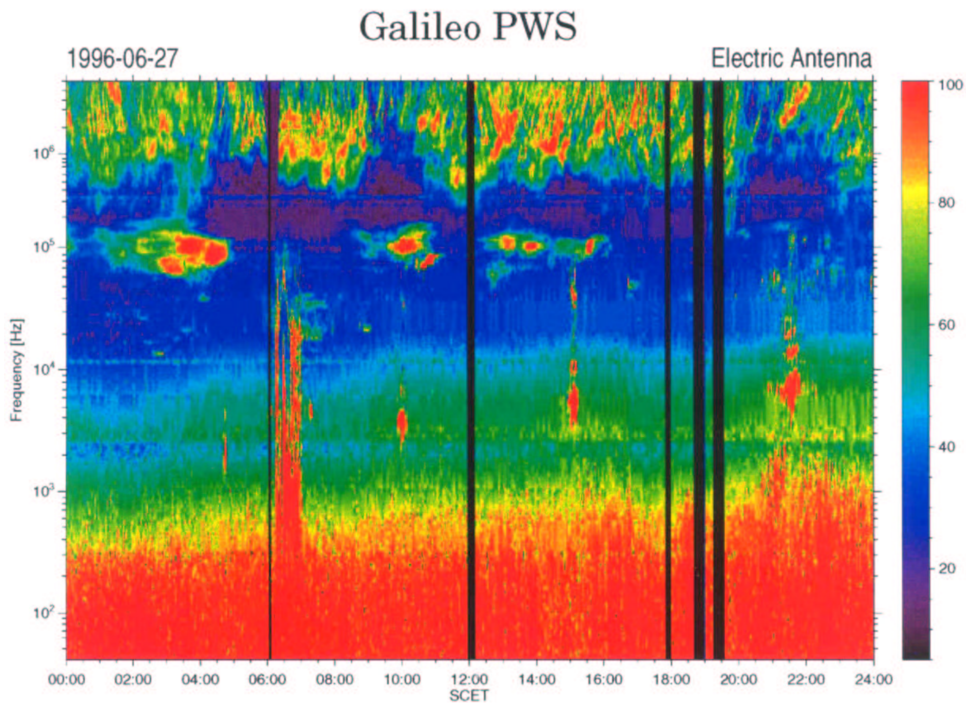

Figure 1: Dynamic spectrum of Jovian radio emissions observed by Galileo/PWS experiment. The HOM beam is observed in the upper part of the spectrum between 100 kHz up to 5.8 MHz.

2.1 WAVES experiment on board the Wind satellite

The WAVES experiment is devoted to the study of the dynamics of the interplanetary medium, the Earth's bow shock and terrestrial magnetosphere. It provides measurements of the radio and plasma wave phenomena in the frequency range from fractions of a Hertz up to about 14 MHz. For our study we use the data of RAD1 and RAD2 receivers, from 20 kHz to 1040 kHz and 1.075 MHz to 13.825 MHz, respectively. Both receivers operate in 256 channels with different bandwidth: 3 kHz for RAD1 and 20 kHz for RAD2. Two orthogonal electric dipoles are connected to the previous receivers, the longer one is 100 m tip–to–tip and the shorter dipole is 15 m tip–to–tip [Bougeret et al., 1995]. The data we have used are available on the WAVES Web page, they correspond to a daily dynamic spectrum averaged over one minute.

2.2 Plasma wave experiment (PWS) on board the Galileo spacecraft

This experiment consists of four different sweep frequency receivers which cover the frequency range from 5.6 Hz to 5.6 MHz for the electric field with 152 logarithmically spaced channels. The PWS receiver is connected to a 6.6 m dipole antenna enabling electric field measurements in the entire frequency range [Gurnett et al., 1992]. In Figure 1 we show the variation of the Jovian radio emission versus time and frequency as recorded by Galileo/PWS experiment. The HOM beam appears in the upper part of the dynamic spectrum. For our studies we use the data recorded by the high–frequency receiver covering the frequency range from about 100 kHz up to 5.6 MHz.

3 Jovian hectometic (HOM) beam patterns

In this section we discuss the beam patterns associated to the Jovian HOM emission and recorded by both spacecraft. In this case we compare HOM beams observed at the Earth by Wind satellite and close to Jupiter by Galileo spacecraft. Taking into consideration this geometric configurations we discuss in the following sections three main items: (a) the selective propagation effects, (b) the high frequency limit of the HOM emission and (c) the spectral arcs associated to the HOM pattern.

3.1 Selective propagation effect

For the study of the propagation effect we consider common HOM events observed simultaneously by both spacecraft. This is mainly the case when Wind, Galileo, and Jupiter are quasi–aligned. It also corresponds to the closest approach on Galileo's orbit with regard to Jupiter. At the Earth orbit, the HOM envelope seems to be quasi–similar to the same one recorded at Jupiter but less intense. In Figure 2 we show part of the dynamic spectrum recorded by the RAD1 receiver between 100 kHz and 1 MHz. The beam pattern recorded by Wind/WAVES experiment presents an enhancement of intensity for particular longitudes 125° and 300° which correspond to the northern and southern HOM sources, respectively. More details about the selective effect could be found in Boudjada et al. [2001].

In Figure 3 we display the occurrence probability of HOM emission versus the central meridian longitude (CML). We consider the data recorded by both experiments during Galileo's second orbit around Jupiter, from August 31, 1996, to October 22, 1996. The total number of Jovian rotations recorded by the Galileo/PWS experiment is about 127 for a period of 53 days. Only a small part (15%) of the rotations were missing on WAVES experiment due to the distance effect and terrestrial environment. When we compare both figures (i.e. Figure 3a and Figure 3b), we find that the HOM emission exhibits a maximum for three longitudes. We note that two maxima are quasi–similar on both data experiments, i.e. for CML of about 100° and 300°. Those maxima are in concurrence to previous studies [Ladreiter and Leblanc, 1989; Kaiser et al., 1996b] and are associated to sources localized in the Northern and Southern hemispheres of the planet. The third maximum is found at about 355° on Galileo/PWS experiment and 40° on Wind/WAVES data. In the discussion we give some interpretations about the origin of the this maximum observed by each satellite.

3.2 High frequency limit of HOM emission

According to Voyager observations, the conventional upper limit frequency of the hectometric emission is about 3 MHz. However, Galileo observations show that this boundary

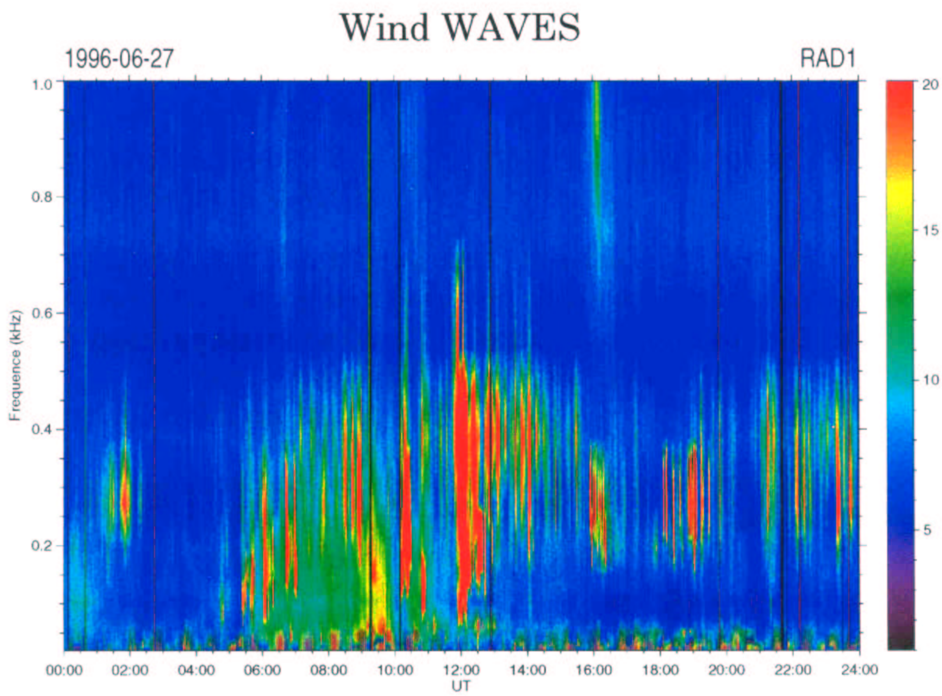

Figure 2: Part of HOM beam observed by WAVES experiment on board the Wind satellite. In the frequency range from 500 kHz up to 1 MHz, we note the enhancement of the HOM beam intensity (between 16:00 and 18:00 UT) due to the HOM beam associated to the Northern hemisphere.

is at least some $2 \div 3$ MHz higher and could even reach higher frequencies. As shown in Figure 1, the HOM emission is usually observed close to 5.6 MHz which is the upper frequency limit of the Galileo/PWS experiment. In this case the HOM spectral pattern should be superposed to emission related to the Jovian decametric (DAM) emission. Kaiser and Garcia [1997] and Lecacheux et al. [1998a] show several DAM arcs which reach very low frequencies at about 1 MHz. This common spectral coverage (from 7 MHz down to 1 MHz) seems to be related to emission coming from the same hollow cone. This one should be related to a Jovian magnetic field region from where both emissions are beamed.

3.3 Spectral arcs of HOM beam pattern

In this subsection we consider the spectral arcs related to the hectometric beams. For one full Jovian rotation, we observe both beams associated to Northern and Southern hemispheres at CML of about 100° and 300°, respectively. Each beam presents two families of spectral arcs: vertex early arcs (VEA) and vertex late arcs (VLA). Such type of arcs were described by Leblanc [1981] using Voyager data. We note the presence of VEA and VLA arcs before and after the maximum of occurrence related to each hemisphere. These emissions are found to be right–hand and left–hand polarized [Ortega–Molina and

Lecacheux, 1991] for the Northern and Southern hemispheres, respectively.

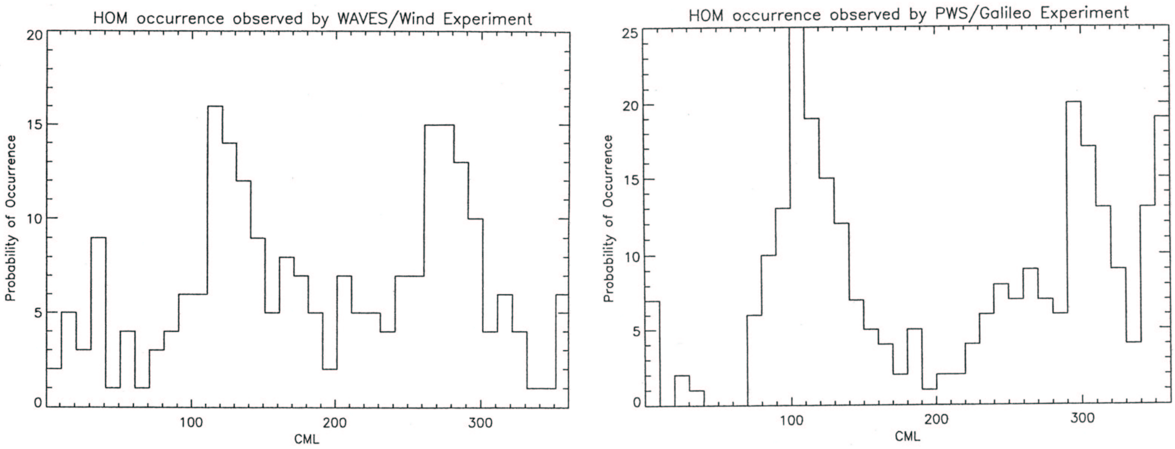

Figure 3: Occurrence probability of HOM emission recorded by WAVES experiment (left panel) and PWS experiment (right panel) during the Galileo's second orbit around Jupiter.

It is well known that the spectral arcs associated to Jovian decametric emission are depending on specific positions of the Io satellite (Io–phase), i.e. at about 90° and 250° [Genova and Aubier, 1985; Boudjada and Genova, 1991]. It is interesting to note that when we combine the CML and the Io–phase, we find that for both HOM and DAM, spectral arcs and their corresponding polarizations are analogous. It is mainly the case for the Southern hemisphere when: (a) $0^\circ \leq$ CML $\leq 100^\circ$ and Io–phase $\sim 90^\circ$ and (b) $300^\circ \leq$ CML $\leq 360^\circ$ and Io–phase $\sim 250^\circ$. More features about such DAM spectral arcs could be found in Figure 4 and Figure 5 of Kaiser and Garcia [1997].

4 Discussion and conclusion

Observations of Wind/WAVES and PWS/Galileo experiments allow us to study spectral features of the Jovian hectometric emission. ¿From our analysis three main features emerge: (a) the presence of two peaks of HOM occurrence with different longitudes, (b) the extension of HOM emission towards higher frequencies and (c) the spectral arcs related to the HOM beam pattern.

The probability of occurrence recorded from August 31, 1996 to October 22, 1996 by both spacecraft presents three peaks in CML. Two of them are observed at the same longitudes and correspond to the Southern and the Northern hemispheres beams. The third maximum is found at about 40° and 355° on Wind/WAVES and Galileo/PWS experiments, respectively. Using Galileo data, Menietti et al. [1999] have also reported on a peak at about 360°. We believe that those peaks could be related to a direct dependence on the local time. The first maximum (at a CML of about 40°) should correspond to a day–side source which is mainly observed by Wind satellite because of its orbit. The second one (at a CML of about 355°) is recorded on the night–side of the planet where

Galileo could observe it during the main part of the orbit. Those two maxima seem to be related to hectometric "sources" localized in the Northern (40°)and Southern (355°) hemispheres.

The second result of our investigation is the presence of common features between the hectometric and the decametric emissions. It appears from our study that the HOM emission cover part of the DAM frequency range, i.e. up to 5.6 MHz. According to the spectral pattern, part of the DAM arcs are surely superposed to the HOM beam pattern which means that they could reach very low frequencies (lower than 1 MHz). As we have also shown analogous spectral arcs (VEA and VLA) are observed for some specifics values of CML and Io–phase with a similar polarization. Such results could not be derived from previous observations (Voyager, and Ulysses) because those experiments covered only part of the spectrum.

Acknowledgements: This work is in part supported by the Austrian Exchange Service: AMADEE 2001–2002 (project number V.2).

References

Barrow, C. H., and M. D. Desch, Solar wind control of Jupiter's hectometric radio emission, *Astron. & Astrophys.*, **213**, 495, 1989.

Boudjada, M. Y., and F. Genova, The left–hand polarization sense of the Jovian decameter radiation, *Astron. & Astrophys. Suppl.*, **91**, 453, 1991.

Boudjada, M. Y., P. H. M. Galopeau, and H. O. Rucker, Jovian hectometric beam observed by PWS and WAVES experiments on board Galileo and Wind spacecraft, *Planet. Space Sci.*, **49**, 1151, 2001.

Bougeret, J. L., M. L. Kaiser, P. J. Kellogg, R. Manning, K. Goetz, S. J. Monson, N. Monge, L. Friel, C. A. Meetre, C. Perche, L. Sitruk, and S. Hoang, WAVES: The radio and plasma wave investigation on the Wind spacecraft, *Planet. Sci. Rev.*, **71**, 231, 1995.

Genova, F., and M. Aubier, Io–dependent sources of the Jovian decameter emission, *Astron. & Astrophys.*, **150**, 139, 1985.

Gurnett, D. A., W. S. Kurth, R. R. Shaw, A. Roux, R. Gendrin, C. F. Kennel, and S. D. Shawhan, The Galileo plasma wave investigation, *Space Sci. Rev.*, **60**, 341, 1992.

Gurnett, D. A., W. S. Kurth, J. D. Menietti, and A. M. Persoon, An unusual rotational modulated attenuation band in the Jovian hectometric radio emission spectrum, *Geophys. Res. Lett.*, **25**, 1841, 1998.

Higgins, C. A., J. L. Green, J. R. Thieman, S. F. Fung, and R. M. Candey, Structure within Jovian hectometric radiation, *J. Geophys. Res.*, **100**, 19487–19496, 1995.

Higgins, C. A., J. R. Thieman, S. F. Fung, J. L. Green, and R. M. Candey, Jovian dual–sinusoidal HOM lane features observed by Galileo, *Geophys. Res. Lett.*, **26**, 389, 1999.

Kaiser, M. L., M. D. Desch, and M. E. Brown, Evidence for an Io plasma torus influence on high–latitude Jovian radio emissions, *J. Geophys. Res.*, **101**, 13, 1996b.

Kaiser, M. L., and L. N. Garcia, Jupiter's low–frequency radio spectrum: Filling in the gaps, in *Planetary Radio Emissions IV*, edited by H. O. Rucker, S. J. Bauer, and A. Lecacheux, Austrian Academy of Sciences Press, Vienna, 17–24, 1997.

Ladreiter, H. P., and Y. Leblanc, Jovian hectometric radiation: beaming, source extension and Solar wind control, *Astron. & Astrophys.*, **226**, 297, 1989.

Ladreiter, H. P., P. Zarka, and A. Lecacheux, Direction finding study of Jovian hectometric and broadband kilometric radio emissions, *Planet. Space Sci.*, **42**, 919, 1994b.

Leblanc, Y., On the arc structure of the DAM Jupiter emission, *J. Geophys. Res.*, **86**, 8564, 1981.

Lecacheux, A., B. Möller–Pedersen, A. C. Riddle, J. Pearce, A. Boischot, and J. W. Warwick, Some spectral characteristics of the hectometric Jovian emission, *J. Geophys. Res.*, **85**, 6877, 1980.

Lecacheux, A., M. Y. Boudjada, H. O. Rucker, J. L. Bougeret, R. Manning, and M. L. Kaiser, Jovian decameter emissions observed by the Wind/WAVES radioastronomy experiment, *Astron. & Astrophys.*, **329**, 776, 1998a.

Menietti, J. D., and M. J. Reiner, Modeling of Jovian hectometric radiation source locations: Ulysses observations, *J. Geophys. Res.*, **101**, 27045, 1996.

Menietti, J. D., D. A. Gurnett, W. S. Kurth, and J. B. Groene, Local time dependence of Jovian radio emissions observed by Galileo, *Geophys. Res. Lett.*, **26**, 529, 1999.

Ortega–Molina, A., and A. Lecacheux, Polarization of Jovian hectometric emission, *J. Geophys. Res.*, **96**, 11441, 1991.

Reiner, M. J., J. Fainberg, and R. G. Stone, Source characteristics and locations of Jovian hectometric radio emissions, *J. Geophys. Res.*, **98**, 18767, 1993b.