MORPHOLOGY OF THE JUPITER IO-D DECAMETRIC RADIO SOURCE

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Abstract

Observations of Jupiter's Io-D decametric radio emissions have been made with the Long Wavelength Array Station 1 (LWA1) from 2012–2015. The LWA1 data show new characteristics in dynamic spectra of Jupiter Io-D emission, including a double–envelope structure filled with spectral arc features, persistent narrow-band events, and ubiquitous modulation lanes and S-bursts. We observe an Io-D peak frequency of 26.5 MHz implying a lower limit of 9.3 Gauss for the southern hemisphere magnetic field magnitude. We estimate a Jovian longitude of 235° for the center location of the Io-D peak frequency source. Many S-burst drift rates were measured as a function of frequency and were found to be consistent with other Io-related sources. The Io-D source occurrence boundaries require new limits: CML $= 0° - 287°$ and $\Phi_{Io} = 50° - 135°$.

1 Introduction

Jupiter radio emission has been observed by ground-based observatories since the discovery in 1955 by Burke and Franklin [1955]. The decameter radio emission (DAM) ranges from about 3 MHz to 39.5 MHz, and these emissions have been used to characterize and define Jupiter's magnetic field, the internal System III rotation period, the general emission mechanism, polarization, spectral features, and the approximate source locations (for reviews, see Carr et al. [1983]; Zarka, [1998]; Clarke et al., [2004]). It is also well-known that the satellite Io influences much of the DAM emission [Bigg, 1964], and some non-Io-related emissions are correlated with the solar wind [Barrow et al., 1986; Hess et al., 2012].

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The Io-A, Io-B, and Io-C sources were initially labeled A, B, and C, or "main", "early", and "late", respectively [Carr et al., 1961; Dulk, 1965]. Warwick [1963] predicted a fourth source and Dulk [1965] first identified it; soon thereafter Gledhill [1967] used the term "Fourth Source" to identify the Io-D component and specified the observed range of Io-D as CML $0° − 70°$ and Io-Phase (Φ_{Io}) $90° − 110°$. Kennedy [1969] determined the LH polarization sense of the Io-D source. Figure 1 shows a general overview of the four Io-related sources and their approximate location in Jupiter's magnetosphere.
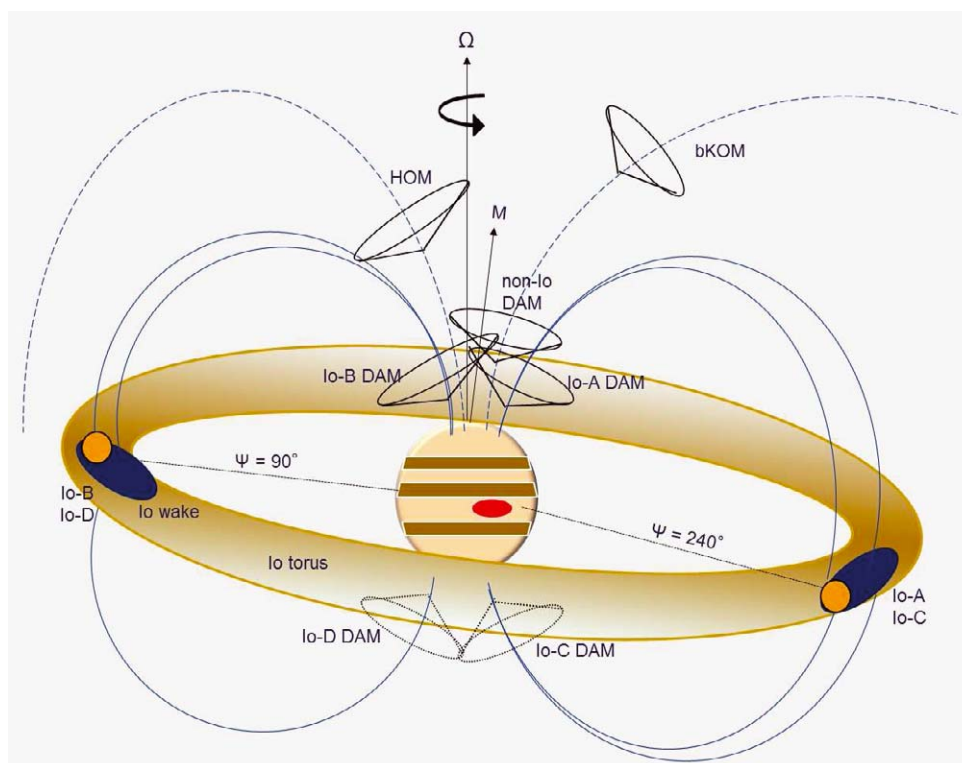

Figure 1: Most of Jupiter's auroral radio emission sources are labeled here: bKOM – broadband kilometric emission, HOM – hectometric emission, non-Io-DAM – decametric emission related to HOM not controlled by Io, and Io-DAM – decametric emission tied to Io flux tube and Io torus. Also seen are the approximate phases of Io (Φ_{Io}) for the Io-related sources (adapted from J. Clarke et al. [2004]).

From the summary of Carr et al. [1983], the Io-D source was known to be left-hand circularly polarized (LHC), show vertex early arc structure having a maximum frequency of 18 MHz, and to occur within the CML range $0° − 200°$ and Φ_{Io} $95° − 130°$. DAM emission is believed to be generated by the cyclotron maser instability (CMI) mechanism and dominated by X-mode emission emitted near the local cyclotron frequency; therefore, because it is LHC polarized the location of the Io-D source is presumably in Jupiter's southern hemisphere. Because the Io phase–CML range of Io-D is similar to the Io-B source, it is considered to be the complement to the northern hemisphere Io-B source. Not many spectral details were known about the Io-D source before the Voyager flybys because the Io-B emission occurs at the same times and is much more dominant. Leblanc [1981] used Voyager observations of Jupiter DAM and found that Io-D had a narrower band of emission, as compared with the other Io-related sources, and appeared as a long

envelope of a vertex-early arc with possible arc-like substructure. She also observed Io-D from 5–22 MHz and found that Io-D had a CML range $0° - 260°$ and a Φ_{Io} range $95° - 140°$.

Genova and Aubier [1985] found the high frequency limits of the Io-related emissions using Voyager data. They compared those limits to the surface gyrofrequency of a magnetic model and deduced that the Io-D emission comes from the field line passing through Io. They show evidence of Io-D emission at nearly all longitudes. Wilkinson [1989] also used Voyager data and an empirical technique to model some of the Io-related spectral structures, including the Io-D source requiring an $86°$ beaming cone half angle. Leblanc et al. [1993] used the Voyager 1 and 2 flyby data to study Jupiter's LH polarized DAM emission. They found that the occurrence probabilities of LH (and RH) emission peak at about 8 MHz, but that the LH probability diminishes significantly above 15 MHz. They found that the probability spectra in CML show a continuity from low to high frequencies, and that the emission extends down to 2.5 MHz. They argued that the emission was highly beamed in hollow cones with large opening angles, and that Io influenced the emission at all longitudes for $\nu < 10$ MHz.

Boudjada and Genova [1991] studied LH decameter events in Nançay spectrograph data and concluded that the maximum frequency for LH events (both Io and non-Io) is 25 MHz which sets a limit of about 9 Gauss for the maximum field strength of Jupiter's southern hemisphere. Dulk et al. [1994] analyzed the polarization state of Io-related storms and found that the emission was 100% elliptically polarized showing little variation over a long period of time. They found that the degree of circular polarization was very high (0.85) for Io-D events. Leblanc et al. [1994] studied Io-D and Io-B LH emission events and identified them as distinct LH southern hemisphere emission sources. Queinnec and Zarka [1998] used combined Nançay and Wind spacecraft data and found Io-D as isolated arcs from approximately 3–23 MHz in frequency–time spectrograms, and show that Io-D shows more complex structure at the higher frequencies. Like other Io-related sources, they find the arc structure is strongly dependent on viewing geometry. Their data and model show that Io-D is a southern hemisphere source having LHC polarization with a beaming cone half-angle of 70°-85° and an envelope shape that is caused by a source along southern Io-flux tube in Io's frame. Their Io-D events fall in the range of CML $55° - 200°$ and Φ_{Io} $80° - 110°$.

As mentioned before, many fine spectral details of the Io-D source were not known because of the overlap with the more powerful Io-B source. This is also true for the millisecond "short" S-burst structures, and before the Clarke et al. [2014] paper only one published Io-D S-burst event was known [Litvinenko et al., 2010]. However, it is likely that Dulk et al. [1994] observed S-bursts related to the Io-D source but attributed it to the Io-B source. No statistics specific to the Io-D source are known. Dulk et al. [1994] measured the complete polarization state of both left-hand and right-hand S-bursts from various sources and found that the LH S-bursts were highly circularly polarized, having a degree of circular polarization $d_c =$ Stokes V/I $= +0.85$ (the RH events had $d_c = +0.55$). Queinnec and Zarka [2001] did a statistical analysis of mostly RH S-bursts and found an emission bandwidth of 0.5–9.0 MHz, a 1 AU normalized average flux density of 4×10^{-20} W m^{-2} Hz^{-1}, and an average radiated power of $\sim 10^9$ W. Hess et al. [2007] measured frequency drifts

of S-bursts and determined that a typical energy of the emitting electrons is 4 keV, and also showed that the drift rates decrease at high frequencies in accordance with adiabatic theory. Recently, Imai et al. [2016] used simultaneous observations of S-bursts from three radio telescopes to constrain the beaming thickness to 2.66". They also found that the occurrence probability of S-bursts peaks at 17–18 MHz. Much more information about Jovian S-bursts can be found in the literature (i.e., Arkhypov and Rucker [2009]; Ryabov, et al. [2007]; Zarka et al., [1996]; Flagg et al. [1991]; Carr et al. [1983]).

2   Observations and data analysis

Observations of Jupiter were conducted from 2012 to 2015 using the Long Wavelength Array Station 1 (LWA1) located in Magdalena, NM, USA, near the site of the VLA. The array consists of 256 inverted V-shaped crossed-bowtie dipoles having all-sky viewing capability from 10–88 MHz. The system operates with 4 independent beams having a beam size of 8.1° at 20 MHz, full Stokes parameters, and a usable bandwidth of 16 MHz. We observed Jupiter with two tunings over the frequency range of 10–38 MHz with a resolution of 5 kHz and 0.21 ms. To ensure accurate polarization determinations, observations were limited to Jupiter elevations above 40°. For more information about the LWA1 instrument see Clarke et al. [2017] and Clarke et al. [2014] and references therein. The LWA1 instrument is an excellent instrument for low frequency radio studies, and the spectrum is reasonably clean down to 10.5 MHz as can be seen in Figure 2 showing excellent Io-B and Io-D Jupiter emission. The right-hand circular (RHC) Io-B emission is shown in red color while the LHC emission is shown in blue. Fine spectral structure is clearly seen in both sources.
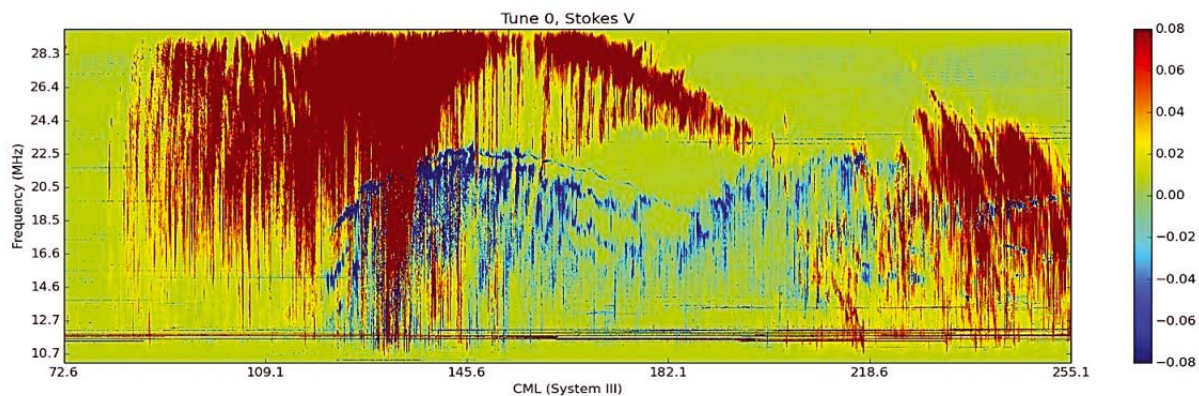

Figure 2: Jupiter Io-B/Io-D emission on 20 January, 2015 beginning at 05:30 UT. Io-B followed by non-Io-A emission is right-hand circularly polarized (red) and Io-D is left-hand circularly polarized (blue). The 5-hour observation shows a frequency range from 10.35 to 29.65 MHz, a CML range of $72.6° - 255.1°$, and a corresponding Φ_{Io} from $80° - 123°$. The colorbar shows Stokes V power spectral density in arbitrary units.

Although Jupiter observations with the LWA1 were conducted from 2012–2015, the Io-D events shown here are selected from 2014–2015. These data are recorded as raw voltages and then processed through a Fourier transform spectrometer using LWA software tools

[Dowell et al., 2012]. Data are converted from linear polarization to R, L and Stokes parameters. A typical observation was 3–5 hours in duration and initially processed at 2 s and 10 kHz resolution (Figures 2, 3, 4). Selected 5-second subsets of these data were processed at 0.25 ms and 5 kHz resolution to analyze fine structures. Occasionally a lower resolution spectrometer mode (40 ms and 20 kHz) was used to observe Jupiter emissions. For more details about the LWA1 Jupiter data analysis procedure, see Clarke et al. [2014].

3   Characteristics of the Io-D radio source

As mentioned in the Introduction, the Io-D radio source has been known since the mid-1960s. Improved receivers, antennas, and software have made it much easier to observe polarization signatures and fine structures in Jovian dynamic spectra. The Io-D decametric radio source is quite easy to detect in spectra of Stokes V as seen in Figures 2, 3, and 4. Io-D shows a typical envelope of emission, comprised of vertex–early arc structures that increase in frequency from < 10 MHz to a peak of 20–24 MHz at about $140° - 150°$ CML and then decrease in frequency until the emission ends. From twelve Io-D events from 2012–2015 where more than 50% of the envelope is seen, we determined that the average peak frequency of the Io-D source is 22.8 MHz, and the average observed position of the peak frequency is 154° CML and 99° Io phase. Queinnec and Zarka [1998] determined a beaming angle for Io-D of $80° \pm 5°$ from arc structures and a field model. Using a symmetric hollow cone beam shape and Jovian ephemeris information, the calculated averaged position of the maximum frequency of Io-D source is approximately 235° in Jovian longitude. This value represents the approximate Jovian longitude position of the Io-D emission source, in good agreement with the study of Genova and Aubier [1985].

The envelope and arc structure are defined by the beaming geometry of the southern hemisphere source [Leblanc et al., 1993; Leblanc, 1981]. However, as seen in Figures 2 and 3, a second envelope of emission appears before the first has dissipated reaching nearly the same maximum frequency. This argues for an extended source region in the southern hemisphere. Hess et al. [2008] were able to simulate many of the Io-related arc structures using an emission beam model, the lead angle between Io and the emitting field line, and the electron energy. In particular, with a very small lead angle, $+8°$, they were able to show observed arc structures for the Io-D source. However, there were discrepancies in the peak frequencies simulated, most likely due to inaccuracies in the Jovian field model near the planet. Previous ground-based and Voyager data show that Io-D emission extends from $0° - 260°$ [Leblanc, 1981], and Figure 2 shows that the Io-D emission may extend to higher longitudes. The Io-D emission splits into three or four distinct bands of emission, and in some cases the bandwidth < 100 kHz. These narrow-band features are N-events having typical bandwidths of 200–600 kHz over many tens of minutes. Figure 4 shows an Io-D envelope that narrows into an N-event and persists for more than 1 hour. Many of these spectral structures are similar to those seen in the Io-B source, and perhaps require similar explanations for the beaming [e.g. Queinnec and Zarka, 1998].

Figure 5 shows an Io-D event that is interesting for two reasons. First the maximum frequency of emission is 26.5 MHz, higher than previously known. Marques et al. [2017] have presented some evidence that Io-D emission reach 27.9 MHz from observations with the
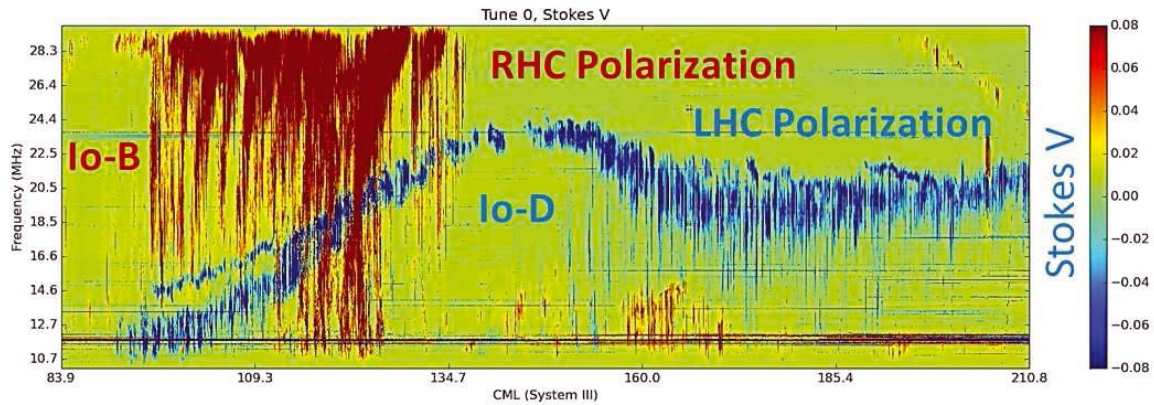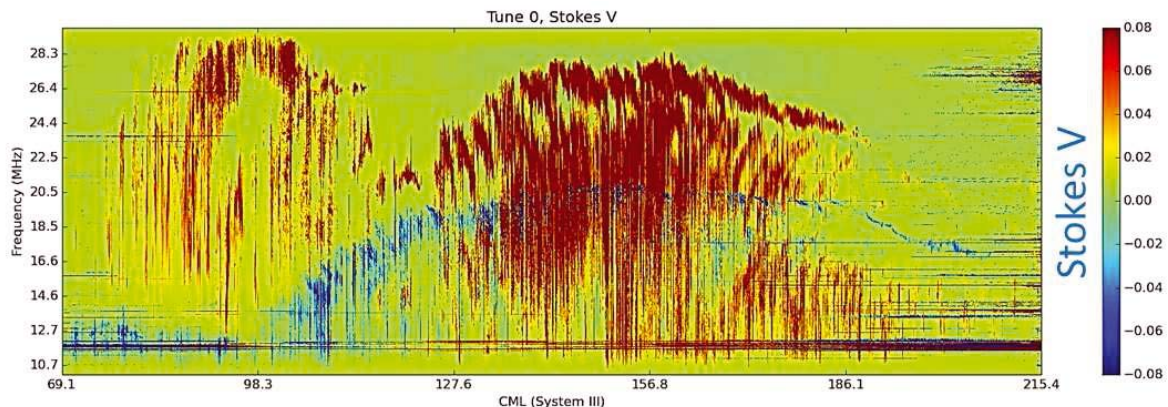
Figure 3: Jupiter Io-B/Io-D emission on 12 December, 2014 beginning at 09:00 UT. The 3.5-hour observation shows a frequency range from 10.35 to 29.65 MHz, a CML range of $83.9° - 210.8°$, and a corresponding Φ_{Io} from $90° - 120°$. The colorbar shows Stokes V power spectral density in arbitrary units.

Figure 4: Jupiter Io-B/Io-D emission on 26 December, 2014 beginning at 10:00 UT. The 4-hour observation shows a frequency range from 10.35 to 29.65 MHz, a CML range of $69.1° - 215.4°$, and a corresponding Φ_{Io} from $68° - 102°$. The colorbar shows Stokes V power spectral density in arbitrary units.

Nançay Decameter Array. In either case, this extension to higher frequencies of a southern hemisphere radio source has profound implications on the maximum field strength in the southern hemisphere; for example, $\nu = 26.5$ MHz requires a field strength of approximately 9.5 Gauss.

These LWA1 observations show Io-D in the CML range $67° - 262°$ and in the Φ_{Io} range $68° - 135°$. Typinski [private communication, 2015] has recorded Io-D up to CML $287°$ and as low as Φ_{Io} $50°$. Clearly, the radio source boundaries on the Io phase–CML occurrence probability map are frequency dependent. Therefore, using these data with the Leblanc (1981) Voyager results, the Io-D region observed from 2.5–26.5 MHz on the Io phase–CML occurrence probability map should have the following limits: CML $= 0° - 287°$ and $\Phi_{Io} = 50° - 135°$. In light of these new data, the limits of the Io-D region need

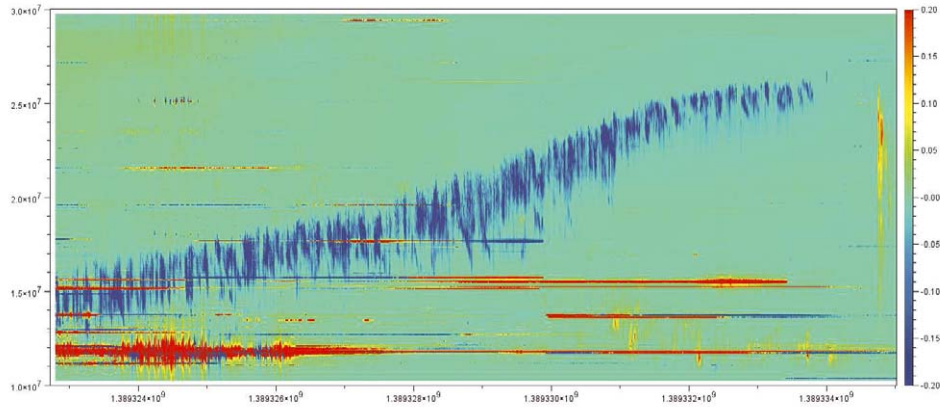*Figure 5: Io-D event on 10 January, 2014 from 03:00–06:24 UT (CML = 86.7° − 210.1°, Φ_{Io} = 106° − 135°) observed using LWA1 spectrometer mode at 40 ms and 20 kHz resolution. The peak frequency is 26.5 MHz. The colorbar shows Stokes V power spectral density in arbitrary units. Horizontal lines are interference with some saturation at 12 MHz.*

redefinition.

Modulation lanes are very common features in Jupiter's Io-related emissions [Riihimaa, 1968; Imai et al., 2002]. Although not shown here, modulation lane structures are easily seen in the LWA1 observations at modest resolutions, 40 ms and 20 kHz [Clarke et al., 2014]. From the current analysis of LWA1 data, modulation lanes are ubiquitous in the Io-D emission, as well as in the other Io-related source emission. These features can be used to place bounds on the source positions and beaming pattern of the radio emission [K. Imai et al., 2017; Imai et al., 2002]. The Io-D modulation lane events could lead to a better understanding of the southern hemisphere radio sources.

Previous detections of S-burst events in the Io-D source are few [Clarke et al., 2014; Litvinenko et al., 2010]. However, these data from LWA1 show that S-bursts are ubiquitous in the Io-D source. A subset of the LWA1 observations were analyzed for S-burst activity, and Figure 6 shows several examples of LH S-bursts within the Io-D source. In many cases, both RH S-bursts from the Io-B source are seen simultaneously. Although Io-D S-bursts are seen at all longitudes of the source region observed with the LWA1 (67° − 262° CML), their occurrence is higher between 67° − 150° CML. That is, more S-bursts were found at the leading edge of the source indicating a strong initial interaction with Io as the source region sweeps past Io. This is consistent with the statistics of S-bursts from the Io-B source [Flagg et al., 1991]. However, this Io-D study is based on a small sample size and more data are needed to quantify this result.

The frequency-time drift rates of Jovian S-bursts have been used to determine the energies of the precipitating electrons, and, therefore, to test radio emission theories [e.g. Zarka et al., 1996]. Figures 6–9 show many S-bursts with a diversity of structure and differing drift rates. Figure 6 shows left-handed Io-D S-bursts between 14–18 MHz (blue) with complex structure, similar to known Io-B S-bursts, and also shows Io-B S-bursts (red) at higher frequencies. Frequency drift rates were measured for at least five S-bursts in each observation. The Io-D drift rates are −12.8 MHz/s at 16 MHz, whereas the Io-B drift
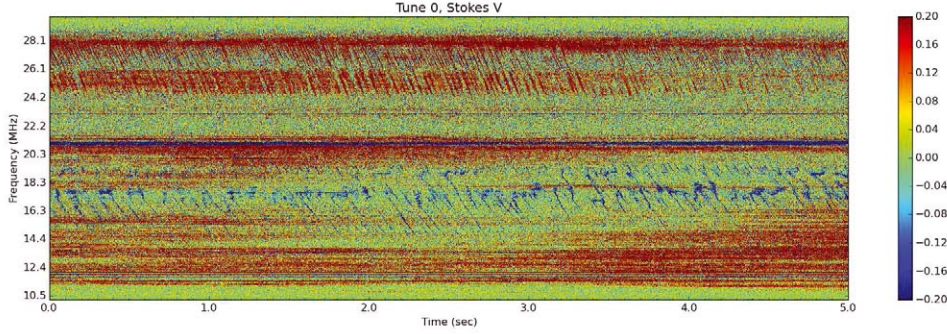
Figure 6: Io-D S-bursts (blue) and Io-B S-bursts (red) on 27 January, 2015 at 09:01 UT (CML = 174.9°, Φ_{Io} = 95.2°). Note the different S-burst drift rates for the Io-B (-21.1 MHz/s) and the Io-D (-12.8 MHz/s) events.

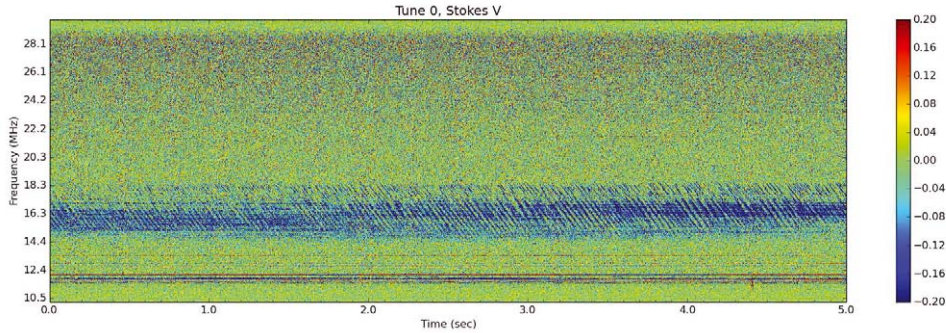*Figure 7: Io-D S-bursts on 27 January, 2015 at 10:19 UT (CML = 222.2°, Φ_{Io} = 106.3°). The S-burst drift rates are -13.8 MHz/s at 17.5 MHz.*

rates are -21.1 MHz/s at 26.5 MHz. The different drift rates of the Io-B and the Io-D sources demonstrate that these emissions are not co-spatial. Figure 7 shows a regular "train" of S-bursts in a clear band of emission between 15–18 MHz; the S-burst drift rates are -13.8 MHz/s at 17.5 MHz. Figure 8 shows weak S-bursts at very low frequencies, down to 10.5 MHz; drift rates are -8.2 MHz/s at 11.5 MHz. Finally, Figure 9 shows simultaneous S-bursts from both the Io-D and Io-B sources. The Io-D S-bursts are seen between 16.5–18.5 MHz and have measured drift rates of -9.2 MHz/s at 17.5 MHz. The drift rate data presented here, when plotted as a function of frequency, are consistent with the adiabatic scenario for generation (see Figure 3 from Zarka et al. [1996]). Again, the differing drift rates and polarization for the Io-D and Io-B S-bursts imply that the bursts are emitted from separate southern and northern hemisphere sources, respectively. An interesting question is whether the Io-B and Io-D S-burst events are related by common Alfvén waves or mirrored groups of electrons; this is left for future work.

4 Conclusions

The Long Wavelength Array (LWA1) is well-suited for studies of Jupiter decameter radio emission (DAM). It has a large bandwidth, full Stokes capability, and excellent resolution
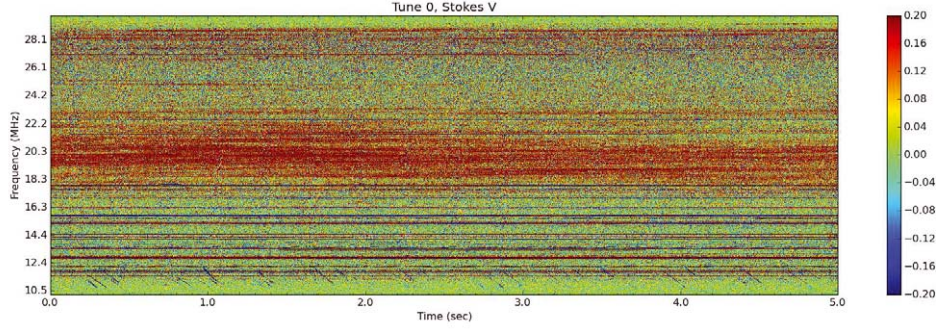
Figure 8: *Io-D S-bursts on 28 February, 2015 at 02:49 UT (CML = 91.0°, Φ_{Io} = 78.3°). The S-burst drift rates are -8.2 MHz/s at 11.5 MHz.*
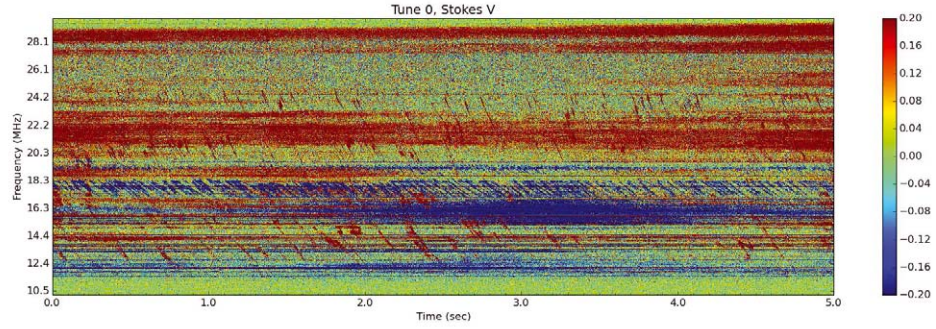

Figure 9: *Io-D S-bursts on 07 March, 2015 at 04:43 UT (CML = 134.2°, Φ_{Io} = 79.5°). The Io-D S-burst drift rates are -9.2 MHz/s at 17.5 MHz. Io-B bursts occur from 12–15 MHz (drift rate of -11.6 MHz/s) and 21–24 MHz (drift rate of -21.0 MHz/s).*

to study Jupiter's fine DAM structures. The Io-D radio source is clearly seen in LWA1 observations and shows characteristic LH polarization, and a sweeping envelope of vertex-early arc structures with substructures. We have presented new morphology attributed to the Io-D emission source. Our results about the Io-D source can be summarized as follows:

- We observe splitting of the main arc envelope into narrow banded events, some persisting for more than one hour.

- We observe a double-envelope structure, implying an extended southern hemisphere source region.

- The peak frequency of Io-D is 26.5 MHz; this requires a lower limit of approximately 9.3 Gauss for the magnitude of the southern magnetic field.

- The average peak frequency source location is estimated to be 235° in Jovian longitude; this result can be used to further test magnetic field models.

- Modulation lanes are commonly seen in Io-D data.

- S-bursts are ubiquitous in the Io-D source, and drift rates are consistent with an adiabatic emission scenario.

- More S-bursts are observed on the leading edge of the Io-D source implying a stronger interaction with Io at that time.

- The Io-D source occurrence boundaries require new, expanded limits: CML $= 0° - 287°$ or greater (see Genova and Aubier [1985]) and $\Phi_{Io} = 50° - 135°$.

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