DATABASE OF SOLAR RADIO BURSTS OBSERVED BY SOLAR RADIO SPECTRO–POLARIMETER AMATERAS

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Abstract

Observations of solar radio bursts is a useful tool to study non-thermal electron acceleration and the plasma environment in the solar corona. The radio bursts in a frequency range from 150 to 500 MHz with fine temporal and spectral resolutions (10 ms and 61 kHz) have been observed with the AMATERAS radio spectro–polarimeter installed at the Iitate Planetary Radio Telescope since 2010. Here we review results obtained from the AMATERAS observation and introduce the database which is open to the public. The AMATERAS receiver consists of a wide-band and low-noise front–end receiver and a digital spectrometer. Both right and left-hand polarized components are simultaneously observed. The combination of a large aperture area of the telescope and the digital receiver enables us to observe the radio burst with high dynamic range and fine spectral resolution. After a daily observation of the Sun, a data processing pipeline generates low and high resolution data sets. The low resolution data with reduced resolutions of 1 s, 1 MHz, and 8 bits is converted to the FITS format and distributed through the AMATERAS Data Center. Quick look (PNG format) and meta-data of the FITS–format file are registered to the Virtual European Solar and Planetary Access (VESPA) and Inter–university Upper atmosphere Global Observation NETwork (IUGONET) database. The high resolution data set has fine resolutions of 10 ms and 61 kHz, but the dynamic range is reduced to be 8 or 16 bits depending on the intensity of the radio burst observed. It is currently provided on request basis.

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1 Introduction

Tohoku University has developed a radio spectro–polarimeter for solar radio observation. The spectro–polarimeter, named AMATERAS (the Assembly of Metric–band Aperture TElescope and Real–time Analysis System), observes the radio bursts in the frequency range between 150 and 500 MHz with an integration time of 10 ms and a bandwidth of 61 kHz [Iwai et al., 2012a]. The non-thermal radio emission from the Sun is mostly generated by energetic electrons produced by some acceleration processes in the solar corona. The energetic electrons excite plasma waves near the local electron plasma frequency and its harmonics and they are converted to radio waves. Because the plasma frequency depends on the electron density in the corona and the density monotonically decreases as increasing height from the Sun, the frequency of the radio emission tells us the height where these plasma processes occur. Using a well known coronal density model (e.g. 10× Baumbach–Allen model), the frequency range of AMATERAS corresponds to the height from the bottom of the coronal to ∼1.4 solar radii from the surface. This frequency range is useful to study energetic electron acceleration and associated plasma processes occurring in the coronal loop structure. The fine temporal and spectral resolutions of AMATERAS resolve spectral structures embedded in the radio bursts and enables us to investigate not only the electron acceleration process but also fundamental plasma processes in the solar corona. This paper introduces the AMATERAS database which is open to the public (Section 2) and shows some results obtained from the AMATERAS observation (Section 3).

2 Specification of AMATERAS and on-line database

The AMATERAS receiver consists of a low-noise front–end amplifier, back–end receiver, and a digital spectrometer (Aquiris AC240 (2 GS/s, 8 bit)). A wide-band radio frequency signal received by a crossed dipole antenna is converted from two orthogonal linear polarized components to left- and right-hand circular polarized components at the front–end receiver. Both signals are guided to the back–end receiver and analyzed by the digital spectrometer. Radio spectra analyzed have a frequency range from 150 to 500 MHz and a spectral resolution of 61 kHz and are accumulated for 10 ms in the spectrometer. The AMATERAS receiver is installed at the Iitate Planetary Radio Telescope (IPRT). IPRT is a ground-based radio telescope developed by Tohoku University and has been operated at the Iitate observatory in Fukushima prefecture Japan since 2000 (Iitate village, Fukushima prefecture, Japan; 37d 42m N, 140d 41m E) [Misawa et al., 2003]. The primary purpose of the telescope is to investigate the time variability of Jupiter's synchrotron radiation. For this purpose, IPRT has another low-noise receiver system at fixed frequencies of 325 and 785 MHz [Tsuchiya et al., 2010; 2011]. The combination of a large aperture area of the telescope (511.5 square meters[1]) and the digital receiver enables to observe the solar radio bursts with high dynamic range and fine spectral resolution. The minimum detectable flux in the observation frequency range is less than 0.7 solar flux units (SFU;

[1]IPRT consists of two rectangular–shaped offset parabolic antennas. The AMATERAS receiver is installed on one of the parabolic antennas.

10^{-22} W/m^2/Hz) with an integration time of 10 ms and a bandwidth of 61 kHz. Tables 1 and 2 show typical specifications of AMATERAS. For a full description on AMATERAS see Iwai et al. [2012a].

Several solar radio spectrographs are operating in this frequency range: ARTEMIS-IV, e-CALLISTO at Trieste, LOFAR, Humain, and so on [e.g. Alissandrakis et al., 2009; van Haarlem et al., 2013]. These spectrographs have fine temporal and spectral resolutions of sub-seconds and several 10s of kHz, respectively. The AMATERAS resolutions of 10 ms and 61 kHz are comparable or finer than other spectrographs. One of the significant characteristics of AMATERAS is the large aperture area of the radio telescope. The large aperture area increases the antenna temperature of the solar radio emissions and suppresses the intensity of artificial interferences picked up through the side lobe of the antenna beam. As a result, dynamic range and quality of the spectrograph data are improved.

Table 1: Mechanical specification of IPRT

Antenna type	Asymmetric offset parabola
Aperture size	1023 m^2
Focal length	12 m (F/D=0.39)
Reflector surface	Stainless mesh (20 mm pitch, 9 mm RMS)
Mount type	altitude–azimuth
Steerable range	EL: 22°–100°, AZ: -270°–270°

Table 2: Electrical specification AMATERAS

Digital spectrometer	Aquiris AC240 (fs=2 GHz, 8 bit)
Frequency range	150–500 MHz
Feed system	Crossed dipole antenna
Polarization	LH and RH
Spectral resolution	10 ms and 61 kHz
Sensitivity	0.7 solar flux units

After a daily observation of the Sun, a data processing pipeline generates a high and low resolution data sets. Table 3 shows a summary of data products provided from AMATERAS. The low resolution data with reduced resolutions of 1 s, 1 MHz, and 8 bits is converted to the FITS format and distributed through the AMATERAS Data Center (`http://pparc.gp.tohoku.ac.jp/data/iprt/`) soon after the observation. The high resolution data set has fine resolutions of 10 ms and 61 kHz, but the dynamic range is reduced to be 8 or 16 bits depending on the intensity of the radio bursts observed.

Quick look data in PNG format and meta-data of the low resolution data are registered to the Virtual European Solar and Planetary Access (VESPA) and Inter–university Upper atmosphere Global Observation NETwork (IUGONET) database. The high reso-

Table 3: AMATERAS data products

	Low resolution data[1]	High resolution data[1]
Time resolution	1 s	10 ms
Spectral resolution	1 MHz	61 kHz
Spectral step	410 steps	6554 steps
Polarization	LH and RH	LH and RH
Dynamic range	8 bit (0.1 dB step)	8 bit (0.1 dB step) 16 bit (0.001 dB step)
Data size	17 MB/day (in winter) 35 MB/day (in summer)	786.48 MB/5min (8 bit) 314.59 MB/min (16 bit)
Access to Data	AMATERAS Data Center[2]	Request to PIs

[1] Data availability: `http://radio.gp.tohoku.ac.jp/db/IPRT-SUN/DATA2/`
[2] `http://pparc.gp.tohoku.ac.jp/data/iprt/`

lution data is currently provided on request basis. Please contact the PIs (H. Misawa, F. Tsuchiya, and K. Iwai) if you are interested in using the high resolution data.

The IUGONET project provides a data analysis software package (IUGONET Data Analysis Software: UDAS). It provides a load procedure for users to download and plot the AMATERAS low resolution data easily. Once you have installed the UDAS on your personal computer (`http://www.iugonet.org/en/software.html`), you can download and plot the AMATERAS data with a very simple procedure shown below (only four steps). The result of this procedure is shown in Figure 1.

```
IDL> thm_init
THEMIS> timespan, ['2016-07-20/21:30','2016-07-21/05:30']
THEMIS> iug_load_iprt
THEMIS> tplot,['iprt_sun_R','iprt_sun_L']
```

3 Solar radio bursts seen by AMATERAS

In this section, fine spectral structures in solar radio bursts seen by AMATERAS are reviewed. Due to the capabilities of high temporal and spectral resolutions and high dynamic range, the AMATERAS data is useful to study energetic particle acceleration and fundamental plasma processes occurring in the solar corona.

The fine spectral structures of solar radio type I bursts were investigated by Iwai et al. [2012b; 2012c; 2013; 2014]. It has been known that the occurrence of type I bursts is independent of solar flares but well correlated with the appearance of active regions on the Sun. With the highly resolved spectral data, the spectral structure of the individual burst elements were satisfactorily resolved (Figure 2). Using the data observed on January 26, 2011, Iwai et al. [2013] derived peak flux distributions of type I burst. They developed

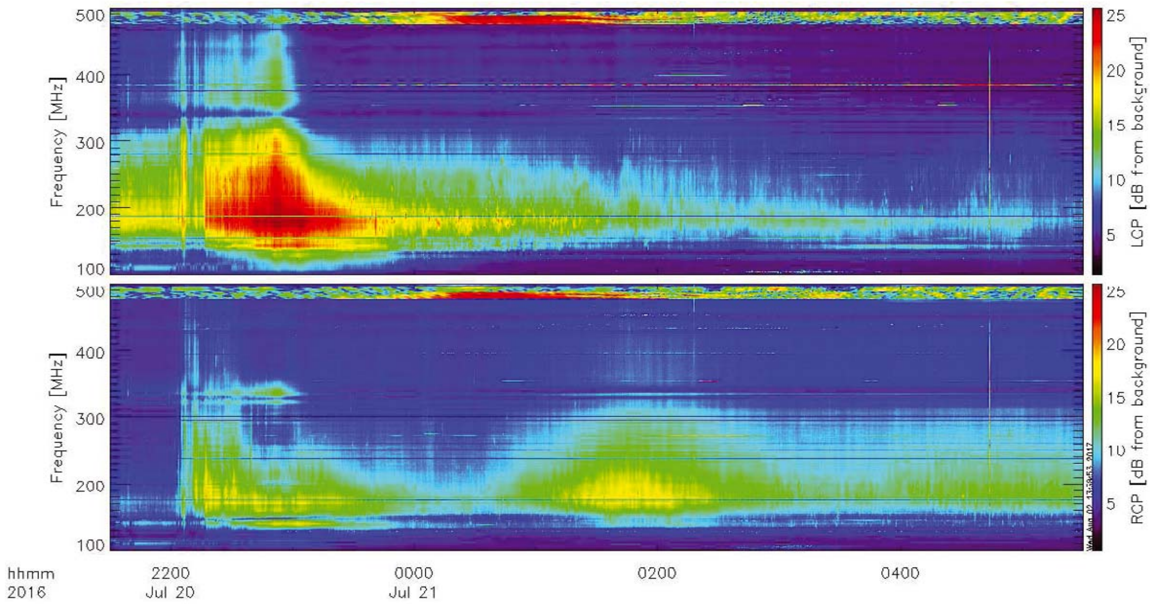

Figure 1: Example of solar radio spectrogram observed on July 20–21, 2016 with AMATERAS. Top and bottom panels show right and left hand polarized components, respectively. Type I, III, and IV bursts are embedded in the spectrogram. Color bars show the intensity of radio emissions with respect to the quiet Sun.

a two-dimensional auto burst detection algorithm that could distinguish each type I burst element from complex noise storm spectra. Burst and continuum components are also distinguished by a two-dimensional maximum and minimum search of the radio dynamic spectra. The peak flux distribution of type I bursts derived using this algorithm follows a power–law with a spectral index between 4 and 5. Iwai et al. [2014] investigated detailed spectral characteristics of type I burst, such as the peak flux, duration, and bandwidth. The peak flux of the type I bursts followed a power–law distribution, whereas their duration and bandwidth were distributed more exponentially. There were almost no correlations between the peak flux, duration, and bandwidth, indicating that there was no similarity in the shapes of the burst spectral structures. They defined the growth rate of a burst as the ratio between its peak flux and duration, and they found a strong correlation between the growth rate and the peak flux.

While type IV radio bursts are known to be radiated from energetic electrons trapped in closed magnetic loops of the solar corona through the synchrotron emission process, fine spectral structures are embedded on it. Kaneda et al. [2015; 2017] found a zebra pattern (ZP) in a type IV solar radio burst and investigated the polarization characteristics. Analyzing highly resolved spectral and polarization data revealed the frequency dependence of the degree of circular polarization and the delay between two polarized components for the first time. The degree of circular polarization was 50–70 percent right-handed, and it varied little as a function of frequency. Cross-correlation analysis determined that the left-handed circularly polarized component was delayed by 50–70 ms relative to the right-handed component over the entire frequency range of the ZP and this delay in-

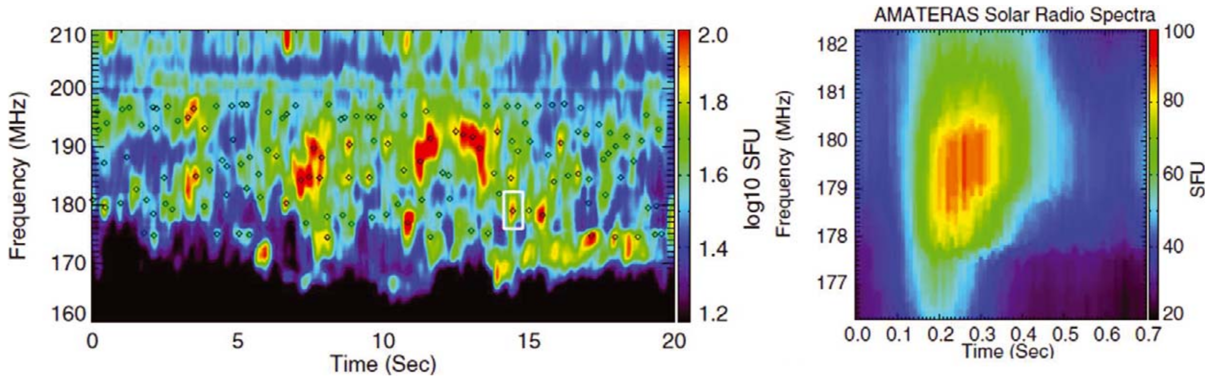

Figure 2: Type I radio bursts observed on 26 January 2011 [after Iwai et al., 2013].

creased with frequency. They examined the obtained polarization characteristics by using pre-existing ZP models and concluded that the ZP was generated by the double plasma resonance process. Their results suggest that the ZP emission was originally generated in a completely polarized state in the O-mode and was partly converted into the X-mode near the source. Subsequently, the difference between the group velocities of the O-mode and X-mode caused the temporal delay.

Katoh et al. [2014] investigated the fine spectral structure in a type IV burst event observed on 7 June 2011. The burst was emitted from the plasmoid eruption identified in the EUV images of the Solar Dynamics Observatory (SDO)/AIA. They found that a slowly drifting narrow band structure (SDNS) appeared in the burst spectra. Using statistical analysis, they reveal that the SDNS appeared for a duration of tens to hundreds of milliseconds and had a typical bandwidth of 3 MHz. To explain the mechanism generating the SDNS, they proposed wave–wave coupling between Langmuir waves and whistler–mode chorus emissions generated in a post–flare loop, which were inferred from the similarities in the plasma environments of a post–flare loop and the equatorial region of Earth's inner magnetosphere.

Since 2010, we have found 13 well-defined metric type II radio bursts from the AMATERAS observation. Metric type II bursts are thought to be a plasma emission excited from non-thermal electrons accelerated by a shock wave. From the AMATERAS observation, it is found that type II bursts commonly appeared as a group of spectral fine structures whose typical duration is within one second. The spectral fine structures can be interpreted as the motion of non-thermal electron beams accelerated in the shock region. This is similar to the mechanism to explain the herring–bone structure which is one of the fine spectral structures previously known, but characteristics of the spectral structure found by AMATERAS are different from the herring–bone; the spectral slope of the fine structure is steeper than that in the herring–bone, and bursts with positive and negative spectral slopes co-exist in the same frequency band.

In addition to observations of fine spectral structures in solar radio bursts, AMATERAS has the capability to observe weak radio bursts. As type III bursts are generated from energetic electrons accelerated at the time of solar flares, a one–to–one correspondence between a type III burst and a soft X-ray (SXR) flare is established for strong type III bursts. On the other hand, AMATERAS found many type III bursts which had moderate or weak radio intensity and did not accompany an SXR flare (or accompanied very weak SXR variations). One of the possible explanations of this characteristic is that the type III bursts are related to compact solar surface phenomena such as an EUV spot or jet, and the lower height or smaller scale size of the magnetic reconnection region cause a quenching of the SXR intensity.

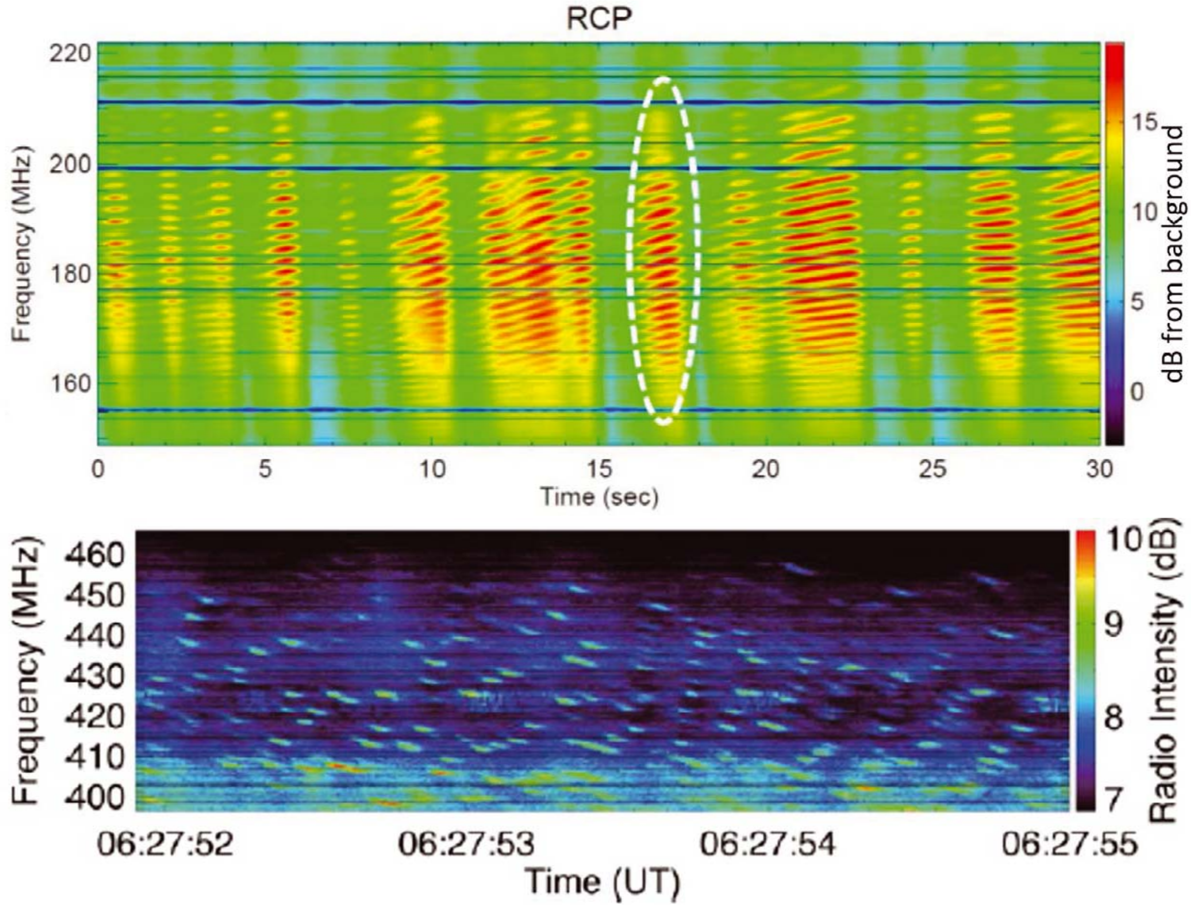

Figure 3: Fine spectral structure in type IV radio bursts. Top: Zebra pattern observed on 21 June 2011 [Kaneda et al., 2015]. Bottom: Slowly drifting narrow band structure (SDNS) observed on 7 June 2011 [Katoh et al., 2014]. Color bars show the intensity of radio emissions with respect to the quiet Sun.

4 Summary

The fine time and spectral resolution radio spectra obtained from AMATERAS resolve spectral structures embedded in the radio bursts and provides us opportunities to investigate the electron acceleration and fundamental plasma processes in the solar corona. The low resolution FITS–format data with resolutions of 1 s, 1 MHz, and 8 bits is available on-line through the AMATERAS Data Center, Virtual European Solar and Planetary Access (VESPA) and Inter–university Upper atmosphere Global Observation NETwork (IUGONET) database. The high resolution data with resolutions of 10 ms and 61 kHz is currently provided on request basis.

Acknowledgments. This project is supported by JSPS and MAEDI under the Japan–France Integral Action Program (SAKURA), the joint research program of the Institute for Space–Earth Environmental Research (ISEE), Nagoya University, and the Inter–university Upper atmosphere Global Observation NETwork (IUGONET) project funded by the Ministry of Education, Culture, Sports, Science and Technology of Japan. Studies on the fine spectral structure in type II bursts were done as master's thesis studies by Shintaro Sato and Hirotaka Kashiwagi (Tohoku University). The study on type III bursts was done as a master's thesis study by Saho Matsumoto (Tohoku University). The Editors thank Anatolii Brazhenko and one anonymous reviewer for their help in evaluating this paper.

References

Alissandrakis, E., A. Kontogeorgos, P. Tsitsipis , C. Caroubalos, X. Moussas, P. Preka–Papadema, A. Hillaris, J. –L. Bougeret, and G. Dumas, New developments in ARTEMIS IV solar radio spectrograph, *Earth Moon Planets*, **104**, 93–95, 2009.

Iwai, K., F. Tsuchiya, A. Morioka, and H. Misawa, IPRT/AMATERAS: A new metric spectrum observation system for solar radio bursts, *Solar Phys.*, **277**, 2, 447–457, doi:10.1007/s11207-011-9919-y, 2012a.

Iwai, K., Y. Miyoshi, S. Masuda, M. Shimojo, D. Shiota, S. Inoue, F. Tsuchiya, A. Morioka, and H. Misawa, Solar radio type-I noise storm modulated by Coronal Mass Ejections, *Astrophys. J.*, **744**, id.167, 9 pp., doi:10.1088/0004-637X/744/2/167, 2012b.

Iwai, K., H. Misawa, F. Tsuchiya, A. Morioka, S. Masuda, and Y. Miyoshi, Survey of accelerated particles in a solar active region using Hinode/XRT and ground-based type-I radio burst observations, in *Hinode-3*, ASP Conference Series, **454**, 249–253, 2012c.

Iwai, K., S. Masuda, Y. Miyoshi, F. Tsuchiya, A. Morioka, and H. Misawa, Peak flux distribution of solar radio type-I bursts from highly resolved spectral observations, *Astrophys. J.*, **768**, L2, doi:10.1088/2041-8205/768/1/L2, 2013.

Iwai, K., Y. Miyoshi, S. Masuda, F. Tsuchiya, A. Morioka, and H. Misawa, Spectral structures and their generation mechanisms for solar radio type-I bursts, *Astrophys. J.*, **789**, id.4, 9 pp., doi:10.1088/0004-637X/789/1/4, 2014.

Kaneda, K., H. Misawa, K. Iwai, F. Tsuchiya, and T. Obara, Frequency dependence of polarization of zebra pattern in type-IV solar radio bursts, *Astrophys. J.*, **808**, id.L45, 6 pp., doi:10.1088/2041-8205/808/2/L45, 2015.

Kaneda, K., H. Misawa, K. Iwai, F. Tsuchiya, T. Obara, Y. Katoh, and S. Masuda, Polarization characteristics of zebra patterns in type IV solar radio bursts, *Astrophys. J.*, **842**, id.45, 12 pp., doi:10.3847/1538-4357/aa74c1, 2017.

Katoh, Y., K. Iwai, Y. Nishimura, A. Kumamoto, H. Misawa, F. Tsuchiya, and T. Ono, Generation mechanism of the slowly drifting narrowband structure in the type IV solar radio bursts observed by AMATERAS, *Astrophys. J.*, **787**, id.45, 6 pp., doi:10.1088/0004-637X/787/1/45, 2014.

Misawa, H., R. Kudo, F. Tsuchiya, A. Morioka, and T. Kondo, Development of a primary feed system for the parabolic rectangular reflector antenna dedicated for planetary radio emission, in *Proc. of 3rd Communications Research Laboratory Technology Development Center Symposium*, Commun. Res. Lab., Kashima, Japan, 2003.

Tsuchiya, F., H. Misawa, K. Imai, A. Morioka, and T. Kondo, Multi–frequency total flux measurements of Jupiter's synchrotron radiation in 2007, *Adv. Geosci.*, **19**, 601–612, 2010.

Tsuchiya, F., H. Misawa, K. Imai, and A. Morioka, Short–term changes in Jupiter's synchrotron radiation at 325 MHz: Enhanced radial diffusion in Jupiter's radiation belt driven by solar UV/EUV heating, *J. Geophys. Res.*, **116**, A09202, doi:10.1029/2010JA016303, 2011.

van Haarlem, M., et al. (200 co–authors), LOFAR: The LOw-Frequency ARray, *Astron. Astrophys.*, **556**, id.A2, 53 pp., 2013.