GROUND-BASED STUDY OF SATURN LIGHTNING

J.-M. Grießmeier*, P. Zarka†, A. Konovalenko‡, G. Fischer§,
V. Zakharenko‡, B. W. Stappers¶, J. N. Girard†, B. Ryabov‡,
D. Vavriv‡, V. Ryabov‖, and H. O. Rucker§

Abstract

Radio signatures of lightning discharges on Saturn have first been discovered by the Voyager spacecraft in 1980/81. After the Voyager flybys, the next sets of measurements only became available in 2004, when the Cassini spacecraft approached Saturn. Since then, Cassini provides continuous monitoring of Saturn's lightning activity. In 2006, ground-based observations became available as a complementary source of information. Using a new broadband receiver at the UTR-2 radio telescope (Ukraine), Saturn lightning was observed over the whole spectral range of the instrument (10-30 MHz). This allows study of the temporal fine structure of the emission with a much finer temporal resolution than that of the routine satellite observations. More recently, Saturn lightning was also observed by two further ground-based radiotelescopes, namely WSRT (the Netherlands) and LOFAR (Europe). We present first results of recent ground-based observations of Saturn lightning performed with the radiotelescopes UTR-2, WSRT and LOFAR, and we describe the aims of future observations using these instruments.

1 Introduction

Not long after the beginning of radio observations, it was found that terrestrial lighting generates a high frequency radio signal. Later, satellite observations showed that this phenomenon is not limited to our own planet, but also takes place elsewhere in the solar

---

* Laboratoire de Physique et Chimie de l'Environment et de l'Espace, CNRS, 45071 Orléans, France& Observatoire des Sciences de l'Univers en région Centre (OSUC), Orleans, France

† LESIA, Observatoire de Paris, UMR CNRS 8109, 92195 Meudon, France

‡ Institute of Radio Astronomy, Ukrainian Academy of Sciences, Chervonopraporna 4, 61002, Kharkiv, Ukraine

§ Space Research Institute, Austrian Academy of Sciences, Schmiedlstrasse 6, A-8042 Graz, Austria

¶ Jodrell Bank Center for Astrophysics, School of Physics and Astronomy, University of Manchester, Manchester M13 9PL, UK

‖ Complex Systems Department, Future University, Hakodate, Hokkaido, Japan, 041-8655

system. However, the limited reach and lifetime of satellite missions meant that the amount of available data was rather limited until recently: HF (high-frequency) radio emission caused by planetary lightning was clearly observed for Saturn (by Voyager 1 and 2) in 1980-1981, and at Uranus (by Voyager 2) in 1986. Due to the faintness of the signal, Saturn lightning emission was not detectable using ground-based telescopes, and measurements only became possible again in 2004, when the Cassini spacecraft approached Saturn. For a more complete picture over Saturn lightning studies, including results by Cassini, the reader is referred to Fischer et al. [2006, 2007, 2008, 2011].

In the recent past, these satellite observations have been complemented by ground-based observations. With improved radio receivers and using Cassini as a trigger (i.e. the selection of an observation window based on the detection of several consecutive episodes of intense lightning activity by Cassini), ground based observations of SEDs ("Saturn Electrostatic Discharges") have finally become possible. The first unambiguous detection of SEDs took place at the giant ($\sim 150,000\text{m}^2$ collecting area) Ukrainian radiotelescope UTR-2 [Braude et al. 1978] in 2006 [Konovalenko et al. 2006]. Since then, additional observations have been performed with the WSRT and with LOFAR. These ground-based observations will be the main subject of the present proceeding.

This paper is organised as follows: The complementarity between ground-based and space-based observations is discussed in Section 2. Recent ground-based observations with UTR-2, WSRT and LOFAR are presented in Sections 3, 4 and 5, respectively. Future observation plans are given in Section 6, and Section 5 closes with a few concluding remarks.

2 The Complementarity of Ground-based and Space-based Observations

Ground- and space-based observations each have their advantages and disadvantages, making both methods strongly complementary. The best results can be obtained by combining both methods. The advantages of ground-based radio observations are the following:

- Observations at high temporal resolution are possible, up to the full time resolution defined by the frequency bandwidth of the observation. For example, for LOFAR (see also Section 5), time resolution can be as small as 5 μs in standard mode, whereas Cassini usually operates with integration times of 10, 20, 40, 80 or 160 ms [Fischer et al. 2006]);
- A large bandwidth can be covered instantaneously (as opposed to frequency sweeping frequently employed in satellites), which makes it possible to study the spectrum of individual events;
- In addition, ground-based observations can be used for long-term monitoring campaigns (e.g. a series of observations spanning many years in order to study seasonal effects).

The disadvantages of ground-based measurements when compared to satellite observations are the following:

- Low flux because of the large distance (e.g. $1.5 \cdot 10^9$ km distance from the Earth to Saturn when compared to a spacecraft which can approach Saturn to a distance of 10^5 km, leading to a difference in received radio flux of over 8 orders of magnitude)
- A small angular size of the target because of the large distance, making it difficult to resolve spatial structures (whereas Cassini has a direction-finding mode [e.g. Fischer et al. 2006]);
- Frequencies below 10 MHz are inaccessible from the ground because of the terrestrial ionosphere, whereas spacecraft can observe at much lower frequencies (e.g. the Cassini spacecraft observes Saturn lightning by rapidly sweeping through the frequency range 0.325-16.125 MHz);
- Observations have to be targeted and dedicated (whereas a spacecraft can record the signal quasi continuously while in orbit);
- Observational constraints arise due to the Earth's rotation;
- Potentially strong RFI ("radio frequency interference") can render observations difficult, especially at low observing frequencies.

None of these disadvantages is critical. The problem of low fluxes can be mitigated by using large antenna arrays (such as UTR-2 or LOFAR). Similary, even for a source with a small angular size, spatial structures can be resolved if the narrow beams of large antenna arrays are used. Even though it is not possible to observe below 10 MHz, observations above this cutoff also yield valuable and complimentary information. For example, the Cassini spacecraft observes in the range 0.325-16.125 MHz, which allows for enough overlap with UTR-2 (8-32 MHz) or LOFAR (10-250 MHz). While satellite observations provide continuous observations as long as they are in orbit, a ground-based facility can provide a longer-term monitoring i.e. through a series of observations spaced over many years. Earth's rotation means that a planetary target can only be observed for a fraction of the day (∼30%), which is inconvenient (especially for target-of-opportunity observations of transient phenomena), but this doesn't prevent useful observations. The RFI-environment, however, requires a good observation strategy and appropriate algorithms. The observations described in the following sections show that these obstacles can be overcome, and that first results have already been obtained.

3 Saturn Observations with UTR-2

Between 2004 and today, a certain number of SED storms have been observed by the Cassini satellite. These storms lasted between a few days and several months. The time between successive storms is equally variable – time periods between a few weeks and over a year have been observed. During storm F, which started in November 2007 [Fischer et al. 2008], Saturn lightning was observed at the UTR-2, using a new, broadband digital receiver [Ryabov et al. 2010]. Details of the observation strategy and of the data analysis are described in Grießmeier et al. [2010], but a few first results of this series of observation should be mentioned here:

- In 22 hours of useful observation distributed over six observation sessions (shown by the thin horizontal line on the top of Figure 2), 3421 individual events were identified as potential SED signal, and 763 events were identified as RFI. Hereby, RFI was statistically estimated by analysis of a reference beam ("OFF-beam") pointing to a location close to, but excluding the target. With this, the number of real detections is ~ 2700, and the fraction of true positives is $\sim 80\%$, i.e. 20% of identified SEDs are in fact RFI. The temporal distribution of these SED events is shown in Figure 1. Values close to or below zero at a given time indicate that at that moment all recorded events are likely due to RFI.
- A total of $\sim 4 \cdot 10^6$ useful spectra were recorded with a time resolution of 20 msec. On average, this corresponds to approximately 0.03 lightning events per second, but this activity strongly varies with time. For one of the episodes (the fourth one in Fig. 1), an occurrence rate of 0.17 per second was found.
- As shown in Fig. 2, the distribution of the duration of SED events observed at UTR-2 was found to follow an exponential distribution with an e-folding time of ~ 30 ms. This is less than the time-constant obtained in previous observations: For Voyager 1, the e-folding time was determined to be $\tau = 41$ ms, and a value of 38 ms was obtained for Voyager 2 [Zarka & Pedersen 1983]. For Cassini, during storms C, D and E, values between 37 and 49 ms were found [Fischer et al. 2007]. The e-folding time can be used to analyze whether individual SED events are independent. A detailed discussion of the difference between the current and earlier observations and its interpretation is deferred to Grießmeier et al. [2011].
- Via analysis of the OFF-beam, the duration of RFI events was found to be different from the duration of SED events. RFI is consistent with independent, randomly distributed events.
- Figure 3 shows a direct comparison between the numbers of SEDs detected by UTR-2 (upper part of the figure) and the normalized number of SEDs detected by the RPWS instrument onboard Cassini (lower part of the figure, displayed downwards) as a function of time (SCET for Cassini at Saturn). The period of Cassini/RPWS detected SED episodes is close to Saturn's rotation period (the rotation of Saturn's equatorial atmosphere is 10h 10min) whereas SED detection from Earth is only possible once per Earth day. Hence, only every second SED episode observed by Cassini/RPWS can have a UTR-2 counterpart. For Cassini/RPWS we calculated a so-called normalized number of SEDs which reflects the intrinsic variability of the SED activity independent of observational parameters like spacecraft distance and position, antenna orientation, and receiver mode. This normalized number is described in more detail in Grießmeier et al. [2011]. The pattern of white and gray areas in Figure 3 indicates the visibility of the SED source as seen from the

respective observatory. White color means that the SED source is on the visible side of Saturn for the respective telescope, while gray color indicates that the storm is on the back side of Saturn (and thus not geometrically visible). Still, a few SEDs are found in this region. This is called the "over-horizon effect", and has already been observed before [Fischer et al. 2006, 2008], where the SED radio signal is trapped below the planetary ionosphere and thus can travel a certain distance around the planet [Zarka et al. 2006].

The comparison of the numbers of observed SEDs between UTR-2 and Cassini/RPWS in Figure 3 shows that the ground-based UTR-2 observatory with its huge effective area seems to be able to observe a number of SEDs similar to that detected by the Cassini/RPWS instrument onboard Cassini. The relative sizes and shapes of the humps in Figure 3 for Cassini/RPWS and UTR-2 observed SEDs match fairly well. A good agreement between the results of UTR-2 and the observations by Cassini has also been reported by Zakharenko et al. [2010] for the same set of observations. A more detailed description of the observations and a discussion of the differences in the measured e-folding times when compared to earlier observations is in preparation [Grießmeier et al. 2011]. Also, now that the comparison of SEDs recorded with Cassini and UTR-2 at a comparable time resolution has shown good agreement, the next step will be the analysis of spectra recorded at higher time resolution [Grießmeier et al. 2011].

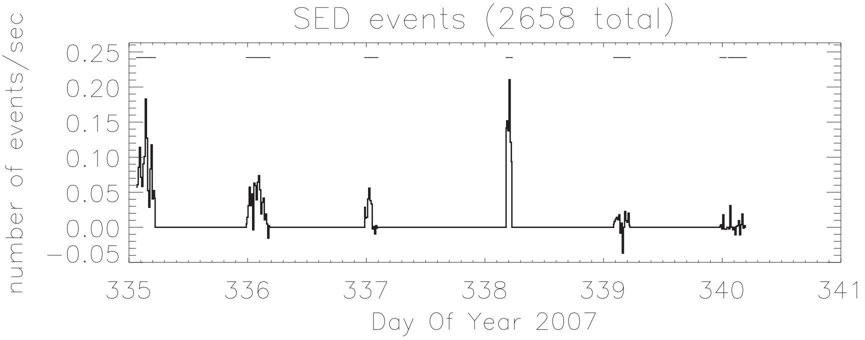

Figure 1: Saturn lightning events observed with UTR-2 in 12/2007. The time windows covered by the observations are indicated at the top of the figure (thin horizontal line).

4 Saturn Observations with WSRT

On 27 February 2010, Saturn was observed with the Westerbork Synthesis Radio Telescope (WSRT) at frequencies between 130 and 156 MHz. As for the observation with UTR-2 and with LOFAR (section 5), the observation took place during times of lightning

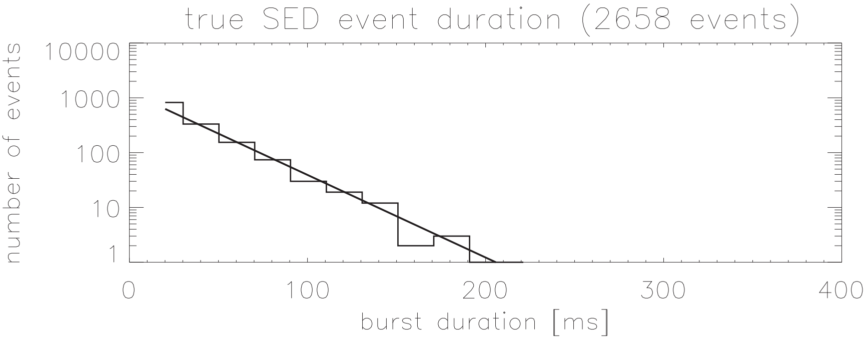

Figure 2: Distribution of true SED events for the observations taken at UTR-2 in 12/2007 with a time resolution of $\Delta t = 20$ *ms. Solid line: Fit with an exponential distribution with an e-folding time of* 29 ± 2 *ms.*

activity, and the Cassini spacecraft was used to trigger the observation. The highest frequency at which Saturn lightning radio emission has been detected previously is 40 MHz (i.e. the maximum frequency detectable by the receiver onboard Voyager), so that the high frequency spectrum of Saturn lightning remains unknown. It is, however, expected that the spectrum of Saturn lightning extends to frequencies above 100 MHz. The flux density is expected to decrease with increasing frequency, so that between 130 and 156 MHz, relatively low flux densities are expected. Models also predict a steepening of the spectrum (from f^{-2} to f^{-4}), but the frequency where this happens is currently unknown. One of the aims of this observation was to determine the position of this change in spectral slope.

The WSRT dataset is currently being analyzed. A preliminary analysis of the data (Figure 4) shows that the distribution of the duration of SED events seems to follows an exponential distribution with an e-folding time of ~ 23 ms. This is less than the time-constants mentioned in Section 3, but this is only a preliminary result of a partial data treatment. Even if this result is confirmed, this would constitute the first detection of SEDs at frequencies above 40 MHz. A complete analysis of this dataset is under preparation.

5 First Saturn Observations with LOFAR

First observations of Saturn lightning have recently been performed with the LOFAR telescope [van Haarlem et al., 2011, in preparation]. Because of its low frequency coverage and high sensitivity, LOFAR is very well adapted to observe Saturn lightning. LOFAR allows observations both at frequencies where this phenomenon is already known (≤40 MHz) and to extend the frequency range in which this effect is studied. As in the observations

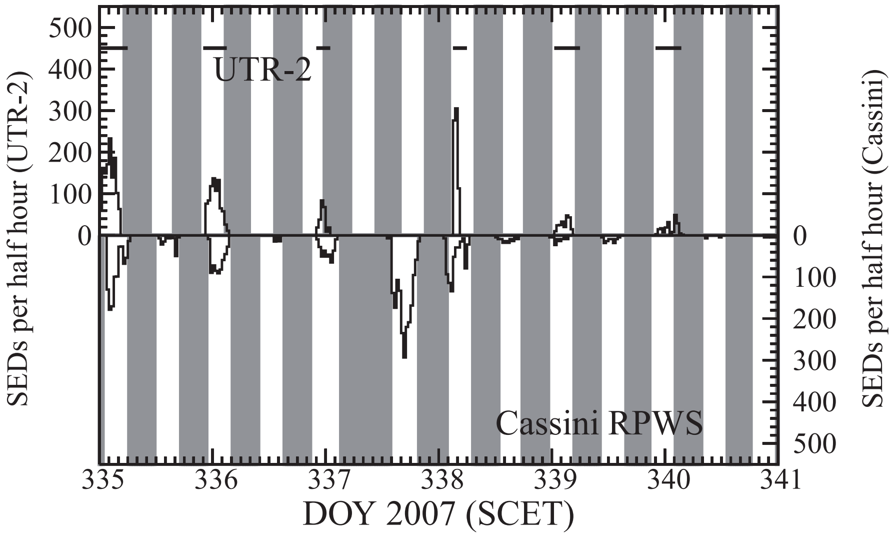

Figure 3: Number of detected SEDs per half hour by UTR-2 (upper histogram) and normalized detection rate from Cassini/RPWS (lower histogram) as a function of time (SCET). Solid line at the top of the graph: Time range of UTR-2 observations. White area: Time range when the storm was on the visible side of Saturn for the respective telescope ($abs(LT_{storm} - LT_{telescope}) < 6h$)*. Grey area: Time range when the storm was behind the geometric horizon of Saturn.*

by UTR-2 and WSRT, the frequency coverage is instantaneous (i.e. all frequency channels are observed simultaneously), which also allows direct observation of the temporal fine structure of the emission, which is not possible with current satellite observations.

Observations with LOFAR can be used to measure the spectrum over a wide frequency band (10-250 MHz), which could increase the range of frequencies with observed Saturn lightning activity by a factor up to 6. The point where the spectral slope changes can be directly measured and compared to terrestrial values. High time resolution (up to 5 microseconds in standard mode) profiles of Saturn lightning can be observed, giving direct access to the stroke duration which is still unknown, but could be extremely short at Saturn. The stroke time scales could be as low as 1 μs, while the terrestrial value is $\sim 70\mu$s [Farrell et al. 2007]. The stroke duration is an important parameter required to estimate the discharge energy, which is uncertain by many orders of magnitude [Farrell et al. 2007].

On 8 April 2010, and again on 16 & 17 December 2010 first LOFAR observations of Saturn lightning we performed. The analysis of these datasets is ongoing.

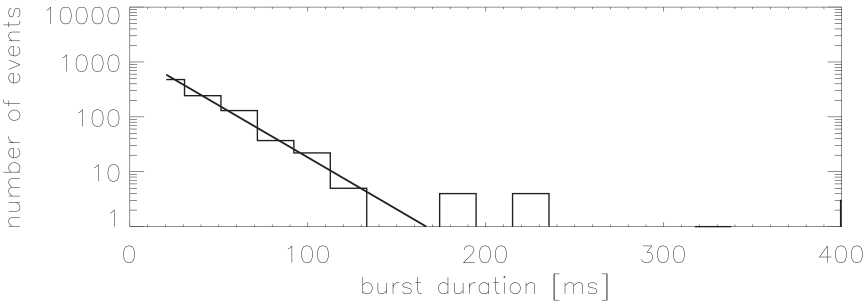

Figure 4: Distribution of true SED events for the observations taken at WSRT 02/2010. Solid line: Fit with an exponential distribution with an e-folding time of 23 *ms.*

6 Planned Observations

After a recent modification, the WSRT telescope can no longer observe in the metric radio domain. Further observations are, however, planned with the radiotelescopes UTR-2 and LOFAR. Also, monitoring by the Cassini spacecraft is ongoing. The scientific questions that will be adressed by these studies will include

- the spectrum of Saturn lightning radio emission,
- the energy of the lightning discharge,
- geographical and seasonal variations,
- atmospheric dynamics.

7 Conclusion

We have discussed the current status of ground-based study of solar system planetary lightning. Observations by UTR-2 were presented. The last observations with WSRT and the first ones with LOFAR were briefly described. We have described the complementarity between ground-based and space-based observations. These first results already show that radio telescopes equipped with current technology hold a great potential for the detection and characterization of Saturn lightning.

Acknowledgements. The observations at UTR-2 were performed within the ANR project "La détection directe des exoplanètes en ondes radio". J.-M. G. was supported by the French National Research Agency (ANR) within the project with the contract number

NT05-1_42530. The Westerbork Synthesis Radio Telescope is operated by the ASTRON (Netherlands Institute for Radio Astronomy) with support from the Netherlands Foundation for Scientific Research (NWO). LOFAR, the Low Frequency Array designed and constructed by ASTRON, has facilities in several countries, that are owned by various parties (each with their own funding sources), and that are collectively operated by the International LOFAR Telescope (ILT) foundation under a joint scientific policy.

References

Braude, S. Ya., A. V. Megn, B. P. Ryabov, N. K. Sharykin, and I. N. Zhouck, Decametric survey of discrete sources in the northern sky: I. the UTR–2 radiotelescope. Experimental techniques and data processing, *Astrophys. Space Sci.*, **54**, 1, 3–36, 1978.

Farrell, W. M., M. L. Kaiser, G. Fischer, P. Zarka, W. S. Kurth, and D. A. Gurnett, Are Saturn electrostatic discharges really superbolts? A temporal dilemma, *Geophys. Res. Lett.*, **34**, L06202, 2007.

Fischer, G., M. D. Desch, P. Zarka, M. L. Kaiser, D. A. Gurnett, W. S. Kurth, W. Macher, H. O. Rucker, A. Lecacheux, W. M. Farrell, and B. Cecconi, Saturn lightning recorded by Cassini/RPWS in 2004, *Icarus*, **183**, 135–152, 2006.

Fischer, G., W. S. Kurth, U. A. Dyudina, M. L. Kaiser, P. Zarka, A. Lecacheux, A. P. Ingersoll, and D. A. Gurnett, Analysis of a giant lightning storm on Saturn, *Icarus*, **190**, 528–544, 2007.

Fischer, G., D. A. Gurnett, W. S. Kurth, F. Akalin, P. Zarka, U. A. Dyudina, W. M. Farrell, and M. L. Kaiser, Atmospheric electricity at Saturn, *Space Sci. Rev.*, **137**, 271–285, 2008.

Fischer, G., U. A. Dyudina, W. S. Kurth, D. A. Gurnett, P. Zarka, T. Barry, M. Delcroix, C. Go, D. Peach, R. Vandebergh, and A. Wesley, Overview of Saturn Lightning Observations, in *Planetary Radio Emissions VII*, edited by H. O. Rucker, W. S. Kurth, P. Louarn, and G. Fischer, Austrian Academy of Sciences Press, Vienna, this issue, 135–144, 2011.

Grießmeier, J.-M., P. Zarka, J. Girard, S. ter Veen, and H. Falcke, Ground-based study of solar system planetary lightning, *Proceedings of the ISKAF2010 Science Meeting, Proceedings of Science*, 22, 2010.

Grießmeier, J.-M., et al. (21 co–authors), Ground- and space-based Saturn lightning observations, in preparation, 2011.

Konovalenko, A. A., A. Lecacheux, H. O. Rucker, G. Fischer, E. P. Abranin, N. N. Kalinichenko, I. S. Falkovich, and K. M. Sidorchuck, Ground-based decameter wavelength observations of Saturn electrostatic discharges, *European Planetary Science Congress 2006*, EPSC2006-A-00229, 2006.

Ryabov, V. B., D. M. Vavriv, P. Zarka, B. P. Ryabov, R. Kozhin, V. V. Vinogradov, and L. Denis, A low-noise, high-dynamic-range, digital receiver for radio astronomy applications: an efficient solution for observing radio-bursts from Jupiter, the Sun, pulsars, and other astrophysical plasmas below 30 MHz, *Astron. Astrophys.*, **510**, A16, 2010.

van Haarlem, M., et al., LOFAR, in preparation, 2011.

Zakharenko, V., et al. (23 co–authors), Ground-based and space observations of planetary thunderstorm activity, *Planet. Space Sci.*, submitted, 2010.

Zarka, P., and B. M. Pedersen, Statistical study of Saturn Electrostatic Discharges, *J. Geophys. Res.*, **88**, 9007–9018, 1983.

Zarka, P., B. Cecconi, L. Denis, W. M. Farrell, G. Fischer, G. B. Hospodarsky, M. L. Kaiser, and W. S. Kurth, Physical properties and detection of Saturn's lightning radio bursts, in *Planetary Radio Emissions VI*, edited by H. O. Rucker, W. S. Kurth, and G. Mann, Austrian Academy of Sciences Press, Vienna, 111–121, 2006.