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Ground-based study of solar system planetary lightning

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Radio signatures of lightning discharges on Saturn and Uranus have been discovered by the Voyager spacecraft in 1980 and 1986, respectively. These impulsive radio bursts are caused by planetary lightning activity. Additional measurements and continuous monitoring only became possible in 2004, when the Cassini spacecraft approached Saturn. Since 2006, ground-based observations are available as a complementary source of information. Using a new broadband receiver at UTR-2 (Ukraine), Saturn lightning has been observed over the whole spectral range of the instrument (10-30 MHz). For the first time, this allows to study the instantaneous spectrum of the discharge, and the temporal fine structure of the emission can be studied with a temporal resolution surpassing that of regular satellite observations. Additional observations were performed with the WSRT and with LOFAR. We present recent and ongoing observations, describe the methods and techniques used and discuss the potential of new-generation radio telescopes for the detection of lightning emission from different solar system planets.

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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 kind of phenomenon is not limited to our own planet, but also takes place elsewhere in the solar system. However, the limited reach and lifetime of satellite missions meant that the amount of available data was rather limited until recently: Radio emission caused by planetary lightning was 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 additional measurements only became possible in 2004, when the Cassini spacecraft approached Saturn.

In addition, tentative detections of lightning were reported for Neptune (Voyager 2 data from 1990-1991), and for Venus (e.g. data from Venus Express), but the case for lightning on Venus remains controversial. Despite theoretical expectations and various observational efforts, no lightning-generated radio emission was yet detected from either Mars, Jupiter, or Titan.

In the recent past, these satellite observations have been complemented by ground-based observations. With improved radio receivers and using Cassini as a trigger, ground based observations of SEDs ("Saturn Electrostatic Discharges") have finally become possible. The first unambiguous detection of SEDs took place at the giant Ukrainian radiotelescope UTR-2 [1] in 2006 [7]. Additional observations were perfomed with the WSRT and with LOFAR. These ground-based observations will be the main subject of the present proceeding. For a more complete overview over solar system planetary lightning studies, the reader is referred to [2, 9, 10, 11].

This paper is organised as follows: The complementarity between ground-based and space-based observations is discussed in Section 2. We present a method for the analysis of ground-based radio data in Section 3. Recent ground-based observations with UTR-2, WSRT and LOFAR are presented in Sections 4, 5 and 6, respectively. Future observation plans are given in Section 7, and Section 8 closes with some concluding remarks.

2. The complementarity of ground-based and space-based observations

Now that both ground-based observations and space-borne satellite are available, we can combine the results obtained by both methods, which are strongly complementary. For example, space-based measurements have the advantage of a high sensitivity, they can be used to localize the source on the planetary disk, and it is possible to observe at frequencies below 10 MHz (e.g. the Cassini spacecraft observes lightning by rapidly sweeping through the frequency range 0.325-16.125 MHz). Also, satellite measurements from a planetary orbit provide continuous monitoring, which is not possible for ground-based telescopes.

As opposed to this, the main advantage of ground-based measurements is that they allow for a considerably higher continuous datarate. This leads to the following advantages of ground-based radio observations:

- Observations at high temporal resolution are possible (up to the full time resolution defined by the observed frequency bandwidth);

- 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 effect)

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 different in received radio flux of 8 orders of magnitude)
- A small angular size of the target because of the large distance, making it difficult to resolve spatial structures;
- Frequencies below 10 MHz are unaccessible because of the ionospheric cutoff;
- Observations have to be targeted and dedicated (whereas a spacecraft can record the signal continuously while in orbit);
- Observational constraints due to the Earth rotation;
- Potentially strong RFI ("radio frequency interference"), 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. It is indeed not possible to observe below 10 MHz, but observations above this cutoff also yield valuable and complimentary information. For example, the Cassini spacecraft observes in the range 0.3-16 MHz), which allows for enough overlap with UTR-2 (8-32 MHz) or LOFAR (10-250 MHz). While satellite observations provide continuous observation 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 ($\sim$30%), which is inconvenient, but doesn't prevent useful observations. The RFI-environment, however, requires a good observation strategy and appropriate algorithms. One such observation method is described in the following section.

3. Ground-based observation strategy

While ground-based observations offer unique advantages and opportunities, they also face unique challenges that are not present for satellite measurements. One of these challenges concerns the terrestrial RFI-environment, which requires an adapted observation strategy. We have developed the following strategy for the observations and subsequent data analysis:

PoS(ISKAF2010)022

- The observations are performed in an simultaneous ON/OFF-mode, i.e. in addition to the beam on the target, a second channel of the receiver is fed with signal coming from the sky close to, but excluding the target. This OFF-beam is processed in the same way as the ON-beam, and is used to estimate the fraction of false positives (see below).

- Tests have shown that in the early morning hours, the RFI situation considerably deteriorates at very low frequencies [5]. For this reason, only observations performed during a certain range of local time can be used in the analysis. For example, for the UTR-2 observation described in Section 4, all observations taken between 5h30 and 20h UT (7h30 and 22h local time) are discarded.

- Both the ON- and the OFF-beam first have to be cleaned of RFI: For each individual spectrum, pixels (i.e. spectral channels) deviating by more than 3 standard deviations from a running average are interpreted as RFI, and are eliminated. This has to be an iterative process to make sure that RFI does not influence the evaluation of the average and standard deviation [12].

- To avoid confusing slow ionospheric oscillations with signal, the data are highpass filtered (slow variations are removed).

- Similarly to the local time of the observation, the frequency range must be carefully selected. For example, for the UTR-2 observation described in Section 4, only the data in the frequency range 18-28 MHz are used, even though the observation covered the range 12-32 MHz. Strong RFI rendered the remaining frequency bands unusable. The integration over the useful frequency band replaces the dynamic spectrum by a single timeseries, and strongly increases the signal-to-noise ratio.

- In the resulting integrated time series, all signal points exceeding a certain threshold value above average are considered as potential signal and are recorded separately for the ON- and the OFF-channel.

- As a final step in the data analysis, we compare the detections in the ON- and in the OFF-beam. All signal appearing in both beams is interpreted as remaining RFI, and is removed. The remaining numbers of events are denoted as n_{ONONLY} and n_{OFFONLY}, respectively.

- The number of OFFONLY detections, n_{OFFONLY}, corresponds to the number of false positives. Thus, an estimate of the number of real detections is $n_{\mathrm{SIGNAL}} = (n_{\mathrm{ONONLY}} - n_{\mathrm{OFFONLY}})$, and the fraction of true positives (or, in other words, the confidence for a given ONONLY signal that it is a true SED) is $f_{\mathrm{SIGNAL}} = \frac{n_{\mathrm{SIGNAL}}}{n_{\mathrm{ONONLY}}}$.

Figure 1 shows how the fraction of true positives varies with the time of the observation for the UTR-2 observation described in Section 4. In this example, data were recorded up to 7h30 UT (9h30 local time), but all observations taken between 5h30 and 20h UT (7h30 and 22h local time) have to be excluded from any subsequent analysis.

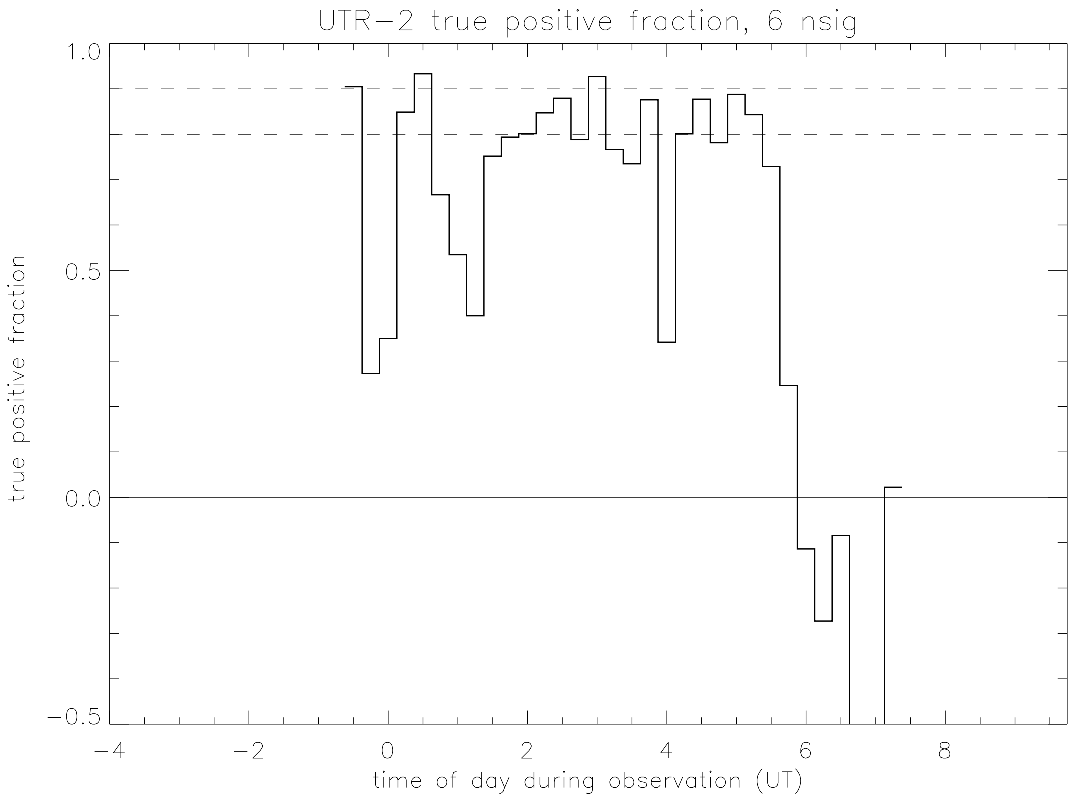

Figure 1: Fraction of true positives f_{SIGNAL} as a function of the time of the observation.

4. Saturn observations with UTR-2

"Saturn Electrostatic Discharges" (SEDs) were first detected during the Voyager 1 flight past Saturn in November 1980. At first, the origin of these impulsive radio bursts was unknown, but soon these events were shown to be caused by lightning activity. This has been further confirmed by subsequent radio observations and by the comparison to optical images. Today, the atmospheric origin is well established [4].

Since 2004, a certain number of SED *storms* have been observed by the Cassini satellite until today. 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 the storm F, which started in November 2007 [4], Saturn lightning was observed at the UTR-2, using a new, broadband digital receiver [8]. First results of this observation include:

- In 22 hours of useful observation, 3421 events were identified as potential SED signal (i.e. $n_{\mathrm{ONONLY}} = 3421$), and 763 events were identified as RFI (i.e. $n_{\mathrm{OFFONLY}} = 763$). With this, the number of real detections is $n_{\mathrm{SED}} \sim 2700$, and the fraction of true positives is $f_{\mathrm{SED}} \sim 80\%$, i.e. 20% of identified SEDs are in fact RFI. The temporal distribution of these events is shown in Figure 2.

- 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 (A4), an occurrence rate of 0.17 per second was found.
- The duration of SED events observed with a time resolution of 20 ms was found to follow an exponential distribution with an e-folding time of ~ 30 ms, which is less than that obtained in previous observations (Voyager and Cassini).
- The duration of RFI events was found to be different from the duration of SED events, and it is consistent with independent, randomly distributed events. This can be used to further discriminate between RFI and SEDs.

A more detailed description of these results is in preparation [5].

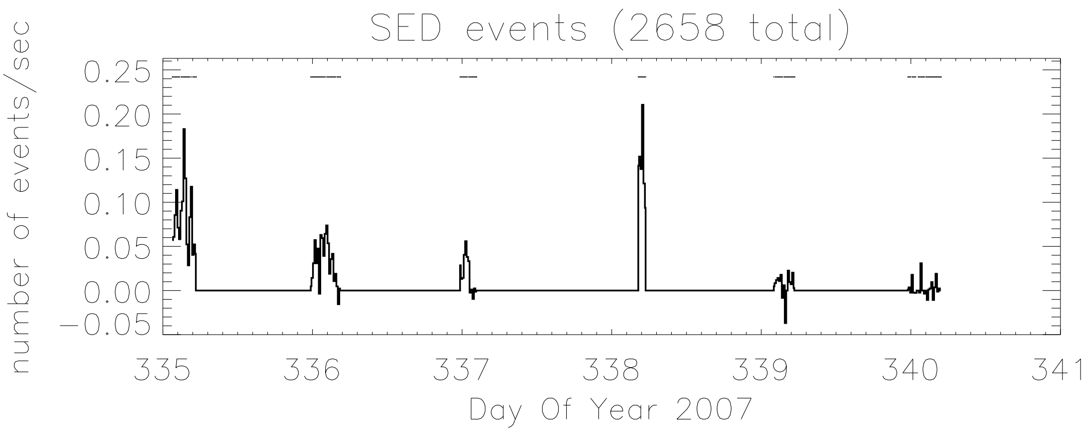

Figure 2: Saturn lightning events observed with UTR-2.

5. Saturn observations with WSRT

On 27 February 2010, Saturn lightning has been observed with the Westerbork Synthesis Radio Telescope (WSRT) at frequencies between 130 and 156 MHz. These data are currently being analyzed. As for the observation with UTR-2 and with LOFAR, the Cassini spacecraft was used to trigger the ground-based observation.

6. First observations with LOFAR

First observations of terrestrial lightning and of Saturn lightning have recently been performed with the LOFAR telescope[1].

[1] www.lofar.org

6.1 First observations of terrestrial lightning with LOFAR

Already with the first prototype station of LOFAR, LOFAR-ITS it was possible to detect terrestrial lightning discharges with a high temporal resolution, and to measure the broad-band spectrum between 10 and 35 MHz [6]. It was found that LOFAR-ITS already was an extremely sensitive detector, as it found a larger number of discharges than the SAFIR lightning detection network of KNMI.

This experiment has been repeated with only five LBA antennae of a single LOFAR station (LOFAR station CS302). The antennae operated in the frequency range 10-90 MHz. For this observation, we used data from the Transient Buffer Boards, which continuously store the full waveform data at antenna level for 1.3 seconds (currently; a further upgrade is possible), thus allowing the construction of a full sky map. Figure 3 shows a lightning event detected on 9 June 2009 at 18:46 local time. The map shows an all-sky image of a single lightning spark with only 5 microseconds of data. The inlay shows the lightning events between 18:45 and 18:50 as recorded by buienradar.nl. Both the radar map and LOFAR show strong lightning activity to the east of the station. The east - west baseline was shorter than the north - south baseline which explains the elongated point spread function. The white circles denote an elevation of 0, 15, 30, 45 , 60 and 75 degrees, respectively.

Note that Figure 3 is based on only a fraction (∼10 %) of a station. With the 18 stations of the core of the full LOFAR telecope, a considerably higher sensitivity and directional accuracy will be achieved.

A trigger system for automated lighting observations is currently under development. The trigger detection algorithm will be implemented on the firmware of the TBB boards. This will allow automatic collection of lightning data during thunderstorms without interfering with other LOFAR observations.

6.2 First Saturn observations with LOFAR

LOFAR is a very well adapted instrument to observe Saturn lightning. The highest frequency at which this emission has been detected so far is 40 MHz (and this was in swept-frequency mode), so that the high frequency spectrum of Saturn lightning remains unknown. LOFAR allows both to observe at frequencies where this phenomenon is already known (<40 MHz) and to extend the frequency range in which this effect is studied. This will allow to directly measure the slope of the Saturn lightning spectrum and the energy of the discharge [3]. In addition, the frequency coverage is instantaneous (i.e. all frequency channels are observed simultaneously), which also allows to directly observe the temporal fine structure of the emission, which is not possible with current satellite observations.

It is expected that the spectrum of Saturn lightning extends to frequencies above 100 MHz. Models also predict a steepening of the spectrum (from f^{-2} to f^{-4}), but the frequency where this happens is currently unknown. Observations with LOFAR can be used to measure the spectrum over a wide frequency band (10-250 MHz), which would increase the range of frequencies with observed Saturn lightning activity by a factor of 6. The point where the spectral slope changes can be measured and compared to terrestrial values. This study will help to solve the standing problem of the stroke duration (which is still unknown, but could be extremely short at Saturn [3]). High

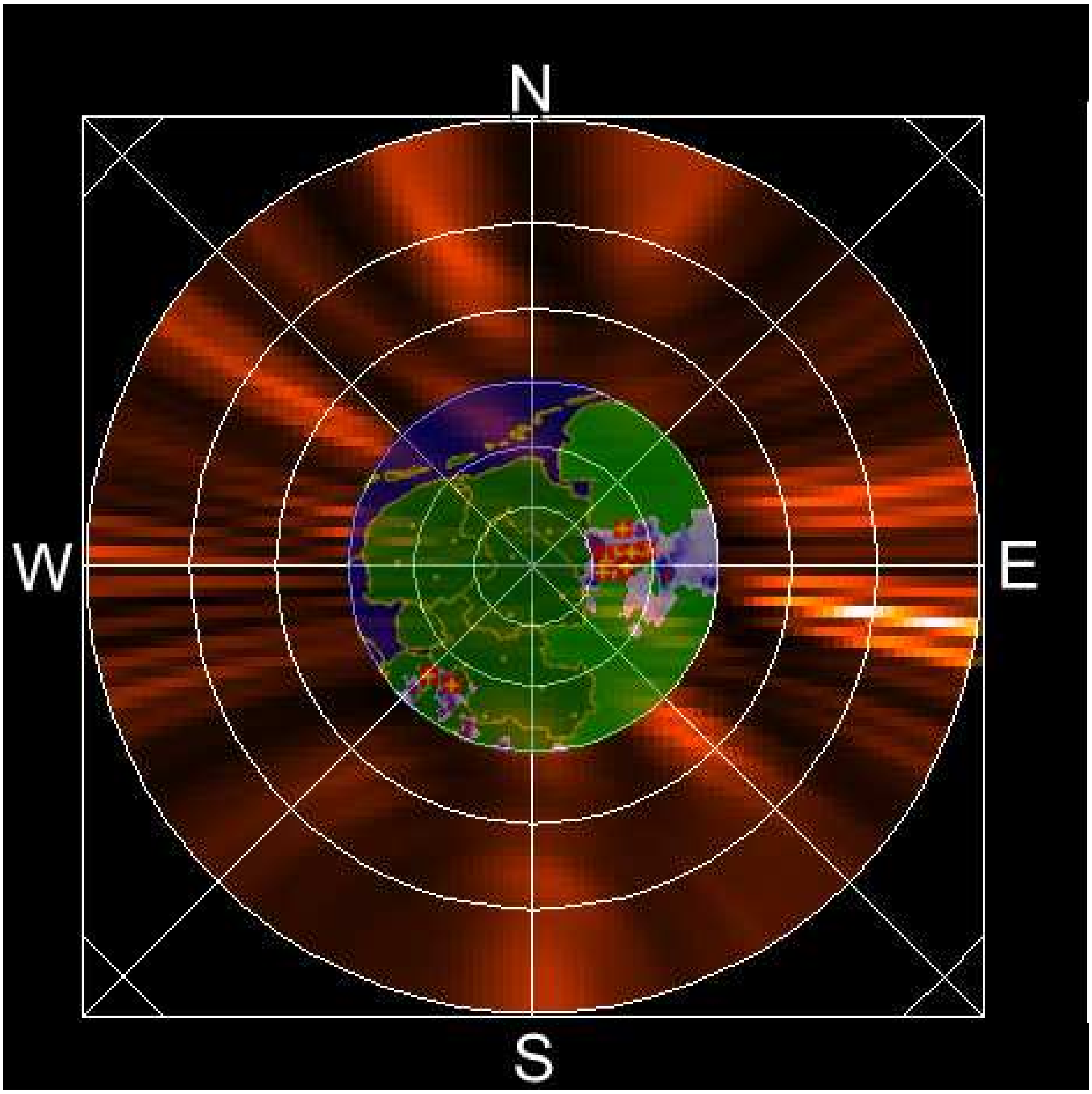

Figure 3: Terrestrial lightning as observed with buienradar (inner part) and LOFAR (outer part).

time resolution (up to 5 microseconds in standard mode, shorter if required) profiles of Saturn lightning can be observed, giving direct access to the stroke duration. The stroke duration is an important parameter required to estimate the discharge energy, which is uncertain by many orders of magnitude [3].

On 8 April 2010, we performed the first LOFAR observation of Saturn lightning. The data analysis is still ongoing.

7. Planned observations

Further observations are planned with the UTR-2 telescope and with LOFAR, for which more observations will be performed as soon as enough stations are available to allow for the detection of weak signals. The list of planned observations includes observations of terrestrial lightning (spectral studies, and 3D mapping of lightning), observations of Saturn electrostatic discharges (to study the spectrum, the geographical and seasonal variations, and correlate the observations to cloud structures observed in the optical), and observations of Uranus (spectral studies and studies of discharge timescales). In addition, we will to follow up on tentative detections of Neptune, Venus, and potential dust cloud discharges on Mars [11].

8. Conclusion

We have discussed the current status of ground-based study of solar system planetary lightning. Observations by UTR-2 and WSRT were presented, methods and techniques were shown, and early test observations with LOFAR were described. We have described the complementarity between ground-based and space-based observations. Putting all together, new-generation radio telescopes hold a great potential for the detection and characterization of lightning emission from several solar system planets.

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