



RADIO SCIENCE FOR HUMANITY

Solar radio astronomy and space weather *Radioastronomie solaire et météorologie de l'espace*

Karl-Ludwig Klein^{1,2}, Carolina Salas Matamoros^{1,3}, and Pietro Zucca¹

¹LESIA, Observatoire de Paris, CNRS (further affiliations: PSL Research Univ., Univ. P&M Curie, Univ. Paris Diderot), ludwig.klein@obspm.fr, pietro.zucca@obspm.fr

²Station de radioastronomie de Nançay, Observatoire de Paris, CNRS (further affiliations: PSL Research Univ., Univ. Orléans, OSUC)

³Space Research Center, University of Costa Rica, San Jose, Costa Rica, carolina.salas@cinespa.ucr.ac.cr

Keywords: Sun: radio emission; Sun: coronal mass ejections; Sun: particle emission; solar-terrestrial relations; space weather

Mots-clefs: Soleil: émission radio; Soleil: éjections coronales de masse; Soleil: émission de particules; relations Soleil-Terre; météorologie de l'espace

Abstract:

The solar corona and its activity induce disturbances that may affect the space environment of the Earth. Noticeable disturbances come from coronal mass ejections (CMEs), which are large-scale ejections of plasma and magnetic fields from the solar corona, and solar energetic particles (SEPs). These particles are accelerated during the explosive variation of the coronal magnetic field or at the shock wave driven by a fast CME. In this contribution we will attempt to illustrate three aspects where radio observations can be important for space weather purposes: Radio emission as (1) a space weather hazard, (2) a tool to estimate CME speeds, (3) a tool to predict SEP events.

Résumé:

La couronne solaire et son activité engendrent des perturbations susceptibles d'affecter l'environnement spatial de la Terre. Les perturbations les plus énergétiques proviennent des éjections coronales de masse, qui sont des éjections à grande échelle de plasma avec le champ magnétique qui le confine, et des particules chargées de haute énergie. Ces particules sont accélérées au cours de l'évolution explosive du champ magnétique de la couronne ou aux ondes de choc engendrées par les éjections de masse rapides. Dans cette contribution, nous tenterons d'illustrer trois aspects où des observations radio peuvent être importantes pour la météorologie de l'espace: l'émission radio en tant que (1) source de perturbations, (2) outil de prévision pour estimer la vitesse des éjections de masse et (3) pour prévoir des événements à particules à la Terre.

1 Introduction: Solar activity and space weather

The solar corona and its activity induce disturbances that may affect the space environment of the Earth. Noticeable disturbances come from coronal mass ejections (CMEs), which are large-scale ejections of plasma and magnetic fields from the solar corona, and solar energetic particles (SEPs). These particles are accelerated during the explosive variation of the coronal magnetic field or at the shock wave driven by a fast CME. When intercepting the Earth's magnetic field, coronal mass ejections may induce currents into the ionosphere whose dissipation heats and ionises the high atmosphere in the polar regions, affecting radio communications and the navigation and functioning of spacecraft. Energetic particles may affect the functioning of spacecraft outside the Earth's magnetosphere or in polar orbits, launcher and space vehicle operations, and astronaut safety. They create secondary particles in the polar atmosphere that also cause ionisation and excess radiation which may reach aircraft altitudes.

Methods to alert about the arrival of solar disturbances in the space environment of the Earth are therefore potentially useful tools to mitigate hazards. The travel times of CMEs to the Earth range from about 15 hours to a few days. Energetic particles travel the distance within a few tens of minutes. What is the time frame for forecasting the arrival at the Earth? Since all eruptive phenomena draw their energy from coronal magnetic fields, one might think of a method that evaluates the stability of an observed configuration, its likelihood to erupt in a given future time interval, and that also predicts the consequences in terms of CMEs and energetic particle fluxes. But there is so far no operational scheme that uses pre-eruptive signatures for forecasting. As

of today, most forecasting schemes are built on early observational signatures of the relevant solar phenomena, that is the liftoff of a CME or some radiative signature that shows particle acceleration. This leaves rather short warning times especially for SEPs.

In this contribution we will illustrate two aspects where radio observations can be important for space weather purposes: radio emission as a space weather hazard, due to its interference with communications at frequencies where the Sun itself produces bursty emission (Sect. 2.1); radio emission as a forecasting tool, allowing us to predict the arrival of coronal mass ejections and energetic particles at 1 AU (Sect. 2.2). We start with a simple scenario of solar eruptive activity.

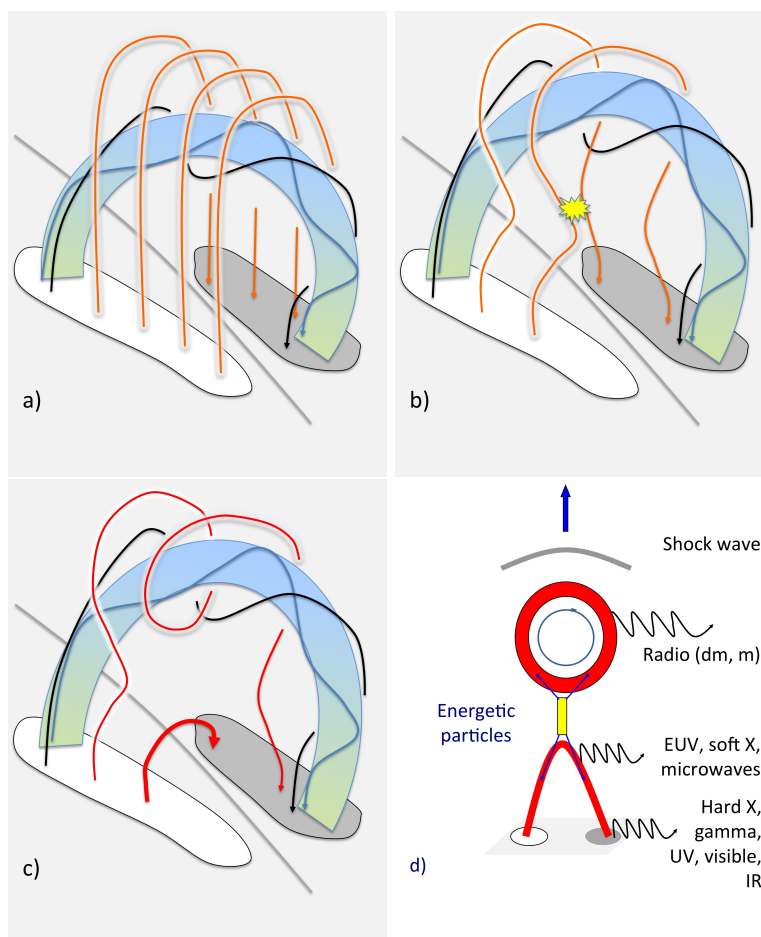


Figure 1 – Cartoon scenario of the magnetic field configuration around a magnetic flux rope in the solar corona (a), and of its evolution during the liftoff of a coronal mass ejection (CME; b,c). The white and grey-shaded areas indicate opposite magnetic polarities in the photosphere, the grey line is the line where the vertical photospheric magnetic field is zero. Figure (d) shows a two-dimensional cut of (c).

2 Solar radio observations for space weather

Transient enhancements of solar radio emission, called radio bursts, are generated when electrons are accelerated to energies well above their thermal energy in the quiet corona, which is about 100-200 eV. The cartoons of Fig. 1 depict a typical scenario where transient electric fields arise that are able to accelerate charged particles. They show major features of a magnetic eruption in the solar corona, which leads to a coronal mass ejection (CME) and a flare.

The pre-eruptive situation in Fig. 1.a shows a magnetic flux rope, defined by the helicoidal magnetic field lines within the flux rope (light blue) and around (black). The Lorentz force of this configuration is directed upward, since the magnetic field lines are more densely packed below the flux rope than above. The upward Lorentz force is balanced in equilibrium by the downward-directed Lorentz force exerted by the surrounding coronal magnetic field, whose field lines are plotted in orange. An excess upward force can be generated for instance by the torsion of one foot of the flux rope and its magnetic field, due to the plasma motions in the photosphere. When this happens, the flux rope is lifted by the Lorentz force (Fig. 1.b), ambient coronal plasma and the

embedded magnetic field are convected from both sides towards the region where it was located before, and oppositely directed magnetic fields can reconnect. This is illustrated in Fig. 1.b and c for two field lines, with the reconnection happening in a limited region schematically indicated by the yellow symbol of an explosion. New magnetic field is then added to the flux rope (the upper part of the field line drawn in red colour), and new magnetic loops form in the low corona.

A 2D projection of this situation is depicted in Fig. 1.d, together with the consequences of the magnetic reconnection: charged particles accelerated in transient electric fields around the reconnection region, and electromagnetic emissions excited directly or indirectly by these particles in different regions of the erupting configuration. Hard X-rays and gamma-rays are generated respectively by electrons and ions through collisional processes, which are most efficient in the dense low atmosphere. Radio emission is generated by energetic electrons in different regions, including the dilute plasma in higher atmospheric layers. Microwave emission is mostly due to incoherent gyro-synchrotron emission of electrons with energies of hundreds of keV to a few MeV. Emissions at longer wavelengths arise from electron distributions which are anisotropic and create microinstabilities. The electrostatic plasma waves generated in these situations can be converted into electromagnetic waves, which escape from the corona and can be observed by radio telescopes on the Earth. Soft X-rays are due to plasma heated to tens of millions of Kelvin.

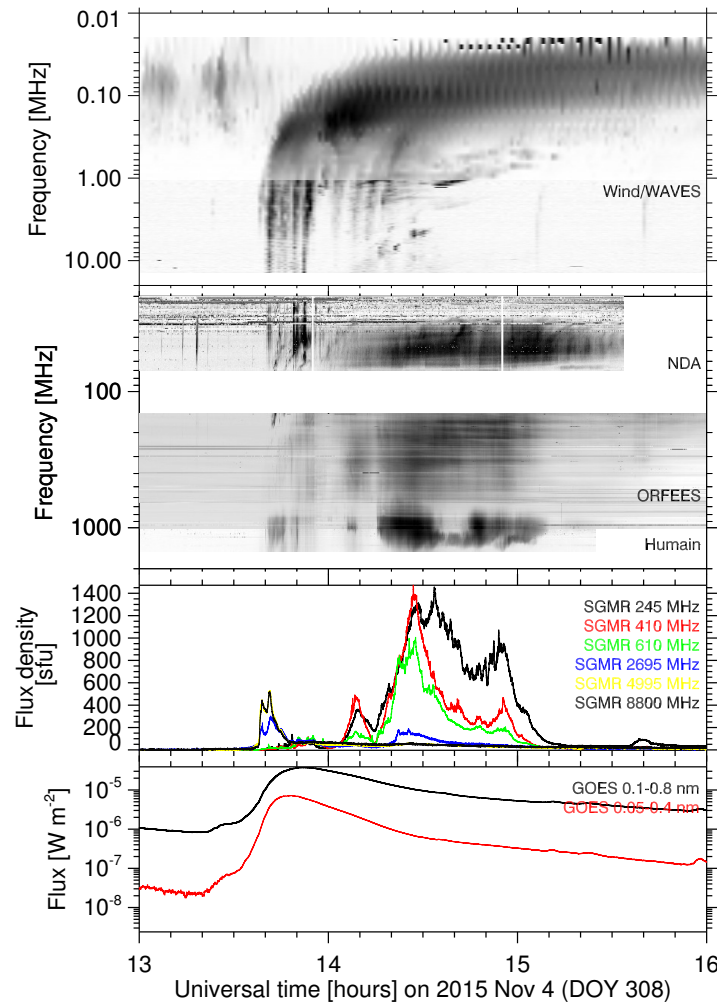


Figure 2 – Time history of whole-Sun X-ray and radio emissions on 2015 Nov 04. From bottom to top: (1) soft X-rays in two wavelength ranges (GOES satellites, NOAA); (2) radio waves at selected frequencies (RSTN, US Air Force); (3) dm-m-wave spectrum represented as a grey-scale plot of flux density in the (time, frequency)-plane (grey shading represents strong emission; Humain and Nançay radio observatories); (4) decametre-to-km-wave spectrum (WAVES spectrograph aboard the Wind spacecraft).

2.1 Radio emission as a space weather hazard

Disturbances of air traffic control radars grounded airplanes for two hours in Sweden on 4 November 2015. Important disturbances of the secondary air traffic control radar, which is operated at 1030 and 1090 MHz, occurred in southern Sweden, especially Malmö and Stockholm, between 14:19 and 14:34 UT, and again between 14:48 and 14:49 UT. Initially the cause was believed to be geomagnetic activity. However, northern Swedish airports were not affected. Furthermore, while the magnetosphere was indeed perturbed on that day, there was no time-coincidence between the disturbance of the radars and the geomagnetic activity. Minor disturbances of air traffic control radar were also reported in Germany and Belgium.

Since the Sun was very low above the horizon, in the field of view of the radar antennas when they looked westward, an alternative cause to geomagnetic activity is a direct effect of a solar event. The standard electromagnetic signature of a solar flare, the whole Sun soft X-ray emission, is plotted in the bottom panel of Fig. 2. A soft X-ray burst starts near 13:20 UT, rises to a maximum of about $3 \cdot 10^{-5} \text{ W m}^{-2}$ in the (0.1-0.8) nm band near 13:52, and then decays slowly over more than an hour. The soft X-ray burst is intense, but by no means outstanding, and does not suggest that the radar disturbances could be due to excessive transient ionisation of the Earth's atmosphere. The most intense emission also occurs an hour before the radar disturbances. The plots in the second panel from the bottom show the evolution of radio emission at eight regularly monitored frequencies between 245 and 15400 MHz, observed by the *Radio Solar Telescope Network* (RSTN) of the US Air Force. The radio emission is intense after the X-ray maximum, in closer time coincidence with the radar disturbances. The time correspondence becomes still clearer when one looks at the detailed radio spectrum between 140 and 1500 MHz, displayed in the third panel from the bottom as a grey-scale plot in the frequency-time plane, where dark shading shows bright emission. This plot is a composite of two observations: those of the Humain radio observatory of the Royal Observatory in Brussels (courtesy C. Marqué, ROB) between 1000 and 1500 MHz, and those of the ORFEES spectrograph at the Nançay Radio Observatory (France), between 140 and 1000 MHz. The radio emission in this band lasts more than an hour and is broadband, typical of the dm-m-wave emission during the liftoff of a CME as illustrated in Fig. 1.d. A particularly intense emission is observed in a more limited band, namely the frequency range (800-1400) MHz. It is brightest from about 14:20 to 14:35, and during a shorter period shortly before 14:50 UT. This corresponds well with the times when the Swedish secondary air traffic control radar was perturbed.

These observations show that intense solar radio emission can be a direct space weather hazard and needs to be considered as such. The importance of this radio emission is evidently not directly related to that of the X-ray burst, since much stronger X-ray bursts than the one of 2015 Nov 04 are observed during strong solar activity, without reported effects on air traffic control radar. However, intense microwave emissions in the GPS frequency range have been reported in the past. It was found that they may reduce the signal-to-noise ratio of the GPS signals in the sunlit hemisphere (see, e.g., [1, 2]). Radio spectra with similar intense emissions in the few-GHz range as seen in Fig. 2 were studied by [3], and tentatively ascribed to a cyclotron maser emission. This process is well established in the magnetospheres of the Earth and Jupiter, where the electron cyclotron frequency exceeds the electron plasma frequency. The inverse is usually thought to happen in the solar atmosphere, so that cyclotron maser emission should not work there. But it is so far unclear if very particular conditions of wave propagation could occur that allow the cyclotron maser to work [4]. An alternative is the more conventional plasma emission. But it is not clear why this plasma emission is intense around 1 GHz in some cases, whereas usually the solar radio burst spectrum has a minimum there [5]. In any case, the occurrence of these exceptionally strong emissions near 1 GHz is not predictable for the time being. More detailed studies of past events, in a close corporation between the operators of sensitive equipment and researchers, are necessary to make a significant progress in understanding the origin of these solar events and the way in which they affect air traffic control radar and GNSS communications.

2.2 Radio emission as a space weather forecasting tool

2.2.1 Speeds and interplanetary propagation times of coronal mass ejections

Coronal mass ejections (CMEs) are usually observed in white light by coronagraphs, which artificially occult the bright emission of the solar disk. The projection on the plane of the sky makes CMEs that travel at about right angles from the line of sight readily visible, and their propagation speed can be easily measured by localising the front of the CME in successive images. It is much more difficult to discern CMEs which propagate along the line of sight. Observing earthward-propagating CMEs with a coronagraph on the Sun-Earth line, such as the LASCO instrument aboard the SoHO mission (ESA/NASA), is hence intrinsically difficult. No direct measurement of the speed of such a CME can be obtained with the classical coronagraphic observing technique.

We established an empirical relationship between the fluence of radio bursts at microwave frequencies and

the speed of the associated CMEs originating near the solar limb. The CME speed was measured in the coronagraphic images from SoHO/LASCO, and is available in the CME catalogue generated and maintained at the CDAW Data Center by NASA and The Catholic University of America in cooperation with the Naval Research Laboratory¹. The microwave data were provided by the four ground-based RSTN observatories². The comparison of the data sets shows that there is a correlation, with broad scatter, between the microwave fluence, especially at the higher frequencies (typically 9 GHz), and the CME speed in the plane of the sky. We assume that this projected speed is the outward propagation speed of the CME, because the CME occurred close to the solar limb and its presumed radial outward propagation is then only weakly altered by foreshortening. Such a relationship had been found by others, albeit rarely with a well-defined selection of limb-CMEs. It is not just empirical, but reflects the physical link between CME acceleration, plasma heating and electron acceleration underneath the rising flux rope in the cartoon scenario of Fig. 1. A quantitative analysis of the relationship between soft X-ray flux and CME speed was conducted by [6]. The empirical relationship allows us to estimate a CME speed when we know the fluence of the microwave burst. This is especially possible when the CME propagates earthward, because then the microwave burst source is expected to be near the centre of the solar disk, and well visible from the Earth.

It is well known from past observations that CMEs that are fast in the corona, with a speed well above typical solar wind speeds ($\sim 400 \text{ km s}^{-1}$), decelerate during their interplanetary propagation. This is due to the accumulation of plasma in front of the outward propagating magnetic obstacle. Empirically the deceleration was related in a linear way to the initial speed of the CME [7]. We fed the CME speed inferred from the radio data to this empirical law to predict the arrival times of eleven Earth-directed CMEs at the Earth's orbit, and compared the predictions with the in situ measurements of the plasma and magnetic field parameters. We considered that the arrival of the CME at the spacecraft is signalled by a sudden drop of the proton temperature. This drop occurs because the CME plasma is confined by its magnetic field, which expands as the CME propagated into a more and more dilute interplanetary medium. The expansion of the confined plasma implies its cooling. The magnetic structure is often preceded by a shock wave and a turbulent sheath plasma behind it.

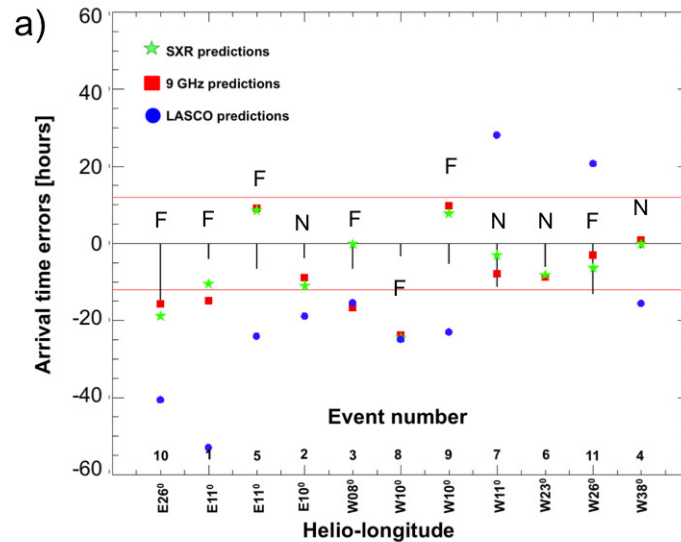


Figure 3 – Difference between observed and predicted CME arrival times at Earth for eleven CMEs ordered by the heliographic longitude of their origin. From [8].

The predicted and observed CME arrival times are compared in Fig. 3. The ordinate shows the difference between predicted and observed arrival times. The zero value corresponds to the exact prediction, positive values to cases where the CME is observed to arrive before the predicted time. The black vertical lines show the time intervals between the arrivals of the shock wave and the magnetic obstacle of the CME. The red horizontal lines mark prediction errors of $\pm 12 \text{ h}$. The solar events are ordered by the heliographic longitude where the CMEs originate. The different symbols and colours distinguish the origin of the CME speed estimate: microwave fluence at 9 GHz (red filled squares), soft X-ray fluence (green asterisks), and an empirically corrected speed derived from coronagraphic observations (blue filled circles). The predictions using soft X-rays and microwaves

¹http://cdaw.gsfc.nasa.gov/CME_list/index.html

²<https://www.ngdc.noaa.gov/stp/space-weather/solar-data/solar-features/solar-radio/rstn-1-second/>

are of comparable quality. A notable feature is that (1) on average the CME arrival is predicted too early (bias towards the lower half of the figure), and (2) the predictions tend to be better for CMEs originating in the western solar hemisphere. This is not a coincidence: a detailed analysis of the CMEs shows that in most (7/11) the Earth intercepts the flank of the CME (events labelled "F"), and only in four events is the vicinity of the nose seen by the spacecraft (events labelled "N"). At the time when the flank is detected at the Earth, the nose is already beyond the Earth's orbit. This is consistent with the early prediction, but it shows of course also the limitation of the method used to test the performance of the method. However, overall the comparison with other prediction methods and with the observations shows that soft X-ray or microwave fluence is a valuable tool to predict the CME arrival, with the supplementary advantage that these fluences are known at the time when the CME is still behind the occulting disk of contemporary coronaographs. The first warning can hence be issued very early, when the CME is still close to the Sun. A more detailed description of this work can be found in [8].

2.2.2 Solar energetic particle (SEP) events

Solar energetic particle events are transient enhancements of the fluxes of protons, ions and electrons detected in the interplanetary space, including the space environment of the Earth. SEP events are associated with solar flares and CMEs, which we collectively call eruptive events in the following. The only practicable forecasting strategy is presently to infer the SEPs to come from the first observations of the eruptive activity in the corona. Several different, but complementary approaches have been developed.

The UMASEP scheme, developed at the University of Malaga [9], combines the monitoring of solar soft X-ray emission and its time-derivative, and of solar protons, using GOES measurements. Simultaneous rises in the soft X-ray flux and the particle intensity are considered as an indicator that an SEP event is to occur. We conduct an exploratory study to see if the soft X-ray data can be replaced or complemented by microwave observations referring to the gyrosynchrotron emission of mildly relativistic electrons accelerated in the associated flare. The motivation is twofold: from a physics viewpoint microwave emission produced by non-thermal electrons may be expected to be more closely related to SEP acceleration than soft X-rays, which are emitted by the plasma heated during the solar eruption. From an empirical viewpoint, the derivative of the soft X-ray time profile is known to mimic the time profile of microwave emission from non-thermal electrons. This can be seen during the rise phase of the soft X-ray burst in the bottom panel of Fig. 2. The microwave emission is strong during the rise, and decays to background near the maximum of the soft X-ray burst in the (0.1-0.8) nm band.

We constructed an uninterrupted series of microwave flux densities at 5 and 9 GHz during a 13-months interval from December 2011 to December 2012. The input data were the light curves observed at the four RSTN observatories. Data were cleaned such as to reduce discontinuities at the transition between two observatories, which are due to calibration problems, incorrect antenna pointing and other instrument failures. This time series was fed to the UMASEP prediction scheme instead of the soft X-ray derivative. The key findings for this thirteen months period with nine SEP events are the following:

- The probability of detection is the same as in the traditional UMASEP scheme, where the derivative of the soft X-ray time profile is correlated with the SEP intensity.
- The false alarm rate is reduced to zero by the microwave data at both frequencies considered (5 and 9 GHz).
- The warning time, *i.e.* the time between the forecast and the instant where the SEP intensity exceeds the official event threshold, is slightly improved with the microwave light curves over the soft X-rays (30.7 *vs* 26.4 min).

This shows that microwave data provide a significant improvement, especially because they are rarer phenomena than soft X-ray bursts. The soft X-ray bursts reveal the heating of coronal plasma during a flare - a process which may or may not be accompanied by particle acceleration. Major microwave bursts need the acceleration of electrons to relativistic energies. Using microwave bursts therefore avoids numerous small and purely thermal fluctuations of the soft X-ray emission. It is to be noted, however, that a few moderately strong SEP events are not related to conspicuous particle acceleration in flaring active regions, and may be missed by a prediction that relies only on non-thermal microwave bursts. Details of this study conducted in collaboration with the University of Malaga can be found in [10].

3 Discussion and Conclusion

It has been known since the 1950s that radio observations are closely related to interplanetary plasma disturbances and energetic particles (see the review in [11]). But the advent and easy availability of soft X-ray

monitoring with the GOES satellites operated by NOAA has diminished the interest for this aspect of radio monitoring. The US Air Force is the only institution to provide 24-hour monitoring of the Sun, using four stations around the Earth. These radio observations are conducted with rather simple patrol instruments, which monitor the whole Sun flux density using parabolic antennae with a typical size of 1 metre. Such data are presently not provided in real time, but there is no technical obstacle to do so. If a reliable calibration and stable and reliable antenna operations can be achieved, microwave patrol observations appear to be a significant addition to our ability to forecast the occurrence of SEP events and the interplanetary travel times of CMEs. In addition to being easy to handle and relatively cheap, radio observations have the advantage that the instruments are protected by the Earth's atmosphere and magnetosphere against space weather hazards.

4 Acknowledgements

This work is supported by the ANR/ASTRID project ORME (*Observations Radio astronomiques pour la Météorologie de l'espace*, contract No. ANR-14-ASTR-0027), by the HESPERIA project, funded by the European Union's Horizon 2020 research and innovation program under grant agreement No 637324, and by the Centre National d'Etudes Spatiales (CNES).

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