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Observations of Low Frequency Solar Radio Bursts from the Rosse Solar-Terrestrial Observatory

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Abstract The Rosse Solar-Terrestrial Observatory (RSTO; www.rosseobservatory.ie) was established at Birr Castle, Co. Offaly, Ireland (53°05′38.9″, 7°55′12.7″) in 2010 to study solar radio bursts and the response of the Earth's ionosphere and geomagnetic field. To date, three *Compound Astronomical Low-cost Low-frequency Instrument for Spectroscopy in Transportable Observatory* (CALLISTO) spectrometers have been installed, with the capability of observing in the frequency range of 10 – 870 MHz. The receivers are fed simultaneously by biconical and log-periodic antennas. Nominally, frequency spectra in the range of 10 – 400 MHz are obtained with four sweeps per second over 600 channels. Here, we describe the RSTO solar radio spectrometer set-up, and present dynamic spectra of samples of type II, III and IV radio bursts. In particular, we describe the fine-scale structure observed in type II bursts, including band splitting and rapidly varying herringbone features.

Keywords Radio bursts · Dynamic spectrum · Type II · Type III · Type IV

1. Introduction

The Sun is an active star that produces large-scale energetic events, such as solar flares and coronal mass ejections (CMEs). These phenomena are observable across the electromagnetic spectrum, from the region of gamma rays at hundreds of mega electron volts to that of

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radio waves with wavelengths of tens of metres. Solar flares and CMEs can excite plasma oscillations which can emit radiation at metric and decametric wavelengths. These bursts are classified into five main types. Type I bursts are short-duration narrowband features that are associated with active regions (Melrose, 1975). Type II bursts are thought to be excited by magnetohydrodynamic (MHD) shock waves associated with CMEs (Nelson and Melrose, 1985), while type IIIs result from energetic particles escaping along open magnetic field lines. Type IV bursts show broad continuum emission with rapidly varying fine structures (McLean and Labrum, 1985). The smooth short-lived continuum following a type III burst is referred to as type V.

Several radio telescope designs have been developed to observe solar radio activity, including interferometers, spectrometers and imaging spectrometers. The *Culgoora Radioheliograph* was a 96-element, 3 km diameter radio synthesis telescope that was operated at 80 MHz (Sheridan, Labrum, and Payten, 1972). Operations began in 1968, but were discontinued in 1986. However, Culgoora still operates a radio spectrograph at 18 – 1800 MHz. Developed in the early 1980s, the *Nançay Decameter Array* consists of two phased arrays producing dynamic spectra at 10 – 80 MHz (Dumas, Caroubalos, and Bougeret, 1982). This array operates alongside a radioheliograph, which produces solar images at a number of frequencies between 150 – 420 MHz. During the 1980s and 1990s, ETH Zurich developed a number of solar radio spectrometers (Benz *et al.*, 1991; Messmer, Benz, and Monstein, 1999). Their latest instrument, *Phoenix II*, is a Fourier-based spectrograph operating at 0.1 – 4 GHz, with 2000 channels and a temporal resolution of better than 1 s. In recent years, the *Green Bank Solar Radio Burst Spectrometer* (GBRBS) has been developed in the US; it is composed of three swept-frequency systems that support observations at 18 – 1100 MHz, with a temporal resolution of approximately 1 ms (White, 2007). Similarly, the *Artemis* spectrograph in Greece observes at 20 to 650 MHz, and operates with a 7 m moving parabolic antenna at 110 – 650 MHz and a stationary antenna for the 20 – 110 MHz range (Kontogeorgos *et al.*, 2006). A new milestone in low frequency radio instrumentation was reached with the establishment of the Dutch-led *LOw Frequency ARray* (LOFAR; de Vos, Gunst, and Nijboer, 2009). LOFAR is the latest development in software-based radio interferometry, and allows for simultaneous recording of dynamic spectra and images of solar phenomena (Fallows *et al.*, 2012).

The CALLISTO (*Compound Astronomical Low-cost Low-frequency Instrument for Spectroscopy in Transportable Observatory*) spectrograph is a new concept for solar radio spectrographs, designed by ETH Zurich (Benz, Monstein, and Meyer, 2005). CALLISTO is a low-cost radio spectrometer used to monitor metric and decametric radio bursts; it has been deployed to a number of sites around the world to allow for 24 hour monitoring of solar radio activity. In order to monitor solar activity and its effects on the Earth, we set up an autonomous solar radio observing station, the *Rosse Solar-Terrestrial Observatory* (RSTO), which has been operating since September 2010. RSTO is located on the grounds of Birr Castle Demesne, Co. Offaly, Ireland, and was named for the Third Earl of Rosse, Sir William Parsons, who constructed the 6-foot diameter "*Leviathan Telescope*" in the 1840s (Hoskin, 2002).

RSTO is part of the e-CALLISTO network.[1] The network consists of a number of spectrometers located around the globe and designed to monitor solar radio emission in the metre and decametre bands (Benz *et al.*, 2009; Figure 1). Each of the instruments observes automatically, and data are collected each day via the Internet and stored in a central database

[1] www.e-CALLISTO.org.

Figure 1 Worldwide distribution of a portion of the radio spectrographs in the e-CALLISTO network. The network also includes spectrographs in Australia (Perth and Melbourne), Hawaii, Germany, Kazakhstan, Sri Lanka, Italy, Slovakia and Malaysia.

at Fachhochschule Nordwestschweiz (FHNW) that is operated by ETH Zurich.[2] One of the important features of RSTO is the particularly low radio frequency interference (RFI) of the site, as further described in Section 3.1.

In this paper, we describe the suite of CALLISTO spectrographs at RSTO (Section 2). Examples of observations are then reported in Section 3, while plans for future instruments at RSTO and conclusions are given in Section 4.

2. Radio Spectrometer Instrumentation

2.1. CALLISTO Spectrometer

CALLISTO spectrometers are designed to monitor solar radio bursts in a frequency range of 10 – 870 MHz. CALLISTO is composed of standard electronic components, employing a Digital Video Broadcasting-Terrestrial (DVB-T) tuner assembled on a single printed circuit board. The number of channels per frequency sweep can vary between 1 and 400, with a maximum of 800 measurements per second. An individual channel has a 300 kHz bandwidth during a typical frequency sweep of 250 ms, and can be tuned by the control software in steps of 62.5 kHz to obtain a more detailed spectrum of the radio environment. The narrow channel width allows for the measurement of selected channels that avoid known bands of radio interference from terrestrial sources.

[2] soleil.i4ds.ch/solarradio/CALLISTOQuicklooks/.

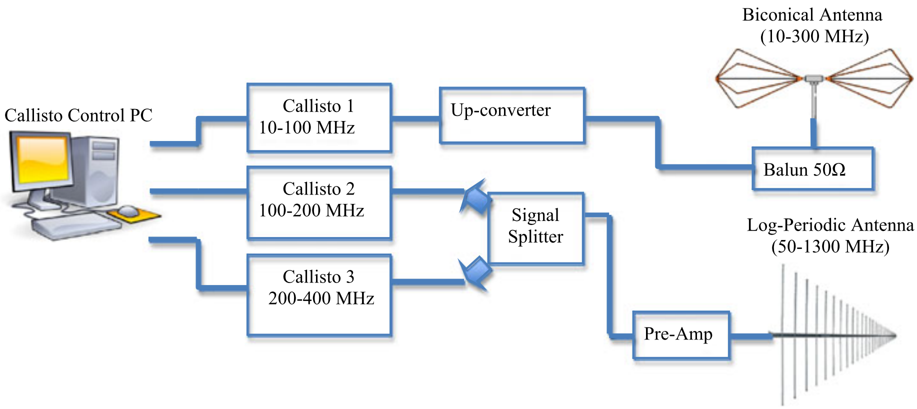

Figure 2 The set-up of the array of three CALLISTO spectrographs at RSTO. The current set-up employs three CALLISTO receivers, one connected to a biconical antenna using a frequency up-converter and measuring from 10 to 100 MHz. The other two receivers are connected to a log-periodic antenna that measures from 100 to 200 MHz and from 200 to 400 MHz. The system can potentially observe between 10 and 870 MHz.

2.2. CALLISTO Spectrometer Set-Up at RSTO

RSTO operates three CALLISTO receivers fed by a broadband log-periodic antenna and a biconical antenna (Figure 2). Nominally, the RSTO set-up operates at 600 channels with a sampling time of 250 ms per sweep. CALLISTO 1 observes at 10 – 100 MHz, CALLISTO 2 at 100 – 200 MHz, and CALLISTO 3 at 200 – 400 MHz. The system has been optimised to measure the dynamic spectra of type II radio bursts produced by coronal shock waves and type III radio bursts produced by near-relativistic electrons streaming along open magnetic field lines. It can also record other radio bursts, such as type IV bursts and type I noise storms.

The log-periodic antenna has a frequency band of 50 to 1300 MHz with a ∼ 50 degree half-power beam width (HPBW). The antenna is fixed to an altazimuth drive which tracks the Sun to optimise its response. The biconical antenna is 4 m long and has a nominal frequency sensitivity from 10 to 300 MHz. It is also mounted on a motorised rotator to track the Sun. CALLISTO 2 and 3 operate with a pre-amplifier that has a frequency range of 5 – 1500 MHz, and a typical noise figure of 1.2 dB; a similar pre-amplifier is separately connected to CALLISTO 1. The system set-up is optimised to reach the ionospheric cutoff frequency at ∼ 10 MHz. To do this, the receiver with a nominal operational band between 45 to 870 MHz must operate with a frequency up-converter, shifting the range between 10 – 100 MHz to 220 – 310 MHz. The observed frequencies are then down-converted in the software.

3. Observations

3.1. RSTO Radio Frequency Interference Survey

An RFI survey at RSTO was performed in June 2009.[3] The detected spectrum is shown in Figure 3. A commercial DVB-T antenna covering a range from 20 MHz to 900 MHz was

[3] www.rosseobservatory.ie/presentations/birr_radio_survey.pdf.

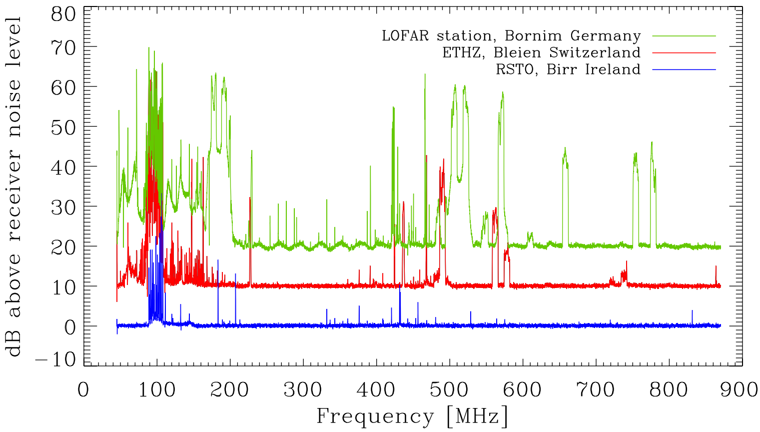

Figure 3 Radio frequency survey from the RSTO in Birr Castle Demesne (blue), Bleien Radio Observatory in Switzerland (red; offset by 10 dB) and Potsdam Bornim (green; offset by 20 dB). The RSTO spectrum is quiet at all frequencies that were tested, except for the FM band covering 88 – 108 MHz. The surveys were conducted using the same equipment. Note, LOFAR operates at ∼ 20 – 240 MHz.

used for the survey; the antenna was directly connected via a low-loss coaxial cable to a CALLISTO receiver with a sensitivity of 25 mV/dB. The channel resolution was 62.5 kHz, and the radiometric bandwidth was about 300 kHz. The sampling time was 1.25 ms per frequency interval, while the integration time was about 1 ms. Figure 3 shows the RFI radio surveys from RSTO, Bleien Observatory in Switzerland, and the Potsdam LOFAR station in Germany. There is a high level of interference at 20 – 200 MHz for the Bleien and Potsdam sites, whereas the RSTO site has a low level of RFI.

The radio spectrum at RSTO is extremely quiet compared to the majority of e-CALLISTO sites around the world. The FM radio and DVB-T interference is less intense than at other sites, making the RSTO site an ideal location for low frequency solar radio observations – Birr Castle Demesne is a near-ideal site for frequency-agile or Fourier-based spectrometers. All protected frequencies for radio astronomy are free from interference and can be used for single frequency observations to determine solar radio flux using broad-band antennas. As a result of this survey, the Irish astronomy community is considering Birr Castle Demesne as a site for a LOFAR station.[4]

3.2. Sample RSTO Dynamic Spectra

Observations started in September 2010, and first light was achieved on 17 November 2010. Since then, numerous radio bursts have been recorded. In this section, we present several observations and give a brief description of each. All RSTO data are provided to the community at www.rosseobservatory.ie.

3.2.1. Type II Bursts

The appearance of type II radio bursts can vary significantly in dynamic spectra. The 22 September 2011 type II radio burst shown in Figure 4 was associated with an X1.4 class flare which started at 10:29:00 UT. The flare was identified to have originated in NOAA

[4] www.lofar.ie.

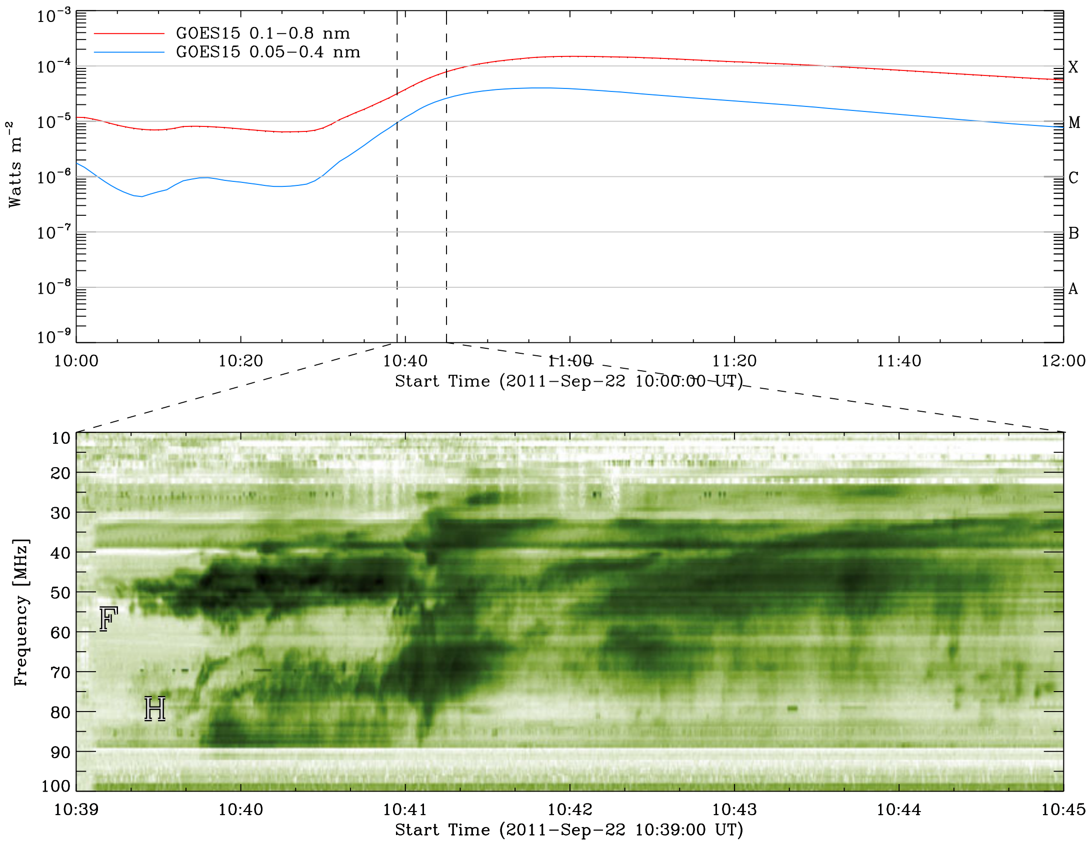

Figure 4 Dynamic spectrum of the 22 September 2011 type II radio burst and related GOES-15 light curve showing an X1.4 flare. This burst shows fundamental (F) and harmonic (H) emission. Band splitting of the order of 10 MHz can also be seen in the harmonic backbone at times around 10:42 UT.

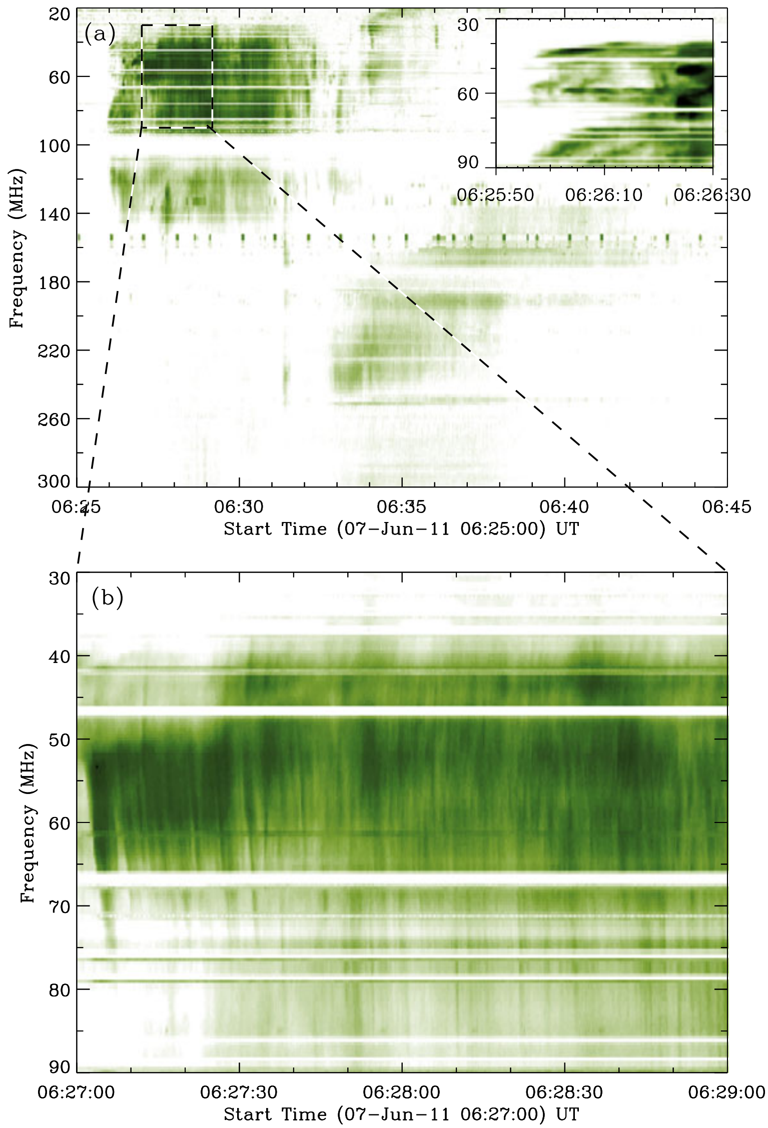

Figure 5 Dynamic spectrum of the 07 June 2011 type II radio burst. In the inset of panel (a) a short-lived fundamental and harmonic backbones are visible. Multiple herringbone structures are visible at $\sim 40-80$ MHz in panel (b).

active region 11302 and was associated with a CME. The burst started at 10:39:06 UT and shows both fundamental (F) and harmonic (H) bands of emission. The fundamental emission is visible between 20 and 60 MHz, while the harmonic backbone lies between 60 and 90 MHz. Emission higher than 88 MHz is attenuated by the presence of the FM band. This structure is typical of the majority of type II bursts; *i.e.*, when the harmonic backbone is present, it is almost always stronger than the fundamental. The two backbones show a drift rate of $\sim 0.22\ \mathrm{MHz\,s^{-1}}$, drifting towards lower frequencies as the plasma becomes less

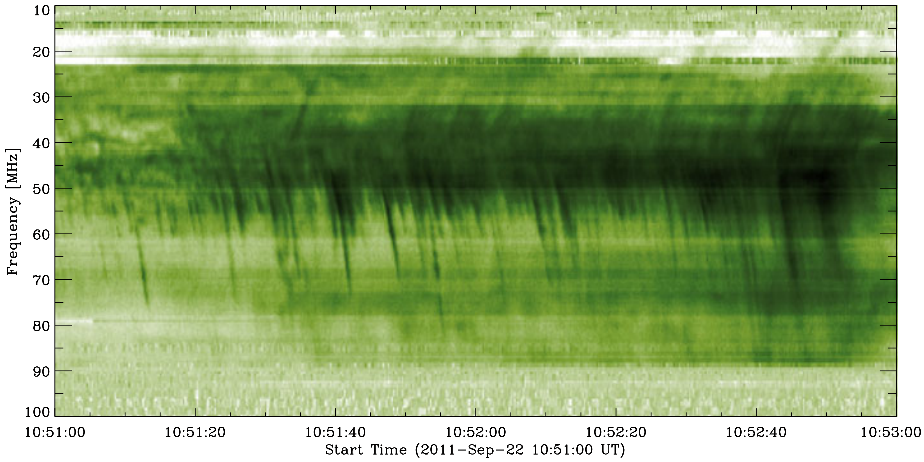

Figure 6 Dynamic spectrum of herringbones following a type II radio burst on 22 September 2011. These are thought to be due to electron beams shooting out from the shock front moving through the upper and lower corona.

dense at larger distances from the Sun. A shock velocity of 1240 km s^{-1} was estimated using the 1-fold Newkirk model (Newkirk, 1961).

Type II bursts typically last 5 – 10 minutes, but bursts exceeding 30 minutes are known. Furthermore, short-duration bursts of less than one minute have been identified. A short-lived type II observed on 7 June 2011 is shown in the inset at the top right of Figure 5(a). It is much more difficult to interpret short-duration type II bursts, particularly if they occur at similar times and frequencies as other radio activity. In addition, the fundamental/harmonic structure is split into two roughly parallel bands as evident in Figure 5(a). The band-splitting phenomenon has two interpretations. It could be due to either the shape of the electron density distribution in the corona (McLean, 1967) or the emission ahead of and behind the shock front (Smerd, Sheridan, and Stewart, 1974).

Another peculiarity of type II bursts is the sporadic presence of herringbones, small features similar to type III bursts that straddle the backbones' emission. In Figure 5(b) and Figure 6, herringbone features are evident. On 22 September 2011, about 50 herringbones drifting upwards in frequency between 40 and 80 MHz and downwards between 40 and 15 MHz are clearly visible between 10:51:00 UT and 10:53:00 UT. These are believed to be due to electron beams ejected from the shock front moving through the upper and lower corona (Holman and Pesses, 1983). The drift in frequency is very fast ($\sim$22 MHz s^{-1}), with a corresponding velocity of $\sim$0.1c.

3.2.2. *Type III Bursts*

Figure 7 shows a series of type III bursts starting at 12:56:05 UT on 21 October 2011. The emission drifts from 400 to 20 MHz in frequency. A broadband emission following the type IIIs, called a type V radio burst, is also evident from 20 to 150 MHz. The event was associated with an M1 flare which occurred in NOAA 11319. Furthermore, an associated type II burst starts at 12:58:12 UT, drifting from frequencies of 350 MHz to 170 MHz over 45 s. Using the 1-fold Newkirk model, we determined a velocity drift of 790 km s^{-1}. This type II burst was possibly associated with a CME that appeared in the SOHO/LASCO C2 field of view at 13:36:00 UT.

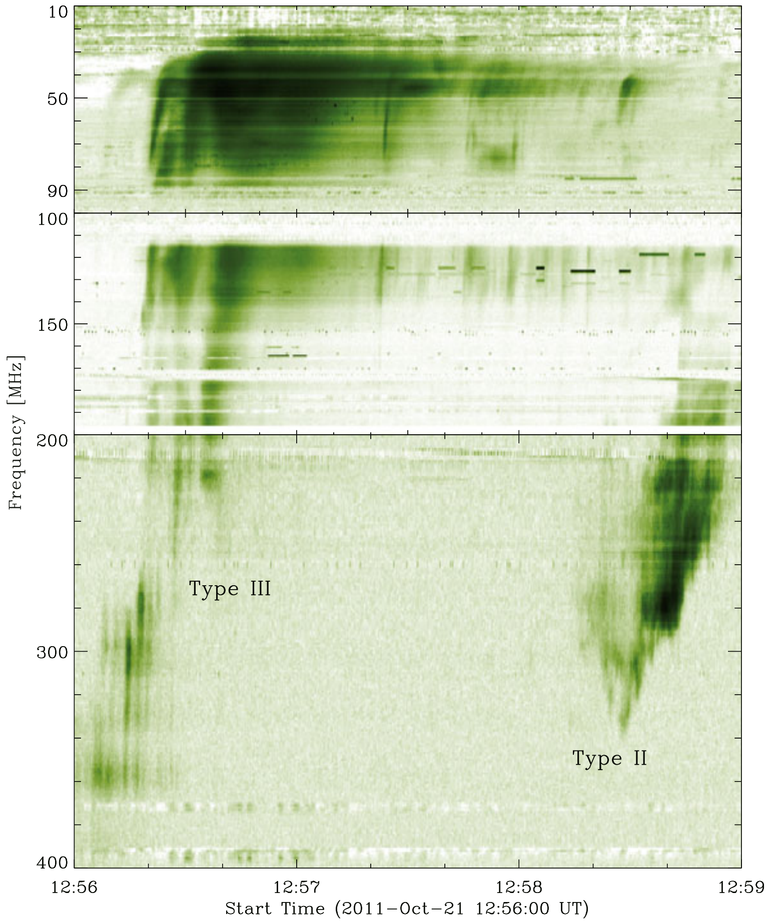

Figure 7 Several type III radio bursts observed on 21 October 2011. Broadband emission is superimposed on the bursts. Also shown is a type II burst between 140 and 330 MHz.

Type III bursts can occur in groups, recurrently over an extended period, and continuously in the form of storms. Type III bursts are very common features in the metric range (Cane, 2003). Since the first light of the CALLISTO-based spectrometer at RSTO, numerous type III bursts have been detected. Type III bursts are produced by relativistic electrons travelling along open magnetic fields; therefore, the drift in frequency detected in the radio spectra is very steep as the electrons travel fast in the corona and the density becomes increasingly tenuous. Similarly to type II bursts, type IIIs can often show a harmonic component. Since the drift rate is very fast, the two components usually merge, making their detection difficult (McLean and Labrum, 1985).

3.2.3. Type IV Bursts

In Figure 8, a type IV burst observed on 07 June 2011 is shown. The emission is related to an M2 flare which occurred in NOAA 11226. A halo CME with an estimated plane-of-sky speed of 1155 km s^{-1} was also detected by LASCO. The broad emission started at 06:32:10

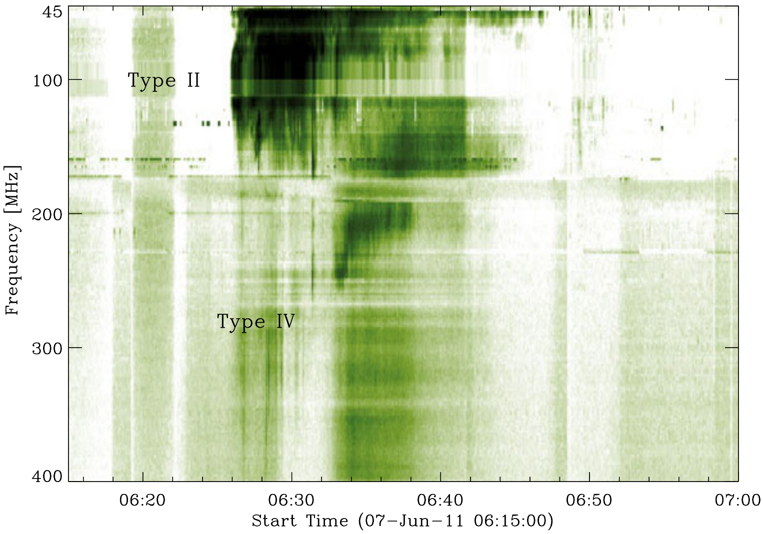

Figure 8 Type II and type IV radio bursts observed on 07 June 2011. The darker feature starting at 06:25:30 between 150 and 45 MHz is a type II radio burst. The spectrum shows a continuum emission starting at 06:31:10 UT between 400 – 130 MHz and a moving type IV starting at 290 MHz drifting downwards in frequency.

UT from 400 to 200 MHz and then spread from 400 to 100 MHz as it gained intensity. The burst extends to 400 MHz for its duration, which is the upper frequency limit of the spectrograph. A drifting feature is also evident, which starts at about the same time as the type IV, but moves to lower frequencies over time. This feature is called a moving type IV and has a bandwidth of approximately 100 MHz.

Type IV continua can exhibit a wide range of forms (Takakura and Kai, 1961). They are broadband and usually 500 MHz wide, but some can exceed two or three times this width. Type IV bursts can be very uniform in intensity, or they can fluctuate with complex underlying internal structures. Small fine structures are superimposed in the drifting continua. They are believed to be generated by the emission of electrons trapped in post-flare loops, and the drift is linked with the formation of the loops at successively higher altitudes (Dulk and Altschuler, 1971).

4. Discussion and Future Directions

Three CALLISTO spectrographs are currently installed at RSTO, sampling the radio spectrum between 10 and 400 MHz with 600 frequency channels and a temporal resolution of 250 ms per sweep. The system can potentially measure between 10 and 870 MHz. This unique configuration of CALLISTO receivers and the use of a biconical antenna and a frequency up-converter allow a good sampling of the spectra with a low-cost system. Since September 2010, a number of radio bursts have been detected, enabling us to identify fine-scale features in type II and type III radio bursts, including type II band splitting and herringbones. One important characteristic of the site is its extremely low RFI. In 2012, a fourth CALLISTO receiver will be added to the RSTO set-up, extending the current observational mode to 10 – 870 MHz and increasing the number of channels to 800 per sweep.

We have also installed an ionospheric monitoring instrument as a complementary instrument to CALLISTO at RSTO, called the *Atmospheric Weather Electromagnetic System for Observation, Modeling, and Education* (AWESOME; Cohen, Inan, and Paschal, 2010). AWESOME is an ionospheric monitoring sensor designed by Stanford University that is used to detect ionospheric disturbances. The Very Low Frequency (VLF) and Extremely Low Frequency (ELF) sensors of AWESOME monitor radio frequencies in the regions of 3 – 30 kHz and 0.3 – 3 kHz, respectively. The AWESOME receiver uses wire loop antennas, each sensitive to the component of the magnetic field in the direction orthogonal to the plane of the loop. ELF/VLF remote sensing enables the study of a broad set of phenomena, each of which impacts the ionosphere in a unique way, including solar flares, cosmic gamma ray bursts, lightning strikes and lightning-related effects, earthquakes, electron precipitation and the aurora. Sudden ionospheric disturbances (SIDs) occur in association with solar flares and have a very strong and relatively long-lasting effect on the ionosphere (Cliverd *et al.*, 2001).

We are now testing a fluxgate magnetometer to measure fluctuations in the Earth's magnetic field in Ireland. Using e-CALLISTO, we will measure the onset time of solar radio bursts near the Sun, measure their effects on the Earth's ionosphere with AWESOME, and ultimately determine their effects on the geomagnetic field in Ireland. As part of a worldwide network of observatories, RSTO will provide an extensive capability to monitor solar activity and its effects on Earth in a real-time, continuous manner. This is made possible by the low RFI of the Birr Castle Demesne site. RSTO has been earmarked as an ideal location for a LOFAR station (www.lofar.ie). When combined with data from space-based observatories, such as NASA's *Solar TErrestrial RElations Observatory* (STEREO) and *Solar Dynamics Observatory* (SDO) spacecraft, this will contribute towards tracking and understanding the propagation of storms from the surface of the Sun to their local effects on Earth.

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