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POlarization Emission of Millimeter Activity at the Sun (POEMAS): New Circular Polarization Solar Telescopes at Two Millimeter Wavelength Ranges

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Abstract We present a new system of two circular polarization solar radio telescopes, POEMAS, for observations of the Sun at 45 and 90 GHz. The novel characteristic of these instruments is the capability to measure circular right- and left-hand polarizations at these high frequencies. The two frequencies were chosen so as to bridge the gap at radio frequencies between 20 and 200 GHz of solar flare spectra. The telescopes, installed at CASLEO Observatory (Argentina), observe the full disk of the Sun with a half power beam width of 1.4°, a time resolution of 10 ms at both frequencies, a sensitivity of 2 – 4 K that corresponds to 4 and 20 solar flux unit (= 10^4 Jy), considering aperture efficiencies of 50 ± 5 % and 75 ± 8 % at 45 and 90 GHz, respectively. The telescope system saw first light in November 2011 and is satisfactorily operating daily since then. A few flares were observed and are presented here. The millimeter spectra of some flares are seen to rise toward higher frequencies, indicating the presence of a new spectral component distinct from the microwave one.

Keywords Flares · Polarization: radio · Radio bursts: microwaves (mm, cm) · Radio emission

1. Introduction

We report the successful operation of two new radio telescopes for monitoring the Sun at 45 and 90 GHz, with circular polarization: POEMAS, from the Brazilian acronym in Portuguese *POlarização da Emissão Milimétrica da Atividade Solar*, which translates into POlarization Emission of Millimeter Activity at the Sun. The telescope is located in the

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Argentine Andes at an altitude of 2550 m, and is fully operational since November 2011. The main goal of these telescopes is to fill the frequency gap between 20 and 200 GHz with simultaneous observations of the Sun at 45 and 90 GHz. The novelty of this instrument, in addition to monitoring at millimeter frequencies, is the measurement of circular polarization.

Currently, there are a few telescopes at GHz radio frequencies dedicated to observations of the Sun. OVSA in California, USA, operates from 1 to 18 GHz (Gary and Hurford, 1994). The RSTN monitoring network with stations all around the world operates at 0.25 – 15.4 GHz (Guidice, 1979). The Nobeyama Radioheliograph (Nakajima *et al.*, 1994), a high spatial resolution interferometer in Japan, observes the Sun daily at 17 and 34 GHz only, and at the same site are the Nobeyama Radio Polarimeters operating at 1, 2, 3.75, 9.4, 17, 35, and 80 GHz (Nakajima *et al.*, 1985). However, because of its location in Japan, there are no simultaneous time periods of observation with the telescopes in Brazil or Argentina.

In Brazil, the Itapetinga Radio Observatory (ROI; Kaufmann *et al.*, 1983) has been observing the Sun at 22 and 43 GHz; however, it is not dedicated to observations of the Sun. Moreover, the site is not suited for high-frequency observation; at 90 GHz it is possible to observe the Sun only a few days a year. On the other hand, in the Argentine Andes, the CASLEO site at an altitude of 2550 m, where the Solar Sub-millimeter Telescope (SST; Kaufmann *et al.*, 2001, 2008) is installed, has very good sky conditions for high-frequency observations. SST is a telescope dedicated to observations of the Sun, operating at 212 and 405 GHz with multiple receivers at each frequency. About 50 % of the time, the zenith opacity is lower than 0.3 neper (Np) at 212 GHz and lower than 1.5 Np at 405 GHz (Melo *et al.*, 2005). The sky opacity at 45 and 90 GHz is estimated from sky-tipping that is performed four times during the day. Thus far, the opacity measurements at 45 and 90 GHz yield 0.03 – 0.08 and 0.02 – 0.06 Np. We expect to observe the Sun at 45 and 90 GHz for about 90 % of the days of the year.

The system consists of two radio telescopes for solar patrol, one centered at the frequency of 45 GHz and the other at 90 GHz. Both radio telescopes are equipped with modern radiometers without intermediate frequency conversion, resulting in a low system temperature and hence high sensitivity and temporal resolution. The field of view of both telescopes was designed to be larger than the solar disk, allowing the detection of all flares, limited only by the minimum detection level.

Owing to the very good sky transparency at the CASLEO site, as mentioned before, it is possible for the first time to obtain regular, almost daily, solar data of unprecedented high quality at these frequencies. These data will be important not only for the research proposed here, but also as a support for other solar observations at different wavelengths that are operated both space- and ground-based.

In addition, the observations at 45 and 90 GHz also include polarization measurements that have not been performed routinely at these frequencies and at this longitude sector so far. Information about polarization is important to distinguish between thermal and non-thermal emission, since thermal emission is only weakly polarized, whereas the polarization of non-thermal emission, such as gyro-synchrotron from accelerated electrons with power-law energy distribution, varies from 30 % to up to 100 % (Dulk, 1985). Moreover, the polarization probes the magnetic field in the emitting source and in the region where the radio waves propagate.

1.1. Radio Emission of Solar Flares

The radio emission produced during solar flares is generally attributed to different mechanisms depending on the wavelength. At frequencies lower than a few GHz, radio waves are usually attributed to plasma emission that gives rise to type II, III, and IV bursts and type I noise storms. Radio emission at GHz frequencies is generally believed to be produced by gyro-synchrotron process as accelerated electrons spiral around the magnetic field lines, or thermal bremsstrahlung as thermal electrons interact with the existing charged particles of the solar atmosphere. The emission produced by the non-thermal electron population, the same one that is believed to generate the hard X-rays, usually has an impulsive temporal behavior, and is produced at the beginning of a flare. A more gradual time profile is observed to peak later in the flare and is thought to be caused by thermal emission from the heated atmosphere surrounding the flare location.

To distinguish between the possible emission mechanisms it is important to have a good spectral coverage by detecting the flare simultaneously in as many wavelengths as possible. Presently, however, there is a large frequency gap at radio frequencies between 20 and 200 GHz. Unfortunately, this gap hinders the determination of important flare parameters such as: i) the frequency of the peak of the spectra, or turnover frequency, which gives information on the energy of accelerated electrons and the magnetic field intensity in the flaring source and electron density; ii) the optically thin frequency slope, which is related to the accelerated electrons with a power-law energy distribution, providing information about the acceleration mechanism; iii) the frequency for minimum emission before the sub-THz spectral component increasing with frequency that was observed in several events; and iv) other physical parameters such as source size and inhomogeneities that may also be estimated from spectra with complete frequency coverage.

The slope of the spectrum on the high-frequency (microwave) part above the turnover frequency is related to the power-law index of the accelerated electron population, which of course depends on the acceleration mechanisms that produced these electrons. Thus accurate spectral coverage in the optically thin part of the spectrum, above the turnover frequency, is crucial to shed light on the acceleration mechanisms.

On the other hand, the turnover frequency at microwaves is related to the accelerated electron energy and the magnetic field intensity where the radio emission is generated. The most common turnover frequency occurs in the range 7 – 10 GHz (Dulk, 1985; Stahli, Gary, and Hurford, 1989; Bastian, Benz, and Gary, 1998). Other works have shown that many bursts exhibit maximum emission at 20 – 35 GHz at least (Croom, 1970, 1973; Shimabukuro, 1970, 1972; Akabane *et al.*, 1973; Zirin and Tanaka, 1973; Correia, Kaufmann, and Magun, 1994), sometimes extending up to 80 GHz (Ramaty *et al.*, 1994; Nita, Gary, and Lee, 2004; Raulin *et al.*, 2004; Bastian, Fleishman, and Gary, 2007; Altyntsev *et al.*, 2008). Unfortunately, most solar radio telescopes only observe up to 20 GHz, and thus do not detect the peak frequency of these sources.

During the period of 1991 through 1994, the Berkeley–Illinois–Maryland Array (BIMA), which operates at 86 GHz in campaign mode, observed ten solar flares. Some of these flares were simultaneously observed at microwave frequencies by the Owens Valley Solar Array (OVSA) from 1 to 18 GHz, such as the 7 January 1992 (Silva *et al.*, 1996) flare and the 1994 flares on 16 August (Raulin *et al.*, 1999) and 18 August (Silva *et al.*, 1997). The large void in frequency from 18 to 86 GHz compromises the determination of the exact spectral slope in the optically thin part of the spectrum, which as mentioned above provides insight into the acceleration mechanism at work in these flares.

Recently, Kaufmann *et al.* (2004) discovered a new spectral component above 200 GHz from observations of the SST. Some of the flares detected show that the flux at 405 GHz is higher than at 212 GHz, implying the existence of a spectral component that increases toward higher frequencies. Some examples are the flares of 6 April 2001 and 20 December 2002 (Cristiani *et al.*, 2008), and the two flares on 2 November 2003 (Silva *et al.*, 2007)

Figure 1 The telescopes already installed and operating at CASLEO Observatory in Argentina.

and 4 November 2003 (Kaufmann *et al.*, 2004). Observation of the 25 August 2001 flare (Raulin *et al.*, 2004) and of 28 October 2003 flare (Lüthi, Magun, and Miller, 2004; Trottet *et al.*, 2008) with the KOSMA telescope also suggest spectral upturning corresponding to this high-frequency spectral component.

This is distinct from the traditional microwave component, with peak frequencies at about 10 GHz. Our knowledge on the nature of both components and the full characterization of solar flare spectra will be improved by the analysis of new observations at the intermediate frequencies obtained by the two radio telescopes of POEMAS with receivers at 45 and 90 GHz, which are capable of measuring circular polarization.

2. Telescope Characteristics

The two 45 and 90 GHz solar polarimeters were conceived to measure the two circular components of radiation, which is split by a quarter-wave plate and fed into separate radiometers. The instruments were built by the German company RPG for operation at CASLEO Observatory, Argentina. The telescopes were successfully installed on the pedestal constructed for this purpose by the CASLEO staff (Figure 1). The temporal resolution of the telescopes is 10 ms.

On 22 November 2011, the solar radio polarimeters at 45 and 90 GHz saw first light. During the four days that followed, data were collected for the characterization of the antennas and receivers. It was very satisfying to see that the preliminary measurements showed that the equipment was operating according to the specifications.

The complete configuration of the two radio telescopes for solar patrol at 45 and 90 GHz consists of two receivers for circular polarization observation of right and left components of radiation, as said before, which implies the addition of two more radiometers at 45 and 90 GHz. That is, a total of four radiometers.

The 45 GHz telescope has a 44 cm diameter offset reflector aperture and the 90 GHz telescope utilizes a 16.5 cm diameter lens, yielding a half power beam width (HPBW) of approximately 1.5 degree at both frequencies. The amplifiers have bandwidths of 4000 MHz at both frequencies. One big advantage of these systems is that the receivers have direct detection and therefore have no need of mixers and local oscillators for the down-conversion of signal.

Table 1 Beam width at half power in degree, at both frequencies.

Frequency (GHz)	Scan	LCP	RCP
45	Azimuth	1.34	1.34
45	Elevation	1.39	1.37
90	Azimuth	1.40	1.37
90	Elevation	1.39	1.37

Table 2 Compilation of the brightness temperature of the Sun.

Reference	T_b(45 GHz) (K)	T_b(90 GHz) (K)	Comment
Kuseski and Swanson (1976)	8600	7400	T_b(45 GHz) interpolated
Linsky (1973)	7760	7670	re-calibrated
Shibasaki, Alessandrakis, and Pohjolainen (2011)	7000 ± 700 K	7000 ± 700	estimated from data in figures
Landi and Chiuderi Drago (2008)	8000 ± 800	7000 ± 700	
Loukitcheva *et al.* (2004)	7500 ± 750	7000 ± 700	
Selhorst, Silva, and Costa (2005)	8660	7670	from the solar atmosphere model

2.1. Beam Shape at 45 and 90 GHz

Measurements of the beams were obtained by performing scans of the Sun in azimuth and elevation of 5° each at 45 and 90 GHz. The ephemeris position of the Sun was used to point each telescope to the center of the Sun as the reference position for the scans. The measurements for the left (LCP) and right (RCP) circular polarization are listed in Table 1. The HPBW was corrected for the convolution of the solar disk of 0.5° in diameter. The observations have also shown that the beams are practically Gaussian, as can be seen in Figure 2 for the 45 and 90 GHz beams. Also shown in the plots are the pointing of the telescope during the scans in azimuth and the elevation of the Sun.

2.2. Aperture Efficiency at 45 and 90 GHz

The new moon happened on 25 November 2011, and thus observations of the moon could be performed and compared to the Sun to estimate the aperture efficiency of the antennas at the two frequencies. The brightness temperature of the new moon is 202 K at 45 GHz and 176 K at 90 GHz according to Linsky (1973). On this day, the sky opacity at 45 and 90 GHz was 0.066 and 0.055 Np.

The aperture efficiency can also be estimated from observations of the Sun, once its true brightness temperature is known. Table 2 lists recent determinations of the solar brightness temperature.

Here we adopt the brightness temperature values for the Sun of 7500 ± 750 and 7000 ± 700 K at 45 and 90 GHz. A 10 % uncertainty in the solar brightness temperatures is assumed.

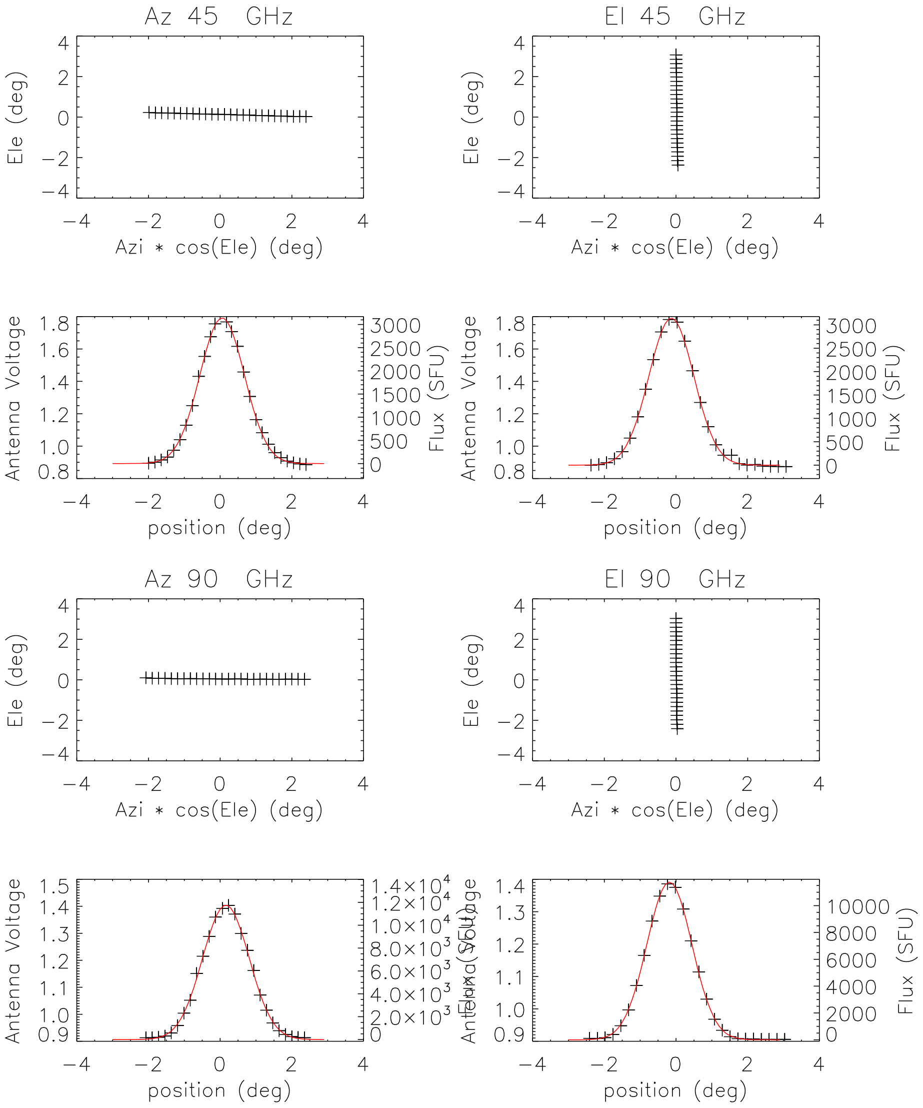

Figure 2 Beam shape for 45 GHz (top) and 90 GHz (bottom) from scans in azimuth (left) and elevation (right). There is a slight discrepancy between the zero of the scan and the peak of the beam pattern that is caused by a small pointing error in the telescopes.

Since the solar diameter is sufficiently smaller than the HPBW of the radio telescopes, the aperture efficiency, also listed in Table 3, is estimated as (Kraus, 1986)

$$\eta = \frac{T_B^{\text{obs}} \lambda^2}{T_B^{\text{true}} A_{\text{geo}} \Omega}, \tag{1}$$

where $\lambda = 6.67$ or 3.33 mm is the wavelength of the observations, $\Omega = 5.98 \times 10^{-5}$ str is the solid angle of either the Sun or the Moon, and A_{geo} is the geometric area of the telescopes,

Table 3 Aperture efficiency of the antennas (in %) at the two frequencies and polarizations for the observations from the Sun and the Moon.

Aperture efficiency	Polarization	45 GHz	90 GHz
Sun	LCP	51 ± 5	82 ± 8
	RCP	49 ± 5	81 ± 8
New moon	LCP	49	72
	RCP	48	63

which is 0.159 and 0.0214 m^2 at 45 and 90 GHz. $T_\mathrm{B}^\mathrm{obs}$ and $T_\mathrm{B}^\mathrm{true}$ are the observed and adopted brightness temperature values for either the Sun or the Moon.

The calculated efficiencies from the measurements of the Moon and Sun are listed in Table 3 for the two polarizations and frequencies.

Since there are uncertainties in both the Sun and Moon measurements of about ±10 %, we adopted the mean values estimated for the aperture efficiency of the polarimeters as 50 ± 5 % at 45 GHz and 75 ± 8 % at 90 GHz, which agrees with the specifications. These values yield the conversion factors from the antenna temperature, T_A, to the emission flux, F_ν (in solar flux unit, 1 SFU = 10^4 Jy), for a point source:

$$F_\nu = \frac{2K_\mathrm{B}}{\eta A_\mathrm{geo}} \times 10^{19} T_\mathrm{A}(\nu) \quad \mathrm{SFU}, \tag{2}$$

where K_B is the Boltzmann constant and T_B is half of the sum of the measured temperatures in RCP and LCP. The conversion factors for the radio telescopes are 3.5 and 17.2 at 45 and 90 GHz.

2.3. Sensitivity

To determine the sensitivity, we calculated the peak-to-peak variation of the brightness temperature. The sensitivity was assumed to be one third of these variations. The peak-to-peak values were estimated in intervals of 100 points, that is 1 s, and were found to be about $2.5-3.5$ K at 45 GHz and $3-4$ K at 90 GHz, whereas the standard deviation is 0.5 and 0.7 K at each frequency, respectively. The sensitivity in flux was estimated using the conversion factors reported above, which resulted in about 4 and 20 solar flux units at 45 and 90 GHz.

Thus, we conclude that the telescopes are working within the initial specifications and are already patrolling the Sun daily.

3. Flare Observation

As mentioned above, the POEMAS polarimeters started monitoring the Sun on 25 November 2011 and since then a few medium-class flares have been observed. These flares are listed in Table 4. Figures 3, 4, 5, and 6 show the time profiles of the emission at 45 and 90 GHz for these flares. The top panel of each figure depicts the soft X-ray profile from the GOES satellite. The dashed (red) curve shows the time derivative of the GOES X-ray flux, which according to the Neupert effect should mimic the high-energy emission. The next panel shows half of the sum of the circular polarizations for the 45 GHz data, while the following panel shows the difference RCP − LCP, an indication of the polarization. The two bottom panels are the same as the previous ones for the 90 GHz emission.

Table 4 Partial list of flares observed during the daily operation of the telescopes at 45 and 90 GHz.

Date and peak time (UT)	GOES Class	Location
SOL2011-12-25T18:15	M 4.0	AR 1387 (S22W26)
SOL2011-12-25T20:27	C 7.7	AR 1387 (S21W24)
SOL2011-12-26T20:17	M 2.3	AR 1387 (S21W42)
SOL2012-01-27T18:15	X 1.7	AR 1402 (N27W71)
SOL2012-03-06T21:04 – 21:06	M 1.3	
SOL2012-03-13T17:25	M 7.9	AR 1429 (N19W59)
SOL2012-07-08T16:30	M 6.9	AR 1515 (S17W74)

Except for the second flare on 25 December 2011 and the following day, the flares also have detectable emission at 90 GHz. The time profiles of the flares on 27 January 2012, 13 March 2012, and 8 July 2012 seem to be similar at both frequencies. The peak times in the derivative of the soft X-rays and the millimeter emission appear to coincide. The 27 January 2012 event appears to be a double explosion with two peaks at millimeter wavelengths and a double-humped soft X-ray time profile. The most intense flare detected by POEMAS so far was the M 7.9 flare on 13 March 2012 with a maximum flux of 1040 ± 50 and 690 ± 160 SFU at 45 and 90 GHz, respectively. Nevertheless, the strongest X-ray flare detected in the same period is the X 1.7 flare on 27 January, which reached only 180 ± 30 and 240 ± 120 SFU for the same frequencies.

The 90 GHz emission of the first flare on 25 December 2011 peaked at a different time than that of the 45 GHz emission. In this case, the higher frequency emission peak was delayed by approximately 1 min. This is a first indication that the spectrum may invert its slope.

All flares show some degree of polarization, except for the flares on 25 December 2011. RCP dominates for the flare on 13 March 2012. The vertical dashed lines in the figure panels depict the instant at which the spectrum was constructed. These times were chosen to coincide with the peak emission at 45 or 90 GHz in most cases.

3.1. Flare Spectra

The spectra of solar flares provide important information about the physics involved in the flaring process. One way toward a better understanding of solar flares is to analyze their radiation, which is an indirect evidence of the energy production and acceleration process. The telescopes presented here aim to investigate the acceleration mechanisms during flares through analyzing the flare emission at millimeter wavelengths, *i.e.*, intermediate between microwaves and sub-millimeter wavelengths, just in time for the next solar maximum.

Figure 7 displays the spectra of the flares shown in the previous figures. The spectra were constructed at the two times marked as dashed vertical lines in the panels of the flare time profiles. These times are listed in each panel for the 45 – 90 GHz spectra. When available, we also included the microwave flux data from the RSTN patrollers reported at the Space Weather Prediction Center (http://www.swpc.noaa.gov/ftpdir/indices/events), which are shown as asterisks in each plot. RSTN uses noise diodes to calibrate the fixed-frequency data and has a standard calibration protocol that is carried out each day, including a separate procedure for the noon flux measurement that is reported as the daily value. In practice, the uncertainty is 10 % most of the time (S.M. White, private communication).

The millimeter flux at each frequency was estimated to be the maximum value of half the sum of the left and right circular polarization emission within an interval of 60 s centered

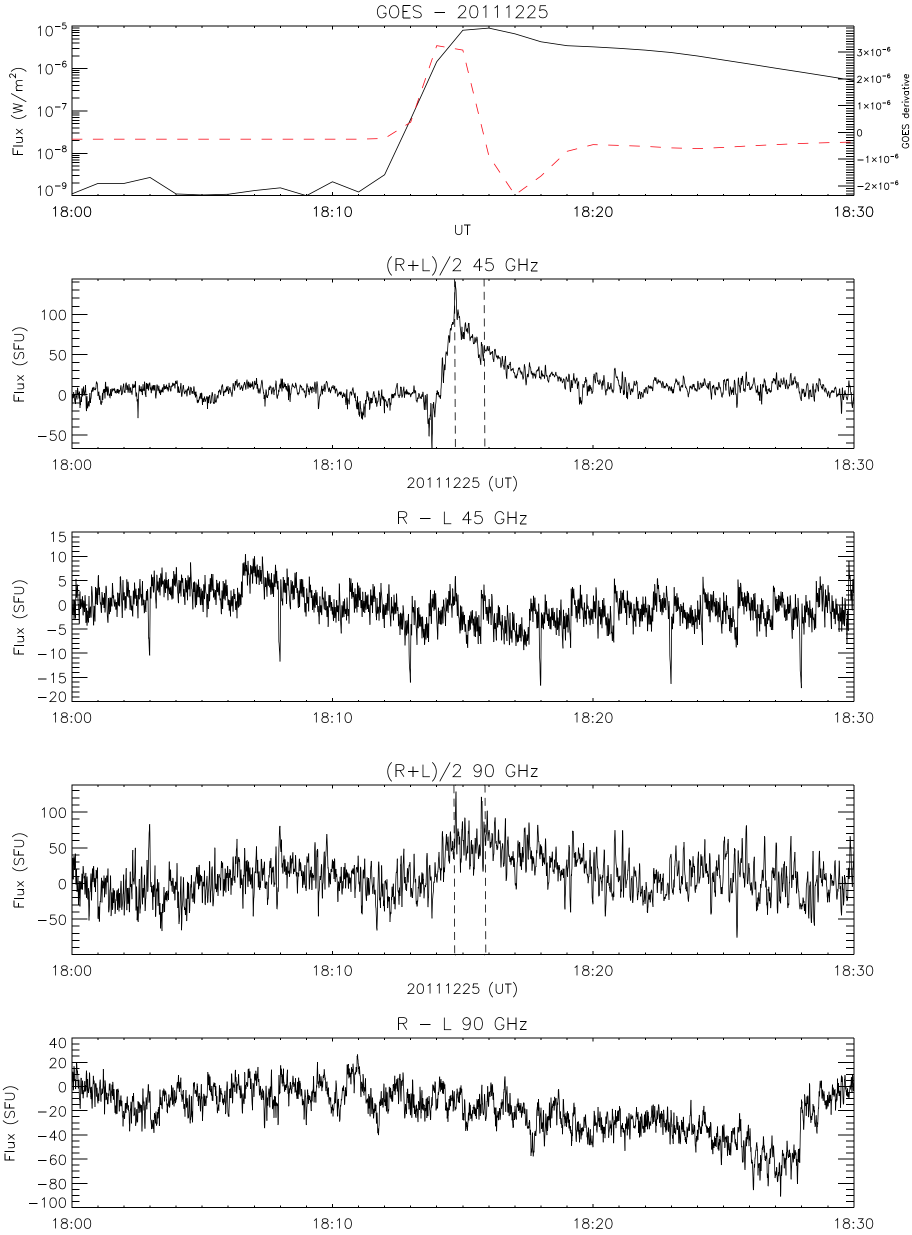

Figure 3 The first flare on 25 December 2011 at 18:15 UT. From top to bottom: GOES soft X-ray flux (solid, black) and its derivative (red, dashed); intensity at 45 GHz; RCP – LCP for 45 GHz; intensity at 90 GHz; RCP – LCP for 90 GHz.

at the times listed in the panels of Figure 7. Before computing the maximum value, the data were first smoothed with a running mean of 500 points, which corresponds to 5 s averaging.

The spectra of the flare on 25 December 2011 show an inversion in the spectral index, turning from a downward to an upward spectrum later on. A different, albeit increasing,

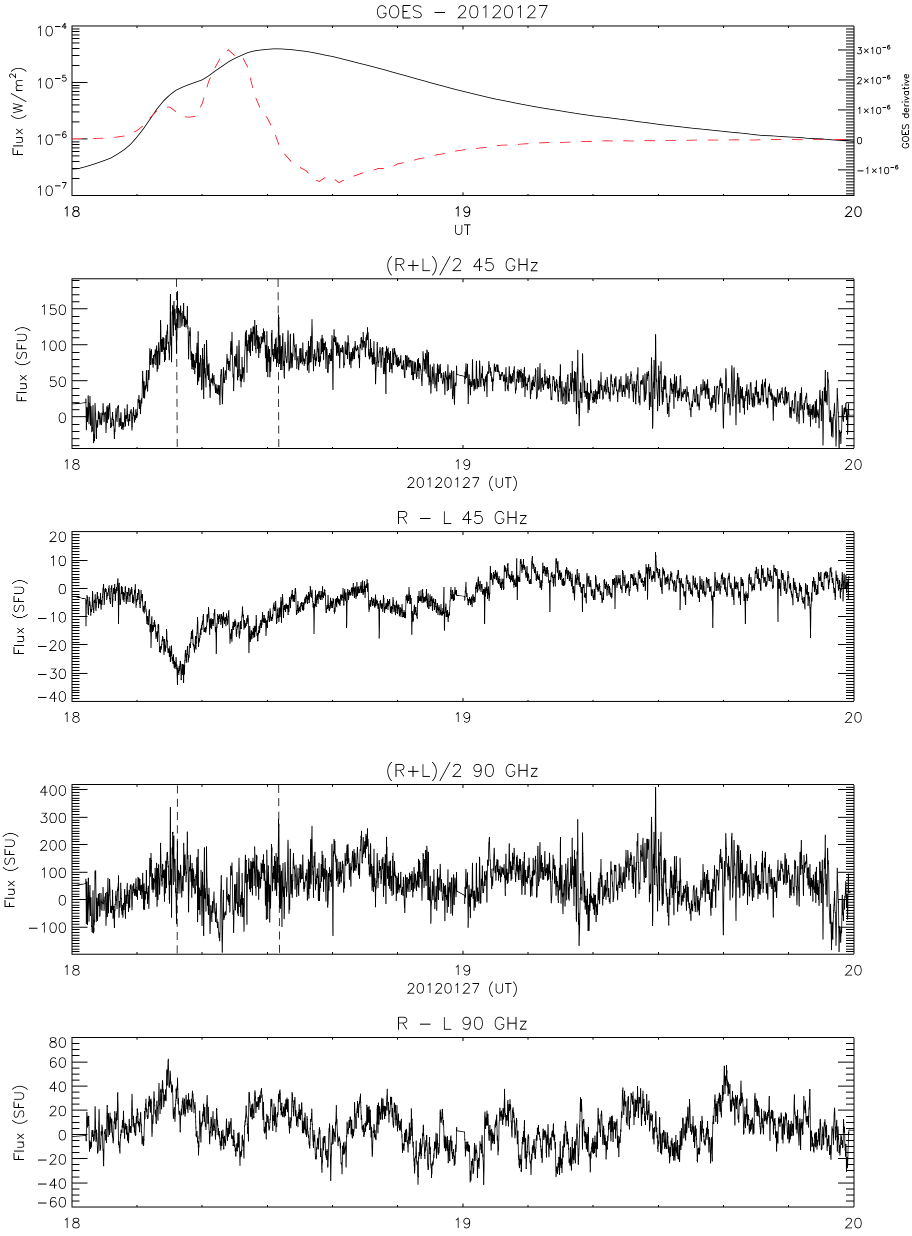

Figure 4 Same as the previous figures for the X 1.7 flare on 27 January 2012.

slope is seen for the 27 January 2012 flare. On the other hand, the flares on 13 March 2012 and 8 July 2012 are the only ones that seem to display the traditional decreasing spectra. However, the millimeter emission apparently is not the simple prolongation of the microwave spectra observed by the RSTN telescopes.

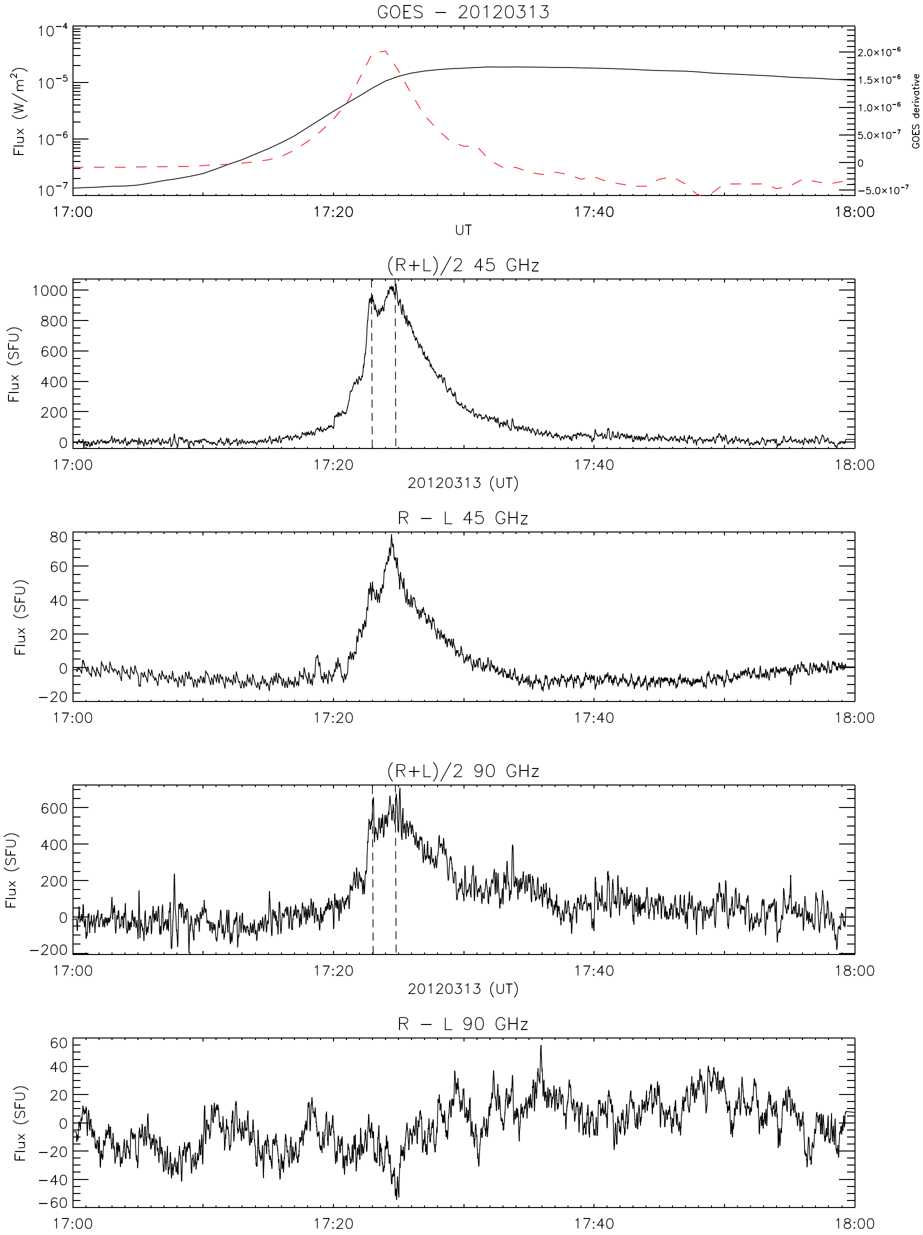

Figure 5 The M 7.9 flare on 13 March 2012.

4. Discussion

POEMAS, the POlarization Emission of Millimeter Activity at the Sun, consists of two radio telescopes operating at the frequencies of 45 and 90 GHz. Their unique feature is to monitor the Sun continuously, measuring both left- and right-hand circular polarization with

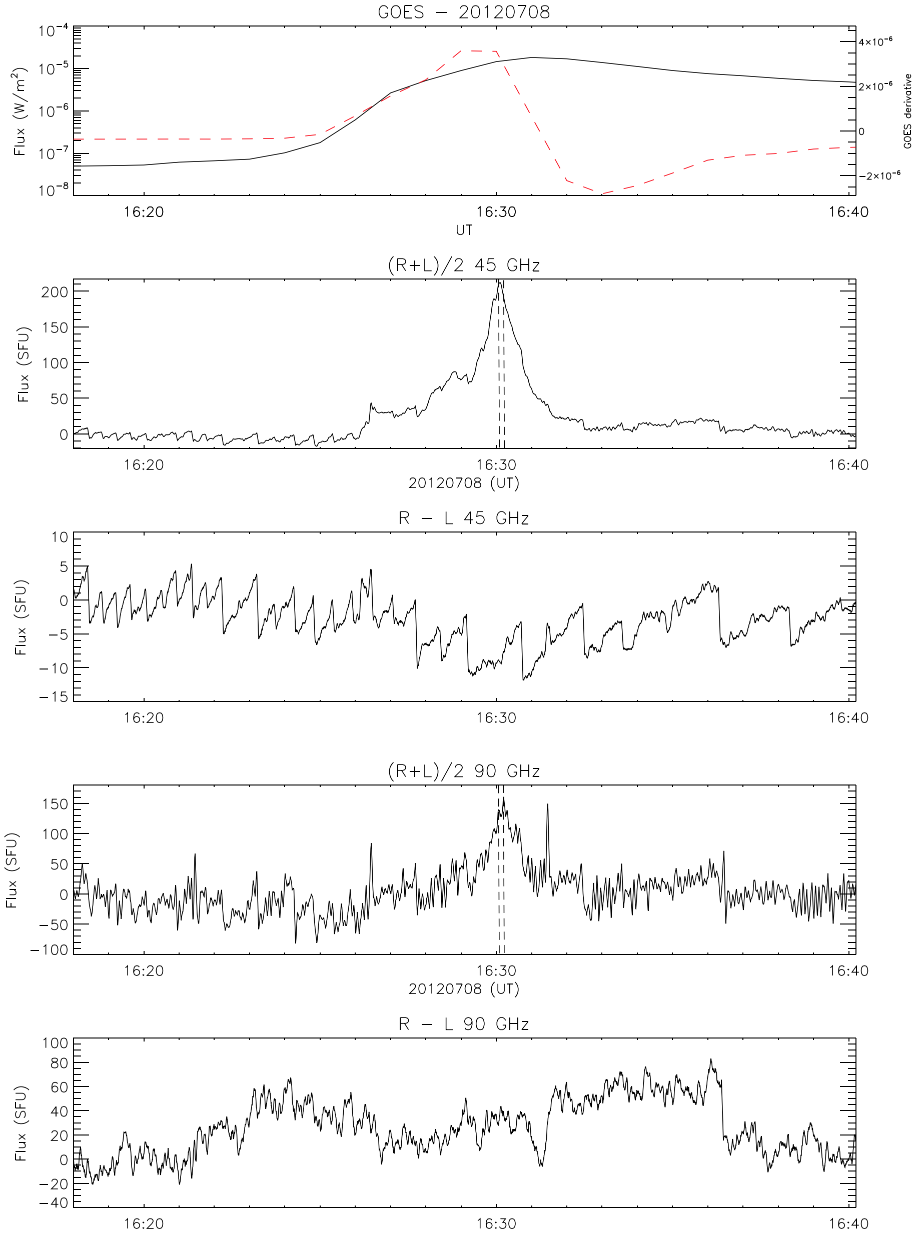

Figure 6 The M 6.9 flare on 8 July 2012. Jumps seen in the third and fourth panels are of instrumental origin and should be corrected for in the future.

a high temporal resolution of 10 ms. The time period covered during a typical summer day of observation is from 13 to 22 UT.

Since its first light in November 2011, it has already detected at least seven flares, which are reported here. The smallest flare is C 7.7 and the largest one is an X 1.7 flare in GOES flare classes. The time profile at 90 GHz does not always coincide with that of the 45 GHz

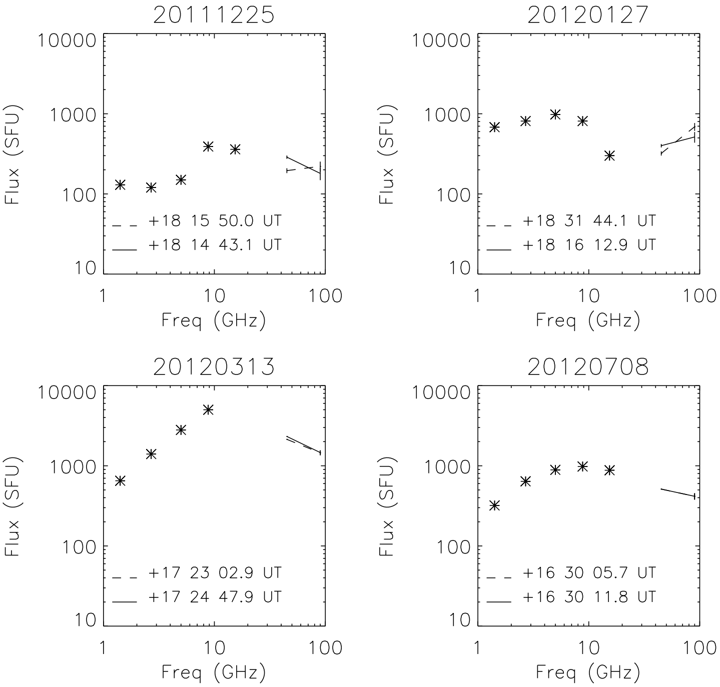

Figure 7 Radio spectra of Stokes I, (RCP+LCP)/2, at the peak time of the flares depicted in Figures 3–6. The millimeter spectra, joined by a straight line, are plotted for the two time intervals shown as dashed lines in the previous figures. The center times of the intervals are written in each panel.

emission. When the emission at 90 GHz is detected, we have constructed the spectrum, adding microwave data from the RSTN patrol telescopes when available.

As can be seen in Figure 7, most flares do not seem to have a simple radio spectrum, that is, the millimeter emission is not the high-frequency counterpart of the microwave spectra, but rather seems to be a separate spectral component at higher frequencies. This is shown by the increasing spectrum toward 90 GHz. Thus, these few medium-size flares show that there probably is a new spectral component at high frequencies that extends into the THz domain.

Spectra with increasing flux toward sub-millimeter wavelengths (Kaufmann *et al.*, 2004) were discovered by the Sub-mm Solar Telescope (SST), which is also installed at CASLEO Observatory. This double-peaked radio spectrum was the driving research theme behind the proposal for the POEMAS telescopes at 45 and 90 GHz. The next step is to look carefully for coincident data in the sub-millimeter frequencies of 212 and 405 GHz of the SST. At least for the 13 March 2012 flare 212 GHz data are available. This event will be investigated in more detail in a following article. The events of 6 March 2012 and 27 January 2012 are also being analyzed separately and will be reported elsewhere.

Despite having successfully met its specification, such as beam size and sensitivity, a few technical problems were detected on the radio telescopes. It was found that strong winds induced vibrations on the 45 GHz antenna. Strong structured arms have been constructed by RPG and were recently installed at the telescope.

Another problem was that for high-elevation positions of the Sun larger than about 60°, the solar disk is partially shifted from the center of the beam, causing a small decrease in the radio telescopes gain. We are currently working to establish the gain correction when this effect occurs.

5. Concluding Remarks

The two solar polarimeters, POEMAS, at 45 and 90 GHz were successfully installed and are operating at El Leoncito in the Argentine Andes since November 2011. Due to the exceptional atmospheric transmission, it is expected to obtain high-quality observations throughout most of the year. These are unique instruments that complete the spectral frequency gap between 20 and 200 GHz and add, for the first time, polarization observations at these high frequencies with high sensitivity and time resolution.

Flare observations at 45 and 90 GHz are expected to contribute to a better understanding of the spectral transition between the well-known microwave frequencies and the new component that increases in flux at sub-THz frequencies. Several solar bursts were already detected, such as the examples shown here.

Finally, we are currently developing a Solar Virtual Observatory that will make the time profiles of the solar emission at 45 and 90 GHz observed by POEMAS available on-line within the next months.

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