Spectral trends of solar bursts at sub-THz frequencies

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Abstract. Previous sub-THz studies were derived from single event observations. Spectral trends for a larger collection of sub-THz bursts have been analyzed for the first time. It consists of a set of 16 moderate to small impulsive solar radio bursts observed at 0.2 and 0.4 THz by the Solar Submillimeter-wave Telescope (SST) in 2012-2014 at El Leoncito, in the Argentinean Andes. The peak burst spectra included data from new solar patrol radio telescopes (45 and 90 GHz), and were completed with microwave data obtained by the RSTN, when available. We evaluate critically errors and uncertainties in sub-THz flux estimates caused by calibration techniques and the corrections for atmospheric transmission, and introduce a new method to obtain uniform flux scale criterion for all events. The sub-THz bursts were searched during reported GOES soft x-ray events of class C or larger, for periods common to SST observations. Seven out of 16 events exhibit spectral maxima in the range 5-40 GHz with fluxes decaying at sub-THz frequencies (3 of them associated to GOES class X, and 4 to class M). Nine out of 16 events exhibited the sub-THz spectral component. From these, 5 events exhibited the sub-THz emission fluxes increasing with frequency separated from the microwave spectral component (2 classified as X and 3 as M) and 4 events have been detected at sub-THz frequencies only (3 classified as M and 1 as C). The results suggest that the THz component might be always present, with the minimum turn-over frequency increasing as a function of the energy of the emitting electrons. In view of the peculiar nature of many sub-THz bursts events, their better understanding requires further investigations of bursts examined on the standpoint of SST observations alone.

Keywords: Solar flares . Sub-THz bursts . Sub-THz atmospheric transmission. Radio-bursts spectra.

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1. Introduction

The extension of solar observations into the sub-THz range of frequencies can help us for a better understanding of the emission mechanisms involved in the flaring process. A new spectral component has been discovered with sub-THz fluxes increasing with frequency, at the same time but separate from the well known microwave component, bringing new challenges for interpretation (Kaufmann et al., 2004; Silva et al., 2007; Fleishman and Kontar, 2010; Krücker et al., 2013). Early solar bursts observations at frequencies up to 100 GHz did indicate spectral trends with fluxes increasing with frequency, some exhibiting spectral structures (Shimabukuro, 1970; Croom, 1971; Akabane et al., 1973; Zirin and Tanaka, 1973; Roy, 1979; Kaufmann et al., 1985; White et al., 1992). More recently, impulsive events were also observed at 30 THz, with fluxes several times larger than that of the microwave component (Kaufmann et al., 2013; 2015a). However nearly all studies on sub-THz carried so far were based on single event observations, in different observational circumstances. In the present study we analyze comparative spectral trends for a large set of events observed at 0.2 and 0.4 THz by the Solar Submillimeter-wave Telescope (SST) (Kaufmann et al., 2001; 2008), complemented by observations at 45 and 90 GHz by solar patrol radio telescopes (POEMAS) (Valio et al., 2013) and at microwaves by RSTN, Radio Solar Telescope Network (Guidice, 1979). Errors in flux determination at sub-THz frequencies are critically reviewed. A convenient method to calibrate the sub-THz data has been adopted to obtain an accurate single and uniform flux scale for all bursts analyzed.

2. Sub-THz errors in flux

The accuracy of solar observations at sub-THz is affected by several errors and uncertainties in flux determination that become particularly critical for weak bursts or small variations in large bursts. They include inaccuracies in atmosphere transmission; corrections in noise temperature calibration; antenna beams gain determination; fluctuations caused by atmospheric propagation and independent uncertainties in source position when using multiple overlapping beams technique for flux estimates. It should be reminded that all burst flux estimates assumes that the burst angular sizes are smaller than the beams angular sizes, and therefore can be estimated by knowing the antenna aperture efficiency for each beam..

Transmission “windows” bands at sub-THz frequencies become available at high altitude sites (Turner et al., 2012; Tremblin et al., 2012). The corrections for sub-THz observations for atmospheric transmission are the main source of error, especially for larger values of the atmospheric attenuation. The atmospheric transmission correction methods have been reviewed and applied to SST at El Leoncito site by Melo et al. (2005).

One simpler indirect inference of attenuation is derived from the “sky” temperature variation with elevation angle (the so called “tipping” method). It is reliable only for small attenuation values. The attenuation can be directly determined from solar signal extinction measurements taken at different elevation angles, taken at days with extremely low atmospheric attenuation (Melo et al., 2005). The method allows the determination of the product of the antenna beam coupling coefficient to the adopted solar brightness temperature. Although both factors are not well known, the product is well determined, allowing a direct estimate of attenuation over a considerably larger range of values compared to the tipping method (Melo et al., 2005).

Figure 1 shows a sample of the actual SST observation during calibration steps, illustrating one of the six beams. SST has 6 independent radiometric back-ends at 0.2 THz with HPBW (half power beam width) of 4 arcminutes and 2 beams at 0.4 THz, with HPBW of 2 arcminutes (see for example Gimenez de Castro et al., 1999; Kaufmann et al., 2001, 2008). Three of the 0.2 THz beams are partially overlapped at the 3 dB levels, and the fourth placed 8 arcminutes apart. One 0.4 THz beam is at the center of the three 0.2 THz cluster of partially overlapping beams, and another with direction coincident with the fourth 0.2 THz beam also displaced from the cluster by 8 arcminutes.

Further measurement uncertainties need to be added due to planet's brightness temperature approximations. The planets brightness temperatures and corresponding fluxes are the standard references for antenna effective aperture (and gain) calibrations, applicable beam angular sizes are larger than the planets' angular sizes. Furthermore, the antenna efficiencies at 0.2 and 0.4 THz, determined from Jupiter and Venus observations (Kaufmann et al., 2001; 2008) may change with time, which is not regularly monitored. Another uncertainty arises from the internal noise temperature references which do change with time and need to be recalibrated, which is not done on regular basis.

A separate uncertainty in flux calculations is independent from atmospheric transmission, temperature scale, or beams aperture efficiencies (or gain) corrections. It is caused by the multiple beams technique algorithm to determine the centroid position of the burst source emission with respect to the SST partially overlapped beams. Once the position is determined, the burst flux can be estimated, assuming the burst angular size is smaller than the HPBW. The method has been fully described elsewhere (Georges et al., 1989; Gimenez de Castro et al., 1999). The burst angular position with respect to the multiple overlapping 0.2 THz beams is obtained with accuracy set by the tracking conditions, which is of the order of 1 arcmin (Kaufmann et al., 2008). The corresponding impact of the multiple beam algorithm on flux calculation depends much on the several beam signal levels compared to signal baseline fluctuations. The net uncertainty may be estimated to be less than about ± 25 %. However, it should be emphasized that actual fluctuations in the observed signal baseline are generally dominated by atmospheric propagation variations. They become more pronounced when (a) the atmospheric transmission is poor, (b) for observations carried with the Sun at low elevation angles, (c) when the SST beams point to flaring sites near the solar limb when some beams are partially filled by the disk emission, and therefore responding more to tracking irregularities.

3. A simple method for uniform sub-THz flux determination

A simple method for flux scale calibration eliminates the first three sources of errors described above (i.e., due to atmospheric transmission, temperature scales, and antenna beams aperture efficiencies). Referring to the calibration set of measurements shown in Figure 1 for one 0.2 THz beam, the presented output data are in ADC units (analog-to-digital conversion). The solar flux to ADC factor can be set directly from the solar disk scans. Solar scans for a single 0.2 THz beam are shown schematically in Figure 2. The solar flux scale for the respective beam is expressed as:

$$S = S_\Theta \, . \, (\Omega_{beam} / \Omega_\Theta) = S_\Theta \, (\theta_{beam} / \theta_\Theta)^2 \quad \text{SFU} \tag{1}$$

where S_Θ is the full solar disk flux, Ω_{beam} and Ω_Θ are the solid angles subtended by the antenna beams and the Sun, respectively, and θ_{beam} and θ_Θ are the respective angular sizes (1 SFU = 10^{-22} $Wm^{-2}Hz^{-1}$).

The solar disk flux is reasonably well known, derived from the surface temperature (see, for example, Gezari, Joyce, and Simon, 1973; Shibasaki, Alissandrakis, and Pohjolainen, 2011, and references therein). We have adopted the empirical formula given by Benz (2009) for the range 6-400 GHz:

$$S_\Theta = 2.79 \, . \, 10^{-5} \, f^{1.748} \quad \text{SFU} \tag{2}$$

where f in MHz is the frequency. We obtain $S_\Theta \approx 57000$ SFU at 0.2 THz and ≈ 176800 SFU at 0.4 THz, respectively.

The ADC-to-flux ratio, k, for each beam is therefore derived directly from the sky-to-Sun observed deflection, $\Delta_{ADC,}$ for each one of the 6 beams. The solar flux scale for each beam is set by $S = k\ \Delta_{ADC}$, $k = S / \Delta_{ADC}$, where Δ_{ADC} is the counts difference between the solar disk and sky levels of the respective beam. The 6 SST beams shapes were determined from planet observations (see Kaufmann et al., 2001). They may also be derived from the deconvolution of the solar disk scans. The 0.2 THz HPBW for the four beams are 4 arcminutes. The 0.4 THz beams shapes were more accurately determined, using a beacon transmitter located in the far-field at El Leoncito, being of about 2x3 arcminutes, (Kaufmann et al., 2008), which was approximated to 2.5 arcminutes for the application of the method presented here.

It is important to emphasize two advantages of this method to calibrate the six beams scales directly in SFU: (a) once the ADC/flux ratio, k, is obtained for each beam, it will remain the same for the flux calculation for bursts located at any position in the solar disk, from center to limb; (b) this method determines burst fluxes without the need of corrections for atmospheric transmission and independently from antenna temperature referred to internal source and from beam gain calibrations. The consistency of this method was verified comparing to flux estimated using all corrections for an intense burst observed under good atmospheric transmission and after recent verification of the antenna beam gains and internal temperature scales (Kaufmann et al., 2004).

The SST burst basic identification criteria requires that excess time structures are observed in the cluster of the 0.2 THz beams and/or at the 0.4 THz beam at its center. For certain weak events, however, the excess signal is not detectable by all 4 beams of the cluster. These bursts were identified if observed at least by two of the sub-THz beams (two at 0.2 THz or one at 0.2 THz and another at 0.4 THz). In these cases, the multiple beam technique provides only lower limits of flux estimate, which is good enough for the purpose of this study.

4. Events Analysis

The sub-THz burst search was carried on time periods for which there were reported GOES soft X-ray bursts on the same active region being tracked by SST. Only well identified impulsive sub-THz bursts were selected, for which the start and peak times are well observed. There were 7751 hours of SST observation under fair to good sky sub-THz transmission conditions, during which 1507 GOES events, of class C or larger, were reported. From these 653 occurred on the same active region tracked by the SST distributed in 564 class C; 81 class M, and 8 class X. Between 2012 and 2014 16 sub-THz impulsive bursts were identified: 5 of them were associated with X-class flares, 10 were associated with M-class flares, and 1 with a C-class flare. Hence 60% of the X-class flares observed, 12% of the M-class flares and only 0.2% of the C-class flares displayed sub-THz emission.

Figures 3, 4 and 5 show examples of three burst time profiles from 45 GHz to 0.4 THz, to illustrate three spectral trends that were found. Their spectra are shown in Fig. 6. Fig. 3 (March 13, 2012) has peak fluxes that reduces with frequency. Fig. 4 (February, 2013) exhibits a spectral inflexion, decaying at microwaves and increasing at sub-THz. Fig 5 (April 12, 2013) displays peaks at sub-THz, without a clear counterpart at lower frequencies.

Burst spectra, shown in Fig. 6 (a)-(d), were derived from fluxes at the peak time structures observed at sub-THz and by the RSTN, at microwave frequencies 2.69, 4.99, 8.8, and 15.4 GHz, when available. Data obtained by the 45 and 90 GHz patrol telescopes, in the period 2012-2013 were added to the spectra. Table I gives the list of the sub-THz events identified in this study. Approximate r.m.s. errors are indicated. They correspond to the square root of an assumed r.m.s.-equivalent caused by the source position uncertainty squared, added to the signal baseline fluctuations r.m.s. squared. Fig. 6 (a)-(d) shows the spectra for all events examined here.

We found that 7 out of 16 events exhibit spectral maxima in the range 5-40 GHz with fluxes decaying at sub-THz frequencies with about the same spectral indices (3 of them classified as X, and 4 as M). Nine out of 16 events exhibited the sub-THz spectral component. From these, 5 events exhibited the sub-THz emission fluxes increasing with frequency separated from the microwave spectral component (2 classified as X and 3 as M) and 4 events have been detected at sub-THz frequencies only (3 of them with flux increasing with frequency, associated to M class GOES events, and one with flux decaying with frequency, associated to the GOES C class event).

5. Discussion and Concluding Remarks

We have analyzed for the first time a collection of sub-THz (0.2 and 0.4 THz) impulsive solar bursts observed by SST, between 2012 and 2014, in the flux range of 10-400 SFU (selected at periods of time of reported GOES Class C or larger flares). A simple calibration method has been introduced, setting the flux scale for each SST beam independently from the knowledge of internal temperature scales; antenna beams gains, and atmospheric attenuation. This allowed the selection of a uniform set of 16 bursts for their qualitative comparison.

On the standpoint of GOES soft X-rays it has been found that generally the larger class X did have a sub-THz impulsive bursts associated (5 out of 8, or 63%). The association of sub-THz bursts becomes poor to negligible for smaller GOES class events (10 out of 81 class M, or 12%, and 1 out of 564 class C, or 0.2%).

Analysis of spectral trends has shown that nearly half of the sub-THz bursts (7 out of 16) display flux maxima in the microwave range (5 - 40 GHz) decaying at 0.2 and 0.4 THz with about the same spectral index. These spectra may be attributed to synchrotron radiation with well-known parameters adopted (Ramaty and Lingenfelter, 1967; Bastian, Benz, and Gary, 1998) with maximum moving towards higher frequencies for larger electron energies and stronger magnetic field. The other half of the sub-THz bursts set (9 out of 16) exhibits a distinct sub-THz component, 8 with flux increasing with frequency and one decaying with frequency. Five bursts exhibit a double spectral structure, one at microwaves, and another at sub-THz. Four bursts exhibited the impulsive time profile at sub-THz but no peaks at lower frequencies.

Bursts with flux spectra increasing towards THz frequencies, well separated from the well known microwave spectra have similar shape as those obtained in larger bursts (Kaufmann et al., 2004; Silva et al., 2007, Kaufman et al., 2009). Many models have been suggested to explain them (Kaufmann et al., 2004; Sakai et al., 2006; Silva et al., 2007; Fleishman and Kontar, 2010; Krücker et al., 2013). The two spectral components simultaneous for a single burst, one in the THz range and another in the microwaves, may be conceived as the composed emission from two distinct sources (Silva et al., 2007). The double spectral feature produce by a single burst source may also be explained as a result from microbunching instability on beams of ultrarelativistic electrons (Kaufman and Raulin, 2006; Klopf et al., 2014).

The flare THz emission, with fluxes increasing with frequency might be common to many events if observations were available at higher range of frequencies. Synchrotron radiation peak emission may shift to higher frequencies for electrons accelerated at higher energies, not observable by SST. The sub-THz burst emission spectra might be extended to the 30 THz range where recently bright impulsive bursts were found (Kaufmann et al., 2013; 2015a). However, the

30 THz bursts might also be also explained by dense plasma thermal response to the impact of highly energetic particles, radiating at 30 THz and white light (Kaufmann et al., 2015a; Trottet et al., 2015; Penn et al., 2016). Both interpretations require electrons accelerated to very high energies.

The sub-THz burst identification search on periods of time when there were GOES reported events might not be the most appropriate approach. It has been known that there are a number of significant sub-THz bursts without clear association with soft X-rays events. This is the case of one burst observed at sub-THz only, simultaneous to a fast Hα flash, preceding microwaves and soft X-rays by ten minutes (Kaufmann et al., 2011). Due to peculiar unknown characteristics of many sub-THz bursts, it is strongly suggested a search of sub-THz on all SST data, unbiased by pre-established criteria to compare to events at other energy ranges, along a meaningful period of time. This represents a considerable amount of work, which will benefit from the simpler flux scale technique presented here.

Observations at higher THz frequencies are necessary to a better understanding of the spectral trends in the THz range and the respective physical implications. A double photometer experiment at 3 and 7 THz, named SOLAR-T, has been recently flown on a stratospheric balloon mission (Kaufmann et al., 2015b; 2016). The first burst analyzed indicates fluxes increasing with frequency at 0.2; 0.4 THz by SST and at 3 and 7 THz by SOLAR-T, which time profiles were correlated to bursts at Hα and EUV, but not at X-rays (Kaufmann et al. 2016). A ground-based photometric telescope to operate at higher THz frequency atmospheric windows (0.85, 1.4 and 16 THz) in a high altitude site has been recently completed (Kaufmann et al., 015b).

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Figure Captions

Figure 1 – SST observation shown for one 0.2 THz channel during calibrations: (1) internal temperature calibration; (2) solar map scans; (3) sky temperature tipping the antenna from zenith/horizon/zenith; (4) tracking of solar center followed by active region source tracking.

Figure 2 – Schematic diagram showing a solar disk scan by one of the SST beam, providing the derivation of the flux scale for that beam (see text).

Figure 3 – The 13 March 2012 sub-terahertz impulsive solar burst time profile exhibiting fluxes reducing with frequency, complementing the overall microwave spectrum (see Fig. 6 (a), third spectrum from the top).

Figure 4 – The 17 February 2013 impulsive solar burst time profile exhibiting the spectral index sense reversal feature, negative at microwaves and positive for sub-THz component with fluxes increasing with frequency (see Fig. 6 (a) bottom spectrum).

Figure 5 – The 12 April 2013 impulsive solar burst time profile which peaks were observed in the sub-THz range only (see Fig. 6(b) bottom spectrum).

Figure 6 (a-d) – Spectra of all bursts analyzed in this study. For 4 bursts there was an underlying microwave burst component without distinguishable related time structures.

Caption to the table

Table 1 – The list of sub-THz SST impulsive bursts searched during reported GOES soft x-ray events of class C or larger, for periods common to SST observations, from 2012 to 2014.