New telescopes for ground-based solar observations at sub-millimeter and mid-infrared

Pierre Kaufmann*[a,b], Hugo Levato[c], Marta M. Cassiano[a], Emilia Correia[a,d], Joaquim E.R. Costa[d], C. Guillermo Giménez de Castro[a],Rodolfo Godoy[c], Robert K. Kingsley[e], Jeffrey S. Kingsley[e], Amauri S. Kudaka[a], Rogério Marcon[f,g], Robert Martin[h], Adolfo Marun[c], Arline M. Melo[a,b], Pablo Pereyra[c], Jean-Pierre Raulin[a], Thomas Rose[i], Adriana Silva Valio[a], Achim Walber[i], Patrick Wallace[j], Azriel Yakubovich[k] and Maria Beny Zakia[b]
[a] Universidade Presbiteriana Mackenzie, Escola de Engenharia, CRAAM, São Paulo, SP, Brazil
[b] Universidade Estadual de Campinas, CCS, Campinas, SP, Brazil
[c] Complejo Astronômico El Leoncito, CONICET, San Juan, Argentina
[d] Instituto Nacional de Pesquisas Espaciais, São José dos Campos, SP, Brazil
[e] University of Arizona, Steward Observatory, Tucson, AZ, USA
[f] Universidade Estadual de Campinas, IFGW, Campinas, SP, Brazil
[g] "Bernard Lyot" Solar Observatory, Campinas, SP, Brazil
[h] Composite Mirror Applications,Inc., Tucson, AZ, USA
[i] RPG - Radiometer Physics, Meckenheim, Germany
[j] STFC Rutherford Appleton Laboratory, Harwell Science & Innovation Campus, Didcot, Oxfordshire, UK
[k] Orbit Technology Group Ltd, Netanya, Israel

ABSTRACT

The solar submillimeter-wave telescope (SST) is the only one of its kind dedicated to solar continuous observations. Two radiometers at 0.740 mm (405 GHz), and four at 1.415 mm (212 GHz) are placed at the 1.5-m dish Cassegrain focal plane, at El Leoncito high altitude site, San Juan, Argentina. The aperture efficiencies are close to design predictions: 20% and 35% for 2 and 4 arcminutes beam sizes at 405 and 212 GHz, respectively. The positioner absolute pointing accuracy is of 10 arcseconds. Spectral coverage was complemented by ground-based mid-infrared telescopes developed for high cadence observations in the continuum 10 micron band (30 THz), using small apertures and room-temperature microbolometer cameras. A new burst spectral component was discovered, exhibiting fluxes increasing for smaller wavelengths, separated from the well known microwave component. Rapid sub-second pulsations are common for all bursts. The pulsations onset times of appear to be connected to the launch times of CMEs. Active regions are brighter for shorter submillimeter-waves. Mid-IR bright regions are found closely associated with calcium plages and magnetic structures near the solar photosphere. Intense and rapid 10 micron brightening was detected on active centers in association to weak flares. These results raise challenging difficulties for interpretation

Keywords: submm-waves telescopes, mid-IR solar photometers, solar flares

1. INTRODUCTION

Observations of solar activity in the terahertz (1 THz = 10^{12} Hz) range are receiving considerable attention for the crucial theoretical implications they bring for the understanding of the physical mechanisms originating the radiations. There were early suggestions that the emission spectra of synchrotron radiation by highly energetic electrons should maximize in the far infrared, or terahertz range[1,2]. Important thermal emission from hot plasmas is also expected in that range[3,4].

In practice, however, very few measurements were accomplished, and the whole solar spectrum from millimeter waves to the visible remained poorly known. Observations are difficult to be accomplished due to technical limitations and to atmospheric opacity. Early observations at short microwaves and at millimeter waves, frequencies up to 100 GHz, have shown that certain solar bursts exhibit fluxes that kept increasing for higher frequencies[5-11]. The first attempt to observe solar activity at a sub-THz frequency was done by Clark & Park[12] using a 250 GHz cooled bolometer at the 1.5-m Queen Mary College optical telescope in UK. They found intriguing intense brightnings on time scales of one minute, restricted by the use of a single pixel and the raster mode of observations, raising challenging interpretation attempts[13]. Another attempt done at 0.85 and 12 THz using cooled bolometers at the 1.5-m optical telescope in Mount Graham, Arizona, US suggested the presence of fluctuations[14].

In order to fill partially the observational gap a solar telescope was conceived to operate at two sub-THz frequencies where the atmospheric "windows" present relatively small attenuation at a high altitude site: 212 and 405 GHz. Known as the submillimeter-wave solar telescope (SST) its development began in 1994, being installed in 1999 at the El Leoncito Astronomical Complex, located at 2550-m altitude in the Argentina Andes[15,16]. In the past years the SST received substantial improvements.

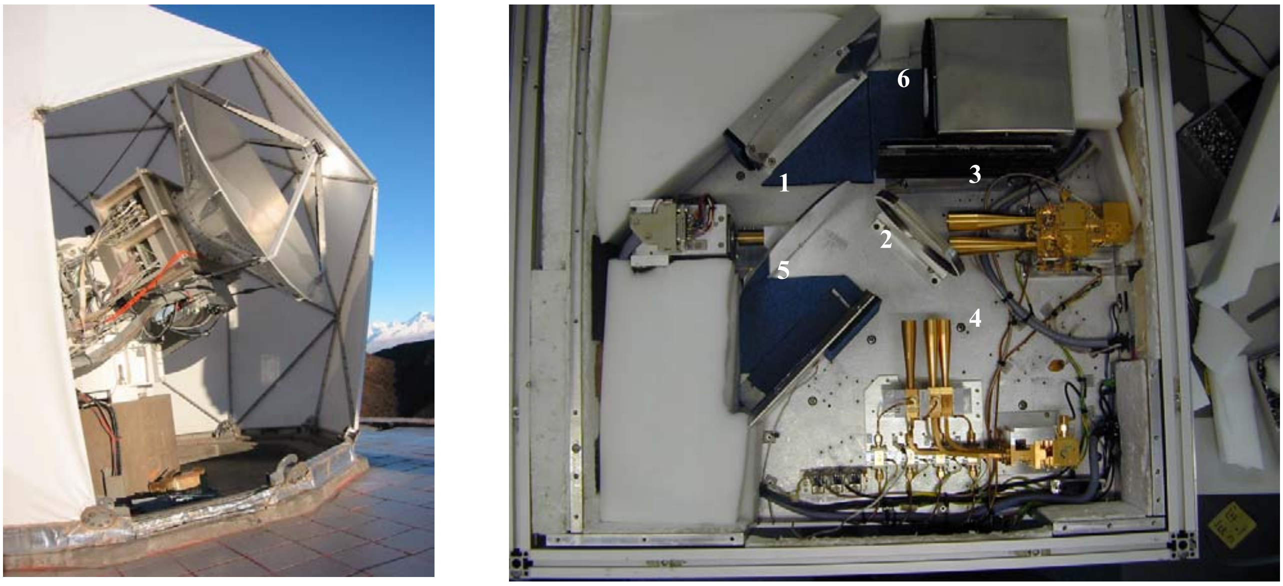
The sub-THz range to the visible range spectral gap was complemented with the implementation of ground-based solar observations in the mid-IR continuum (7-15 μm band, or 30 THz), for which the terrestrial atmosphere exhibit excellent transparence[17,18].

In this paper we present the SST radio telescope setup description, the six radiometers arrangement, the system performance, atmosphere transmission at the site and the relevant solar activity problems addressed by this new and unique instrument. We also describe the mid-IR optical setups for the high cadence data acquisition system, and the first results.

2. THE SOLAR SUBMM-WAVE TELESCOPE

2.1 Hardware

Fig. 1 (a) shows the SST – solar submm-wave telescope, consisting in a 1.5 m Cassegrain reflector on a alt-azimuth mount, all installed inside a ESSCO GoreTex radome with 3 m in diameter, installed at El Leoncito, Argentina Andes.



(a) (b)

Fig. 1 (a) The 1.5 m diameter Cassegrain reflector inside the 3 m diameter GoreTex radome, with the door removed for servicing, installed at El Leoncito, Argentina Andes. (b) Receiver's box seen from the top: (1) rotating flat mirror that is pointed to the subreflector, or to the room temperature load (5) or the hot load (6); (2) polarizing grid allowing one polarization plane into two 405 GHz radiometers (3) and another plane into four 212 GHz radiometers.

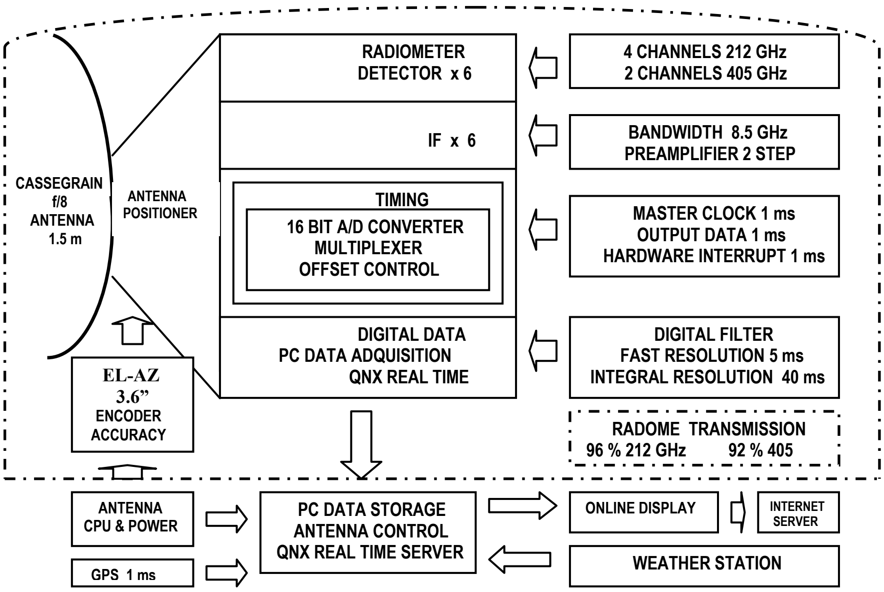
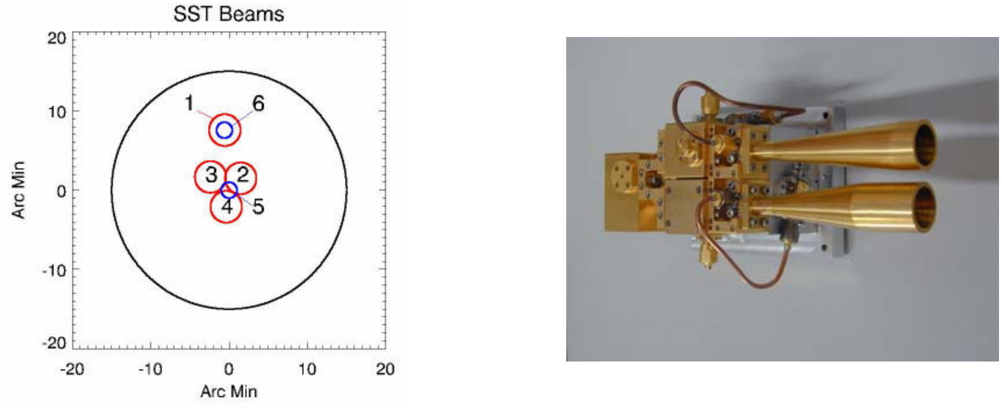


Fig. 2 The block diagram of the latest configuration of SST, exhibiting the main subsystems with their main specifications.

The latest configuration of all basic SST functional subsystems is shown in Fig. 2. The 1.5 m reflector, f/D = 8, has surface and back-structure made of aluminum. It was built using a new “slumping” technique to mold the metal sheet before machining[19] at Steward Observatory, University of Arizona, Tucson, AZ, USA. Final mechanically measured surface accuracy was of 20 µm, r.m.s. (the required overall r.s.s. of all losses should be of the order of 50 µm).

The six radiometers operate simultaneously. They are arranged at the focal plane to produce the beams shown in Fig. 3 (a), where beams 1,2,3 and 4 are at 212 GHz, and beam 5 and 6 at 405 GHz. The beams 2,3 and 4 are partially overlapping at the 3 dB level, to allow the comparison of antenna temperatures during solar bursts in order to determine their centroid of emission[20]. The radiometers were custom made by Radiometer-Physics, Meckenheim, Germany. They were upgraded in 2006, exhibiting substantial improvement in bandwidth, noise and performance. Fig. 3 (b) shows the 405 GHz corrugated horns, with 20λ opening for optimum tapering, mounted on the mixer and LO blocks of radiometers 5 and 6.



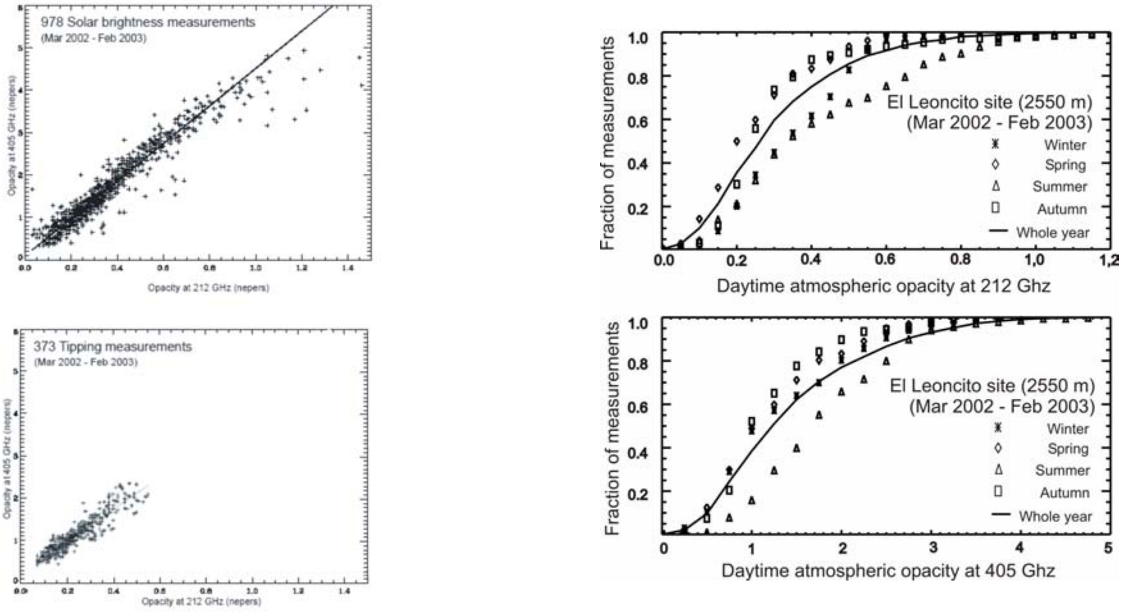
(a) (b)

Fig. 3 (a) The SST six beams projected in the solar disk. (b) The complete 405 GHz radiometers 5 and 6 assembly.

The box containing the receivers is placed under the antenna back-structure, which is fixed on a precision alt azimuth positioner driven by a controller, capable of axis encoder readings with accuracy of 1.8”, built by Orbit Technology Group Ltd., Netanya, Israel.

2.2 Performance

The atmospheric transmission at the two sub-THz frequencies deserves permanent attention. Transmission measurements are regularly performed at least three times per day using the “tipping” method: SST scans the sky in elevation and the best optical depth is fitted to the data.. Solar disk brightness has been determined at low elevation angles for days with small attenuation, to derive the opacity relationship that can be extrapolated for days with large attenuation when the “tipping” method cannot be used at 405 GHz[21]. The sub-THz sky transmission results for El Leoncito for one year are shown in Fig. 4.



(a) (b)

Fig. 4 (a) Atmospheric opacity at 212 and 405 GHz, in nepers, derived from the solar disk brightness temperature (top) and from “tipping” (bottom). (b) One year distribution of atmospheric opacity at El Leoncito for the two SST frequencies[21].

The antenna beam-shapes were determined at 405 GHz using a beacon transmitter located at the far field with respect to the SST, or from deconvolution of radial solar disk scans at the two frequencies[22]. Figure 5 shows the beacon location and the 405 GHz beam pattern obtained after the main SST reflector surface was repaired.

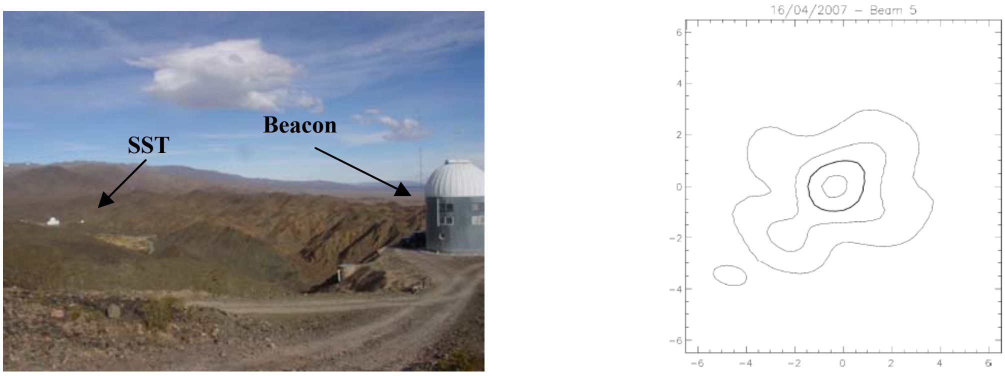


Fig. 5 The 405 GHz beacon location with respect to SST (left) and the 405 GHz antenna pattern obtained (right)

Antenna efficiency measurements are made using Jupiter and Venus (adopting brightness temperatures of 170 K and 270 K, respectively). The best results were obtained after the second phase of the reflector repair, in 2007, providing 20% at 405 GHz and 35% at 212 GHz. These results are close to the theoretical expected prediction.

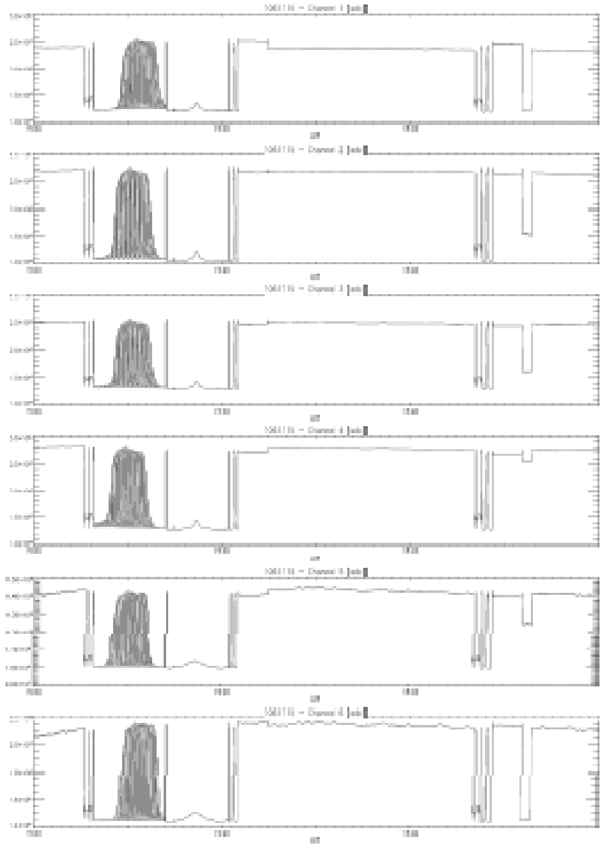


Fig. 6 SST control plots for the 6 radiometers, 1-4 (212 GHz) from the top, 5-6 (405 GHz) at the bottom.

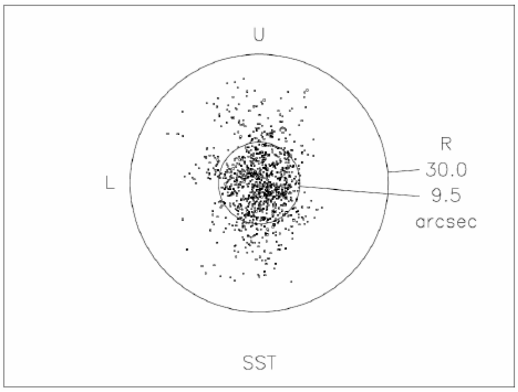


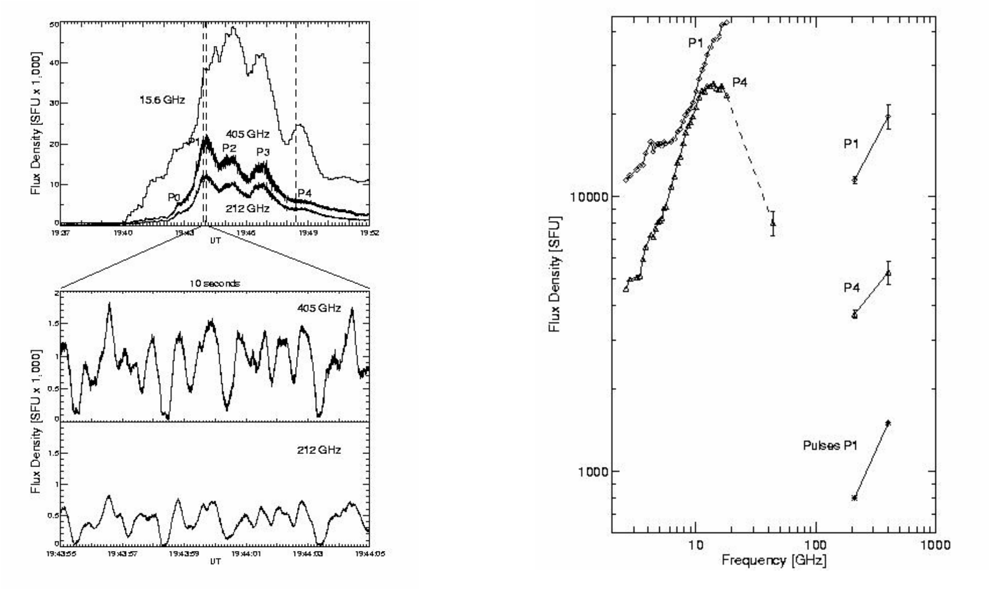
Fig.7 Scatter diagram of SST pointing errors distribution showing absolute r.m.s. pointing accuracy of 10 arseconds [23].

We show in Fig. 6 a sample for typical two hours plot displaying, from top to bottom, the total power outputs of channels 1-6, for the corresponding radiometers and beams shown in Fig. 3(a). The automatic routine produces solar scans for mapping purposes, followed by a sky tipping in elevation, tracking the solar center for 4 minutes, then moving to the selected active region. Temperature calibrations are seen later, with the ambient and hot load levels. The radiometers system temperatures are 2260 K (1), 1680 K (2), 3340 K (3), 2110 K (4), 4260 K (5) and 3780 K (6). Data are stored with time resolution of 5 and 40 milliseconds. With 8.5 GHz DSB width we get the corresponding 3 sigma antenna temperature detection limits on 5 ms data of about 0.4 K for radiometers 1-4, and of about 0.6 K for radiometers 5 and 6. For sources small compared to the respective antenna beams, they correspond to flux detection sensitivity of about 2 and 5 10^{-23} $Wm^{-2}Hz^{-1}$ (or 0.2 and 0.5 solar flux units) at 212 and 405 GHz, respectively.

The tracking and pointing accuracies were derived from models based on the solar disk central positions for a large number of maps carefully corrected for atmospheric transmission and refraction. The T-Point Software has been used to optimize the SST pointing, exhibiting absolute accuracy of 10" r.m.s.[23], shown in Fig. 7.

2.3 Results

New aspects of solar activity have been found at the SST two sub-THz frequencies. Although their presentation is beyond the scope of this paper, it is relevant to mention the detection of burst superimposed subsecond pulsations, with repetition rates time profiles well correlated to fluxes, as well to hard X- and γ-rays time profiles[24-27]; the submm-wave pulsations onset association to the launch time of Coronal Mass Ejections[28]; the excess brightness of quiescent active centers for the higher SST frequency[29]; and the discovery of a new burst spectral component extending into THz frequencies spectrally separated from the well known microwave spectra[30-32] (see example in Fig. 8). These results are bringing challenging questions for their interpretation.



(a) (b)

Fig. 8 The 4 November 2003 solar burst time profiles in (a) at 405, 212 and 15.6 GHz (from OVSA), and 10 seconds zoom showing the rapid superimposed pulsations. (b) The THz spectral component separated from the OVSA microwave spectra[30].

3. THE 30 THZ CONTINUUM GROUND-BASED TELESCOPES

The first SST results brought significant new insights on the radiation mechanisms involved, signalizing the need of measurements at still higher frequencies. New ground-based mid-IR solar telescopes were built, operating in the 7-15 μm band (30 THz), where the terrestrial atmosphere present good transmission.

3.1 The mid-IR telescopes

Two optical setups were developed. One is shown in Fig. 9, installed at El Leoncito[17]. The sun is tracked by a two flat mirror Jensch-Zeiss coelostat (A) that sends the radiation to the optical setup consisting in 11 cm diameter Cassegrain aperture (B), subreflector (C), a flat mirror (S) and a concave mirror (D) to produce a parallel beam lo allow afocal aligment feeding the mid-IR camera (F). We used a camera with 240 x 320 pixel room temperature microbolometer array, with germanium optics, preceded by a thick heat absorber germanium disk (E). High cadence observations of the full solar disk are performed, with data digitally stored.

The other telescope is shown in Fig. 10 (left)[18]. It uses a 15 cm diameter parabolic reflector (A), flat mirrors (B,C) directing the beam into a 3x4 diaphragm opening in an aluminum plate (D) acting as a heat dissipater. The Ge lens (E) is adjusted to produce the solar image at the room temperature focal array.

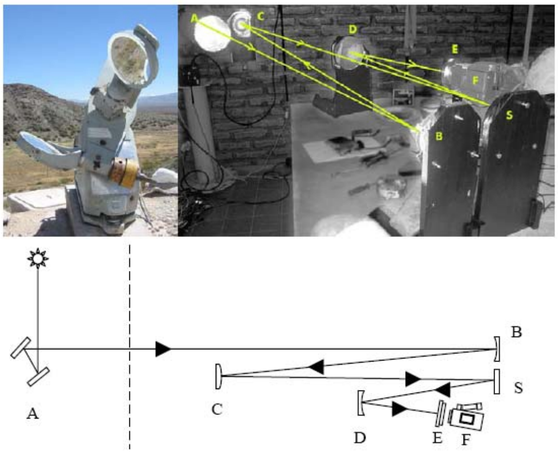
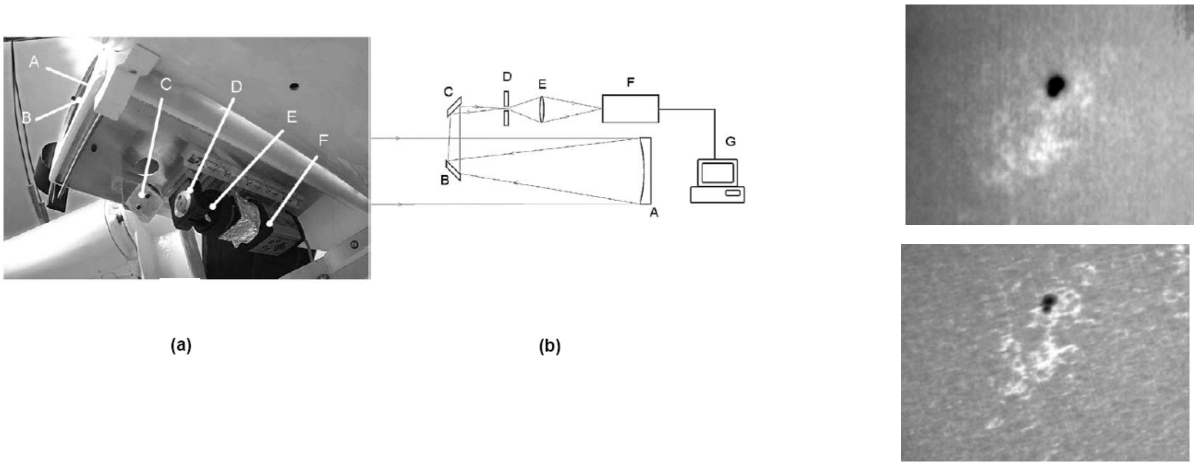


Fig. 9 mid-IR 10 cm solar telescope setup at El Leoncito.



(a)

(b)

Fig. 10 – (a) and (b) mid-IR 15 cm solar telescope setup at "Bernard Lyot" Solar Observatory, Campinas, SP, Brazil. The two panels in the right shows in the top the 30 THz plage (for AR 904, on September 11, 2006) compared to CaII K1v Meudon plage (bottom)[18].

Fig 10 (a) and (b) shows the use of a concept similar to the Dutch Open Telescope to prevent overheating of the IR camera optics and focal plane array. Both mid-IR solar telescopes are able to perform high cadence observations (up to 30 frames/s).

3.2 Results

First results obtained with the mid-IR indicate new extended areas for research, using small apertures, on relatively weak levels of solar activity. Their description is also beyond the scope of this paper. To illustrate briefly, it was found easy to identify bright "plages" always associated to sunspot groups[17,18]. One example is shown in Fig. 10, upper right panel, compared to a Ca plage, bottom.

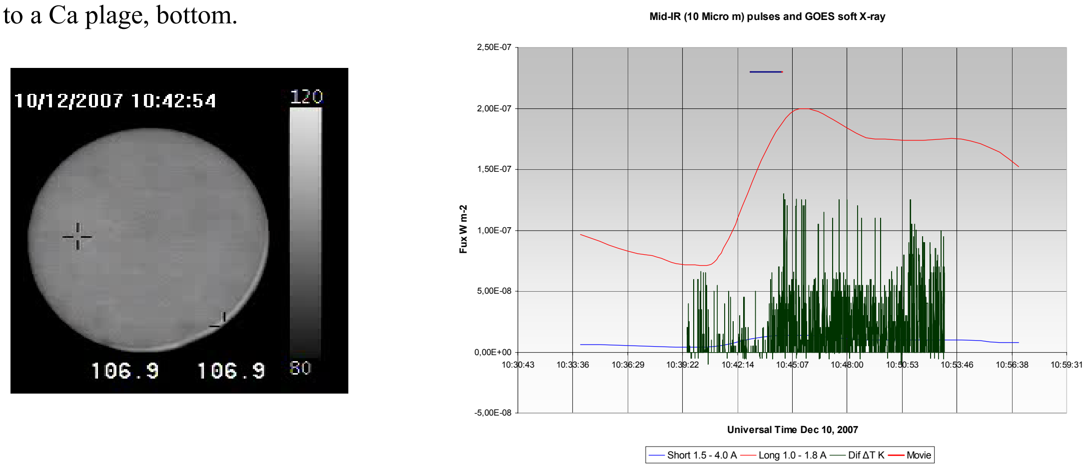


Fig. 11 30 THz solar burst producing rapid flashes observed on December 10, 2007. Temperature differences were derived from the full Sun camera searching "cross" compared to the reference (left), plotted together with GOES soft X-ray B2.0 burst (right).

The first mid-IR (30 THz) solar bursts were obtained[17]. Recent burst observation is shown in Fig. 11, obtained with 5 frame/s cadence. The optical setup produced a solar disk with apparent size of 11^0 (i.e. 22 times larger than the actual diameter), and temperature of 106.9 C (or 379.9 K). Assuming the disk brightness of 5000 K at 30 THz[34], there was a "dilution" by a factor of 13. As a small soft X-ray burst, GOES class B2.0 occur, rapid mid-IR flashes are observed, with time scales ranging from a fraction to few seconds. The system sensitivity was of 0.2 K r.m.s. Maximum flare flashes temperatures at the input of the system were of about 4 K, corresponding roughly to 70 solar flux units (1 SFU = 10^{-22} $Wm^{-2}Hz^{-1}$).

4. NEW DEVELOPMENTS

Current developments are directed to implement ground-based measurements at near and mid-IR bands centered at 1.5 and 5 μm using small aperture telescopes, and at 670 and 850 GHz using bolometric photometer arrangement at the SST primary focus. Space experiments are being developed to observe solar activity at THz frequencies, using bolometer photometers: the DESIR on board of SMESE France-China satellite[35], and SIRA at a stratospheric balloon platform[36].

Acknowledgements

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