Space and Ground-Based New Tools for THz Solar Flare Observations

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***Abstract*—Recent sub-THz and 30 THz observations revealed an unexpected new spectral component, with fluxes increasing towards THz frequencies, simultaneously with the well known component peaking at microwaves, bringing challenging constraints for interpretation. The knowledge of the complete THz flare spectrum is the essential requirement for understanding the origin of this radiation. We present the concept, fabrication and performance of telescope photometric systems to observe solar flares at 3 and 7 THz from above the atmosphere, named SOLAR-T, and at 0.85 and 1.4 THz from the ground at a high altitude site, named HATS. The innovative optical setup allows observations of the full solar disk with high sensitivity to detect small burst transients (tens of solar flux units) with time resolution of less than one second. The SOLAR-T space experiment uses two Golay cell detectors at the focus of 7.6 cm Cassegrain telescopes. The incoming radiation undergoes low-pass filters made of rough surface primary mirrors and membranes, 3 and 7 THz band-pass filters, and choppers. The system has been integrated to data acquisition and telemetry modules for this application. Tests comprised the whole system performance, on ambient and low pressure and temperature conditions. SOLAR-T is being integrated to U.C. Berkeley gamma-ray GRIPS experiment to be flown on a long duration stratospheric balloon mission over Antarctica. The HATS telescope utilizes the same principles, with a 46 cm rough mirror Newtonian telescope, a Golay cell sensor preceded by low pass filter, and a double window chopper, each one with band pass filters at 0.87 and 1.4 THz. HATS now undergoes operational tests in Brazil, and is planned for operations in 2015 at a site to be selected in the Andes Cordillera, above 5000 m altitude.**

I. GHz, Sub-THz and THz Flare Observations

A number of solar bursts observed at GHz, sub-THz and 30 THz frequencies indicate an emission spectral component at this range [1-4], distinct from the well known microwaves emission that maximizes at few to tens GHz. These results raise serious interpretation problems to explain both the sub-THz and the concurrent microwave component [5,6] (Figs. 1 and 2). The physical nature of the THz emission remains mysterious.

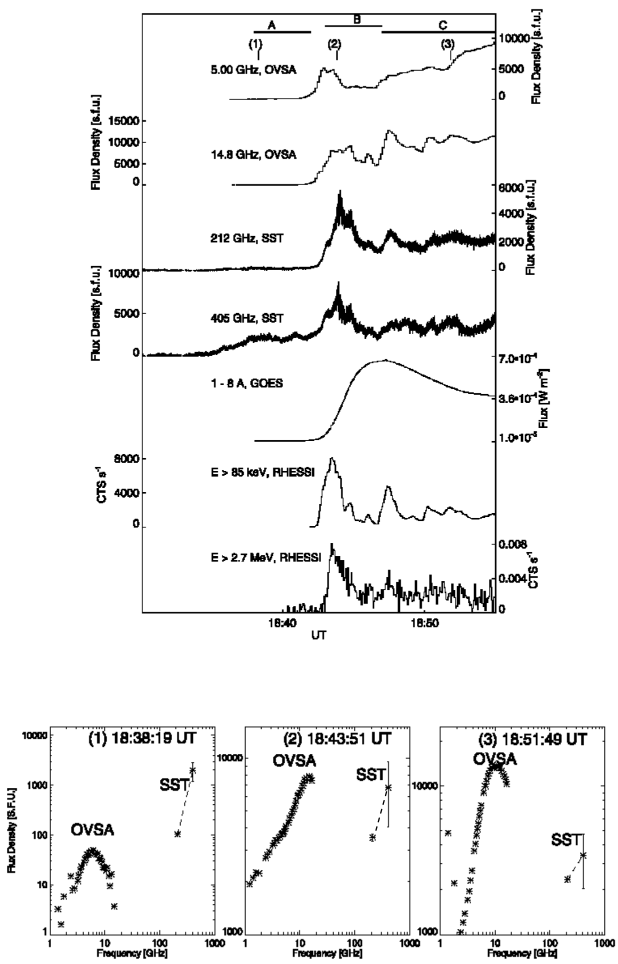

Fig. 1 - Solar burst of December 6, 2006 with time profiles in the upper panel, from top to bottom, at GHz (OVSA) and sub-THz (SST) frequencies, GOES soft X-rays and RHESSI soft and hard X-rays. In lower panel, the two GHz and sub-THz spectral components at different phases of the burst (after [3]).

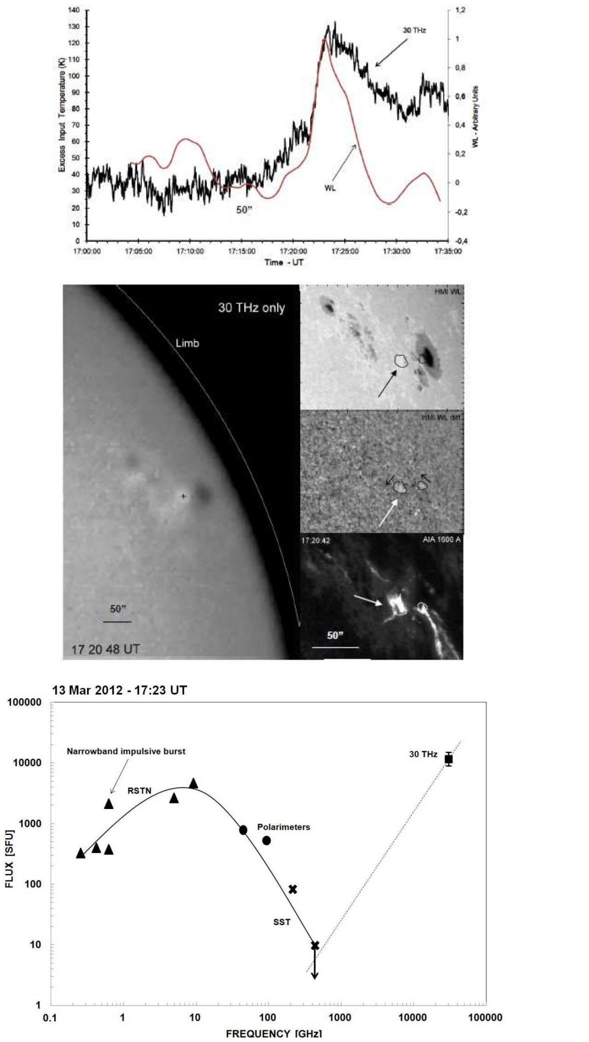

Fig. 2 - The March 13, 2012 solar burst was observed at a wide range of frequencies, from MHz, GHz (RSTN and solar mm-w polarimeters), sub-THz (SST), 30 THz (at El Leoncito), visible, UV (SDO), GOES soft X-rays, RHESSI soft and hard X-rays and FERMI hard-X rays. Time profiles at the top are for the impulsive phase at white-light and 30 THz. Corresponding images at the mid panel . The lower panel shows the suggested double spectral components, one in the GHz to sub-THz range, another extending to 30 THz (after [4]).

New insights on the physical processes involved need the complete THz spectral description. This requires observations with detectors outside the terrestrial atmosphere. Experiments SIRE [7] and DESIR [8] have been proposed to observe solar flares in the THz range from space. Solar activity may also be observed through few atmospheric THz transmission "windows" at exceptionally good high altitude ground based locations [9].

II. The 3 and 7 THz SOLAR-T Space Experiment

The THz solar photometers system, named SOLAR-T, is the result of more than ten years of research on detecting devices, development and characterization of materials, filters and systems. Several prototypes have been built and tested for their performances [10-11]. The definitive system to be flown on stratospheric balloon, has been built at Tydex LCC, Saint Petersburg, Russia, integrated to data acquisition and telemetry modules developed for this application, and tested at Propertech Ltda. and Neuron Ltda. in Brazil [12]. It utilizes two modern versions of Golay cell detectors [13,14] preceded by low- pass filters made of rough surface primary mirrors [15,16] and membranes [17] to suppress visible and near IR radiation, 3 and 7 THz metal mesh band-pass filters [18,19], and choppers. One innovative photon concentrator [14, 20] combines the formation of a full solar disk image at the focal plane with size smaller than the size of the surface of the detecting element with the primary aperture. It becomes possible to use apertures large enough to detect small solar bursts without the need to point at a particular location on the solar disk with narrow beams, a limitation found in usual coherent optical configurations. The SOLAR-T will be flown together with U.C. Berkeley, SSL, gamma-rays experiment GRIPS [21] on long duration stratospheric balloon mission (one month) over Antarctica, scheduled for the southern summer 2015-2016. Fig. 3 illustrates the SOLAR-T design concept and the complete experiment with the data acquisition and Iridium telemetry modules (the aluminium lateral blocks), being assembled on GRIPS boom.

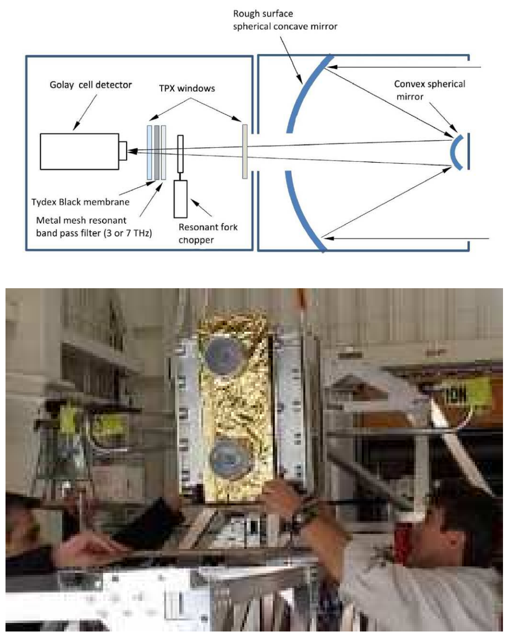

Fig. 3 – The SOLAR-T photometers assembly concept, upper panel, shows the Golay cell detector, preceded by TydexBlack low-pass filter membrane, a resonant metal mesh band-pass filter, and a resonant tuning fork 20 Hz chopper. The 76 mm Cassegrain telescope on the right has a rough surface to further diffuse the visible and near IR radiation. The lower panel shows the complete experiment being adapted to boom of the GRIPS experiment at SSL, U.C. Berkeley.

III. SOLAR-T Tests and Performance

The Golay cells have two relevant characteristic response properties for the observations proposed here: (1) the noise fluctuations is constant and the same for the whole range of input temperatures and (2) the voltage outputs are proportional to the input temperatures. The calibration produced characteristic photometer output response of 4.2 K/mV at 3

THz and 9.8 K/mV at 7 THz. Measured output system stability in response to a hot source input, with data points every 256 ms, smoothed over 11 points, exhibited peak-to-peak fluctuations of about 5 10^{-2} mV, which corresponds to 0.5 K for both THz photometers. Neglecting the air attenuation above the atmosphere, the aperture efficiencies obtained were of 0.2 and 0.15 at 3 and 7 THz, respectively. The three sigma detectable flux densities for $\Delta T \approx 0.5$ K correspond to less than about 150-200 SFU at 3 and 7 THz respectively.

Operational tests performed at SSL, U.C. Berkeley have confirmed SOLAR-T performance. Samples of data acquired with 256 ms time resolution were transmitted from SOLAR-T by the Iridium based Short Data Burst services and received without any data point lost.

IV. THE GROUND-BASED HATS EXPERIMENT

The terrestrial atmosphere present transmission windows at sub-THz and THz frequency bands at high altitude sites for low precipitable water vapour content (PWV) [9,22]. Transmissions better than 50% at 0.67 and 0.85 THz bands and better than 15% at 1.3 and 1.5 THz bands can be attained at 5000m altitude with PWV < 1mm.

A telescope has been designed for photometry of solar flares at 0.87 and 1.4 THz. It utilises the same optical concept of SOLAR-T[12]. A short focal length 46 cm diameter mirror, producing a solar image smaller than the Golay cell detector input cone placed at its Newtonian focus, as shown in Figures 4 and 5. Band-pass metal mesh filters were fabricated with bandwidth of 20% of the central frequencies. They are placed at the separate chopper wheel windows. To account for the 40 ms Golay cell response time constant [23], the input radiation gets into the filter during 50 ms, then blocked along 250 ms for the cell return to the ground level, followed by the next frequency filter and blockage. A set of readings are recorded at the end of each phase. A synchronous detection firmware has been developed for the data acquisition of the two frequency photometric readings. The radiation input at each frequency is measured once every 600 ms.

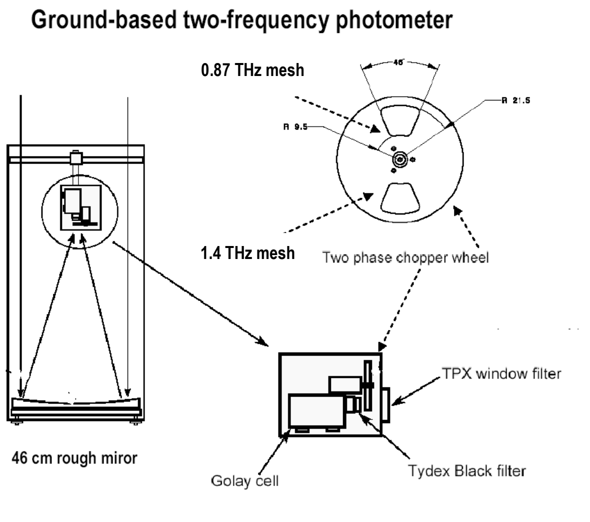

Fig. 4 – Schematic diagram of HATS photometric telescope

Figure 5, left, show the complete HATS assembly. Right panels, top right: the case containing the Golay cell and chopper placed at the Newtonian focus; middle: the chopper wheel exhibiting the windows with metal mesh band-pass filters, one at 0.87 THz and another at 1.4 THz; lower panel shows the 46 cm rough surface mirror.

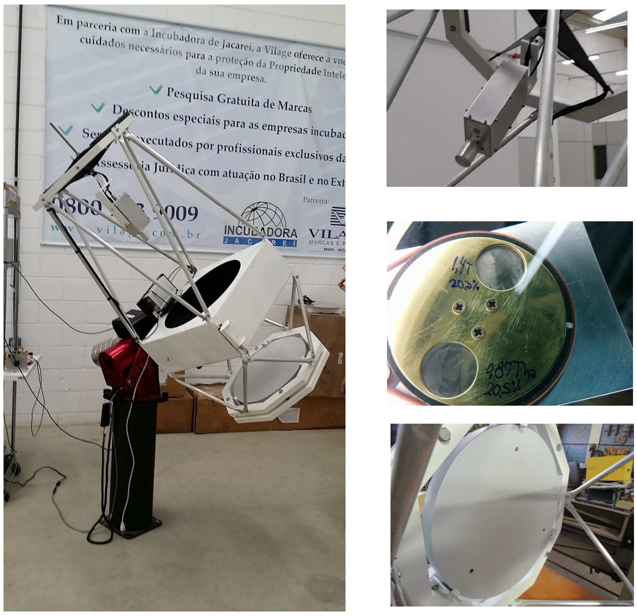

Fig. 5 – Left: the complete HATS system assembly undergoing operational tests. Right, top: the Golay cell and double window wheel front-end case at the Newtonian focus; middle: chopper wheel with 0.87 and 1.4 THz band-pass filter windows; bottom: the 46 cm rough surface reflector with three small polished mirrors for alignment adjustments.

The HATS system operational tests performed at Propertech facilities, Jacareí, SP. Brazil have demonstrated appropriate performance. The telescope was placed at a robotic Paramount polar mount [24]. The fine tracking corrections will be supported by a Hutech-Hinode sun-guider [25] installed on the telescope body, interfaced to the mount tracking software.

Preliminary measurements have shown that the system can detect three sigma excess temperature excess smaller than 0.5 K at each frequency. The three sigma solar burst detection sensitivity can be predicted for the aperture effective area taking into account all transmission factors at the two frequencies: (1) instrumental (a) physical blockage, 0.85; (b) low-pass filter rough mirror reflection, 0.90; (c) two 2 mm thick TPX windows 0.76 at 0.87 THz and 0.72 at 1.4 THz; (d) Tydex low-pass filter LPF23.1 membrane, 0.7 at 0.85 THz and 0.5 at 1.4 THz; and (e) band-pass filter, 0.9. Net transmissions due to instrumental losses: 0.37 and 0.25 at 0.85 and 1.4 THz respectively. (2) Atmospheric transmission of about 0.5 at 0.87 THz and 0.15 at 1.4 THz, in the zenith direction, might be assumed for a high altitude location exhibiting precipitable water vapour content < 1 mm [22]. For solar observations at an elevation angle of 45 degrees the net aperture effective areas become 0.023 m^2 at 0.87 THz and 0.003 m^2 at 1.4 THz, respectively. For three sigma $\Delta T < 0.5$ K the predicted minimum detectable flux densities become < 5 SFU at 0.87 THz and of < 40 SFU at 1.4 THz. A new data sampling technique is being added to further improve the HATS response to small THz burst levels.

A site is being selected for definitive installation and operations in 2015. The atmosphere THz transmission conditions described before are attained at Chajnantor, Chile Atacama plateau, at 5000 m altitude, for about 100 days each year [22]. Good transmission conditions are expected at Famatina Mountain, above 5200m altitude, in Argentina La Rioja region.

V. Concluding Remarks

In the course of 2015-2016 it is expected to obtain the unprecedented solar flare spectral coverage at 45, 90, 212, 405 GHz (El Leoncito); 0.87 and 1.4 THz with HATS; 3 and 7 THz from space, and ground-based 30 THz in Argentina and Brazil. These observations, combined with other ground-based radio, visible, space EUV, X- and Gamma rays, will provide an unique extended spectral description of the solar flare emissions which shall bring new clues to understand the still mysterious energy conversion physical processes in the Sun.

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References

[1] P. Kaufmann *et al.* “A new solar burst spectral component emitting only in the terahertz range”, *Astrophys.J.,* vol. 603, pp. L121-L124, 2004.

[2] A.V.R. Silva *et al.,*"Evidence that synchrotron emission from nonthermal electrons produces the increasing submillimeter spectral component in solar flares", *Solar Phys.,* vol. 245, pp. 311- 326, 2007.

[3] P. Kaufmann *et al.,*“Sub-terahetz, microwaves, and high energy emissions during the December 6, 2006 flare at 18:40 UT”, *Solar Phys*., vol. 255, pp. 131-142. 2009.

[4] P. Kaufmann *et al.:* “A bright impulsive solar burst detected at 30 THz”, *Astrophys. J*., vol. 768, 134 (9pp)-. 2013.

[5] G.D. Fleishman, E. Kontar, “Sub-THz Radiation Mechanisms in Solar Flares, *Astrophys. J.,* vol. 709, pp. L127-L132, 2010.

[6] S. Krucker *et al.:* "Solar flares at submillimeter wavelength", *Astronon. Astrophys. Rev*, vol. 21, , article id. #58, 2013.

[7] D. Deming, T. Kostiuk, D. Glenar,“The Solar Infrared Explorer (SIRE): a small Explorer mission for solar physics”, *BAAS*, vol. 23, pp. 1038, 1991.

[8] G. Trottet, L. Klein, G. Molodij, A. Semery, "Far infrered observations of solar flares during the next solar maximum“, 36th COSPAR Scientific Assembly, 13-23 July, Beijing, China, Abstract #1788, 2006.

[9] J. Suen, M. Fang, P. Lubin, “Global distribution of water vapor and cloud cover—sites for high-performance THz applications”, *IEEE Trans. THz Science and Technology*, vol. 4, pp. 86-100, 2014,

[10] P. Kaufmann *et al.,* “SOLAR-T : Terahertz Photometers to Observe Solar flare Emission on Stratospheric Balloon Flights”, *Proc. of SPIE*, vol. 8442, pp. 8442L1-8442L9, 2012,

[11] R. Marcon *et al.,* “Terahertz photometer to observe solar flares in continuum”, *J. Infrared, Millimeter and Terahertz Waves,* vol. 33, pp.192-205, 2012.

[12] P. Kaufmann *et al.,*“ THz photometers for solar flare observations from space”, *Experimental Astronomy*, vol. 37, pp. 579-598 ,2014,

[13] M.J.E. Golay, "The theoretical and practical sensitivity of the pneumatic infra-red detector", *Rev. Sci. Instrum*, vol. 20, pp. 816-820, 1949.

[14] http://www.tydexoptics.com/pdf/Golay_cell.pdf.

[15] T. Kostiuk, D. Deming, "A solar infrared photometer for space flight application". *Infrared Physics*, vol. 32, pp. 225-233, 1991.

[16] M.A Kornberg *et al.,* "Rough mirrors for the THz frequency range", *Proc. MOMAG 2008 – 13th SBMO and 8th CBMAG,* Florianopolis, SC, Brazil, 7-10 September, pp.365-367, 2008.

[17] http://www.tydexoptics.com/pdf/THz_Low_Pass_Filter.pdf

[18] A.M. Melo. *et al*.,"Metal mesh resonant filters for terahertz frequencies". *Applied Optics*, vol. 47, pp. 6064-6069, 2008.

[19] E.C. Bortolocci *et al.,* "THz band-pass resonantmetal mesh filters for a space solar photometry experiment", *VII Workshop on Semiconductors and Micro & Nano Technology - Seminatec*, pp. 77, 2012.

[20] R. Marcon, P. Kaufmann, “Método para maximizar ganho na detecção simultânea de radiaçãode fontes pequenas em campo extenso de visão” Brazil Patent Application, Universidade Estadual de Campinas and Instituto Presbiteriano Mackenzie, Patent filed March 30, 2011.

[21] N. Duncan *et al.,* “Detector and imaging systems for the gamma ray imager/polarimeter for solar flares (GRIPS) instrument”, *SPIE Proc.,* vol. 8862, pp. 8862OW-1-8862OW-11, 2013.

[22] S. Matsushita, *et al.,* “FTS measurements of sub-milliemeter atmospheric opacity at Pampa la Bola II: Supra-Terehertz windowsn and model fittings”, *PASP*, vol. 51, 603-624, 1999.

[23] A.K. Kaveev, E.G. Kaveeva, and E.A. Adaev, “Pulse shape measurements using Golay detector”, *J.Infrared Milli Terahz Waves*, vol. 33, pp. 306-318, 2012

[24] http://www.bisque.com/sc/pages/Paramount-ME.aspx.

[25] http://www.sciencecenter.net/hutech/Hinode-sg/index.htm