ELSEVIER

Infrared Physics & Technology 43 (2002) 33–38

INFRARED PHYSICS & TECHNOLOGY

www.elsevier.com/locate/infrared

Cosmic-ray spikes localization and correction in FT spectrometer data

G. Bianchini *, U. Cortesi, L. Palchetti, E. Pascale

Istituto di Ricerche sulle Onde Elettromagnetiche, CNR-IROE "Nello Carrara", Gruppo Stratosfera, Via Leone Pancaldo 3/37, 50127 Florence, Italy

Received 28 March 2001

Abstract

Bolometric infrared detectors are the best choice for sensitive radiometric measurements in the far infrared and millimeter wave spectral region. Nevertheless, these devices, when operating on board high-altitude balloons or aircrafts, are also affected by cosmic-ray (CR) crossing of the detector elements. Each of these events degrades the radiometric data on a time scale that depends on the detector's characteristics. In this paper, we describe an automatic procedure based on discrete wavelet transform that can be used to localize CR events in the data flow, even when they occur in correspondence with high signal levels, and to optimally remove them for minimum data loss. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Cosmic rays; Bolometers; Fourier transform spectroscopy

1. Introduction

The effect of cosmic-ray (CR) events in the output of high-sensitivity bolometric detectors is a well-known problem [1,2] which may seriously degrade the quality of acquired data in a wide range of experimental systems. This problem becomes a critical concern particularly in the case of experiments working on high-altitude platforms, such as satellites, stratospheric balloons and aircrafts. This is because the CR background tends to increase with altitude, due to weakening of the shielding effect of the Earth's magnetosphere.

A correction procedure that permits detecting single CR events and correcting their effect with minimum data loss can be an important part in the data analysis process of experiments using bolometric detectors. This is the case of those experiments operating at high altitudes such as atmospheric far-infrared spectrometers on balloon or aircraft platforms [3,4] and balloon-borne or space-borne infrared astronomy experiments [5,6]. Furthermore, the problem is particularly serious in the case of Fourier transform spectroscopy, which requires a continuous data acquisition.

In this paper, we will show a method that makes it possible to locate and correct single CR events ("spikes") in a generic data stream obtained from the output of a bolometric detector, independently from the experimental setup.

Making use of a good knowledge of the mathematical forms of the signal transient due to a CR

* Corresponding author. Tel.: +39-55-4378540; fax: +39-55-432694.

E-mail address: gb@iroe.fi.cnr.it (G. Bianchini).

1350-4495/02/$ - see front matter
PII: S1350-4495(01)00122-0

event, described next in this paper, it is possible not only to locate the spike exactly, but also to measure its amplitude without its being affected by either the signal or the noise on which the spike is superimposed. The obtained parameters, spike position and amplitude, are then used as starting values for a fitting procedure that makes it possible to subtract the effect of the spike from the data stream reducing its residual effect well below the noise level.

The effectiveness of the proposed correction method is tested by applying it to the data acquired from the spectroscopy of the atmosphere using far infrared emission/airborne (SAFIRE/A) Fourier transform spectrometer.

2. The SAFIRE/A spectrometer

The data conditioning system described in this paper was developed as a part of the data analysis system for the SAFIRE/A instrument [4].

SAFIRE/A is a Fourier transform spectrometer operating on board the high-altitude aircraft M-55 Geophysica. The spectrometer operates in a limb-scanning observation mode, acquiring atmospheric emission spectra corresponding to different observation directions. Vertical distribution profiles of the concentration of atmospheric constituents are then retrieved from the calibrated atmospheric spectra by means of a data inversion process (Ref. [7] and references therein).

The instrument is capable of operating on a frequency interval extending from 10 to 250 cm^{-1}, depending on the type of detector used. The 10–50 cm^{-1} frequency range is covered by liquid ^3He cooled bolometric detectors. From data acquired in various measurement campaigns, these detectors have been shown to be very sensitive to CR events.

Fig. 1 shows a typical interferogram acquired with SAFIRE/A during a flight performed in the antarctic region, at an altitude of about 20 km. Two CR events are clearly visible, not only well

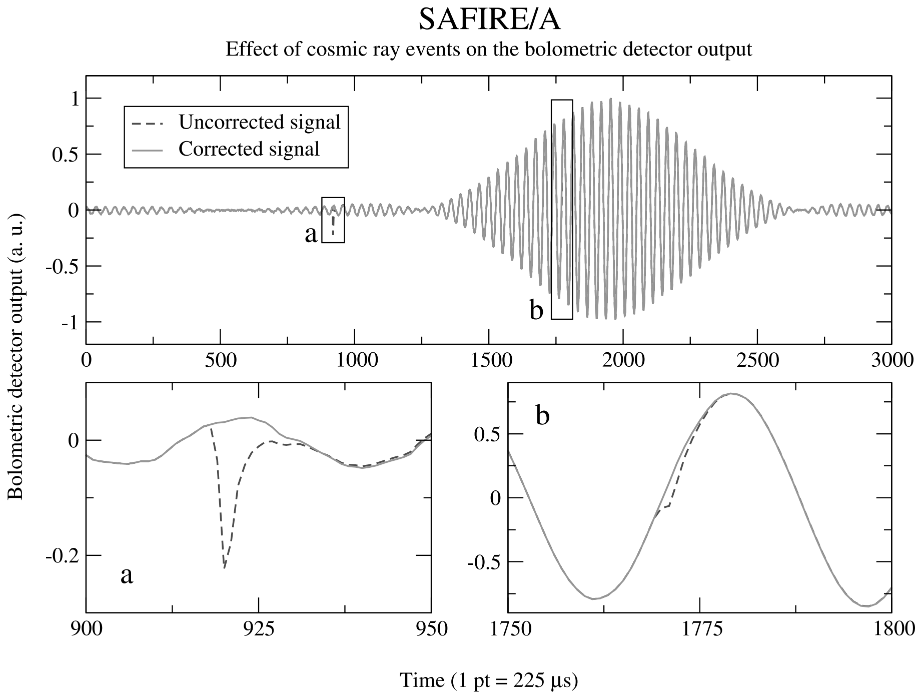

Fig. 1. A typical interferogram acquired with the SAFIRE/A bolometric detector during a flight performed at an altitude of about 20 Km in the antarctic region. Two CR spikes with an amplitude comparable with the interferometric signal are clearly visible in the acquisition. The shape of the spikes is shown in the insets.

above noise level, but also with an amplitude that is comparable to the interferometric signal peak amplitude. Most importantly, the CR events can occur at any time during the data stream. Due to the wide signal dynamic typical of FTS instruments, this can give rise to cases where the spike is easily detectable because its amplitude is greater than the signal level, but also to cases in which the spike is hidden by the signal itself (Fig. 1, inset b). As we will see in Section 4, this variability in the possible cases makes the detection of CR events not an easy task.

When atmospheric emission spectra are obtained from Fourier-transforming SAFIRE/A raw data, any CR spike introduces a spurious oscillation in the spectrum, as shown in Fig. 2. This can seriously alter instrument accuracy in detecting atmospheric components characterized by weak spectral lines.

3. Mathematical formula of the signal transient

A typical composite bolometer, as shown in Fig. 3, is made by a small semiconductor thermistor and an absorber disk [8]. Let G_1 be the thermal conductance between these two elements. The full detector is then connected to a thermal bath at a temperature T_0 through a link of conductance $G_0 \ll G_1$. A bias current in the thermistor generates a readable output voltage dependent on the temperature of the detector by means of the thermistor resistance. This output voltage is then filtered by the electronic response, digitized and acquired. When a charged particle (CR) hits the absorber, a certain amount of energy is transferred to the detector, which raises its temperature. Such an event has a characteristic time that is much shorter than the detector time constant. To optimally subtract a spike from the signal, we need to

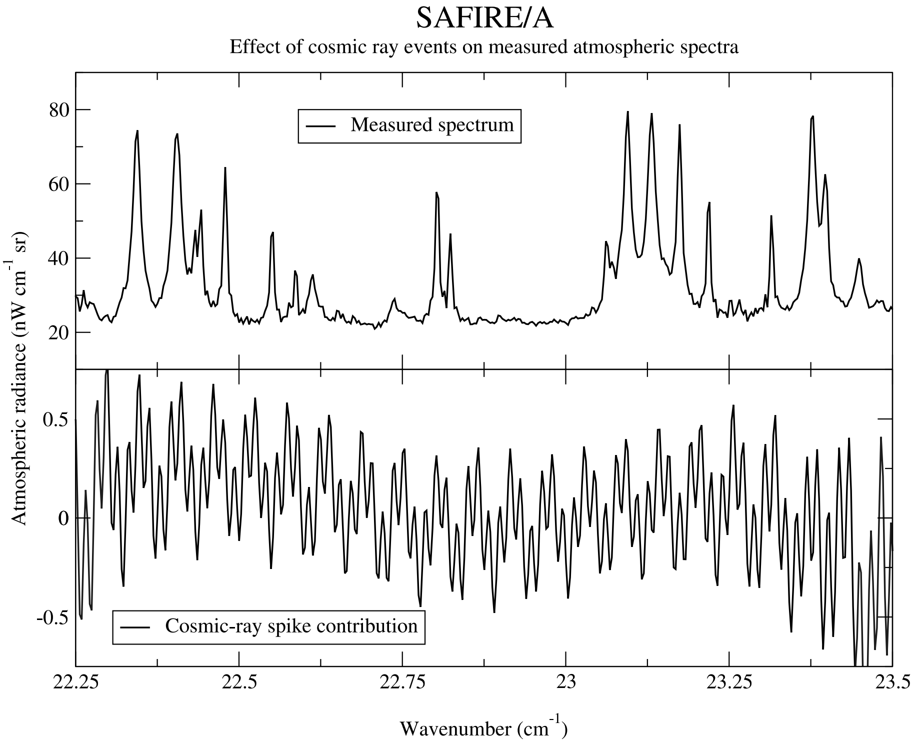

Fig. 2. Effect of CR spikes on the atmospheric emission spectrum obtained from the interferogram of Fig. 1. The spurious contribution due to the presence of spikes in the interferogram data stream is shown in the lower plot, that is obtained subtracting from the uncorrected spectrum, the spectrum with the CR correction applied.

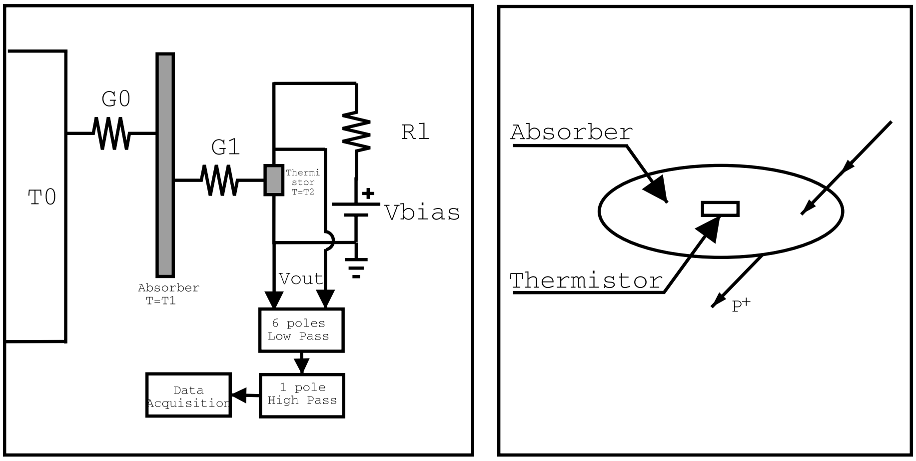

Fig. 3. Diagram of the thermal and electrical circuitry of a typical composite bolometer (left panel). The right panel shows a composite bolometer hit by a charged particle.

characterize the bolometer's response to a CR event. Under static conditions, the equations of the bolometer described in Fig. 3 can be written as

$$Q = (T_1 - T_0)G_0 + (T_1 - T_2)G_1,$$
$$P = (T_2 - T_1)G_1,$$

where T_1 is the absorber disk temperature, T_2 is the thermistor temperature, Q is the background power on the detector, and P is the electric power dissipated in the thermistor. A signal $\Delta Q \ll Q$ on the detector leads us to the equation of the bolometer expanding the static equations up to the first order [8,9]:

$$\Delta Q = \Delta T_1\left(G_0 + G_1 + (T_1 - T_0)\frac{\partial G_0}{\partial T_1} + (T_1 - T_2)\frac{\partial G_1}{\partial T_1}\right) - \Delta T_2\left(G_1 - (T_1 - T_0)\frac{\partial G_0}{\partial T_2} - (T_1 - T_2)\frac{\partial G_1}{\partial T_2}\right) + C_1\frac{\mathrm{d}\Delta T_1}{\mathrm{d}t},$$

$$\Delta P = \Delta T_1\left((T_2 - T_1)\frac{\partial G_1}{\partial T_1} - G_1\right) + \Delta T_2\left((T_2 - T_1)\frac{\partial G_1}{\partial T_2} + G_1\right) + C_2\frac{\mathrm{d}\Delta T_2}{\mathrm{d}t},$$

where C_1 and C_2 are the thermal capacity of the absorber and the thermistor, respectively. Since $\Delta P \propto \Delta T_2$, by rearranging the terms in the above equation:

$$\frac{\mathrm{d}\Delta T_1}{\mathrm{d}t} + \alpha\Delta T_1 + \beta\Delta T_2 = \frac{\Delta Q}{C_1},$$
$$\frac{\mathrm{d}\Delta T_2}{\mathrm{d}t} + \eta\Delta T_1 + \psi\Delta T_2 = 0.$$

Solving this system of equations in the case of a CR event where $\Delta Q = \text{const.}$ for $0 < t < \Delta t$, zero elsewhere, and Δt is much shorter than the characteristic time of the detector, leads us to the response of the thermistor under a CR event:

$$\begin{aligned} &\Delta T_2 \propto (1+\epsilon) - (\mathrm{e}^{-t/\tau_0} + \epsilon\mathrm{e}^{-t/\tau_1}) \quad && 0 < t < \Delta t, \\ &\Delta T_2 \propto \mathrm{e}^{-t/\tau_0} + \epsilon\mathrm{e}^{-t/\tau_1} && t > \Delta t. \end{aligned} \tag{1}$$

This function must be convoluted with the response of the signal acquisition system in order to fit it on a spike in the data stream and optimally subtract the event from the data flow. In fact, the electronics introduces high and low frequency cuts that must be considered for an accurate description of the spike functional form.

4. Spike detection

As we have seen in Section 2, CR events may happen in the tails of the interferogram, where the signal amplitude is quite small. In that case the spike is easily detectable by means of a very simple algorithm that checks for any sharp signal greater than the noise. But for all practical purposes, a spike may occur also inside the main lobe, where its recognition is difficult even to the eye, as shown in Fig. 1. Taking advance from the fact that a spike, like a delta function, spreads all over the frequencies while the signal is limited to a narrow band, we adopt a multiresolution analysis [10] based on a discrete wavelet decomposition (DWT) and using a Daubechies 20-coefficient wavelet (Refs. [11,12] and references therein). This approach lets us to separate the frequency content of the data without losing the information in the time domain. Fig. 4 shows the DWT of the interferogram from Fig. 1. The signal fills a region of the time–scale plane that is broad in the time domain and localized in the scale domain, while the CR spikes are localized in time and spread all over the scales.

The bottom panel of Fig. 4 plots the signal content of the smallest scale in which the CR spikes are the only visible features. A search algorithm is then built to find sharp signals on the smallest DWT scale. The time location of an event is then known with a precision of plus or minus one data point in the original stream. This is because of the Heisenberg principle: at scale 1, the information knowledge on frequencies is twice that of the original stream, and so the uncertainty regarding the times is twice as great as before. From the signal content at scale 1 we also estimate the amplitude of the original event: the amplitude of the event at scale 1 is related, through a proportional constant, to its amplitude in the original data stream. Time position and amplitude are then used as initial guess in the fitting procedure described below.

5. Spike correction

CR events are removed from the SAFIRE/A data stream subtracting the fitted theoretical

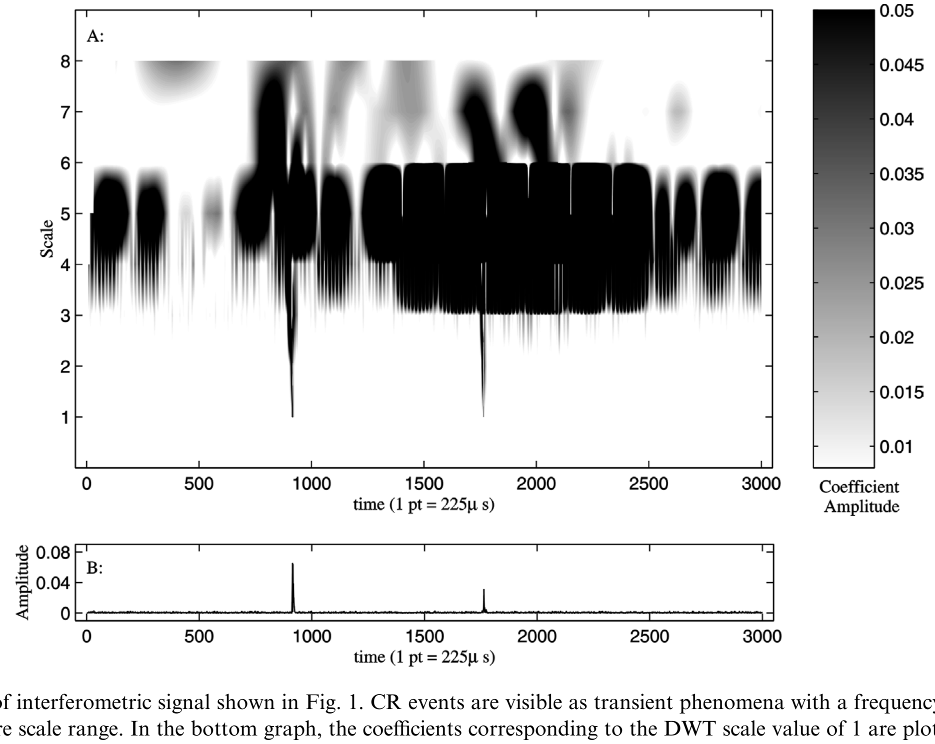

Fig. 4. DWT of interferometric signal shown in Fig. 1. CR events are visible as transient phenomena with a frequency spectrum that covers the entire scale range. In the bottom graph, the coefficients corresponding to the DWT scale value of 1 are plotted, evidencing the transient CR events over the interferometric signal.

expression described in Section 3 convoluted with the measured response function of the instrumental electronics. The bolometric time constant are measured only once in this process and the fitting procedure is only required for fine tuning the amplitude and time position of the spike obtained from the analysis of the lower scale DWT coefficients.

For a good quality fit, we need to add a base line, due to the interferometric signal, to the theoretical function in the fit. This can easily be done since, as can be noted in Fig. 4, the interferometric signal contains significant power only in a well-delimited frequency range and, mainly, does not contain high frequency components. Consequently, the interferometric signal can be simply modeled in the short time interval in which the CR event takes place. We use a linear predictive algorithm [12] to calculate this base line from few points before the CR occurrence. This method works quite well thanks to the periodic characteristics of the interferometric signal.

After the fitting, the theoretical expression is then subtracted (without base line) from the original data stream and the results are shown in Fig. 1.

It should be noted that the procedure described is fairly insensitive to the amplitude of the useful interferometric signal that is superimposed on the unwanted perturbation due to the spike. This is of fundamental importance in the case of near real time data processing, in which all correction procedures must be operated automatically, without supervision, and then must be as insensitive as possible to variations in all operating parameters.

6. Conclusions

We described the application of multiresolution analysis to the detection and correction of transient phenomena due to the occurrence of CR interaction in bolometric detectors. The method described exploits the advantages of the DWT to obtain high sensitivity in the discrimination between the spurious spikes due to CR events and the useful part of the detector signal. This makes it possible to detect and correct also spikes that are much smaller than the signal.

The capability to detect spurious effects with an amplitude smaller than the signal is particularly useful in the case of Fourier transform spectroscopy, where wide signal dynamics are present.

Due to this peculiarity, this method can easily be applied even in the case of near real time data analysis, thus providing a powerful tool for environmental physics and all the other fields of application that require unsupervised processing of huge amounts of data.

References

[1] I.G. Nolt, J.V. Radostitz, M. Carlotti, B. Carli, F. Mencaraglia, A. Bonetti, Cosmic-ray backgrounds in infrared bolometers, Int. J. Infrared Millimeter Waves 6 (1985) 707.

[2] M. Lanfranchi, B. Carli, A. Gignoli, C. Lee, M. Ridolfi, Cosmic-ray flux detected by an IR bolometer operated on board of a stratospheric aircraft, Infrared Phys. Technol. 40 (1999) 379–386.

[3] B. Carli, F. Mencaraglia, A. Bonetti, Submillimeter high-resolution FT spectrometer for atmospheric studies, Appl. Opt. 23 (1984) 2594–2603.

[4] B. Carli, P.A.R. Ade, U. Cortesi, P. Dickinson, M. Epifani, F.C. Gannaway, A. Gignoli, C. Keim, C. Lee, C. Meny, J. Leotin, F. Mencaraglia, A.G. Murray, I.G. Nolt, M. Ridolfi, SAFIRE/A spectroscopy of the atmosphere using far-infrared emission/airborne, J. Atm. Ocean. Technol. 16 (1999) 1313–1328.

[5] P. de Bernardis et al., A flat universe from high-resolution maps of the cosmic microwave background radiation, Nature 404 (2000) 955.

[6] S. Hanany, et al., MAXIMA-1: a measurement of the cosmic microwave background anisotropy on angular scales of $10'$ to $5°$, astro-ph/0005123, 2000.

[7] M. Carlotti, B. Carli, Approach to the design and data analysis of a limb-scanning experiment, Appl. Opt. 33 (1994) 3237–3249.

[8] R.C. Jones, General theory of bolometer performance, J. Opt. Soc. Am. 43 (1953) 1.

[9] J.C. Mather, Electrical self-calibration of nonideal bolometers, Appl. Opt. 23 (1984) 3181–3183.

[10] A. Barreto, et al., Multiresolution characterization of interictal epileptic spikes based on a wavelet transformation, Proceedings of the Fourteenth Southern Biomedical Engineering Conference, 1995, pp. 193–196.

[11] I. Daubechies, The wavelet transform, time–frequency localization and signal analysis, IEEE Trans. Inform. Theory 36 (1990) 961–1005.

[12] W.H. Press, et al., Numerical Recipes in C, second edition, Cambridge University Press, Cambridge, 1996.