INTERCALIBRATION OF THE HARD X-RAY SPECTROMETERS ON THE PVO AND ICE (ISEE-3) SPACECRAFT

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ABSTRACT

The energetic photon spectrometers aboard the ICE (International Cometary Explorer, formerly ISEE-3) and PVO (Pioneer Venus Orbiter) are described briefly and the procedure for their in-flight calibrations is discussed. Successful intercalibration of these two instruments allowed stereoscopic observations of 100 keV—2 MeV photon sources in solar flares and the study of the directivity and height structure of these sources. The impulsive hard X-ray source is found to extend from the chromosphere to the corona, the brightness of the source decreasing rapidly with increase in height above the chromosphere. The analysis so far indicates no systematic directivity for the hard X-ray source. The observations are consistent with energetic electrons accelerated in the corona propagating downwards towards the chromosphere. However, when averaged over the duration of an impulsive hard X-ray flare, the “beaming” of electrons is found to be small in most flares.

INTRODUCTION

Observations of solar hard X-ray bursts by different instruments sometimes appear to give somewhat different results. For example, the variation of the hard X-ray spectrum during the impulsive phase, as measured by the OGO-5 hard X-ray spectrometer, was found to be “soft-hard-soft,” the hardest spectrum being emitted at the flux maximum of the impulsive burst /1/. However, the OSO-5 measurements indicated that the spectrum did not vary appreciably during the impulsive phase /2/. Apparent discrepancies between different measurements are sometimes caused by differences in the details and response characteristics of the detectors and can be identified and corrected by appropriate calibration and analysis /3/. Calibration of individual instruments and intercalibration of two or more instruments attain vital importance when the interpretation of the observations depends critically on the absolute fluxes measured by the instruments as in the case of the measurements of the directivity or the height structure of the hard X-ray photon source through “stereoscopic” observations of a flare with two or more spacecraft separated in heliocentric longitude /4,5,6,7/.

We present below the general considerations for calibration of solar hard X-ray spectrometers on spacecraft followed by a brief description of the basic characteristics of the hard X-ray and low energy gamma-ray spectrometers aboard the ICE/ISEE-3 (International Cometary Explorer, formerly ISEE-3) and PVO (Pioneer Venus Orbiter) spacecraft. As an additional check on the calibration, the photon spectra observed by the ICE and PVO instruments in one solar flare are compared with the spectra observed simultaneously by the HXRBS (Hard X-Ray Burst Spectrometer) and GRS (Gamma-Ray Spectrometer) on the SMM (Solar Maximum Mission) satellite. Finally examples of the stereoscopic observations of solar hard X-ray flares made with these instruments are presented and their implications for the spatial structure of the hard X-ray sources and the existence of “electron beams” in solar flares are indicated.

GENERAL CONSIDERATIONS

Factors Affecting the Detector Response

The major factors that determine the response of a hard X-ray spectrometer are: (i) entrance window, (ii) type and thickness of detector, (iii) geometrical area, (iv) spectral resolution, (v) pulse height to energy conversion factor and its dependence on photon energy, (vi) overall geometry, and (vii) directional response. The first six factors are known from the instrument design and can be determined accurately in the laboratory through calibration with appropriate radioactive sources. The last factor, the directional response depends on design of the instrument as well as its location on the spacecraft.
Hence it is often not well known. For solar instruments on spacecraft, which are spin-stabilized but the spin axis is not in the solar direction, uncertainties in the knowledge of the directional response may introduce significant uncertainty in the deduced solar hard X-ray flux.

Effect of the Spacecraft Launch Environment

The principal difficulty in the design of solar X-ray instruments flown aboard spacecraft is that, in spite of all precautions, some of the instrument parameters may change substantially during the launch because of the exposure to a high level of vibrations, large and rapid variations in temperature or contamination by outgassing and other pollutants. The scintillation crystal, for example, may develop micro-fractures and/or separate partially from the optical coupling to the photo-multiplier tube resulting in the loss of light collection (and hence pulse height) and spectral resolution. In-flight calibration with an on-board radioactive source can help in determining the extent of these post-launch changes in the instrument response, but in practice this may be possible only to a limited extent because of the limitations in the number and strength of the on-board radioactive sources, the number of pulse-height channels and the available telemetry. Also the difference between the magnitude and spectrum of the detector background in space compared to that in the laboratory is very likely to introduce additional uncertainties in the calibration of the instruments.

Requirements for In-Flight Calibration of Solar Instruments

Thus, in order to determine accurately the absolute response of a hard X-ray spectrometer in space, it is desirable that the instrument observe in flight an astronomical X-ray source with a well known photon spectrum covering a wide range of energies and with a high stability in time. Unfortunately most astronomical hard X-ray sources with stable spectra are too weak for good observation by many solar instruments. The X-ray emission from solar flares is intense but the spectrum varies widely from one flare to another and is not known a priori. The other transient emission, cosmic gamma-ray bursts, have an additional complication that the source may be located at a large angle to the primary axis of symmetry for the detector field of view. Solar flares therefore provide a more suitable, although variable, source for intercalibration of two or more instruments. Since the hard X-ray source in flares may be anisotropic, due, for example to the presence of electron beams, the X-ray flux measured by an instrument may depend on its view angle \( \theta \), where \( \theta \) is defined as the angle between the line joining the instrument to the location of the solar flare and the outward solar radius at the location of the flare. Hence for intercalibrating two different instruments in flight with a solar flare, it is necessary that their view angles be as nearly the same as possible.

Procedure for Intercalibration with Solar Flares

Intercalibration of two instruments with solar hard X-rays involves a comparison of the X-ray spectra measured independently by the two instruments. In practice such a comparison has considerable uncertainties because of the differences in the energy range, spectral resolution, number of energy channels and detector background for the two instruments. In the case of the double power law spectrum, as is often emitted by solar flares /7/, the presence of the break-point energy within or outside the range of an instrumental response may affect the deduced X-ray spectrum. The uncertainties in the intercalibration can be reduced by comparing the photon fluxes at specific energies measured by the instruments in a variety of solar flares.

RESPONSE OF ICE (SEE-3) AND PVO INSTRUMENTS

Basic Characteristics of the ICE and PVO Instruments

We have applied the above considerations to the intercalibration of the hard X-ray and low energy gamma-ray spectrometers aboard the ICE and PVO spacecraft. The two instruments have been described in detail elsewhere /8,9,7/. Their basic characteristics are summarized in Table 1. Both instruments have on-board memories to store high time resolution data for a short interval of time suitable for observing the transient cosmic gamma-ray bursts. In the case of solar flares, the real time data have been found to be more useful and hence only those data will be discussed here.

The ICE instrument measures 26 keV–3.2 MeV photons in 12 energy channels. For most of the real time data the time resolution is 0.5 sec for the 7 channels covering 26–308 keV and 1–4 sec for higher energy channels. The PVO instrument measures 100 keV–2 MeV photons in 4 energy channels. The complete spectrum is read out in \( \geq 2 \) sec depending on the spacecraft telemetry rate.
TABLE 1 Characteristics of the Hard X-ray Spectrometers on ICE and PVO

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>ICE (ISEE-3)</th>
<th>PVO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instrument</td>
<td>X-ray spectrometer</td>
<td>Gamma-ray burst detector</td>
</tr>
<tr>
<td>Detector</td>
<td>NaI(Tl)</td>
<td>CsI(Tl)</td>
</tr>
<tr>
<td>Anticoincidence Shield</td>
<td>Plastic scint</td>
<td>Plastic scint</td>
</tr>
<tr>
<td>Detector Arrangement</td>
<td>Phoswich</td>
<td>Phoswich</td>
</tr>
<tr>
<td>No. of Detectors</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Total Effective Area (cm²)</td>
<td>22</td>
<td>20</td>
</tr>
<tr>
<td>Entrance Window (g/cm²)</td>
<td>0.133 Mg+0.185 Be</td>
<td>0.288 Pb</td>
</tr>
<tr>
<td>Spin Axis Orientation</td>
<td>Perp to ecliptic</td>
<td>Perp to ecliptic</td>
</tr>
<tr>
<td>Spin period (sec)</td>
<td>3</td>
<td>12</td>
</tr>
<tr>
<td>Spin Modulation Period (sec)</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>Average Flux Modulation</td>
<td>≤10%</td>
<td>≤45%</td>
</tr>
<tr>
<td>Energy Range (keV)</td>
<td>26—3200</td>
<td>100—2000</td>
</tr>
<tr>
<td>No. Of Energy Channels</td>
<td>12</td>
<td>4</td>
</tr>
<tr>
<td>Time Resolution for</td>
<td>0.5—4</td>
<td>≥2</td>
</tr>
<tr>
<td>Real Time Data (sec)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spectral Resolution</td>
<td></td>
<td></td>
</tr>
<tr>
<td>at 60 keV (\Delta E/E)</td>
<td>17%</td>
<td>20%</td>
</tr>
<tr>
<td>On-board Calibration Source</td>
<td>(^{241})Am</td>
<td>(^{247})Cf</td>
</tr>
</tbody>
</table>

**Calibration with Radioactive Sources**

On the ground the ICE instrument was calibrated with a variety of radioactive sources including \(^{109}\)Cd and \(^{241}\)Am. In-flight calibration was performed by a relatively weak \(^{241}\)Am source sandwiched between two solid state detectors placed close to the NaI(Tl) scintillator-phoswich assembly. The source provided ~60 keV photons and simultaneous ~5 MeV alpha-particles. Whereas the alpha-particles were stopped and detected by the solid state detectors, the photons penetrated through the solid state detectors and were detected by the NaI scintillator. The calibration photons were thus identified by their coincidence with an alpha-particle and were prevented from being counted as photons of solar or cosmic origin. Because of the possible contamination from large fluxes of solar flare X-rays, the calibration was performed only during periods of very low solar activity. The pulses from the calibration photons were analyzed in 12 pulse height (energy) channels. The gain of the system was deduced from a minimum \(\chi^2\)-fit between the observed and expected counts in the different energy channels.

In the case of the PVO instrument, a \(^{249}\)Cf source was used for the in-flight calibration. The response from this source provides an identifiable signature in the phoswich circuit which produces a distribution of counts between two broad energy channels. These counts are continuously monitored for each individual sensor. Although this mechanism does not provide an accurate measure of the detector gain, it has verified the stability of the individual sensors. When exposed to a parallel beam of constant X-ray flux, the spacecraft spin was found to cause modulation of the detector counting rate. The modulation is most significant (~45%) for the lowest energy channel (100—200 keV) and is believed to be caused by a variation in parts of the spacecraft structure and instruments in the detector field of view. The counting rates of the lowest energy channel are therefore multiplied by the average correction factor 1.8 to take into account the effects of spin modulation.

**Response to Solar Flares**

We have compared the response of the ICE and PVO instruments to solar flares and cosmic gamma-ray bursts. Only the response to solar flares will be discussed here. While the PVO orbits the planet Venus, ICE (ISEE-3) is in a heliocentric orbit. The two spacecraft are thus at different distances from the Sun. The times of observation and measured photon fluxes are therefore normalized to the Earth's distance from the Sun (~1 AU). An example of the ICE and PVO counting rates during a common flare in full view of both the instruments is shown in Figure 1.
The ICE observations of a large number of flares have shown that, in most flares, the hard X-ray spectrum is consistent with a double power law of the form

\[
j(E) = \begin{cases} 
K_1E^{-\gamma_1} & \text{for } E \leq E_B \\
K_2E^{-\gamma_2} & \text{for } E > E_B 
\end{cases}
\text{photons/(cm}^2\text{sec keV)}
\]  

where \(K_1, \gamma_1, K_2, \gamma_2\) are the spectral parameters and \(E_B\), the break-point energy, is given by \(K_1E_B^{-\gamma_1} = K_2E_B^{-\gamma_2}\). Since the ICE instrument measures the spectrum in 12 channels a double power law spectrum of the above form was fitted to the counting rates. In the case of PVO, where only 4 channels are available, only a single power law spectrum of the form \(j(E) = KE^{-\gamma} \text{photons/(cm}^2\text{sec keV)}\), \(K\) and \(\gamma\) being spectral parameters, was fitted to the counting rates. The results obtained for the 16 October 1978 (2145 UT) and 4 June 1980 (0655 UT) flares are shown in Figures 2 and 3 respectively. In both cases the difference in the view angles \(\theta_P\) and \(\theta_I\) of the PVO and ICE instruments respectively was \(|\theta_P - \theta_I| \approx 7^\circ\). From Figures 2 and 3 it can be seen that the photon spectra measured by PVO are consistent with those measured by ICE.

For a more quantitative comparison, the photon fluxes \(j(E)\) measured at 150, 350, and 750 keV by PVO and ICE in five relatively large flares are presented as regression plots in Figures 4, 5, and 6 respectively. It can be seen that, in general, the photon fluxes measured by the two instruments are in good agreement (within \(\approx 20\%\)), the maximum difference being \(\leq 50\%\).

**Comparison with Other Instruments**

We have compared the response of the ICE instrument to solar flares with the responses of other hard X-ray spectrometers such as those on P78-1 and SMM (Solar Maximum Mission) satellites. Results of the comparison of ICE and P78-1 instruments have been described elsewhere /9/. In Figure 7 we compare the photon spectrum observed by ICE and PVO in the 4 June 1980 (0655 UT) flare (Figure 3) with the spectra observed simultaneously by the HXRBS (Hard X-ray Burst Spectrometer) and GRS (Gamma Ray Spectrometer) instruments on SMM /10/. It can be seen that the four instruments are in very good agreement. For example, the hardening of the spectrum above 300 keV observed by ICE and PVO is consistent with the SMM observations.
Fig. 2. The differential photon energy spectra measured by the PVO and ISEE-3 instruments at the peak of the solar hard X-ray burst on 16 October 1978. Note the good agreement between the two measurements /7/.

Fig. 3. Same as in Figure 2 for the solar hard X-ray burst on 4 June 1980.
Fig. 4. Regression plot of the 150 keV photon fluxes $j_P$ and $j_I$ observed by the PVO and ISEE-3 instruments respectively during five large unocculted solar flares. The difference in the view angles of the two instruments was $|\theta_P - \theta_I| = 5^\circ - 9^\circ$. A straight line representing the constant flux ratio $j_P/j_I = 1.05$ is also shown for comparison. The statistical error bars (when not shown) are smaller than or equal to the size of the full circle representing each flare [7].

Fig. 5. Same as Figure 4 for 350 keV photons. The straight line represents the flux ratio $j_P/j_I = 0.85$ [7].
Fig. 6. Same as Figure 4 for 750 keV photons. The straight line represents the flux ratio $j_p/j_I - 1$.

Fig. 7. A comparison of the differential photon spectra measured by HXRBS and GRS instruments on SMM on 4 June 1980 with those measured at the same time by the ISEE-3 and PVO instruments. Note the excellent agreement between the different instruments.
SOME RESULTS FROM THE STEREOSCOPIC OBSERVATIONS MADE WITH ICE AND PVO

Successful intercalibration of the hard X-ray and low energy gamma ray spectrometers aboard the ICE and PVO spacecraft have led to stereoscopic observations of solar hard X-ray flares. Such observations provide unambiguous measurements of the directivity and vertical (height) structure, two important characteristics of the 100 keV—1 MeV photon sources in solar flares. This technique of measuring the directivity is superior to that using the center-to-limb variation of the occurrence frequency of hard X-ray flares in that, unlike the latter, the former measures the directivity of individual flares without making any assumptions regarding the "log N-log S" distribution (dependence of the number N of flares during a given time on the peak or average hard X-ray flux S). Also since no imaging observations are presently available for sources of X-rays >100 keV, the stereoscopic observations of flares partially occulted by the photosphere from the view of one of the two spacecraft provide the only available measurements of the height structure of the >100 keV X-ray sources. During the period of 1 October 1978—31 October 1980 the ICE and PVO instruments observed simultaneously 46 solar flares. Of these 39 flares were in full view of both the instruments and 7 flares were partially occulted from the view of one of the two instruments. The analysis of these “common” events in terms of the directivity and/or the height structure of the hard X-ray source has been presented elsewhere /5,6,7/.

Here we present, as an example, the regression plot (Figure 8) of the ~350 keV photon fluxes \( j_p \) and \( j_I \) measured by the ICE and PVO instruments respectively in the common unocculted flares. It can be seen that the observations are consistent with the ratio of the photon fluxes \( j_p/j_I \) is ~0.85 independent of the difference \( |\theta_p - \theta_I| \) in the view angles of ICE and PVO. Thus, contrary to the findings based on the center-to-limb variation of >300 keV photon flares observed by the SMM-GRS instrument /11/, there seems to be no evidence of systematic directivity of hard X-ray flares in the ICE and PVO data analyzed so far.

Some results from the stereoscopic observations of partially occulted impulsive flares are presented in Figure 9. It shows that the impulsive hard X-ray source extends from the chromosphere to the corona. The brightest part of the >100 keV X-ray source is located at heights below ~2000 km above the photosphere. The brightness of the source decreases rapidly with increase in the height, the coronal source at ~3 x 10^4 km being about ~100 times less bright than the chromospheric source.

Fig. 8. Regression plot of 350 keV photon fluxes \( j_p \) and \( j_I \) observed respectively by PVO and ISEE-3 at the time for all unocculted common flares during the period 1 October 1978—31 October 1980. The difference \( |\theta_p - \theta_I| \) in the PVO and ISEE-3 view angle for each flare is also indicated. The straight line representing the ratio \( j_p/j_I = 0.85 \) is also shown for comparison. An isotropic source is expected to produce a constant ratio (e=1) /7/. The straight line representing the ratio \( j_p/j_I = 0.85 \) is also shown for comparison. An isotropic source is expected to produce a constant ratio (e=1) /7/.
CONCLUSIONS

Intercalibration of different hard X-ray spectrometers requires patience and cooperation from the relevant experimenters. However, it is a worthwhile goal and should be pursued whenever possible. The successful intercalibration of the ICE (ISEE-3) and PVO instruments made it possible to obtain stereoscopic observations of \( >100 \) keV photon sources in solar flares and to study the directivity and height structure of these sources. The analysis so far indicates that: (1) the impulsive hard X-ray source extends from the chromosphere to the corona, the brightness of the source decreasing rapidly with the increase in height; and (2) the systematic directivity of the hard X-ray source in most flares is small. The observations are consistent with energetic electrons accelerated in the corona propagating downwards towards the chromosphere in a mode, such as diffusion, where the "beaming" of the electrons is very small.

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