Problems, Peculiarities and Phenomena in RHESSI Spectroscopy

David Smith, dsmith@ssl.berkeley.edu

Version 1, 04/12/02

This document outlines two categories of phenomena which can complicate RHESSI spectroscopy: peculiarities of individual detectors, and behaviors of the instrument as a whole which can fool the user. For deep background on the RHESSI spectrometer, see the companion document, **Behind, Beneath, and Before RHESSI Spectroscopy** (BBB). For an introduction to the data analysis procedure for spectroscopy, see Brian Dennis's Spectroscopy First Steps document at **http://hesperia.gsfc.nasa.gov/~dennis /spectroscopy/first_steps.htm**.

Background Variations

The RHESSI x-ray/gamma-ray background consists of a number of components, including 1) secondary photons from cosmic ray interations with the Earth's atmosphere and the spacecraft, 2) the cosmic diffuse x-ray background, 3) radioactive decays in the Ge crystals and the spacecraft of unstable isotopes and isomers created by interactions of cosmic rays, and 4) bremsstrahlung in the Earth's atmosphere and in the spacecraft from electrons occasionally precipitating from the radiation belts. Most of the background is due to 1) and 3) most of the time, meaning that there is a very roughly sinusoidal variation that dominates the background changes: this is due to the change in magnetic latitude of the spacecraft, since the Earth's magnetosphere shields against cosmic rays best at the equator and worst near the magnetic poles. RHESSI gets to approximately 50 degrees magnetic latitude at the most. Not only is this the time of the highest cosmic-ray-induced background, it is also the time when electron precipitation is most likely to happen.

In addition, on several consecutive orbits each day, RHESSI passes through the South Atlantic Anomaly (SAA), i.e. it is briefly inside the Earth's radiation belt and interacts with the trapped population of protons and electrons. Generally the RHESSI detectors are disabled during these periods, but sometimes the spacecraft just nicks the edge of this region, producing a peak in the background. Figure 1 shows

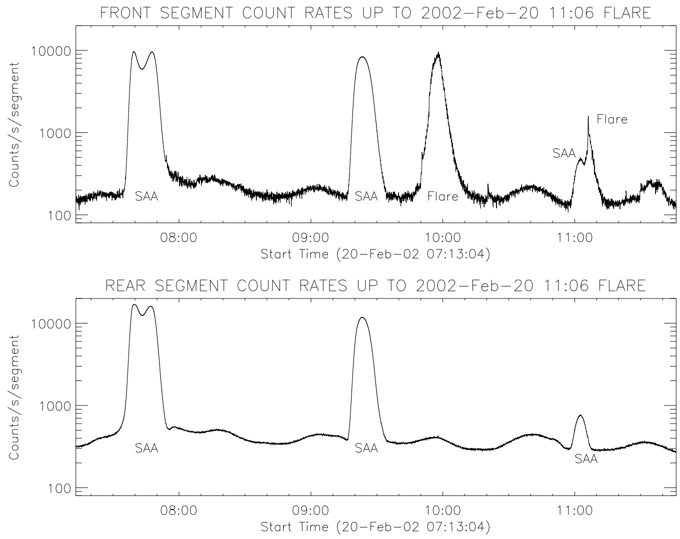

Figure 1: Background behavior, front and rear count rates from monitor rate data, up to and including the time of the flare of 2002-Feb-20 11:06 UT.

RHESSI front and rear segment count rates in plots that demonstrate the background variations due to magnetic latitude, the SAA, and solar flares. Note that any increase in count rate can easily be identified as solar if it occurs more strongly in the front segments than the rears. Any of the non-solar background components is always brighter in the rear segments.

In order to get an idea of the way background variations will affect your analysis, it is a good idea, whenever you are going to study a flare in depth, to **use the Observing Summary Data to examine the count rates for a couple of hours before and after your flare**, so you can see how your data will be affected. Figure 1 shows monitor-rate data (similar to what is available in the Observing Summary but with no energy discrimination) in the region of the flare of 20-Feb-2002, 11:06 UT. By seeing the SAA pass on the previous orbit, we recognize that this flare occurs during one of the rare periods where the spacecraft nicks the edge of the SAA without shutting off the detectors, and therefore presents a particular challenge for background subtraction.

Figure 2 shows background count rates in the rear of detector G1 during two consecutive days. On 2002-Mar-18 (crosses), there was no significant electron precipitation. The next day (solid line), the magnetosphere was disturbed so as to produce intense precipitation at the highest magnetic latitudes RHESSI encounters. Notice that the usual background modulation with magnetic latitude (low-level "sine" wave) and the passes through the SAA (events > 10000 c/s) are very similar from day to day. Figure 3 shows the spectrum of the precipitation using spectra taken at corresponding times on each of the two days, chosen so that in the 19th it was a time of intense precipitation. Above 300 keV or so the agreement is excellent. The precipitation (bremsstrahlung) spectrum is softer than the overall background spectrum. In the front segments, it is always harder than a flare. It addition, these events can be distinguished from flares by the front/rear ratio: flares always produce higher count rates in the front segments, and precipitation events always produce higher rates in the rears.

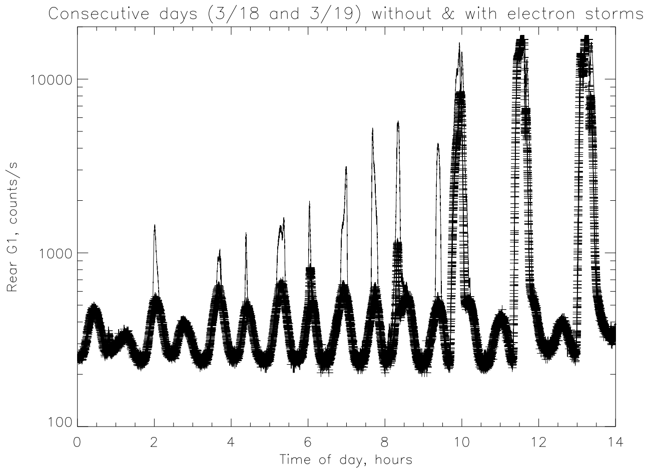

Figure 2: Count rates vs. time on consecutive days illustrating the presence and absence of electron precipitation events.

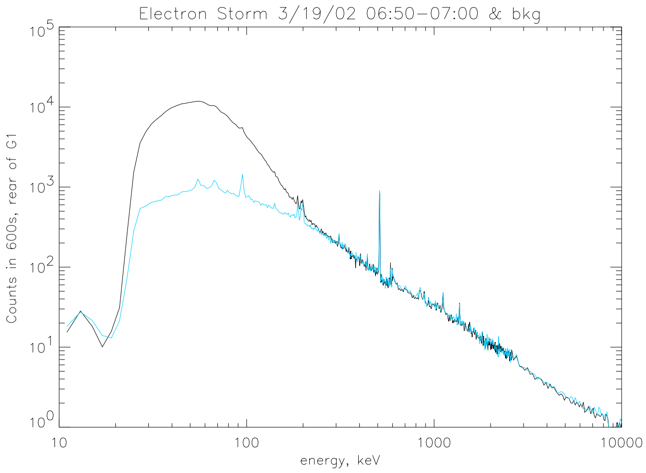

Figure 3: Rear-segment energy spectra with and without a major precipitation event in progress.

Image events & other coincidences

When the clouds of electrons and holes liberated by a gamma-ray event move through the detector, they create induced charges on the electrodes of the segment in which they are moving. The change in time of this induced charge is the current pulse which is amplified and integrated by the CSA to become the detected event. However, they also induce charges on the electrodes of the empty segment. The difference is that the image charges reverse sign in the empty segment as the clouds approach the electrodes of the segment in which they are actually moving. The result is that the image signals (current vs. time) in the empty segment are bipolar in shape and integrate to zero charge.

The RHESSI electronics, however, do not integrate the signals for an infinite time; the peaking time of the shapers is only a few microseconds. Therefore a small amount at the very end of each pulse is not counted. Since it is the negative part of the bipolar signal in an empty segment that comes last, the result is that there is a very small, positive residual from

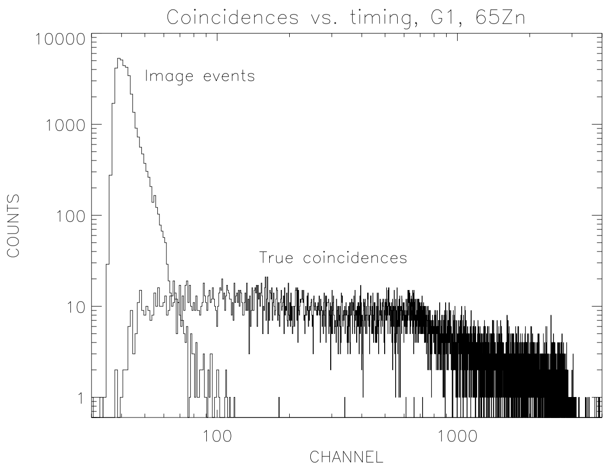

Figure 4: Spectra of front segment events coincident with rear segment events. The events were sorted by timing (see the table), but the spectral division is obvious: the image events are very low energy, while the true coincidences are all higher energy, as would be expected from their origin in Compton scattering.

the bipolar signal: in other words, a 1 MeV event detected in one segment will create a simultaneous (but false) event in the other segment of a few keV.

There are two other ways events can be coincident between two segments (or two detectors): there could be real energy deposits in both segments from the same initial photon or cosmic ray (we sometimes call this a "true coincidence") or there could be two separate photons that arrive nearly at the same time by chance ("accidental coincidence").

Usually, the simplest way to do spectroscopy is to throw out all coincident events (defined as events within N binary microseconds of each other, where the best value of N is 4 or 5). **This is the default behavior of the data analysis routines.** When you want to get every last photon to detect a faint gamma-ray line, however, you will want to include front/rear coincidences and coincidences between adjacent rear segments (the software will have a single flag to specify this configuration). When the count rates are very high, you may not want to reject coincidences at all, since a large fraction of events will be accidental coincidences.

At moderate count rates, it is possible to separate image events from true coincidences by the precise relative timing of the two events. If the separation in binary microseconds between the two events is Δ, then this table describes the relation between the events:

First Event	Δ	Event type
FRONT	1	Image event in front
FRONT	0	Image event in front
REAR	0	True coincidence
REAR	1	True coincidence
REAR	2	True coincidence
REAR	3	Image event in rear
REAR	4	Image event in rear

Events of any other spacing are probably accidental coincidences. Figure 4 shows how sorting coincident events by Δ and by which occurs first can cleanly separate image events from true coincidences.

You may also hear image events referred to as "bipolar pulses" or "false coincidences".

Radiation damage

Radiation damage has always been a major performance issue for germanium detectors in space. Nuclear interactions with high-energy protons or neutrons cause displacements in the Ge crystal lattice. These displacements can become traps which remove some of the holes liberated by a gamma-ray interaction as they travel through the crystal. The electrons moving in the opposite direction from these holes are relatively immune. This trapping broadens a gamma-ray line in a way proportional to its energy, because gamma-ray interactions in some parts of the crystal force the holes to move through more damaged germanium than interactions in other parts, and thus different gamma-rays of the same energy suffer different percentage amounts of signal loss through trapping.

RHESSI's orbit grazes the inner edge of the proton belt a few times a day at the South Atlantic Anomaly (SAA). Most of the trapped protons (those below about 40 MeV) are stopped by the aluminum surrounding the detectors, but protons from 40-100 MeV interact in the outer few mm of the detector and the (relatively few) protons around 200 MeV and higher produce damage throughout the crystal. A smaller amount of damage throughout the crystal is caused by cosmic rays. **There is no evidence for any radiation damage two months into the RHESSI mission, and we don't expect a detectable effect for about a year.**

The damage is minimized in several ways. First, since the holes travel to the outer electrode and most of the detector volume is at large radii, most hole clouds travel only a short distance through damaged germanium. Second, the detectors are very cold (about 75K), even though they can operate at much higher temperatures (up to 110K or higher), and we keep

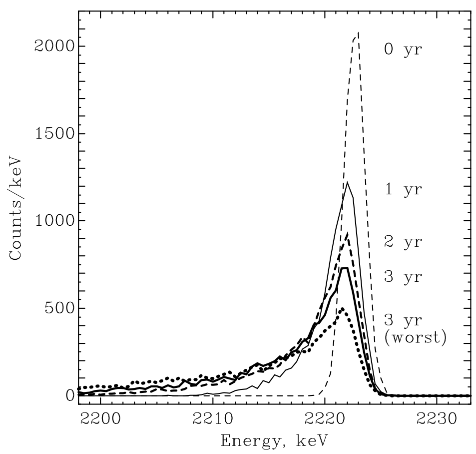

Figure 5: Expected effect of radiation damage on the profile of the 2.2 MeV line over the RHESSI livetime.

the HV on at all times. Although the number of crystal displacements is only a function of the radiation dose, very low temperatures and uninterrupted HV can prevent the accumulated crystal displacements from becoming active as traps. Third, the RHESSI crystals have a scattering of naturally occurring electron traps due to impurities. Thus the resolution will actually become slightly better at first as hole traps are created: when electrons and holes are equally trapped, there is no effect on the line shape, just a slight overall decrease in gain. Fourth, for some minutes after RHESSI emerges from the SAA, the large currents that were going through the detector while it was bathed in the radiation belts will have filled up all the traps in the crystal, so that the resolution will be temporarily better. Within one orbit, however, the traps will empty out again.

Finally, we have heaters near the detectors which can bring the array to 100°C; annealing for about a day at this temperature should remove most of the accumulated radiation damage. From our estimate of the proton dose on orbit, we expect to anneal after the RHESSI baseline mission of two years. Figure 5 shows the expected profile for the 2.2 MeV line (neutron capture on ambient protons in the solar atmosphere) as a function of elapsed mission time. Note that only the two delayed lines from flares, 511 keV and 2.2 MeV, are narrow enough for radiation damage to matter. All the other solar lines are broad enough that their natural width is higher than any amount of resolution loss we might expect from radiation damage.

Microphonics

The detectors are kept cold by a Stirling-cycle refrigerator with a piston that operates near 58.6 Hz. It contains an actively-driven counterweight which moves opposite the piston to cancel out most of the vibration, but there is still vibration transmitted to the spacecraft at higher frequencies (harmonics of the piston frequency and even higher frequencies which may be related to valves or other moving parts in the cooler). Vibrations can cause a degradation in the resolution of the RHESSI detectors by the same principle used in a capacitor microphone: small motions make small changes in capacitance, producing small changes in voltage, which are read as noise on the CSA output. The susceptible capacitance could be in any of several places in the detector/HV/FET system.

For the most part, the RHESSI detectors are resistant to this sort of noise, through both mechanical design features and the design of the DIB electronics (baseline restorer circuit). Several of the detectors can display a minor loss of resolution, however, mostly due to what we believe is a mechanical resonance with the 14th harmonic of the piston frequency (820 Hz). The severity of this problem varies with the cryocooler power and the temperature of the spectrometer shell (and therefore the cryocooler body). By adjusting the cooler power and by operating heaters on spectrometer exterior, we have reduced this problem until it is negligible in most segments, the exception being a moderate loss of resolution in detector G5 (see below).

Because the microphonics effects all occur at low frequencies compared to the risetime of a single photon pulse, they affect only the energy resolution: unlike the white noise source in the front segment of G7 (see below), they cannot produce false events at low energies and therefore do not affect the setting of the LLDs (and therefore the low-energy limit of our observations).

Spectral Artifacts

A very small fraction of events near or above 3 MeV that should be analyzed with the high-energy gain range of the rear segments do not trigger the gain shift in the fast channel, and therefore pile up in the top few (64) channels of the low-energy scale. This should be the first interpretation for any unexpected excess around 3 MeV. To verify, look at the raw data (in channel space rather than energy space) and see that the extra counts correspond to the top 64 channels (8128-8191). We eventually expect to have the data analysis software deal with this problem by looking only at the events tagged for the high-energy scale in making spectra for this energy range. The small number of counts piled up at the bottom of the low-energy range will be redistributed according to the spectral shape determined from the high-energy range in order to get the correct intensity in that band. Other artifacts (like a gap in the spectrum) may also appear near 3 MeV due to the gain switch until we have refined the analysis software.

At extremely high rates only, a similar artifact appears in the 64 channels preceding the halfway point of the spectrum (i.e. channels 4032-4095). When analyzing the brightest flares, the user should remain aware what of energy range this channel range maps to and be cautious interpreting results there. This artifact can also appear at low rates in G5 (see below).

Front segment dropouts

Each front segment shuts off for variable periods with durations of hundreds of milliseconds, up to once every few seconds, for a net loss of about 10-40% of the total data. This is NOT measured by the livetime counter on the spacecraft, although a ground-software patch is in progress. Although we're not certain of the cause of this, we suspect it may be due to the response of the electronics to heavy cosmic rays, which leave more energy in the detector than anything available on the ground during pre-flight testing. The rear segments are not susceptible to this problem. Detector G2, which is being run as a monolithic crystal with the signal going through the front segment electronics chain (see below), seems to have only a minor case, as does detector G5, which has the thickest front segment. Since this is not an energy-dependent effect, it is more important for imaging and photometry than spectroscopy, although it **will** affect spectroscopy if both front and rear segments are used. The software fix under development should take care of this by simply accounting for the deadtime due to these gaps. The dropouts are difficult to see by eye at low count rates, since there can naturally be periods of tens of milliseconds without an event. But each dropout is preceded by a reset event (see BBB) – this is how the analysis software identifies them.

K-shell escape

When either of the shutters is in place (see BBB), the user should be careful in interpreting the data below 10 keV. The real photons in this energy range, although copious, are so highly attenuated that this band can be dominated by photons which are NOT seen at their true energy. Mostly, these are photons approximately 10 keV higher than the energy at which they appear; the missing 10 keV leaves the detector in the form of a germanium K-shell fluorescence photon. Thus, if a shutter is in, raw lightcurves of $<$ 10 keV photons may follow the time profile of the harder, impulsive emission rather than the thermal, gradual emission. This effect is accounted for in the full response matrix (with non-diagonal elements included), but the effectiveness (precision) of that correction has not yet been completely tested. Thus it is probably too soon to try to interpret data below 10 keV with one or both shutters in.

Pileup

Conversely, when both shutters are out, pileup (two photons close together in time having their energies added) can greatly distort the spectrum, particularly in creating a false spectral component *above* 10 keV or so. Figure 6 shows spectra taken during a bright flare just before and just after the thin shutter was pulled out. With the shutter out, the recorded front segment livetime was 45% (meaning the true livetime was about 26% – see BBB). The flare spectrum itself wasn't changing over the few seconds that separate these observations. Trace 1 is the raw spectrum observed when the shutter was in. Trace 2 is the same data, but corrected to remove the absorption due to the shutter. This is probably a good approximation of the true flare spectrum above about 10 keV; below 10 keV, it probably suffers from the K-shell escape problem mentioned in the previous section and is an overestimate. Trace 3 is the raw spectrum with the shutter out, and trace 4 is the same thing corrected for deadtime (i.e. divided by 0.26). In the absence of pileup, these spectra should agree above 10 keV or so. It is apparent that ignoring pileup here would give a completely false idea of the shape and extent of the spectrum.

Aside from some experimental periods early in the mission, we try to bring the thin shutter in anytime the recorded livetime drops below 85% to avoid such

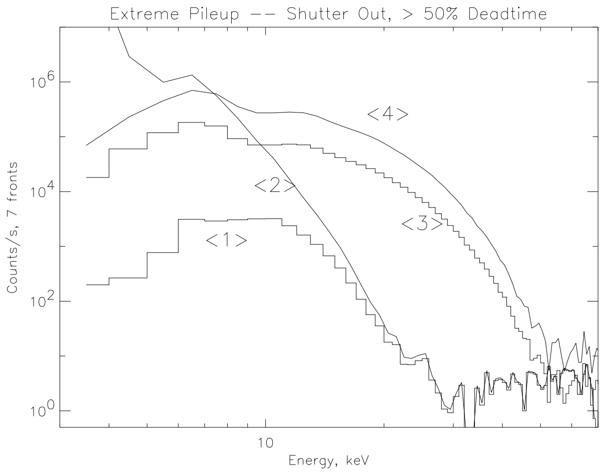

Figure 6: An extreme case of pileup. 1) Raw data, shutter in. 2) same, corrected for shutter transmission. 3) Raw data, shutter out, livetime = 26%. 4) same, corrected for livetime. The difference between 2) and 4) is mostly due to pileup.

extreme situations. However, when the shutter is brought in, the count rate drops so much, and the livetime gets so close to 100%, that it's impossible to tell when to bring it back out again. Currently the flight software pulls out the shutter briefly every 4 minutes to "peek" and the real state of the flare, and puts it back in immediately if the livetime is too low: this is how the data in Figure 6 were obtained. We are currently trying to find a better way to know when to pull the shutter out.

The livetime correction code mentioned in BBB does little to help in this case, both because the level of pileup is too severe and because the shutter is out and therefore most of the photons are of such low energy that they can't trigger the pileup detection circuit. We are working on improving the pileup correction algorithm before it is included in the standard analysis.

Peculiarities of individual detectors

G2: Since the final assembly of the spectrometer, this detector was unique in that it had a very high sensitivity to vibrations from the cryocooler (microphonics – see BBB). Shortly after it was turned on on orbit, other problems cropped up as well, and currently this detector cannot run at a high enough voltage to separate into two segments (see BBB). The result is that this detector is now being operated as a single detector at a lower voltage (about 2400 V vs. 4000 V nominal). In other words, what the software takes to be the "front segment" is actually the whole detector, and what the software takes as the "rear segment" is empty – events never occur. This means that the "front" background is much higher than for other detectors, since it includes rear segment events. In addition, because it's being run in a mode that was never intended, the noise level is also much higher than the other detectors: the energy resolution is about 9 keV FWHM compared to 1 keV for most of the detectors, and the low-energy cutoff (imposed by the electronics) is at about 25 keV instead of 3 keV. G2 should therefore not be used for spectroscopy at all, although it should still be useful for imaging in the 30-200 keV range. A table of the achieved resolution in each segment is given in BBB.

G7: Since the final assembly of the spectrometer, this detector has been somewhat noisier than the others in its front segment. The front segment resolution is about 3 keV FWHM (versus the nominal 1 keV), and it's threshold (low-energy cutoff) is at about 7 keV instead of 3 keV. Although this segment could still be marginally useful for spectroscopy in the non-thermal regime (above 15 or 20 keV), the safest thing in most cases will be to leave it out. The rear segment performs fine, and should be included in gamma-ray work with all the others (except G2).

G8: This detector is located right next to the aft antenna, one of two antennae used for data downlink, and when that antenna is active, the detector becomes very noisy: this manifests itself as a deficit of counts in the rear segment and an excess of counts in the front (these are not the rear segment's counts getting transferred – they are just noise). Thus you don't want to use this detector while the aft antenna is transmitting, which is usually a matter of 1-12 periods per day of 2-12 minutes each. We hope to soon have an easy way of determining when this is, but for now you'll want to check on our website before you go to analyze your flare. To do this, go to **http://hessi.ssl.berkeley.edu/ground_systems/products/HESSI/** and look in the directory YYYY_DDD where YYYY is the year and DDD is the Day-Of-Year. In that directory will be a file called HESSI_YYDDD_LINKPD (YY is now the last two digits of the year), and in this file is a table which has "Aft-Antenna-Access-Zone" in its header. That will tell you the time periods to beware of.

G5: This detector is subtly unusual in several ways. First, it is for some reason less susceptible to front segment dropouts than the others (see above). Second, the spectral artifact between channels 4032 and 4096 can appear even at low count rates (also see above). Finally, the front segment is slightly microphonic, i.e. the energy resolution is degraded because of vibrations from the cryocooler, but not badly: the resolution is about 1.5 keV FWHM instead of 1.0 keV (as it is for the fronts of G1,3,4,6,8 and 9).