

**A tutorial for the use of
MESSENGER Gamma-Ray Spectrometer Anti-Coincidence Shield Products
Generated After the 25 February 2013 Flight Software Patch**

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Introduction:

The purpose of this document is to familiarize interested data users with the format of MESSENGER Gamma-Ray Spectrometer (GRS) Anti-Coincidence Shield (ACS) data products and how they can be used for Mercury science investigations. The document includes an introduction to the instrument and data products, an overview of the ACS pulse height spectra and applicable data corrections, and the use of the high-time-resolution ACS count rate measurements to identify and characterize energetic particle events.

1. Overview of MESSENGER Gamma-Ray Spectrometer

1.1 Introduction

The MESSENGER spacecraft carried a Gamma-Ray and Neutron Spectrometer (GRNS) to measure the elemental composition of the surface of Mercury [Goldsten *et al.*, 2007]. The GRNS was in practice two distinct subsystems: the Gamma-Ray Spectrometer (GRS) and the Neutron Spectrometer (NS). This document focuses on the use of the GRS_CAL_SH3 and GRS_CAL_SCR data products, produced from GRS measurements collected following a flight software patch that was uploaded to the spacecraft on 25 February 2013. Data product format and contents overviewed in sections 2.2 and 3.4.

GRS was comprised of two sensor elements: a high-purity germanium (HPGe) sensor and a cup-shaped, boron-loaded BC454 plastic scintillator (see Figure 1). The HPGe sensor provided measurements of gamma rays from Mercury's surface, data that were used to derive the elemental composition of near-surface materials [Peplowski *et al.*, 2011; 2012a, 2012b, 2014, 2015a; Evans *et al.*, 2012, 2015]. The primary purpose of the BC454 scintillator was to detect and veto galactic-cosmic-ray events from the HPGe measurements. The BC454 + PMT is therefore an anti-coincidence shield (ACS). ACS and HPGe coincident events were electronically removed from the HPGe measurements to produce the "anticoincidence" spectrum, which has improved signal-to-

background when compared to the raw (not ACS vetoed) HPGe measurements. Due to the boron content of the BC454, the ACS was also sensitive to neutrons (n) via the $^{10}\text{B} + n$ capture reaction. Boron capture reactions produce a distinct energy deposition signal (peak) in the ACS pulse-height spectrum (section 1.2), providing a means of characterizing the ACS-incident neutron flux [Peplowski *et al.*, 2015b].

HPGe is only sensitive to gamma rays when it operates at cryogenic temperatures of ~ 90 K. A cryocooler was therefore included in GRS. The cryocooler ceased operating on 15 June 2012 following 9,500 hours of use (exceeding its expected lifetime of 8,000 hours). Without the cryocooler, the HPGe sensor was no

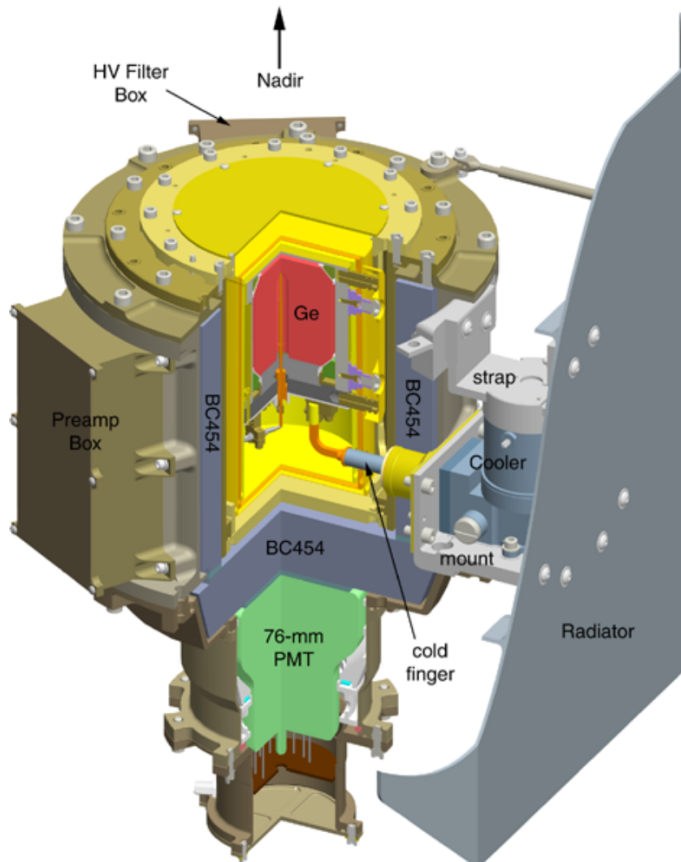


Figure 1. A CAD model cutaway view of the GRS sensor. The 5 cm x 5 cm HPGe sensor is shown in red. Note how the cup-shaped BC454 anti-coincidence shield (ACS) surrounds the HPGe sensor on all but the nadir-facing side. Figure reproduced from Goldsten *et al.* [2007].

longer capable of measuring gamma-ray emissions from Mercury. As a result, GRS operations after 15 June 2012 were refocused on maximizing science from the ACS measurements. This document describes those measurements.

1.2 Anti-Coincidence Shield

The cup-shaped ACS surrounded the HPGe sensor on all but one side (Figure 1). This geometry resulted in a boresight for the HPGe sensor (Figure 1). When the boresight is aligned with the nadir (spacecraft-to-planet-center) vector, the HPGe has a view of the surface of Mercury that is unobstructed by the ACS. Unlike the HPGe, which provided high-energy-resolution measurements of sensor-incident gamma rays, the ACS was a low-energy-resolution system that recorded energy deposition from a range of particle types that included:

1. High-energy (> tens of MeV) charged particles that penetrated the housing of the GRS and directly interacted with the BC454. This type of event includes galactic cosmic ray (GCR) protons. These events manifest as a continuum of measured energies in the ACS energy deposition spectrum, and provided the basis for the anti-coincidence mode of operation. At high altitudes, these events dominate the ACS measurements (see the red spectrum in the top panel of Figure 2)
2. Neutrons, which easily penetrate the GRS housing and interact with the BC454 sensor via the neutron capture reaction $^{10}\text{B} + \text{n} \rightarrow ^7\text{Li} + \alpha$. This reaction converts the neutron to charged particles (^7Li , α) that deposit their full energy in the ACS. Because the energy of the daughter particles sum to the Q-value of the $^{10}\text{B} + \text{n}$ reaction (2.790 MeV), neutron capture events measured by the ACS appear as a peak in the ACS energy deposition spectrum. The peak is broad due to the low energy resolution of the ACS. Neutron capture events are rare in high-altitude (HA) spectra but common in low-altitude (LA) spectra (black spectrum, Figure 2 top panel), suggesting that Mercury is the dominant source of neutrons observed by the ACS. The shape and magnitude of the neutron signal is shown in the residual (LA – HA) spectrum (blue, Figure 2 bottom panel).
3. Low-energy charged particles (e.g. $< \sim 1$ MeV electrons, $< \sim 15$ MeV protons), which themselves do not penetrate the GRS housing but that produce Bremsstrahlung radiation (x-rays, low-energy gamma rays) in the housing that does reach the BC454. Since BC454 is inefficient at stopping gamma rays, these events appear as low-energy events in the ACS spectrum. Electron events are primarily distinguished by their spatial and temporal properties, not their energy spectrum. These events are discussed in Section 3, which includes example spectra.
4. Spacecraft- and planet-originating gamma rays, which contribute to the ACS energy spectrum measurements in a smoothly varying way that depends on the spacecraft altitude above Mercury's surface. These events account for some of the difference in the spectral shape of the HA and LA measurements. Again, since BC454 is inefficient at stopping gamma rays, these events appear as low-energy events in the ACS spectrum.

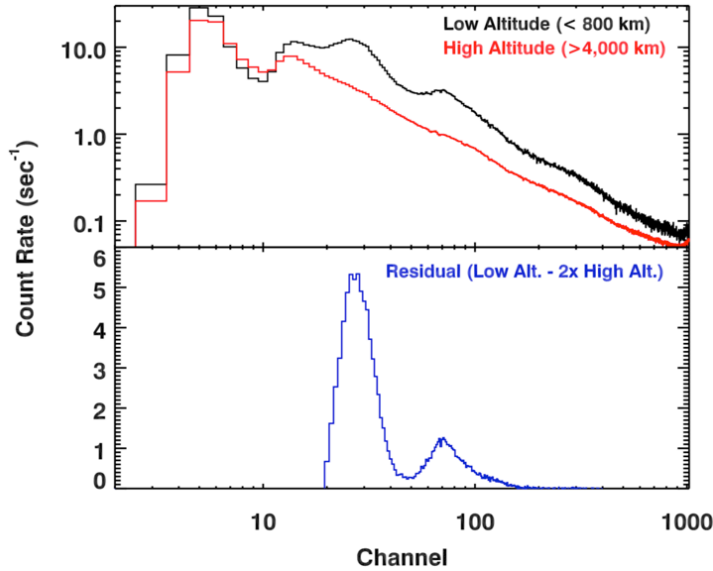


Figure 2. ACS energy deposition (pulse height) spectra for MESSENGER orbit 1847 (1 April 2013), summed from data collected at low (<800 km) and high (>4,000 km) altitudes. The residual spectrum (Low altitude spectrum - scaled high altitude spectrum) is shown in the bottom panel in order to highlight the locations of the neutron capture peaks, which only appear at low altitudes. The presence of two neutron capture peaks is addressed in Section 2.2.

Note that the ACS spectra are recorded as pulse-height spectra, where the pulse height recorded by the system is proportional to the light output of the scintillator, which is proportional to the energy deposited in the BC454 by the incident particle. This document refers to the pulse height channel simply as “channel”. Unlike the case for the HPGe measurements, there is no energy calibration for the ACS. This is due to 1) non-linearity in the light collection of the sensor and 2) convolved signals from the two ACS sensor components (see section 2.4). As a consequence, all ACS energy deposition values are relative. The only reference points in the spectra are the neutron capture peaks, which are located at 2.790 MeV but differ in channel position due to the geometry of the ACS (see section 2.4).

1.3 ACS Data Products

The GRS ACS operates independently of the HPGe sensor, therefore the end-of-life of the cryocooler did not affect the quality of ACS data. As a consequence, post-cryocooler-failure GRS operations were refocused on the ACS measurements. This was accomplished via an update to the GRS flight software on 25 February 2013. This flight software patch resulted in the addition of two new GRS data products:

1. GRS_CAL_SH3: The data content of this product is identical to GRS_CAL_SH2, except that the gain of the ACS shield was changed to facilitate neutron peak characterization. Additionally, production of the ACS data products transferred from the University of Arizona to the Johns Hopkins University Applied Physics Laboratory. This transfer of responsibilities resulted in a change to the format of the gain-modified ACS spectrum, which motivated the change in naming from GRS_CAL_SH2 to GRS_CAL_SH3

A new data product, called “shield count rate” (GRS_CAL_SCR), was added. SCR reports the total count rate in the ACS in 10 ms intervals. The objective of the SCR data product was to provide new insights into the charged particle environment around Mercury, particularly the energetic electron events.

This document provides an overview of the SH3 and SCR data products.

1.4 Event Types

There are a number of particle interaction mechanisms that produce an energy deposition event in the ACS. These event types, depicted in Figure 3, include:

1. A particle with an initial energy E_i penetrates the GRS housing, deposits a portion of its energy (dE) in the BC454 via one or more interactions, and escapes with energy E_f ($\leq E_i - dE$). This type of event is depicted as “Event Type 1” in Figure 3. High-energy galactic cosmic ray (GCR) protons are a major contributor to Event Type 1.
2. A particle with an initial energy E_i penetrates the GRS housing and deposits all of its energy ($dE = E_i$, or $dE < E_i$ if some energy was lost in the ACS housing) in the BC454. This type of event is shown as “Event Type 2” in Figure 3. Low energy charged particles and low-energy gamma rays are the most likely candidates to produce an Event Type 2.
3. A neutron with an initial energy E_i penetrates the GRS housing, perhaps downscattering within the BC454, before undergoing the neutron capture reaction $^{10}\text{B} + n \rightarrow ^7\text{Li} + \alpha$. The resulting charged particles (^7Li , α) deposit all of their energy (the Q value of the reaction, 2.79 MeV) in the BC454, producing the distinct neutron capture peak ($dE = 2.79$ MeV, e.g. Figure 2) in the ACS spectrum. This type of event is shown as “Event Type 3” in Figure 3.
4. A low-energy charged particle (e.g. a 0.3 MeV electron) hits the GRS but does not penetrate the housing and therefore does not reach the BC454. While stopping within the housing, the electron produces Bremsstrahlung radiation (low-energy photons with energy less than that of the electron) does reach the BC454. A fraction of the Bremsstrahlung photons deposits a fraction of their energy in the BC454, resulting in a summed dE value that is significantly less than the initial energy (E_i) of the electron ($dE \ll E_i$).

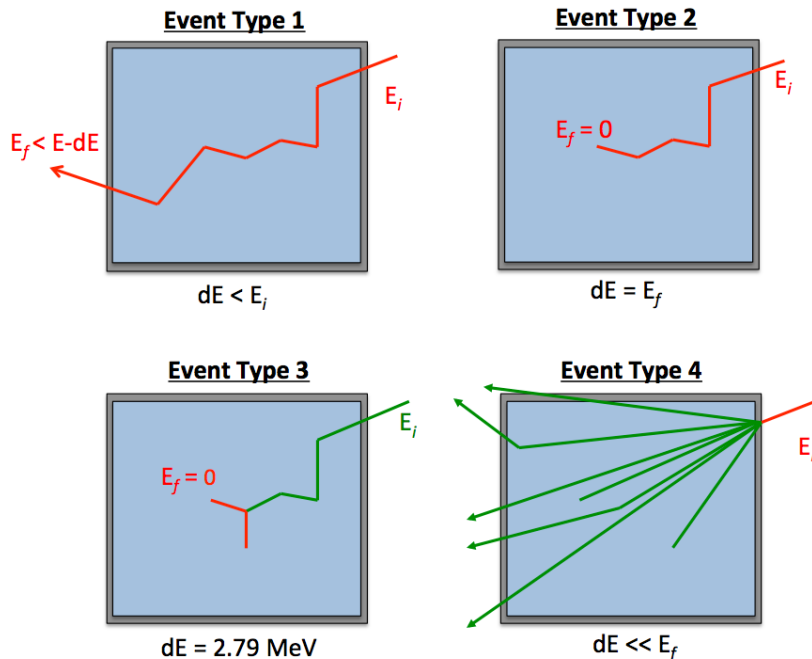


Figure 3. A cartoon depicting expected ACS event types. Red lines depict charged particles, green lines are neutral particles. Blue represents the ACS scintillator material, grey is the GRS housing. The geometry is notional and does not represent the GRS/ACS.

2. Neutron Science from the Shield Spectra (SH3) product

2.1 Science Motivation

Mercury's airless surface is subject to constant bombardment from high-energy radiation, including galactic cosmic rays (GCRs). GCRs, primarily protons, range in energy from <1 MeV/nucleon to >10 GeV/nucleon, peaking around 1 GeV/nucleon. At these energies, GCRs penetrate Mercury's surface to depths of ~ 2 meters, along the way interacting with materials via a number of processes that includes nuclear spallation. Spallation dissociates atomic nuclei, liberating protons and neutrons from their host nuclei. The spallation neutrons traverse the near-surface materials, interacting with nuclei via elastic, inelastic, and capture reactions. Some spallation neutrons escape into space, and measurements of the flux (magnitude and energy dependence) of these escaping neutrons provides a measure of the elemental composition of near-surface materials. Specifically, "fast" ($> \sim 0.5$ MeV) neutrons are a measure of average atomic mass, epithermal (0.2 eV to 0.5 MeV) neutrons vary as a function of hydrogen, and thermal (<0.2 eV) neutrons vary with the total concentration of thermal-neutron-absorbing elements (e.g. Fe, Ti, Cl). MESSENGER neutron measurements identified enhanced hydrogen concentrations at Mercury's north pole [Lawrence *et al.*, 2013], contributed to the identification of geochemically distinct terranes in the northern hemisphere [Peplowski *et al.*, 2015b; Lawrence *et al.*, 2017], and provided evidence for carbon-bearing materials in Mercury's "low reflectance" spectral units [Peplowski *et al.*, 2016].

2.2 SH3 Data Product

The GRS_CAL_SH3 (SH3) products were provided to the PDS in the form of daily records. Each daily record contains the collection of measurements (data accumulations) acquired on that date, and includes:

1. *Ephemeris* – data related to the spacecraft's position (relative to Mercury) and orientation. The values represent the orientation at the midpoint of the data accumulation period.
2. *Housekeeping* – data related to the instrument status during the record.
3. *Science* – pulse-height spectrum of events recorded by the ACS, histogrammed over each data accumulation period.

The exact contents and format of each entry are described in the SH3 format file, which can be retrieved from the PDS at:

http://pds-geosciences.wustl.edu/messenger/mess-e_v_h-grns-3-grs-cdr-v1/messgrs_2001/label/grs_cal_sh3.fmt

The procedure for producing ephemeris data from spacecraft kernels, converting housekeeping data from engineering data to physical values, and calibrating the science measurements is detailed in the GRS CDR-RDR-DAP Software Interface Specification document, located at:

http://pds-geosciences.wustl.edu/messenger/mess-e_v_h-grns-3-grs-cdr-v1/messgrs_2001/document/grs_cdr-rdr-dap_sis.pdf

This section of the tutorial discusses uses of the calibrated SH3 data, located at:

http://pds-geosciences.wustl.edu/messenger/mess-e v h-grns-3-grs-cdr-v1/messgrs_2001/

SH3 products can be identified by the statement STANDARD_DATA_PRODUCT_ID = "GRS_CAL_SH3" in the product label file and by a file name of the form GRS_CS3yyyydddZZZ.TAB. The file INDEX/INDEX.TAB lists all products in the archive. The product contains a time-ordered collection of neutron spectra, ephemeris, and housekeeping data. Close to Mercury (altitude < ~6,500 km), measurements (pulse-height spectra from the ACS) were typically acquired with an accumulation period of 20 s. Far from Mercury (altitude > ~6,500 km), the data acquisition interval was increased to 300 s.

This section of the tutorial describes the process for deriving neutron counting rates from the ACS spectra in the GRS_CAL_SH3 product. This information can be used to study the composition of Mercury's surface. Individual measurements have limited statistical precision, therefore many measurements are summed (typically by location) to produce a statistically significant measurement. Prior to summing, a number of corrections are required to normalize the data to a common viewing geometry. The following sections describe these corrections, which are directly transcribed from prior analyses of SH3 CDRs data [Peplowski *et al.*, 2015b]. Analysis efforts starting from the GRS_CAL_SH3 product require similar corrections; therefore data users should consider the following text as a guide for their own efforts.

2.3 ACS Spectra: Interpretation

The ACS is composed of two pieces of boron-loaded BC454 scintillator, the "puck" and "annulus" (see Figure 4). Both pieces of scintillator are served by a single photomultiplier tube (PMT) readout. Optical pads join the puck and annulus as well as the puck and PMT. The scintillators are surrounded by reflective material on all but the PMT-facing side, producing a "light guide" effect that directs the scintillation photons toward the PMT. Within the PMT, photons are converted to electrons, which are multiplied within the PMT and are subsequently measured by a charge-sensitive preamplifier. The current in the preamplifier is proportional to the light output of the scintillator, which itself is proportional to the energy deposition in the scintillator. Because the relationship between light output and energy deposition can be highly non-linear and geometry dependent, no attempt was made to calibrate the pulse height values to energy deposition in the BC454.

For a simple geometry, e.g. a square-shaped block of BC454 coupled to a PMT, neutron interactions in the scintillator would produce a single neutron capture peak corresponding to the 2.79 MeV energy deposition resulting from the neutron capture process (section 1.2). However, two neutron capture peaks are observed in the ACS spectra (Figure 2). The GRS instrument team attributes the two peaks to the two sensor elements in the ACS – the puck and the annulus. We proposed that, due to the ACS geometry, the relationship between light output and event energy differs

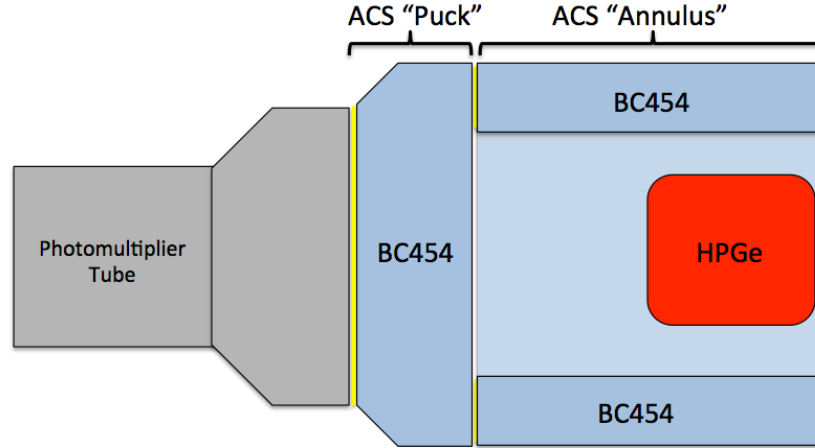


Figure 4. Simplified, cut-away depiction of the GRS Anti-Coincidence Shield (ACS). All components are labeled, except the optical coupling pads, which appear as yellow. GRS mechanical components, for instance the housing, HPGe thermal shields, and HPGe signal and cryocooler cold finger feedthroughs are not shown.

for the puck and the annulus. Specifically, the lower channel peak was attributed to the annulus, and the higher channel peak was attributed to the puck. Because channel is proportional to light output, this suggests that the PMT records more light from the puck than it does from the annulus. This result is expected given the relative distances from the PMT. This explanation for the two peaks is supported by ground-calibration data. Prior to MESSENGER's launch, an AmBe neutron source was placed next to GRS, such that the annulus had a clear field of view to the source but the puck view was obscured by the annulus. During those tests, a single peak was measured at the position of the first peak. As a result of the non-identical light collection, puck- and annulus-measured neutrons are separable. To date, only the lower-energy (annulus) peak has been used for ACS neutron mapping, due to its higher signal-to-background [Peplowski *et al.*, 2015b]. Because of the slightly different energy dependent responses of the two elements (e.g. the puck is somewhat more sensitive to high energy neutrons as compared to the annulus, see Peplowski *et al.* [2015b]) some new science may be enabled by an independent analysis of the two peaks.

2.4 ACS Spectra: Fitting the Neutron Peak

The ACS continually recorded energy deposition events within the BC454 originating from a variety of particle types (section 1.2) and, with the exception of neutron events, these interactions did not produce a particle-species-diagnostic signal (section 1.4). Although ACS events cannot be categorized on an event-by-event basis, particle types do behave in characteristic ways on the basis of energy deposition and altitude dependence. Specifically:

1. Contributions from GCR protons form a large portion of the continuum, and their ACS-incident rate varies as $1-\Omega(h)$, where Ω is the altitude (h) dependent solid angle subtended by Mercury as observed by the GRS.
2. Mercury originating neutrons, which appear within a constrained channel window in the ACS spectra (capture peaks; Figure 2), have a count rate that varies as a function of $\Omega(h)$.

3. Spacecraft-originating gamma rays, produced by GCR interactions with spacecraft materials, contribute to the spectral continuum with a count rate that varies as $1-\Omega(h)$ due to obscuration of GCRs by Mercury.
4. Mercury originating gamma rays, which contribute to the spectral continuum (mainly at low energies) with a count rate dependence that varies as $\Omega(h)$.
5. Solar energetic particles (SEPs) and energetic electron events (EEEs), which are distinguishable on the basis of their time dependence. SEP- and EEE-compromised data are flagged (value = 1) in the “bad_data_flag” housekeeping values in the GRS_CAL_SH3 product.

In principle, there is a spacecraft-originating neutron component produced from GCR interactions in spacecraft material. However, the lack of neutron capture peaks in the high-altitude spectra (Figure 2), coupled with the $1-\Omega(h)$ dependence for any GCR-induced signals, means that this background is insignificant.

Deriving the neutron count rate from the ACS spectra requires isolating component #2 from the other contributions. For any given spectrum, the statistical precision of the measurements makes spectral fitting of the continuum difficult, particularly for channels $> \sim 40$. To avoid this complication, *Peplowski et al.* [2015b] adopted an approach whereby high-altitude (HA) data is used as a template for the low-altitude (LA) background. For each LA ($< 2,000$ km) spectrum, a corresponding (same-orbit) HA summed spectrum was created from all valid (no bad data flag), high-altitude ($> 8,000$ km) data. The same-orbit criterion is tested using the “orbit_number” housekeeping value. The good data criterion is that the “bad_data_flag” has a value of zero. All spectra meeting these requirements, plus the altitude $> 8,000$ km condition, are summed in channel to produce the summed high-altitude spectrum. Bad_data_flag, orbit_number, and altitude are all reported in the GRS_CAL_SH3 product.

This HA summed spectrum was scaled to the low-altitude spectra in the background (BG) region (Figure 5) and then subtracted from the low-altitude spectrum, leaving a continuum-removed spectrum from which the neutron capture peak count rate can be easily derived from region-of-interest summing (Figure 5). This is just one approach for deriving neutron capture peak rates from ACS data, other methods are possible and should be explored by independent data analysts.

Neutron count rates are derived from neutron capture peak areas by summing all counts in the sum region of the residual (HA subtracted) spectra (e.g. Figure 5, but with raw counts not counting rates), and subsequently dividing by the “live time” of the respective low-altitude spectrum. Measurement live time (T_L) is calculated as:

$$T_L = T_A (1 - F_D)$$

where T_A is the preset integration time for the spectrum (typically 20 or 4 s at low altitudes) and F_D is the dead time fraction. F_D is calculated as:

$$F_D = 16 \times 10^{-6} \left(\frac{DTC}{T_A} \right)$$

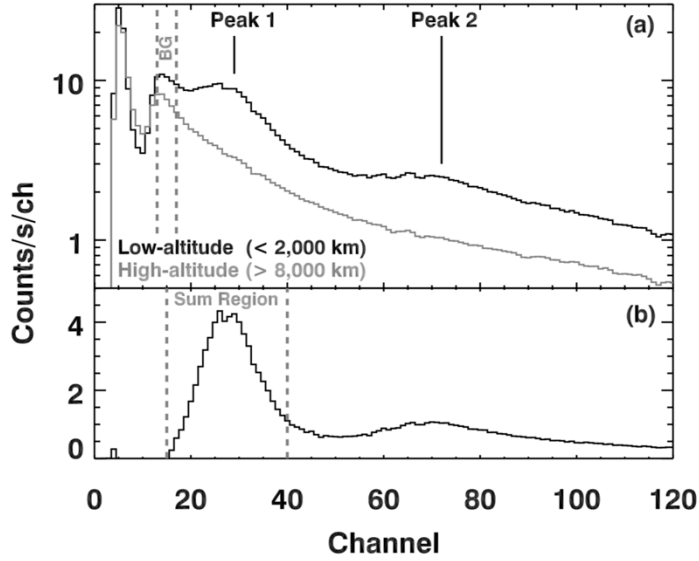


Figure 5. High- and low-altitude neutron spectra (top panel), with the peaks and background (BG) region of interest noted. Residual spectrum is high-altitude spectrum, normalized to the low-altitude spectrum in the “BG” region, subtracted from the low-altitude spectrum. In this example, the low-altitude spectrum is a summed spectrum, but in practice individual (non-summed) low-altitude spectra, which have higher statistical uncertainties, will be used. Reproduced from Peplowski et al. [2015b].

where DTC is the “dead time counter”, a scalar value that is reported in `GRS_CAL_SH3`. The DTC records the number of instances for which the GRS electronics are busy processing an event and is thus incapable of recording a new event. For the low-altitude spectra, F_D is typically $\sim 7\%$.

2.5 Neutron Count Rate: Systematic Variability

The ACS-derived neutron count rate varies predictably as a function of spacecraft altitude above Mercury’s surface, as expected given that Mercury is the source of the vast majority of neutrons measured by the ACS. Neutron count rates also vary as a function of detector orientation relative to Mercury, due to GRS-adjacent spacecraft components that can attenuate neutron signals from Mercury. The altitude and orientation dependencies in the neutron count rate are demonstrated in Figure 6, and all relevant values are reported as ephemeris information in `GRS_CAL_SH3`.

The GRS coordinate system, which defines the relative ACS viewing

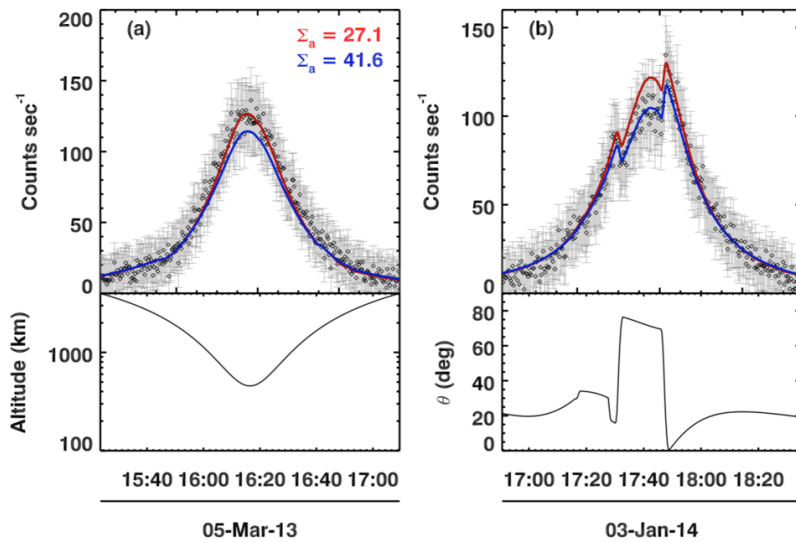


Figure 6. ACS-derived neutron count rates as a function of time (top panels of Figures a and b), with the altitude (Figure a, bottom panel) and orientation (Figure b, bottom panel) shown for comparison. Orientation is detailed via the “theta angle” θ , which is the angle between the GRS boresight vector and the nadir (spacecraft-to-planet center) vector (see Figure 7). Figure reproduced from Peplowski et al. [2015b].

geometry, is shown in Figure 7. Important parameters include the “theta angle” – the angle between the GRS boresight vector and the nadir (spacecraft-to-planet-center) vector – and the “phi angle” – the rotation of the GRS about the boresight vector. Each quantity is reported in the GRS_CAL_SH3 product. These angles define the relative position of Mercury as seen by the GRS, an important parameter given that GRS-surrounding components can attenuate the Mercury originating neutron signal. This is demonstrated in Figure 6, where a sudden decrease in neutron counts is observed at large theta angles. This is a consequence of obscuration of neutrons by GRS-adjacent spacecraft components.

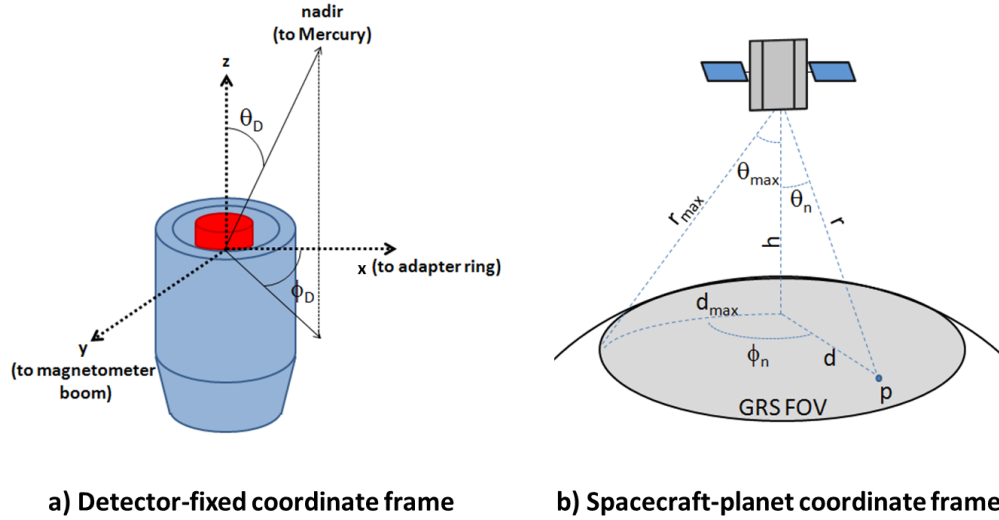


Figure 7. Illustrations of the coordinate systems relevant to GRS data analysis. Reproduced from Peplowski et al. [2012a]. Here the nadir vector, which is calculated as the vector between the spacecraft center and Mercury center, is equated with the vector between the GRS HPGe center and Mercury center. This approximation is justified due to the small size of the offset (~ 1 m) relative to the vector magnitude (>2500 km). Panel a) details the GRS sensor geometry, where red is the HPGe sensor and blue is the BC454 sensor.

GCR-induced particles, including neutrons from Mercury and spacecraft backgrounds, have a time-dependence that results from changes in the local GCR flux. These changes occur over a wide range of timescales – from long (e.g. the 22-year solar cycle) to short (day to hour scale variations in the local solar magnetic field). Of specific interest is that, as the Mercury incident GCR flux increases, so do neutron emissions from the surface. Increases/decreases in neutron count rates resulting from increases/decreases in Mercury incidence GCRs must be removed (detrended) from the derived neutron count rates, or else they might be mistaken for signatures of variable surface composition. Peplowski et al. [2015b] achieved this detrending by adopting the NS “triple coincidence counter” as a proxy for the local GCR flux. The triple coincidence counter measures the rate of particles that interact with all three of the NS sensors – events that are most likely >150 MeV protons and thus GCRs [Feldman et al., 2010]. The NS triple coincidence counter is interpolated to the time basis of the ACS data and stored in GRS_CAL_SH3. By plotting the neutron count rate vs. the “triples” rate, the time dependence resulting from GCR

variability can be detrended from the neutron measurements via a linear fit and normalization to a reference triples value (see Figure 7).

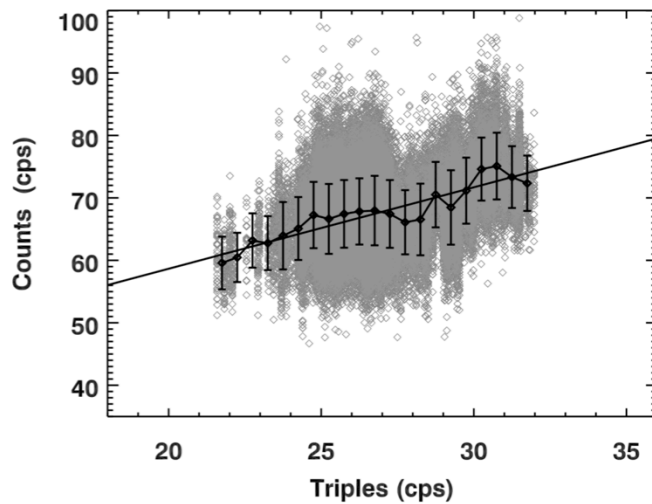


Figure 8. Measured neutron count rates (1 March 2012 to 28 February 2013), after correcting for altitude and vertical velocity, versus NS triples coincidence count rate (triples). Raw data are shown in gray, values re-binned by triples value are shown in black. Error bars are standard deviations of the binned neutron count rates. The black line shows a linear fit to the data, which can be subsequently detrended from the neutron count rate to remove the GCR dependence. Figure reproduced from *Peplowski et al. [2015b]*.

2.6 Vertical velocity

The relationship between neutron count rates and altitude is complicated by a second-order effect originating from Doppler enhancement/suppression of on the inbound/outbound portions of MESSENGER's orbit (e.g. *Feldman and Drake, [1986]*). Because this effect is correlated with altitude as a result of MESSENGER's elliptical orbit about Mercury, *Peplowski et al. [2015b]* carried out a two-dimensional correction for vertical velocity simultaneously with the altitude correction. Derivation of this correction was complicated by the relationship between latitude and altitude, which meant that latitude-dependent variations in surface composition could be mistaken for systematic variations. Because of these interrelationships, *Peplowski et al. [2015b]* leveraged radiation transport modeling in their derivation of the altitude and vertical velocity corrections. Other velocity effects were observed (e.g. relationships between the neutron count rates and the x and y components of the spacecraft velocity), but with much smaller magnitude. They were detrended from the data using empirical methods [*Peplowski et al., 2015b*].

2.7 Neutron mapping

Corrected neutron count rates were mapped to Mercury's surface (see Figure 9). These data were converted to neutron absorption using a modeled calibration between ACS neutron count rates and surface composition, and then compared to other surface composition data. Details can be found in *Peplowski et al. [2015b]*, who used just one year of ACS neutron data. Although the entire (26 month) GRS_CAL_SH3 dataset has been delivered to the PDS, as of 28 February 2017 much of the data, including that collected during the low-altitude orbits at the end of MESSENGER's mission, has yet to be analyzed and published. Low-altitude Neutron Spectrometer data from the low-altitude orbits was used to identify carbon in small

(~50-km-diameter) deposits of low-reflectance materials [Peplowski *et al.*, 2016], demonstrating the usefulness of low-altitude neutron measurements of Mercury.

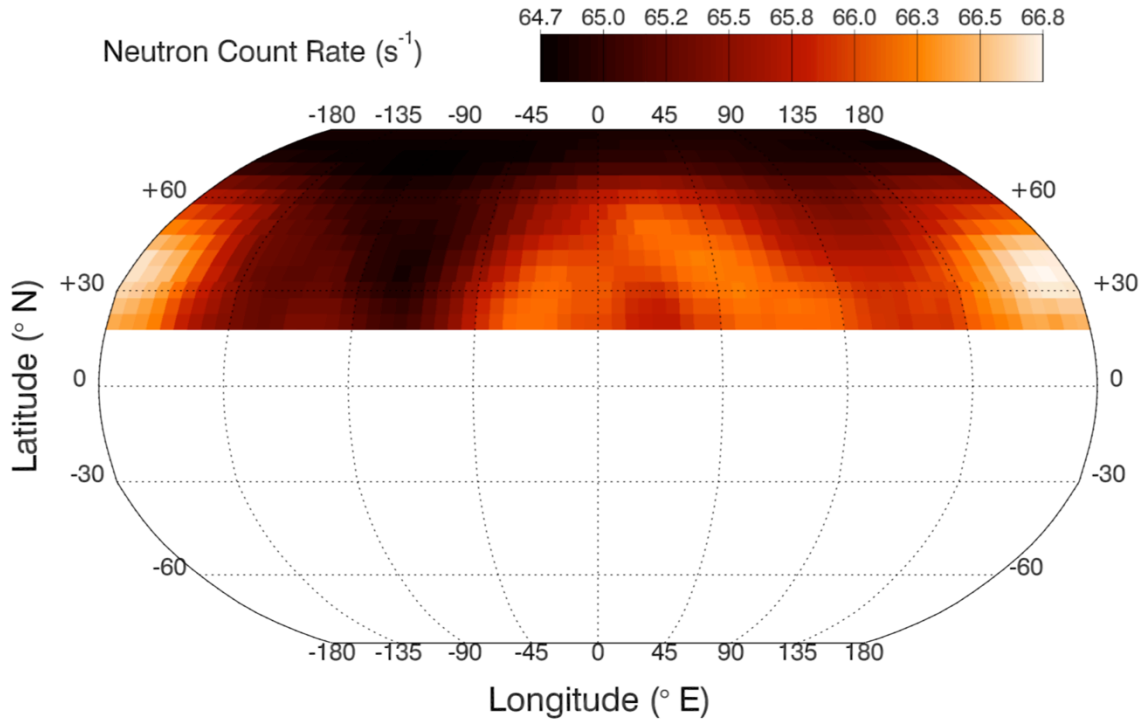


Figure 9. ACS-measured, corrected and normalized neutron count rates mapped in Mercury's northern hemisphere. Figure reproduced from Peplowski *et al.* [2015a]. Variable neutron fluxes are related to variable elemental composition across the surface.

3. Electron Event Science from the “Shield Count Rate” product

3.1 Science motivation

During Mariner 10's first flyby of the planet Mercury (in 1974), its Low-Energy Telescope (LET) – part of the Charged Particle Telescope instrument – observed bursts of energetic particles that included four high-energy events. These data were interpreted as the detection of >300 keV electrons and >550 keV protons [Simpson *et al.*, 1974]. Subsequent analysis of the data indicated that the signals could be explained by pile-up of lower-energy (<170-keV) electrons alone, such that energetic protons may not have contributed [Armstrong *et al.*, 1975]. At the time, it was unclear how Mercury's magnetosphere could provide sufficient energy to accelerate electrons to energies >100 keV [Russell *et al.*, 1988], although a number of hypotheses were subsequently put forward (e.g. Eraker and Simpson [1979]; Baker [1986]; Luhmann *et al.* [1998]).

The controversy over the nature and origin of the Mariner-10-detected energetic particle events contributed to the decision to include the Energetic Particle and Plasma Spectrometer (EPPS) on MESSENGER. The EPPS Energetic Particle Subsystem (EPS) was designed to be sensitive to 25 keV to 1 MeV electrons and 25 keV to 3 MeV protons [Andrews *et al.*, 2007], however a failure of the time-of-

flight system during cruise compromised EPS' ability to characterize ions, including protons [Ho *et al.*, 2011a].

EPS data were used to characterize [Ho *et al.*, 2011b] and eventually map [Ho *et al.*, 2012] Energetic Electron Events (EEEs) within Mercury's magnetosphere. Unexpectedly, MESSENGER's X-Ray Spectrometer (XRS) and Gamma-Ray and Neutron Spectrometer (GRNS) also proved to be sensitive to EEEs [Ho *et al.*, 2011a; McNutt *et al.*, 2011; Lawrence *et al.*, 2015; Baker *et al.*, 2016; Ho *et al.*, 2016]. Comparisons of EPS, XRS, and GRNS EEE detection rates revealed that the GRNS sensors are more efficient for EEE detection than EPS and XRS. With respect to EPS, the difference between the EPS and GRNS EEE detection rates is attributed to EPS's low geometric factor ($\sim 0.03 \text{ cm}^2 \text{ sr}$) as compared to the $\sim 2\pi$ field of view and $\geq 100 \text{ cm}^2$ areas of each GRNS sensor. Thus, GRNS sensors provide a valuable dataset for studying EEEs.

3.2 Physics of Event Detection

Analysis of EEE events from the Mercury flybys (XRS; Ho *et al.*, [2011a]) and early orbital data (GRNS; McNutt *et al.* [2011]) indicated that the EEE primary particles (electrons) have a maximum energy of a few 100's of keV [McNutt *et al.*, 2011]. At these energies, EEE electrons do not penetrate the Mg housing of the GRNS sensors ($>1 \text{ MeV}$ is required) and therefore GRNS EEE detections are not direct measurements. Radiation transport modeling shows that the GRNS EEE events correspond to the detection of secondary radiation, specifically Bremsstrahlung photons produced by the interactions of electrons within the GRNS housing materials. The Bremsstrahlung radiation produced during these interactions penetrates the housing and interacts with the GRNS sensors (Type 4 event, Figure 3). Details of the radiation transport modeling are presented in Lawrence *et al.* [2015].

3.3 Characteristics of Events as Observed by GRNS

Characteristics of EEE detections in the GRNS ACS sensor are:

1. Rapid onset of an increased event rate in the sensor, independent of the more slowly varying altitude-dependent variations in total count rate (see Figures 10, 11).
2. "Hardening" of the ACS energy deposition spectrum – e.g. increased counts are found at preferentially at low pulse height values in the ACS pulse height spectra (e.g. Figure 5 for example ACS spectrum).
3. Detections occur within the Mercurian magnetosphere.

There are several methods for automatically detecting EEEs in the ACS dataset using the GRS_CAL_SH3 and/or GRS_CAL_SCR products. One option is to perform a high-bandpass filter of the SCR data or SH3-derived count rates to remove the altitude dependence of the ACS count rate time series. Outlying values are then flagged as candidate EEEs. An example of this kind of analysis is shown in Section 3.5. Note that prior to performing this procedure, the ACS dataset should be filtered to remove data acquired during solar particle events (SPEs), which could be mistaken for EEEs. SPE-compromised data is indicated as such by the "BAD_DATA_FLAG" values reported in GRS_CAL_SH3 and GRS_CAL_SCR.

Mariner 10 data showed time structure in EEEs at the 3-min timescale of the LET measurements. The “burst mode” of the NS provided evidence for time structure at the 1-s timescale. Characterizing sub-1-s timescale structure was not possible before the 25 February 2013 GRNS flight software patch, which added the 10-ms count rate measurements (GRS_CAL_SCR product) to GRS science products. These measurements are the highest-time-resolution measurements of Mercury’s EEEs to date, and facilitate detailed studies of the EEE acceleration mechanism [Baker *et al.*, 2016]. Time-domain analysis of an EEE event with the SCR products is detailed in Section 3.6.

3.4 SCR Data Product

The GRS_CAL_SCR (SCR) products were provided to the PDS in the form of daily records. Each daily record contains the collection of measurements (data accumulations) acquired on that date, and includes:

1. *Ephemeris* – data related to the spacecraft’s position (relative to Mercury) and orientation. The values represent the orientation at the midpoint of the data accumulation period.
2. *Housekeeping* – data related to the instrument status during the record.
3. *Science* – pulse-height spectrum of events recorded by the ACS, histogrammed over each data accumulation period.

The exact contents and format of each entry are described in the SH3 format file, which can be retrieved from the PDS at:

http://pds-geosciences.wustl.edu/messenger/mess-e_v_h-grns-3-grs-cdr-v1/messgrs_2001/label/grs_cal_scr.fmt

The procedure for producing ephemeris data from spacecraft kernels, converting housekeeping data from engineering data to physical values, and calibrating the science measurements is detailed in the GRS CDR-RDR-DAP Software Interface Specification document, located at:

http://pds-geosciences.wustl.edu/messenger/mess-e_v_h-grns-3-grs-cdr-v1/messgrs_2001/document/grs_cdr-rdr-dap_sis.pdf

This section of the tutorial discusses the calibrated SCR data (CSC), located at:

http://pds-geosciences.wustl.edu/messenger/mess-e_v_h-grns-3-grs-cdr-v1/messgrs_2001/

The specific example data product that was used for the analysis presented in this section is the CSC file including data acquired on 1 April 2013, which can be retrieved at:

http://pds-geosciences.wustl.edu/messenger/mess-e_v_h-grns-3-grs-cdr-v1/messgrs_2001/data/2013/04/grs_csc2013091zzz.tab

SCR products can be identified by the statement STANDARD_DATA_PRODUCT_ID = "GRS_CAL_SCR" in the product label file and by a file name of the form

GRS_CSCyyyydddZZZ.TAB. The GRS_CAL_SCR data take for form of a time-ordered collection of ACS event totals (per 10-ms interval), ephemeris, and housekeeping data. Close to Mercury (altitude < ~6,500 km), measurements (number of events detected by the ACS) were acquired at 10-ms-intervals within an accumulation period of 20 s. Far from Mercury (altitude > ~6,500 km), the data acquisition interval was increased to 300 s.

The 10-ms-interval event totals were recorded as individual entries within a 16,384-ch-long array that was repurposed from a prior data product (section 1.3). For example, entry 20 of the array was acquired 200 ms into the respective accumulation period and represented the total number of events recorded by the ACS in that 10-ms interval. The array is not always fully populated; close to Mercury, the GRS data acquisition interval is 20-s, and 20-s divided by 10-ms is 2000. Accordingly, only the first 2000 channels of the shield count spectra array are populated in that scenario, array entries with channel >2000 are zero. For the 300-s-long accumulations, there are 30,000 measurements and all measurements beyond the 16,384th entry in the array are summed in that final (overflow) channel. Finally, note that the first ~50 channels of every SCR science array are empty. This is due to the fact that, at the beginning of each accumulation period, the GRS electronics are “busy” closing the previous file and as a result are do not process new events for ~500 ms.

3.5 Identifying EEE events with the ACS

As an example of one methodology that is useful for identifying EEEs, consider the ACS data collected on 1 April 2013 (GRS_CAL_SCR file = grs_csc2013091zzz.tab, see section 3.4). This dataset contains 1967 measurements, each corresponding to a separate GRS integration period (20 s at low altitudes, 300 seconds at high altitudes). For GRS_CAL_SH3 data (section 2.2), the total count rate per integration can be derived by summing over all channels in the 1064-ch-long Shield pulse height spectrum, denoted “Shield” in GRS_CAL_SH3. For the SCR data product, the total count rate per GRS accumulation period (e.g. 20-s at low altitudes) can be derived from the 10-ms measurements by summing over all values in the 16384-ch long “shield count spectra” in GRS_CAL_SCR. In all cases, count rates are derived from total counts by dividing the respective count rates in each integration period by the dead-time corrected accumulation time (section 2.4).

Figure 10 plots the ACS count rates, derived by summing over the “shield count spectra” in 1 April 2013 GRS_CAL_SCR product divided by the integration time, as a function of time. The figure also includes the spacecraft altitude. It is apparent that during each close (periapse) approach to Mercury, the total count rate in the ACS increases to a peak of ~500 counts/sec. Far from Mercury, the nominal rate is ~200 counts/sec. Contributions to the count rate include GCRs, Mercury originating neutrons and gamma rays, and EEE events, which have altitude dependencies that are discussed in section 2.3.

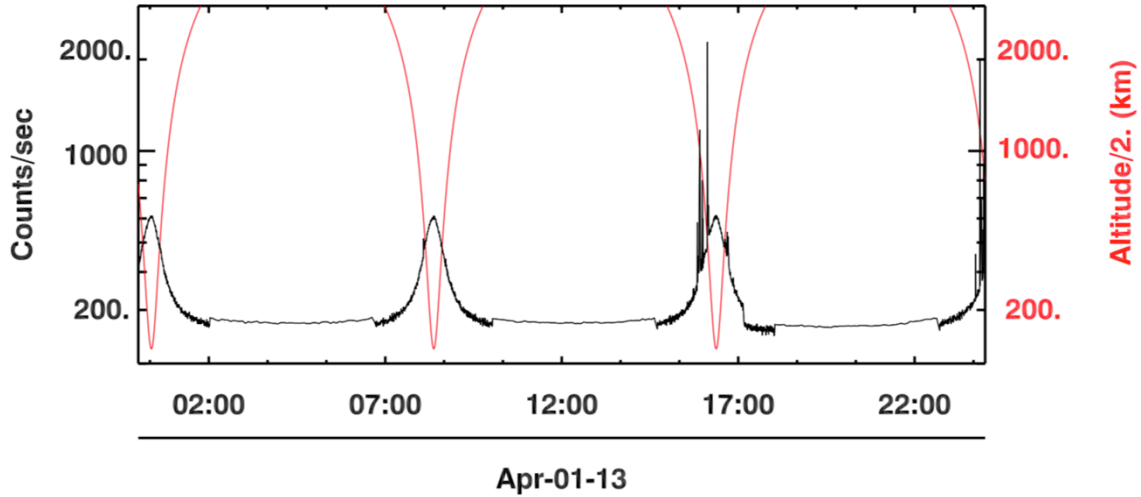


Figure 10. Time series of the total count rate in the ACS (summed over integration period) on 1 April 2013. The altitude is overplotted in red, and serves to highlight the correspondence between count rate and proximity to Mercury. EEEs manifest as rapid, short-lived increases in the measured count rate, which for this example appear just prior to the third periapse pass over Mercury (around 16:00).

On 1 April 2013, EEEs were measured just prior to the third periapse pass over Mercury ($\sim 16:00$ in Figure 10). While the EEEs are apparent in the time-series data, a methodology for isolating the individual data records with EEE events is desirable. In the past, the GRNS instrument team utilized a “high-pass filter” (HPF) methodology to isolate EEE events. The HPF method relies on the fact that the time scale for EEE variability is significantly shorter ($< \sim 1$ min) than the timescale for other variability, which is primarily altitude dependent.

Use of a HPF to isolate EEE events is shown in Figure 11. For this process, a 100-channel-wide boxcar smooth of the ACS time series (red line, Figure 11 top) is calculated from the raw time-series data (black, Figure 11 top). The difference between the raw and smoothed data (termed residual and shown in Figure 11 bottom) highlights periods for which the ACS count rate diverged from the trend derived from the smoothed time series. EEE events can be flagged in the residual data via application of a simple threshold (orange points, Figure 11 bottom) or a more complicated statistical analysis (e.g. *Lawrence et al.* [2015]). For this example, an arbitrary EEE threshold of $250 \text{ counts sec}^{-1}$ residual was applied, and the events classified as EEEs are shown in orange points in Figure 11 (bottom).

The eight GRS_CAL_SCR records that meet the EEE detection criteria for the 1 April 2013 example are entries 1292, 1293, 1294, 1296, 1297, 1308, 1334, and 1335. They all occurred during orbit 1848, at altitudes ranging from 2,100 to 900 km from Mercury. For each event, GRS was near nadir looking, as the angle between the GRS boresight and the spacecraft-to-planet vector was $\sim 25^\circ$ or less. Note that it is important to examine the spacecraft ephemeris carefully, as a sudden change in orientation (e.g. nadir angle, an ephemeris value provided in all GRS_CAL_SCRs) can induce a rapid change in the count rate that might be mistaken for an EEE using the HPF methodology.

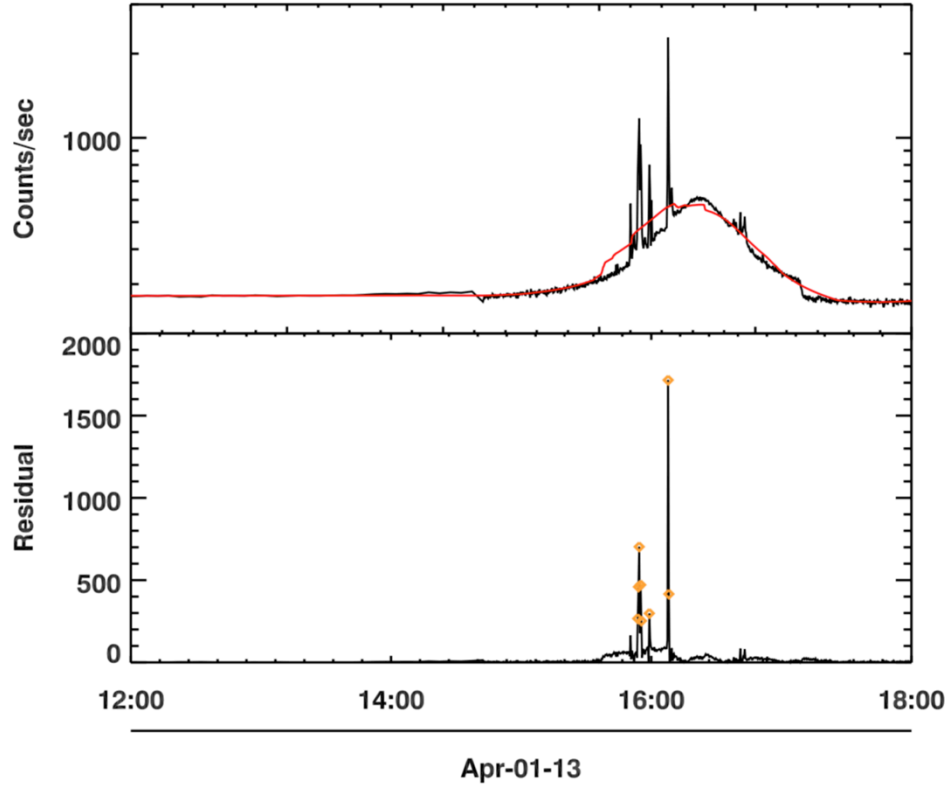


Figure 11. (Top) ACS count rate time series, in black, and a 100-channel-wide boxcar smooth of the time series, in red. (Bottom) Residual count rate, calculated as the raw time series minus the smoothed time series. Those residual values above 250 counts sec^{-1} , an arbitrary threshold, are defined as EEEs.

3.6 Plotting the 10-ms Resolution Measurements

The prior example, which examined data collected on 1 April 2013, resulted in the classification of eight SCR records as having recorded an EEE event. This section examines one of these events, which occurred during measurement #1334, in detail using the 10-ms-resolution measurements.

Measurement 1334 represents a single, 20-s long GRS accumulation period. Within that period, the count rate in the ACS was recorded at a 10-ms cadence in the 16,384-channel-long “shield count spectra” array (in `GRS_CAL_SCR`). Note that 20-s divided by 10-ms is 2000, and accordingly we observe that only the first 2000 channels of the shield count spectra array are populated. Entries with channel >2000 are zero. Also of note is the fact that the first 56 channels of the array are empty. This is due to the fact that at the beginning of each accumulation period, the GRS electronics are “busy” closing the previous file and as a result are blind to new events for ~ 500 ms. This is true for all SCR shield count spectra arrays.

In order to examine the time-structure of the EEE event sampled before, during, and after measurement 1334, we concatenate the ACS count rate measurements from the first 2000 channels of records 1332-1336. The result is shown in Figure 12. Some general observations of this data include:

1. While records 1334 (red) and 1335 (orange) were flagged as including EEE detections using the HPF method (see section 3.5), Figure 12 shows that the EEE started toward the end of the prior record, 1333 (purple).

2. There is “missing” data at the beginning of each record, which is the previously mentioned ~500-ms-long dead period of the GRS electronics.
3. During the highest-count-rate periods, there are periodic dips in the count rate that are likely an artifact of the ACS electronics processes. They should not be interpreted as a manifestation of a physical property of the EEE event.
4. Within the EEE, there are two obvious forms of time variability – a sharp increase followed by a slower decrease, along with a “beat pattern” having a period of ~5000 ms.

The midpoint mission elapsed time (MET) for each record is listed in the plot, as is the throughput-induced deadtime fraction for each record. MET is included in GRS_CAL_SCR, and deadtime was calculated as described in Section 2.4. Note that deadtime peaks during the middle record (1334). Normally, the deadtime would be useful for correcting the count rate (e.g. Peplowski et al., 2015), however in this scenario caution must be used as the reported deadtime is the average for the record (e.g. 1334) and does not necessarily represent the value for each (10-ms-long) channel in the SCR count rate array.

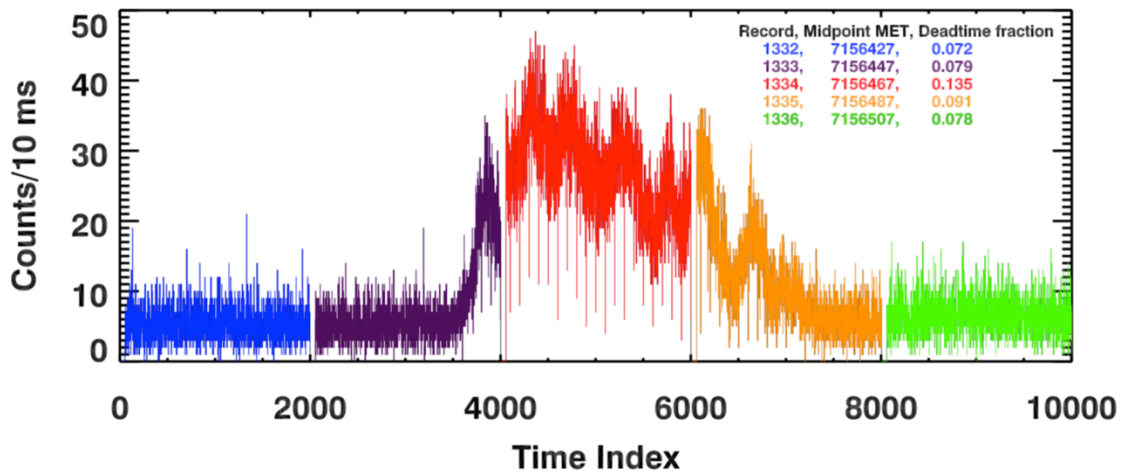


Figure 12. Count rate in the ACS (counts per 10-ms bin) as a function of time, for records 1332-1336 of the 1 April 2013 SCR CDR. Data for each record is color coded (see legend). The time series was constructed by concatenating the first 2000 channels of the “shield count spectra” for each record. The records were collected at midpoint mission elapsed times (METs) as listed.

Examining the time structure of EEE events reveals features that may be indicative of EEE acceleration mechanisms. This EEE is approximately 3500 channels (35 s) long, with a relatively fast onset (~1000 channel, 10 s long) and a longer (~3000 channel, 30 s long) die-away time. Within the event, there is a superimposed ~500 channel (5 sec) periodicity, as revealed by a fast-Fourier transform (FFT) of the time series. FFT analysis is valuable for identifying periodicity in EEE events (e.g. Lawrence et al. [2015]). When considering EEE time structure, it is important to remember that MESSENGER is moving throughout the event. So the onset and length of the EEE may be related to the event itself, or the spacecraft’s motion through the region of Mercury’s magnetosphere occupied by the

EEE. *Lawrence et al.* [2015] mapped EEE locations and found that they occupied a specific region of Mercury’s magnetosphere, but that they are not always present.

In the EEE event classification scheme of *Lawrence et al.* [2015], the EEE event shown in Figure 12 would be classified as a “bursty” EEE event. This contrasts with the “smooth” events, which show little structure at time scalers smaller than the duration of the event. ACS measurements include both types of events, and the high time resolution of the ACS measurements makes this dataset a unique resource for studying EEEs. *Baker et al.* [2016] studied a small subset of EEE ACS events, however the vast majority ACS-detected EEEs are, as of this writing, unexamined and unreported in the literature.

3.6 EEE parent population

The nature of the electrons incident on the ACS during an EEE can be constrained via the ACS pulse-height spectrum. Pulse height is an indication of the energy deposited by the ACS-incident particles, although as noted in section 1.2, the relationship between pulse height and energy is both nonlinear and not calibrated.

The raw ACS spectrum contains contributions from all events incident on the ACS, which can include neutrons, gamma rays, GCRs, and other charged particles (including EEEs). Section 2.3 provides additional details on sources of ACS signal. The EEE-originating contributions to the ACS pulse-height spectra can be isolated by characterizing the difference spectrum, e.g. the difference between the spectra acquired during the event relative to that immediately before and after the event. This process is illustrated in Figure 13 for the event shown in Figure 12, where the shield spectrum during the EEE (Records 1334 + 1335) is shown, along with the spectra acquired before and after the event.

Figure 13 (bottom) shows the difference spectrum, which we attribute entirely to events corresponding to the EEE. The lack of a clear energy calibration complicates the interpretation of the spectrum, however we know that channels ~30 and ~70 are at 2.79 MeV (neutron capture peak) for the annulus and puck, respectively. Even without an accurate energy calibration, several useful observations can be made. The power-law-like shape of the spectrum supports the hypothesis, detailed by *McNutt et al.* [2011] and *Lawrence et al.* [2015], that EEE detections by the ACS are measurements of electron-induced Bremsstrahlung. So does the lack of any structure (the apparent structure below channel ~12 is due to the detector and electronics readout).

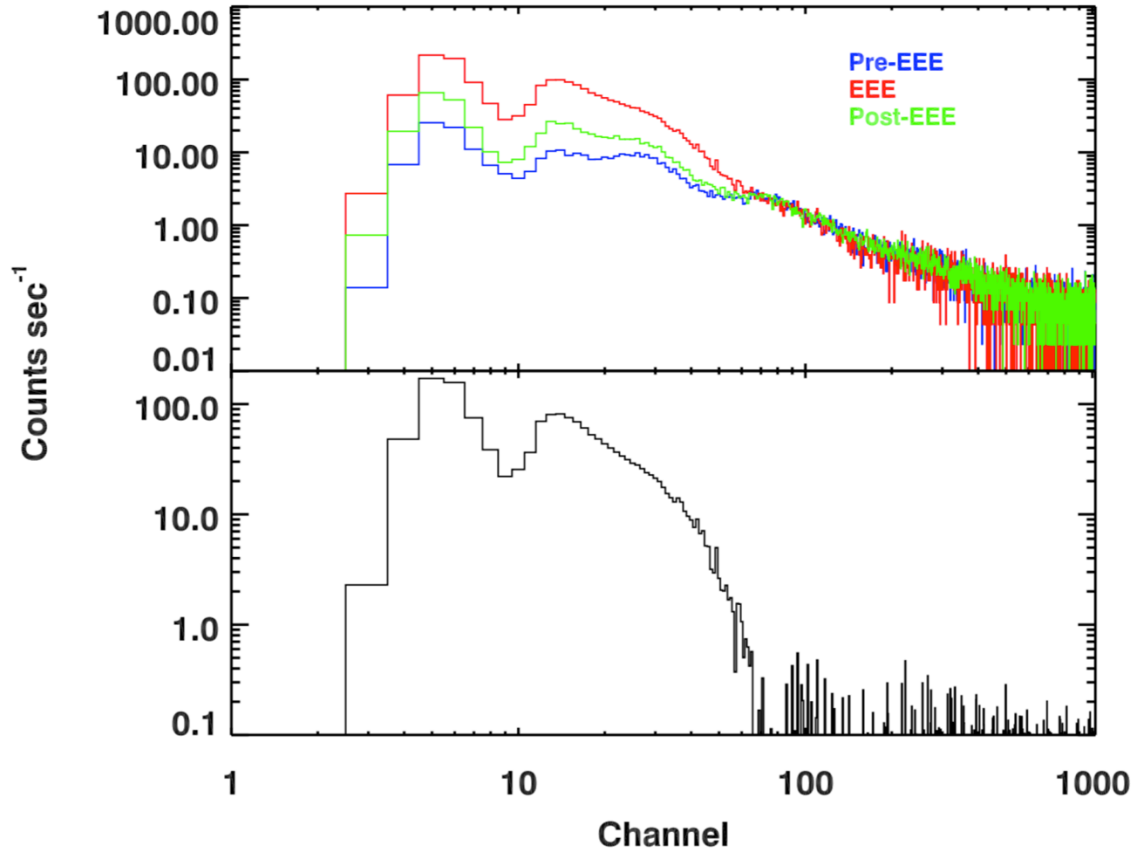


Figure 13 – (Top) Pulse-height spectra from the ACS before (blue), during (red), and after (green) the EEE detailed in Figure 12. The color code is the same as Figure 12. (Bottom) Residual spectrum (EEE spectrum – mean Pre-/Post-EE spectrum), which highlights the portion of the ACS pulse-height spectrum that can be attributed to the EEE. The channel scale of the SHI spectra is discussed in section 1.2.

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