# Hardware, Software, Science Planning, and User Support Management of Space Radiation Damage to the Spitzer InfraRed Spectrograph Detector Arrays (with an attempt at some context with PACS and the Herschel Space Observatory)

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# 1. Preamble

Documentation which summarizes the on-orbit effects of space weather on the performance of the IRS detector modules at lower levels of the detector physics and effects on and from the shared electronics is not available. A top-down overview of temporal trends of pixel behavior and particle-induced noise in extracted spectra is also not (yet) written into a detailed report, of the kind published by Heras et al. (2000) on SWS detector performances over the length of ISO's cold mission. Aspects extracted from systematic analysis and monitoring of campaign-based calibration observations, judged to be of highest importance to end users for science planning and analyses, are described in the Spitzer Observer's Manual (SOM, online), with links to periodically updated sensitivity tables, qualitative descriptions of impacts on performances, and AOR planning recommendations. Presentations made by IRS Instrument Support Team (IST) at SSC-sponsored data reduction workshops also provide descriptions useful to end users. Similarly, formal and detailed reports on MIPS detector performances are not publicly available. However, descriptive general context with instrument operations planning can be drawn from lessons learned from responses to space weather effects on the IRS.

# 2. IRS and Spitzer Camera Detectors

The IRS uses four Boeing Si:As and Si:Sb BIB detector arrays in 128x128 pixel formats. The As-doped arrays are used at the shorter wavelengths (5-20 μm), the Sb-doped arrays cover the longer wavelengths (20-38 μm).

## 2.1 The Si:As detectors.

The IRAC 5.8, 8.0, and MIPS 24 μm modules also use Si:As arrays, where the MIPS 24 μm detector is also a 128x128 array of identically-sized pixels fabricated by Boeing Technologies and Research. IRAC's Si:As arrays are built by Raytheon Corp. The five Si:As arrays are each operated at different cryogenically maintained temperatures, and at different bias levels, and they exhibit *essentially* no lasting changes in photometric sensitivities or dark current properties by impacts from energetic cosmic and solar particles or their secondaries on the detectors and associated electronics. In other words, elevated pixel signal in latency from an impact while signal accumulates up the ramp is generally mitigated in subsequent signal ramps by voltage reset and bias boost (pertaining to IRS and MIPS). Pixels saturated to the A/D limit that continue to exhibit hysteresis generally recover following periodic annealing. IRAC employs fowler-sampling for data readout, and also anneals periodically.

Nonetheless, the IRS Si:As arrays are more generally more susceptible than MIPS-24 to radiation effects on its pixels. This is partly a consequence of differences in operating temperatures (IRS at 4.7-6.2 K, MIPS-24 at < 4.2 K), bias settings, and handling of multiplexed channel readouts, with the effect of increasing the MIPS-24 well depth to about twice that of the IRS Si:As pixels. Pre-flight requirements on radiation damage to pixels are more lax for the IRS, < 5% at an electron fluence of > 40 e-/s, compared to < 3% damaged pixels at > 150 e-/s for MIPS-24. For the IRS, moreover, degraded pixels have a selectively greater influence on its data products, measured in terms of the signal/noise ratios of extracted spectra (this will be shown below).

At no time has it been judged necessary to adjust the operating parameters of the IRS Si:As arrays, leaving mitigations to data processing methods and observing strategy recommendations (described below).

## 2.2 The IRS Si:Sb detectors.

Space weather (solar weather more correctly) is not benign to the IRS Si:Sb arrays, especially the detector used with the long wavelength echelle module (Long High, or LH). The 3$^{rd}$ largest solar flare in the last 25 years occurred during the Science Verification phase of In-Orbit Checkout, dumping 1.9 x $10^9$ protons $cm^{-2}$ (integrated) on the arrays, amounting to roughly half the dosage predicted for the 2.5 yr nominal mission lifetime. Particle energy levels could not be directly measured, as Spitzer carries no dedicated radiation detector, but the event was classified by NOAA GOES-2 to yield ~1000 particles $s^{-1}$ $sr^{-1}$ $cm^{-2}$ with energies exceeding100 MeV. IRS was powered on during the storm, with resulting damage to ~4% of the LH pixels, and degraded responsivities of many more pixels. Figure 1 shows the dramatic differences to the LH array before and after the flare event.

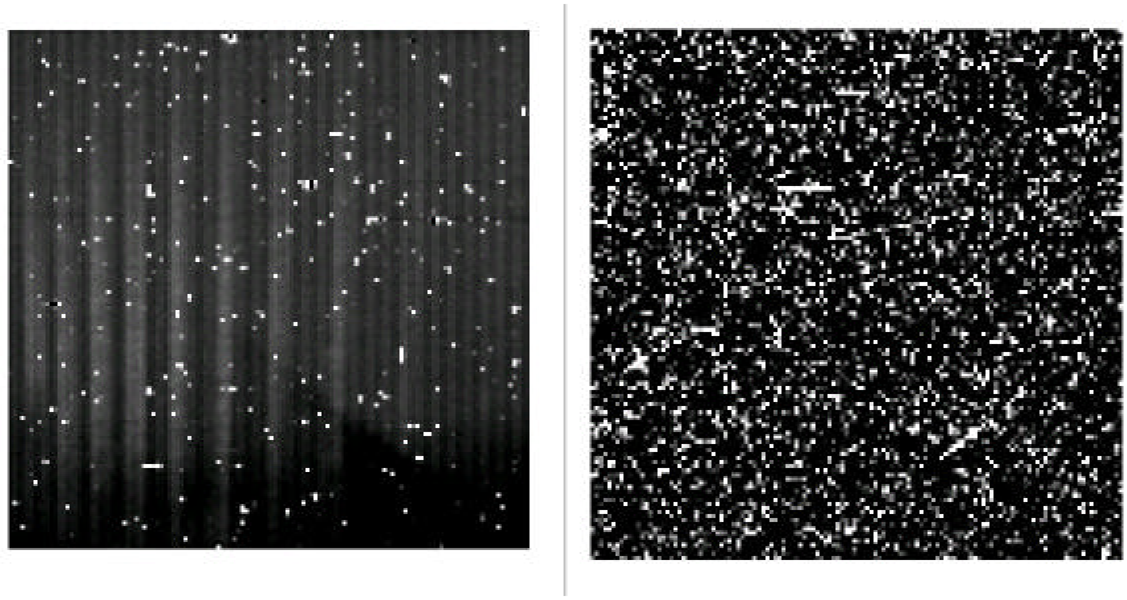

**Figure 1** The LH array, during a checkout campaign over 27-28 Oct 2003, starting with dark current measurements as part of the standard startup sequence (left, 27/11/03, Reqkey 7645440) and at the end of the campaign (right, 28/11/03, 7645184). Greyscale stretch is the same on bothsides. 4% of the pixels were permanently damaged by energetic protons from the solar flare. In both examples the telescope was pointed at the north ecliptic pole for dark sky measurements. Most of the impacts visible on the left-hand image are due to cosmic rays, and could be removed by thermal annealing.

The condition of the Si:Sb arrays following the solar flare required that they be operated at reduced bias voltages, on the basis of pre-launch radiation tests at the Harvard Cyclotron Laboratory and the Cornell Detector Physics Laboratory which indicated how warm and hot pixels would respond photometrically at different bias settings. In operations this required a quick a turnaround (~36 hours) of data analysis, assessment of the optimum setting turned into an uplink patch, and evaluation of performances. The solar storm of 28/11/03 occurred 5 days before the first full Science Verification campaign for IRS to take a large suite of spectral, photometric, and optical calibration observations of celestial standards. The effort to adjust the operation of the Si:Sb arrays in time for this campaign was over the workload projected during this period of checkout for the instrument team and schedulers (a mini-campaign had to be inserted), and introduced a discontinuity with 5 weeks of earlier calibration results.

The flare of 28/11/03 currently stands as the strongest since Spitzer's launch, but several lesser events have occurred in the meantime, and the Si:Sb arrays have continued to accumulate pixel damage in two forms:

1. Permanent damage, where pixel signals are persistently hot at the A/D limit;
2. Unruly or "rogue" behaviour, with unstable photometric response, and drifting dark currents on timescales of hours to days (or campaigns).

In neither case does thermal annealing work to recover pixels identified to be bad or unruly. Voltage annealing and stim-flashing are also ineffective.

The plot in Fig. 2 shows the trend in the number of rogue LH pixels over the Routine Phase (starting Dec 2003). An average of 1.5 pixels/day turns to rogue behavior (here rogue now refers to both unruly pixels and persistently hot pixels).

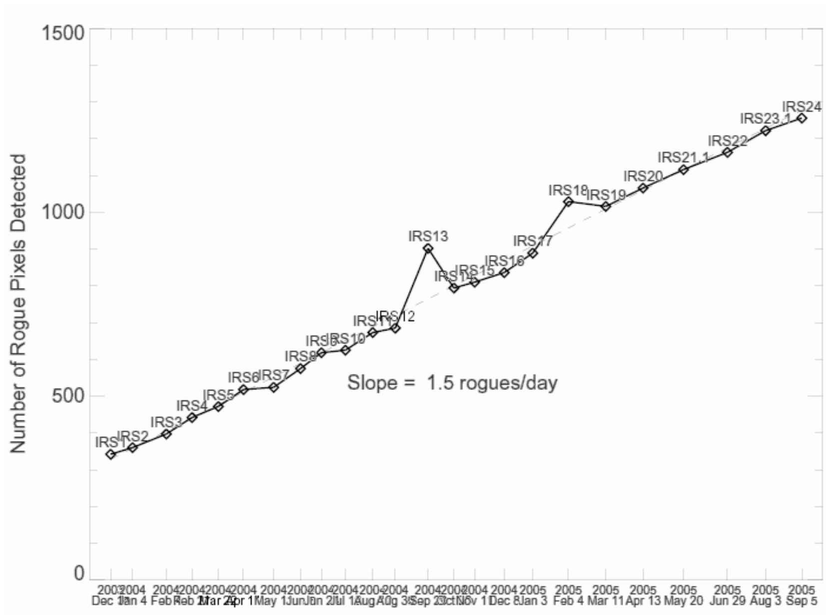


**Figure 2** Number of LH pixels exhibiting rogue behaviour since beginning of Routine Operations, demonstrating the accumulation of radiation damage since downward adjustment of the bias voltage near the end of the In-Orbit Checkout phase. [By J. Ingalls, from the SSC's public pages.]

## 3. Impact of the Space/Solar Weather on Calibrations and Science

The presence of permanently damaged or otherwise unstable pixels imposes complications to carry out calibration analyses --- complications which were not well anticipated before launch mainly because it was not expected that a one-day rain of particles would expose the arrays to 50% the dosage predicted to accumulate over the nominal 2.5-year mission.

The detectors were not recalibrated during the checkout phase with flight updates to signal ramp linearity, pixel photocurrent coupling, charge bleed (in CCD terminology) and other inter-pixel calibrations, which imposed systematic errors and non-gaussian noise on the first set of inflight photometric calibrations (flatfields and flux scales). Signal/noise ratios in level 2 (extracted spectra) data products are of course limited by errors in the fitted readout and correlated errors in the response calibrations, which are dependent on the basic detector calibrations. It has been incorrectly stated to users that the *sensitivities* have been limited specifically by the quality of the flatfielding and residual fringing, but these affect the final signal/noise ratios, whereas the sensitivities are basic internally to the detectors (read noise, shot noise, DQE), the telescope and passband optics.

The effort to achieve reliable detector calibrations over science operations has been hampered by complications with numerous rogue pixels, in such ways as:

1. Establishing the quantitative criteria for roguish behavior (which is probably present in the majority of the pixels, but is approached as a threshold);
2. Re-examining the method to handle the rogues, since pixel photometric response and dark currents are affected by neighboring pixels (they cannot be masked from analysis);
3. Considering possible temporal variations in linearity, responsivities, and dark current drift as the arrays age.

The impact on the subsequent photometric calibrations is obvious, flatfielding and flux conversion cannot reverse pixel damage or unambiguously restore signal where it was lost. The concept of super-flats and super-darks (applied to science observations across many campaigns) had also to be relaxed, as the goal of approaching noiseless calibrations by combining many calibration measurements could not be achieved in a straightforward way with the changing state of the arrays. Nonetheless, detector calibrations at a given bias setting are treated as static.

Assuming well-calibrated detectors at the basic (linearity, dark currents, coupling coefficients) and photometric (flatfields, flux calibration) levels, science observations will still exhibit poor continuum signal/noise ratios and false emission lines in spectra extracted from the spectrograms peppered with NaN's or unreliable signals from the rogues. The reason is that the extraction elements contain several pixels in both directions (dispersed and spatial), and 5-10% truly errant pixels and an undetermined number of grey cases randomly distributed on the array will degrade an unacceptably high number of extraction elements, especially in LH data. Figure 3 shows an example.

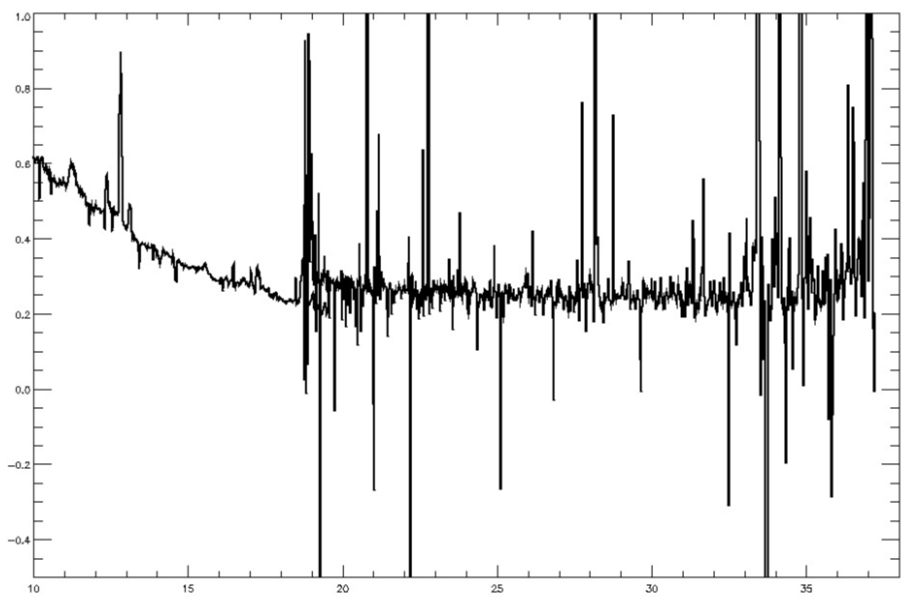


**Figure 3** SH and LH spectra of a stellar source, extracted in the standard pipeline. Noise in the LH spectrum is due to numerous outlying pixels within the 2-D extraction elements, not well treated by default dark current or pixel-pixel response calibrations.

# 4. Managing the Problem

## 4.1 Operating Parameters

Detector biases have been adjusted twice since launch, LL and LH initially after the 28/11/03 solar storm, and LH in August 2005. The adjustments are technically well justified by the instrument team's knowledge and expectations on pixel recovery from existing radiation damage, tested with engineering experiments on orbit.

The most serious disadvantage to altering a fundamental detector operating parameter is the burden on the ground segment, for building a new complete set of calibrations (detector and higher spectrophotometric), implementing the time dependencies in science data processing, accommodating the break of continuity in trending and statistical calibration work, and documenting and communicating the sensitivity changes to the users. The work is several FTE months (urgently crammed into the checkout phase for the first adjustment), and is generally the same for any space-borne instrument which does not acquire a complete set of measurements which can be used to independently calibrate every science observation on the fly. Science operations management usually regards changes to fundamental operating parameters as a last resort to rebalance the science returns.

## 4.2 Contemporaneous Pipeline Calibrations

In the case of the IRS, dark current measurements are taken several times per campaign at all of its integration times on the darkest patch of sky within Spitzer's constant viewing zone. Pixels with slow drifts in response and dark current levels are more accurately corrected during dark current subtraction using facility measurements taken nearest in time, or at least on a campaign basis. These replace the standard or "fallback" dark current calibration files applied to all observations (at the same detector bias) in second-pass pipeline processing.

The mitigations are not complete, however, with errors remaining in pixels with short-term drifts and others affected by impacts in the time elapsed between science and the applied dark current measurements. The nearest-in-time strategy also requires a second pass of processing in the pipeline once all data from the campaign have been downlinked, and multiple dark current calibration files have been created (and their quality assured) in a calibration thread designed for this purpose, then substituted for the time-independent fallback. The correct file is then automatically picked by software for subtraction of the dark currents from science observation by their timestamps. The overall signal/noise levels of nominally-behaving pixels are reduced in this scheme, since they cannot be optimized by combining many measurements. This scheme also implies additional calibration observing time, contrary to the goal of increasing instrument science observing efficiency after checkout phase, which did result in a number of early campaigns with only single dark current measurements.

## 4.3 Pipeline Software

Cosmic ray detection, flagging and correction are done in stages in the pipeline, using a scheme which is similar to that used in ESA's ISO-SWS offline pipeline. This has some effect to estimate more accurate signal ramp slopes on pixels exhibiting a jump in signal above some read-noise threshold during integration, but does not attempt to identify or treat pre-existing instability or transfer information to the processing of subsequent exposures. In other words, all basic (level 0 to level 1) processing is done on a data collection event or integration basis, and only tables or image data served from a calibration server provide parameter values across observations.

## 4.4 Observation Planning

Since the end of the science verification phase of checkout it was immediately obvious that OFF-source observations acquired immediately preceding or following the ON-target observations, and consistent with the ON observations, provide the best means to mitigating the drifting behavior of rogue pixels. These are guaranteed to be more contemporaneous with the state of the arrays than the nearest-in-time dark current observations. Most all calibration observations acquired by the SSC for photometric work with celestial sources include OFF observations since early in the Routine Phase, for optimal correction of the pixels and removal of the diffuse background fluxes.

However, OFF observations are paid by the observer, and dark current calibration measurements are paid by the facility. The reluctance to enforce (through AOT change) or strongly urge (via user support) observers to acquire OFF observations at their program expense at least for the most affected array left uncertainty or little knowledge by most guest observers to distinguish the benefits of standard and discretionary calibrations, unresolved until the GO2 cycle.

## 4.4 Interactive Software

The condition of the arrays at campaign startup and shutdown is tracked by the SSC and Cornell instrument team, and masks which identify pixels evaluated to exhibit unsteady photometric response and dark current levels are made available to users. Figure 4 shows masks applicable to the beginning of science operations and the current state for contrast. The masks are represented as the number of rogues near the end of each campaign, and may be used in interactive software under development to re-estimate the affected pixel signals using neighboring pixels in flanking rows (cross-dispersed). This is meant to be done on the 2-D data prior to extraction of the spectra. Methods are being worked out to identify rogue pixels on-the-fly from the science observations, to improve on the time resolution of pixel condition during science data collection. This is the first interactive application specifically designed to treat the problem, soon to be released via SSC user support.

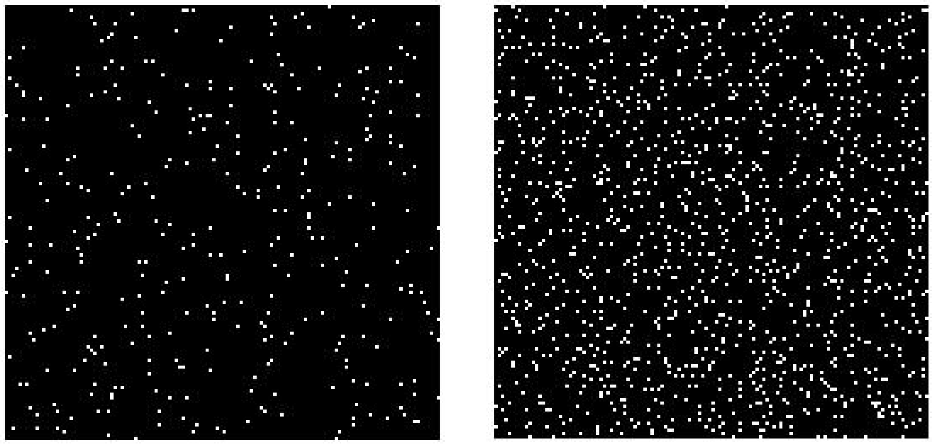

**Figure 4** Rogue pixel masks for the LH array provided to users by the SSC. The left and right correspond to the 1st and 24th IRS science campaigns.

4.5 User Outreach: What do “sensitivities” in harsh space weather mean?

Response to detector damage by space weather involves characterization of the performances, translated into terms understandable by the user community necessary for science observation planning to the users’ detection requirements. From experience, users fully expect to plan around instrumental sensitivities of the total system, for predicting signal/noise ratios as realistically as current knowledge of the instrument’s performance allows. Therefore, and also from experience, it is crucial not to distinguish or segregate space weather output noise in the sensitivity figures communicated to users for time estimation. Sensitivities estimated from pixels explicitly selected to be unaffected by cosmic radiation provided ideal measures by which to compare to ground-based sensitivities and performance predictions in a radiation-free but unrealistic environment, and the idealness resulted for many users in overestimated signal/noise ratios, entangled with the state of basic detector signature removal through the first year of science operations. The developing state of pipeline data processing to restore signal information in damaged pixels and affected neighboring pixels is an unsafe guarantee on improvements to signal/noise in the final data product, varying on a case by case basis. Sensitivity is instead defined by detector performance, and detector damage impacts sensitivity that users understand.