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Stability of Mid-Infrared Detectors for Future Space-based Transit Spectroscopy Measurements

Craig McMurtry, Judith Pipher, William Forrest, Meghan Dorn, Mario Cabrera

University of Rochester

Outline

- Requirement drivers for the detectors
- Si:Sb detector arrays
- Si:As detector arrays
- HgCdTe detector arrays
- ROIC
- Controller electronics
- Sources
- Image processing

Requirement Drivers

- Future space telescopes that are designed to observe exo-planets using transit spectroscopy, e.g. OST (Origins Space Telescope), will require:
  - Detector arrays and their controllers to be stable to < 5 ppm.
    - 1 hour, 10 hours and 1 day.
      - No discussion here of the system-level flow-down for the stability requirement itself.
  - Detector arrays that cover wavelengths in the range of 5-38 μm

Prior Achievements

- Spitzer Space Telescope
  - IRAC InSb & Si:As stability of 100 -200 ppm , but possibly as low as 50 ppm.
- Hubble Space Telescope
  - WFC3 stability of ~25 ppm.
- If anyone knows of other stability measurements in this range, please forward references. Most are internal documents which tend not to be published.
- JWST NIRSpec is predicting ~50 ppm.
  - At best, current technologies need to be improved by at least a factor of 5 for OST! Likely need 10x.

Si:Sb Detector Arrays

- Blocked Impurity Band (BIB) or Impurity Band Conduction (IBC) technology which has a cutoff wavelength of about 38 μm.
  - Dark currents can be non-linear during integrations if that dark current is bias dependent.
    - BIB detector arrays are usually operated in fully depleted (bias is very large) mode. However, cosmic ray susceptibility is higher for higher biases.
  - Thermal dark currents are OK, but may require higher temperature stability.

Si:Sb Detector Arrays

- Detective Quantum Efficiency (DQE) is <7% beyond 35 μm, very low at 38 μm.
  - DQE is bias dependent for BIBs, i.e. higher bias = higher DQE.
    - Again, recall that higher bias also gives higher susceptibility to cosmic rays.
    - Does this translate to a concern for stability? Probably, since calibration would be dependent on non-linear dark current AND the source + background flux.
    - Can we calibrate this? In theory, we know everything and can do the calibration. In practice, we know very little and calibration is currently not possible at the 5 ppm level.

Si:Sb Detector Arrays

- Reset Anomaly
  - Typically the first few frames of a sample-up-the-ramp data set do not follow a linear behavior. This can be corrected to 1^{st} order, but extremely difficult to remove entirely, i.e. residual non-linear ramps.
- Inter-Pixel Capacitance (IPC) Moore 2005
  - The signal from each pixel is coupled to its neighbors. Sounds simple at first, but it isn't just the coupling of nearest neighbors, but also next-nearest and next-next-nearest…
  - Also dependent upon flux! High flux source or background gives a very different IPC than low flux situations. Donlon et al. 2017

Si:Sb Detector Arrays

- Residual Images
  - Bright and even modest sources will produce a residual (ghost/latent) image.
    - Traps are the enemy, just as they are for tunneling dark currents.
  - Time constants can be a few msec to a few hours.
    - 1st order correction is of course possible knowing past observing history, source location, brightness and time since observing those sources.
    - Decay from residual is not something that can be fully subtracted due to probabilistic nature.
- Non-linearity
  - Integration with time doesn't scale as t*e-/s.
  - 1st order is linear term (yes, the non-linearity is in-part linear), but higher order terms are present.

Si:Sb Detector Arrays

- Current status of Si:Sb
  - DRS is the ONLY VENDOR who can supply these!
  - Last production run was for SOPHIA FORECAST (T. Herter) and was unsuccessful
    - ~2009
    - High dark currents due to stacking faults in Si
  - Last successful run was for Spitzer
    - ~1998
  - Most of that original staff at DRS have since retired.
  - The foundry for the Si has also "retired" that original reactor.
    - Trial funded by JAXA to revive the technology have not yet resulted in a viable array.
  - Projected cost to achieve working Si:Sb arrays at Spitzer level is $3M+, excluding cost of any ROIC development.
    - Final development cost likely >$10M to meet requirements of a future space mission.

Si:As Detector Arrays

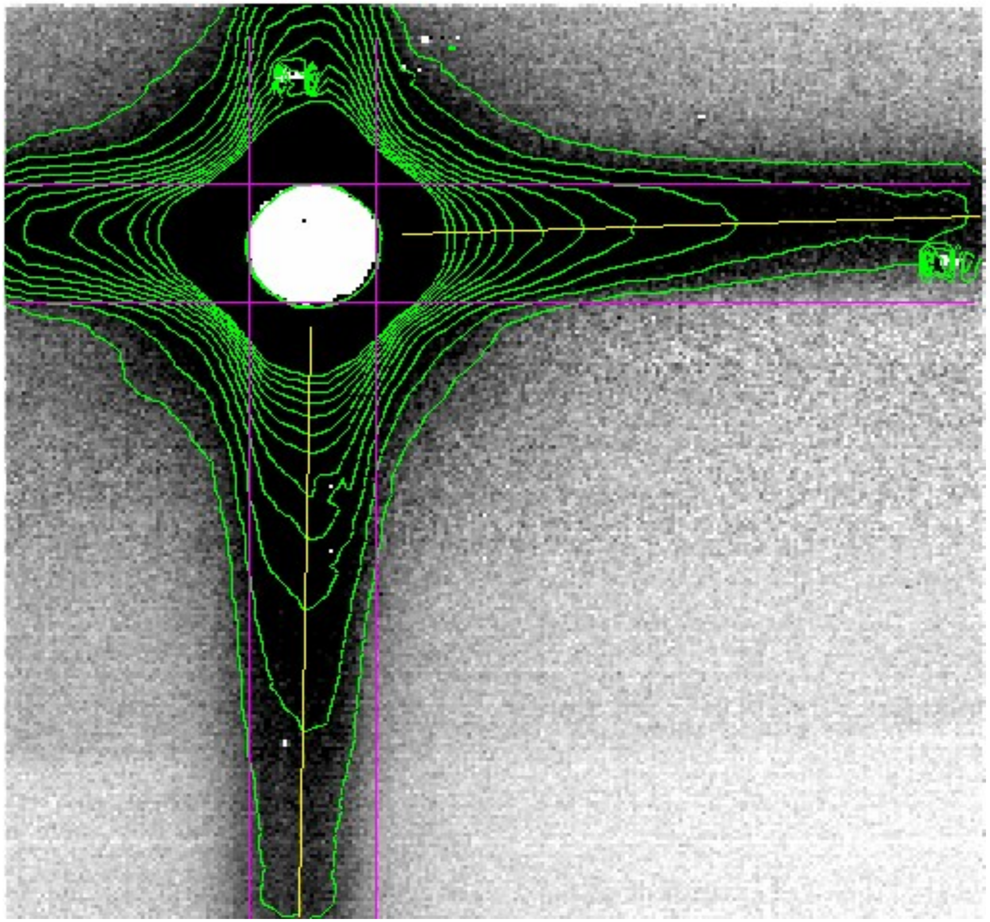
- BIB technology with cutoff wavelength around 27 μm.
- Very similar situations to Si:Sb
  - Dark current
  - DQE
  - Residual Images
  - IPC
  - Reset Anomaly
  - Non-linearity
  - Availability from the “preferred” vendor Raytheon Vision Systems (RVS) is also not guaranteed.
    - Raytheon wants a ground-based instrumentation consortium to buy a large lot of detector arrays for $8-10M.

Si:As Detector Arrays

- Many in the ground-based instrumentation community have reported on Excess Low Frequency Noise (ELFN).
  - Certainly seen when backgrounds are high.
    - ELFN is so bad that many instrument designers are turning to HgCdTe to observe in the N band at ground telescopes.
  - Possibly seen to a much lesser extent when the background is low, but the source flux is high. (G. Rieke, private communication)

Si:As Detector Arrays

- Transparency issues!
  - Below about 11 μm, the active layer is not a very good absorber.
  - Bands with slight tilt along rows and columns
  - Full array pull-up
  - Caused by diffraction, scattering and reflections within the detector/epoxy/bump/pad/ROIC interfaces.
  - Pipher et al. 2004, G. Rieke private communication



HgCdTe Detector Arrays

- Ternary compound $Hg_{1-x}Cd_xTe$, where varying mole fraction of Cd to Hg changes cutoff wavelength.
  - More Hg pushes cutoff to longer wavelengths.
- WISE, JWST & others have used λ ~5μm HgCdTe arrays.
- For the NEOCam project, we have developed 10 μm cutoff HgCdTe. McMurtry et al. 2013
- For other space missions, particularly those aimed at detecting atmospheres of exo-planets, we further developed longer cutoff wavelengths.
  - Cabrera et al. 2017
  - 15 μm aimed at detecting the broad CO_2 feature

HgCdTe Detector Arrays

- Benefit of using HgCdTe over Si:As or Si:Sb for wavelengths less than 15 μm:
  - Passive cooling possible (e.g. JWST, WISE post cryo, Spitzer post cryo)
    - 5μm @ T~45K, 10 μm @ T~40K, and 15 μm @ T~30K
    - Compare with Si:As @ T=6.7K or Si:Sb @ T=4.8K
  - Lower cost (no cryogens or active coolers, lower mass)
  - Longer lifetime
  - Higher QE (>80% versus 50%)
  - Lower read noise (<20e- versus 30e-) – ROIC issue
  - No banding/pull-up

HgCdTe Detector Arrays

- What are some of the issues that impact radiometric stability? Quite a few similarities to the Si:As and Si:Sb detector arrays:
  - Dark current
  - But not QE!
  - Residual Images
  - IPC
  - Reset Anomaly
  - Non-linearity

Read-Out Integrated Circuit

- Read-Out Integrated Circuit (ROIC) is the electrical interface to the actual individual detectors in an array. The ROIC selects, pixels, resets pixels and amplifies outputs after integration.
  - ROIC is a MAJOR SOURCE OF BIAS DRIFT.
    - Recall dark current, QE.
  - Source of Reset Anomaly
    - Stray capacitances
  - Small part of the IPC is due to ROIC

Read-Out Integrated Circuit

- Read noise
  - Entirely (or mostly for Si:X) from ROIC
- Clock feed-through
- 1/f drift for voltage supplies
- Pixel-to-pixel variations
  - Thresholds of FETs in unit cells,
  - R and C for all voltage supplies

Control Electronics

- Similar to ROIC, many aspects of the radiometric stability are a function of how accurately we control the detector
  - Voltage supply drift (thermal, 1/f)
  - AD converter drift (thermal)
  - Luckily, Bob Leach has already been working on an improved design for the ARC Gen-IV controller.
    - TBD how stable this is.

Stable Sources

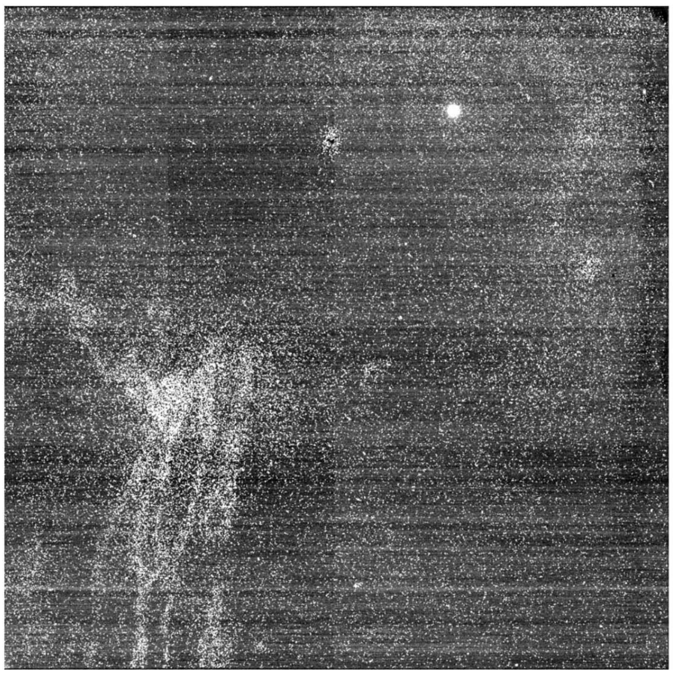
- Now that we have a perfectly stable detector array, ROIC and control electronics, we will need a stable source to check the overall stability.
  - Highly temperature controlled blackbody
    - Must be inside dewar
  - Fe55 or similar x-ray source
    - Must be inside dewar
  - IR LED with extreme current control
    - Must be inside dewar

Image Processing

- How much can image processing help or hurt the image stability?
  - Turns out to be a lot! Typical astronomical IR data are processed in such a way you inherently limit the photometric calibrations to no better than 1%.
  - Rauscher et al. 2018 (SPIE this June, private communication)
    - Higher order terms/fits to data show promise to getting better calibrations.

Image Processing

- Corrections with reference pixels are very beneficial, if done properly.
  - Adds overhead to data taking
  - Rauscher et al. 2017



a) Traditional

b) IRS^2

Conclusions

- There is a lot of work to be done to improve the stability of the various IR detector technologies.
  - Multi-year, multi-proposal, multi-million $ effort
  - Which aspects are most important?