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Vicarious calibration of the thermal IR spectral response of GOES instruments by observation of the planet Mercury

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Overview

- Why look at Mercury with an Earth-viewing weather/climate instrument on a GOES satellite?
  - Detect anomalies in thermal IR (TIR) spectral response functions (SRF's)
  - Cross-calibrate among instruments on different platforms
  - Verify co-registration of TIR channels in atmospheric absorption bands
- Observational constraints
- Mercury's orbital parameters on selected dates
- Radiometric model & spectral irradiance
- Effective temperature of Mercury vs. wavelength
  - ABI
  - Imager
  - Sounder
- Approximations & inaccuracies
- Observational procedures
- Conclusions
- Recommendations
- Acknowledgements

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The GOES-R Cal/Val Plan encourages celestial target observations & spectral response function (SRF) measurements

[NOAA/NESDIS, “GOES-R Calibration and Validation Plan, Version 0.2” (2007)]

- “Celestial targets are of particular interest --- for two reasons”
  - “an independent check of on-board sensor calibration”
  - “common targets for all earth & space-based instruments”
- “[spectral response function] measurement uncertainty as well as spectral shift in response to temperature changes and filter aging have been identified as major sources of uncertainties.”
- “There are differences in SRFs between even identically manufactured satellite radiometers, and these differences translate to SRF-related radiance biases between instruments once they are in orbit.”
- “At the slope regions of atmospheric spectra, a small shift of the SRF can cause biases in observed radiances.”

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Advanced Baseline Imager (ABI)

- Primary instrument on GOES-R series of geostationary weather satellite (Initial launch planned for 2015)
  - Weather and climate trending
  - Full-Earth disk in 5 minutes, severe storm images in 30 sec
- Field of regard: 11^{o} radius, centered at nadir
- Optical System:
  - Off-axis 27 cm telescope with intermediate field & Lyot stops
  - Two scan mirrors (N/S & E/W)
- Spectral bands:
  - 6 solar-reflective channels (visible, NIR, SWIR)
  - 10 thermal IR (TIR) channels: 3.9-13.3 μm,
  - Large linear detector arrays with (56 μrad)^2 IFOV's
  - Airy disk diameter > 56 μrad for λ > 6.2 μm

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Imager and Sounder

- Field of regard:
  - ± 10.5° N/S
  - ± 11.5° E/W
- Optical system:
  - On-axis, 30 cm Cassegrain telescope with central obscuration & spider
  - Single 2-axis scan mirror
  - Scan mirror reflection angle varies with E/W angle
- Imager's spectral channels:
  - One visible channel & four TIR channels: 3.9-13.3 μm,
  - 2 detectors per TIR channel: $(112\ \mu rad)^2$ IFOV's
- Sounder channels:
  - One visible channel & 18 TIR channels in three bands: 3.74-14.71 μm
  - 4 detectors per TIR band w/filter wheel: 242 μrad diameter IFOV's

On-board TIR calibration & star sensing modes
(similar for ABI, Imager, & Sounder)

- Onboard blackbody, the Internal Calibration Target (ICT)
  - Observe ICT through full aperture & end-to-end optical path
  - Observe dark space (~ no external radiation) before & after ICT for instrument TIR background subtraction
  - ICT observed at one pair of scan angles
  - Narrow range of ICT temperatures
- Star sensing mode
  - Primarily function: inertial reference for image navigation
  - Slew to east of anticipated position of star & observe its W to E motion through a visible channel's IFOV
  - Determine inertial attitude from (Az, El) vs. stellar (dec, RA)
  - Secondary function: long-term trending of Imager's visible channel [Chang, *et.al*., *Proc. SPIE*, **7081**, pp. 70810G-1 – G-13 (2008)]
  - Measured co-registration of Imager's visible and 3.9 μm channels [Chu, Baucom, Baltimore, & Bremer, *Proc. SPIE*, **5151**, pp. 424-432 (2003)]

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Spectral response function (SRF) measurements with Mercury

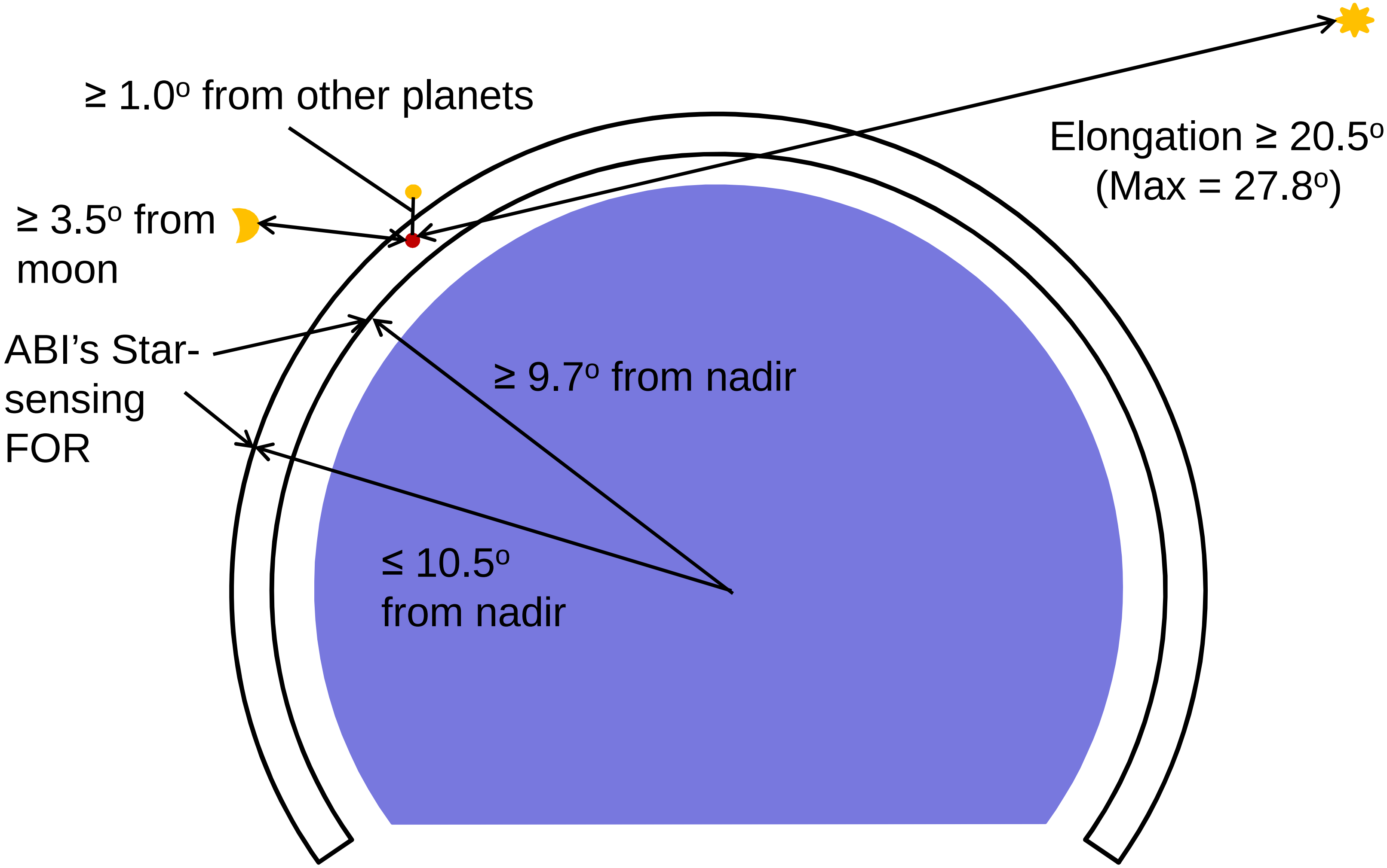
- Stable TIR irradiance: ~ no atmosphere, slow rotation rate
- TIR irradiance within the useful dynamic range of most channels, but more highly weighted toward short wavelengths than the ICT
  - Temperature of sunlit surface >> ICT temperature
  - Apparent diameter 25-50 μrad with varying phases
  - Solid angle of sunlit surface < ABI's $(56\ \mu rad)^2$ TIR IFOV's
- Ratio of signals from Mercury/ICT increases rapidly with decreasing wavelength, sensitive to small SRF shifts
  - SRF variation among detector elements in a TIR channel
  - SRF shifts with scan mirror reflection angle by successive measurements on west & east sides of the field-of-regard (FOR)
  - Cross-calibration between nominally identical channels on different instruments, including transfer between spacecraft
    - Important for long-term climate trending
    - ~ 1 arcmin parallax between GOES-E & GOES-W

Other measurements with Mercury

- Irradiance near top of dynamic range of 3.9 μm channel (400 K)
  - Required for observations of fires
  - Signal from Mercury >> signal from ICT
  - Comparable to sunlit surface of moon (full IFOV @ ~390K)
- Co-registration among detector arrays in the ABI's atmospheric absorption channels at 6.19, 6.95, 7.34, & 9.61 μm
  - Ground features are unobservable in 6.19, 6.95, & 7.34 μm channels, (H_2O absorption) & 9.61 μm channel (O_3 absorption)
  - Technique demonstrated with GOES Imager star observations in visible and 3.9 μm channels & planned for operational use on ABI [Grounder, Virgilio, & Ellis, ITT Document ABI05253A, Rev. A. (2009)]
  - Star irradiances are too weak at $\lambda > 6$ μm

Observational constraints (TBR)

Mercury's phase restricted to ~50º – 130º by elongation constraint



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Optimal time intervals for observations of Mercury by the Imager and/or Sounder

| Declination | ≤ 10.5^o

Elongation ≥ 20.5^o

- 2010: July 30 - August 22
- 2011: April 24 - May 19 and July 26 - August 3
- 2012: April 4 - May 7
- 2013: March 17-April 20 and Sept. 22 - Sept.24
- 2014: March 25 - April 3 and Sept. 3 - Sept. 18
- 2015: August 16 - Sept. 18

(Lunar & planetary avoidance may impose additional constraints)

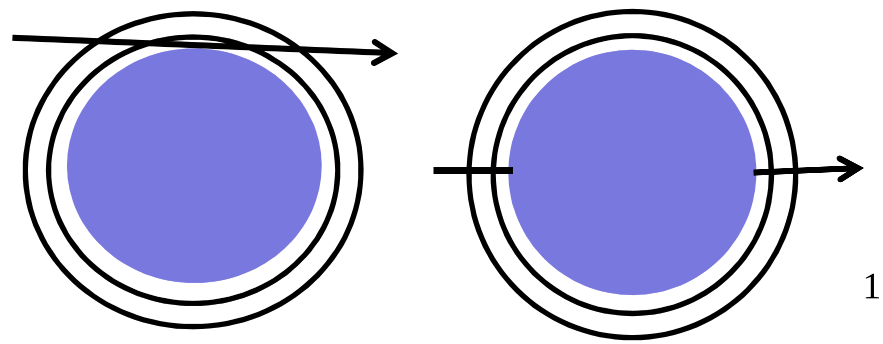
Orbital Parameters of Mercury in Aug. 2010

Date (year 2010)	213 (August 1)	233 (August 21)
Dec. & R. A. (deg)	9.14, 156.88	0.61, 168.35
Distance from Sun (A.U.)	0.459	0.445
Distance from Earth (A.U.)	0.975	0.697
Elongation (deg)	26.58	21.56
Phase angle (deg)	81.63	123.32
Disk diameter (μrad)	33.52	46.90
Visible magnitude	+0.16	+1.20
Solar dec. & R. A. (deg)	18.10, 131.09	12.22, 150.03
Local S/C time in FOR	0122-0130 & 0156-0204	0031-0034 & 0152-0155

Trajectories through ABI's

star-sensing FOR

(>9.7^o & <10.5^o from nadir)



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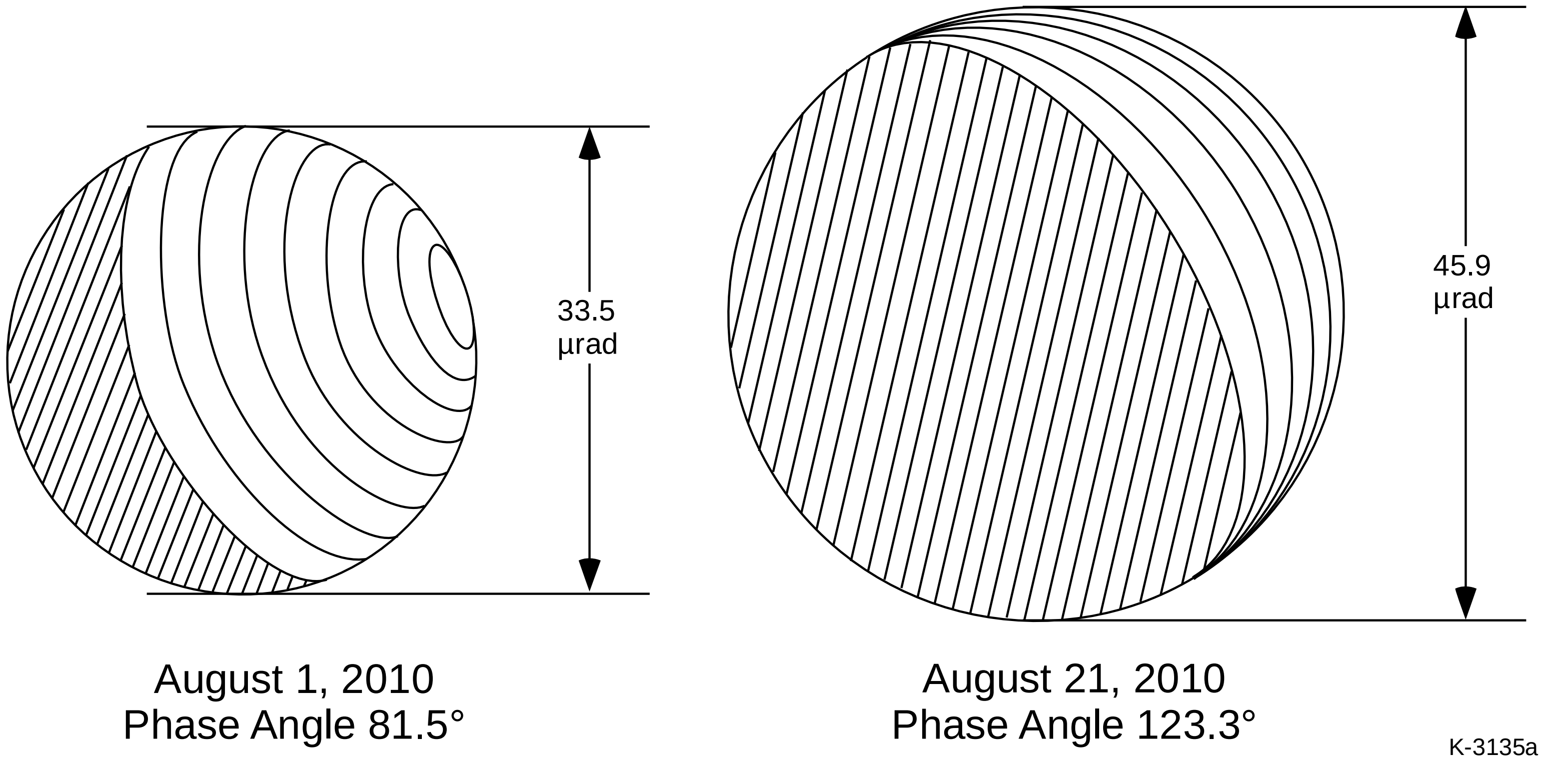
Profiles of Mercury on Aug 1 & Aug 21, 2010



Nine sunlit zones with solar zenith angles, $\theta_k = k*10^o - 5^o$, k = 1-9

Each zone absorbs 94% of solar radiation & re-radiates as a blackbody

$$T_k = (387.9\ K)(\cos \theta_k)^{1/4} d_s^{-1/2}$$

d_s = Mercury-Sun distance (AU)

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Temperatures and visible solid angles of zones on Mercury's sunlit surface

IFOV = $(56\ \mu rad)^2 = 3{,}136\ \mu rad^2$

Date (year 2010)	213 (August 1)		233 (August 21)	
Zenith angle, θ_k, (deg)	T_k (K)	A_k (μrad^2)	T_k (K)	A_k (μrad^2)
5	572.0	3.89	581.0	----
15	567.6	13.12	576.5	----
25	558.7	26.79	567.4	----
35	544.7	43.16	553.3	0.8
45	525.0	60.25	533.3	15.4
55	498.3	75.99	506.1	41.4
65	461.6	88.47	468.9	74.6
75	409.4	96.20	414.8	110.6
85	311.1	98.24	316.0	145.1

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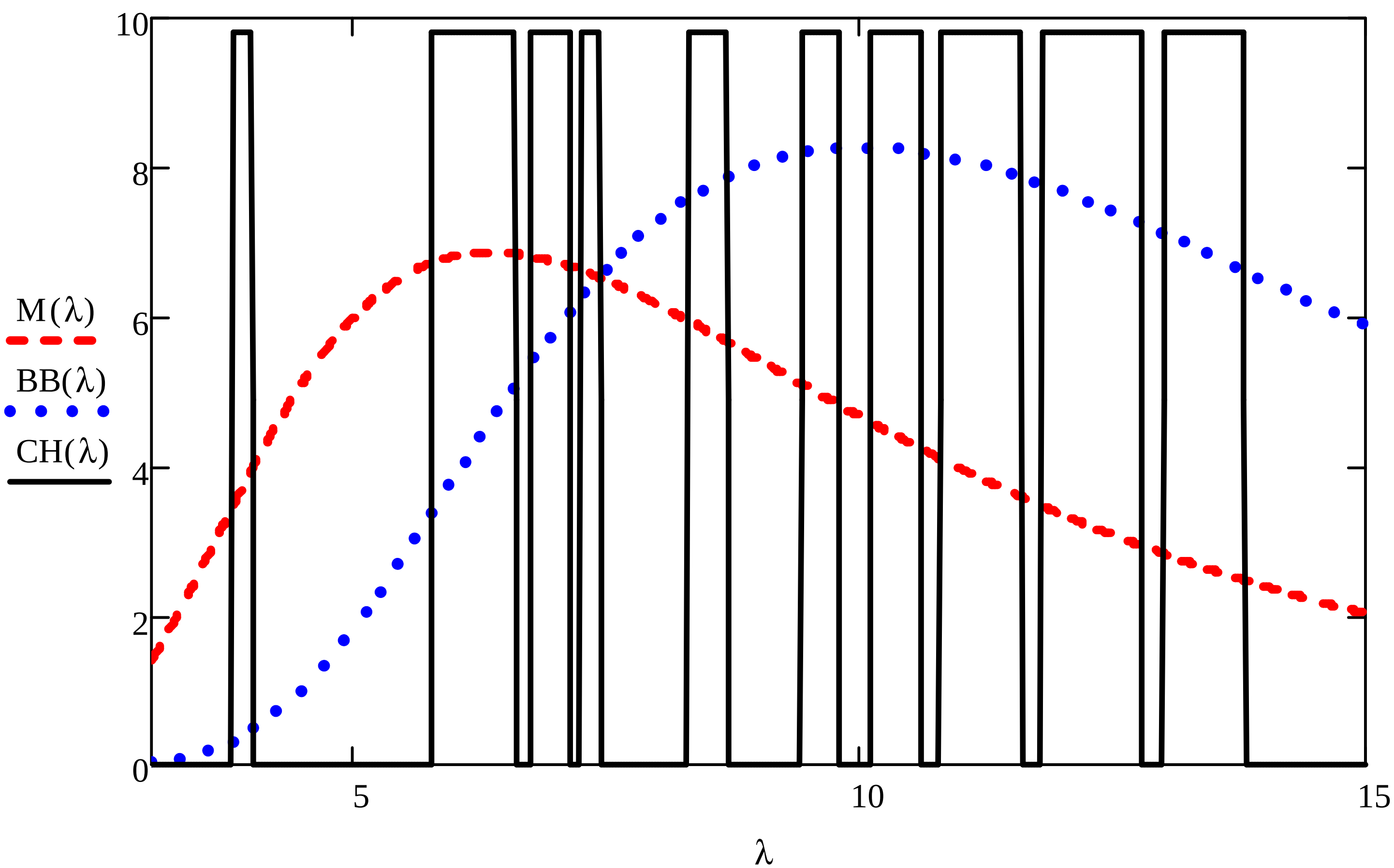
Radiance of ICT @ 290 K in (56 μrad)^2 IFOV (········) & Irradiance of Mercury on Aug 21, 2010(– – –)



Wavelength (μm)

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Teff = effective temperature of Mercury in an ABI TIR IFOV

Teff > Max T (Saturated detector elements)

ΔT (K) = Teff(0.999λ) – Teff(λ)

(Ensquared point diffraction): lowers Teff, raises –d(Teff)/dλ, raises ΔT

Date (year 2010)		213 (August 1)		233 (August 21)	
λ_n (μm)	Max T_n (K)	$Teff_n$ (K)	ΔT_n (K)	$Teff_n$ (K)	ΔT_n (K)
3.90	400	391.54	0.094	352.57 (349.41)	0.092 (0.093)
6.19	300	***345.25***	0.105	***308.22*** ***(301.50)***	0.099 (0.102)
6.95	300	***332.98***	0.107	296.67 (289.41)	0.100 (0.102)
7.34	320	***327.15***	0.107	291.20 (283.68)	0.100 (0.103)
8.50	330	311.38	0.108	276.44 (267.74)	0.101 (0.103)
9.61	300	298.16	0.108	264.11 (253.37)	0.100 (0.102)
10.35	330	290.21	0.107	256.70 (244.13)	0.100 (0.102)
11.20	330	281.80	0.106	248.87 (233.85)	0.099 (0.101)
12.30	330	271.92	0.105	239.66 (221.14)	0.098 (0.100)
13.30	305	263.79	0.103	232.08 (210.21)	0.096 (0.099)

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Teff = effective temperature of Mercury in an Imager TIR IFOV

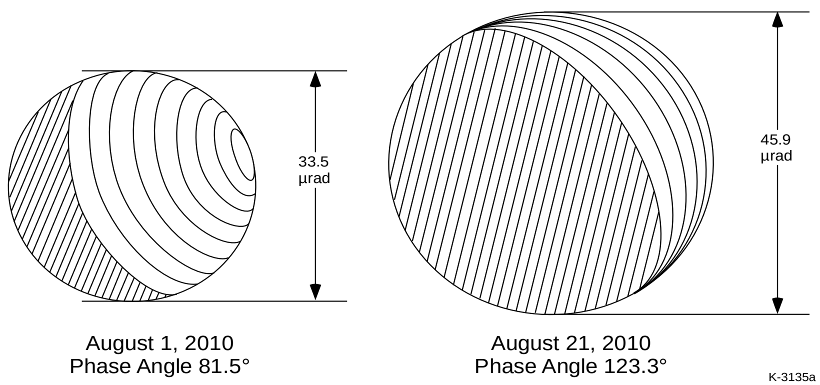
Two (112 μrad)^2 IFOV's per channel

Teff > Max T (Saturated detector elements)

ΔT (K) = Teff(0.999λ) – Teff(λ)

(Ensquared point diffraction) Airy disk diameter & IFOV ≅ at 13.3 μm

Date (year 2010)		213 (August 1)		233 (August 21)	
λ_n(μm)	Max T_n (K)	$Teff_n$ (K)	ΔT_n (K)	$Teff_n$ (K)	ΔT_n (K)
3.9	335	***341.32***	0.115	311.32 (311.32)	0.108 (0.108)
6.5	320	280.42	0.121	245.94 (245.94)	0.111 (0.111)
10.7	320	221.52	0.113	201.02 (201.00)	0.104 (0.104)
13.3	320	197.60	0.107	179.09 (179.07)	0.098 (0.098)



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Teff = effective temperature of Mercury in a Sounder TIR IFOV

Four 242 μrad diameter IFOV's per channel

ΔT (K) = Teff(0.999λ) – Teff(λ)

Date (year 2010)		213 (August 1)		233 (August 21)	
λ_n(μm)	Max T_n (K)	$Teff_n$ (K)	ΔT_n (K)	$Teff_n$ (K)	ΔT_n (K)
11.03	345	179.22	0.108	165.32	0.099
9.71	330	193.25	0.113	178.21	0.103
7.43	310	224.49	0.121	206.83	0.110
7.02	295	231.36	0.122	213.13	0.112
6.51	290	240.60	0.123	221.59	0.113
4.57	320	284.83	0.126	262.21	0.116
4.52	310	286.22	0.126	263.49	0.116
4.45	295	288.18	0.126	265.30	0.116
4.13	340	297.54	0.125	273.94	0.116
3.98	345	302.16	0.125	278.22	0.116
3.74	345	309.91	0.124	285.39	0.115

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Simplified model of Mercury's TIR Spectrum

- Blackbody approximation for Mercury's surface
  - Ground-based measurement of Mercury's TIR emissivity is difficult due to atmospheric absorption and Mercury's solar proximity
  - Mercury's emissivity appears to peak near 1.00 at λ ~8 μm [Sprague & Roush, *Icarus*, **33**, pp. 174-183, (1998)]
  - The Moon & Mercury appear to have similar surface compositions
  - The emissivity of a lunar sample from Apollo 11 varies from ~1.00 at λ = 8.3 μm to ~0.96 at λ = 11 μm [Potter & Morgan, *Proc. Lunar Planet. Sci.*, **12B**, pp. 703-713, (1981)]

- Reflected solar radiation can contribute several percent in the 3.9 μm channel

- MERTIS, an imaging TIR grating spectrometer on ESA's Bepi Colombo mission, will provide hyperspectral data
  - 500 m spatial resolution
  - TIR spectrum: λ = 7-14 μm; 80 spectral channels, $\Delta\lambda$ = 0.09-0.20 μm
  - Schedule; 2014 launch, 2020 arrival at Mercury 1-2 yrs observation

Radiometric equations for narrow spectral bands

Determine $Teff_n$, the ICT temperature that produces a signal level equivalent to that of Mercury at wavelength λ_n

$$(IFOV)\int \lambda^{-5}[\exp(c_2/\lambda Teff_n)-1]^{-1}\tau_n(\lambda)d\lambda =$$

$$\Sigma_{k=1-9}\{A_k \int \lambda^{-5}[\exp(c_2/\lambda T_k)-1]^{-1}\tau_n(\lambda)d\lambda\}$$

where c_2 = 14,388 μm-K.

Narrow band approximation: replace $\tau_n(\lambda)$ with $\delta(\lambda_n)$, where λ_n is the centroid wavelength of channel n

$$(IFOV)/[\exp(c_2/\lambda_n Teff_n)-1] = \Sigma_{k=1-9}\{A_k/[\exp(c_2/\lambda_n T_k)-1]\}$$

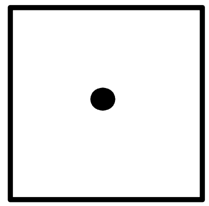
$$1/Teff_n = (\lambda_n/c_2)\ln\{1+(IFOV)/[\Sigma_{k=1-9}\{A_k/[\exp(c_2/\lambda_n T_k)-1]\}]\}$$

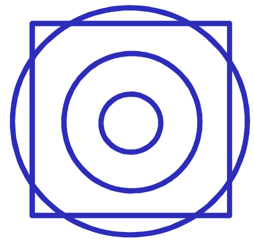
Use measured SRF’s to improve model (eliminate errors due to quadratic variation in Planck function within the bandpass)

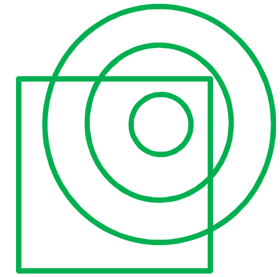
Teff & ΔT in ABI's IFOV's August 21, 2010 for three irradiance distributions

Point source | Centered Airy disk | Airy disk decentered ¼ IFOV/axis

(56 μrad)[2] IFOV
27 cm aperture







λ_n (μm)	MaxT$_n$ (K)	Teff$_n$ (K)	ΔT$_n$ (K)	Teff$_n$ (K)	ΔT$_n$ (K)	Teff$_n$ (K)	ΔT$_n$ (K)
3.90	400	352.57	0.092	349.41	0.093	348.22	0.094
6.19	300	***308.22***	0.099	***301.50***	0.102	297.96	0.103
6.95	300	296.67	0.100	289.41	0.102	283.57	0.104
7.34	320	291.20	0.100	283.68	0.103	276.59	0.104
8.50	330	276.44	0.101	267.74	0.103	257.59	0.105
9.61	300	264.11	0.100	253.37	0.102	241.73	0.104
10.35	330	256.70	0.100	244.13	0.102	232.23	0.103
11.20	330	248.87	0.099	233.85	0.101	222.14	0.102
12.30	330	239.66	0.098	221.14	0.100	210.16	0.101
13.30	305	232.08	0.096	210.21	0.099	200.14	0.099

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Observational Procedures

- ABI, Imager & Sounder have similar star sensing and TIR calibration modes
- Quantitative comparison of the radiance of the ICT (an extended source) & Mercury's ensquared/encircled irradiance requires:
  - Accurate knowledge of the IFOV's solid angle
  - Accurate positioning of Mercury in the IFOV (especially for the ABI)
  - IFOV & position are equal among channels for each of Sounder's TIR detectors
- Minor modifications of the star sensing mode allow observations of Mercury in all Imager & Sounder detectors or in selected ABI detector elements
  - Satisfy all bright object avoidance constraints
  - Input Mercury's declination & right ascension in star sensing mode
  - Make 2-3 passes through each selected detector element
- Calibrate with ICT before and/or after observing Mercury

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Conclusions

- Observation of Mercury ---
  - is a sensitive technique for detecting SRF deviations in TIR channels
    - Effective T within useful dynamic range of most TIR channels
    - Effective T near top of 3.9 μm channel's dynamic range
    - SRF $\Delta\lambda/\lambda$ = - 0.1% produces $\Delta T \approx$ + 0.1 K, comparable to NEΔT in most ABI TIR channels; diffraction increases sensitivity
    - Variation among detector elements within a spectral channel
    - Variation with scan mirror angle from west to east in FOR
  - is an effective method of cross calibration among TIR channels on different instruments
  - can verify co-registration among TIR channels in atmospheric absorption bands
  - can be implemented with minor modifications to existing star sensing modes (Imager, Sounder, & ABI)

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Recommendations

- Observe Mercury with the Imager and/or Sounder prior to observations with the ABI
  - Characterize these present instruments
  - Refine procedures for the ABI
  - Initiate a baseline for transferring calibration to the ABI
- Refine model to make quantitative determinations of SRF shifts
  - Improve upon simple model of Mercury (sphere with 9 blackbody zones on sunlit surface) Add reflected sunlight at 3.9 μm
  - Replace narrow band approximation with measured SRF's
  - Iterate using multi-channel predicted vs. measured effective T's
  - Need accurate positioning knowledge (for ABI) & IFOV solid angles compare Mercury's ensquared/encircled irradiance to ICT's radiance
- Investigate reduction of ABI's elongation constraint
  - ABI's off-axis telescope w/o central spider should be less sensitive to stray radiation than on-axis Cassegrain telescope of Imager & Sounder
  - ITT (ABI contractor) proposes 7.5º (TBR) for star sensing
  - ABI can operate when Sun is eclipsed

Acknowledgements

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- Most of this material was presented on Aug. 4, 2010 at SPIE, Earth Observing Systems XV, & in *Proc SPIE*, 7807.
- Mr. Robert Feiertag of SGT, Inc. performed an independent confirmation of Mercury's orbital parameters on selected dates.
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Effective temperature of Mercury (Teff) approximated as a point source at wavelength λ_n ensquared in a (56 μrad)^2 IFOV

Table_A =

	0	1
0	"Wavelength"	"Ensquared irradiance"
1	3.9	0.91
2	6.19	0.845
3	6.95	0.839
4	7.34	0.836
5	8.5	0.819
6	9.61	0.786
7	10.35	0.756
8	11.2	0.717
9	12.3	0.663
10	13.3	0.613

$$(IFOV)/[\exp(c_2/\lambda_n Teff_n)-1] = Ensq_n \Sigma_{k=1-9} \{A_k/[\exp(c_2/\lambda_n T_k)-1]\}$$