GSFC· 2015

Science Goals to Requirements

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Science Goals Drive System Requirements

- Data must be stable
  - During a given observation, results can not change as instrument environment changes.
- Data must be reproducible
  - Two or more measurements of the same signal must agree
- Data must be calibrated
  - Performance of onboard calibration systems must be understood
- Data must be capable of being taken over the required dynamic range
- Data must be obtained at the required frequency
- Data must meet the required noise performance
- Data must be flowed to the user community in a timely manner
- Requirements cross system boundaries

Mission Instrument Examples

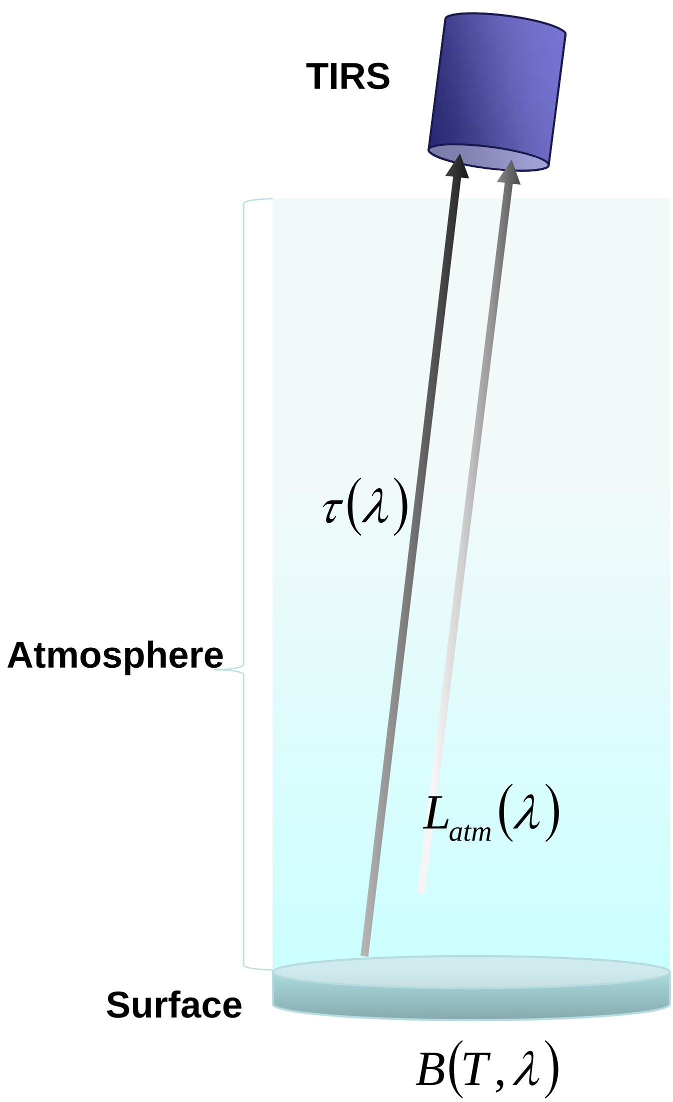
- Thermal InfraRed Sensor (TIRS) on Landsat 8
  - Very low temperature cryogenic detector
  - Fast data turn-around required
  - Instrument had to be built in ~3 years – ~one year faster than usual
- Ralph instrument on New Horizons Pluto/Kuiper Belt Mission
  - Low light levels very far from the sun (more than 30 times further than the Earth)
  - Very low mass instruments required
  - Very long duration in flight (9.5 years and counting)
- OSIRIS-REx Visible and InfraRed Spectrometer (OVIRS) on OSIRIS-REx Asteroid Sample Return Mission
  - Low light levels from dark object (asteroid Bennu < 5% reflectance)
  - Broad spectral range (0.4 – 4.3 μm)
  - Large range of sun-object-spacecraft angles and close in-observations
  - Requirement flow similar to Ralph and won’t be discussed separately

Example 1: Thermal IR Sensor (TIRS) on Landsat 8

- Landsat 8 has two imaging systems
  - The Thermal IR Sensor has 2 channels in the 10-12 μm spectral range (100 meter spatial resolution)
  - The Operational Land Imager (OLI) has 9 spectral channels in the visible to Near-IR range (15 and 30 meter spatial resolution)
  - Both instrument operate in pushbroom mode with 185 km swath

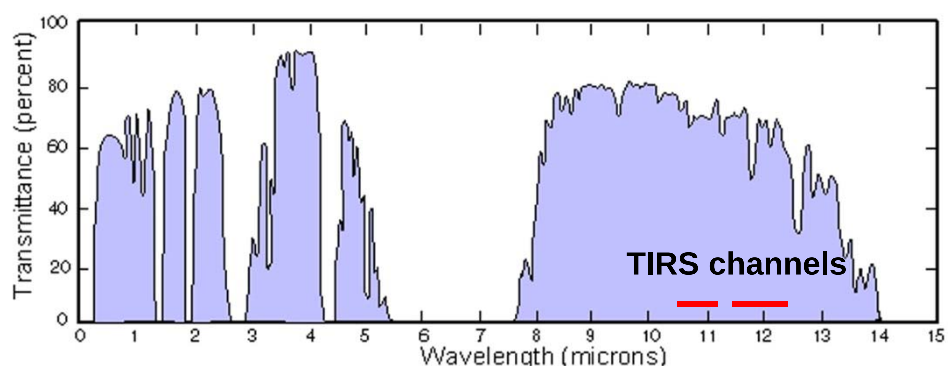
- Product example: TIRS data used to monitor water use on a field-by-field basis in the U.S. West and internationally
  - Evapotranspiration cools vegetation (plants "sweat" as part of photosynthesis)
  - Parametric models use measured vis/NIR and thermal radiation, surface classification and estimates of soil thermal transport to derive soil moisture estimates
- Reliability of product depends heavily on measurement noise
  - Required that radiance measurement noise be ≤ 0.5% @ 300 K

Radiance Detected by TIRS from Surface and Atmosphere



$$L_s = \frac{\int \left(B(T,\lambda)\cdot\tau(\lambda) + L_{atm}(\lambda)\right)\cdot R'(\lambda)\cdot d\lambda}{\int R'(\lambda)\cdot d\lambda}$$

- $B(T,\lambda)$ • **Emitted and reflected surface radiance**
- $\tau(\lambda)$ • **Transmission of atmosphere**
- $L_{atm}(\lambda)$ • **Emitted and scattered radiance of atmosphere**
- $R'(\lambda)$ • **Spectral response of detector**
- L_s • **Detector integrated radiance**

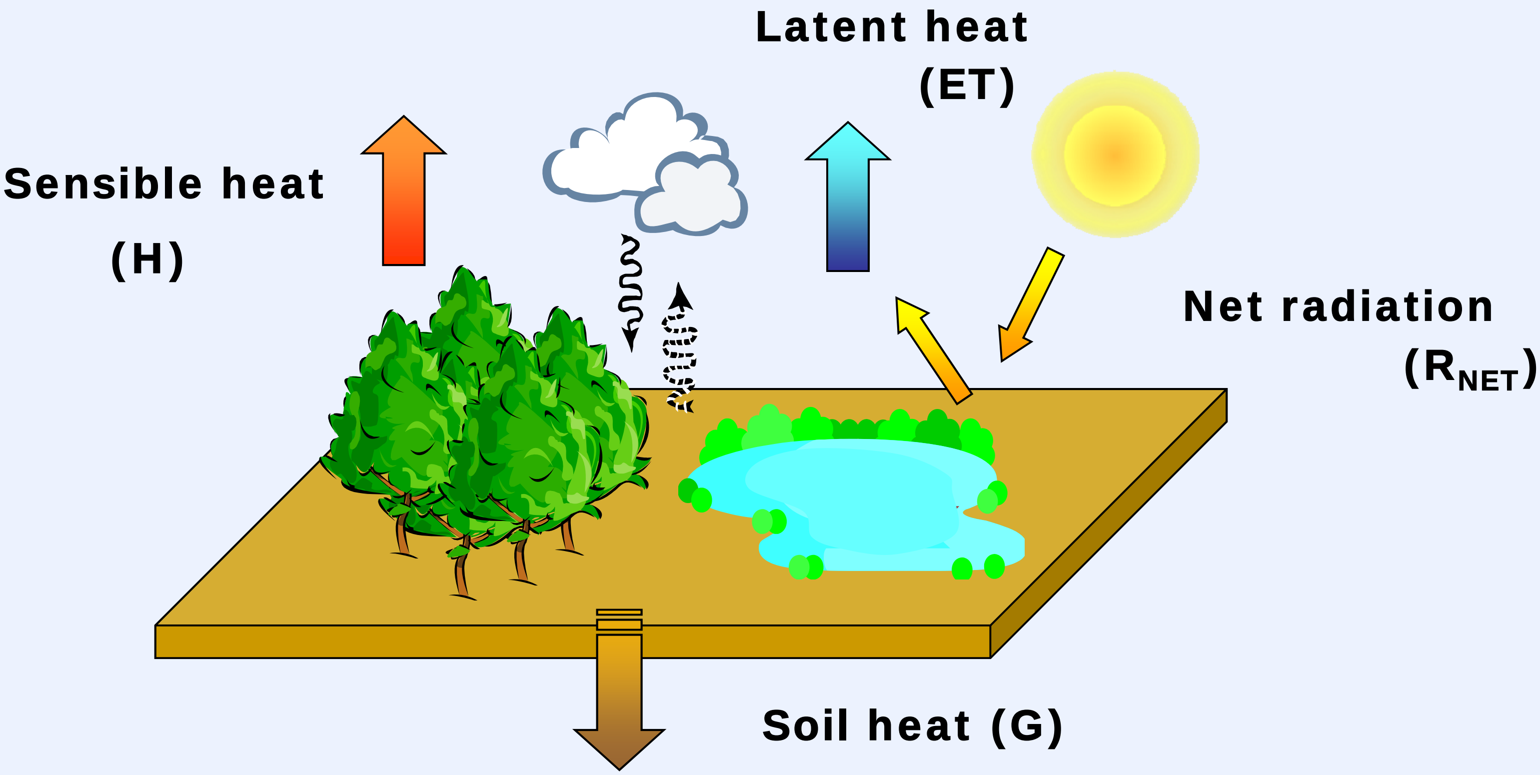


Two channel “split window” techniques correct for atmosphere and improve retrieved surface temperature

Data Product: Water Management Using Surface Energy Balance

$$R_{NET} = G + ET + H$$

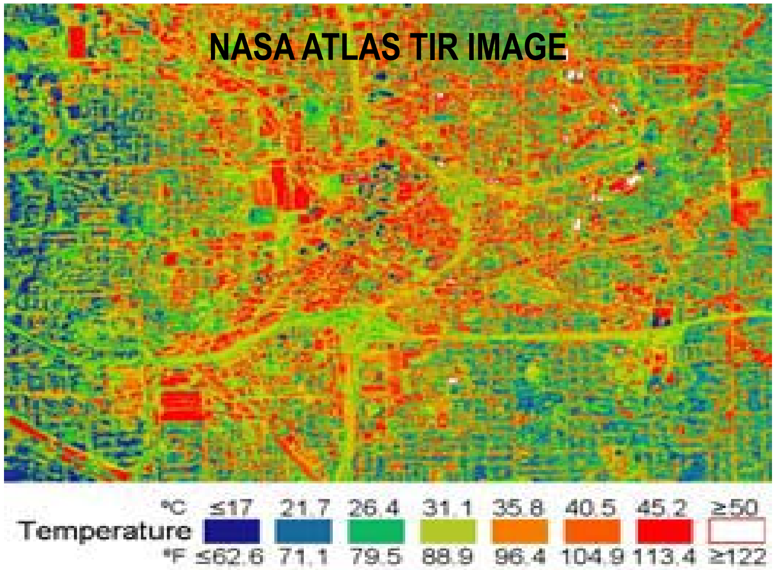
$$R_{NET} = (SW_{dn} - SW_{up}) + (LW_{dn} - LW_{up})$$

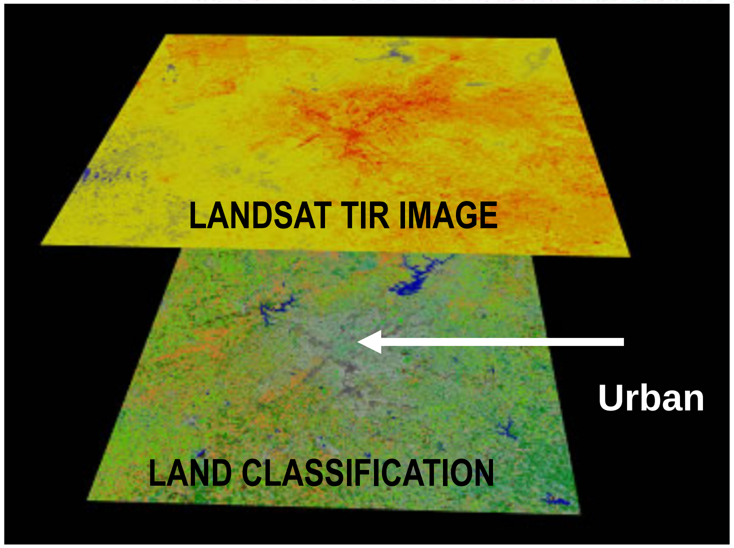


- Net Radiation is the balance between incoming minus outgoing radiation
- OLI albedo required to calculate the SWup (short wave upwell)
- TIRS radiance data required to calculate the LWup from surface temperature

Additional TIRS Science

- Mapping urban heat fluxes for air quality modeling (urban heat island)
- Volcanic hazard assessment, monitoring, and recovery
- Cloud detection and screening
- Mapping lake thermal plumes from power plants
- Burnt area mapping / Wildfire risk assessment
- Tracking material transport in lakes and coastal regions
- Identifying mosquito breeding areas and vector-borne illness potential





(Images from D. Quattrochi)

TIRS Driving Requirements

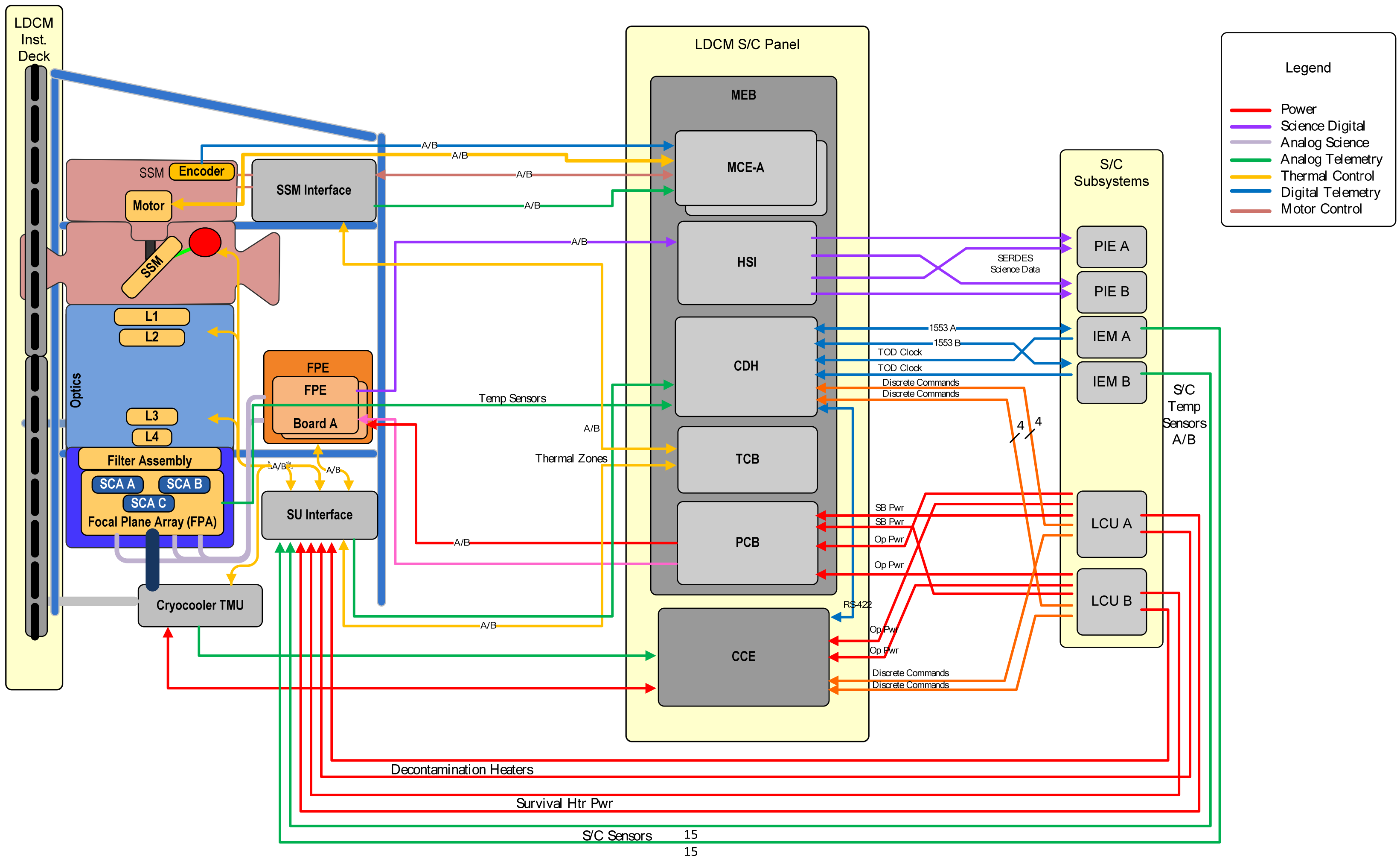
	RD #	TIRS #	Parameter	L3 Requirement	Systems Affected	Notes
Radiometry	5.6.2.1	FS-461	NEΔL	$\leq$ 0.059 W/m^2 sr μm (10.8 μ channel) $\leq$ 0.049 W/m^2 sr μm (12 μ channel)	Optics, Thermal, FPE, FPA	Stability based over 24 second WRS-2 scene
	5.6.4	FS-562	Stability	0.7%	Optics, Thermal, FPE, FPA	Over 40 minutes
	5.5.6	FS-442	Bright Target	<1% radiance outside an 11x11 pixel area affected	FPA, FPE, Optics	
Spatial Performance	5.5.2.1	FS-400	RER	> 0.007 /m in-track and cross-track	Optics	
	5.5.2.2	FS-404	Edge Extent	<150 m in-track and cross-track	Optics	
	5.5.1	FS-386	GSD	<120 m	Optics, FPA, FPE	
Spectral Shape	5.4.1.2	FS-374	Center Band	Band 10 (Thermal 1) 10.8 μ ($\pm$ 200nm) Band 11 (Thermal 2) 12 μ ($\pm$ 200nm)	Optics, FPA	
	5.4.1.2	FS-799	Bandwidth	Band 10 - 10.3 μ to 11.3 μ Band 11 – 11.5 μ to 12.5 μ	Optics. FPA	
	5.4.3	FS-376	Uniformity	Within $\pm$ 5% FWHM of measured mean	Optics, FPA	

TIRS Driving Requirements - Continued

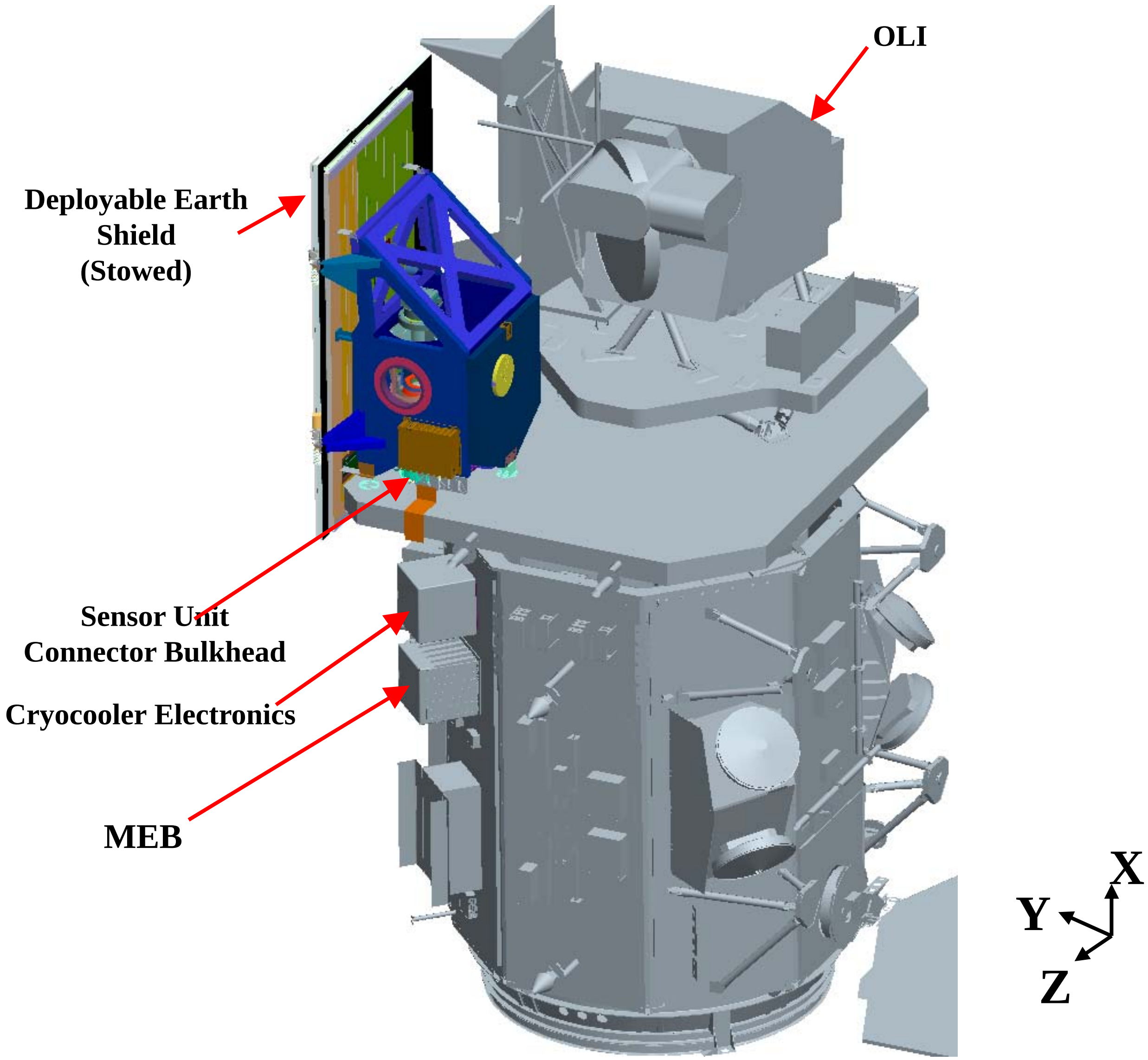
	RD #	TIRS #	Parameter	L3 Requirement	Systems Affected	Notes
Out of Spec Detectors	5.6.5.1	FS-566	Dead Pixels	< 0.1% dead pixels within any row	FPA	2 for 1 ground pixel selection allowed
	5.6.5.2	FS-570	Inoperable Pixels	<0.25% fail to meet specifications during any WRS-2 scene	FPA, Algorithms	2 for 1 ground pixel selection allowed
Image Registration	5.7.1	FS-625	LOS	27 microradians per axis	Thermal, Mechanism, Mechanical	Knowledge per 16 day orbit repeat cycle
	5.7.2	FS-179	Timing Accuracy	Timestamp science data within $\pm$0.001 seconds of LDCM time stamp	MEB	
	5.7.3.1	FS-606	Registration	2 thermal bands co-registered within <18 m after geometric correction	Mechanism, Algorithm	Stability from band to band (2.5 seconds)
	5.7.3.2	FS-608	Geoditic	Pixels at earths surface located relative to reference system to within 76 m	Mechanism, Algorithm	

FPE (Focal Plane Electronics)
FPA (Focal Plane Assembly)
MEB (Main Electronics Box)

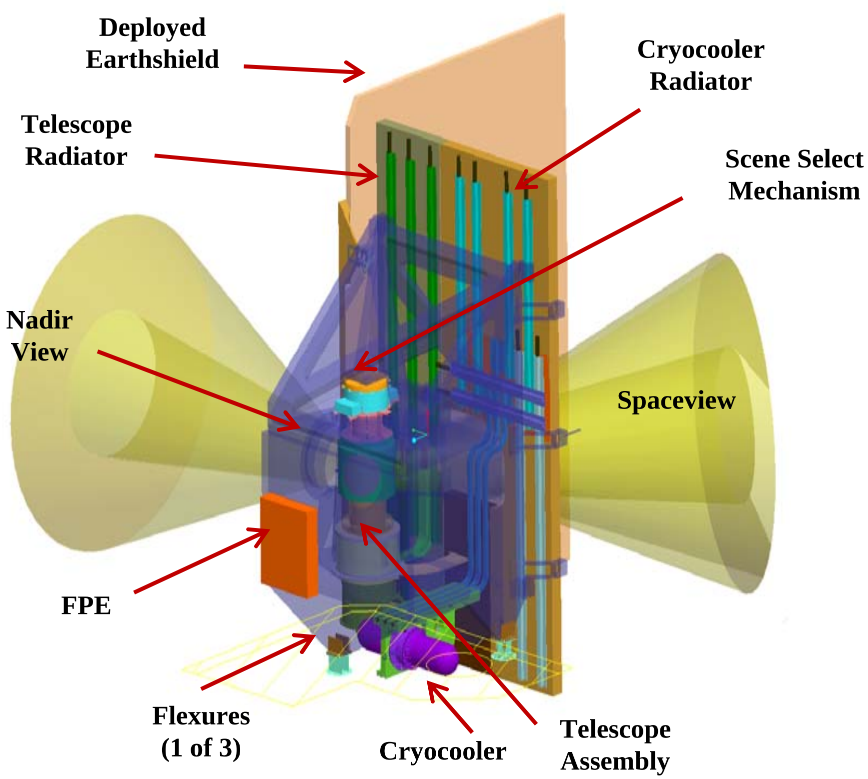
TIRS Block Diagram

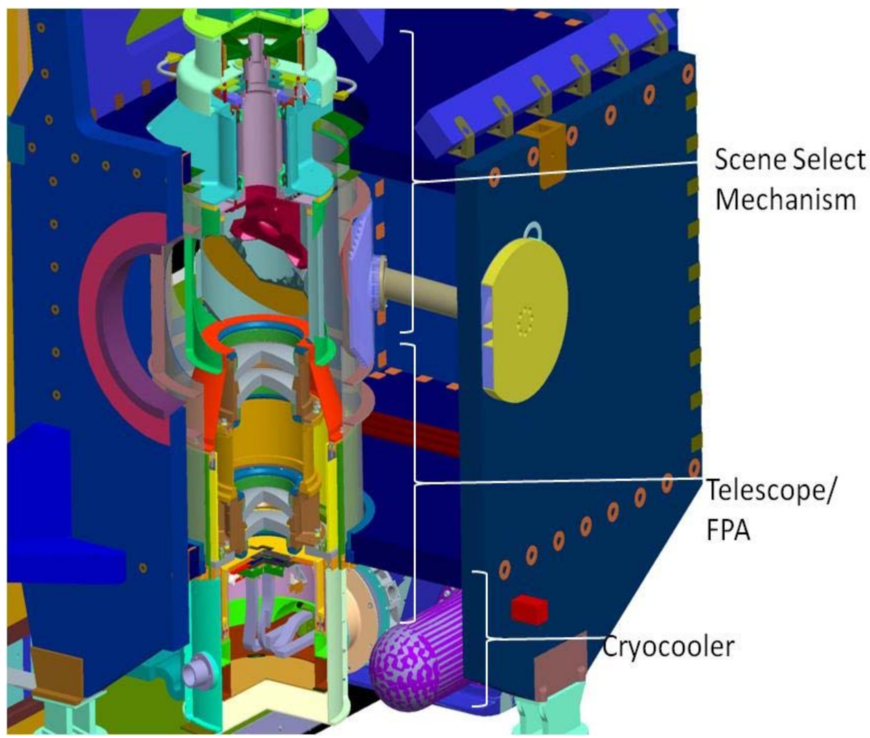


TIRS on Landsat 8 Spacecraft

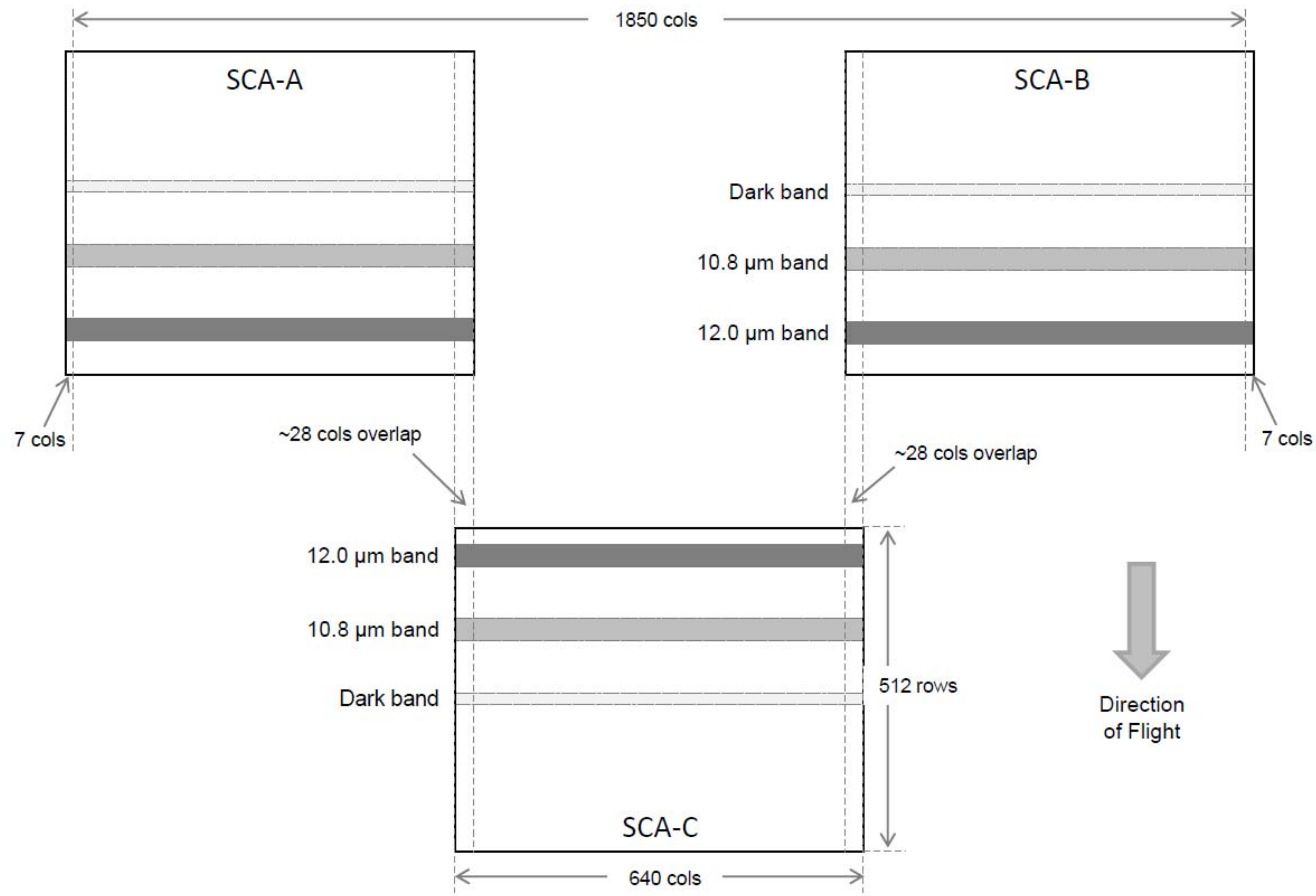


TIRS FOVs and Telescope Detail



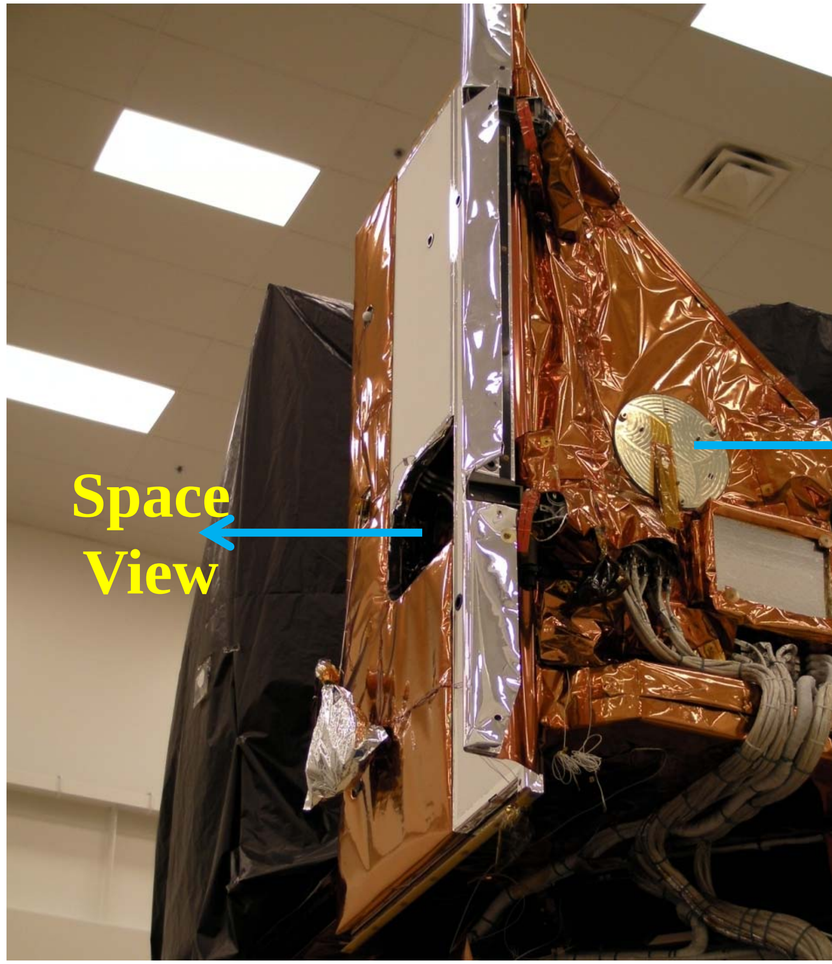


TIRS Focal Plane Layout (3 QWIPs)



HERE'S TIRS

Leaving Goddard Space Flight Center



On the Spacecraft, Showing Views
(Earth View – Space View) = Source Radiance

Requirements Flowdown

LDCM Level 3 Specifications

- RD
- SCTR
- OBS-IRD
- LEVR
- IMAR

- Level 3 requirements specify
  - Mission performance
  - Mission environment
  - Testing (instrument and subsystem)
  - Design process

TIRS Level 4 Specifications

- Flight Specification
- Simulator/EGSE Specification
- Calibration Test Plan
- Environmental Test Plan

- Level 4 specifications capture TIRS instrument, algorithm, simulator and testing requirements
- Predicted performance and margin shown against Level 4
- Instrument verification will be performed against Level 4
  - Verification by analysis, test, inspection, design or some combination

Subsystem Level 5 Specifications

- Telescope
- Focal Plane Assembly
- Focal Plane Electronics
- Main Electronics Box
- Thermal
- Mechanism
- Cryocooler
- Algorithms
- Mechanical
- Harness

- Level 5 specifications are populated with allocated or derived requirements
- Captures specific subsystem requirements necessary for subsystem buy-off
- PDLs are responsible for verification before delivery to to I&T
  - Verification by analysis, test, inspection or some combination

Level 3 to 4 Requirements Trace

	LDCM TIRS RD 257	LDCM O-IRD 386	LDCM LEVR 606	LDCM I-MAR 400	LDCM SCTR 54	LDCM TOTAL 1703
TIRS Flight System Specification	182	190	-	-	-	372
TIRS GSE Specification	70	-	-	-	-	70
TIRS Calibration/ Validation Plan	-	-	-	-	54	54
TIRS I&T Plan	-	-	606	-	-	606
TIRS MAIP	-	-	-	398	-	398
N/A	5	196	-	2	-	204
TOTALS	257	386	606	400	54	1703

16

TIRS Noise Drives Thermal Requirements

- TIRS noise is a function of inherent signal variance (electron "shot noise"), system instability noise, electronics and array noise ("read noise") and quantization noise – terms dependent on thermal system
- For an integration time t, Source flux F(S), Background flux F(B), Scene Select Mirror flux F(M), Optics flux F(O) and detector dark current I(D)
- $N = \{[2*g*t*(F(S) + F(B) + F(M) + F(O) + ID)] +$

$$[t^2*(((\delta F(B)/\delta T)\Delta T(B))^2 + ((\delta F(M)/\delta T)\Delta T(M))^2 + ((\delta F(O)/\delta T)\Delta T(O))^2 + ((\delta ID/\delta T)\Delta T(D))^2)]$$

$$+ [RD^2 + RE^2 + Q^2]\}^{1/2}$$

$F(S) = B(S)*CE*\tau_l*\tau_f*r_m*\pi/(1+(2f)^2)$, $F(B) = B(B)*CE*\tau'_f*\pi*(\Omega_b\text{-}1 /(1+(2f)^2)$,

$F(M) = B(M)*CE*\tau_l*\tau_f*\varepsilon_m*\pi/(1+(2f)^2)$, $F(O) = B(O)*CE*\tau_f*\varepsilon_o*\pi/(1+(2f)^2)$,

$B(x)$ = appropriate radiance integral for temperature x

$ID = K*\exp(-1.4388*cutoff/T_d)$[K and cutoff depend on array], RD = detector read noise

RE = electronics read noise, Q = 12 bit quantization noise = $(\text{well depth}/4094)/(12)^{1/2}$

CE = conversion efficiency, τ_l = lens transmittance, τ_f = filter transmittance, f = f/#

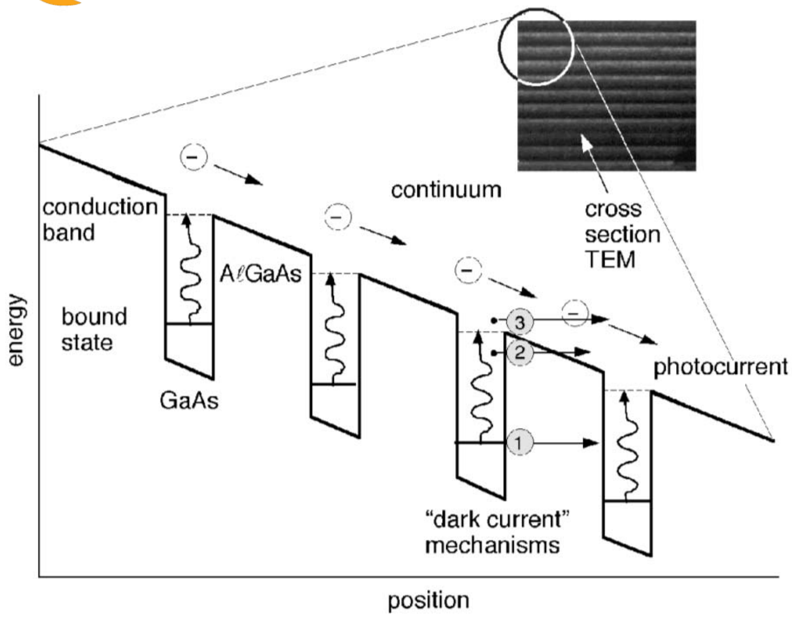
r_m = mirror reflectance, ε_m = mirror emittance, ε_o = optics emittance , $\tau'_f = (1+\tau_f)/2$

Ω_b = solid angle above cold shield, g = photoconductive gain

Noise terms of particular note

- Long wavelength cutoff of detector requires very low temperature operation to reduce dark current
  - Poisson statistics give a noise term whose variance is proportional to the charge collected
- Large derivative in dark current with temperature requires very stable detector temperature (milli-Kelvin stability) to reduce noise contribution
- Long wavelength operation also means thermal emission signal from the instrument is significant
  - Again, Poisson statistics give a noise term whose variance is proportional to the charge collected
  - Also requires stable instrument temperature to reduce noise
- Used photoconducting detector because it gave best uniformity
  - But also has both charge regeneration and recombination noise terms giving rise to factor of sqrt(2) in the flux noise term.
- Numerous trades available
  - Detector temperature, instrument temperature, electronic noise, f/#, etc. etc…

TIRS Detectors: 10-13.5 µm Quantum Well IR Photodetectors

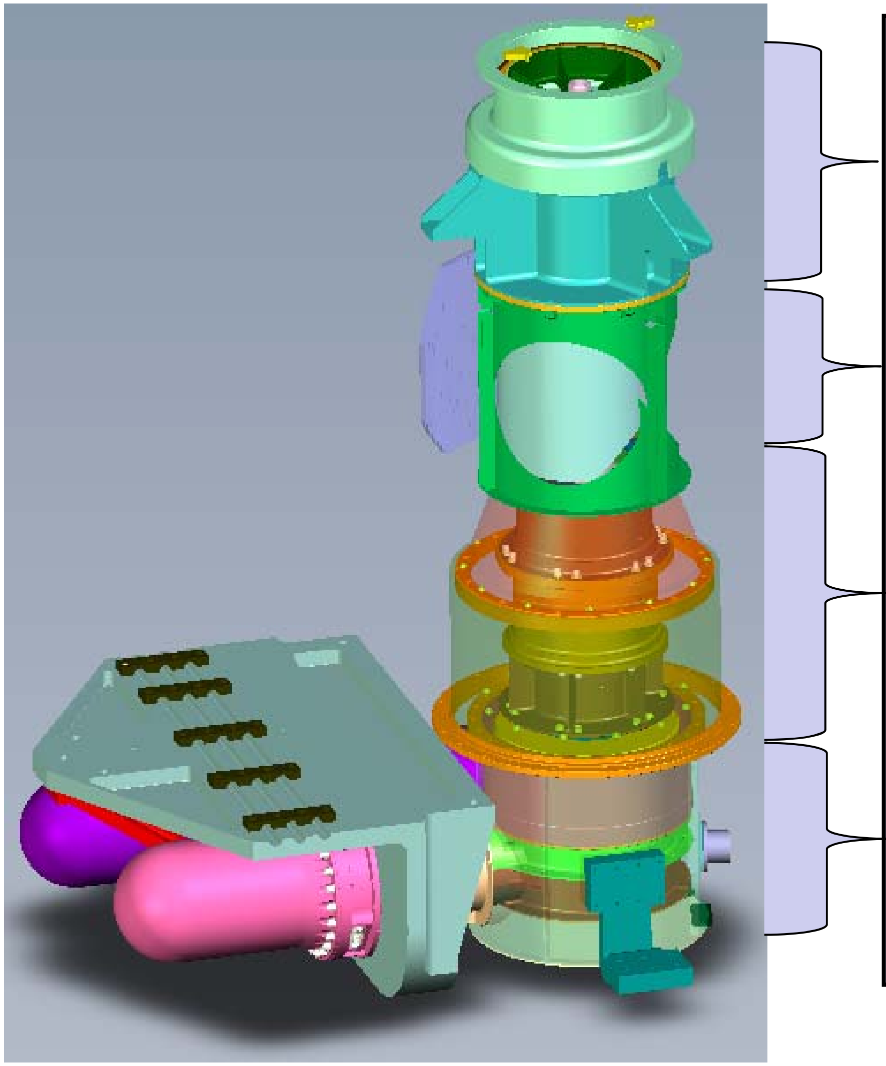


• QWIPs operate as "particle in a box" [quantum well] photoconductors
• TIRS: bound to quasibound QWIPs
• IR photon excites electron from lower, bound states to states near conduction band
•Thermal energy excites electrons too
• E-Field causes excited electrons to conduct and be counted as signal

λ_c = 13.4 µm

20000 A	GaAs	1×10^{18} cm^{-3}	
50 A	AlGaAs (x = 0.16)	undoped	
60 A	GaAs	0.6×10^{18} cm^{-3}	X 60
700 A	AlGaAs (x = 0.16)	undoped	X 60
60 A	GaAs	0.6×10^{18} cm^{-3}	
50 A	AlGaAs (x = 0.16)	undoped	
2500 A	GaAs	1×10^{18} cm^{-3}	
	GaAs	n+ SUBSTRATE	

Thermal Design Provides Required Performance



Thermal Zones:

Warm End

-Scene Select Mechanism

-Scene Select Mirror & Baffles (≤293K)

-Stability ±1K (35 sec)

-Stability ±2K (44Min)

-Blackbody Calibrator (270 to 320K)

-Stability ±0.1K (35 sec)

Cold End

-Tel Stage: Tel Assembly (185K)

-Stability ±0.1K (35 sec)

-Stability ±0.25K (44Min)

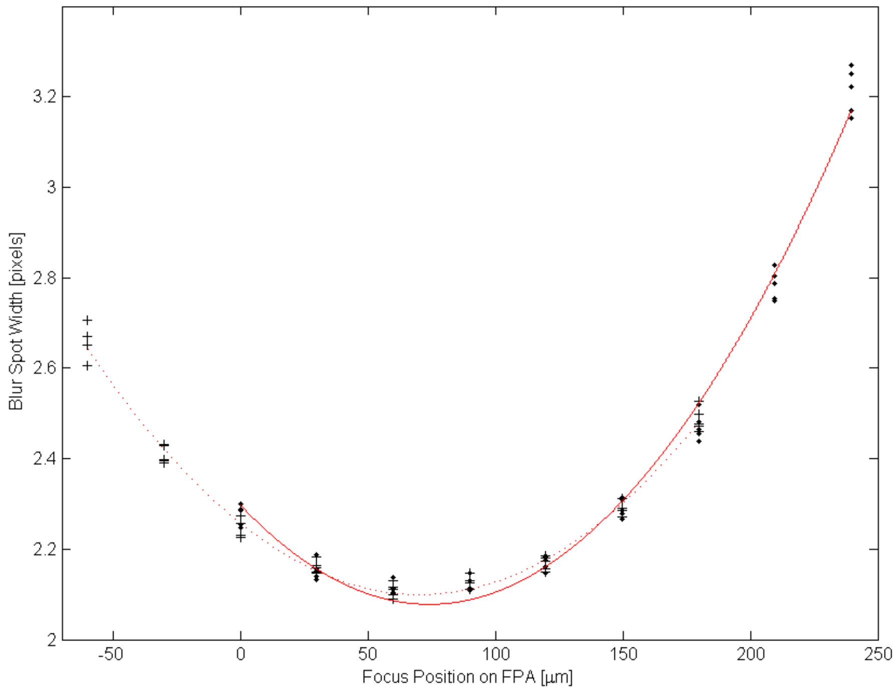
-Warm Stage: FPA Shroud (≤88K)

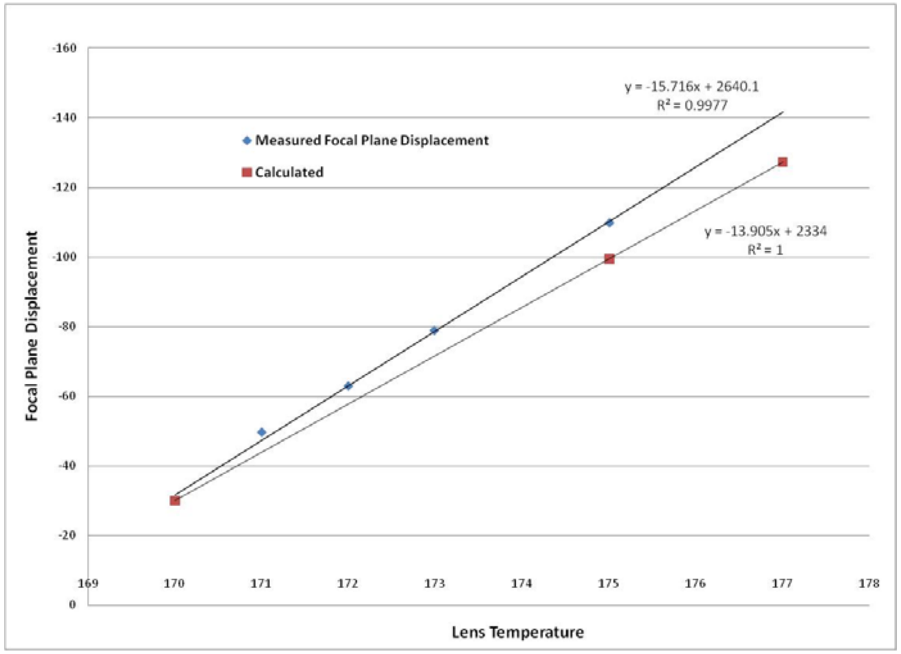
-Cold Stage: FPA (≤43K)

-Stability ±0.01K (35 sec)

-Stability ±0.02K (44 min)

TIRS Uses T-dependent Index of Refraction of GE to Adjust Focus

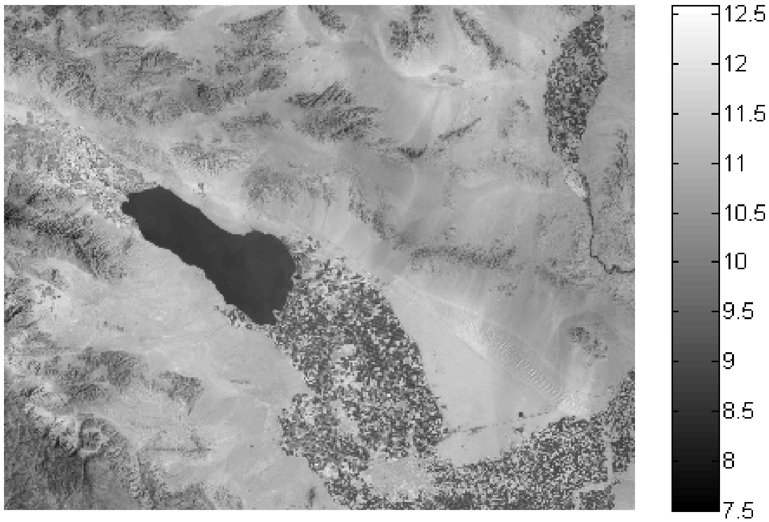




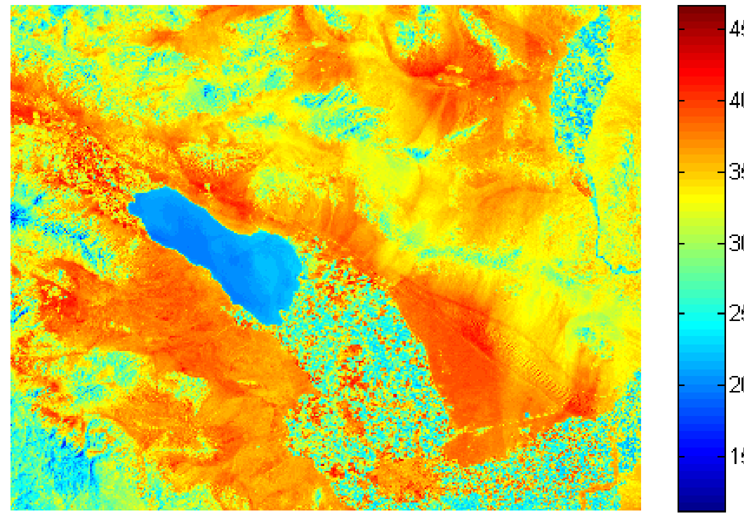
- 100 µm shift of focus smears the image by ~ 40%
- Requirement for focus adjustment caused requirement that lens temperature be adjustable from 180 to 190 K
    - Corresponds to ~ ± 75 µm focus shift.
    - Required lens temperature stability ± 2 K
- Noise stability required is more stringent

TIRS Surface Temperature Map – Salton Sea, CA

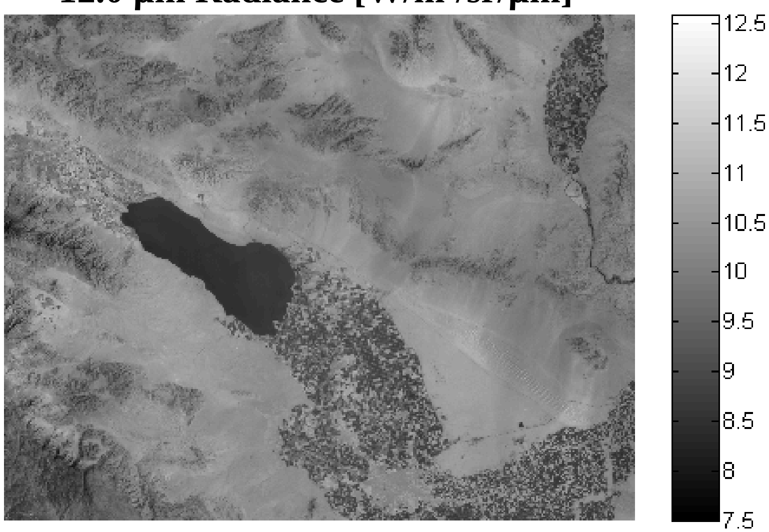
10.8 µm Radiance [W/m²/sr/µm]



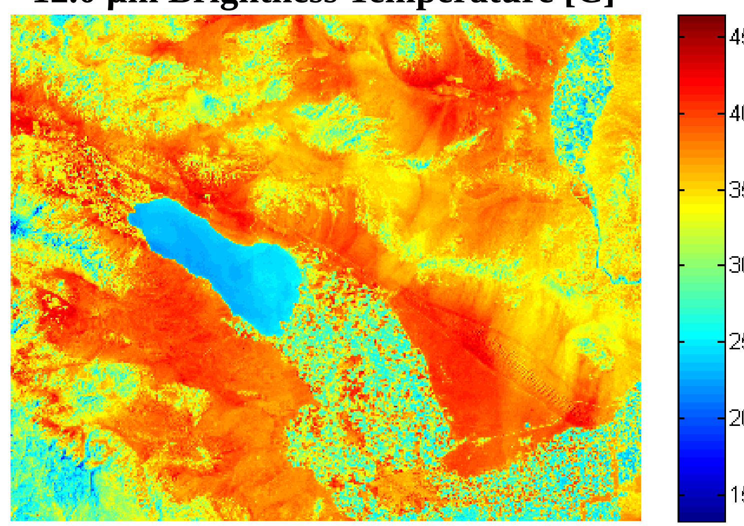
10.8 µm Brightness Temperature [C]



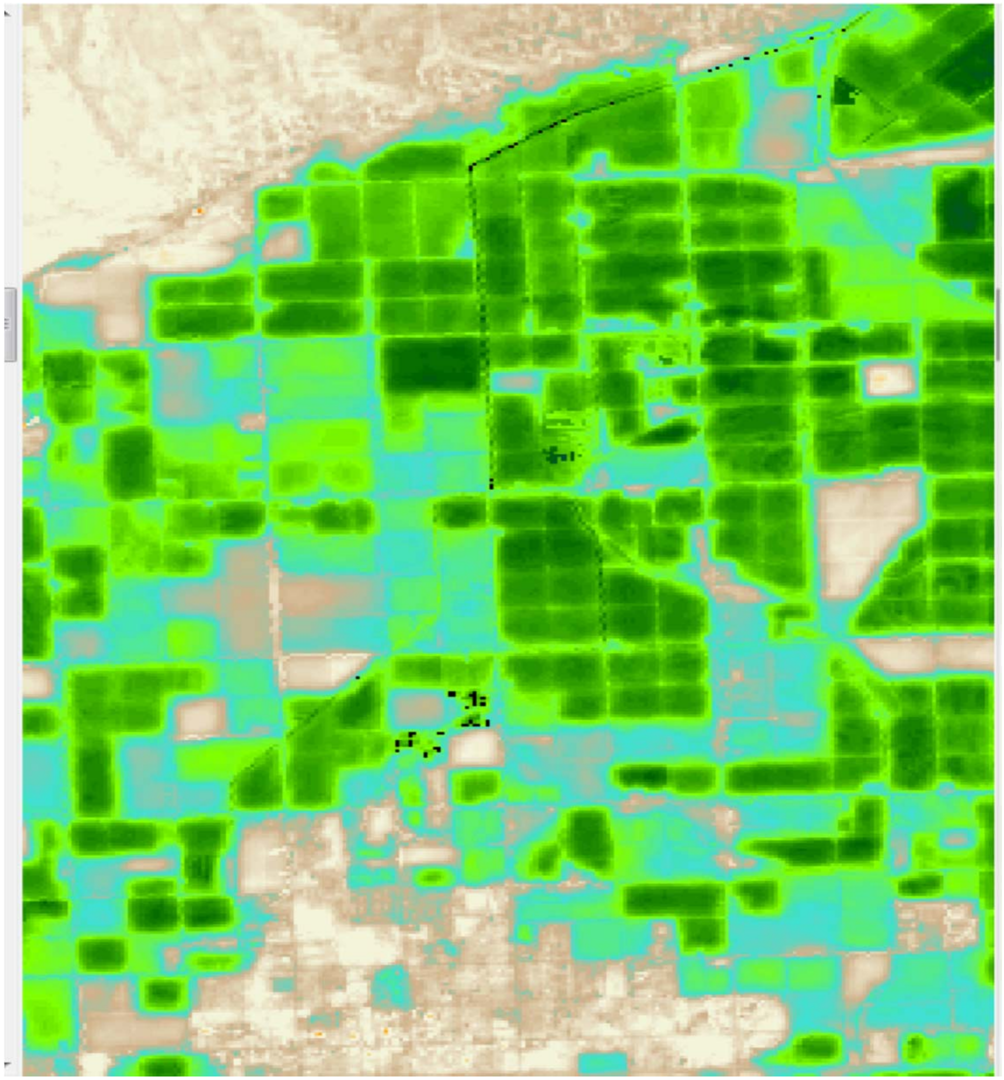
12.0 µm Radiance [W/m²/sr/µm]



12.0 µm Brightness Temperature [C]



Product: Derived Evapotranspiration Palo Verde, CA



Dark greens indicate higher ET and blues and beiges progressively lower ET.

Example 2: Ralph Instrument on New Horizons Pluto/Kuiper Belt Mission

- Passively cooled Ralph instrument has two components: MVIC and LEISA
- MVIC (Multi-spectral Visible Imaging Camera)
  - Panchromatic (400 – 975 nm) channel and four color channels
    - Blue (400–550 nm)
    - Red (540–700 nm)
    - NIR (780–975 nm)
    - Methane (860–910 nm)
  - Focal plane < 175 K
  - Color channels and two panchromatic channels operate in TDI (Time Delay and Integrate) mode
- LEISA (Linear Etalon Imaging Spectral Array)
  - 1.25 μm to 2.5 μm spectral imager with resolving power ($\lambda/\delta\lambda$) ~ 225
  - 2.1 μm to 2.25 μm spectral imager with resolving power ($\lambda/\delta\lambda$) ~ 545
  - Operates in push-frame mode
  - Focal plane < 115 K

New Horizons Mission Objectives

PRIMARY OBJECTIVES:

- CHARACTERIZE GLOBAL GEOLOGY AND MORPHOLOGY OF PLUTO AND CHARON
- MAP SURFACE COMPOSITION OF PLUTO AND CHARON (< 10 KM)
- CHARACTERIZE THE NEUTRAL ATMOSPHERE OF PLUTO AND ITS ESCAPE RATE

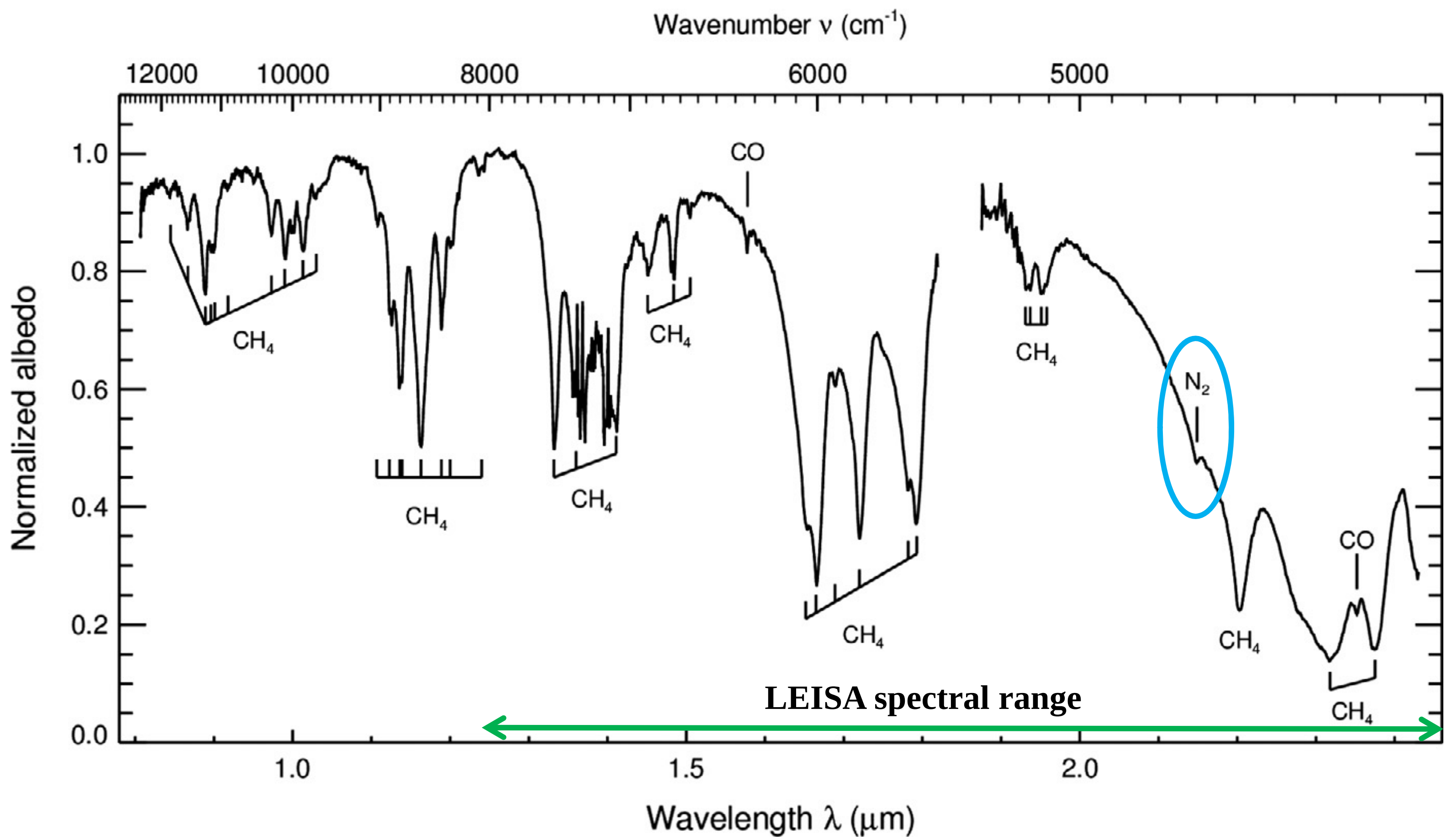
SECONDARY OBJECTIVES:

- CHARACTERIZE TIME VARIABILITY OF PLUTO'S SURFACE AND ATMOSPHERE
- IMAGE PLUTO AND CHARON IN STEREO
- MAP TERMINATORS OF PLUTO & CHARON AT HIGH RES
- MAP COMPOSITION OF SELECTED AREAS OF PLUTO AND CHARON AT HIGH RES
- CHARACTERIZE PLUTO'S IONOSPHERE AND SOLAR WIND INTERACTION
- SEARCH FOR NEUTRAL SPECIES, HYDROCARBONS, AND NITRILES IN PLUTO'S UPPER ATMOSPHERE
- SEARCH FOR ATMOSPHERE AROUND CHARON
- DETERMINE BOND ALBEDOS FOR PLUTO AND CHARON
- MAP SURFACE TEMPERATURES OF PLUTO AND CHARON

TERTIARY OBJECTIVES:

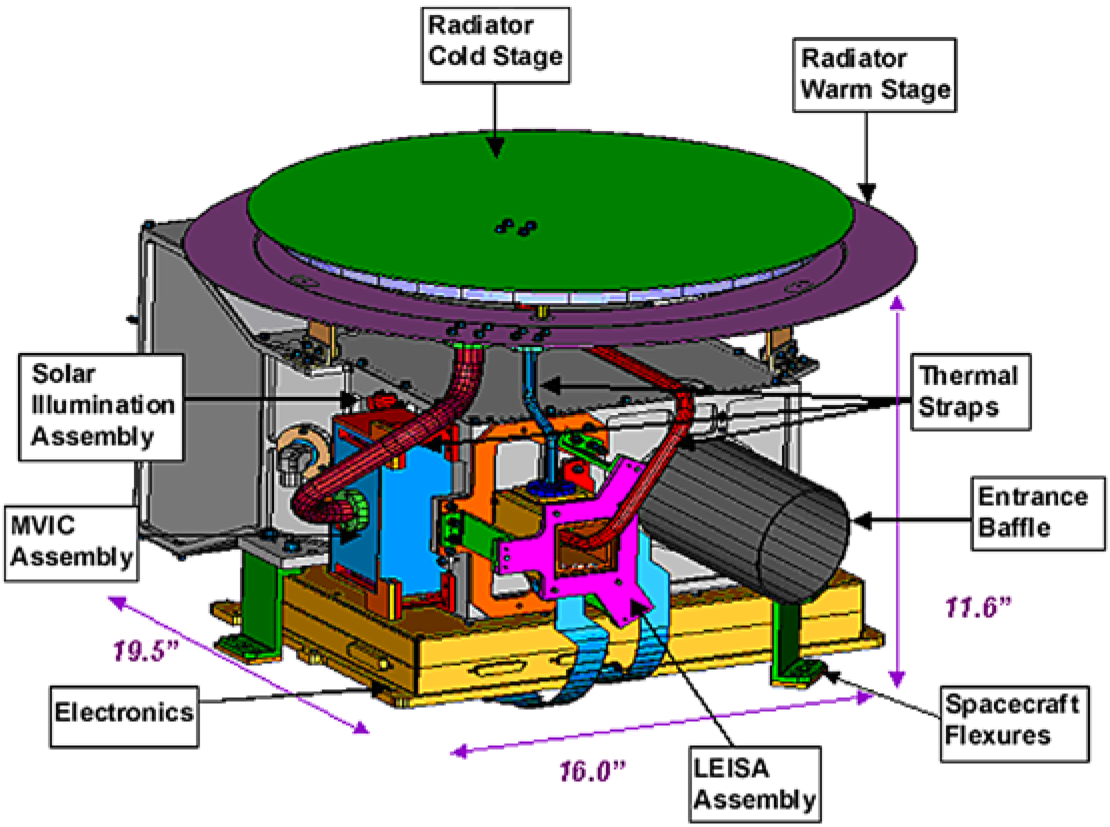
- CHARACTERIZE ENERGETIC PARTICLE ENVIRONMENT OF PLUTO AND CHARON
- REFINE BULK PARAMETERS (RADII, MASSES, DENSITIES) AND ORBITS OF PLUTO AND CHARON
- SEARCH FOR MAGNETIC FIELDS OF PLUTO AND CHARON
- SEARCH FOR ADDITIONAL MOONS AND RINGS

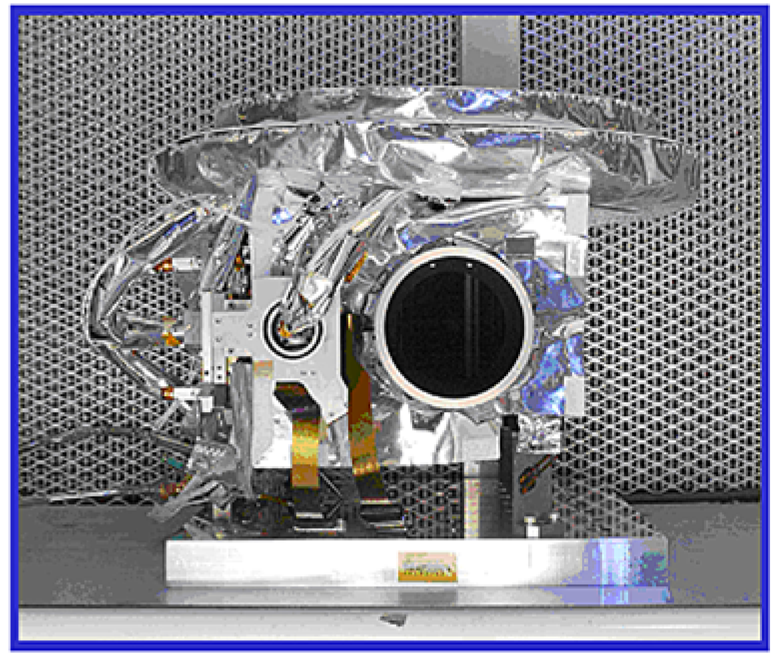
Example: Mapping Composition Using reflected Solar Spectra



Average of the best ***ground-based*** (whole disk) spectra of Pluto (including the light from Charon) from 65 data sets obtained from 2001 to 2013 in a monitoring program (Grundy et al., 2013). Reproduced courtesy Elsevier. Weak spectral features (e.g. N_2) drove LEISA sensitivity requirements including enclosure and detector temperatures.

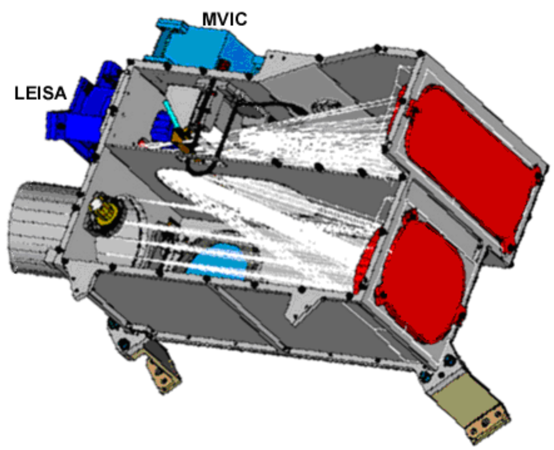
Ralph on New Horizons

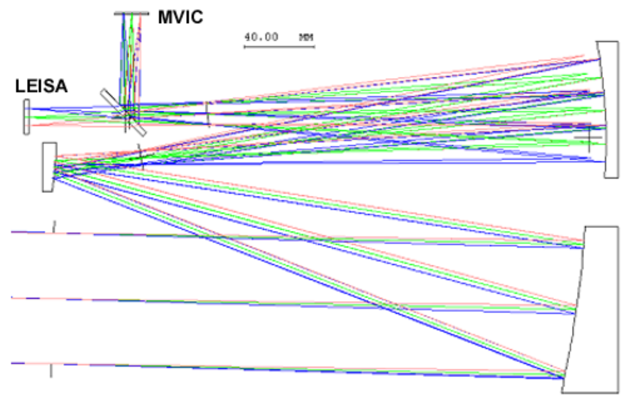


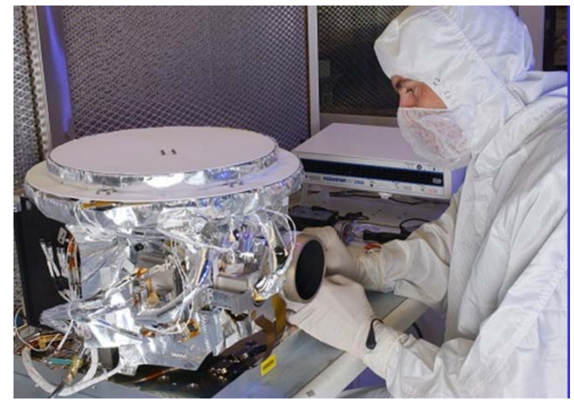


(*Left*) Model of the Ralph instrument with principle structures labeled. (*Right*) Picture of Ralph, looking down the aperture, before the addition of most of the multi-layer insulation (MLI)

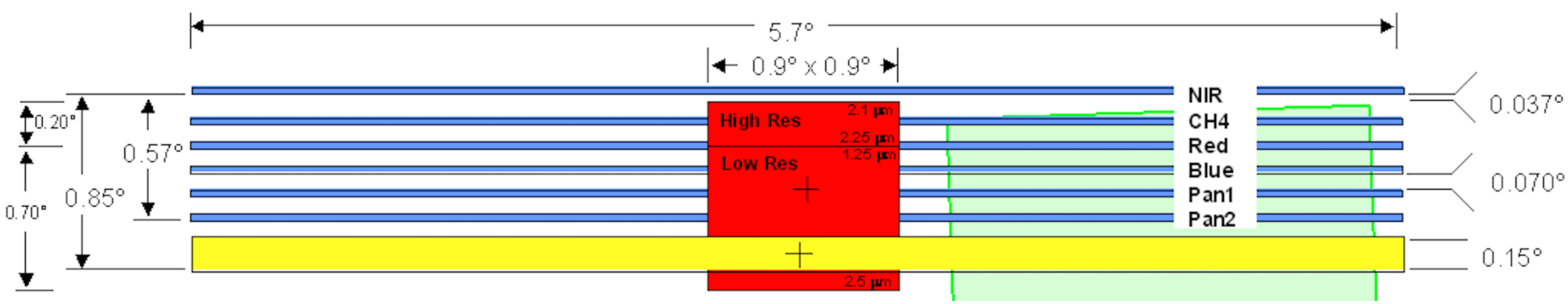
Ralph: Two Cameras in One Box





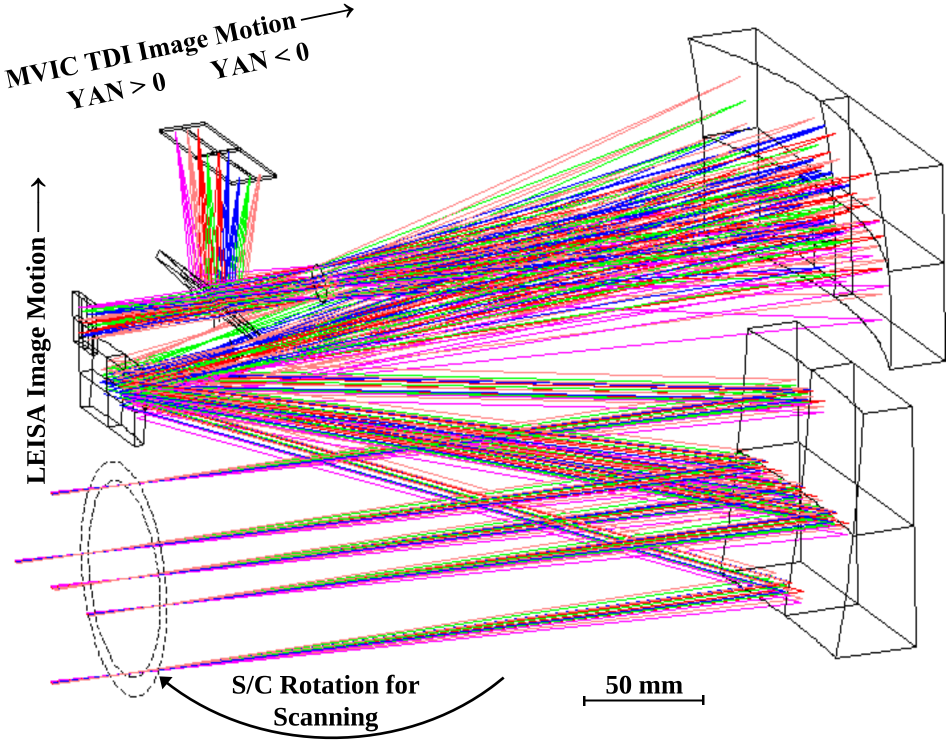


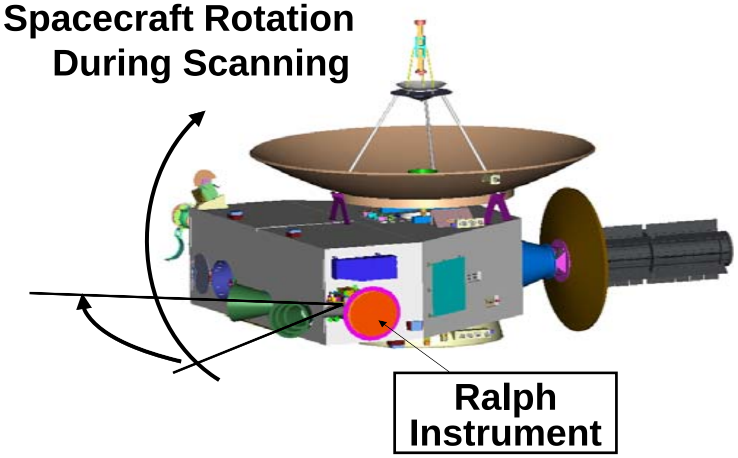
MVIC FOV



LEISA FOV

A Single Set of Optics Feeds Both Focal Planes





(*Left*) Raytrace diagram showing the path to the LEISA and MVIC focal planes and the Field of View (FOV) of both systems. (*Right*) Spacecraft rotation provides the image motion needed for scans.

Ralph MVIC Specifications & Requirements

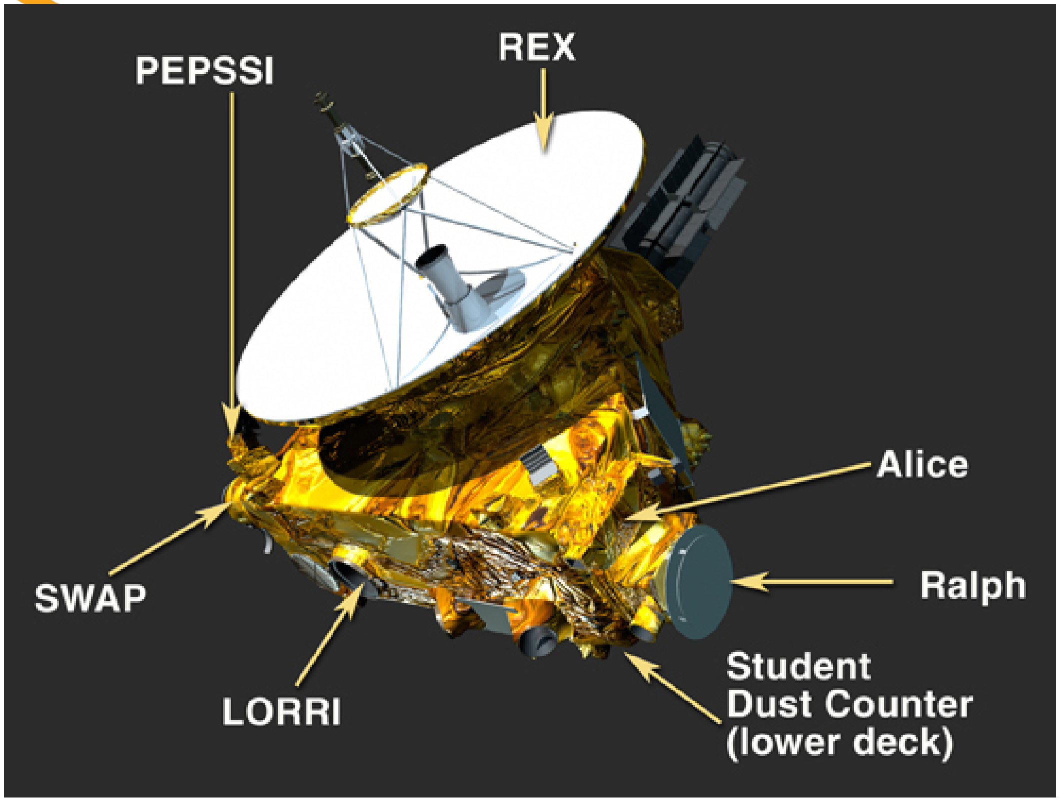
Field of View (FOV)		5.7° x 0.83°	
Modulation Transfer Function (MTF)		> 0.15 (Pan over 5.7° x 0.2°)	at 20 cycles/mRad
		> 0.15 (NIR over 3.7°)	at 20 cycles/mRad
MVIC Color/Pan Bands S/N Specifications			
Panchromatic	400 - 975 nm	S/N > 50 single pixel	at albedo = 0.35
Blue	400 - 550 nm	S/N > 50 single pixel	at albedo = 0.35
Red	540 - 700 nm	S/N > 50 single pixel	at albedo = 0.35
Near IR	780 - 975 nm	S/N > 50 single pixel	at albedo = 0.35
Methane	860 - 910 nm	S/N > 15 single pixel goal	at albedo = 0.35
Optical Navigation Requirements			
Image Pluto and at least 4 stars with a S/N > 7			
90% encircled energy diameter <36 microns			
Alignment			
Ralph shall have an alignment cube			
Ralph line-of-sight with respect to alignment cube		< 3.2 mRad	
Aperture Cover			
Ralph shall have an aperture cover		One-time operation with transparent window	
Temperatures			
Housing	< 230 K	1.2 K Gradients (Passive)	
MVIC Detector	< 180 K		

Ralph LEISA Specifications & Requirements

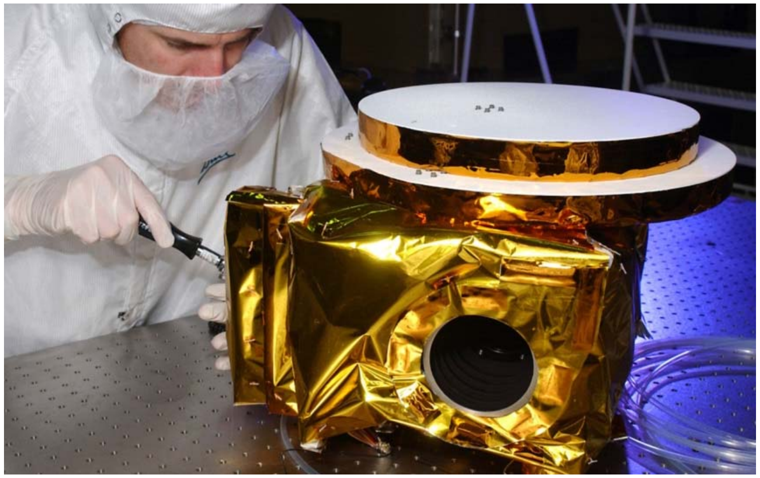
- **Imaging Performance (MTF @ Nyquist) not specified by will be higher than MVIC due to larger pixels, smaller field, longer wavelength**

Detector Element	40 μm by 40 μm	
Resolution (IFOV)	62 μR/pix	⇒ 650 mm EFL
FOV	0.90 deg x 0.90 deg	
MTF	None	will be >30% @ Nyquist
LEISA S/N Specifications at specific wavelengths		
1250 nm	S/N > 31/pix	at albedo = 0.35
2000 nm	S/N > 27/pix	at albedo = 0.35
2150 nm	S/N > 18/pix	at albedo = 0.35
Spectral Performance		
Spectral Range	1250 to 2500 nm	
Spectral Resolution	$\Delta\lambda/\lambda > 220$	at 1250 - 2500 nm
	$\Delta\lambda/\lambda > 520$	at 2100 - 2250 nm
Temperature		
LEISA Detector	< 130 K	
Alignment		
LEISA with-respect-to MVIC	None	will be <1 mrad

New Horizons Spacecraft with Instruments



New Horizons Spacecraft showing the positions of all seven instruments. The Ralph MVIC and LEISA images are obtained by scanning the fields of view across the target by spacecraft motion.



Ralph instrument swathed in MLI in preparation for mounting on spacecraft. Boresight is facing forward in this picture

LEISA Noise Drives Thermal Requirements

- LEISA noise is also a function of inherent signal variance (electron "shot noise"), system instability noise, electronics and array noise ("read noise") and quantization noise – terms dependent on thermal system
- For wavelength λ, an integration time t, Source flux FS_λ, Background flux FB_λ, Optics flux FO_λ and detector dark current I(D)
- $N(\lambda) = \{[t*(FS_\lambda + FB_\lambda + FO_\lambda + ID)] +$

  $[t^2*(((\delta FB_\lambda(B)/\delta T)\Delta T(B))^2 + ((\delta FO_\lambda (B)/\delta T)\Delta T(B))^2 + ((\delta ID/\delta T)\Delta T(D))^2)]$

  $+ [RD^2 + RE^2 + Q^2]\}^{1/2}$

$FS_\lambda = RS_\lambda*QE*\tau_f*r_m{}^3*\pi/(1+(2f)^2)$, $FB_\lambda = B_\lambda (B)*QE*\tau'_f*\pi*(\Omega_b-1 /(1+(2f)^2)$,

$FO_\lambda = B_\lambda (B)*QE*\tau_f*3*\varepsilon_m*\pi/(1+(2f)^2)$,

RS_λ = Reflected solar flux at wavelength λ, $B_\lambda (x)$ = Planck radiance at λ for temperature x

ID = $K*\exp(-1.4388*cutoff/T_d)$[K and cutoff depend on array], RD = detector read noise

RE = electronics read noise, Q = 12 bit quantization noise = $(\text{well depth}/4094)/(12)^{1/2}$

QE = Quantum Efficiency, τ_f = filter transmittance, f = f/#, r_m = mirror reflectance

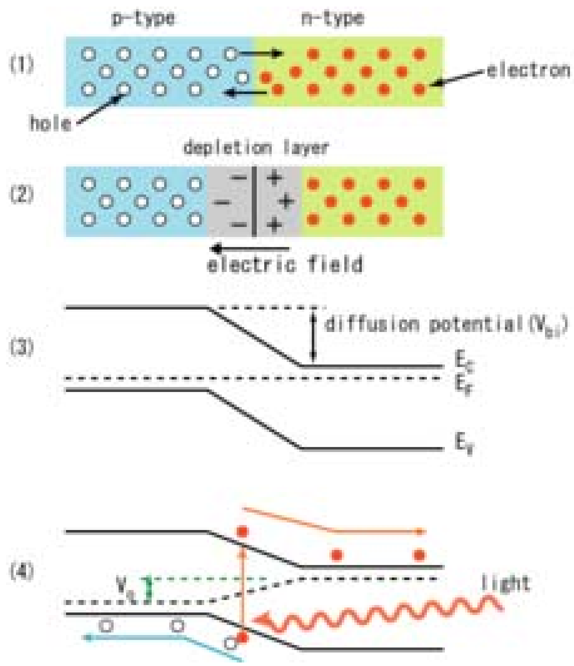
ε_m = mirror emittance, $\tau'_f = (1+\tau_f)/2$, Ω_b = solid angle above cold shield

g = photoconductive gain =1

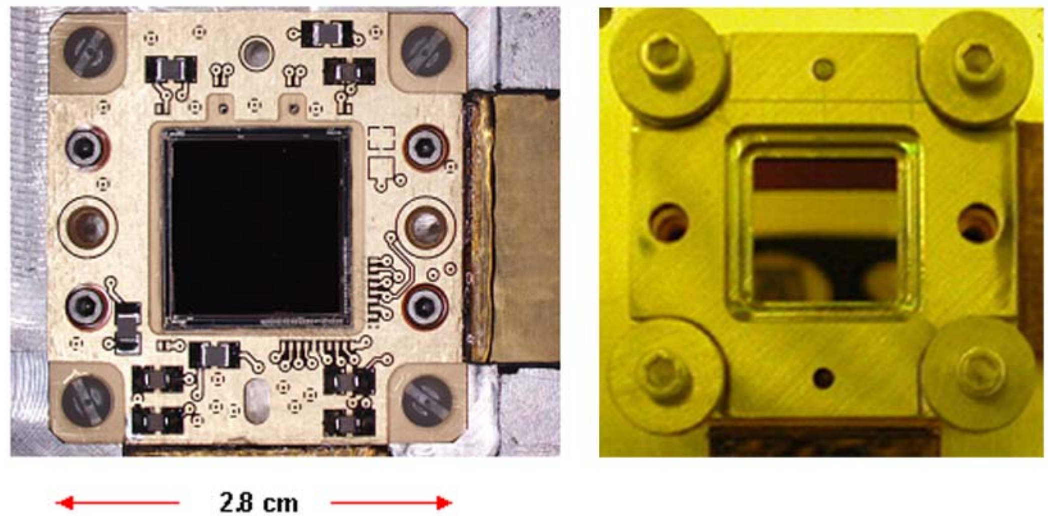
Noise terms are similar to TIRS but some differences

- The wavelength cutoff of detector requires low temperature operation to reduce dark current
  - Because this is a passively cooled system this is a very significant driver
- Temperature stability is not a significant driver
  - Small temperature changes don't affect dark current or background as much
- Thermal emission signal from the instrument is significant but, because a wedged filter is used to obtain spectra, only the longer wavelengths are affected
- Used photovoltaic detector because increased QE is very important at low light levels
  - Also only has both charge generation noise term so no factor of sqrt(2) in the flux noise term.
  - At 2.5 micron cutoff, HdCdTe detectors give decent uniformity and stability.
- Again, numerous trades available
  - Detector temperature, integration time, electronics noise, QE, f/#, etc. etc…..

LEISA detectors 256 x 256 pixel HgCdTe

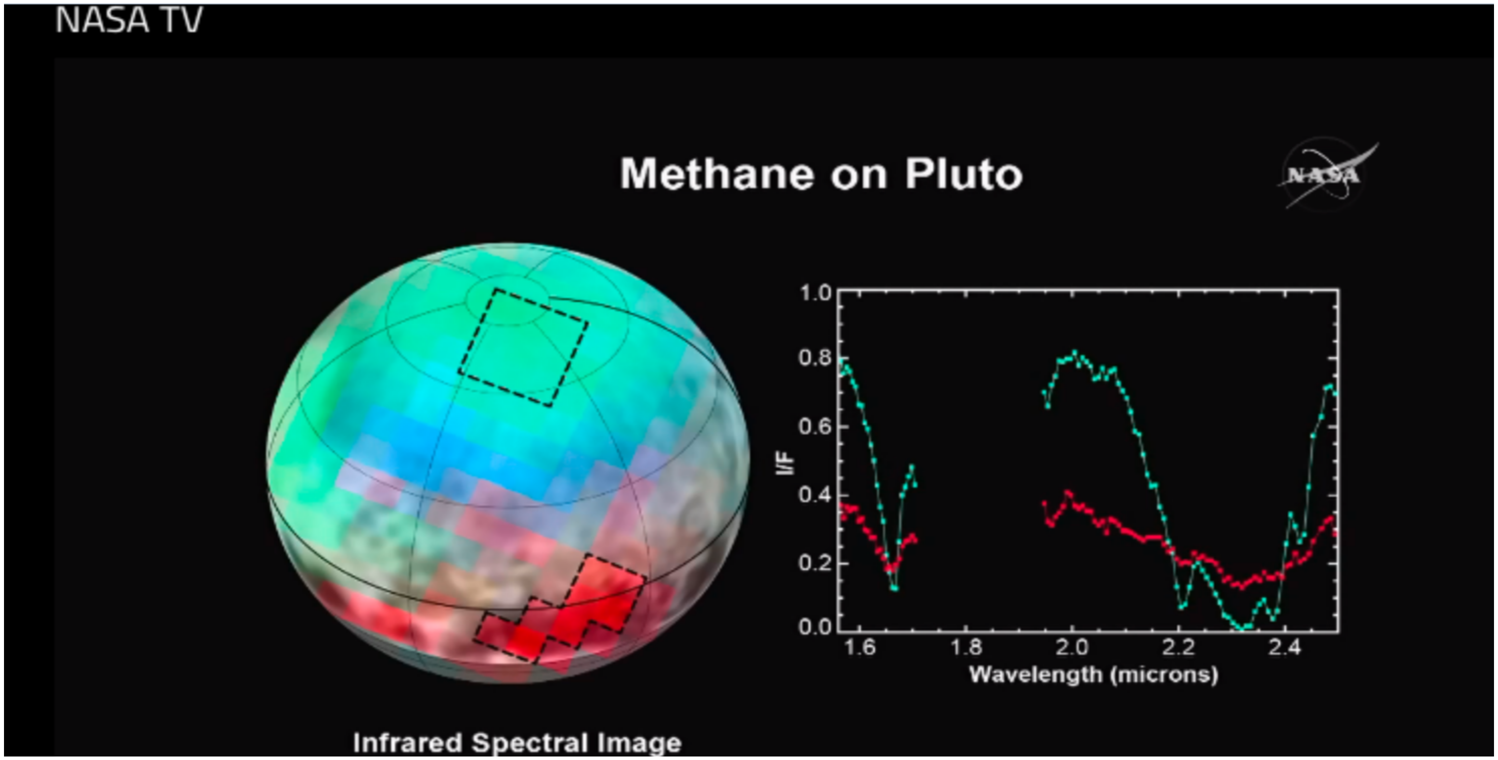


In photovoltaic detectors an applied voltage induces a large junction region from which photons can eject carriers into the conduction band with essentially no recombination loss. The well depth is the number of carriers required to remove the depletion layer.



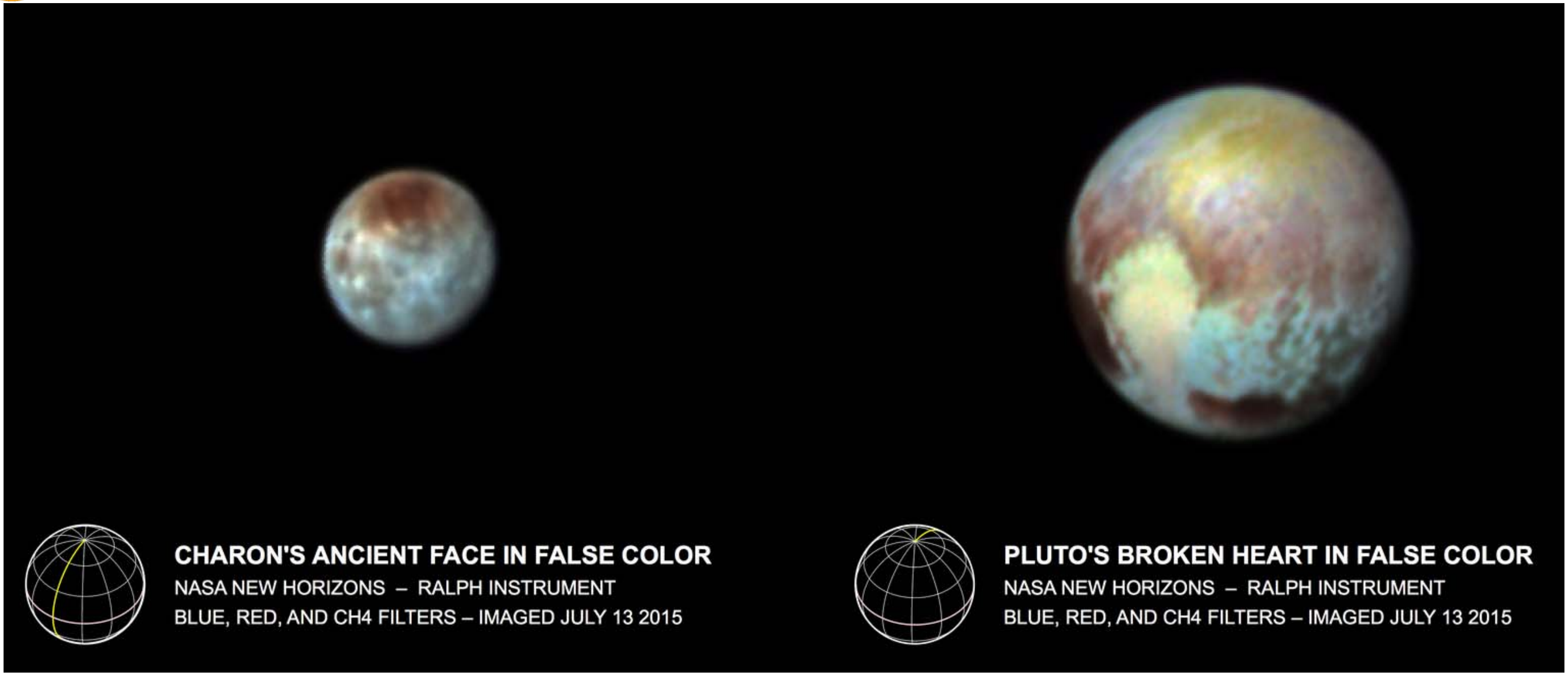
(*Left*)The 256 x 256 pixel LEISA detector. The active area of the array is the the central dark region. (*Right*) The full LEISA focal plane assembly with the wedged filter shown mounted above the array.

Pluto Methane Map Obtained with LEISA Shows Spatial Differences



(Left) an image of Pluto showing the methane distribution obtained using IR spectra generated by Ralph/LEISA. (Right) Examples of Pluto relative reflectance spectra. The blue spectrum shows absorption bands characteristic of solid methane (CH_4). The red spectrum, while showing evidence of the methane bands, is broader and has much less structure. It may be representative of absorption by water and/or a mixture of species known as tholins in addition to CH_4. The spatial resolution of these data is on the order of 150 km. Later observations of Pluto obtained spectra at a spatial resolution of about 6 km, or roughly 25 times higher than that shown here.

False Color Map of Pluto and Charon Shows Remarkable Surface Variety



This July 13, 2015, image of Pluto and Charon is presented in false colors to make differences in surface material and features easy to see. It was obtained by the Ralph instrument, using three filters to obtain color information, which is exaggerated in the image. The apparent distance between the two bodies has been reduced. (Right) The bright heart-shaped region of Pluto includes areas that differ in color characteristics. The western lobe, shaped like an ice-cream cone, appears peach color in this image. A mottled area on the right (east) appears bluish. Even within Pluto's northern polar cap, in the upper part of the image, various shades of yellow-orange indicate subtle compositional/ differences. (Left) The surface of Charon is viewed using the same exaggerated color. The red on the dark northern polar cap is attributed to hydrocarbon materials including a class of chemical compounds called tholins. The mottled colors at lower latitudes point to the diversity of terrains on Charon.

Some Closing Thoughts

- Once defined, the science goals are a significant driving force in defining the system requirements
  - Of course, implementation and survival requirements are critical, but they are relative to the system being designed to obtain the science
- However, there is typically some leeway in the science goals, and it behooves all to recognize this.
  - The degradation of a product typically starts slowly when requirements are exceeded
  - When 10% of the goal is causing 90% of the implementation problems, it is time to have a discussion
- Effort should be made to meet the requirements at a subsystem level
- However, the system performance is dependent on all requirements – there is usually an opportunity to make sub-system level trades
  - It is very important that there be open communication about problems
- **Please let the system engineers and the scientists know when meeting a particular requirement is becoming problematic**.
  - We are ready to believe you.