How does Inter-calibration support Crosstrack Infrared Sounder (CrIS) post-launch calibration?

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    - Using VIIRS image Band as a reference

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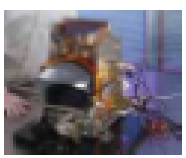
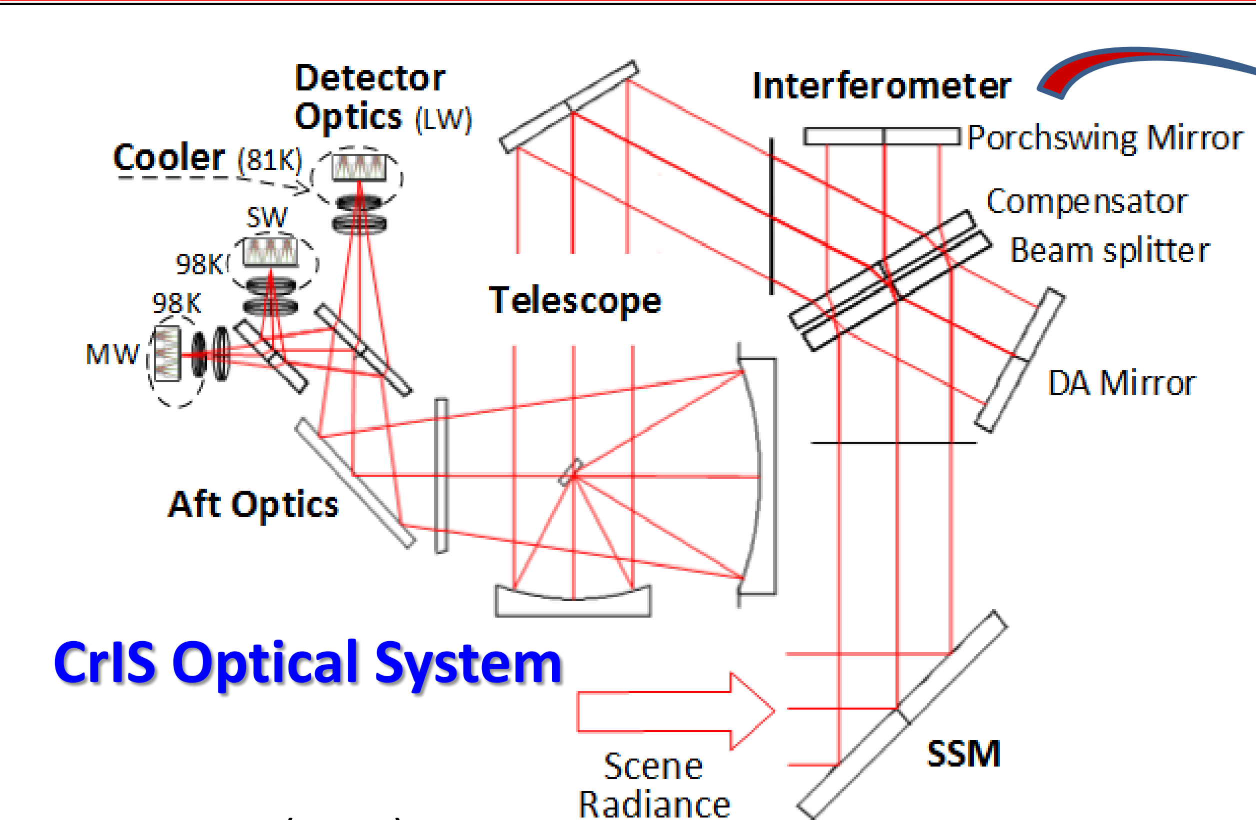
Soumi NPP/JPSS Instruments

NPP/JPSS Instrument		Benefits to the NOAA Mission
	ATMS (NGES)	ATMS and CrIS together provide high vertical resolution temperature and water vapor information needed to maintain and improve forecast skill out to 5 to 7 days in advance for extreme weather events, including hurricanes and severe weather outbreaks.
	CrIS (ITT)	
	VIIRS (Raytheon SAS)	VIIRS provide a large set of parameters including snow/ice cover, clouds, fog, aerosols, fire, smoke plumes, vegetation health, phytoplankton abundance/chlorophyll needed for environmental assessments which impacts human health and key economic sectors (transportation, fishing, energy, agriculture)
	OMPS (Ball Aerospace and Technology Corp)	Total ozone for monitoring ozone hole and recovery of stratospheric ozone and for UV index forecasts
	CERES	Provide climate quality measurements of the Earth's outgoing radiation budget.

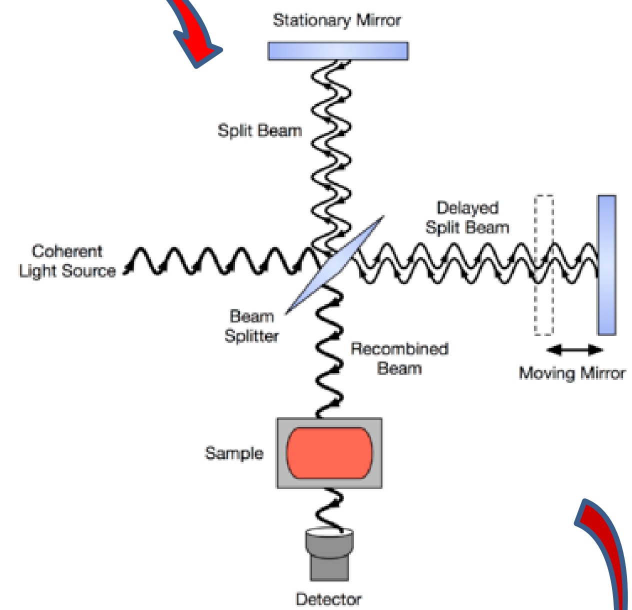
From M. Goldberg (2014)

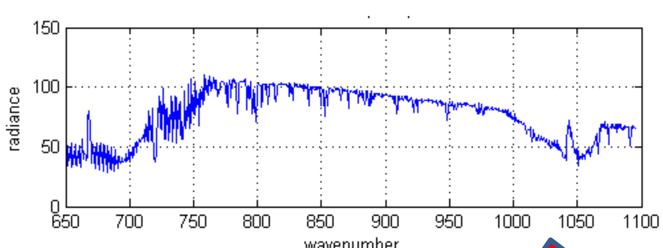
CrIS: Interferometer



CrIS Optical System

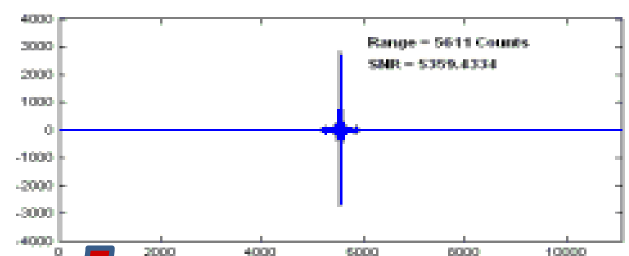
Yong Han (2014)





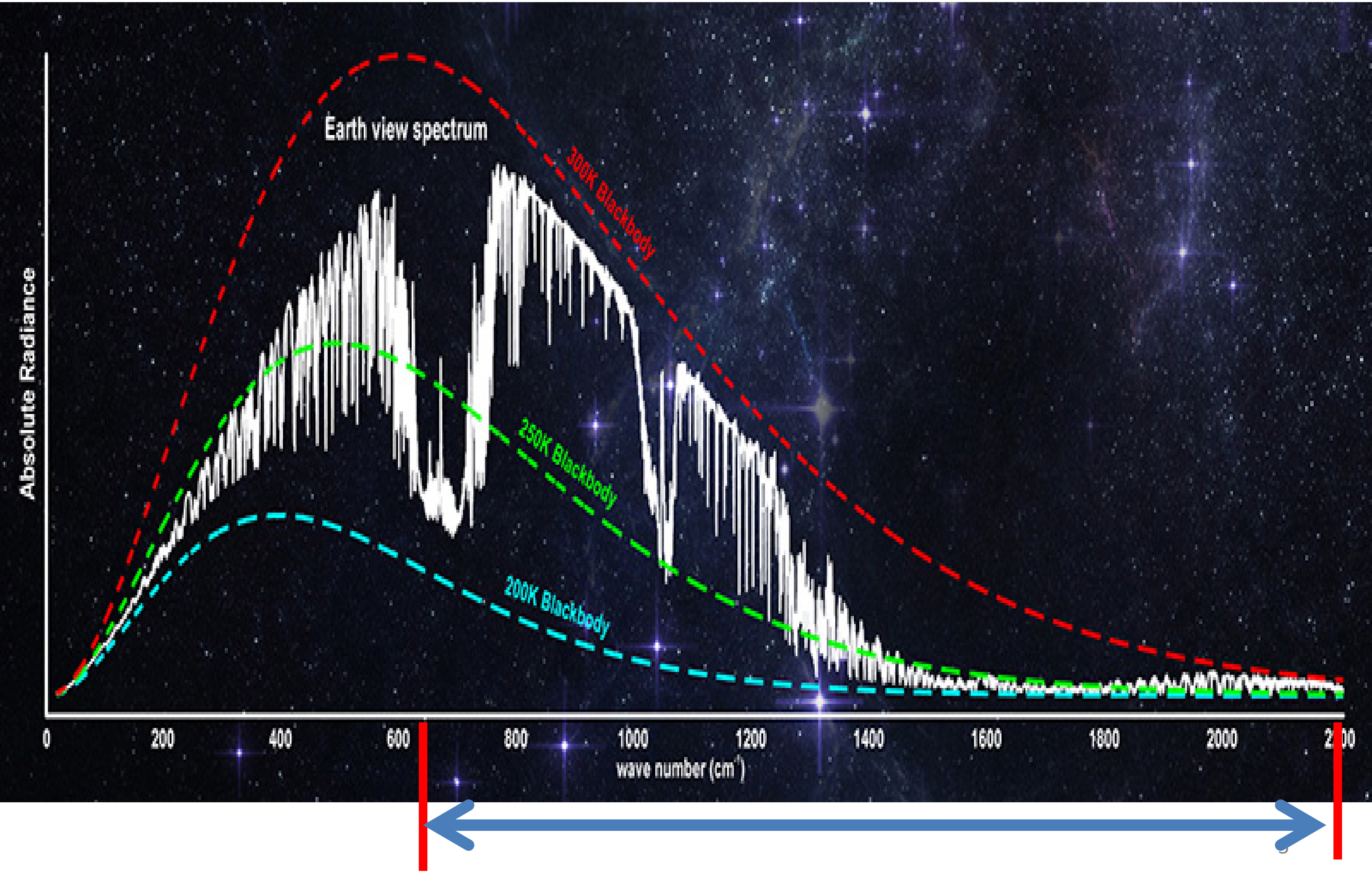
IR spectrum

Fourier Transform

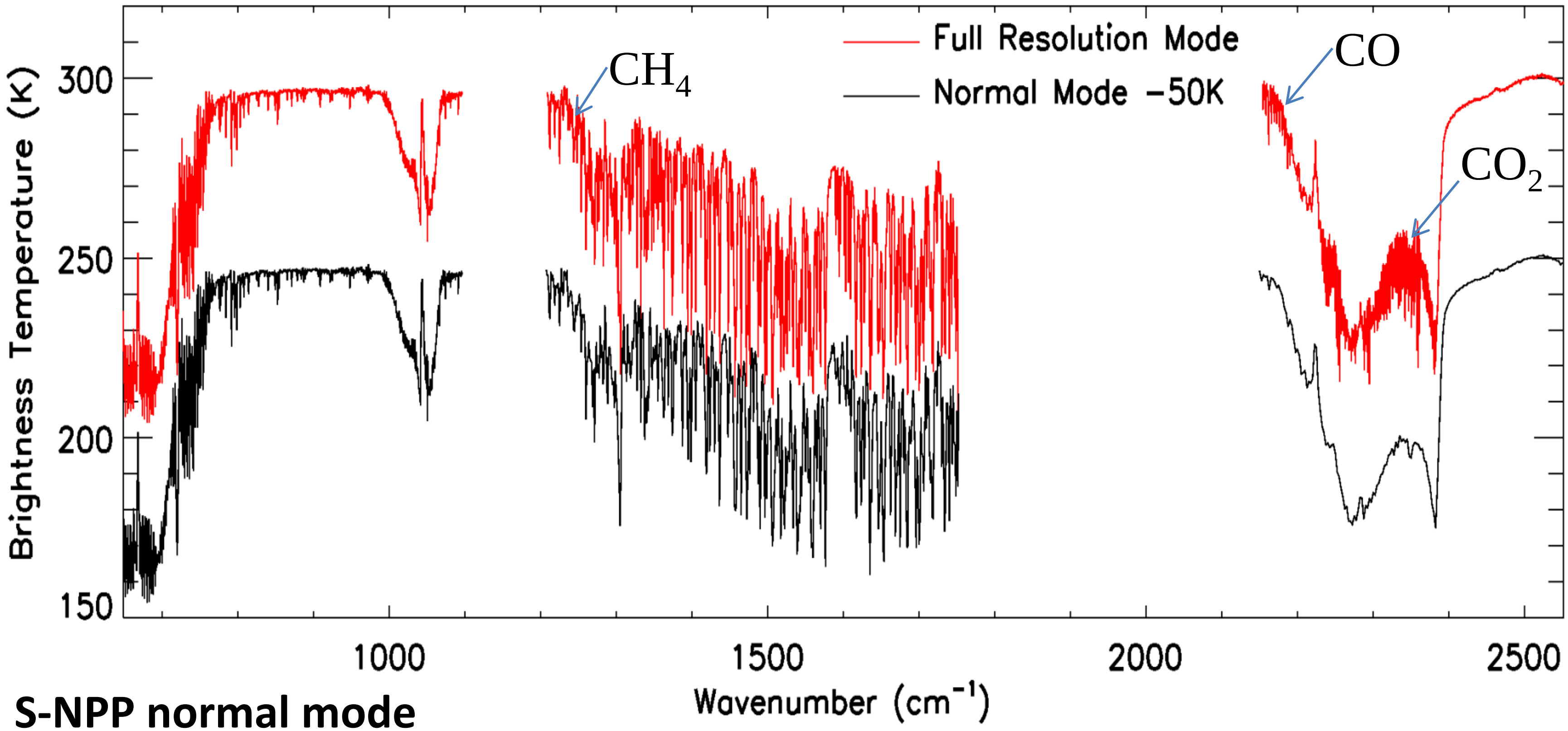


Interferogram

Earth IR Spectral Radiance



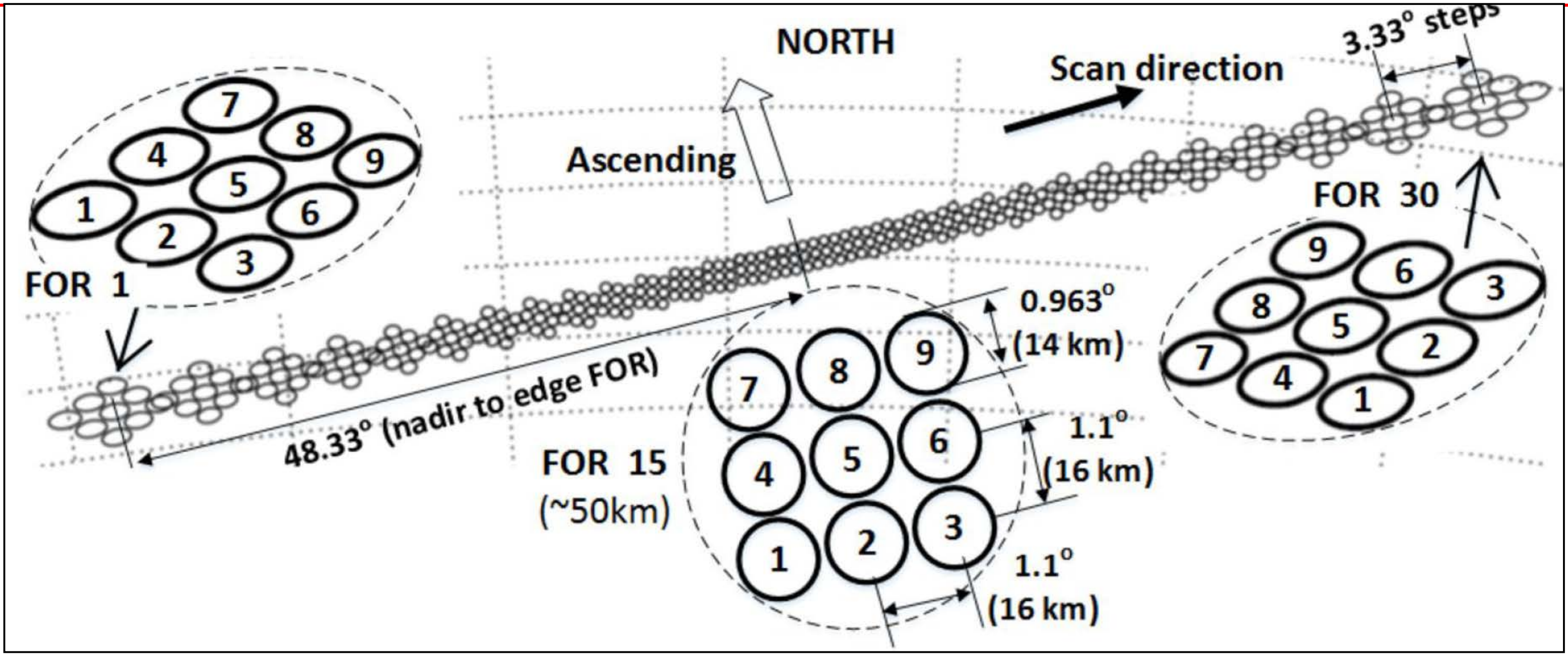
CrIS Spectral Bands



*** S-NPP normal mode**

Band	Laser Grid Range (cm^{-1})	User Grid Range (cm^{-1})	Spectral Resolution (cm^{-1})	Maximum Optical Path Difference (cm)
LWIR	603.2 – 1140.8	650-1095	0.625 (*0.625)	0.8
MWIR	1153.4 – 1806.6	1210 - 1750	0.625 (*1.25)	0.8
SWIR	2103.6 – 2601.3	2155-2550	0.625 (*2.5)	0.8

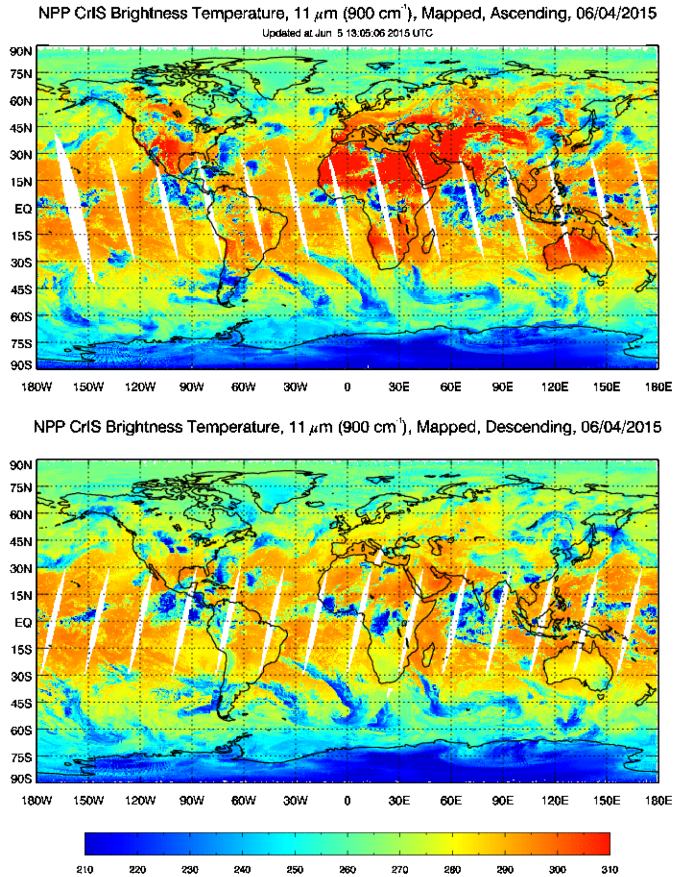
CrIS Scan Patterns



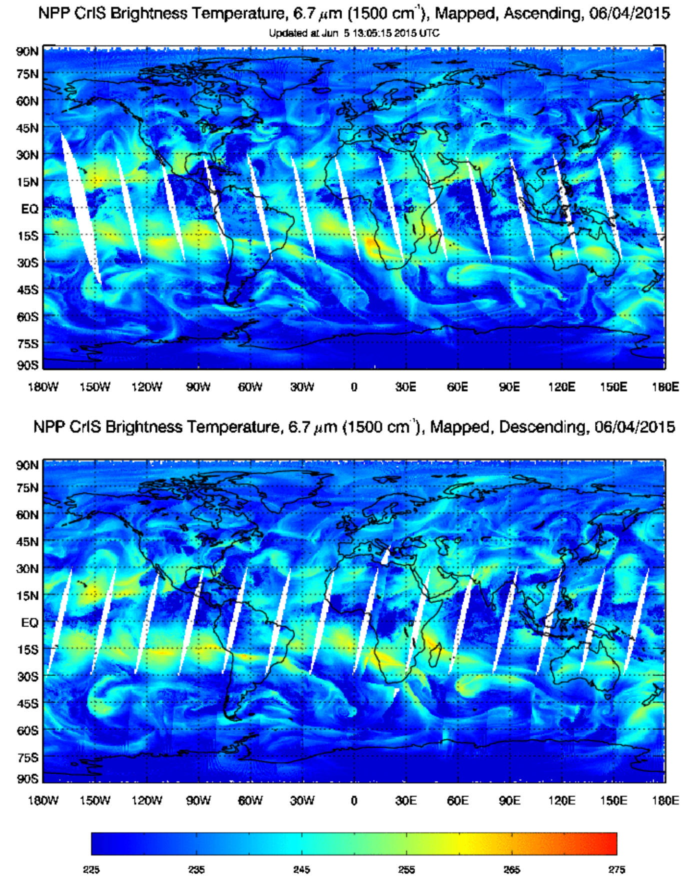
From Yong Han et al. (2014)

- For one mirror sweep, each focal planes illuminate 9 FOVs.
- The 9 FOVs form one FOR.
- Swath is 2200 Km (FOR1 to FOR 30).
- CrIS acquires 1 scan line every 8 seconds.
- CrIS measures 8.7 million spectra per day.

CrIS Images



Window channel



Water Vapor channel

Main Users:

1) **Radiances as inputs for NWP Data Assimilations**
2) **Atmospheric profiles retrievals (Temperature and Humidity)**
3) **Trace gas retrievals (CO_2, CO, CH4 …)**
4) **Inter-calibration references for other broadband or narrow band instruments**

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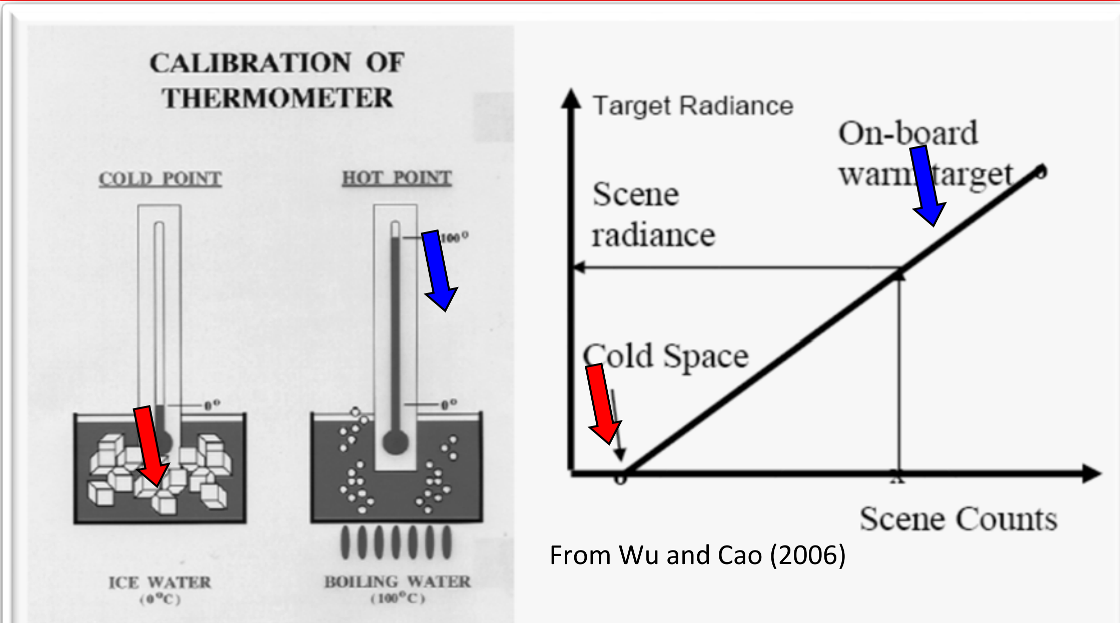
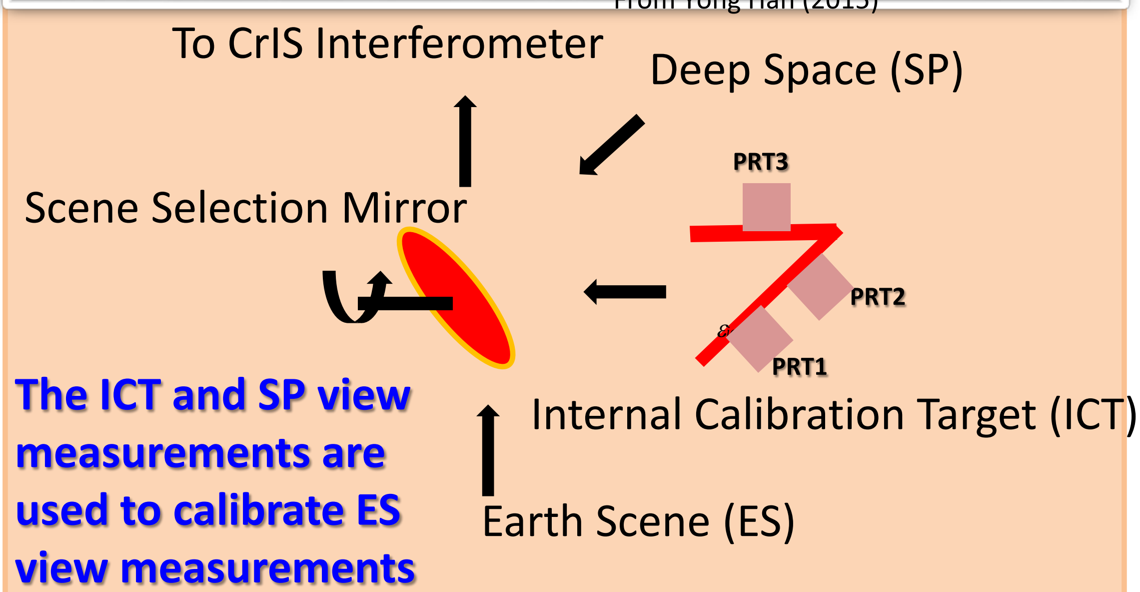
How to calibrate satellite sensor?



From Yong Han (2015)



The ICT and SP view measurements are used to calibrate ES view measurements

Digital Counts (No Unit)

↓ Level 1B data

Radiance (Unit)

WMO IMOP Guidance:

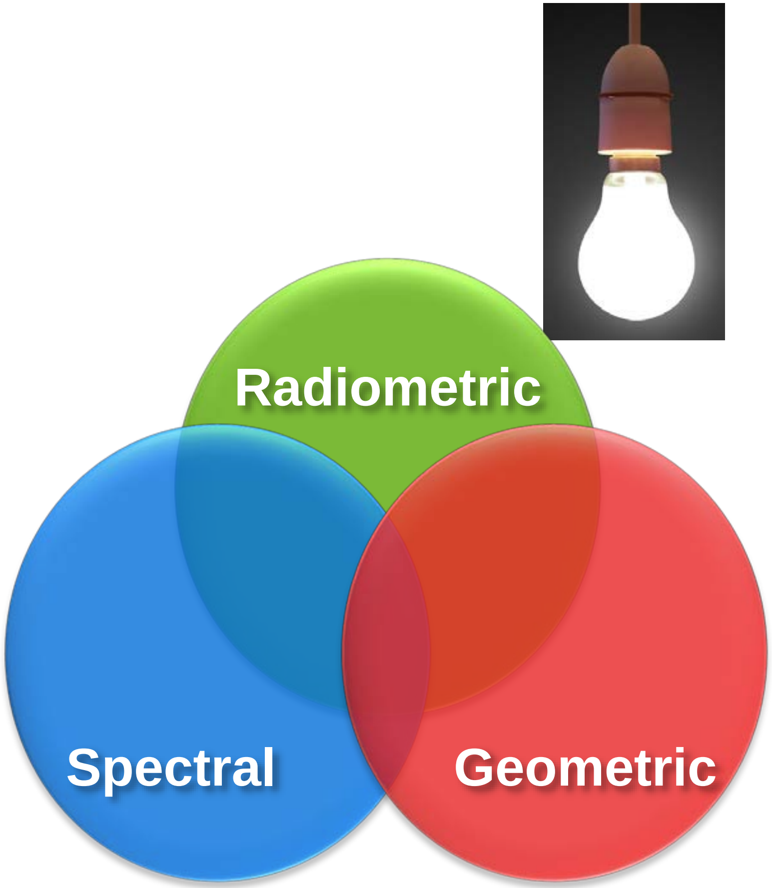
“Calibration is the process of quantitatively defining the satellite instrument response to known, controlled signal inputs . The calibration information is contained in a calibration formula, or calibration coefficients that are then used to convert the instrument output (“counts”, previously “analogue signals”) into physical units (e.g., a radiance value).”

Satellite Sensor Calibration

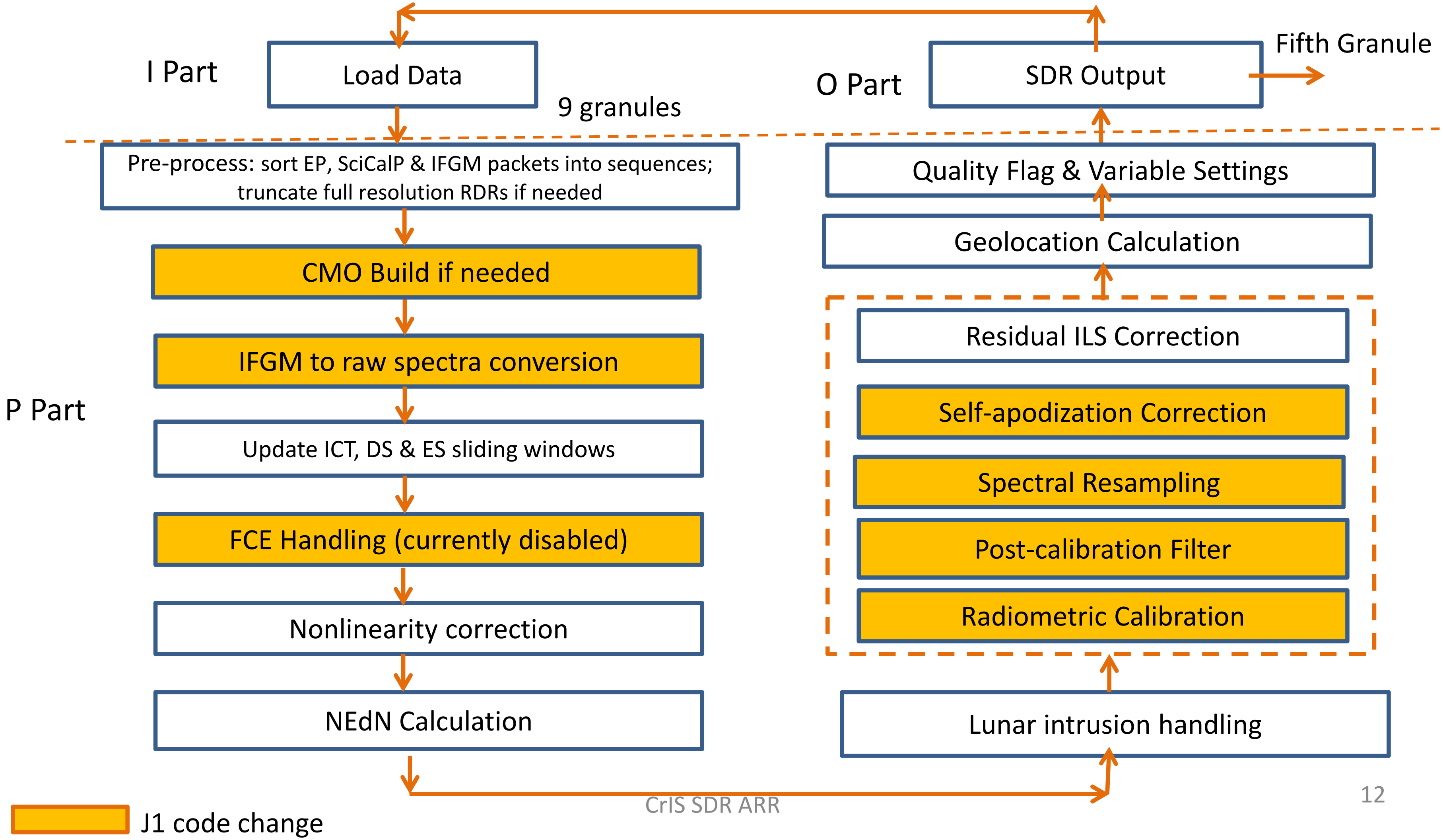
- Radiometric – how strong is the radiance
  - Precision (Noise): NEDN or NEDT
  - Accuracy: Radiometric Uncertainties
  - Polarization

- Spectral Calibration – at which wavelength is radiance from?
  - Central wavenumber
  - Spectral uncertainties

- Geometric Geometric: where does radiances come from?
  - Geolocation (Latitude and Longitude)
  - Band-to-Band Registration



CrIS SDR Processing Major Modules

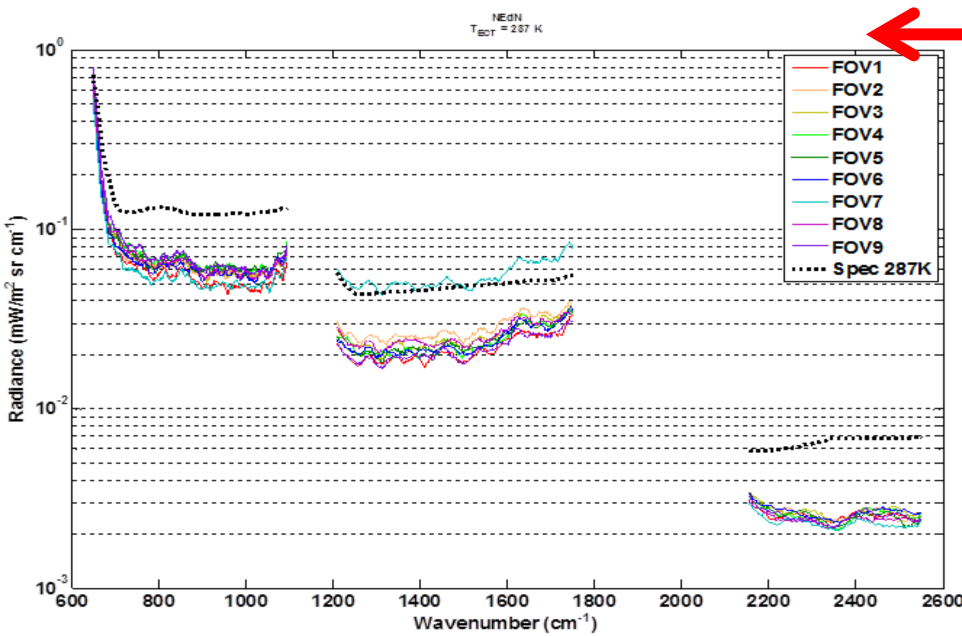


From Yong Han (2015)

NPP CrIS Sensor Data Record Calibration Uncertainty Specifications

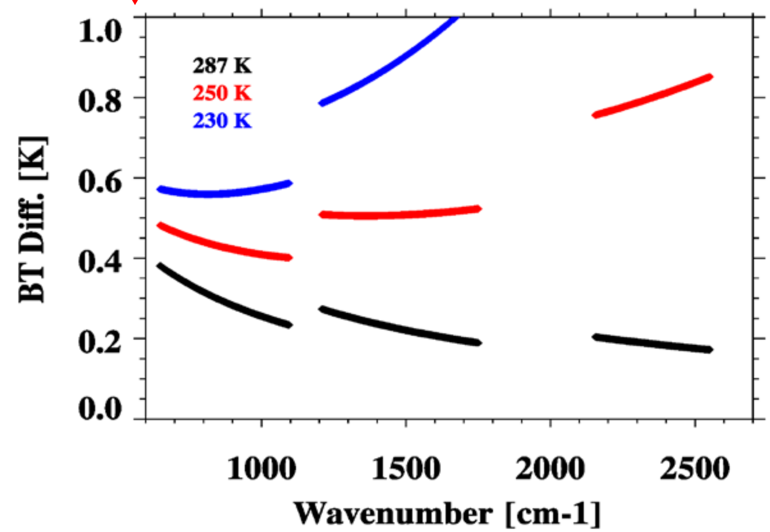
SDR Calibration Uncertainty

Band	Spectral range (cm^{-1})	N. of chan.	Resolution (cm^{-1})	FORs per Scan	FOVs per FOR	NEdN @287K BB mW/m²/sr/cm^{-1}	Radiometric Uncertainty @287K BB (%)	Spectral (chan center) uncertainty ppm	Geolocation uncertainty km
LW	650-1095	713	0.625	30	9	**0.14**	**0.45**	**10**	**1.5**
MW	1210-1750	433	1.25	30	9	**0.06**	**0.58**	**10**	**1.5**
SW	2155-2550	159	2.5	30	9	**0.007**	**0.77**	**10**	**1.5**



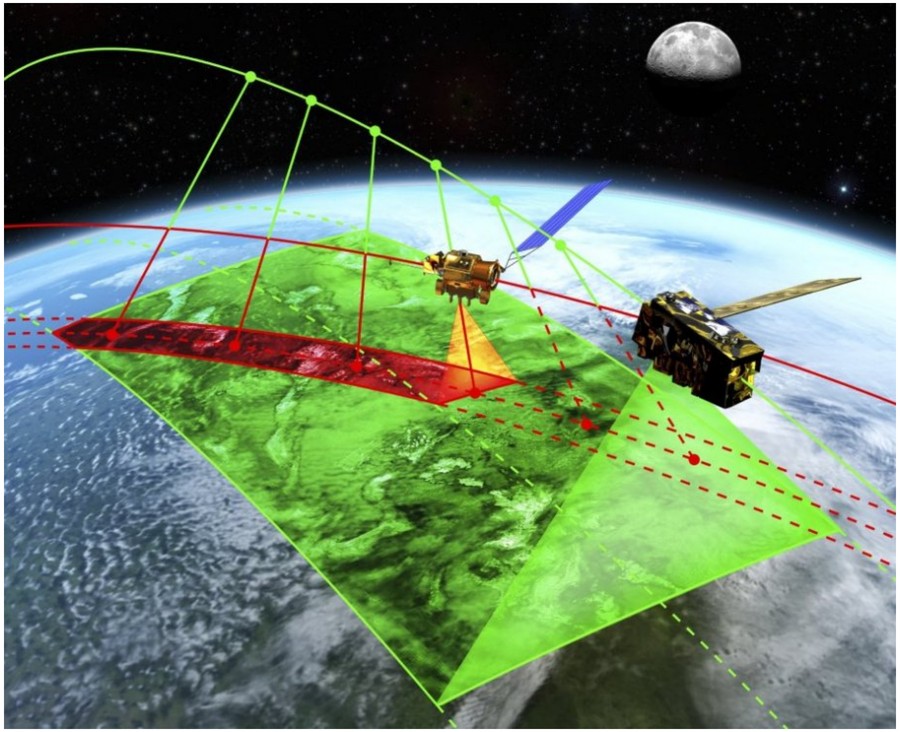
From Vladimir Zavyalov of USU/SDL

Radiometric uncertainty specification converted to that expressed in brightness temperature



Inter-calibration for Post-launch Calibration

- **After satellite was launch, the calibration coefficients can change on-orbit. We need to quantify the calibration uncertainties. However, there is no truth on orbit.**
- **Inter-calibration methods compare a reference instrument, with well-known calibration characteristics, with collocated observations from another instrument.**
- **It can identify problems and increase the confidence in the operational calibration of individual satellites. Hence, inter-calibration can serve as a monitoring tool for the operational calibration.**
- **it can provide the basis for a normalised calibration, which is a prerequisite for the derivation of global products from different satellites.**



From CLARREO Program website

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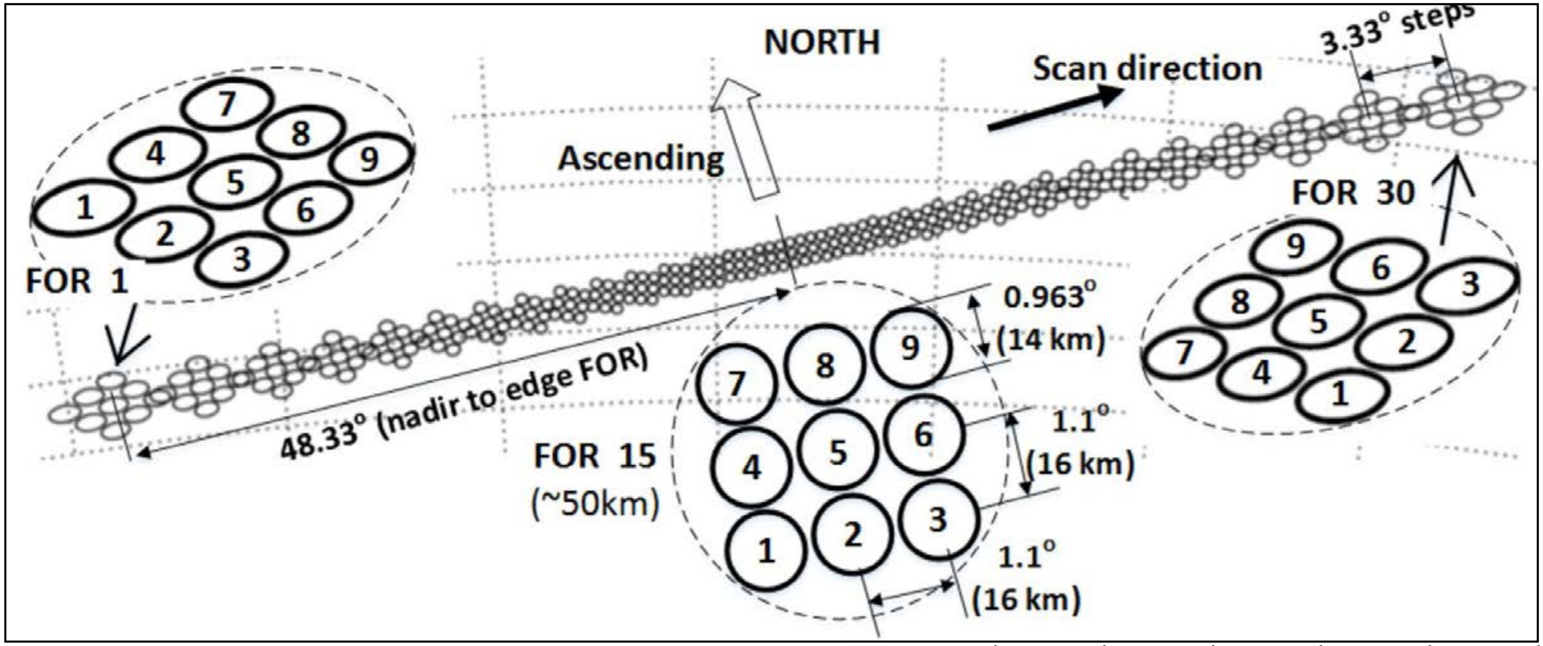
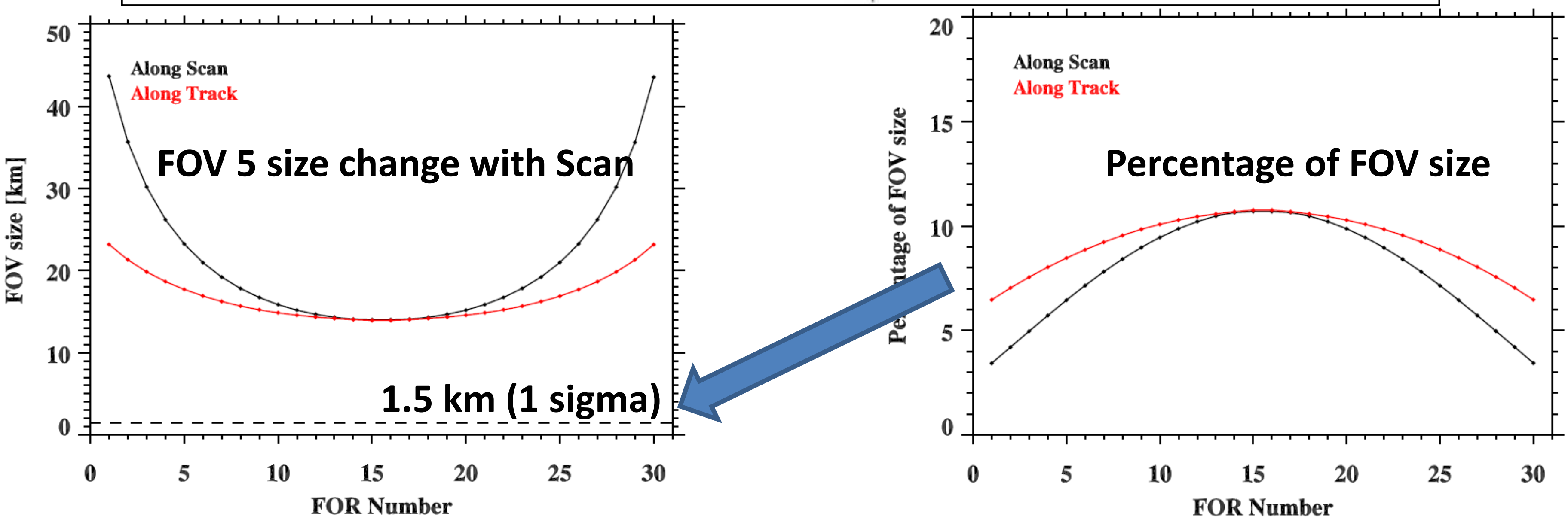
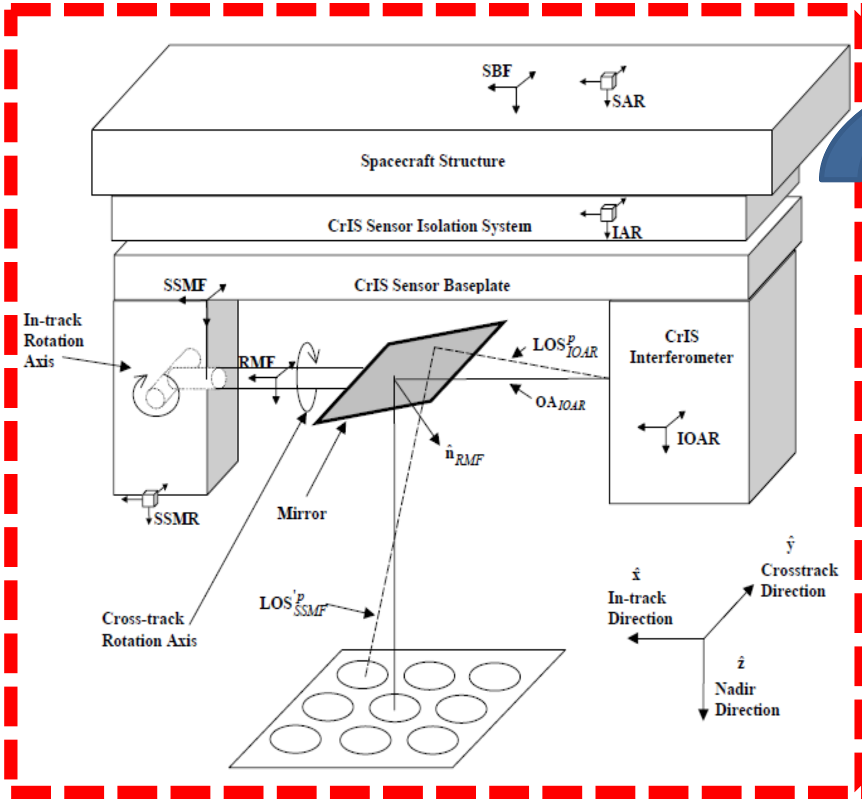
CrIS Scan Patterns and Specification





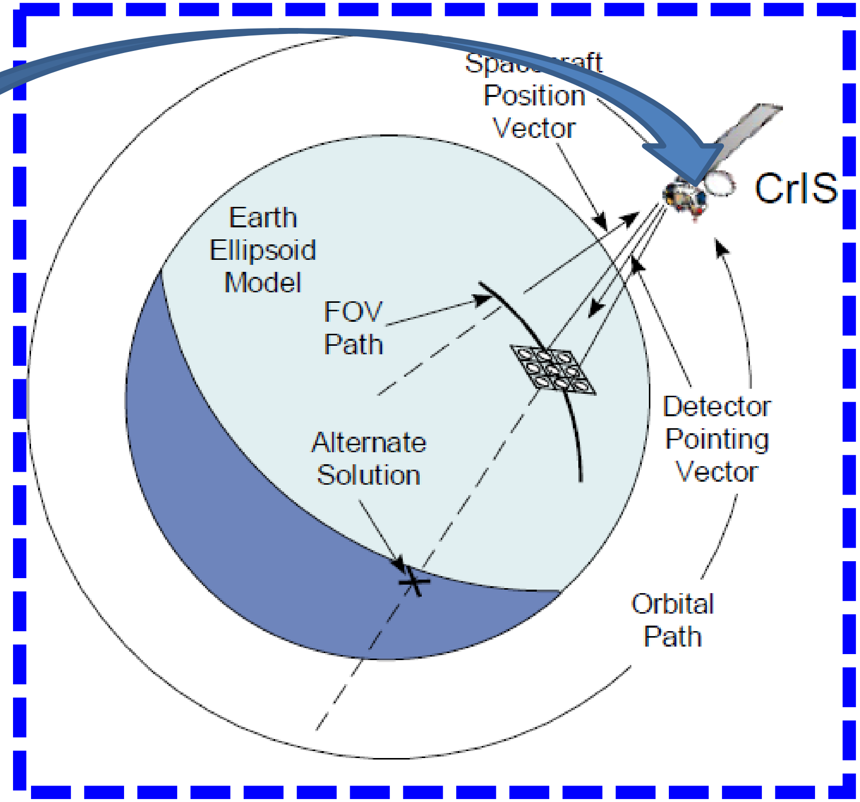
CrIS Geometric Calibration Algorithm

Sensor Specific Algorithm



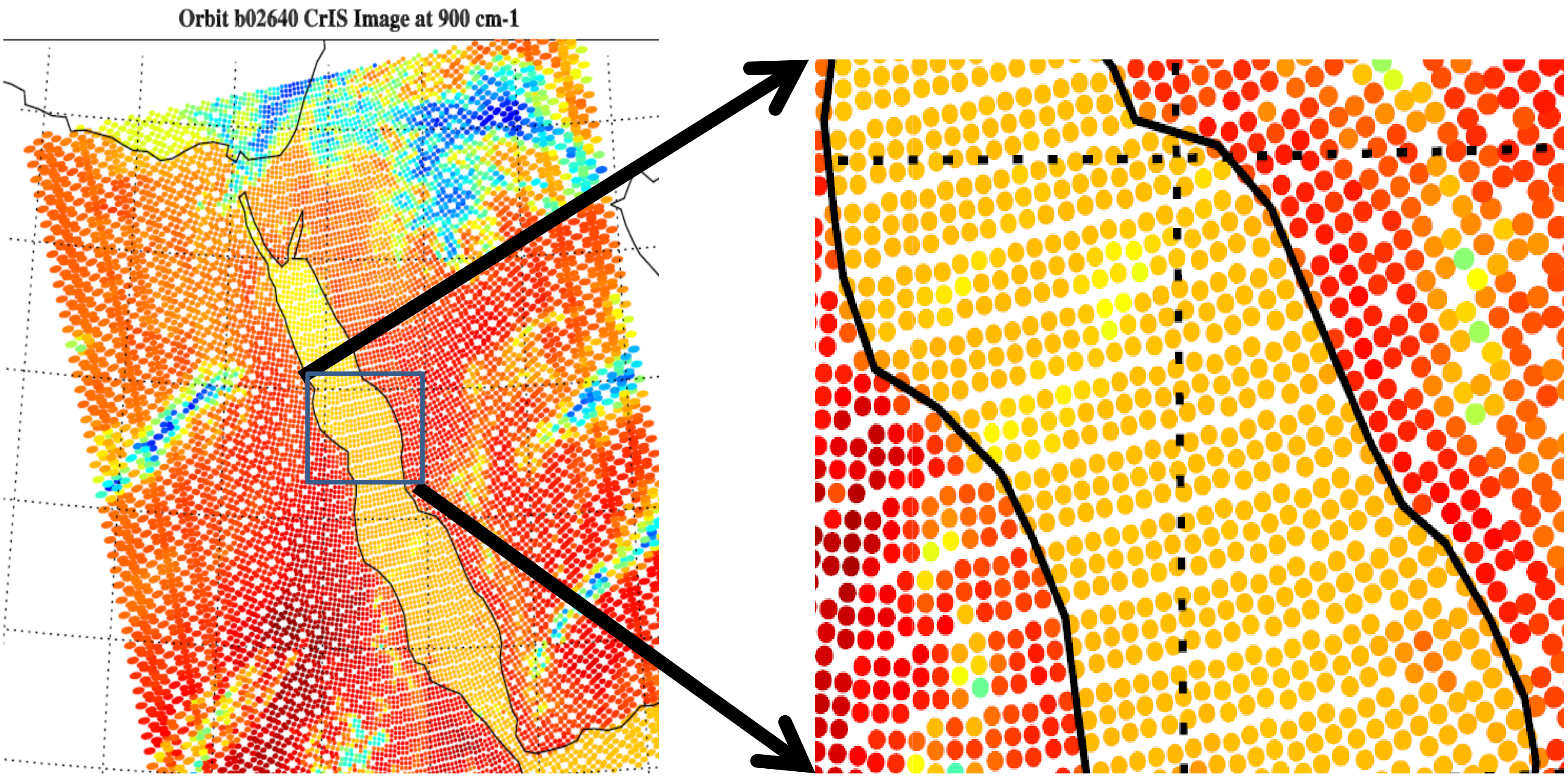
Compute the LOS relative to S/C for each FOV (3x3) at each scan position (30)

Common Geo Algorithm



Resolve LOS intersection with Earth Ellipsoid (LOS, mounting matrix, satellite attitude and ephemeris)

Challenges for On-orbit Assessment



Unlike an imager, it is very hard to assess geolocation sub-pixel accuracy for CrIS using the land feature method because of 1) relatively large footprint size (above 14 km); 2) the gap between footprints; and 3) Uneven spatial distribution of CrIS Footprints

CrIS Geolocation Assessment Paper

JOURNAL OF GEOPHYSICAL RESEARCH: ATMOSPHERES, VOL. 118, 1–15, doi:10.1002/2013JD020376, 2013

Geolocation assessment for CrIS sensor data records

Likun Wang,[1] Denis A. Tremblay,[2] Yong Han,[3] Mark Esplin,[4] Denise E. Hagan,[5]
Joe Predina,[6] Lawrence Suwinski,[6] Xin Jin,[7] and Yong Chen [1]

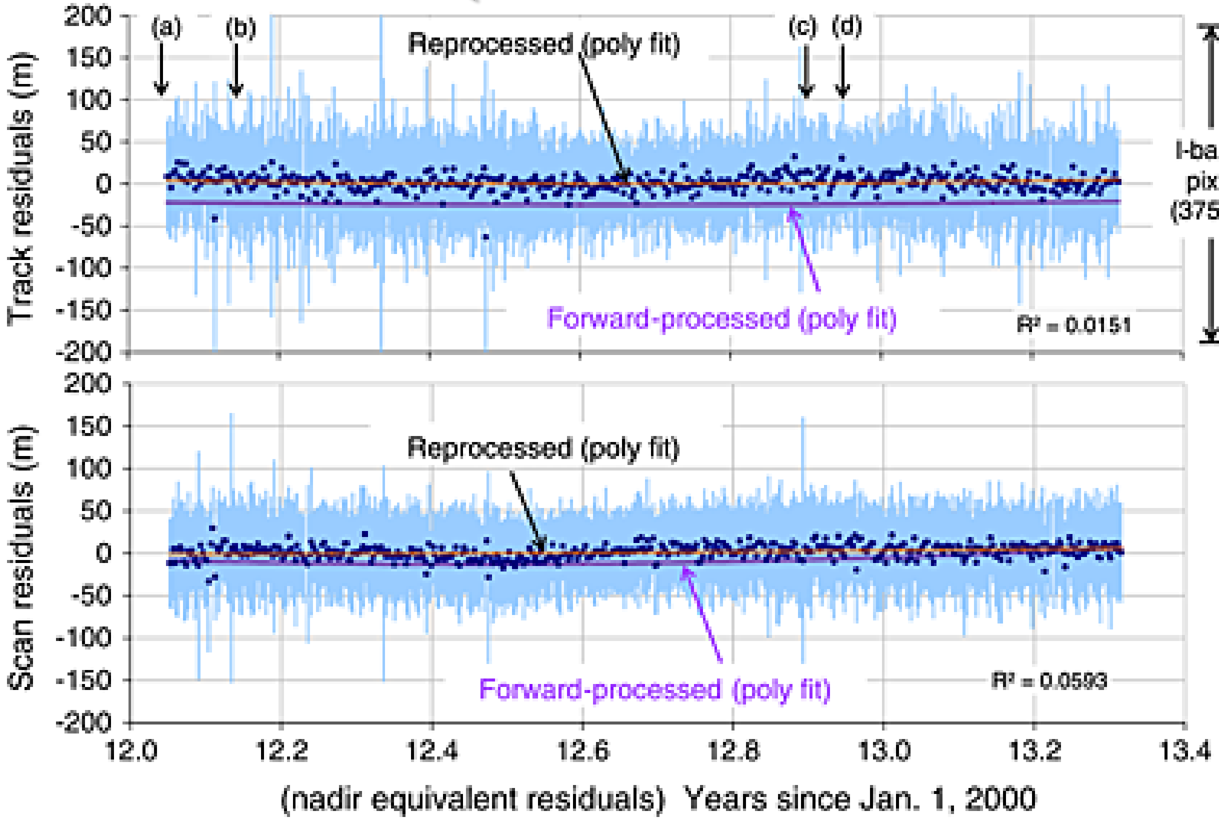
Received 17 June 2013; revised 23 October 2013; accepted 27 October 2013.

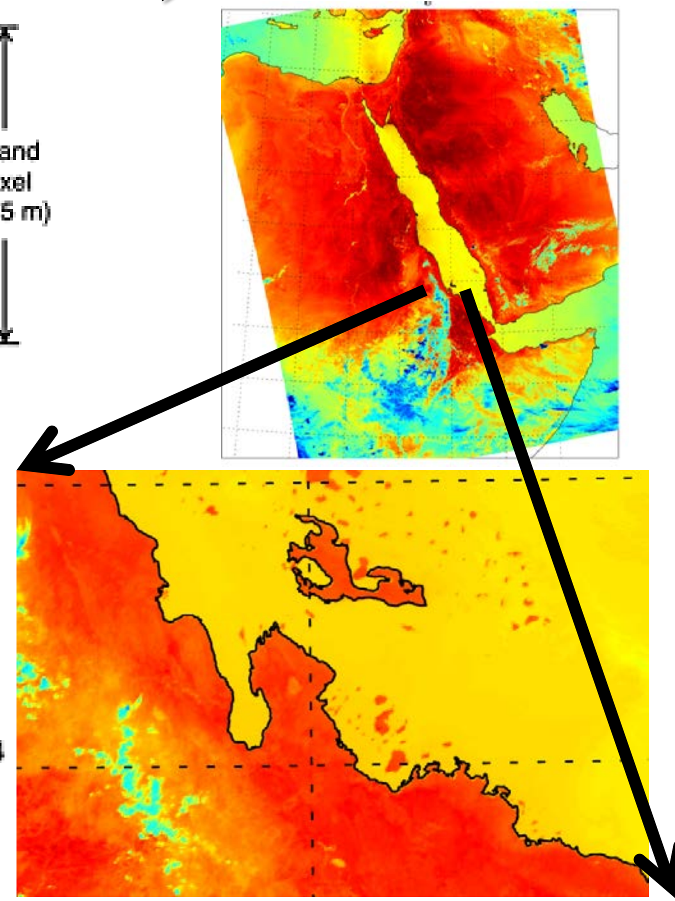
[1] As important as spectral and radiometric calibration, the geometric calibration is one of the requisites for the Suomi National Polar-Orbiting Partnership Cross-track Infrared Sounder (CrIS) Sensor Data Records (SDR). In this study, spatially collocated measurements from the Visible Infrared Imaging Radiometer Suite (VIIRS) band I5 are used to evaluate the geolocation performance of the CrIS SDR by taking advantage of high spatial resolution and accurate geolocation of VIIRS measurements. The basic idea is to find the best collocation position between VIIRS and CrIS measurements by shifting VIIRS images in the track and scan directions. The retrieved best collocation position is then used to evaluate the CrIS geolocation performance by assuming the VIIRS geolocation as a reference. Sensitivity tests show that the method can well detect geolocation errors of CrIS within 30° scan angle. When the method was applied to evaluate the geolocation performance of the CrIS SDR, geolocation errors that were caused by software coding errors were successfully identified. After this error was corrected and the engineering packets V35 were released, the geolocation accuracy is 0.347 ± 0.051 km (1σ) in the scan direction and 0.219 ± 0.073 km in the track direction at nadir.

Citation: Wang, L., D. A. Tremblay, Y. Han, M. Esplin, D. E. Hagan, J. Predina, L. Suwinski, X. Jin, and Y. Chen (2013), Geolocation assessment for CrIS sensor data records, *J. Geophys. Res. Atmos.*, *118*, doi:10.1002/2013JD020376.

Paper published in Suomi NPP Cal/Val Special Issue

Reference: Using VIIRS Geolocation (I5 band: 375m resolution)





from Wolf et al. 2013

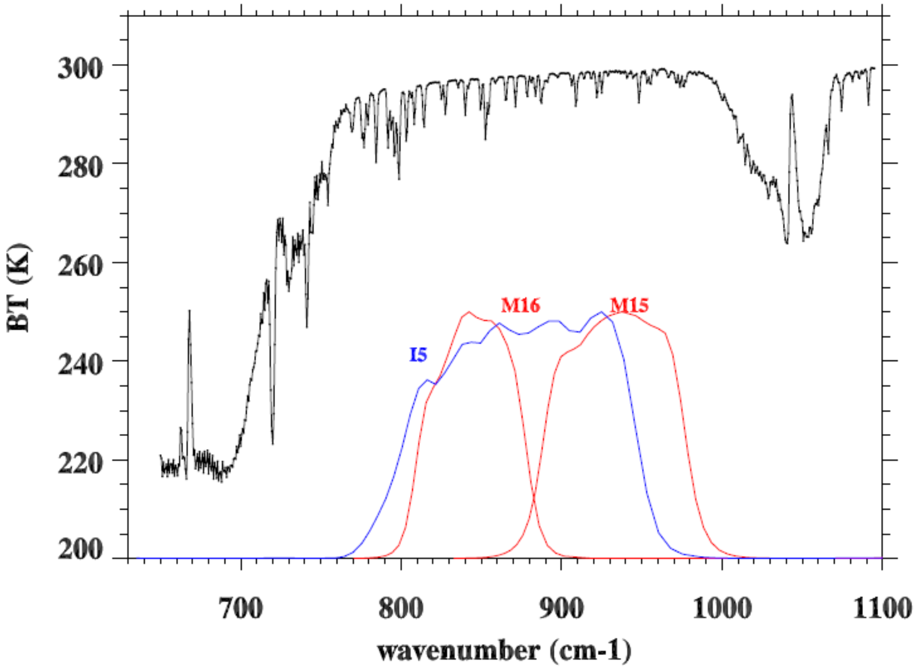
Table 2. VIIRS Geolocation Accuracy

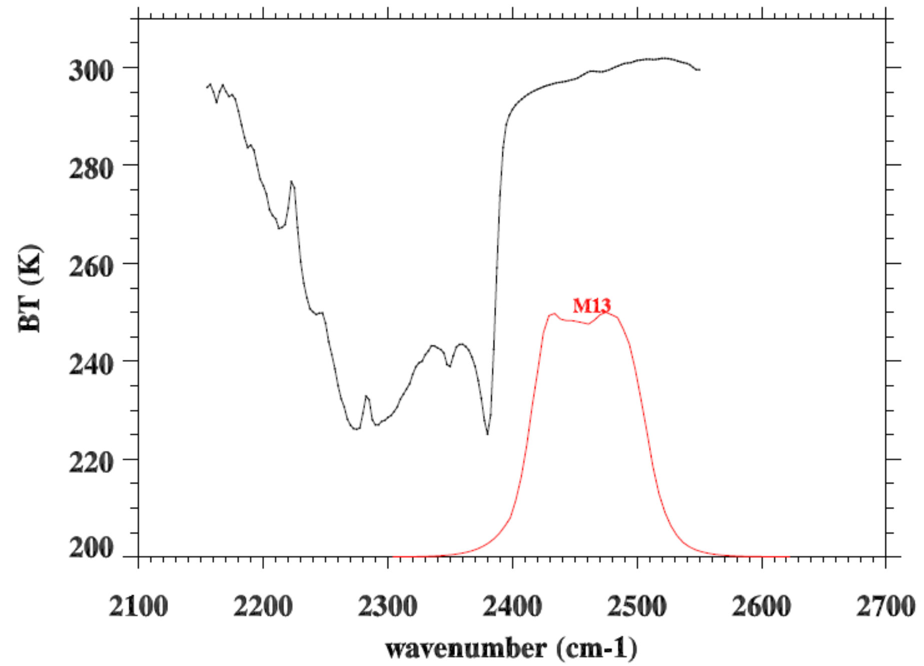
Residuals	First Update 23 February 2012	Second Update 18 April 2013
Track mean	**−24 m, −7%**	**2 m, 1%**
Scan mean	**−8 m, −2%**	**2 m, 1%**
Track RMSE	**75 m, 20%**	**70 m, 19%**
Scan RMSE	**62 m, 17%**	**60 m, 16%**

Spectral Integration: from CrIS to VIIRS

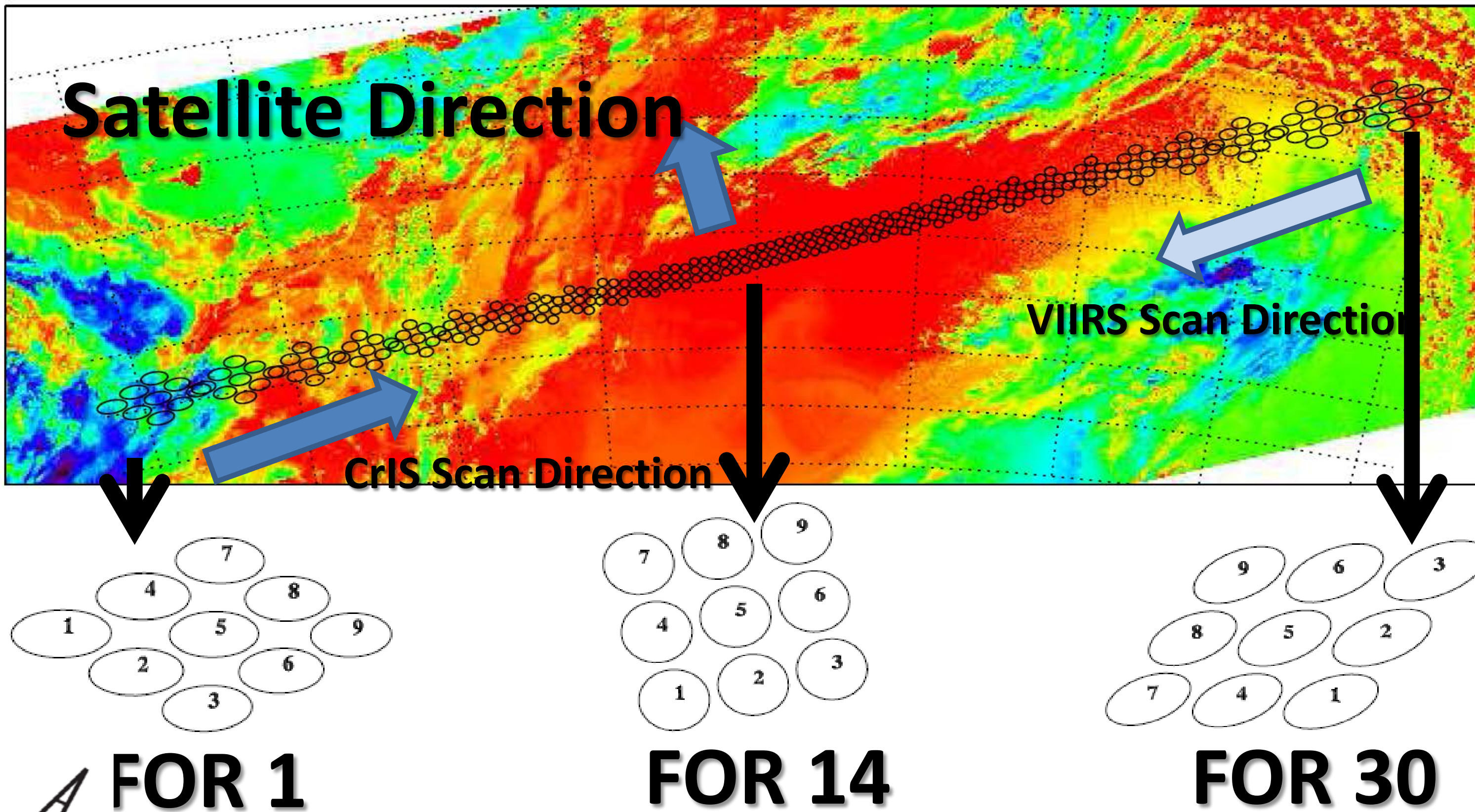
CrIS spectrum is convolved with VIIRS SRFs for I5 band (375m spatial resolution)

$$L_i = \frac{\int_{\nu_1}^{\nu_2} R(\nu) S_i(\nu) d\nu}{\int_{\nu_1}^{\nu_2} S_i(\nu) d\nu}$$

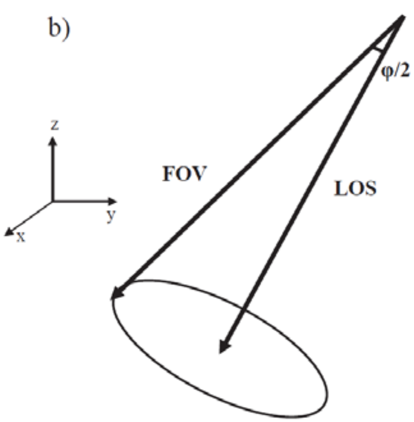




Compute CrIS FOV Footprint

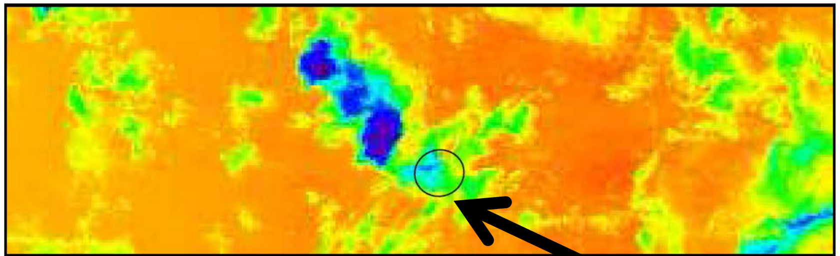


b)



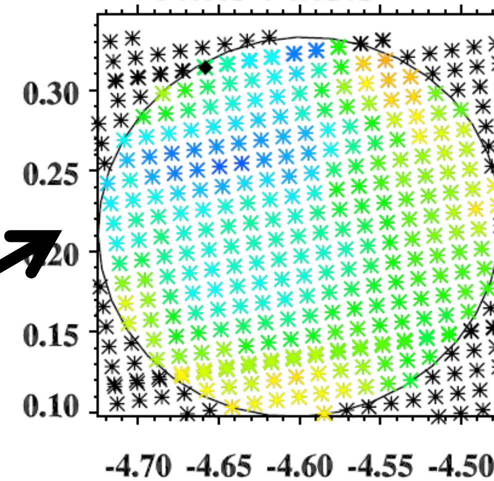
$$
\begin{aligned}
V_{rot} &= rotate(V, \theta, k) \\
&= V\cos\theta + (k \times V)\sin\theta + k(k \cdot V)(1 - \cos\theta)
\end{aligned}
$$

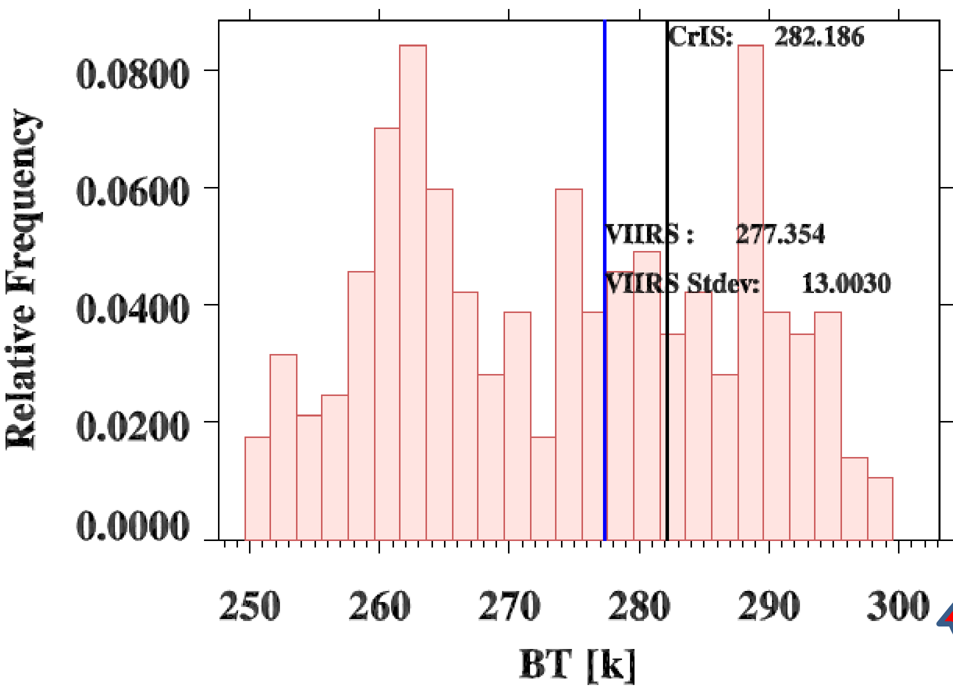
Collocating VIIRS with CrIS FOV



CrIS FOV footprint

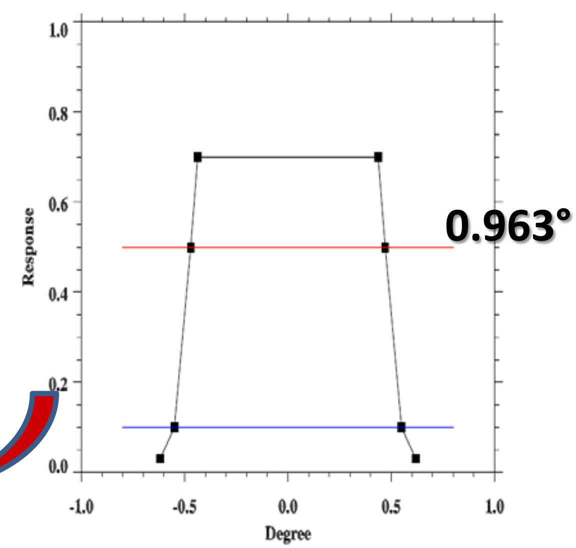
VIIRS Pixels





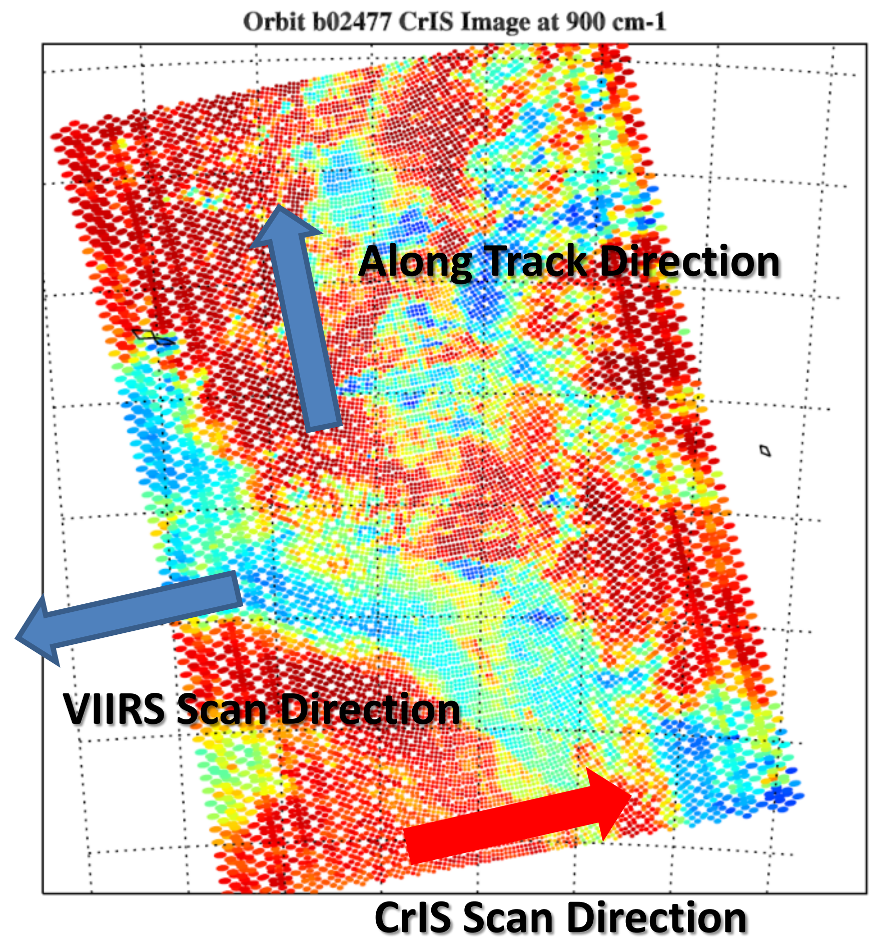
Histogram of VIIRS M16 in CrIS FOV

CrIS FOV Spatial Response



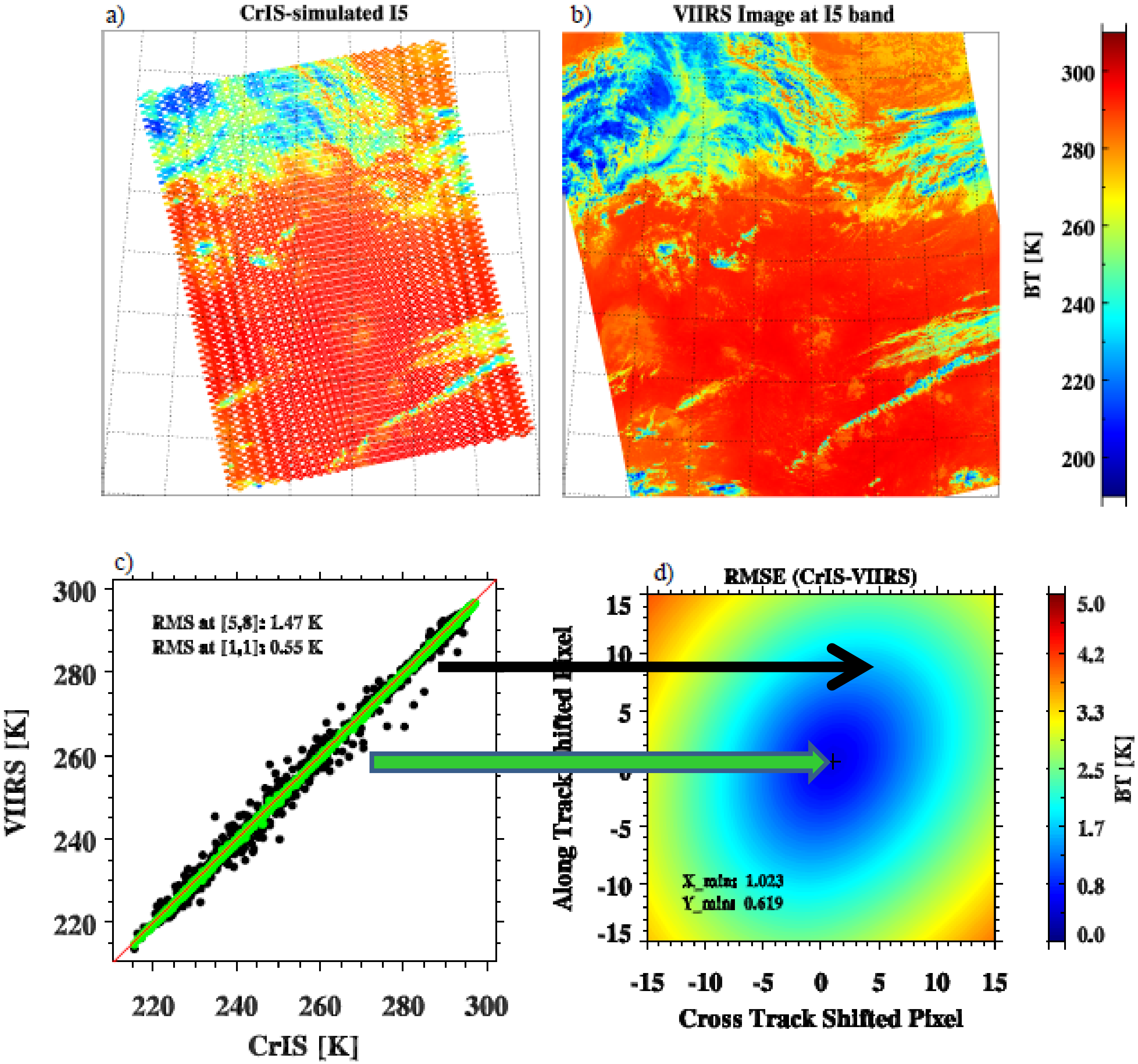
Quantitative Assessment

- Choose un-uniform (better for cloud scene) CrIS granules over tropical region (large dynamic range)
- Collocate VIIRS with CrIS **nadir** FOVs (FOR 13-16) and then compute spatially averaged radiances
- Convert CrIS spectra into VIIRS band radiances using VIIRS spectral response functions (SRFs)
- Define the cost function as ***Root Mean Square Errors (RMSE)*** of CrIS-VIIRS BT difference
- Shift VIIRS image toward **along-** and **cross-**track direction to find the minimum of the cost function, which represent best collocation between VIIRS and CrIS



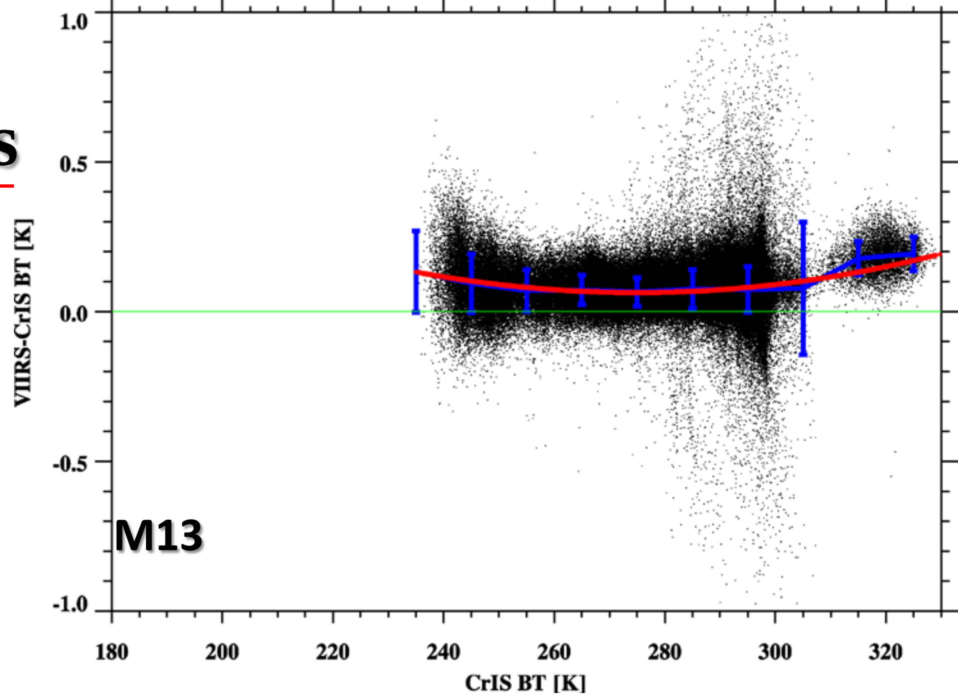
Orbit 02477 on April 20 2102

An Example

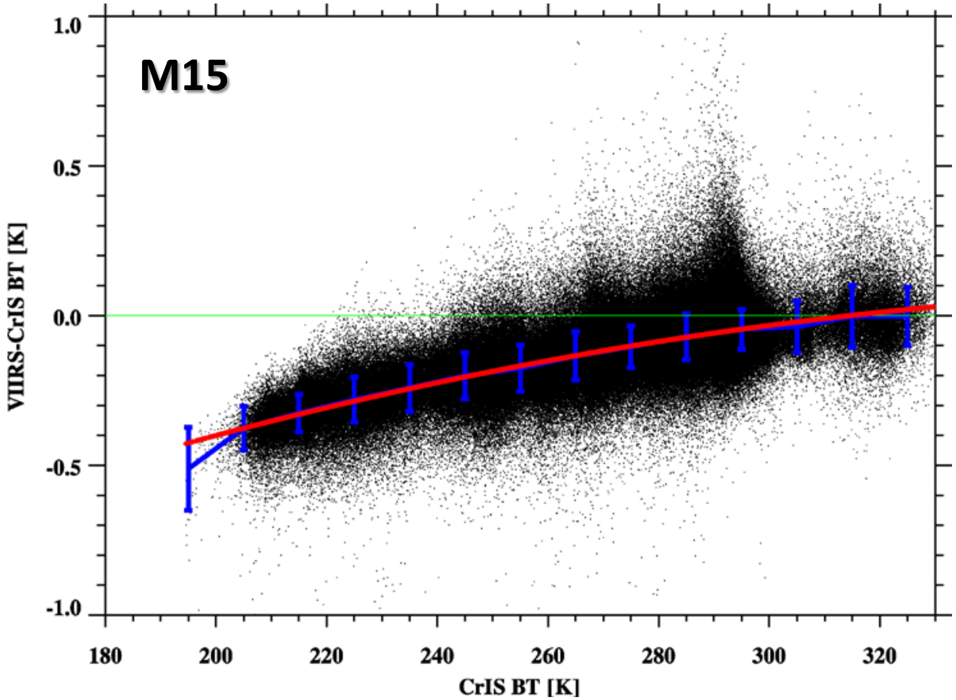


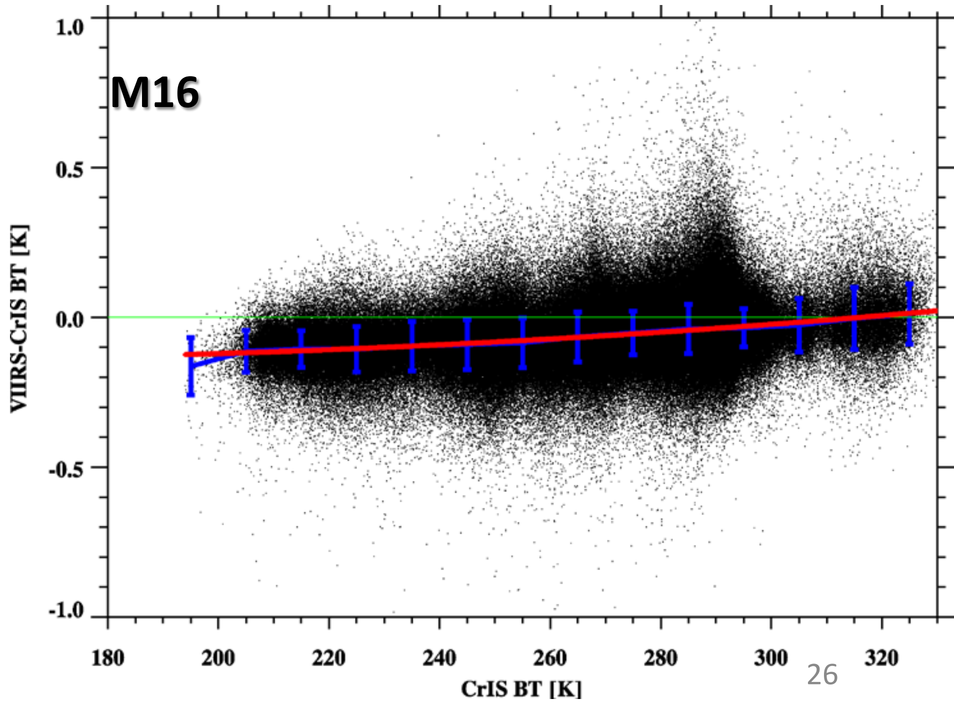
a)
CrIS-simulated I5
b)
VIIRS Image at I5 band
BT [K]
300
280
260
240
220
200
c)
RMS at [5,8]: 1.47 K
RMS at [1,1]: 0.55 K
VIIRS [K]
CrIS [K]
d)
RMSE (CrIS-VIIRS)
Along Track Shifted Pixel
Cross Track Shifted Pixel
X_min: 1.023
Y_min: 0.619
BT [K]
5.0
4.2
3.3
2.5
1.7
0.8
0.0

VIIRS-CrIS Radiometric Differences

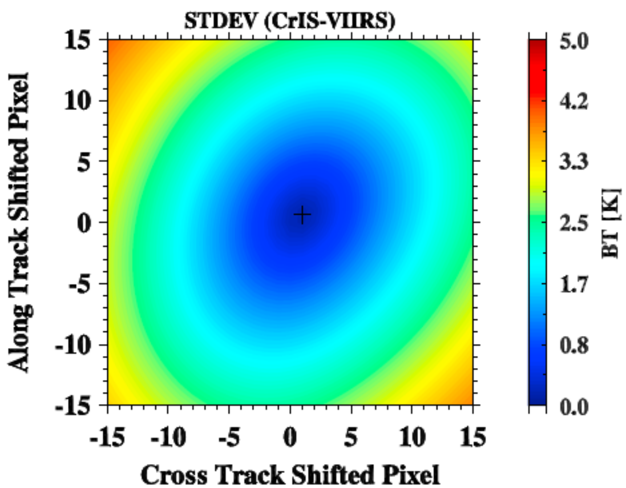


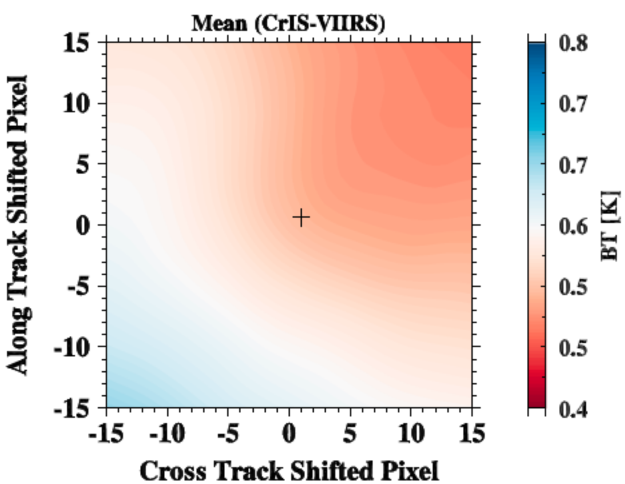
Red Line: Fitting Line
Blue Line: Bin Average





Effects of Radiometric Discrepancy Between CrIS and VIIRS

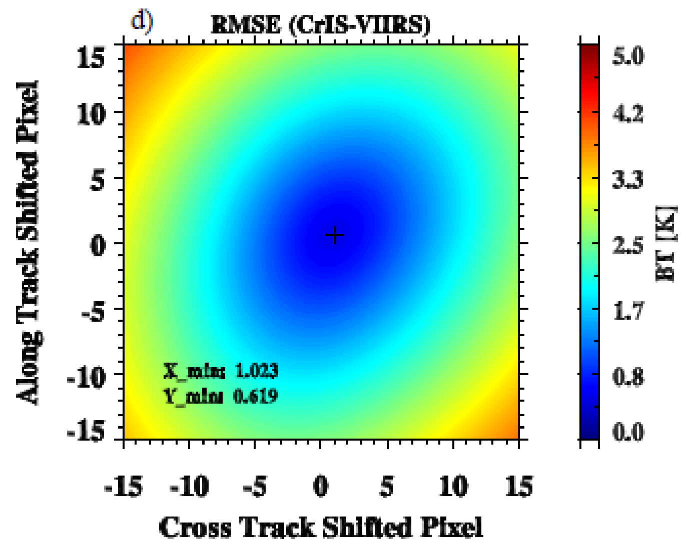




Stdev

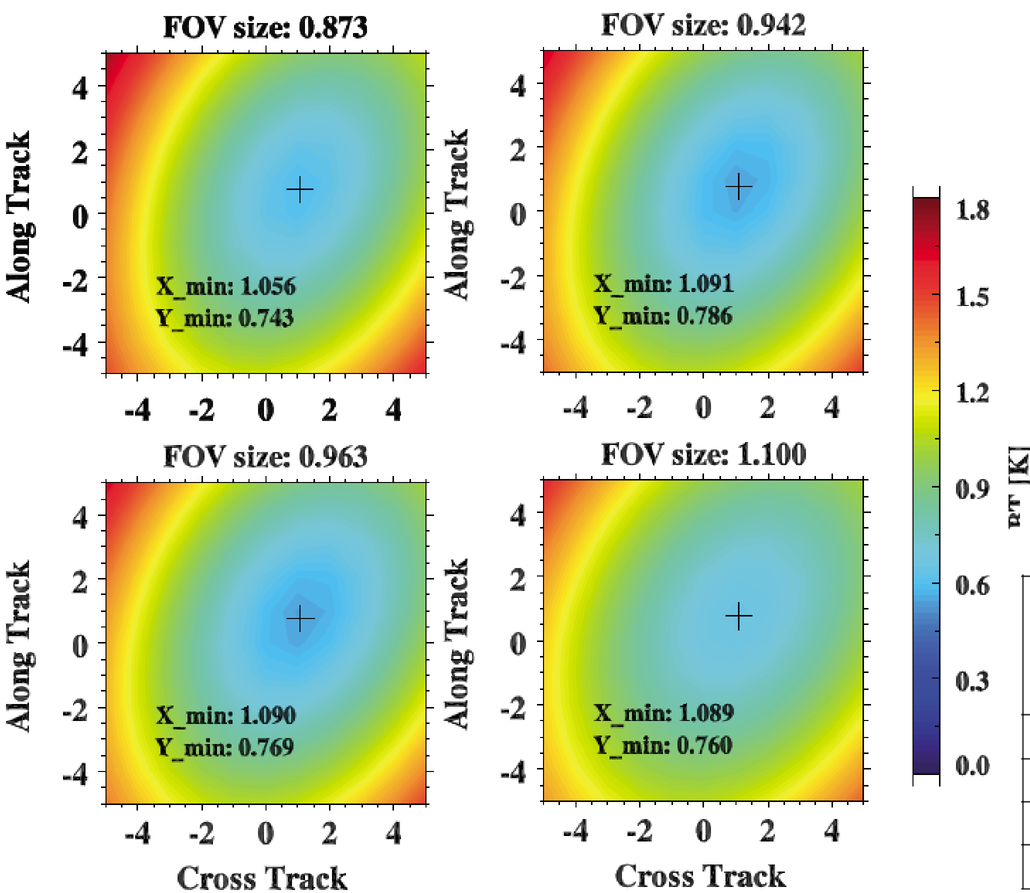
Mean

RMSE

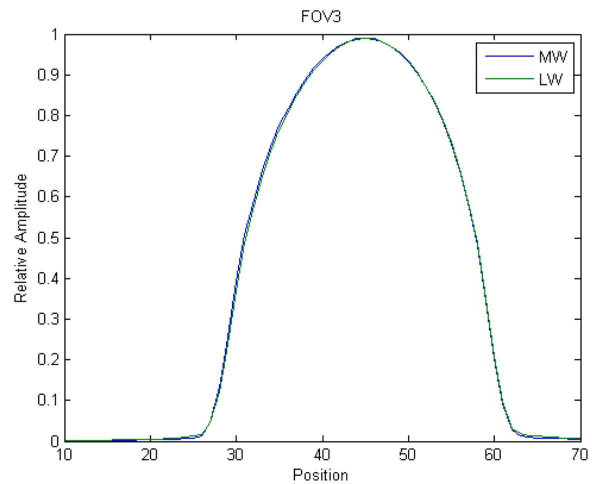


The small radiometric discrepancy between CrIS and VIIRS has negligible effects on the geolocation assessment

Effects of CrIS Spatial Response Function



CrIS Spatial Response Function

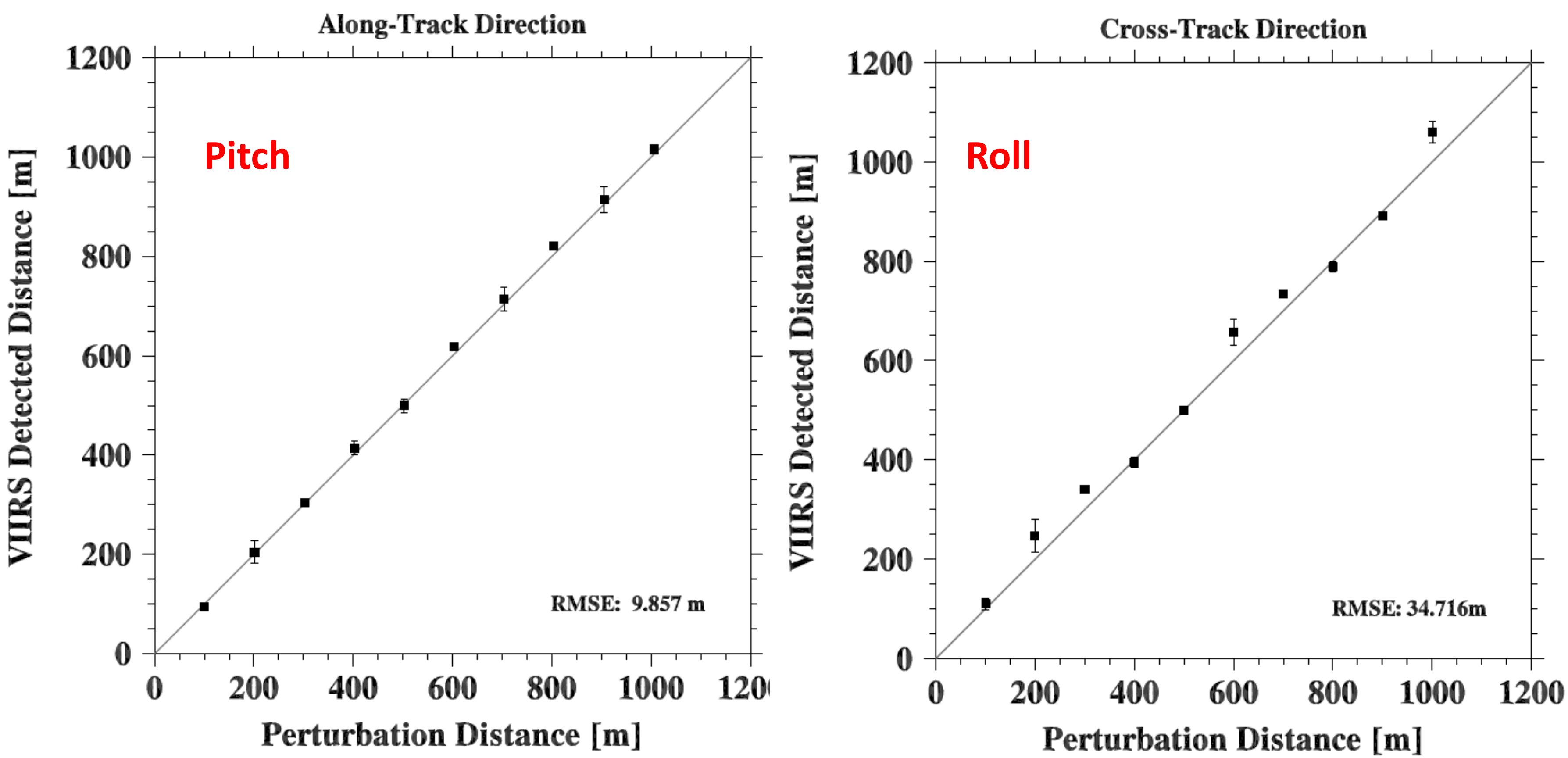


From Mark Esplin

Table 3: FOV shape characteristi

	FOV Shape (degrees, Cross Track)	FOV Shape (degrees, In Track)
70% of Peak Response Width	> 0.8735	> 0.8735
50% of Peak Response Width	0.942	0.942
10% of Peak Response Width	< 1.100	< 1.100
3% of Peak Response Width	< 1.238	< 1.238

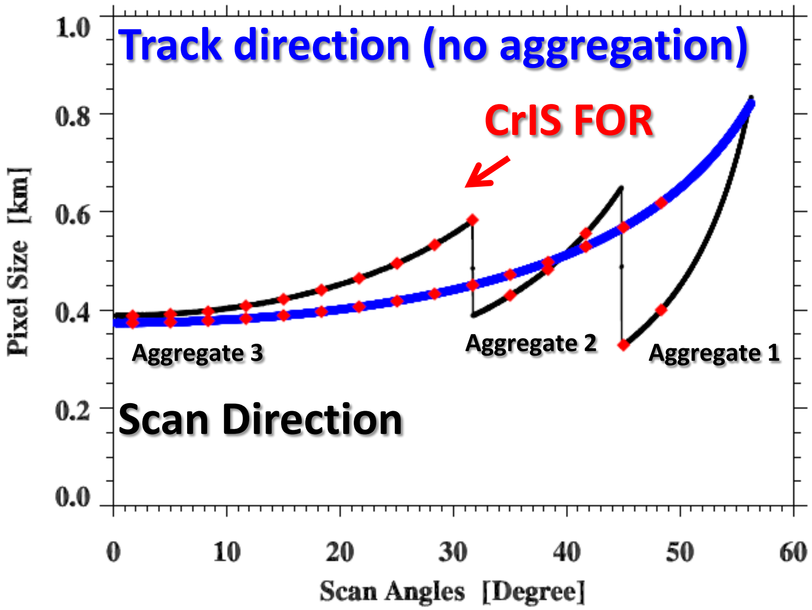
Sensitivity Test
Pitch and Roll Angels

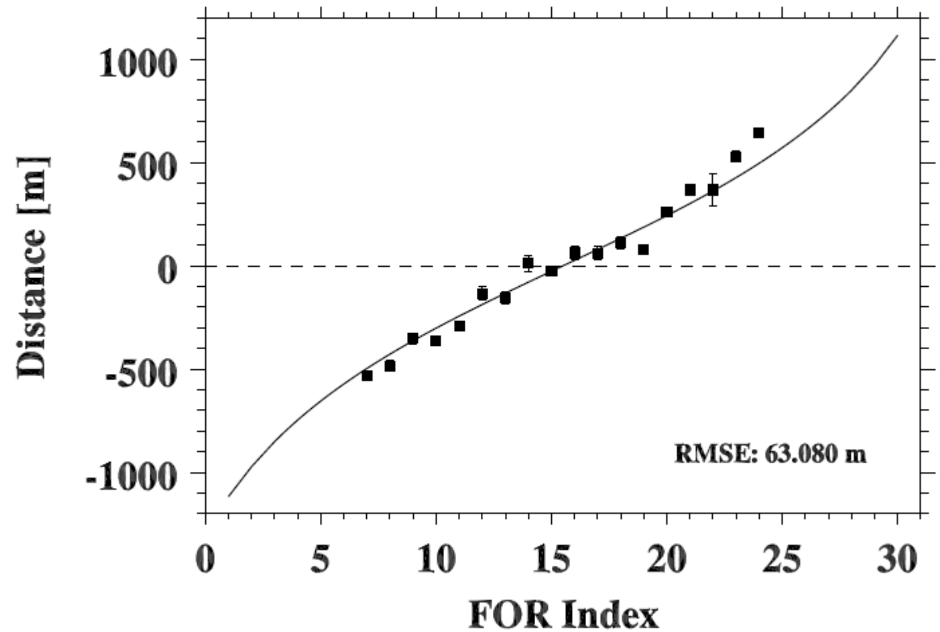


A series of perturbation tests are designed by intentionally adding systematic errors, which are then examined using the VIIRS measurements to check whether the VIIRS-CrIS collocation method can detect the known perturbation errors.

Sensitivity Test
Yaw Angels within 30 degree scan angle

VIIRS pixel size varying with Scan angle

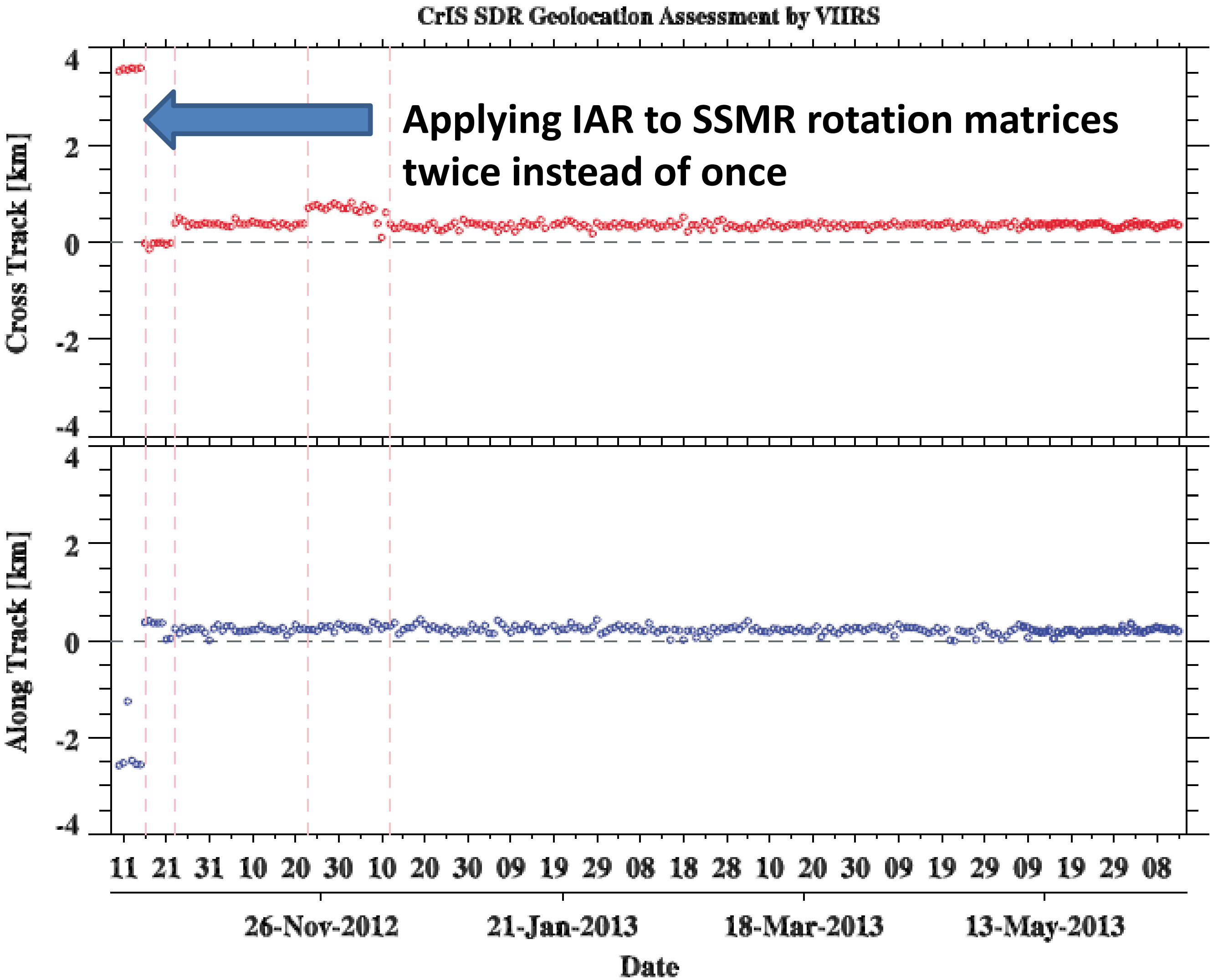


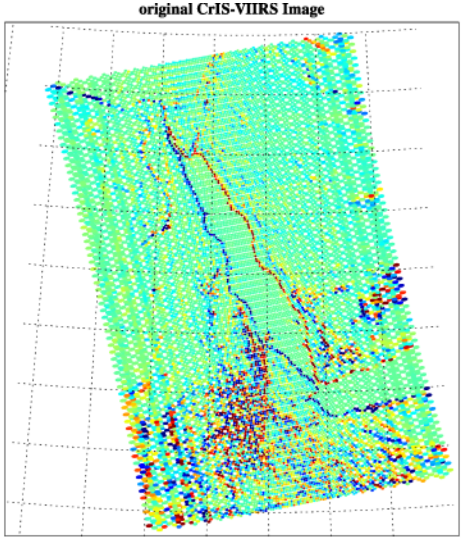


In VIIRS data, in order to minimize data rate, some of this redundant data is not transmitted and thus referred to as "bowtie deletion" when scan angle is larger than 32°.

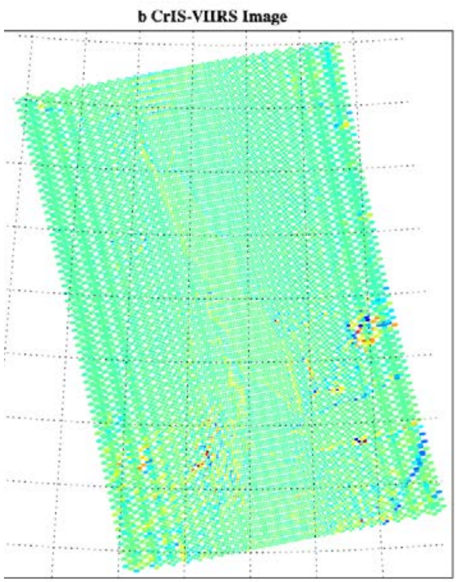
Sensitivity test for the yaw angle perturbation. The black line indicates the actual geolocation change due to the yaw angle perturbation, while the squares represent the detected geolocation change using the VIIRS measurements.

Time Series of Assessment Results (1)



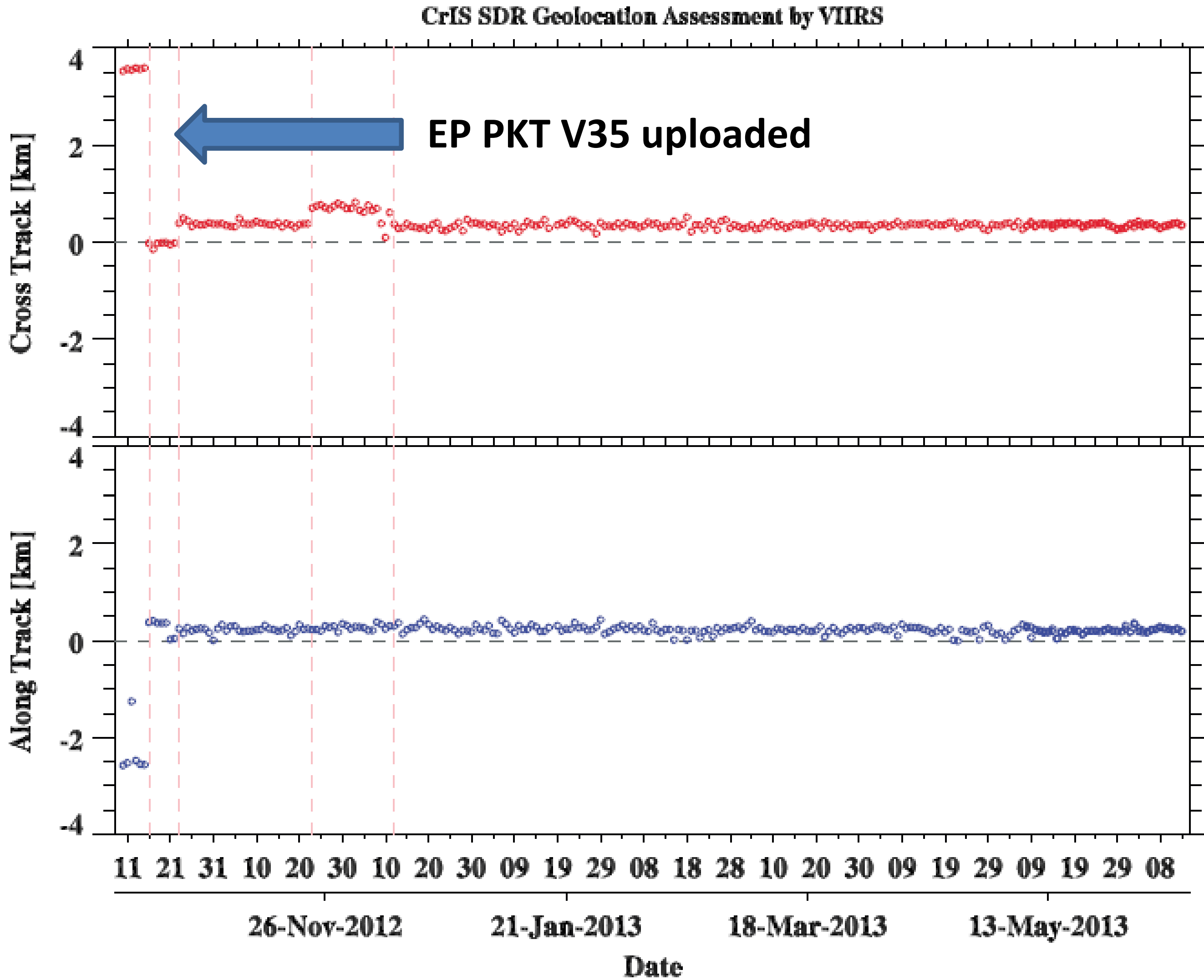


Before bug fixed



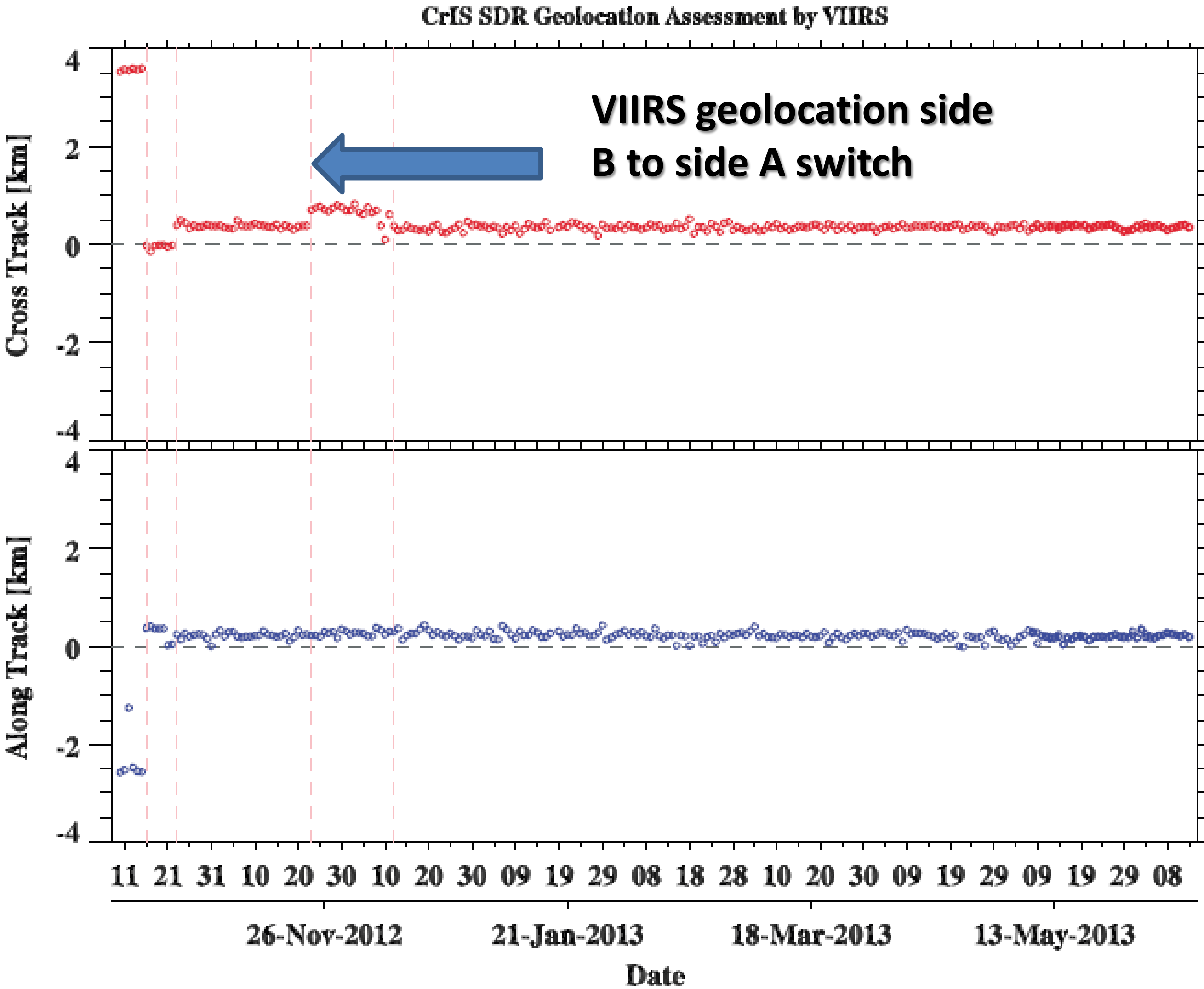
After bug fixed

Time Series of Assessment Results (2)



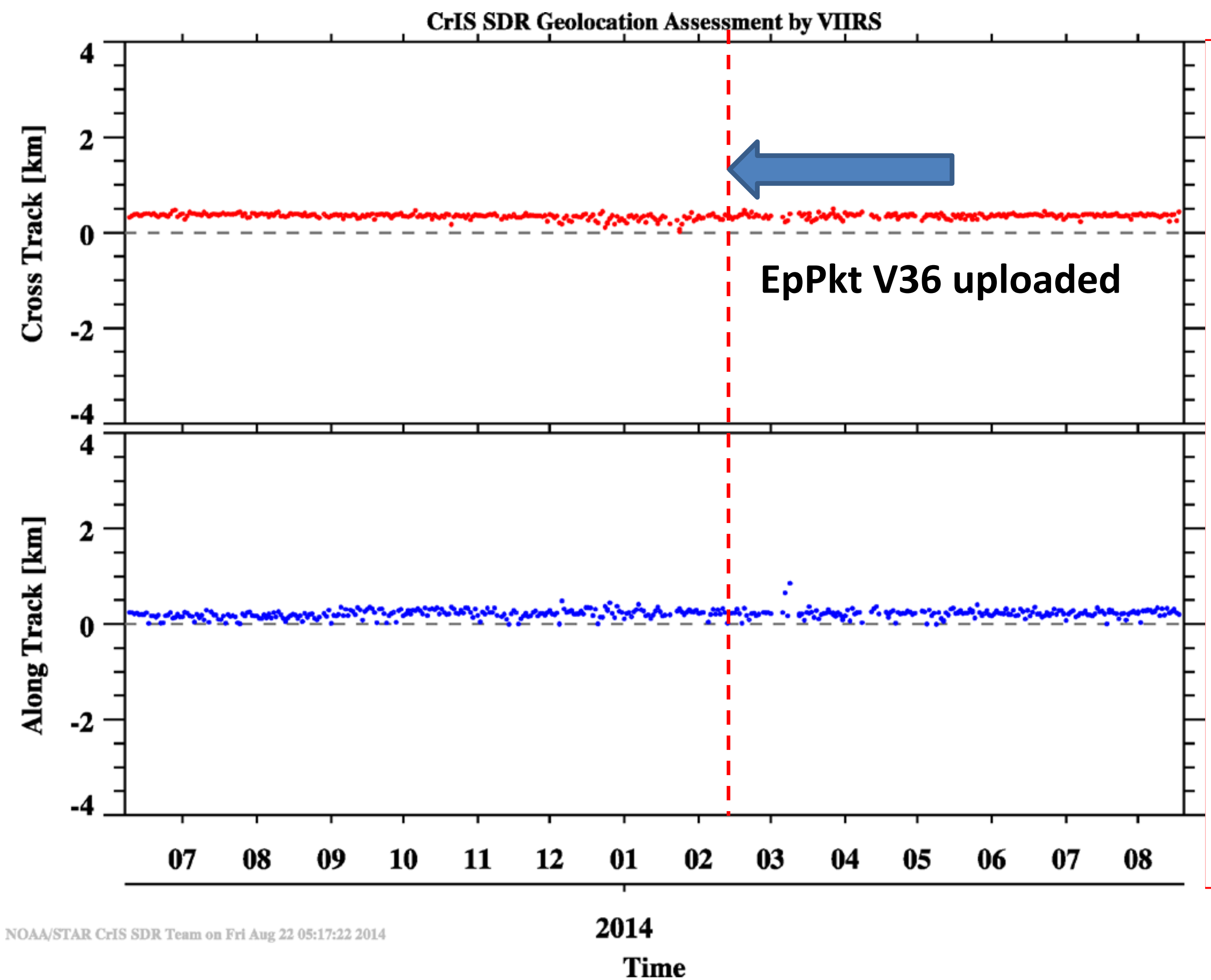
Angle change: Interferometer bore sight to SSMR yaw and pitch angles of engineering packet EP35 was set as zero suggested by Exelis.

Time Series of Assessment Results (3)



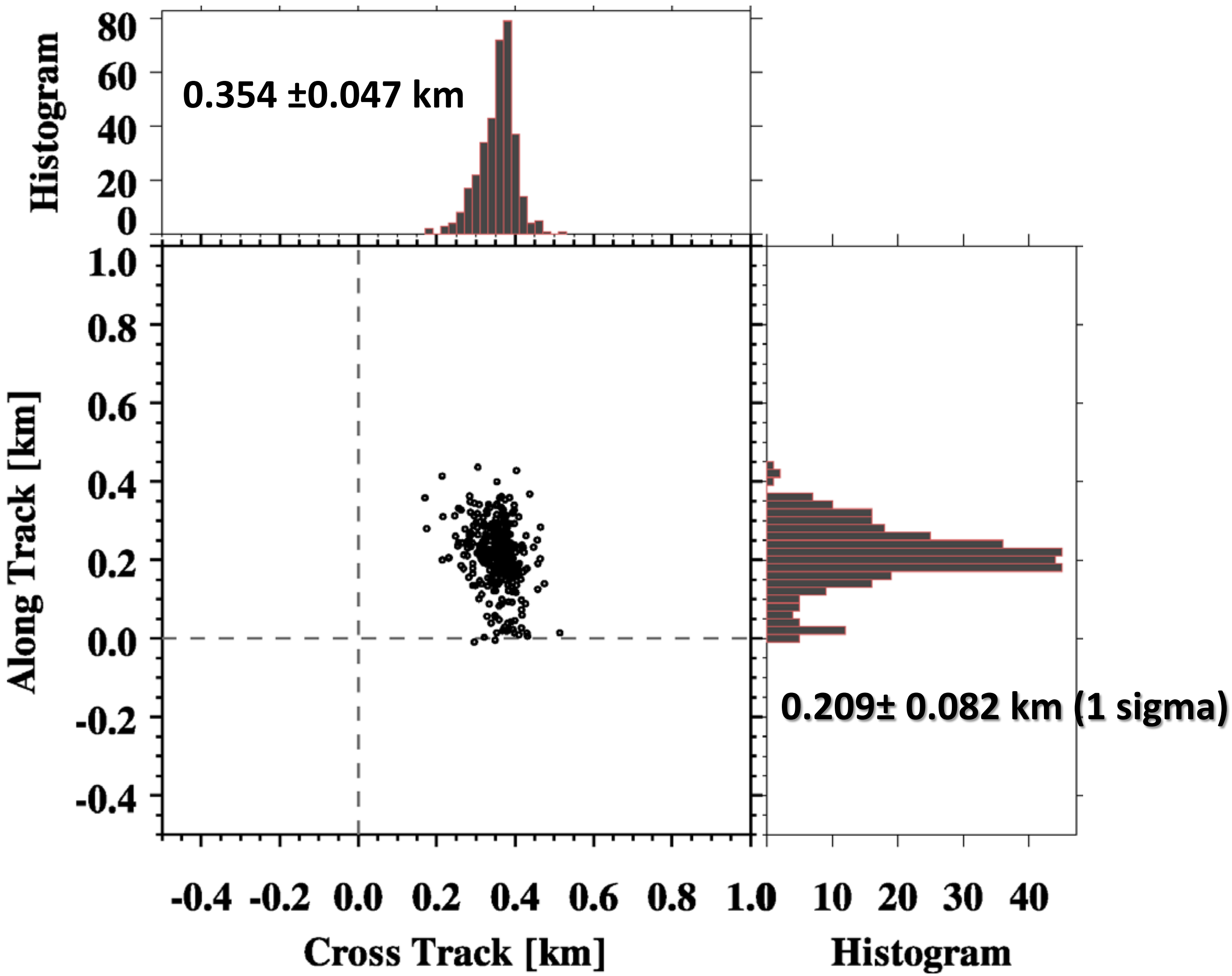
On 22 November 2012 at 1632 UTC, Suomi NPP VIIRS entered petulant mode. When the power was restored at 2207 UTC, the scan control electronics (SCE) was switched from side B to side A. At that time, geolocation look-up tables (LUTs) containing incorrect parameters for SCE side A introduced a nadir geolocation bias of ~325m in the scan direction. Corrected LUTs were applied starting 11 December 2012 (data day 346) at 1918 UTC, and the geolocation products' accuracy returned to normal.

Time Series of Assessment Results (4)

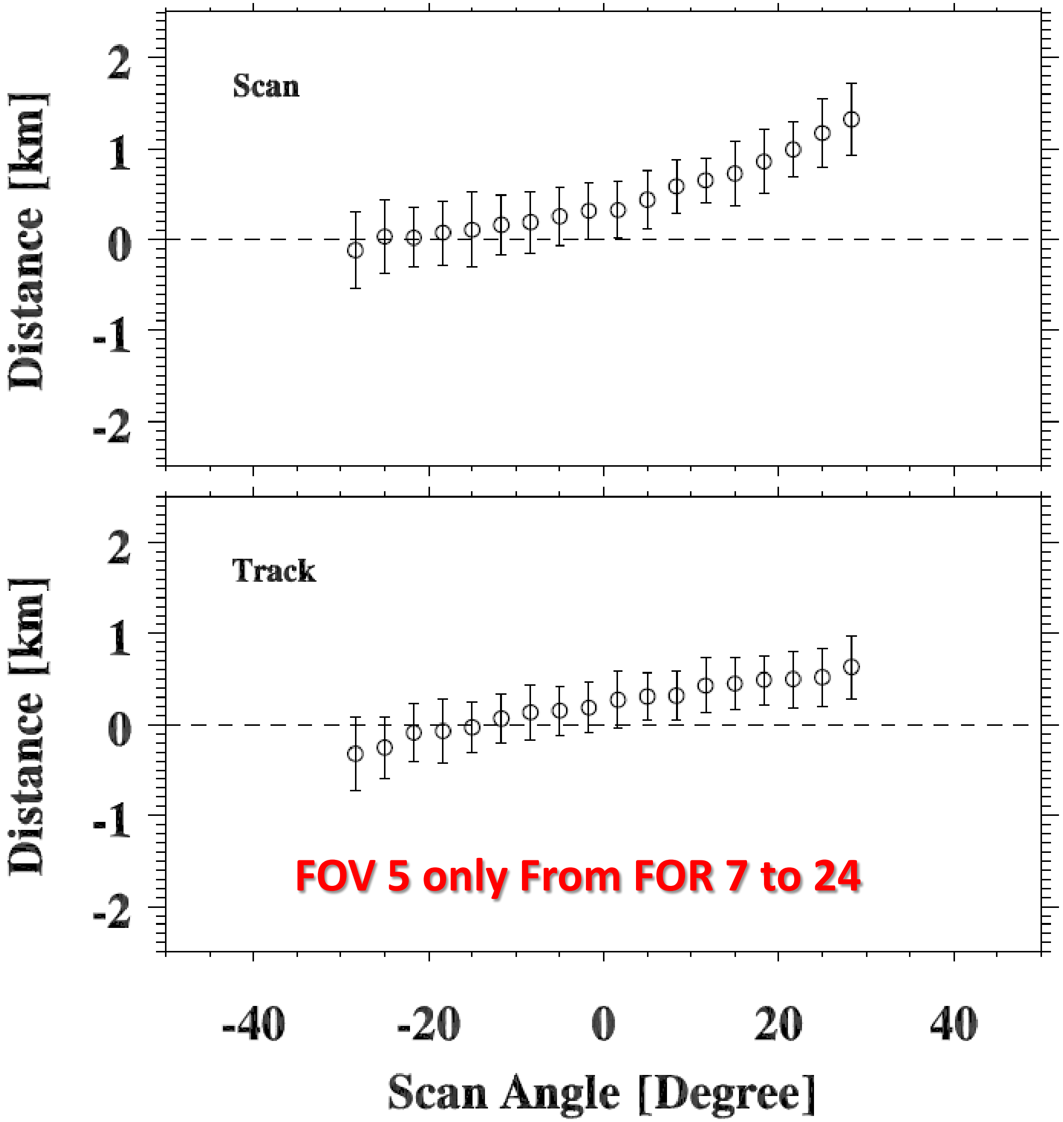


On Feb 27 2014. EpPkt V36 was uploaded with new ILS parameters. There is no apparent geolocation changes relative to VIIRS (less than 70 m).

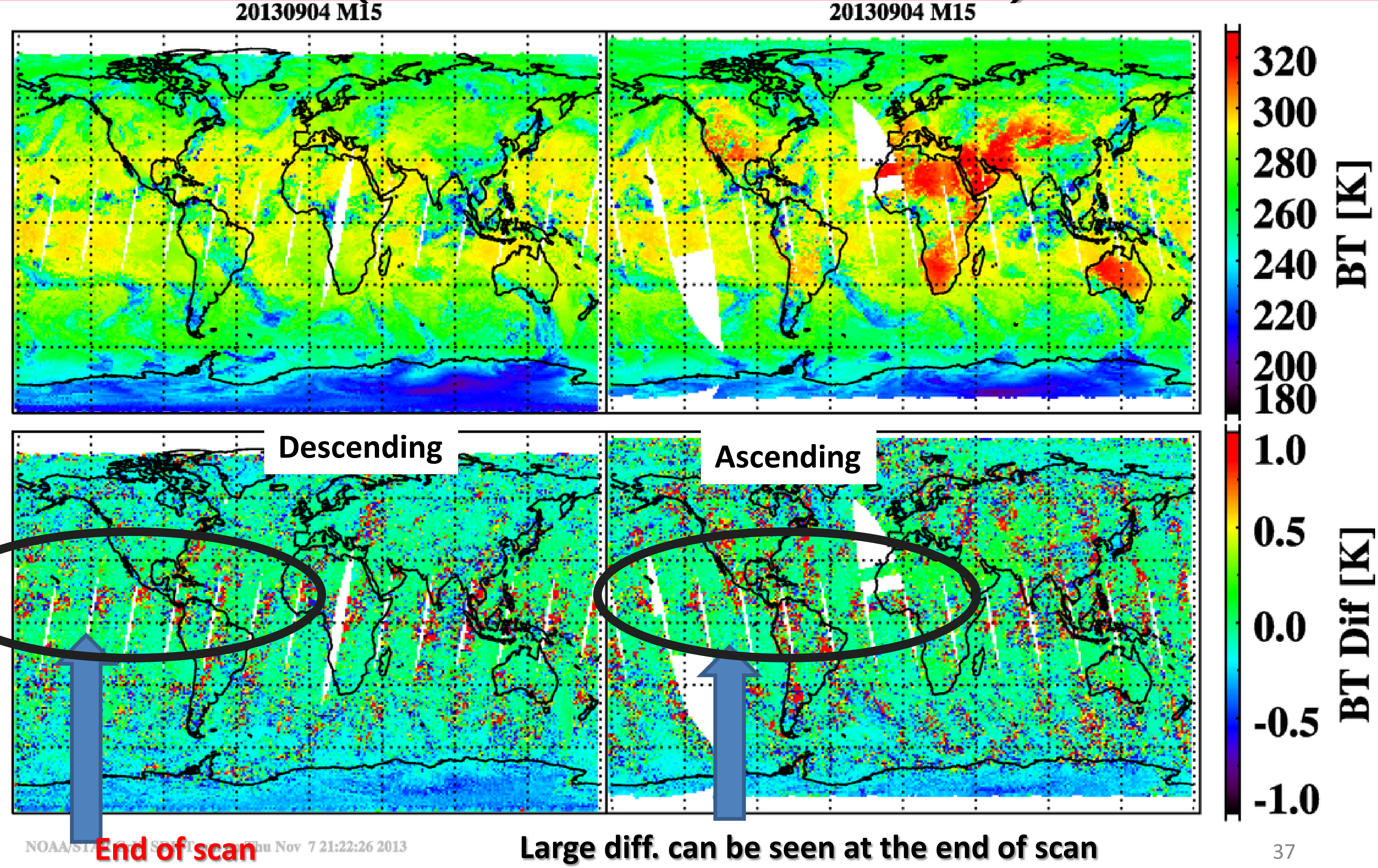
Statistical Results



Off-Nadir Assessment (within 30 degree scan angles)



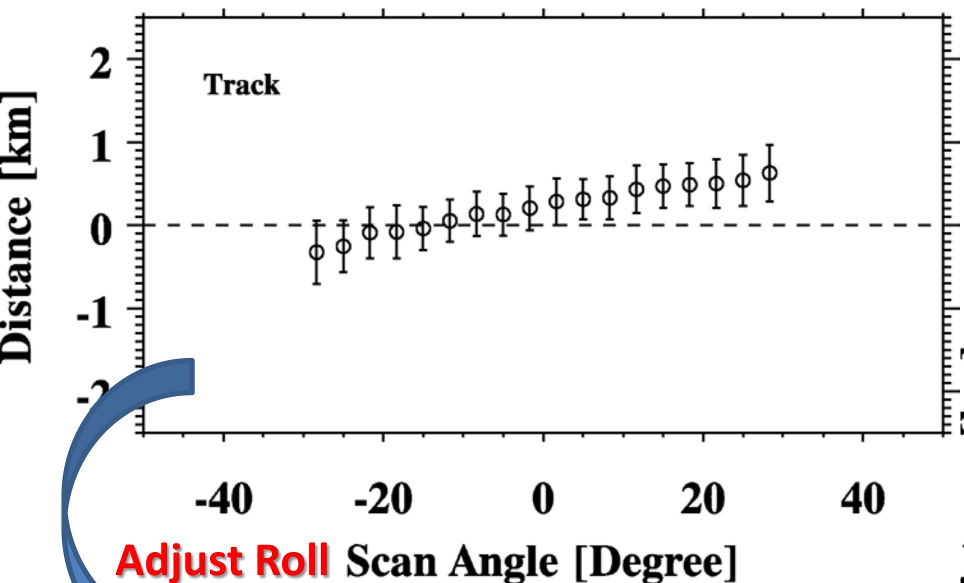
CrIS-VIIRS BT Diff. Map (Still not well understood)

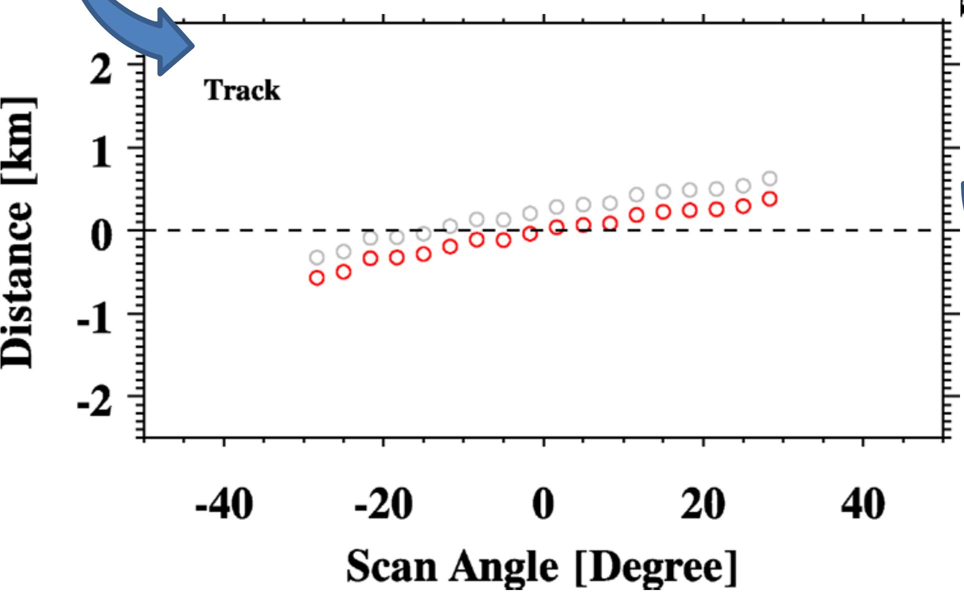


Large diff. can be seen at the end of scan

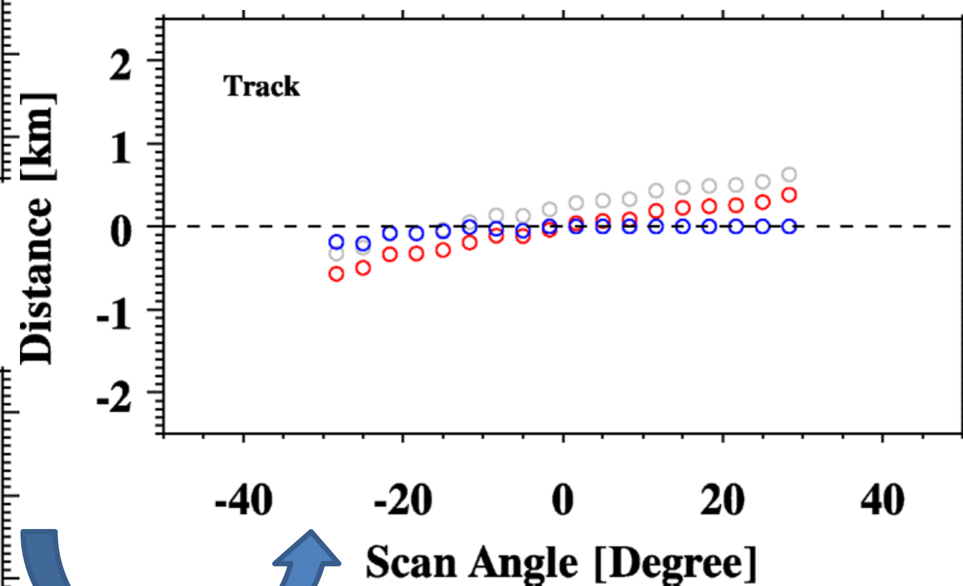
Possible Angle Adjustment to remove geolocation offset

However, there is no evidence on which angle causes this mismatch. The team decided to leave this issue for further investigation.





Adjust Yaw



Conclusion and Lessons Learned

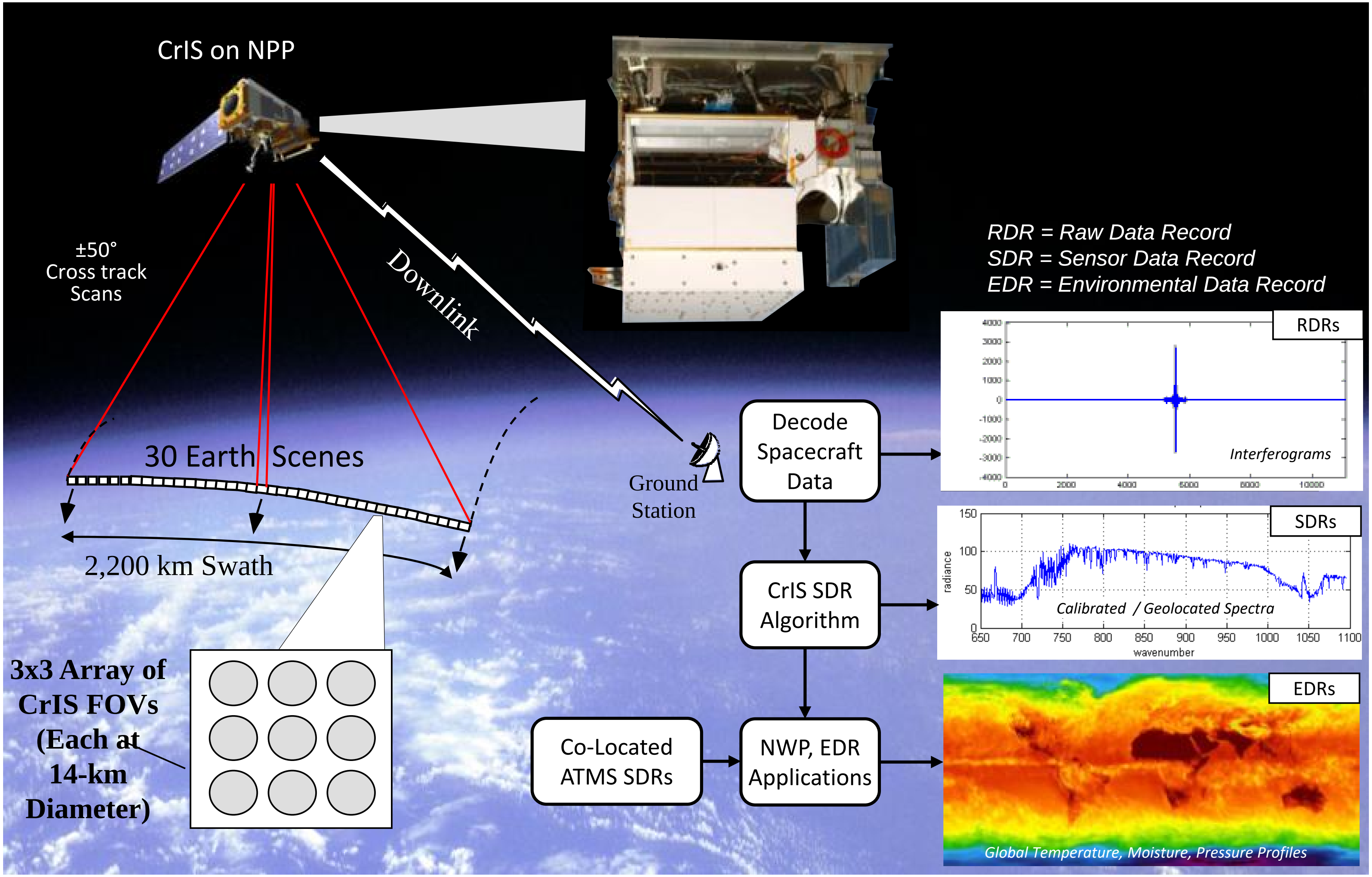
- Once satellite was launch, there is no truth on-orbit. Therefore, inter-calibration plays an important role of post-launch calibration.

- We demonstrate an example of using VIIRS as a references to evaluate CrIS geometric calibration accuracy.
  - At nadir: 0.354 ±0.047 km in scan direction and
    0.209 ± 0.082 km in track direction
  - Within 30 degree scan angles: less than 1.3 km
  - End of Scan CrIS and VIIRS mismatch (Under Investigation)

- Lessons Learned:
  - Inter-calibration must be well designed and directly serves for sensor-level calibration.
  - Inter-calibration results must be carefully classified based on root causes
    - Caused by inter-calibration method?
    - Caused by instrument sensor?
      - Reference instrument?
      - Compared instrument
        - » Instrument anomaly
        - » Calibration parameters
        - » Calibration algorithms
  - Inter-calibration must be performed routinely during the whole life of instrument sensor

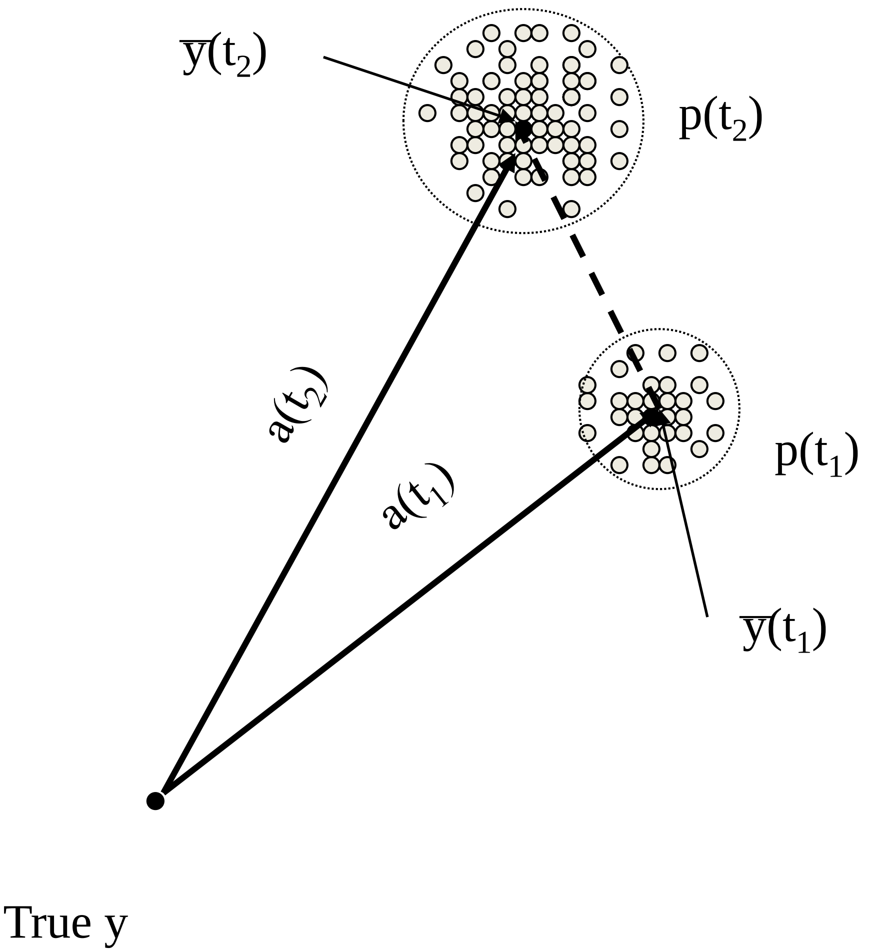
Backup Slides

CrIS Operational Concept



Error Characteristics

- Accuracy (bias): **a**
- Precision (standard deviation): **P**
- Uncertainties: $u = \sqrt{a^2+p^2}$
- Stability: **a(t)** and p(t)



From Goldberg (2006)