The Diagnosis, Derivation and Validation of a Point Spread Function to Mitigate the Slight Blurring Manifested in the MTSAT-1R Visible Channel Imagery

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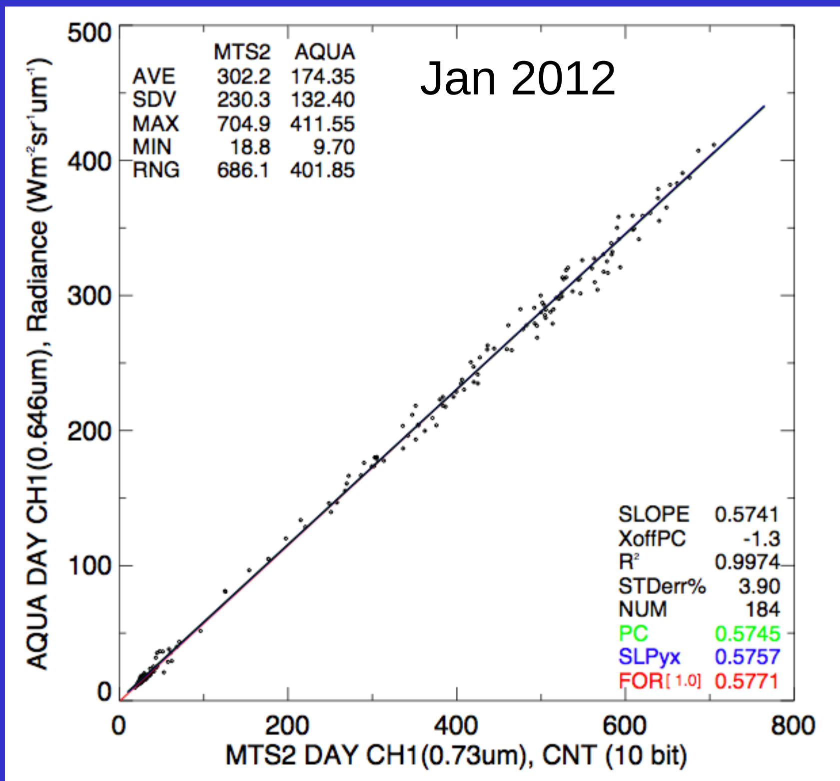
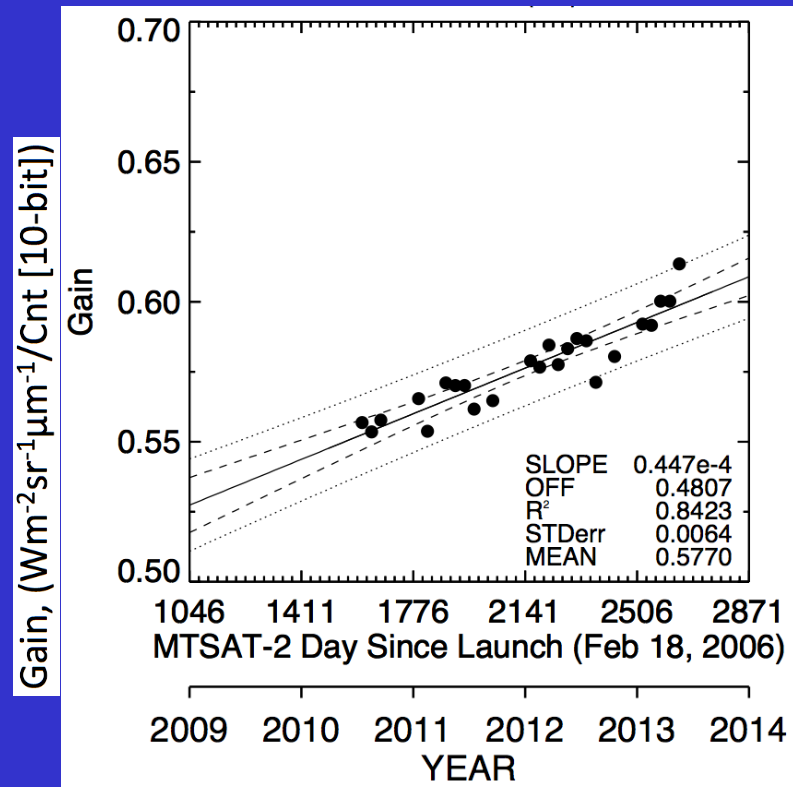
Fig from Doelling et al. 2014 and Khlopenkov et al. 2014, accepted TGRS

GEO to MODIS Cross-Calibration Method

- None of the GEO visible sensors have onboard calibration
- Ray-match GEO counts (proportional to radiance) and MODIS radiances within a 0.5° ocean regions using selection constraints
  - ΔSZA< 5° (15 minutes), ΔVZA<10°, ΔRAZ < 15°, no sunglint
  - Domain ±20° E,W and ± 15° N,S near sub-satellite point to maximize coincident matches
  - Use Aqua-MODIS Collection 6 as reference
  - Use a SCIAMACHY spectral band adjustment factor derived from all SCIA footprints over the same equatorial region
  - Normalize the cosine solar zenith angle
- Perform monthly linear regressions and derive monthly gains
  - Use published offsets
- Compute timeline trends from monthly gains

Successful MTSAT-2 (145° E) /Aqua-MODIS ray-match inter-calibration

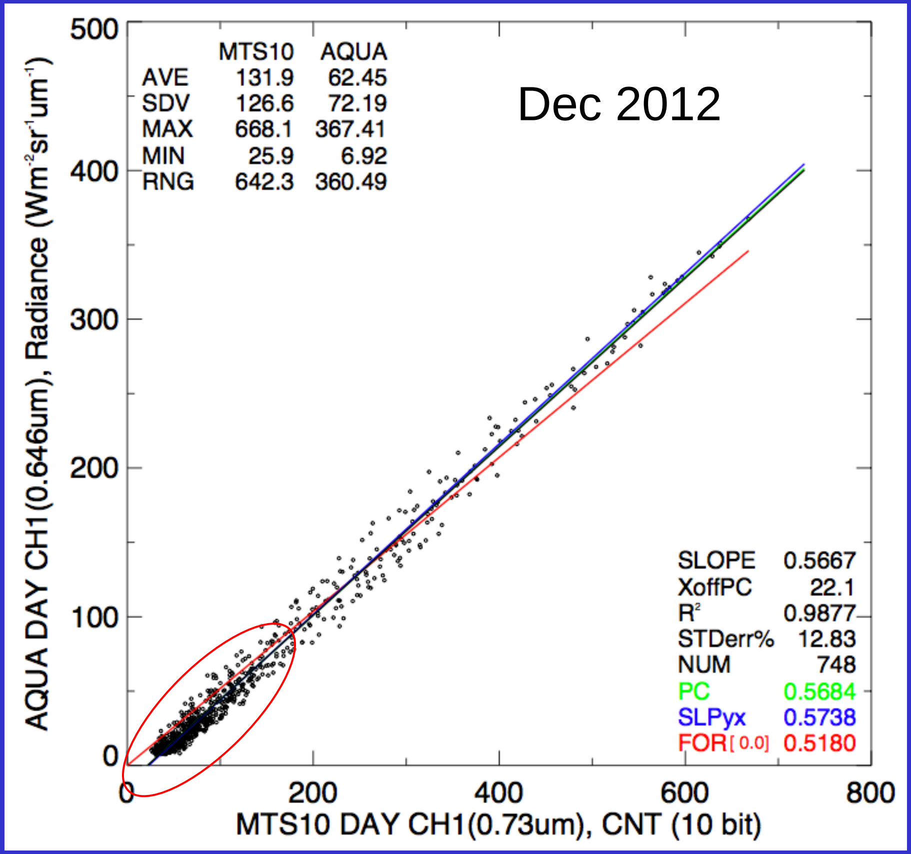


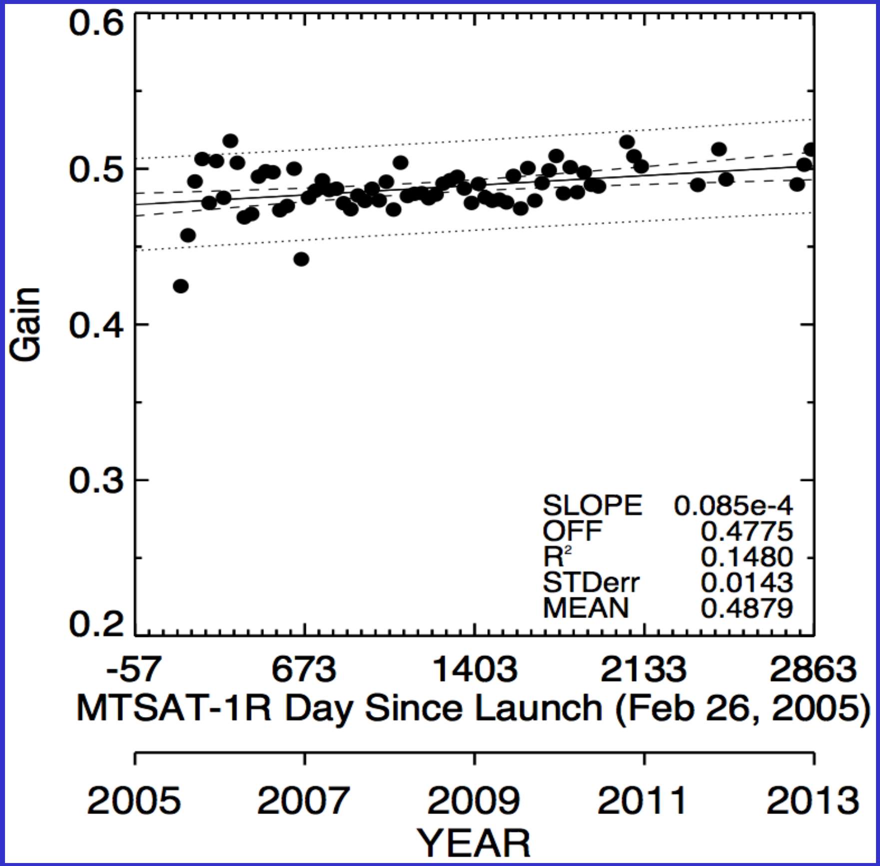


- Angle match (ΔSZA< 5° (15 minutes), ΔVZA<10° , ΔRAZ < 15° , no sunglint) coincident Aqua-MODIS and MTSAT-2 50-km radiance pairs monthly over sub-satellite domain ±20° E/W and ± 15° N/S

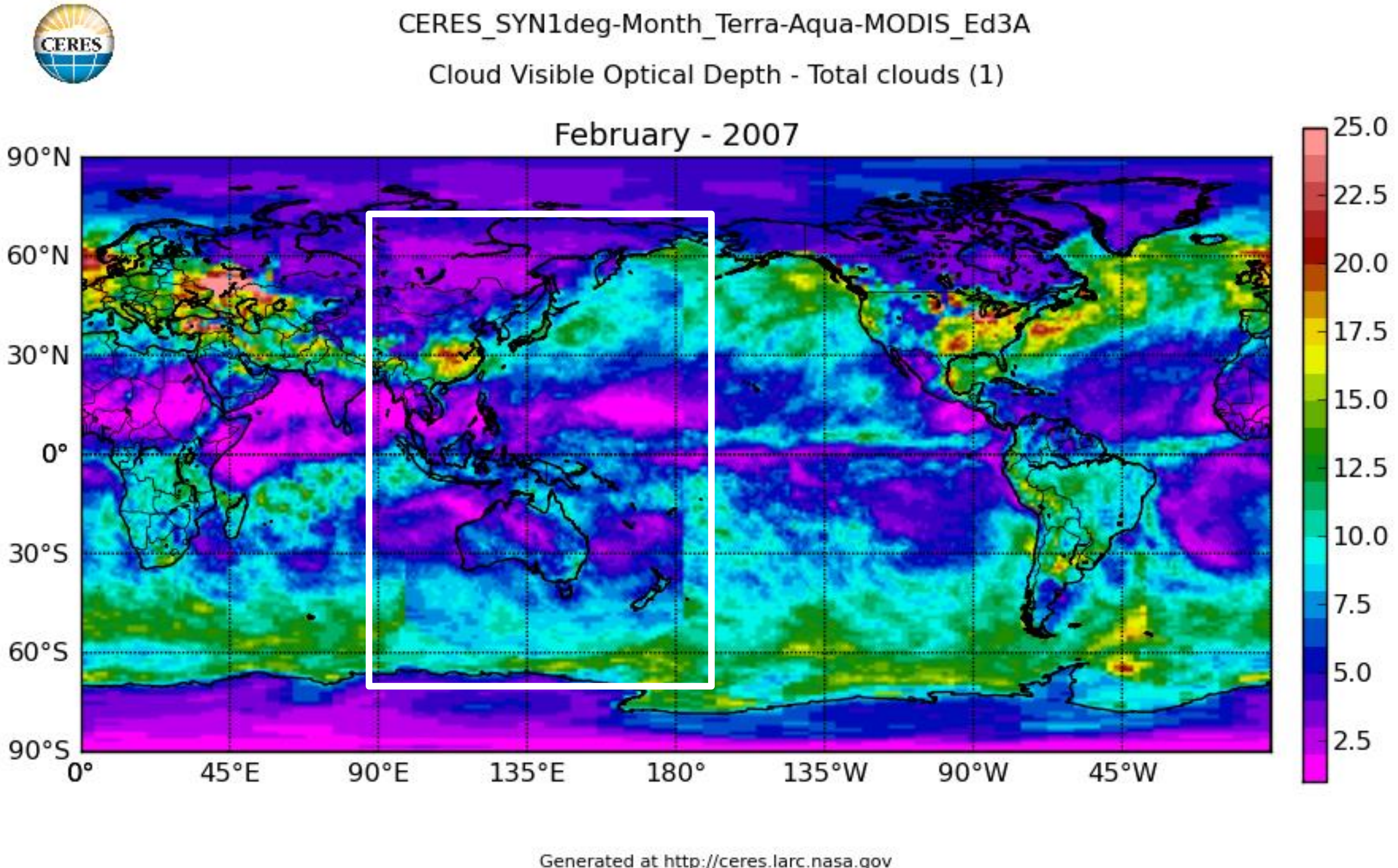
$$R_{modis} * SBAF_{geo/modis} * (\mu_{0geo}/\mu_{0modis}) = g * (C - C_0)$$

Unsuccessful MTSAT-1R (140° E) /Aqua-MODIS ray-match inter-calibration

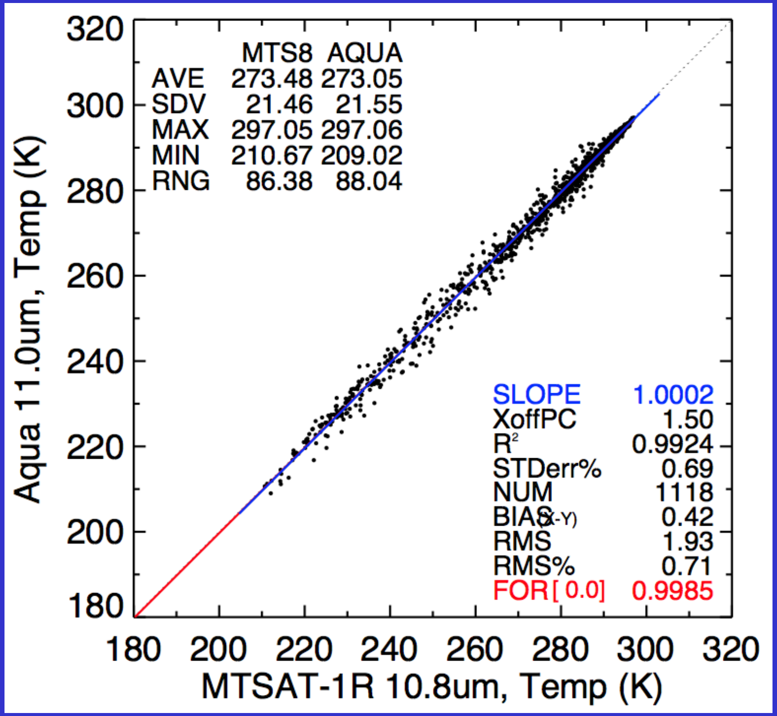




MTSAT-1R derived optical Depth using ray-matched calibration gain



Is it navigation?



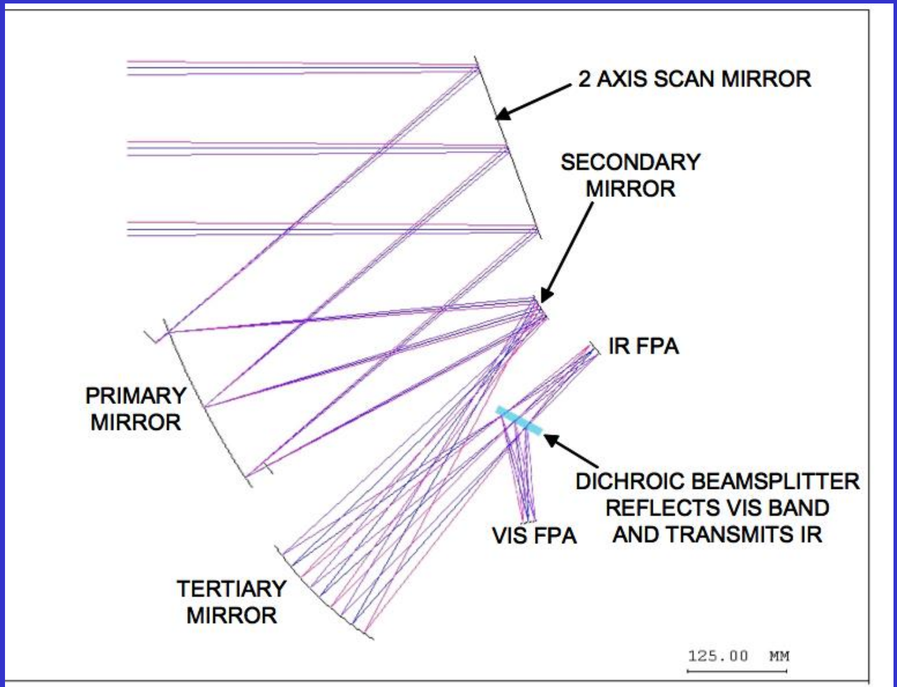


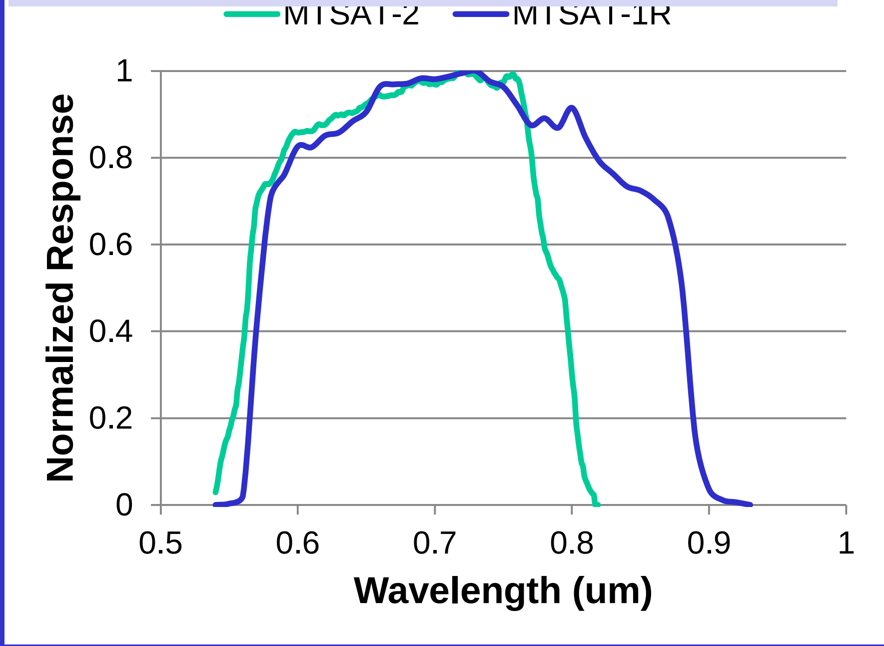
Figure 4. JAMI's straightforward optical layout is at the heart of this advanced technology instrument.

Puschell et al. 2003 SPIE

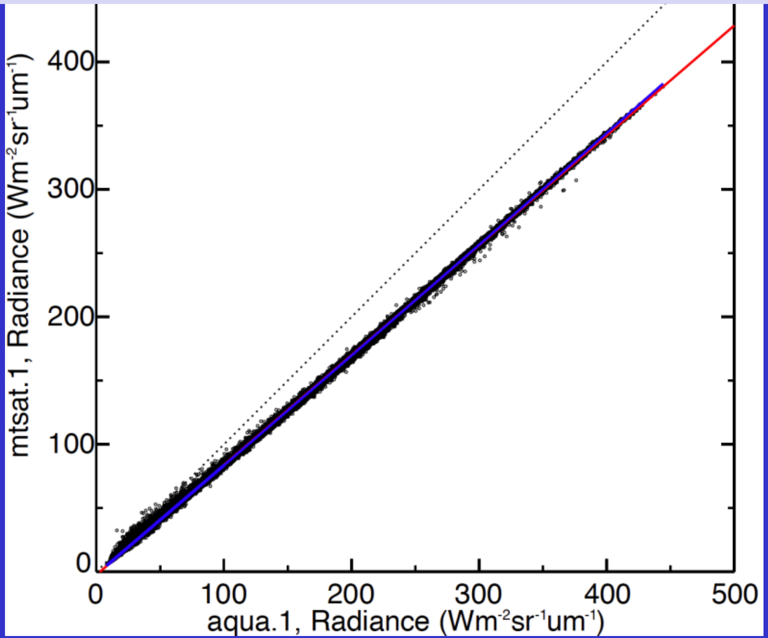
- The MTSAT-1R visible and IR detector assembly share the same optics
- IR shows no non-linearity, using same matching criterion
- The MTSAT-1R IR ray-matching results are very similar to other GEOs

Is it due to spectral channel difference?

MTSAT-1R and MTSAT-2 spectral response functions

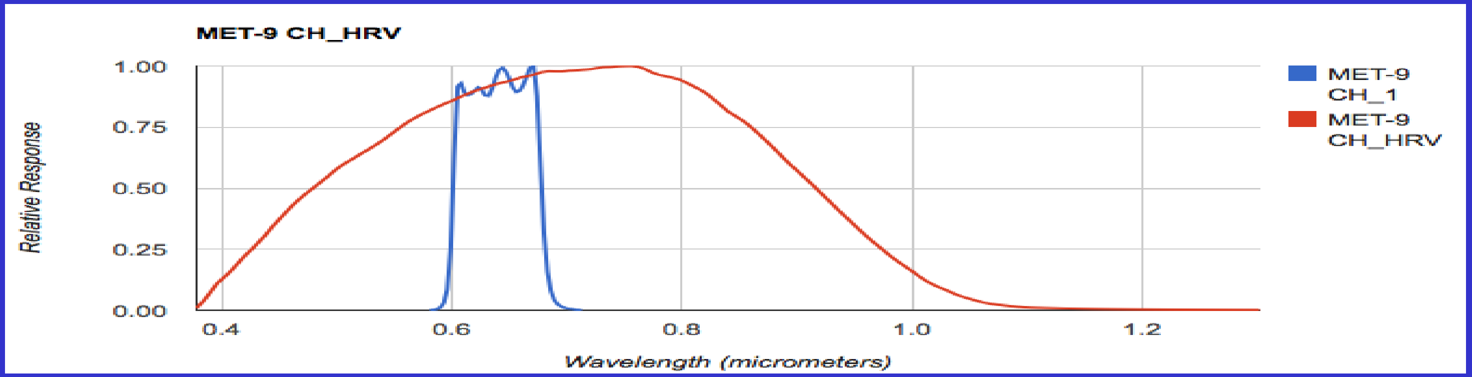


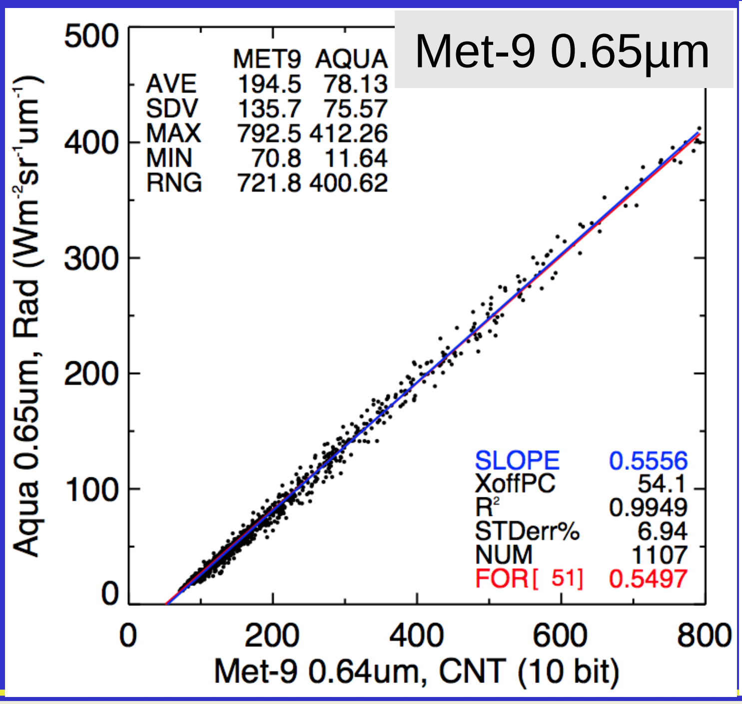
SCIAMACHY footprint pseudo radiance radiance pairs over MTSAT ocean domain

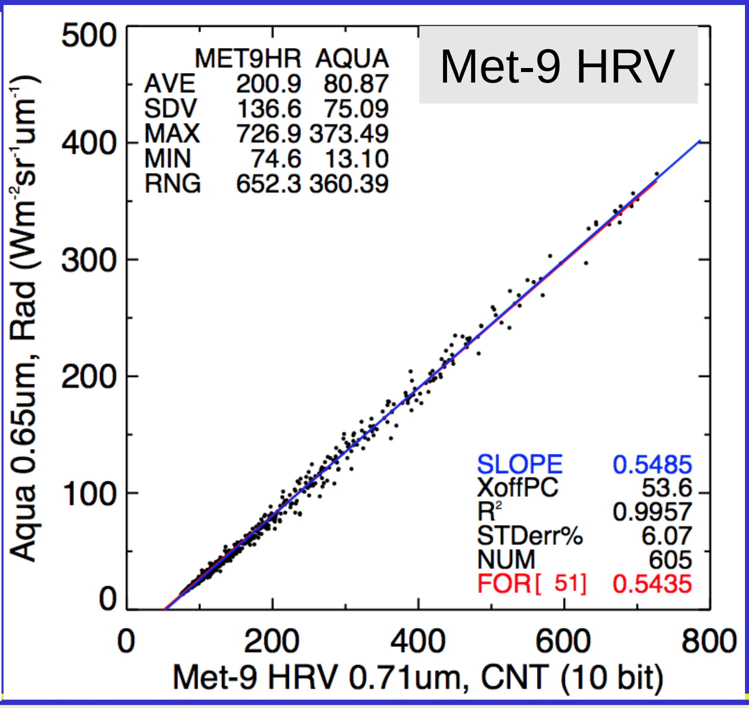


- The SCIAMACHY Spectral Band Adjustment Factor (SBAF) correction is much smaller than the observed ray-matched nonlinearity

Spectral differences



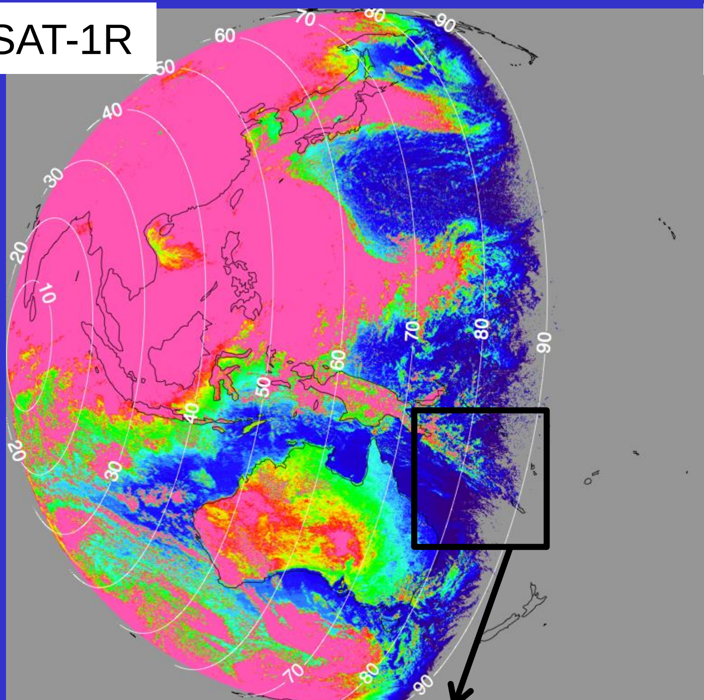




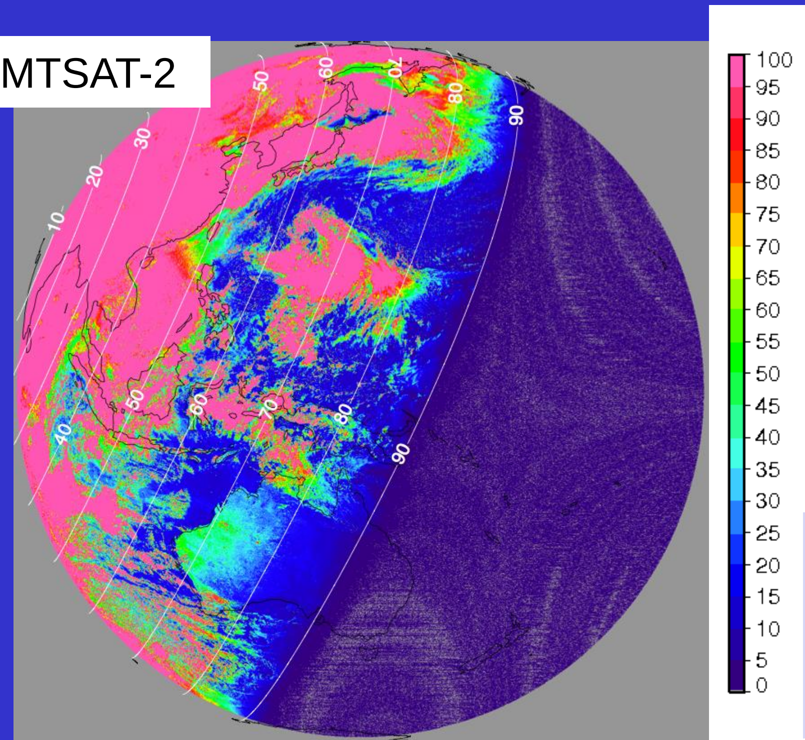
- The ocean ray-matching method does not cause the non-linear feature

Is the space offset?

MTSAT-1R

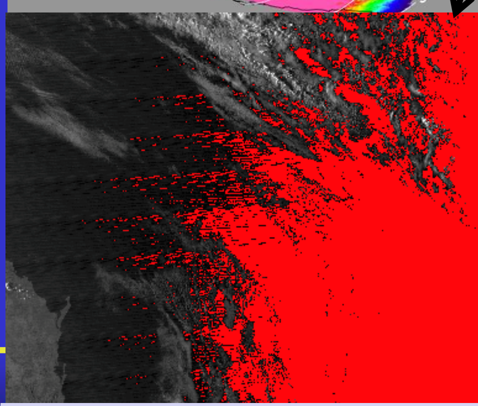


MTSAT-2



Gray indicates a visible pixel count of 0

MTSAT-1 Sept 15, 2007, 6:30 GMT
MTSAT-2, July 15, 2012, 7:30 GMT

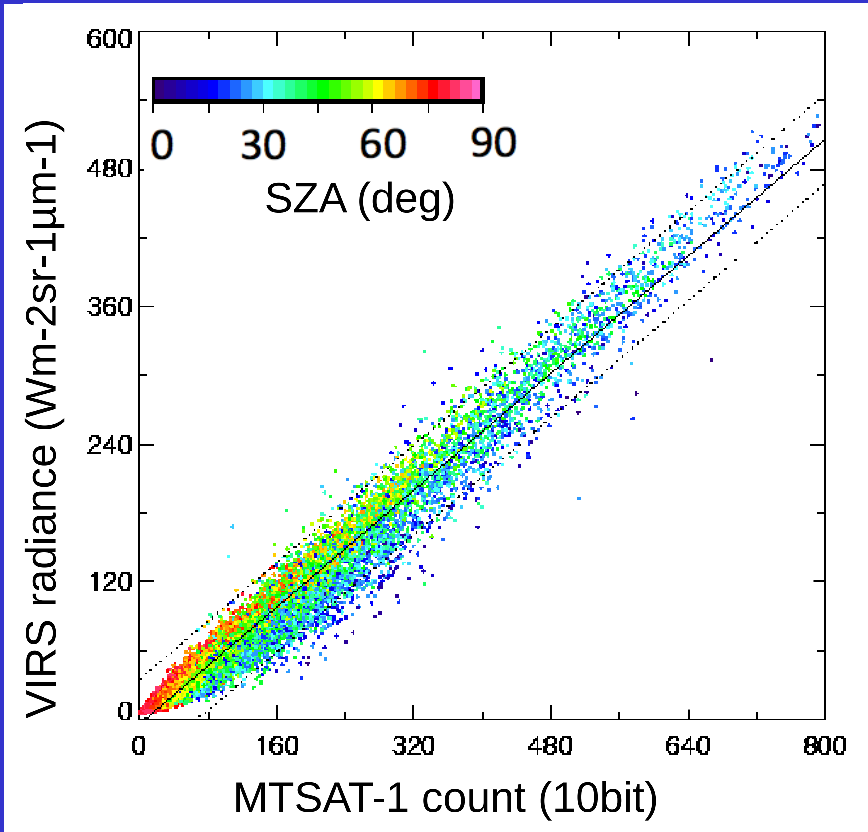


Red indicates a visible pixel count of 0

- The MTSAT-1R space count is 0
- Since the space count was not given a positive count offset, a count of zero can also translate to a positive radiance value

MTSAT-1R/TRMM-VIRS ray-match inter-calibration

During September 2007 and August 2008



- TRMM is in a precessionary satellite with a 46 day repeat cycle with an inclination of 35°
- The nonlinear feature is diurnally dependent
- The dark Earth radiances are brightened more with lower SZA
- This plot verifies that the space count is <0

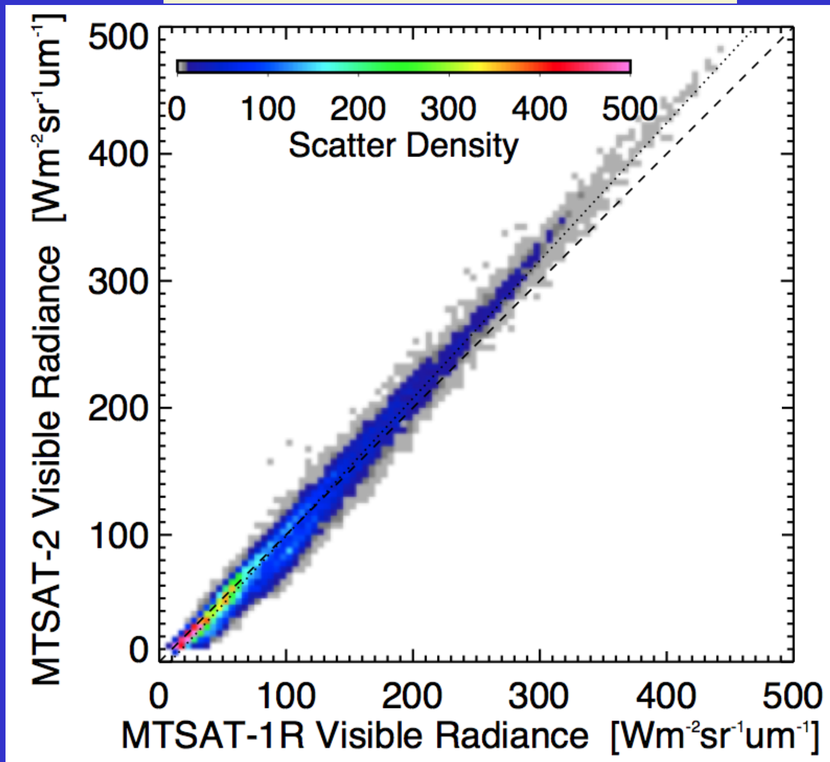
The Breakthrough

- 5 days of December 17 to 21, 2010 MTSAT-2 commissioning images were received from JMA
  - MTSAT-1R was launched Feb. 26, 2005 and became operational June 28, 2005 (replaced GOES-9 at 155° W)
  - MTSAT-2 was launched Feb, 18, 2006 and became operational on July 21, 2010
  - MTSAT-1R is the operational satellite during ground system maintenance of MTSAT-2 (Oct. 7 to Dec. 21, 2010)
  - MTSAT-2 operational after December 22, 2010
- This is a Global Space-based Inter-Calibration System (GSICS) success story
  - The coincident MTSAT-2/MTSAT-1R provided by JMA was only possible through the collaborative efforts of the GSICS program.

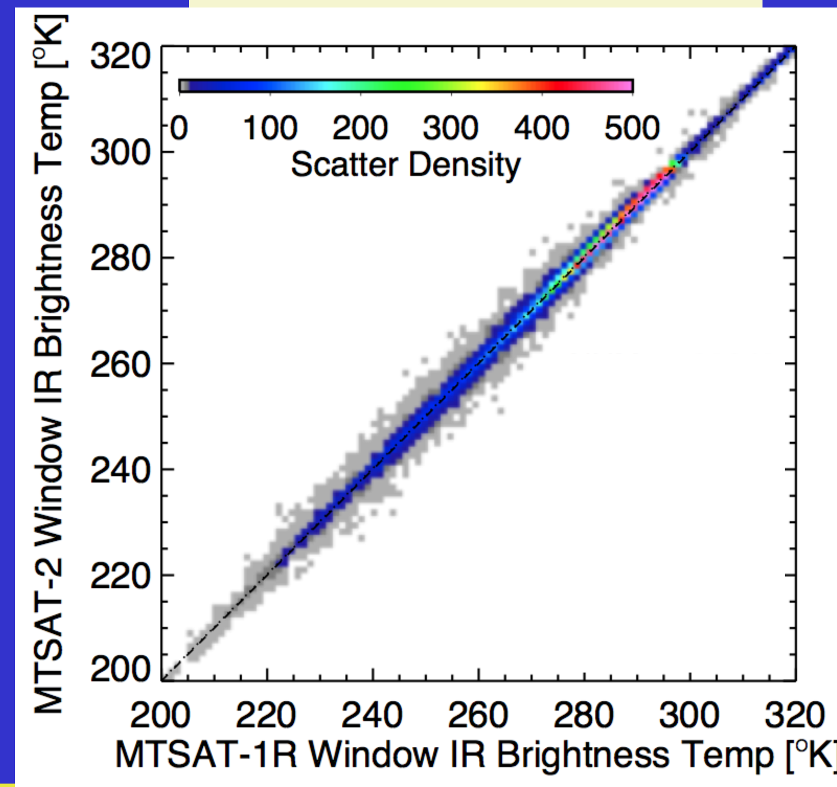
MTSAT-1R vs MTSAT-2 comparisons

- Compare coincident 1° x 1° lat/lon gridded radiances

VIS MTSAT-1/MTSAT-2
2010 Dec 21 2:30Z



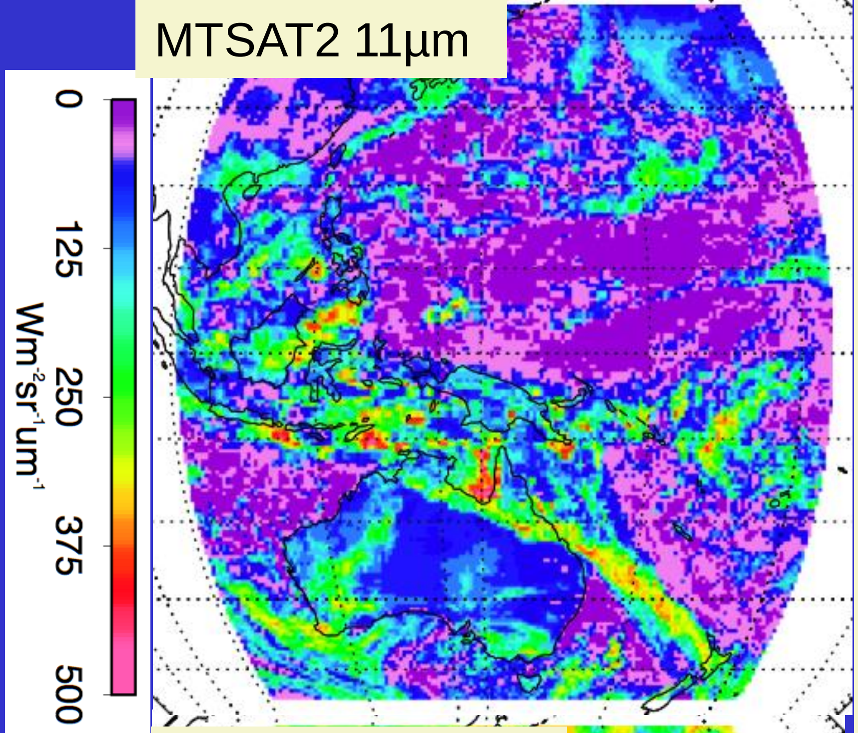
IR MTSAT-1/MTSAT-2
2010 Dec 21 2:30Z



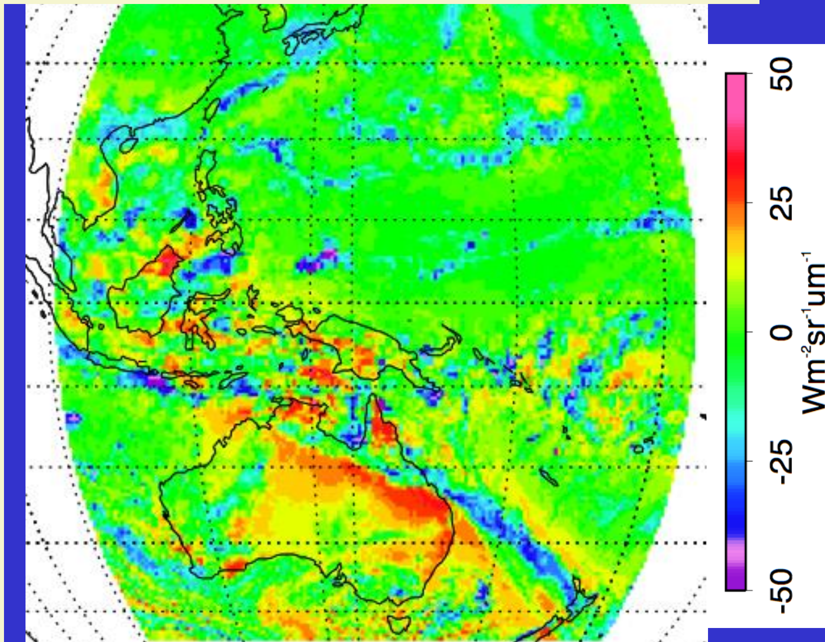
$g_{M1} = g_{M2}(SC_{M1}/SC_{M2})$

IR demonstrates good navigation

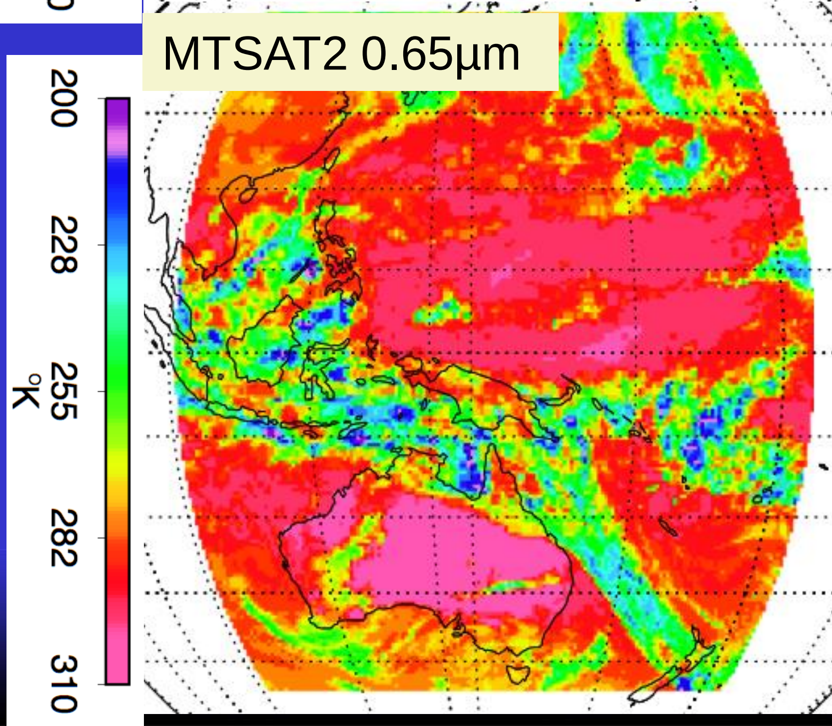
MTSAT1 – MTSAT2 comparison
2010 Dec 21 0:30Z



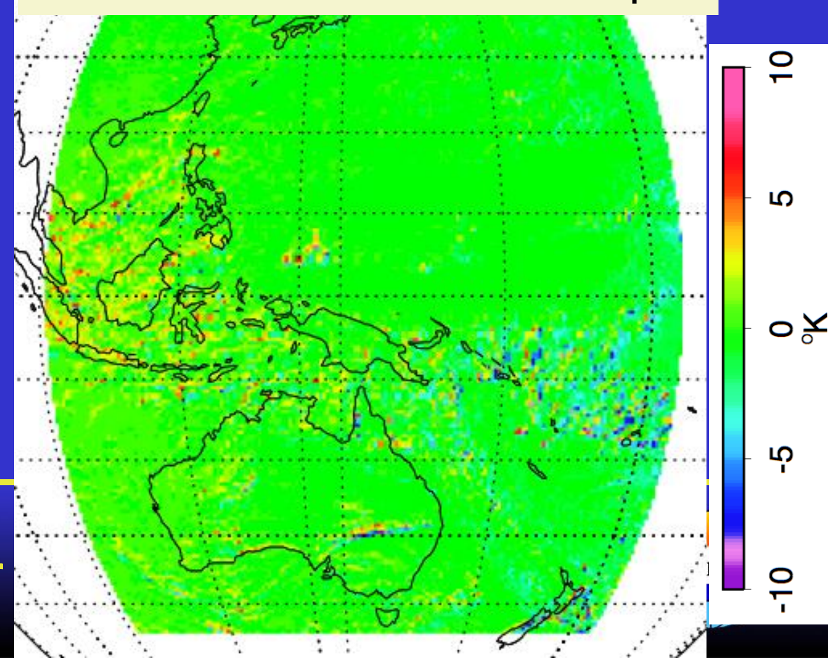
MTSAT2 11µm



MTSAT1 minus MTSAT2 0.65µm

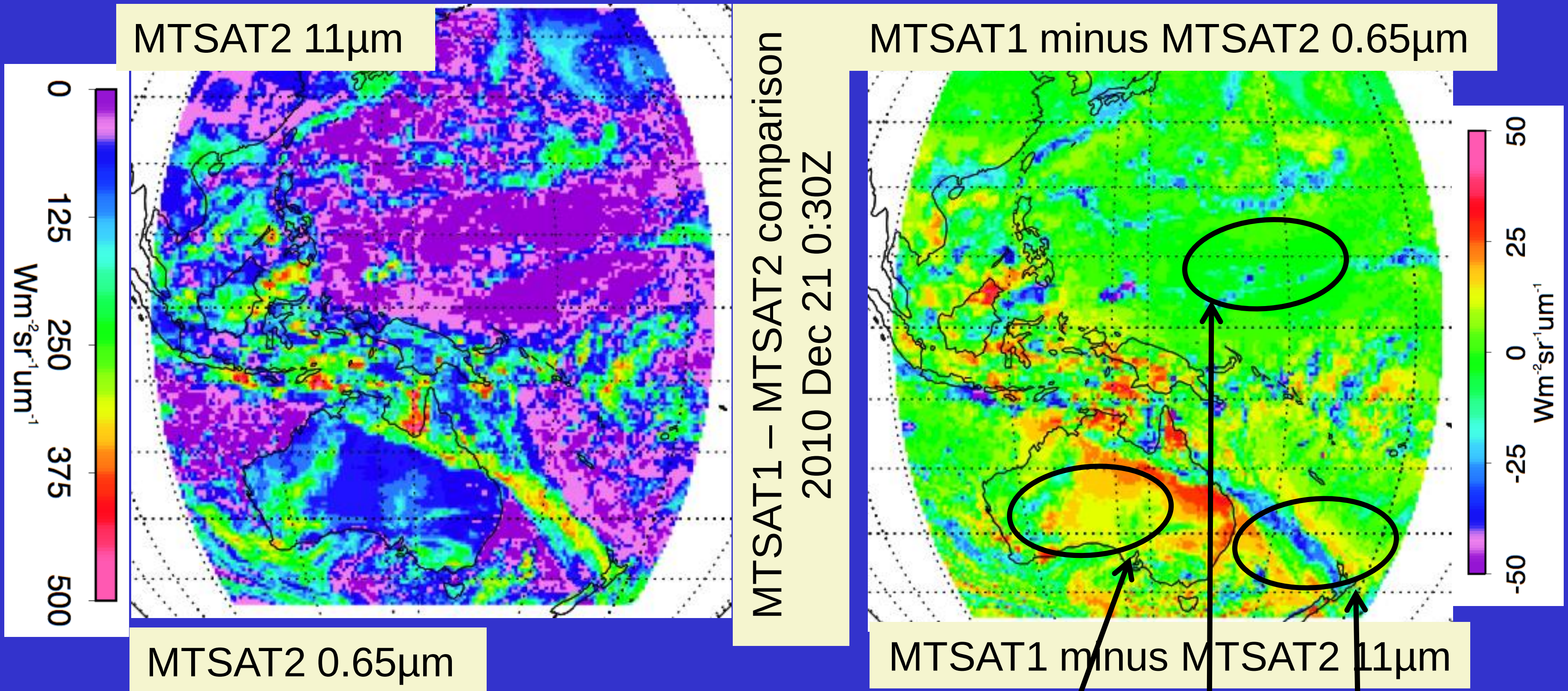


MTSAT2 0.65µm



MTSAT1 minus MTSAT2 11µm

Center



- Clear-sky ocean near bright clouds can be overestimated by 100%
- Clear-sky ocean not surrounded by clouds are not effected
- There are spectral response function differences, evident over Australia

PSF Formulation

- MTSAT-1R is of different design than MTSAT-2
  - Additional mirrors were used to increase the optical path length to reduce the possibility of stray light
  - MTSAT-2 similar to GOES 2nd generation and have been in operation since 1995
- The slight optical blurring manifested only in the visible
  - The wavelength dependent blurring of the mirrors may be caused by non-perfect polishing or dust
  - Tahara et al. 2005 states that the MTSAT-1R visible sensitivity was reduced by half from the pre-launch value consistent with possible dust contamination of the mirrors
- Reconstruct the pixel level PSF by allowing a small portion of the light to come from surrounding regions
  - Use MTSAT-2 as the truth

PSF algorithm

Suppose the blurred MTSAT-1 signal $f_1(t)$ is a convolution of the original signal $f_2(t)$ with a kernel function $K(t)$ representing the unknown PSF:

$$f_1(t) = \int f_2(t-\tau)\, K(\tau)\, d\tau$$

We assume that $K(t)$ is a nearly perfect response function, Dirac δ-function, but having a weak blurring response in the form of Gaussian function:

$$f_1(t) = \int f_2(t-\tau) \left(\delta(\tau) + G(\tau) \right) d\tau$$

Fourier transform of a convolution is a product of the corresponding spectra:
(here $f(\tau) \rightarrow F(\omega)$; $\delta(\tau) \rightarrow 1$; $G(\tau) \rightarrow G(\omega)$)

$$F_1(\omega) = F_2(\omega) \cdot \left(1 + G(\omega) \right)$$

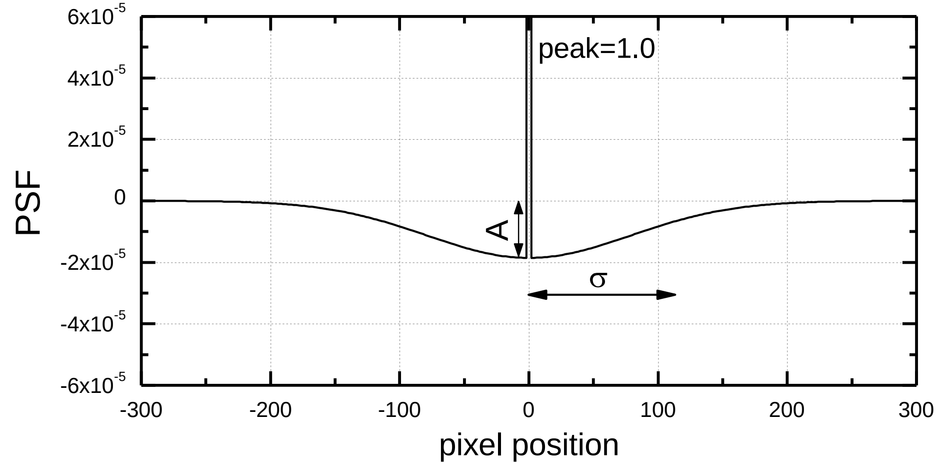
Because blurring is weak ($G(\omega) << 1$) we can approximately rewrite it as:

$$F_1(\omega) \cdot \left(1 - G(\omega) \right) \approx F_2(\omega)$$

Taking the inverse Fourier transform we finally obtain that the original signal $f_2(t)$ can be recovered by applying a negative Gaussian response function:

$$\int f_1(t-\tau) \left(\delta(\tau) - G(\tau) \right) d\tau \approx f_2(t)$$

Gauss function is defined by 2 unknown parameters: the magnitude **A** and the width **σ**:



Derivation of PSF-function

1. Detect a piecewise spatial displacement between two images of simultaneous observation of MTSAT-1 and -2 and build a 2D vector map of these displacements. By using this map, the MTSAT-2 image is warped so as to correct for this non-linear displacement. This virtually eliminates any spatial mismatch between the images, which allows us to run a regression analysis reliably on a pixel-by-pixel basis.

2. Mask out all pixels over land and in the areas of sun glint.

3. Calculate the PSF function for a set of the 4 parameters **A**, σ, ε, and θ.

4. Apply the PSF to the MTSAT-1 image.

5. Degrade the resolution of both images by 4 times by sinc-resampling to reduce differences caused by cloud shadows and due to stereoscopic effect on elevated cloud features.

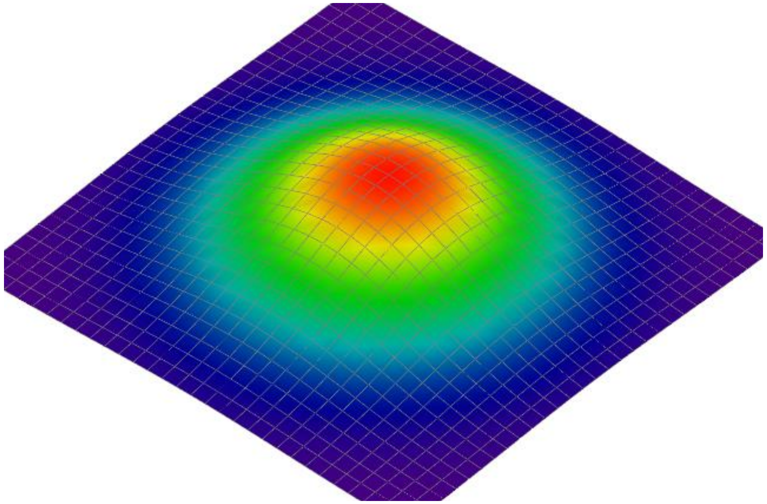
6. Build a linear regression between corrected MTSAT-1 and MTSAT-2 and calculate the R^2 value.

7. Repeat from step 3 to obtain the optimal set of parameters by means of the Powell's conjugate direction method that minimizes a function in multi-dimensional space.

8. Find the set of 4 parameters for each occurrence of simultaneous observation between MTSAT-1 and -2.

2-Dimensional Case

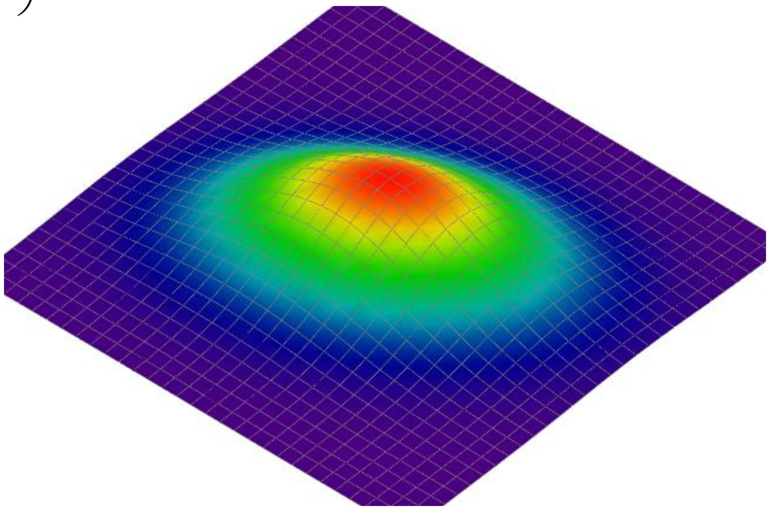
$$G(x,y) = -\frac{A}{\pi\sigma_x\sigma_y}\exp\left[-\left(\frac{x^2}{\sigma_x^2}+\frac{y^2}{\sigma_y^2}\right)\right]$$



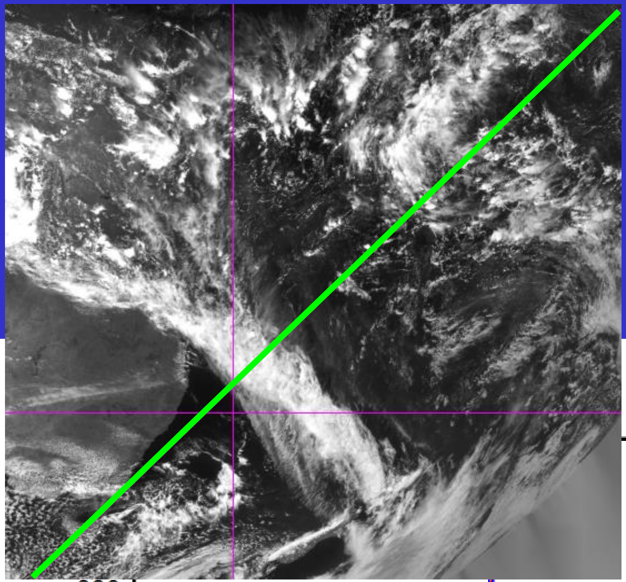
Assuming that $\sigma_x \neq \sigma_y$ we can introduce unknown eccentricity ε and rotation angle θ of the blob.

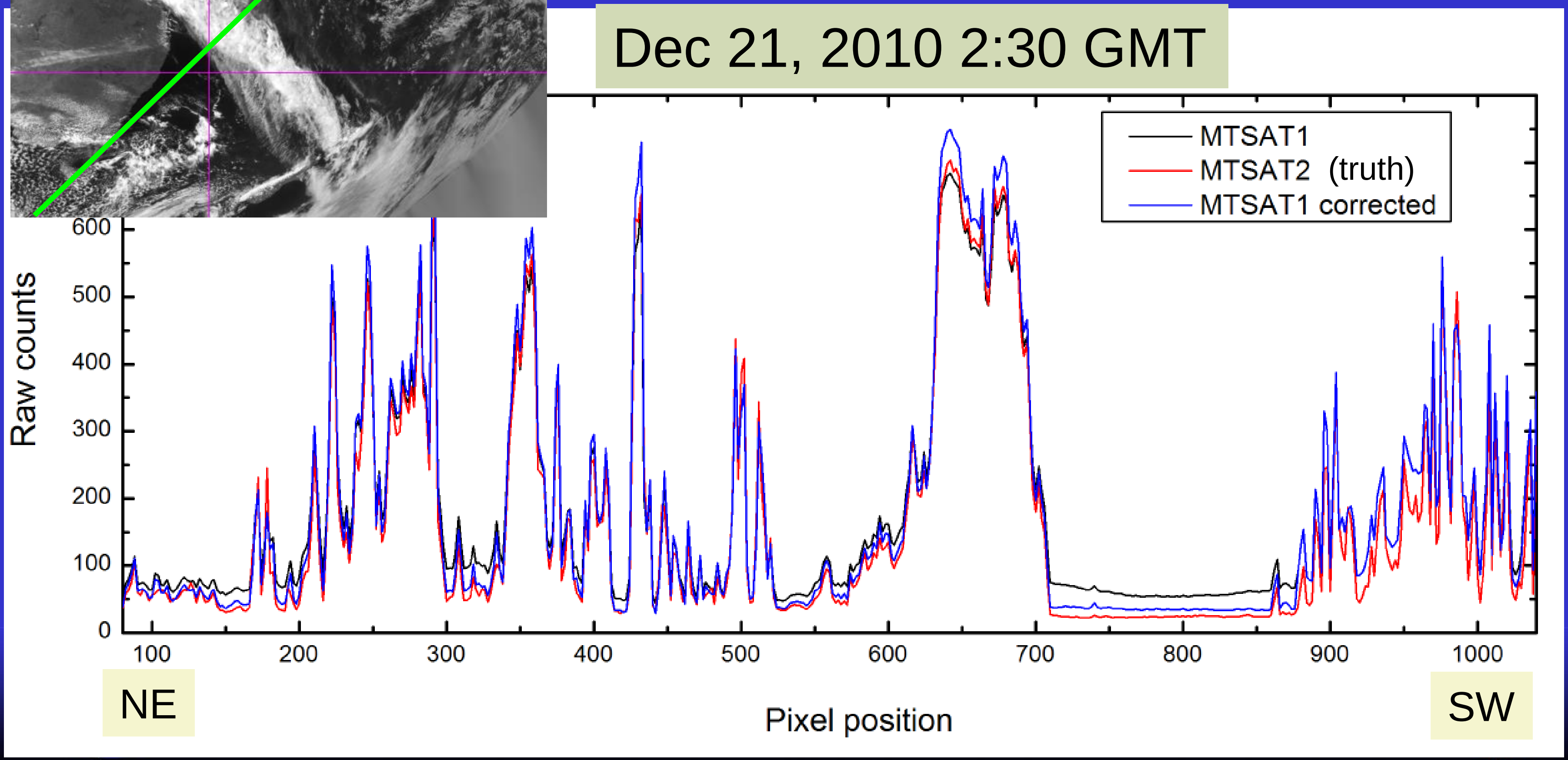
$$G(x,y) = -\frac{A}{\pi\sigma^2\sqrt{1-\varepsilon^2}}\exp\left(-\frac{x^2+y^2-\varepsilon^2(x\cos\theta - y\sin\theta)^2}{\sigma^2(1-\varepsilon^2)}\right)$$

Finally, the sought shape of the PSF function is defined by the 4 unknown parameters: **A**, $\boldsymbol{\sigma}$, $\boldsymbol{\varepsilon}$, and $\boldsymbol{\theta}$.



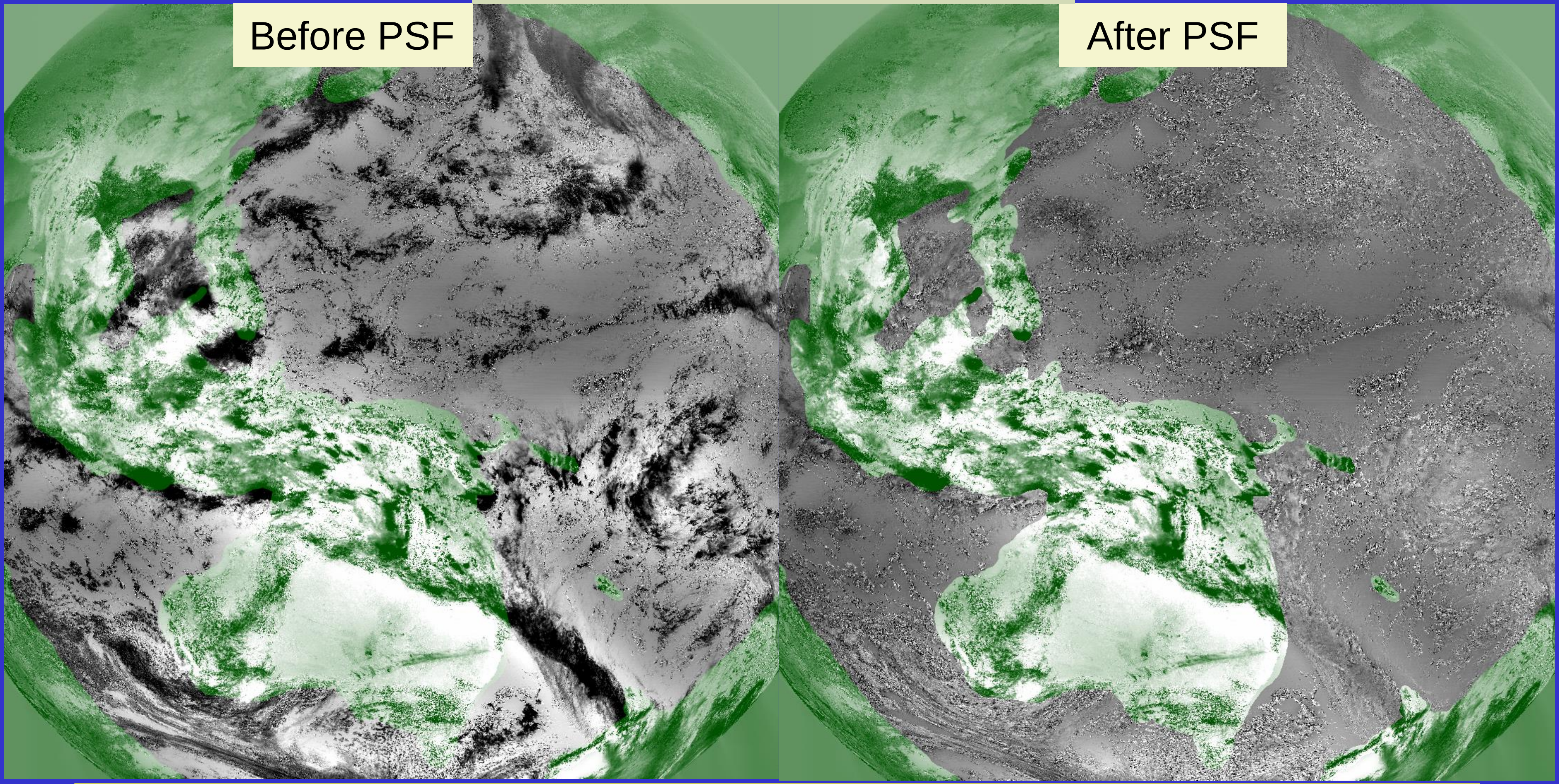
Test the PSF function using a Diagonal Cross Section





MTSAT1R minus MTSAT2

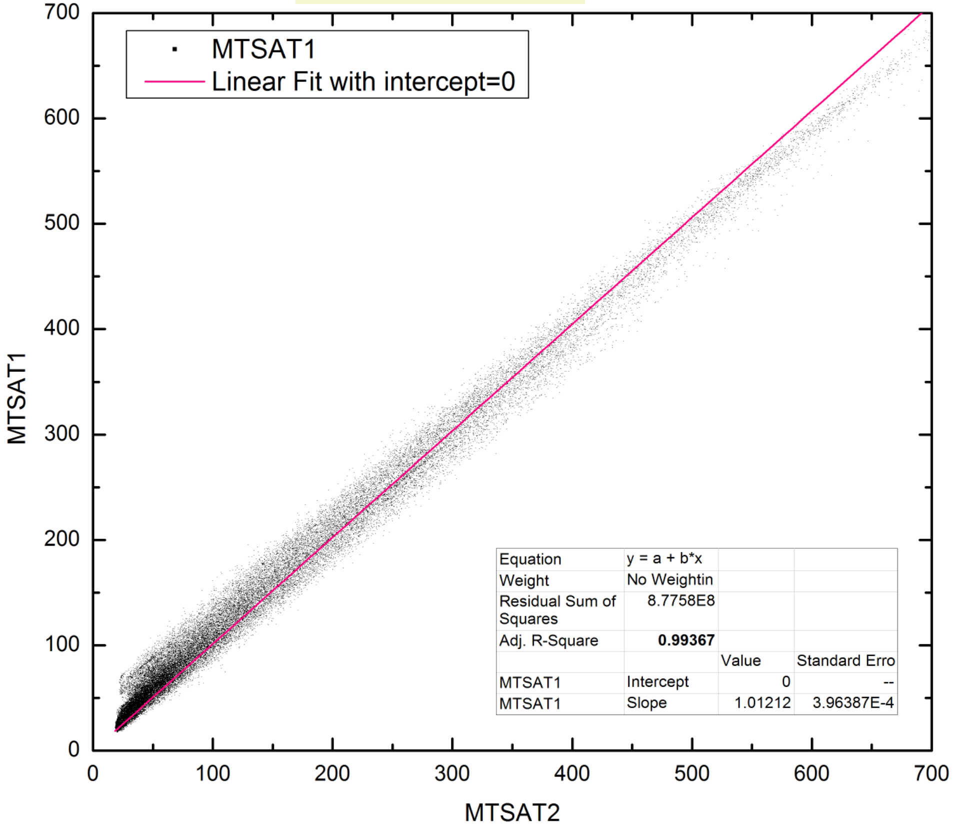
Dec 21, 2010 2:30 GMT



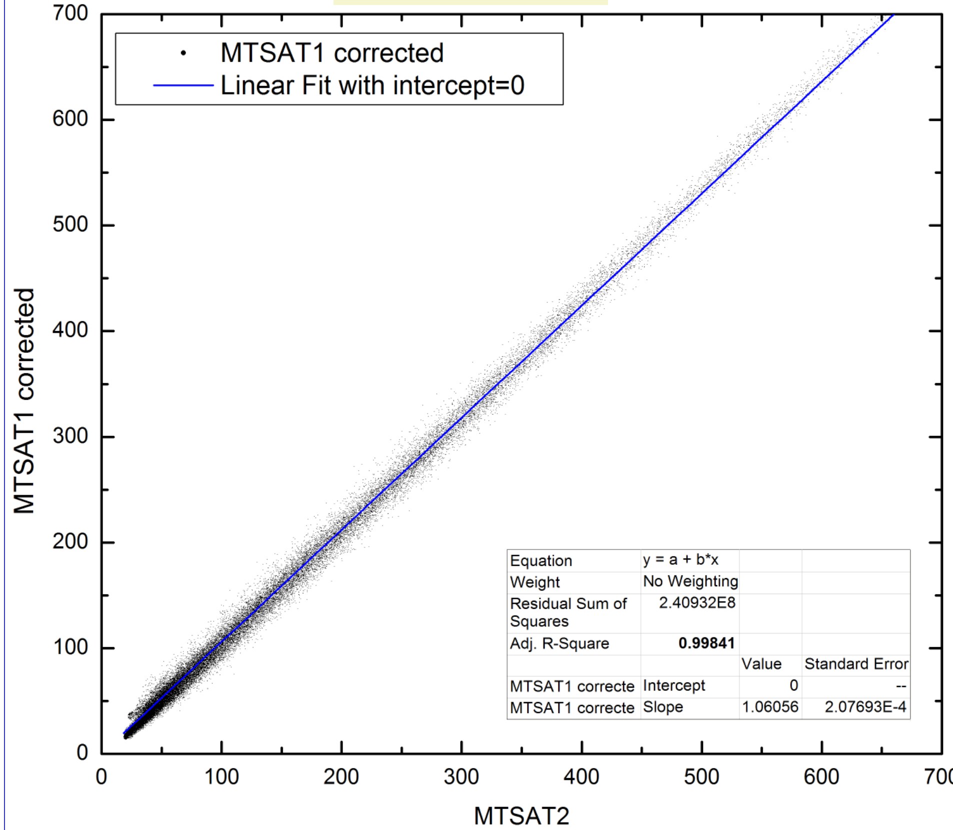
PSF coefficients derived only over ocean regions

MTSAT1/MTSAT2 pixel pair scatter plot

Before PSF



After PSF

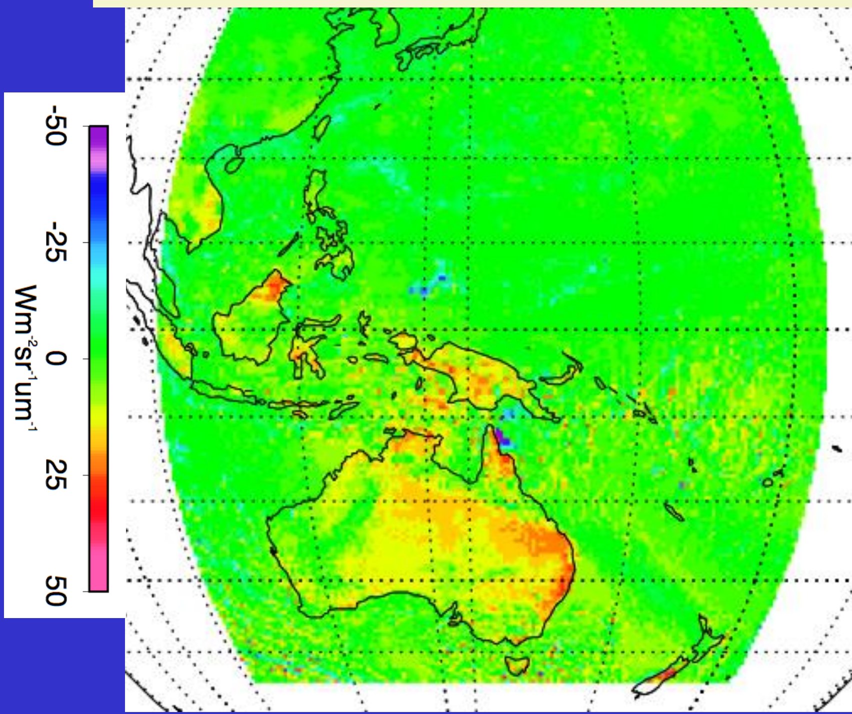


The PSF weighted radiance pairs have a linear relationship through the space count

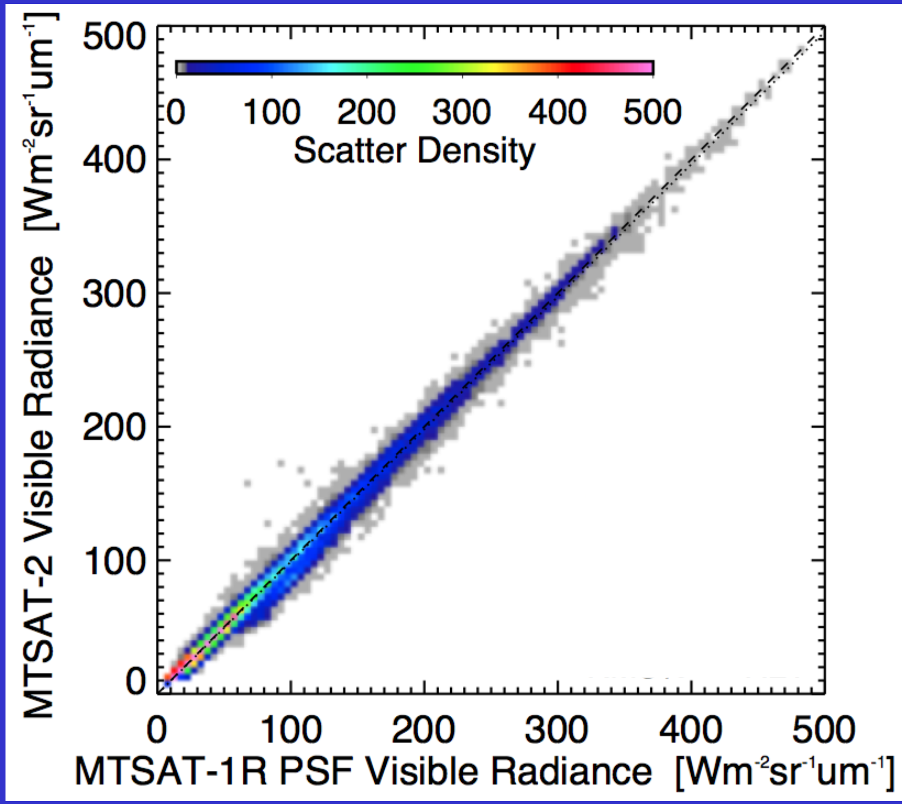
Dec 21, 2010 2:30 GMT

After application of the PSF

MTSAT1 minus MTSAT2 0.65µm



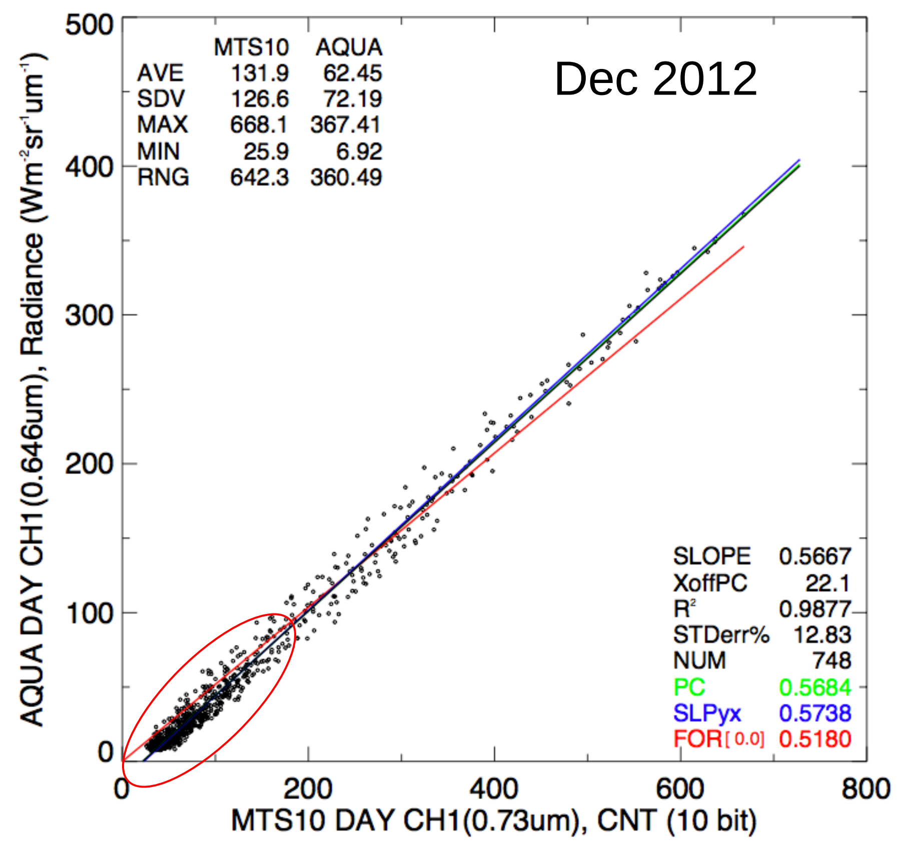
MTSAT1 – MTSAT2 comparison
2010 Dec 21 0:30Z



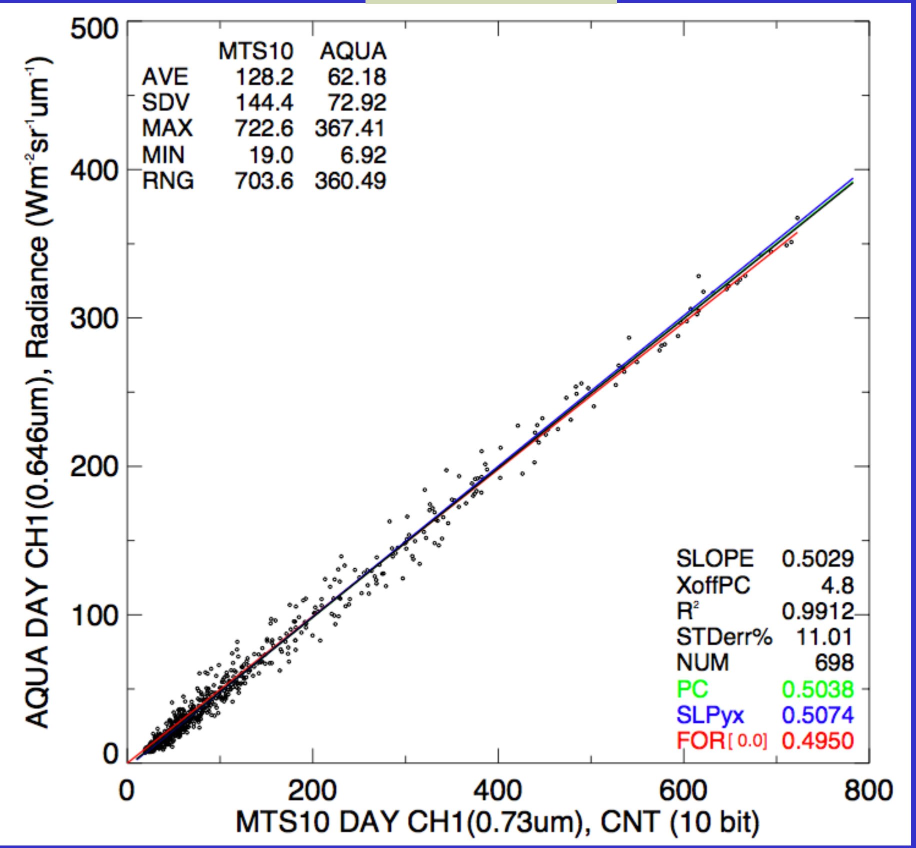
- The residual differences are mainly over land and are due to the spectral band difference
- The coefficients were found to be very similar over 5 days of images
- The spatial RMS has been reduced by 80% after applying the PSF

Successful MTSAT-1R/Aqua-MODIS ray-match inter-calibration

Before PSF

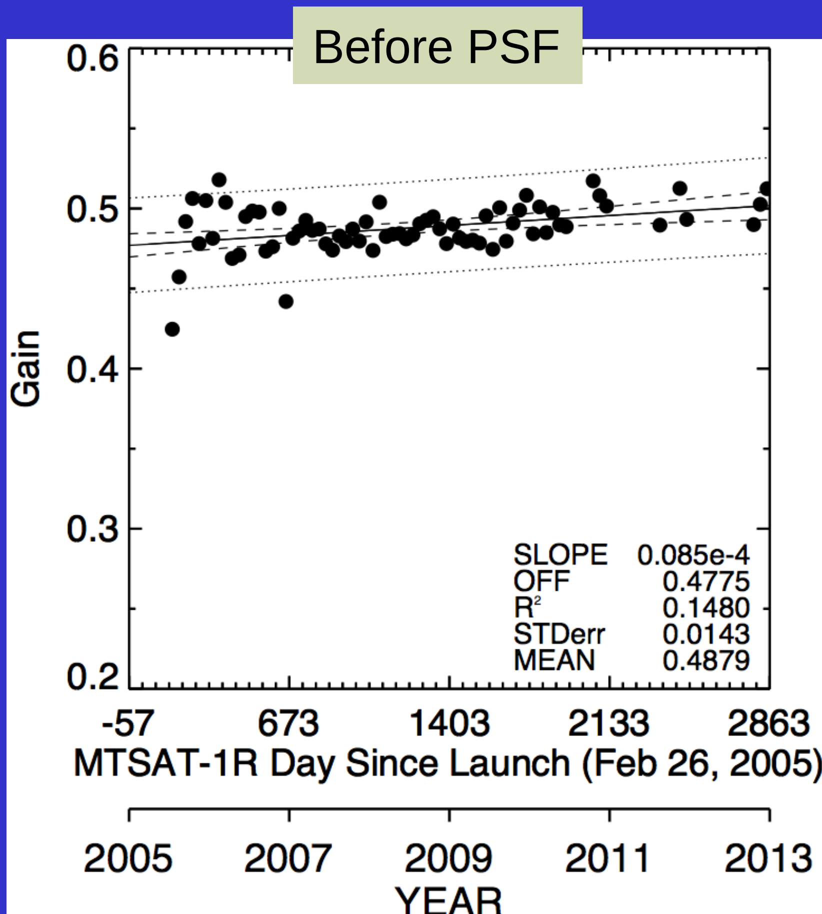


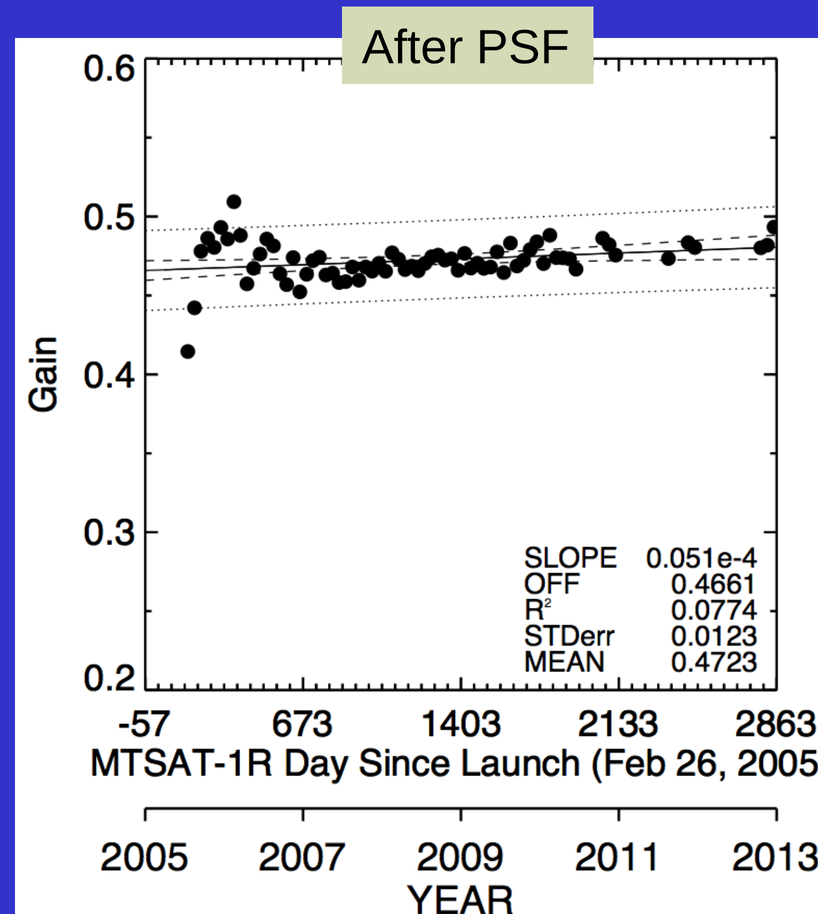
After PSF



- After PSF correction, the MTSAT-1R counts are now linearly proportional to radiance and intersect the space count of 0

<u>Successful</u> MTSAT-1R/Aqua-MODIS ray-match inter-calibration





- The monthly temporal variability has been reduced
- It seems that after 2007 the optical degradation has stabilized

Conclusion

- Verifying sensor response over its dynamic range is crucial to obtaining flux and cloud retrievals
  - The MTSAT1/MODIS radiance pair regression is now linear
- Redefining the visible channel point spread function has greatly improved the science value of the MTSAT-1R imager
- The development of this algorithm is a GSICS success story!
  - The interaction between calibrating groups facilitated by GSICS has benefited the entire science community
- Suggestion during commissioning:
  - Compare coincident 1° x 1° lat/lon gridded radiances to validate linearity of sensor during commissioning phase before placing standby mode until operation
  - The MTSAT-2 was in standby mode for 5 years before becoming operational
  - During this 5-year period the MTSAT-1R had reduced science quality

Backup Slides

PSF coefficient diurnal dependency