GOES15 Sounder Real Time De-Striping Algorithm

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Acknowledgement

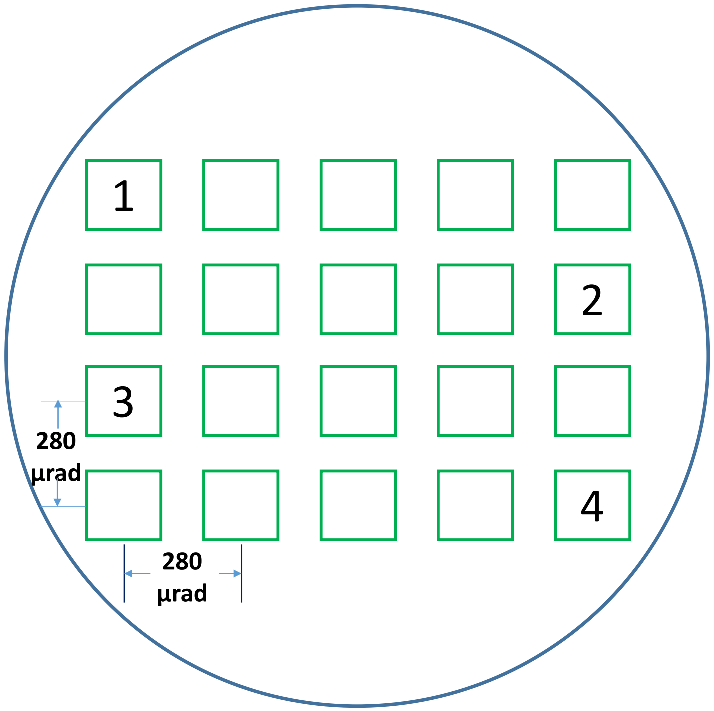
- A Team Effort:
  - ITT Excelis performed the initial analysis on the GOES 15 Sounder Image striping characteristics.
  - STAR and Wisconsin groups performed the data validation and verification.
  - OSPO/EMOSS Engineers performed the software regression tests and radiometric validation.
  - OPSO GOES Instrument Lead Hyre Bysal coordinated testing, data validation, and system integration.

Agenda

- Sounder Operation and history.
- GOES 15 Sounder Striping Characteristics.
  - Detector to Detector (D2D) Striping
  - Scan to Scan (S2S) Striping
- Realtime De-Striping Algorithms
  - D2D correction Algorithm
  - S2S correction algorithm
- Implementation in GOES Ground System.

Sounder Operations and History

- GOES Sounder
  - 18 IR Channels and one visible channel.
  - Each channel has 4 detectors
  - One E/W scan generates 4 lines.
- GOES15 Sounder operation
  - Reference Longitude 135 degrees.
  - Sounder coverage include Northern pacific, Hawaii, and Pacific Coast
  - Generates 47 images every 24 hours,
    - About one image every half hours.
    - The operation schedule is fixed.
- The GOES15 Sounder striping was first discovered during the GOES 15 Post Launch Test.
  - ITT first investigated the striping issues.
  - The de-striping algorithm was developed and implemented in 2013.
  - The most serious one is channel 15 image
  - It has become operational in Mid 2014.



Sounder Detector Layout

The Accumulative Histogram

- A quantitative measure for striping of multi-detector instruments
- Defined as

$$H_{i,d}(k) = \frac{1}{N_{i,d}} \sum_{l=0}^{k} \left(\sum p \in (l,i,d) \right)$$

- The indices i, d are the detector ID and the scan directions.
- The accumulative histograms should be the same for an image with no striping
- Define the distance between different histograms:

$$g_{i,d,i',d'}(P) = k - k'$$

With

$$H_{i,d}(k) = H_{i',d'}(k') = P$$

- The distance represents the severity of the striping.
  - The histogram lookup approach based on the distance is has been developed for the de-striping algorithm for GOES.
    - Limitation: the striping can not be location dependent.
    - Needs the whole image for de-striping algorithm

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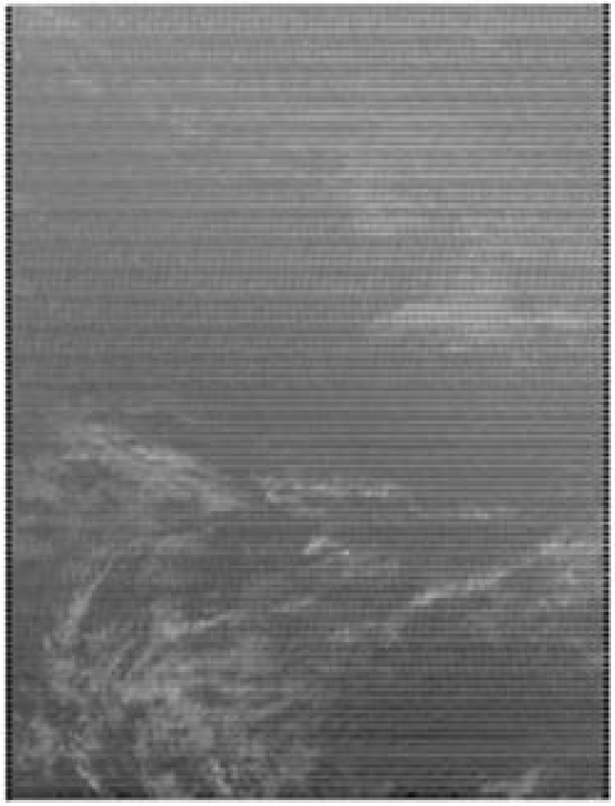
A Typical Channel 15 image with Striping



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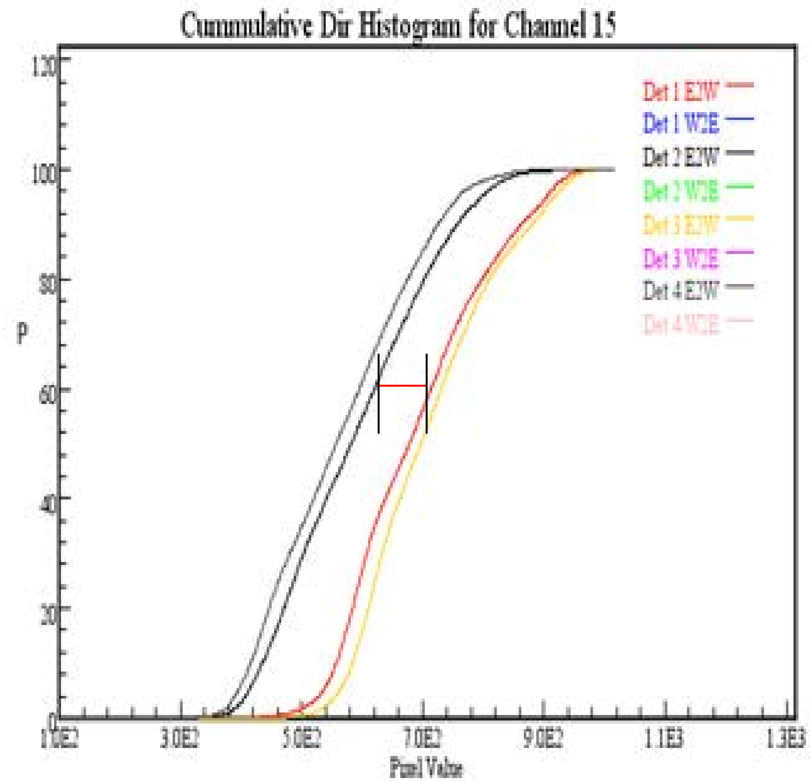

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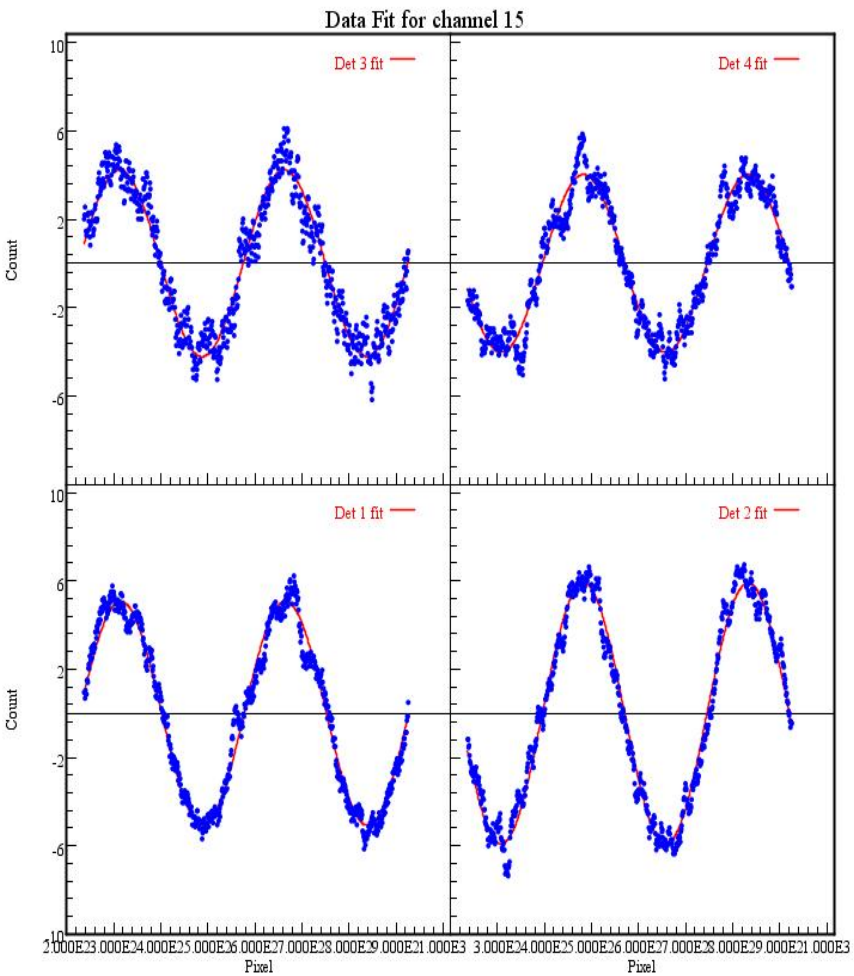
The red line shown in the histogram is the distance shown
In the previous slide

GOES 15 Sounder Striping Characteristics

- Detector to Detector (D2D) Striping:
  - Sinusoidal Oscillation across E-W scan
  - Varies in phase and amplitudes over the course of the day.
  - Has wavelength about 350 pixels.
  - Detector 1&3 and 2&4 in pairs with opposite phase.
  - Seen in both channel 15 and 14.
  - Location and time dependent
- The D2D striping for an image can be measured by D2D metric:

$$M_{i,j}^{D} = \frac{1}{N_d}\left|\sum_k T_i(k) - \sum_k T_j(k)\right|$$

  - The requirement is the metric should be less than 0.15 degrees in brightness temperature



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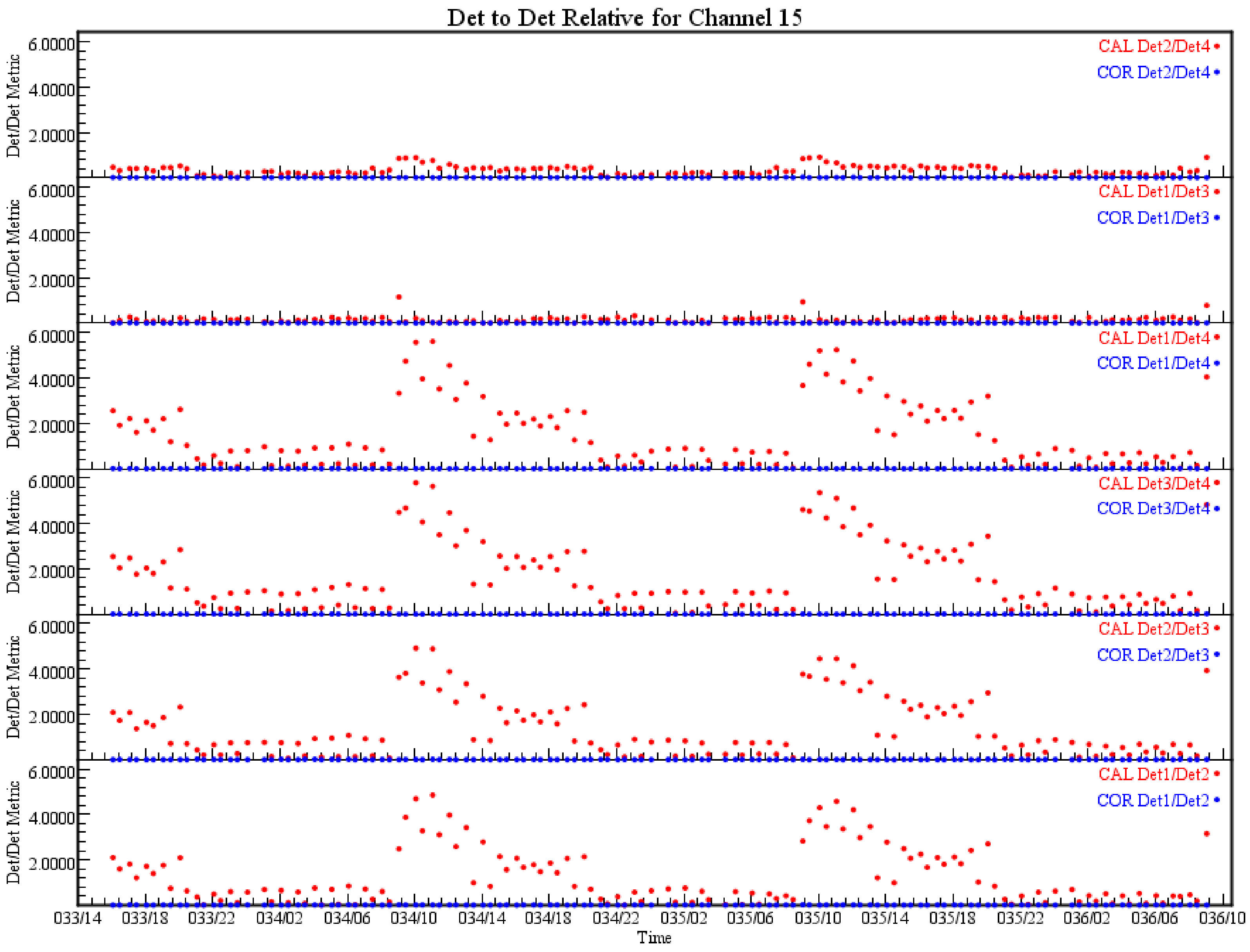
GOES Sounder Striping Characteristics

- Scan to Scan (S2S) Striping:
  - The difference between E2W and W2E scan.
  - The magnitude and sign of the difference are time dependent and location independent.
- The S2S metric:

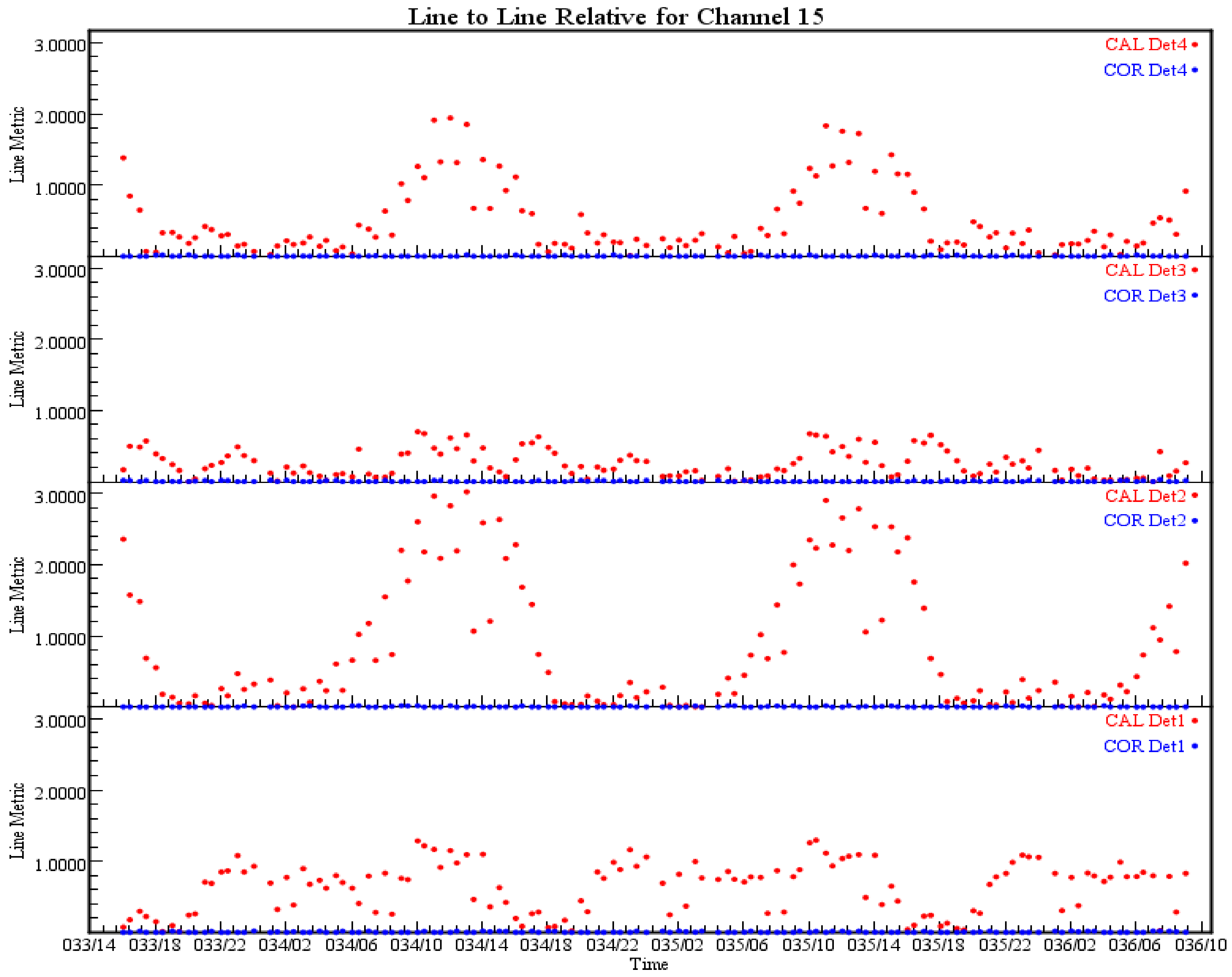
$$M_i^S = \frac{1}{N_d}\left|\sum_k T_i(k \in E2W) - \sum_k T_i(k \in W2E)\right|$$

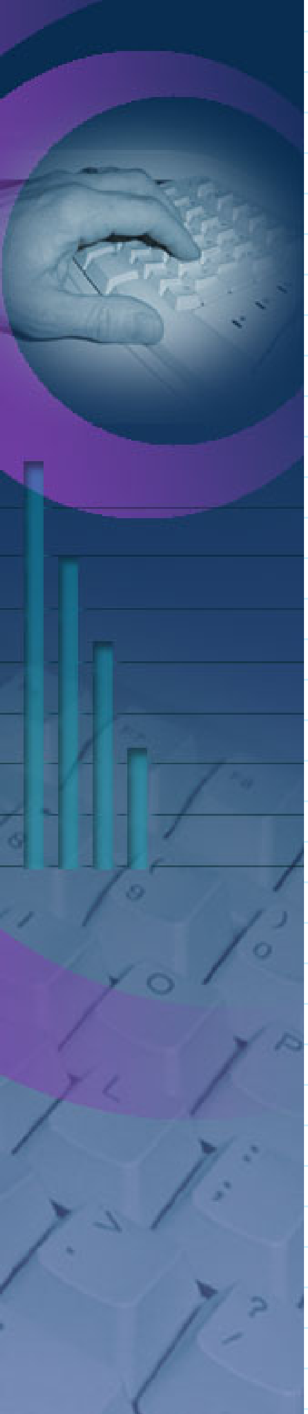
- Both D2D and S2S striping have a repeatable 24 hour periodical behavior.

D2D metric data.



S2S Metric for channel 15 Images





The De-Striping Algorithm Requirements

- Correct both D2D and S2S striping
- Realtime de-striping operations.
  - Efficient so that has minimum impact on the data processing latency.
- The de-striping must be done on the scan by scan basis.
  - GOES Instrument Data processing unit in ground system process the Sounder data on the scan by scan basis.
- The de-striping is performed on the calibrated Sounder data.
  - The de-striping algorithm is invoked after the data on each scan are calibrated.
    - Trade off has been made on whether to perform the de-striping on the un-calibrated data. The striping characteristics are much more stable for the calibrated data.
- The de-striped image are packed into GVAR.
  - GVAR Sounder data block also contains the raw (un-calibrated data, which is unchanged).

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The D2D algorithm: The offset function

- Define the offset function as

$$f(x) = \left(G_1(x) + G_3(x) - G_2(x) - G_4(x)\right)/4$$

- Because det 1,3 and det 2,4 has the opposite phase. The offset function enhances the contribution from D2D striping, and reduces the contributions from the actual content of the image.
- The offset function is location dependent, and can be expressed as:

$$f(x) = A_0 + A_1 \sin\left(\frac{2\pi(x+\varphi)}{\lambda}\right)$$

- Using the Fourier Expansion:

$$f(x) = \frac{2}{N}\sum_{k=0}^{N} w_k g_k \cos\left(\frac{\pi k x}{N}\right) \text{ where } w_k = \begin{cases} 0.5 & k = 0, N \\ 1 & 0 < k < N \end{cases}$$

- The D2D component:

$$f^{D2D}(x) = \frac{2}{N}\sum_{k=0}^{N} w_k g_k^{D2D} \cos\left(\frac{\pi k x}{N}\right) \text{ where } w_k = \begin{cases} 0.5 & k = 0, N \\ 1 & 0 < k < N \end{cases}$$

- with

$$g_k^{D2D} = \begin{cases} g_k & k < k_c \\ 0 & k \geq k_c \end{cases}$$

How to determine the cutoff K_c

- Define the frequency in the Fourier Expansion as

$$f = \frac{k}{N}$$

- The frequency corresponds to the D2D is

$$f^{D2D} = \frac{1}{175}$$

- Because the size of the scan is generally not the multiple of 175, we select a range of the frequencies around 175

$$0 < f <= 2.0 f^{D2D}$$

- This corresponds to the cutoff:

$$k_c = 2.0 \frac{N}{175}$$

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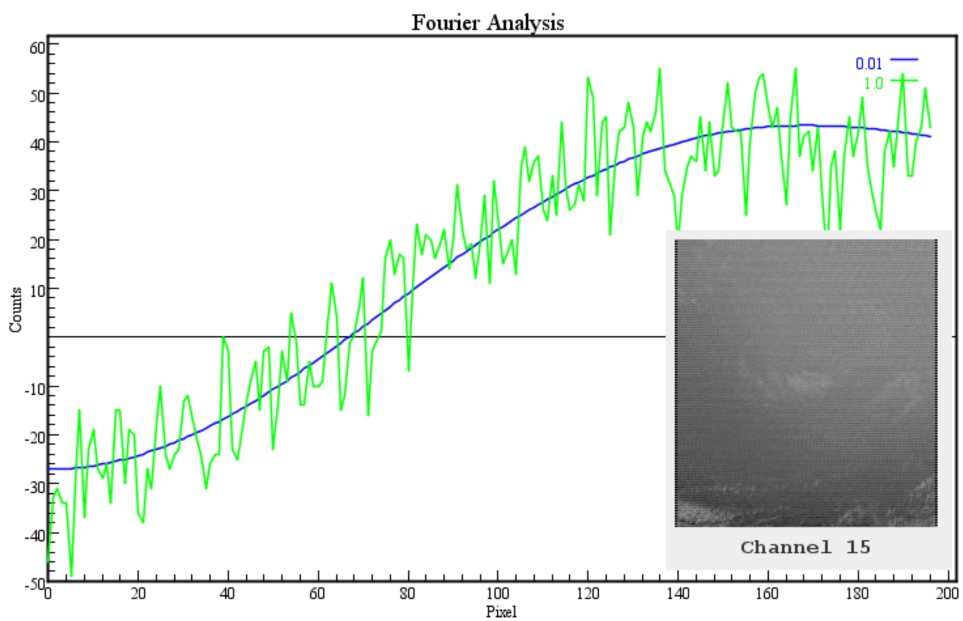
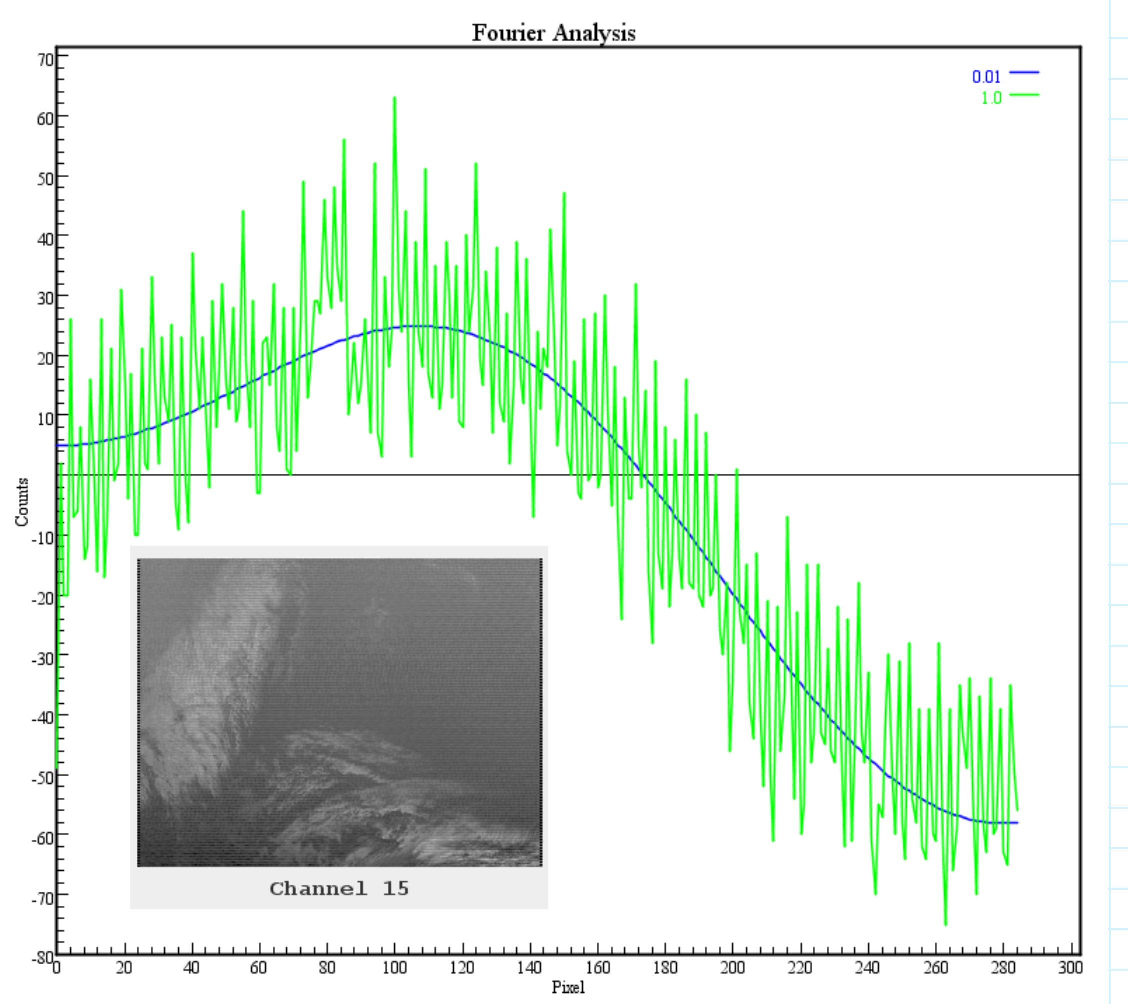
The offset functions for the actual images: Pacific Coast



- The green line is the offset function.
- The blue line is the D2D component of the offset.
- The width of the image is about 200, and the size N used in the formula is 512 when FFT is used. the cutoff k=5.
- The offset function more or less remain the same for the whole image, except some fluctuation in the local area.

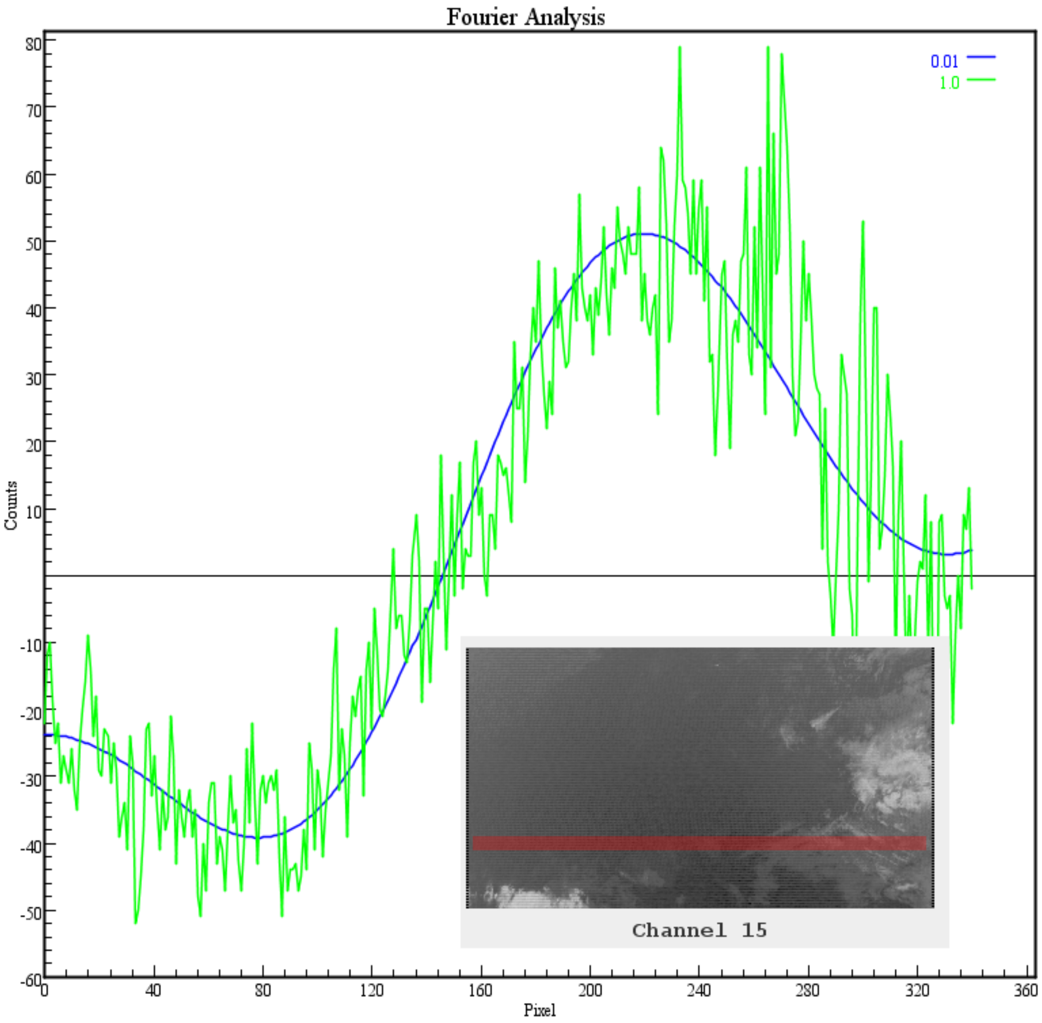
The Offset Function for Northern Pacific

- The size N used in the formula is 1024, and the cutoff k=11.



The Offset Function for Hawaii region

- The size N=1024, and the cutoff =11.
- The D2D component is very stable for the whole image.



D2D de-Striping Algorithm

- The algorithm has the following steps:
  - For each scan:
    - Calculate the offset function
    - Extract the D2D component from the offset function.
    - Subtract the D2D component of the offset from det1 and 3
    - Add the D2D component of the offset to det 2 and 4.
  - The corrected GVAR counts for each detector is

$$G^{C}_{1,3}(x) = G_{1,3}(x) - f^{D2D}(x)$$

$$G^{C}_{2,4}(x) = G_{2,4}(x) + f^{D2D}(x)$$

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S2S Striping Correction

- The S2S striping is time dependent, but location independent.
- The value of a pixel at coordinate x is

$$G_{i,d}^{d}(x) = G_{i,d}(x) + g_{i,d}^{S2S}$$

- Taking the average:

$$\frac{1}{N_{i,d}} \sum_{x} G_{i,d}^{d}(x) = \frac{1}{N_{i,d}} \left(\sum_{x} G_{i,d}(x) + \sum_{x} g_{i,d}^{S2S} \right)$$

$$g_{i,d}^{S2S} = M_{i,d}^{d} - M_{i,d}$$

- The $M_{i,d}^{d}$ is the mean value for lines with detector d and scan direction *i*, $M_{i,d}$ is mean value of the corrected data.
- Assuming the mean value for the whole image does not change before and after correction.

$$g_{i,d}^{S2S} = M_{i,d}^{d} - M$$

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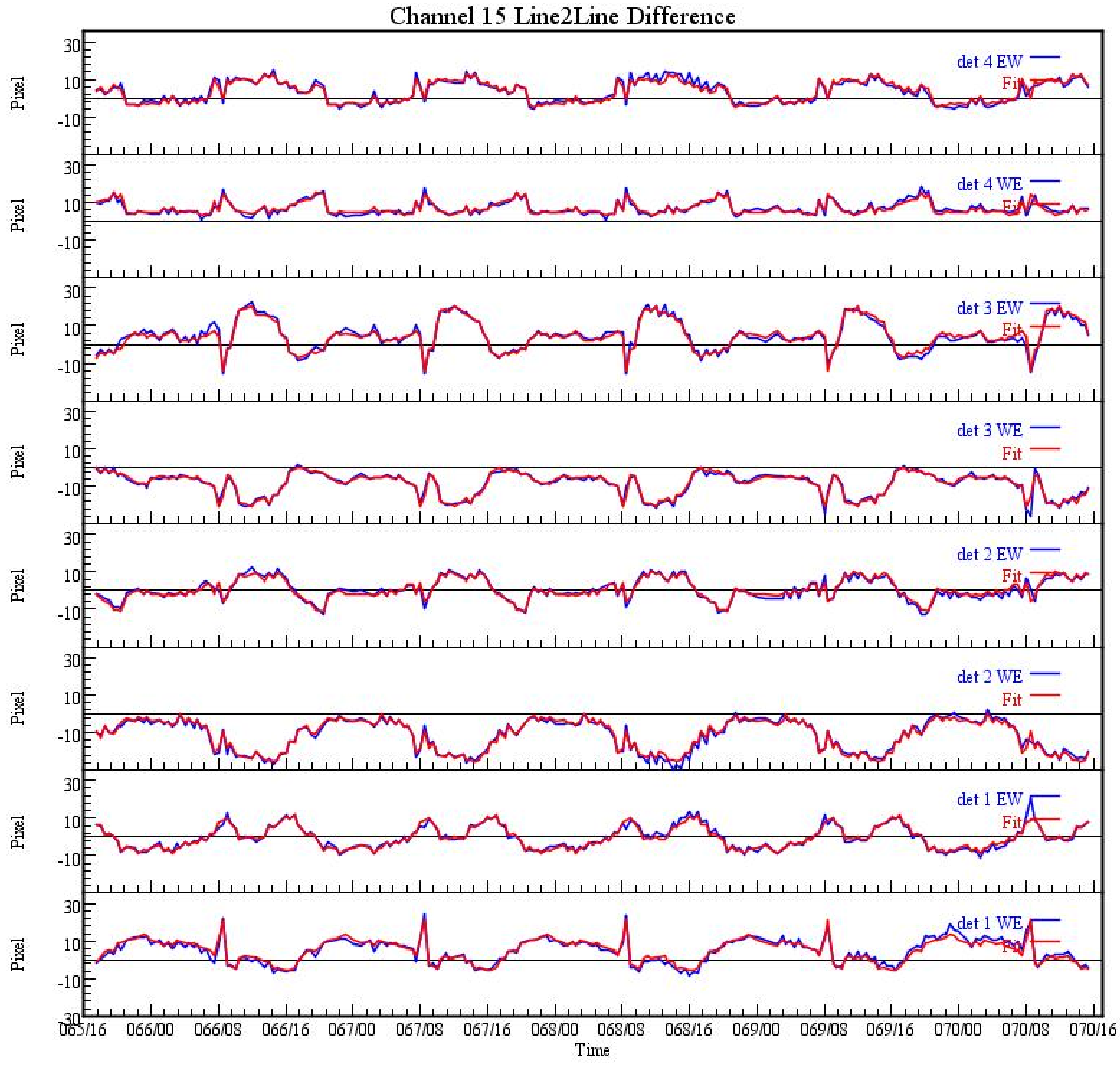
The offset value

- Stable from day to day for each image.
- The implementation of the offset values is a 8x48 array, which represents the 47 images for a given day.
  - The first index represents the detector ID plus the scan direction
  - The second index corresponds to the image time, about one in every half hour.
  - The values for each element is the average of the five images during the 2 day period.
- The detector 2 in WE direction has the largest offset value.
- The offset value for the current image is the average of the previous 2 days:

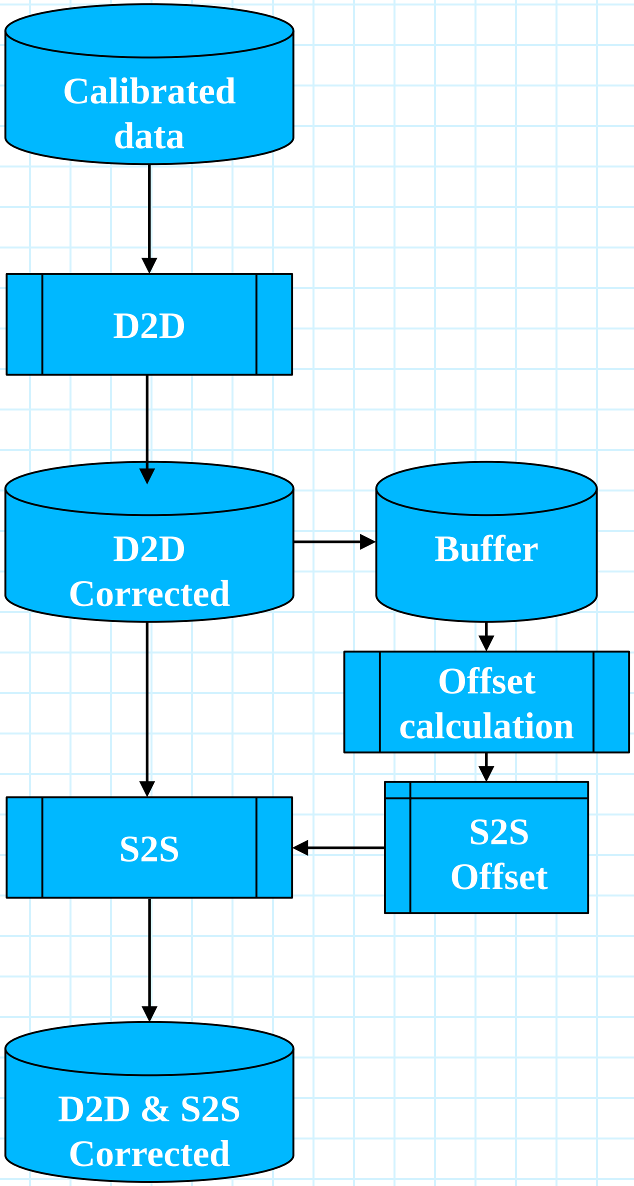
$$g_{i,d}^{Sd}\left(t_j\right) = \frac{1}{2}\left(g_{i,d}^{Sd}(t_j - T_0) + g_{i,d}^{Sd}(t_j - 2T_0)\right)$$

The Offset Value: stable from one day to the next

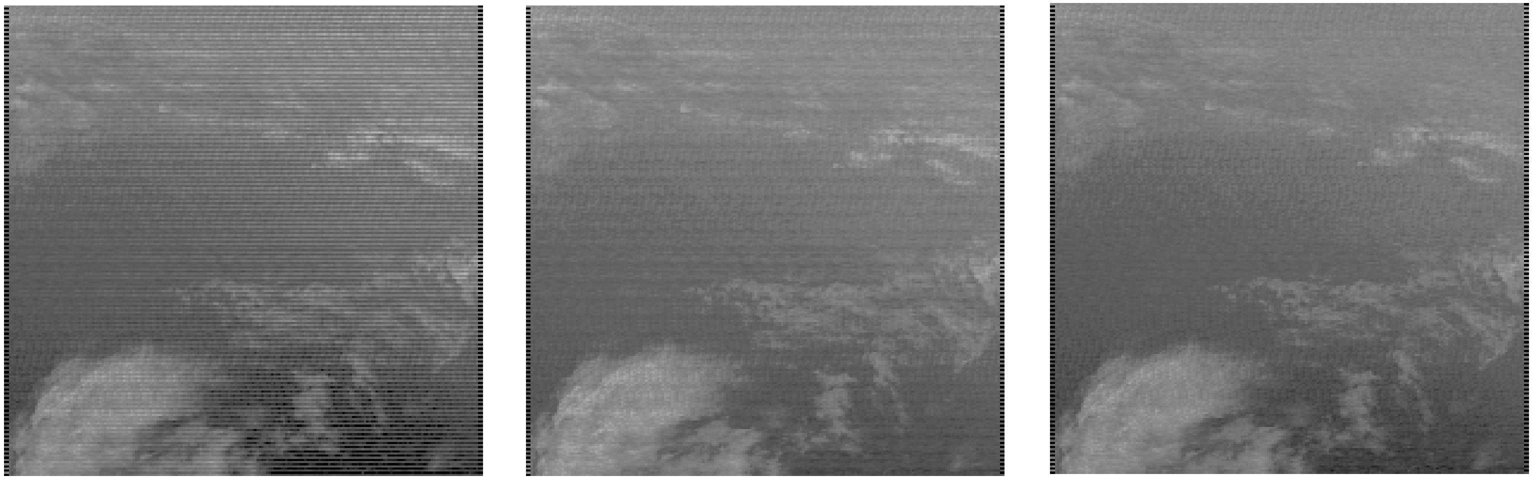


D2D and S2S combined de-striping algorithm

1. Retrieving the offset function from the scan data.
2. Calculate the Fourier spectrum of the offset function
3. Obtain the D2D striping function.
4. Apply the D2D striping correction
5. Collecting the data for each detector and scan direction for the scan used to calculate the mean values
6. Apply the effective S2S correction by subtracting the mean offset value from previous 2 days from the D2D striping corrected data.
7. At the end of each Sounder image, calculate the mean offset values of the image to obtain the effective S2S striping term and store it in a buffer to be used for the image next day in the same time.



The typical result:



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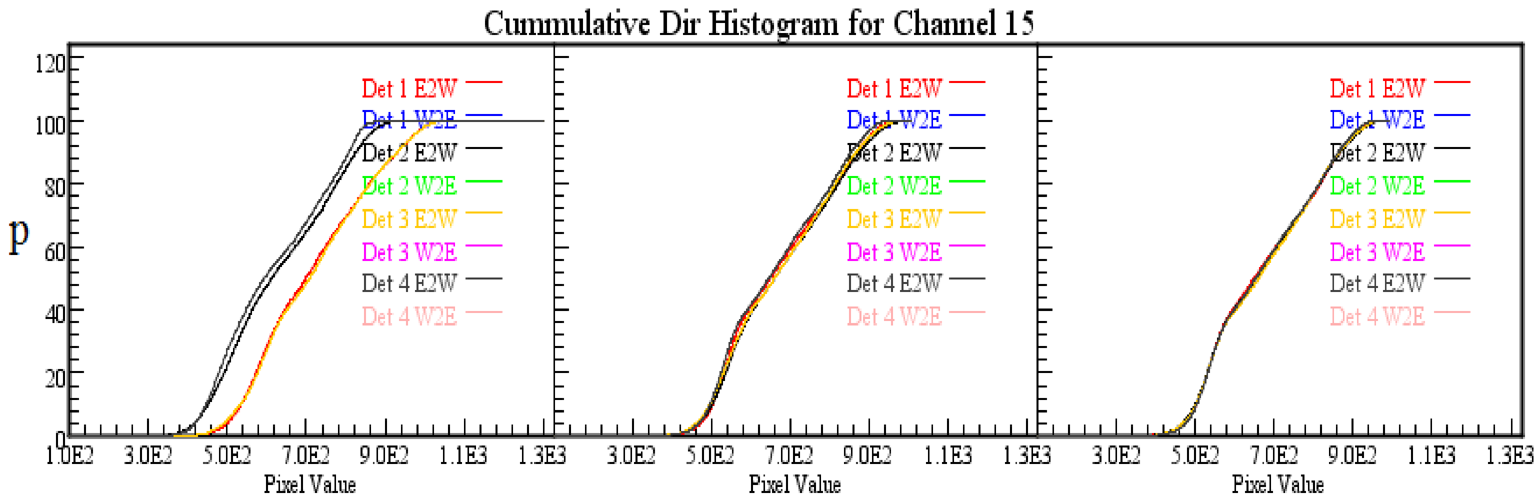

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GOES Ground System Implementation

- The De-Striping algorithm is implemented in the Sensor Processing System (SPS) in GOES ground system for the real time de-striping.
  - Receives the GOES Instrument data (both Imager and Sounder), performs the calibration and image navigations.
  - Pack the calibrated and navigated data into GVAR and rebroadcast by GOES to users.
- The de-striping process is invoked after the scan data are calibrated, and before the data are packed into GVAR block.
- Only the data in channel 15 are striping corrected.
- The GVAR Sounder block for GOES contains the striping corrected data for channel 15 data.
  - The raw (un-calibrated) data are also in the GVAR block.
- No impact on the latency requirement.
  - Moving the SPS to the new Blade server helped great deal.