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On-orbit characterization of the GOES Imager channel-to-channel co-registration

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ABSTRACT

The channel-to-channel co-registration of a satellite imaging system is an important performance metric that has a direct impact upon the reliability of the imager's quantitatively-derived products. In this work, standard full-disk image data is used to measure the on-orbit channel-to-channel co-registration of the infrared channels of several GOES Imagers at a sub-pixel level. This is accomplished with two separate methods, one of which furthers preliminary research by Wu et. al.[1] using GOES-8 and 9 spatial-spectral brightness temperature gradients, the other of which uses a statistical approach. The diurnal, seasonal, and long-term co-registration behavior is analyzed.

Keywords: Co-registration, channel-to-channel, band-to-band, registration, GOES, ABI, on-orbit, PLT

1. INTRODUCTION

The next generation of geostationary satellites operated by the National Oceanic and Atmospheric Administration (NOAA), the Geostationary Operational Environmental Satellite R-Series (GOES-R), will host a suite of instruments with improved capability for monitoring the Earth and its surrounding space environment (including the Sun). One such instrument, the Advanced Baseline Imager (ABI), represents a marked improvement over the current GOES Imager in nearly every respect, including spatial resolution, the number of spectral channels, and image acquisition time[2]. Utilizing these new capabilities, NOAA will release quantitative products derived from ABI images to be used for weather forecasting and climate applications, as well as other applications like monitoring the cyrosphere, ocean, and hazards. Some examples of the 25 "baseline" products are "Cloud Top Pressure", "Sea Surface Temperature", "Clear Sky Masks", and "Hurricane Intensity Estimation"[3].

To generate a given product, NOAA will often combine data from some of the 16 separate spectral channels of the ABI. An underlying assumption is that the channels are properly co-registered, so that a pixel from one channel can be properly matched to a corresponding pixel from another channel. If the channels are not properly co-registered then the accuracy of the quantitative products will be compromised. In addition, organizations using ABI data for scientific or other purposes may depend upon proper channel-to-channel co-registration. For these reasons, the Center for Satellite Applications and Research (STAR) of the National Environmental Satellite, Data, and Information Service (NESDIS) within NOAA is developing a software tool that will characterize the on-orbit channel-to-channel co-registration of the ABI.

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The ABI data will be remapped before distribution. This concept is similar to that used for GOES-SA (South America), where the image is remapped to a ‘perfect projection’ before GVAR is disseminated[4]. The current GOES-East and West Imager data, however, are not remapped, and therefore the quantitative products derived from these instruments depends on proper co-registration even more so than those from the ABI. For this reason, there is a performance specification that “at any scan location the relative positions of the centroids of the infrared imaging IGFOVs shall be within a circle of 28 μrad radius under dynamic (active scan) conditions”[5]. Note that the pixel (IGFOV) size for most of the infrared channels is 112 μrad, and that there is a 1.75:1 oversampling factor in the East-West direction, resulting in an 64 μrad pixel center-to-pixel center distance in that direction. At the sub-satellite point, 28 μrad equates to 1 km. Due to this specification, no two channels should have registration error that exceeds 56 μrad - the diameter of a 28 μrad circle - when including both the East-West and North-South offsets.

On May 16, 2012, the Cooperative Institute for Meteorological Satellite Studies (CIMSS) of the Space Science and Engineering Center (SSEC) at the University of Wisconsin-Madison, along with the NOAA NESDIS group co-located there, reported that co-registration error between GOES-13 Imager Channel 4 (10.7 μm) and Channel 2 (3.9 μm) was causing erroneous output from a fog product. Their qualitative analysis indicated a co-registration error in the East-West direction of approximately one image pixel (64 μrad). To validate this finding and examine whether other situations also exhibited out-of-specification behavior, the ABI co-registration tool was applied to on-orbit data from GOES-13 and other GOES Imagers. This also presented an opportunity to evaluate the effectiveness of the tool using proxy data.

The objective of this study is to characterize the co-registration error of GOES-13 Imager Channel 4 to Channel 2 in the East-West direction and validate the Wisconsin finding. Also, the day-to-day variation in co-registration error over a 26 day period is used for the purpose of uncertainty estimation. The characterization is then applied to the North-South direction, to other infrared channel pairs, and to Imagers on other GOES. Finally, the seasonal and long-term variations in co-registration error are also analyzed.

2. METHODOLOGY

2.1 Spatial-spectral brightness temperature gradients

Wu et al.[1] developed a means by which to use the brightness temperature conversions of two separate channels to determine whether the channels are mis-registered. Consider the geometry depicted in Figure 1. In a situation where two channels are perfectly registered, a given “Channel B” pixel would align perfectly with its corresponding “Channel A” pixel. If the channels are not perfectly registered, however, as is the case in the figure, the “Channel B” pixel will somewhat overlap “Channel A” pixels other than that of the center. For the example in Figure 1, the overlapped pixels would be those to the North, North-East, and East.

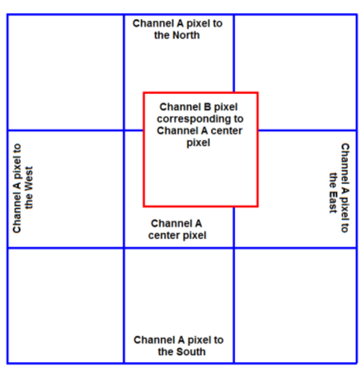


Figure 1. Geometry of mis-aligned imager channels.

The method uses brightness temperature gradients following the conversion of all pixel radiances to brightness temperature using the Planck Function (the accuracy of this conversion is discussed later). Spatial gradients are measured within a channel between a given pixel and any of its neighbors. Spectral gradients are measured between corresponding pixels of the two channels of interest. If there is mis-registration, there will be some correlation between the spectral gradients and some of the spatial ones. Again considering the geometry in Figure 1, we would expect correlation between the spectral brightness temperature gradient and the spatial brightness temperature gradients to the North, North-East, and East.

Mis-registration can be identified using spatial versus spectral brightness temperature gradient histograms like those shown in Figure 2, assembled from radiance data of several images. The bin size used is one degree Kelvin spatially by one degree Kelvin spectrally, and the direction of the spatial gradient is indicated above each plot. A greater number of occurrences corresponds to a lighter shade, and the shades differ logarithmically, with the darkest shade representing counts from 1-10, the next from 11-100, and so on. The inaccuracy in the radiance-to-brightness temperature conversion is evidenced by the high number of occurrences with a large magnitude of spectral gradient but much smaller spatial gradient. This is expected, since the separate channels are designed to detect physical interactions by way of including or excluding spectral absorption regions. If the measured radiance from each channel were a perfect measure of temperature, there would be no value in using separate channels.

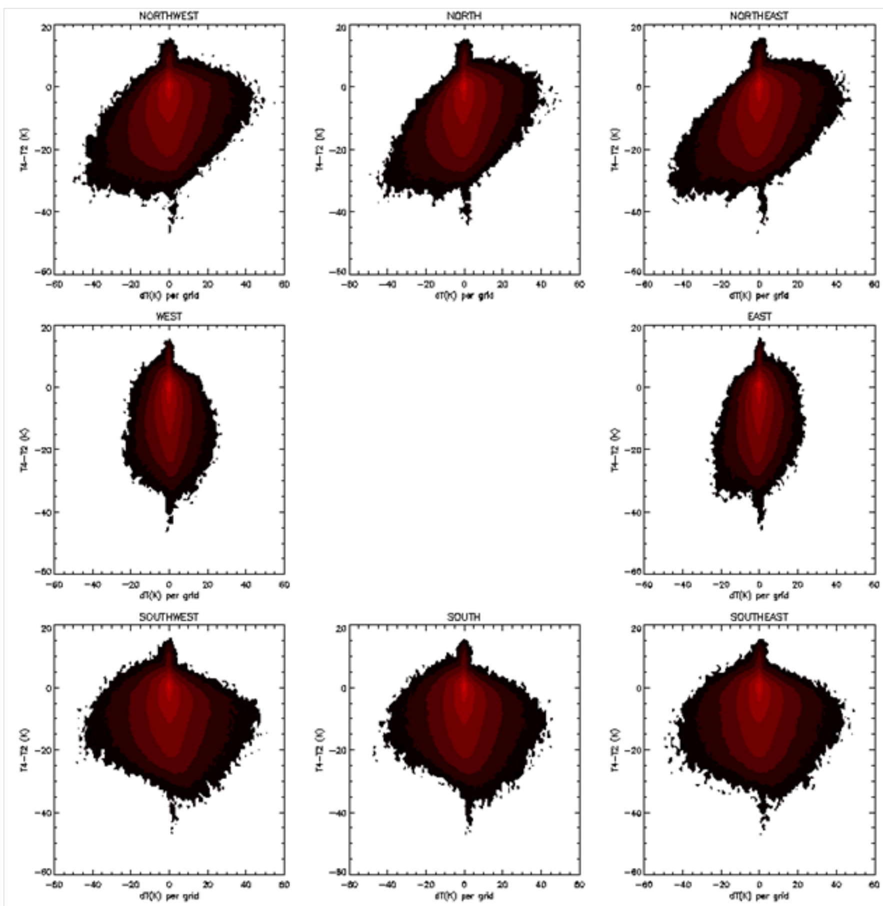


Figure 2. Two-Dimensional histograms of spatial versus spectral brightness temperature gradients between Channel 2 and 4 of the GOES-13 Imager, assembled from 9 images acquired between April 29th, 2011 and June 9th, 2011. The x-axis represents the spatial gradient and the y-axis represents the spectral gradient. Brighter shades indicate a greater number of points using a base-10 logarithmic scale.

Most of the histograms do not indicate any spatial-spectral correlation, as there is reflective symmetry about the y-axis and a positive spectral gradient is as likely to be matched to a negative spatial gradient as a positive one (likewise for a negative spectral gradient). However, in looking at the "Northwest", "North", and "Northeast" plots, the darkest shades do show a spectral-spatial correlation, as evidenced by the "slanted" orientation. In these regions, a positive spectral gradient is more likely to be matched to a positive spatial gradient (likewise negative spectral gradient to negative spatial gradient). Thus we can conclude that there is a mis-registration to the North and East.

2.2 Use of spatial interpolation to "fix" co-registration error

The Wu et al.[1] spectral versus spatial gradient analysis presented thus far can identify the existence and direction of mis-registration, but our goal is to characterize it. To do so, we assume that the more poorly registered two channels are, the more they will show spectral-spatial brightness temperature gradient correlation ("slant") in some direction. Channels that are very well registered will show no such correlation. Obviously, we only have the nominal images from the two channels, not the images that would result had they been registered differently. But we can still *guess* at what those images might be by using simple linear interpolation. In the example shown in Figure 2, we might try to better align the channels by interpolating the Channel 4 radiance data to the South.

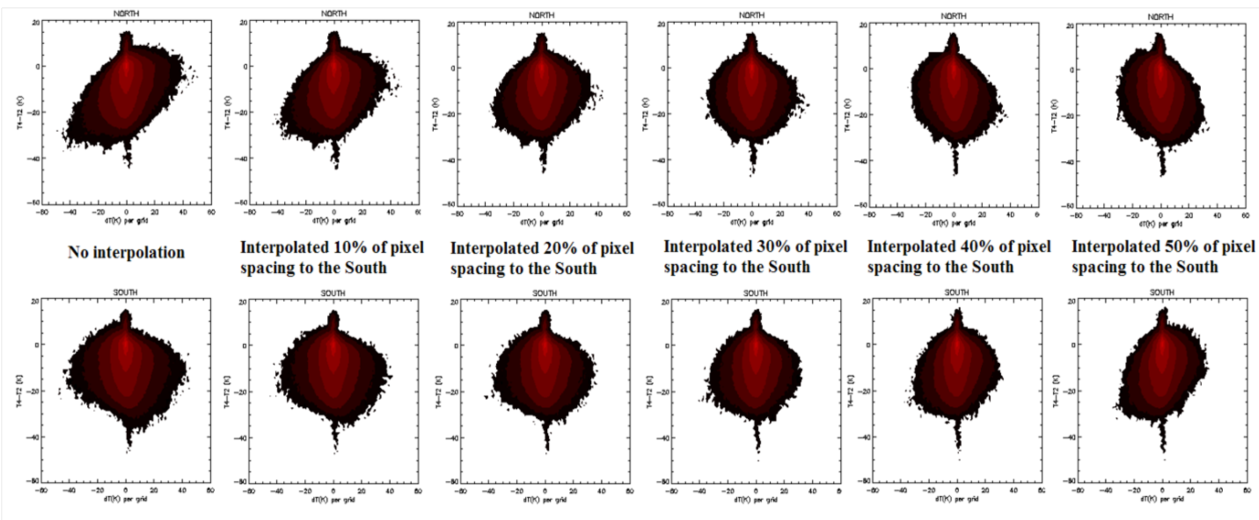
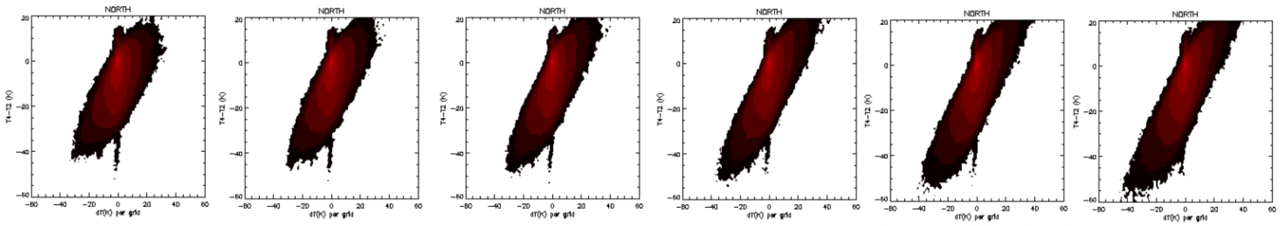


Figure 3. North (upper) and South (lower) spatial versus spectral gradient histogram plots for various levels of pixel interpolation to the South. The input data are the same as used to generate Figure 2.

Figure 3 shows North (upper) and South (lower) spatial versus spectral gradient histogram plots using the same data shown in Figure 2 but spatially interpolated to certain distances to the South. At an interpolation distance of 30% of the pixel center spacing, the North spatial versus spectral gradient histogram plot seems to stop showing a spatial-spectral correlation, indicating proper co-registration. As the interpolated distance increases from 30% to the South, the South spatial versus spectral gradient plots (the bottom row) begin showing a spatial-spectral correlation as the mis-registration correction has been over-compensated. This motivates the general procedure to co-registration characterization: spatially interpolate to find the point that indicates the greatest degree of co-registration. Note that this distance is opposite to that of the co-registration error. Also, because of the non-linearity in brightness temperature versus instrument output, the spatial interpolation for each position is performed using radiance, which is followed by conversion to brightness temperature.



Interpolated 50% of pixel spacing to the North | **Interpolated 60% of pixel spacing to the North** | **Interpolated 70% of pixel spacing to the North** | **Interpolated 80% of pixel spacing to the North** | **Interpolated 90% of pixel spacing to the North** | **Interpolated 100% of pixel spacing to the North**

Figure 4. North spatial versus spectral gradient histogram plots for various levels of interpolation to the North. The input data are the same as used to generate Figure 2.

The concept of using interpolation to find the point of co-registration can also be inverted. If interpolating ~30% to the South causes proper registration, then interpolating ~70% to the North should cause the Channel 4 pixels to correlate highly with the Channel 2 pixel to the North (very poor co-registration). The North histogram plots for that scenario are shown in Figure 4. Beyond approximately 70% to 80% of interpolation to the North, the data in the North plots grow "wider", and are therefore less correlated, indicating over-compensation.

2.3 Co-registration characterization methods

The co-registration validation tool developed for the ABI can employ either of two methodologies. These are labeled the "Linear Fit" and "Statistical Correlation" methods.

2.3.1 The "Linear Fit" method

It is still necessary to be able to quantify the spatial-spectral correlation so that the co-registration can be characterized. The "Linear Fit" method works under the assumption that a greater degree of spatial-spectral correlation will result in the 2-D histogram data fitting better statistically to a 1:1 spatial-spectral brightness temperature gradient line. To quantify the correlation, the data are regression-fit (though neither the y-intercept nor slope is allowed to change) to the 1:1 spatial-spectral brightness temperature gradient line, and the chi-squared goodness-of-fit statistical value is measured. A greater chi-squared value indicates that the data correlate less with the 1:1 line. Therefore, a greater chi-squared value indicates a smaller spatial-spectral gradient correlation, and a *greater* degree of channel-to-channel registration. Note that it is not the absolute chi-squared value that is important per-se, but how the value changes for different levels of spatial interpolation – the interpolation that yields the highest value indicates the point at which the channels are best-registered.

If it is desired to measure the North-South co-registration, both the North and South spatial-spectral brightness temperature gradient plots are created at each level of spatial interpolation along with their associated chi-squared value, and the smaller of the chi-squared value between the two is output. Therefore, at each interpolated position, the direction for which the data best correlate is used, and over-compensation will be appropriately handled. The East and West direction is treated in the same manner (because the GOES Imager operates differently between the North-South and East-West directions, a direct 2-dimensional co-registration characterization using the "Linear Fit" method is not possible, so the North-South and East-West directions must be analyzed separately). Finally, every data point input is set either to value of zero, indicating that there were no occurrences within the histogram bin, or one, indicating at least one occurrence within the bin. This increases the emphasis on those bins with small occurrences, which are also the bins that best indicate the spatial-spectral gradient correlation, as seen in Figure 2.

There is one element of the procedure not yet mentioned, which is to "scramble" the data prior to any spatial interpolation. This step will be best understood later in the paper, so at this point it is merely mentioned.

2.3.2 The "Statistical Correlation" method

Co-registration characterization using the "Linear Fit" method can be computationally intensive, so another method that does not involve spatial-spectral gradients has been devised. Also, because the "Linear Fit" method is novel with no obvious means for validation, it is beneficial to have another dissimilar means for co-registration characterization. Should the two produce similar results then they effectively validate each other.

The "Statistical Correlation" Method also begins with data "scrambling" (to be explained in the next section), and then uses spatially linearly-interpolated radiances followed by conversion to brightness temperature to "fix" the co-registration error. However, instead of calculating spatial-spectral brightness temperature gradients, the two channels are compared at each interpolation point using a sample Pearson correlation coefficient. In this way, proper co-registration of the channels is found similar to using cross-correlation, where one channel has been converted to a high-resolution grid using interpolation.

The "Statistical Correlation" method is not unlike the work of other researchers[6]. However, that work did not convert to brightness temperature or use data "scrambling", and used Fourier zero-padding to create the high-resolution grid, whereas this study uses linear interpolation. This is intentional. Any interpolation other than a linear one will involve pixels not immediately surrounding each interpolation point, and since the point-spread function does not typically extend beyond a few pixels with any meaningful magnitude, this study considers only the nearest pixels. With that understanding, it is acknowledged that other interpolation schemes, including Fourier zero-padding, might be useful, especially considering that using linear interpolation decreases spatial variability. One interpolation scheme that might be pursued in future work is a polynomial fit using point-spread function (PSF)-value weighting.

In addition to the superior computation speed, this method has an advantage over the "Linear Fit" one in that it can be performed directly in two dimensions. The "Linear Fit" method cannot do so because the GOES Imager spatial gradients are generally smaller in the East-West direction than North-South. This is due to both East-West oversampling and differences in the East-West and North-South Modulation Transfer Functions (MTFs). This causes the spatial-spectral correlation "baseline" to be different East-West than it is North-South. Since the "Statistical Correlation" method does not use gradients, instead comparing each interpolated point directly with the other channel, the difference between the East-West and North-South imaging is unimportant. The point of proper co-registration can be found using a 2-dimensional bilinear interpolation. This is not to say, however, that the uncertainty will be the same in the two directions, as oversampling and differences in the MTF are expected to cause the East-West uncertainty to be greater.

2.4 Data "scrambling": intentionally introducing interpolation error

If the "Statistical Correlation" method is applied without the data "scrambling" step, a plot of the result will look similar to that seen in Figure 5. The maximum correlation coefficient and therefore the measurement of co-registration error (or more exactly, the displacement needed to "fix" the error) is clearly visible at 0.34 IR pixel widths (34% of the infrared pixel size). However, there are "kinks" – points where the correlation coefficient slope becomes discontinuous – at the -1.00, 0.00, and 1.00 IR pixel width positions. What these points have in common is that they are at integer multiples of the IR pixel width, and therefore *no interpolation error was introduced at these points* (the interpolation was "perfect"). This highlights a systematic error. The algorithm uses interpolated points, and, in general, the amount of error introduced from the interpolation will be greatest at those positions that are farthest from the nominal pixel positions, and smallest at those positions that are closer. In this particular example, the existence of these "kinks" is not too disturbing, as the point of co-registration is well-defined and distinct from the other features. Should the point of co-registration happen to lie near a "kink", though, its proper value might be obscured.

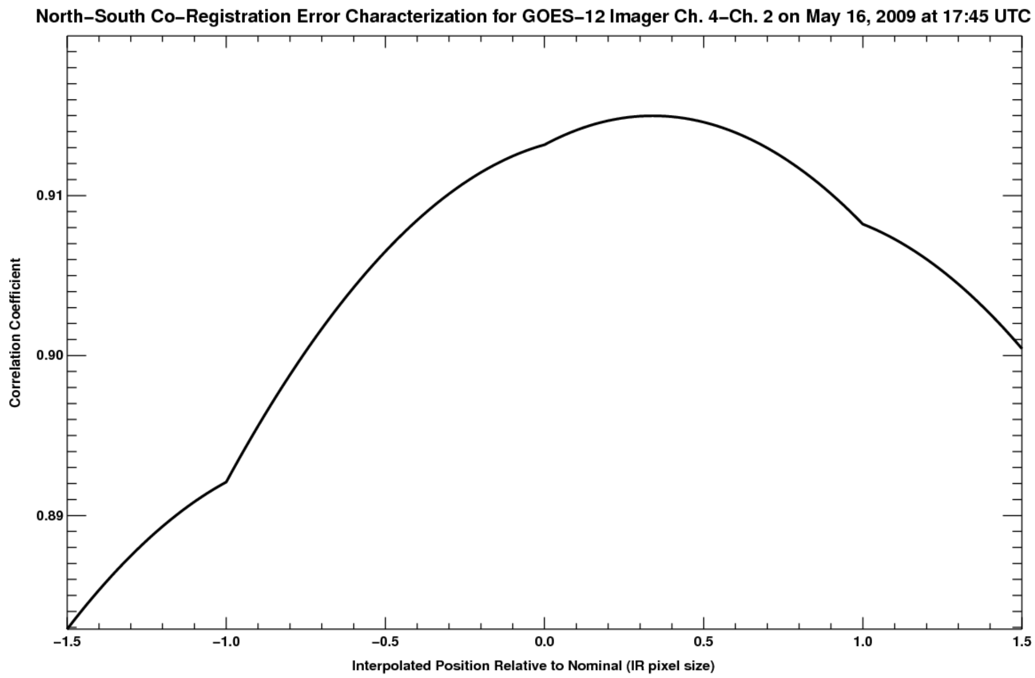


Figure 5. Co-registration characterization plot for GOES-12 Imager Channel 4 relative to Channel 2 on May 16, 2009 at 17:45 UTC.

We cannot remove the varying interpolation error (or, at least, we don't know how). We can, however, *introduce* error such that each interpolated point will have a similar amount of interpolation error. To do so, we "scramble" the data, as shown in Figure 6. After the necessary imagery is acquired and before the process of characterization, the image that will be shifted to statistically match the other is spatially interpolated several times in several directions, but eventually interpolated back to its nominal position. This process is non-reversible, so the resulting image is not the same as the original. Now, each "test" point for co-registration characterization will carry a similar amount of interpolation error. For instance, if the data "scrambling" covers a distance of 6 pixel widths, then "test" points of -0.10, 0.00, 0.10, 0.20, will have been interpolated a total distance of 6.10, 6.00, 6.10, and 6.20 pixel widths, instead of 0.10, 0.00, 0.10, and 0.20 pixel widths had there not been any scrambling.

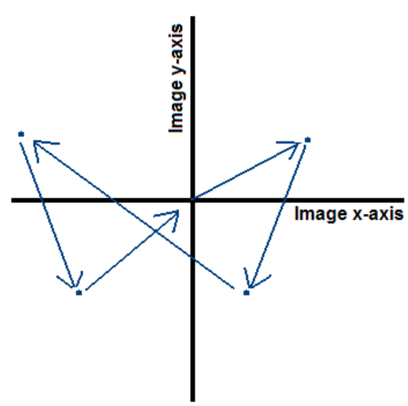


Figure 6. Diagram showing the data "scrambling" process.

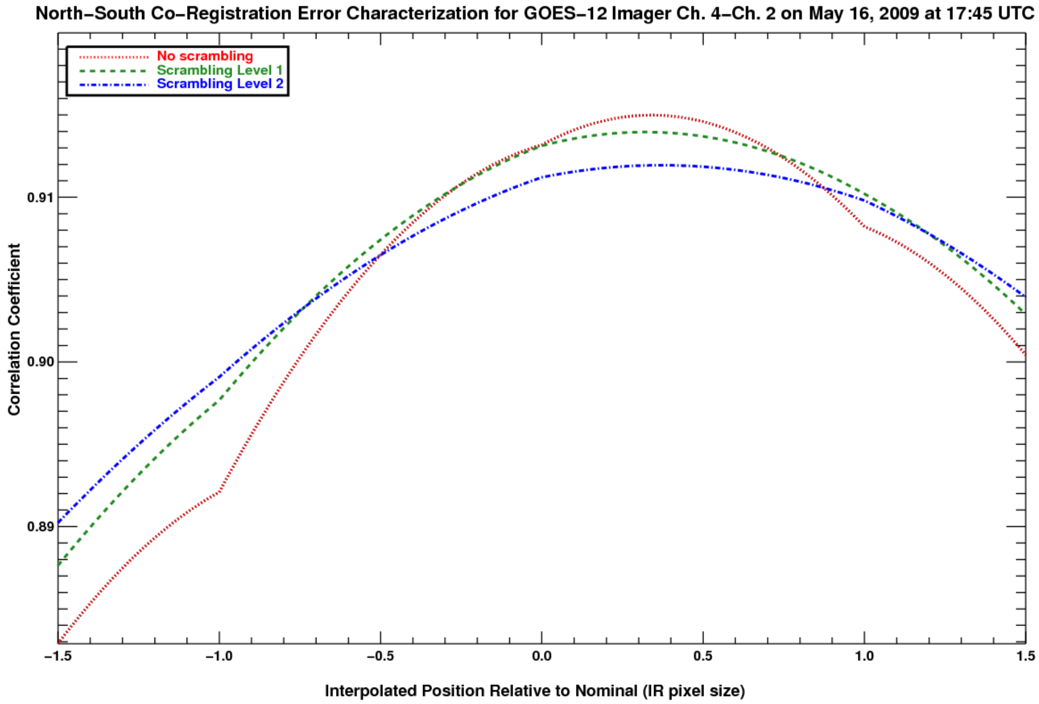


Figure 7. Effect of scrambling on co-registration characterization for GOES-12 Imager Channel 4 relative to Channel 2 on May 16, 2009 at 17:45 UTC. The "Level 1" scrambling corresponds to a total distance of 5.94 IR pixel widths, and "Level 2" corresponds to a total distance of 13.19 pixel widths.

There is a trade-off when implementing data scrambling. As the data are interpolated greater distances, the variability in the image decreases (this is especially troublesome for the "Linear Fit" method). The effect is seen in Figure 7. As desired, the "scrambling" clearly reduces the "kinks" seen at the -1.00, 0.00, 1.00 interpolated positions. However, greater scrambling also "flattens" the correlation coefficient curve, making the point of co-registration less distinct. In this example, the point of co-registration measurement changes little, from 0.34 with no scrambling, 0.32 with Level 1 scrambling, and 0.36 with Level 2 scrambling. The data used to produce the results shown in the remainder of the paper were scrambled to level 1 (5.94 IR pixel widths).

3. RESULTS AND DISCUSSION

3.1 Methodology validation and error estimation

Both the "Linear Fit" and "Statistical Correlation" methods have novel components. While their motivation may seem logical, a validation that the methods produce reasonable results is needed. While there is little previous work to which to compare, the results from the methodologies presented in this paper can be compared to each other. This is reasonable because they use largely different techniques for characterization. A time series of GOES-13 Imager Channel 2 to Channel 4 co-registration characterization results for 27 consecutive days using data from the same time of day from both the "Linear fit" and "Statistical Correlation" methods is shown in Figure 8. The regression fit results from the two methods agree to within about 8%.

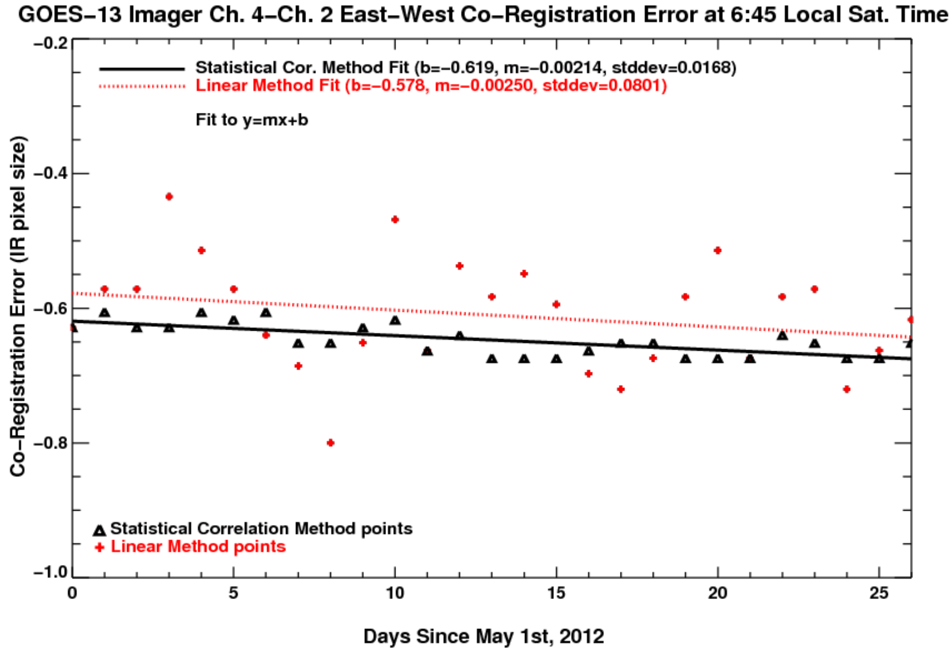


Figure 8. GOES-13 Imager Channel 2 to Channel 4 East-West co-registration error results generated by "Statistical Correlation" and "Linear Fit" methods from full disk data at 6:45 local time for 27 consecutive days beginning May 1st, 2012.

When CIMSS discovered the erroneous GOES-13 Imager fog product, they demonstrated that it was due to co-registration error by comparing spatial features appearing in both the Channel 2 and 4 images. (They also demonstrated using other sensors, such as MODIS or AVHRR which did not exhibit the larger band differences.) These features were shifted by one pixel in the East-West direction between Channel 2 and 4. This indicated a co-registration error of approximately one image pixel. Further validation of the "Statistical Correlation" method was achieved by quantifying the error in the CIMSS comparison images and verifying that it was indeed approximately one pixel. Likewise, images for which the "Statistical Correlation" method characterized the error as small were visually inspected to verify that spatial features between the two channels were not shifted.

There is an important technical point that needs to be addressed. When the GOES Imager acquires an image, it oversamples in the East-West direction, causing the distance in that direction between neighboring image pixel centers to be smaller than the physical size of those pixels. Put another way, neighboring pixels "overlap". Therefore, a shift in a spatial feature of approximately one *image* pixel in the East-West direction actually corresponds to an error of 1.00/1.75 = 0.57 pixels in terms of physical size (1.75 is the oversampling factor). Since the GOES-13 Imager IR pixel size (except for Channel 6) is 112 µrad, an East-West error of one *image* pixel physically equates to 112/1.75=64 µrad.

Table 1. Co-registration characterization "Statistical Correlation" Method error estimates using both GOES-12 and GOES-13 Imager data.

	Error Estimate (IR pixel size)			
	-------GOES-12-------		-------GOES-13-------	
Channel Pair	East-West	North-South	East-West	North-South
Channel 3 to Channel 2	0.051	0.082	0.025	0.081
Channel 4 to Channel 2	0.030	0.051	0.017	0.046
Channel 6 to Channel 2	0.040	0.058	0.022	0.069

Returning to Figure 8, the data suggest a fairly good linear fit, so the standard deviation of the residuals provides a reasonable estimation of error. In actuality, the residual data show a potential sinusoidal-like pattern, so a simple linear fit may overestimate the error. From the residuals, the estimated error of the “Statistical Correlation” method is 0.029 in IR pixel size, and the estimated error of the “Linear Fit” method is 0.140 in IR pixel size. The “Statistical Correlation” method has the least error and is also the least computationally intensive, so it was used for all the co-registration characterization results presented later in this paper. It was applied to the data from all IR channel pairs at the same times as the data points in Figure 8 for both GOES-13 and 12 Imagers. The estimated error results are found in Table 1. Strangely, the East-West estimated errors are smaller than the North-South. Because of MTF effects and oversampling, it was expected that the opposite would be true. This discrepancy will be examined in the future.

3.2 Diurnal variation

Figure 9 shows the diurnal pattern in the Channel 4 to Channel 2 Co-Registration error in both the East-West and North-South directions for the GOES-8, 9, 10, 11, 12, 13, and 15 Imager on DOY 136-137. The CIMSS estimation that the GOES-13 Imager East-West Channel 4 to Channel 2 co-registration error is as large as 1 image pixel is validated in the plot, recalling that the largest magnitude in GOES-13 Imager East-West error of approximately 0.7 *IR pixel sizes* corresponds to approximately 1.2 *image* pixels in distance. While the GOES-13 Imager East-West co-registration error is the largest, historical data show large errors for previous GOES Imagers as well.

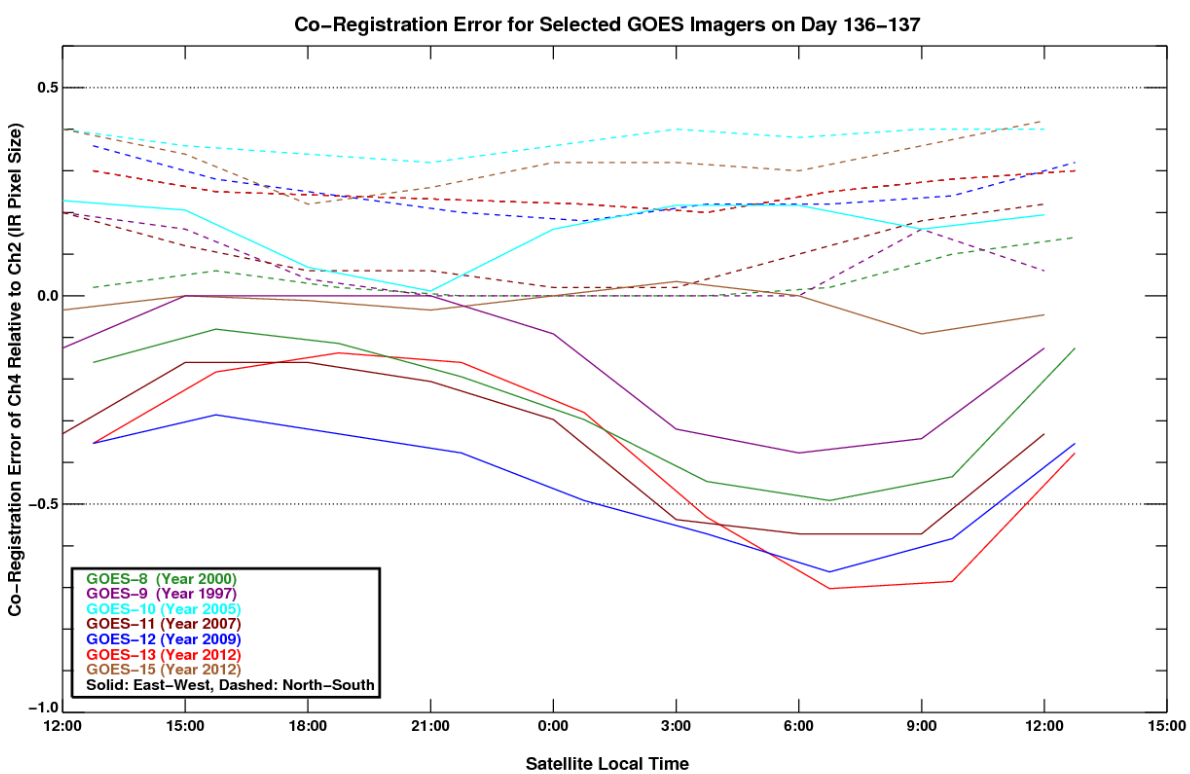


Figure 9. East-West and North-South co-registration error diurnal pattern results for DOY 136-137 for GOES-8, 9, 10, 11, 12, 13, and 15 Imagers. Points beyond the -0.5, 0.5 straight dotted lines indicate co-registration error that is definitely exceeding the performance specification. Other points may also indicate out-of-specification behavior when the East-West and North-South directions are considered in concert.

The co-registration error requirement specification states that “at any scan location the relative positions of the centroids of the infrared imaging IGFOVs shall be within a circle of 28 µrad radius under dynamic (active scan) conditions”[5].

Because the requirement does not indicate any particular direction, determining whether the co-registration error exceeds specification should consider both the East-West and North-South direction in concert. Therefore, if a given point in Figure 9 is within the specification lines shown, the overall error may still exceed specification. On the other hand, if a point is outside the specification lines then the overall error definitely exceeds specification. Several of the GOES Imagers plotted in Figure 9 exceeded specification at least some of the time.

The strong sinusoidal pattern in the East-West direction for most of the GOES Imagers is suggestive of an underlying diurnal temperature fluctuation cause, although more work is needed to be conclusive. The repeated pattern between imagers is also a further validation of the co-registration characterization methodology, as is the near-equality of the datapoints at the beginning and end of the 24-hour cycles. It is interesting to note that the Imagers that do not exhibit the strong East-West pattern also have the lowest overall error. In the North-South direction, the overall variation is generally much smaller, with less of a pattern. There appears to be no strong correlation in an Imager's overall co-registration error between the East-West and North-South directions.

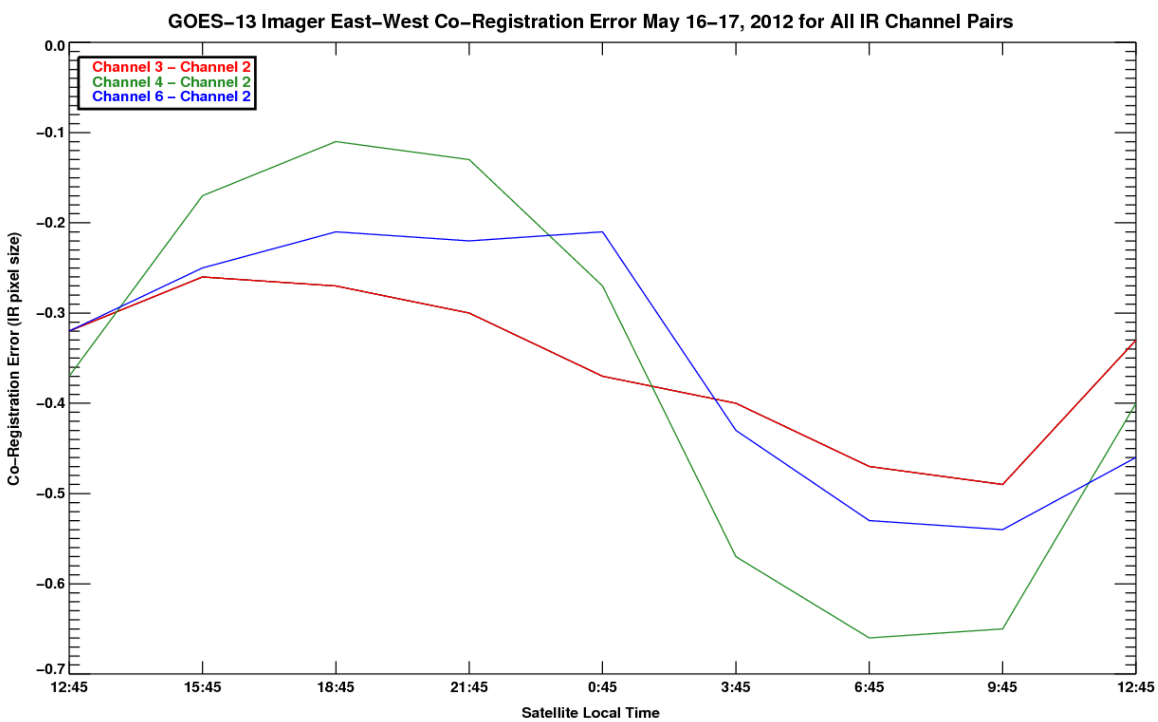


Figure 10. GOES-13 Imager East-West co-registration Error for all IR channels: Channel 2 (3.9 µm), Channel 3 (6.5 µm), Channel 4 (10.7 µm), and Channel 6 (13.3 µm).

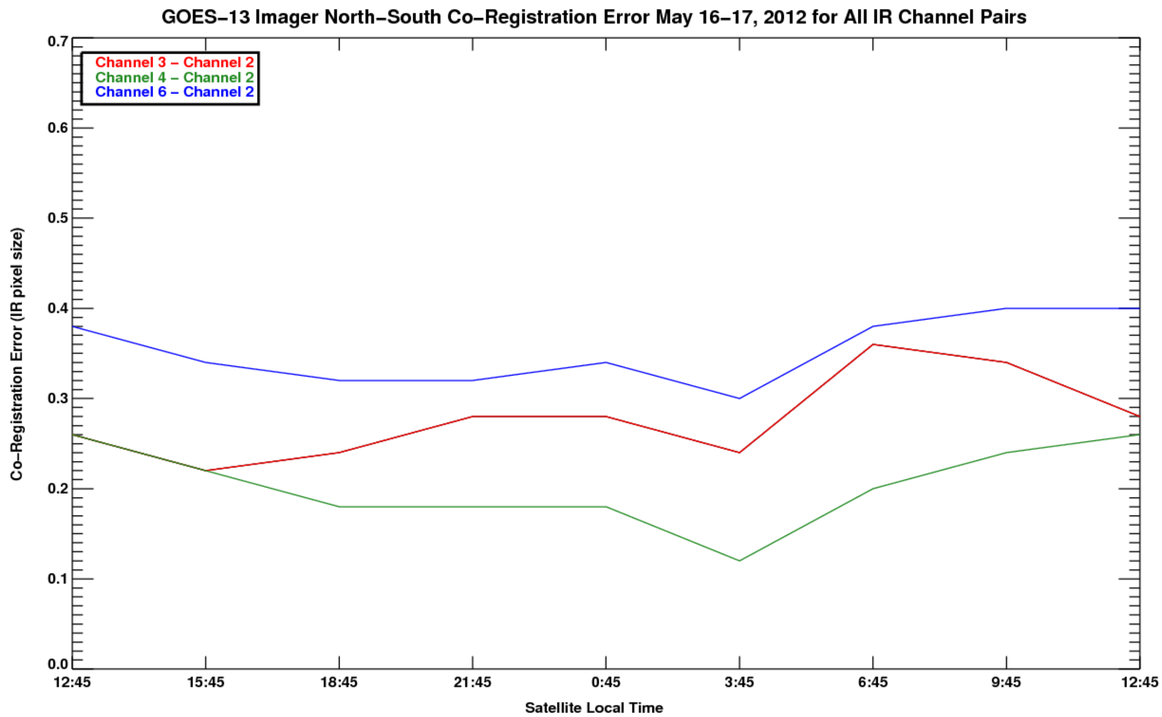


Figure 11. GOES-13 Imager North-South co-registration error for all IR channels: Channel 2 (3.9 µm), Channel 3 (6.5 µm), Channel 4 (10.7 µm), and Channel 6 (13.3 µm).

Figure 10 shows the GOES-13 Imager East-West Co-Registration Error for all IR channels: Channel 2 (3.9 µm), Channel 3 (6.5 µm), Channel 4 (10.7 µm), and Channel 6 (13.3 µm). Figure 11 shows the North-South error. The detectors for GOES-12 and 13 Imager Channel 6 are twice as large in each direction as the other IR channels, so the GOES-13 Imager Channel 6 data were repeated in order to match the resolution of Channel 2 (this is also the case for GOES-8 through 11 Imager Channel 3). The East-West sinusoidal pattern is evident in all three channel comparisons, though it is strongest for Channel 4 to Channel 2. The North-South direction shows less of a pattern with generally smaller variation.

The other channel pairs for the other GOES Imagers (not shown), except GOES-10 and 15, showed a strong sinusoidal variation in the East-West direction. Usually the Channel 4 to Channel 2 error was the largest, but not always. There was no consistent pattern in the North-South direction. However, for the GOES-8, 9, 10, and 11 Imagers, the Channel 4 to Channel 2 and Channel 5 to Channel 2 North-South error were nearly identical for all measurement times.

3.3 Seasonal and long-term variation

Figures 12 and 13 show the GOES-13 Imager Channel 4 to Channel 2 East-West/North-South co-registration diurnal cycles for the 16th and 17th of every month of the year 2011. There is some correlation between adjacent months, as the diurnal pattern for one month is likely to be similar to the last. Notable exceptions are the patterns from July and December. In the East-West direction, they exhibit little variation and have generally smaller error than the other months. In the North-South direction, they deviate little like the other months, but their overall error is distinct.

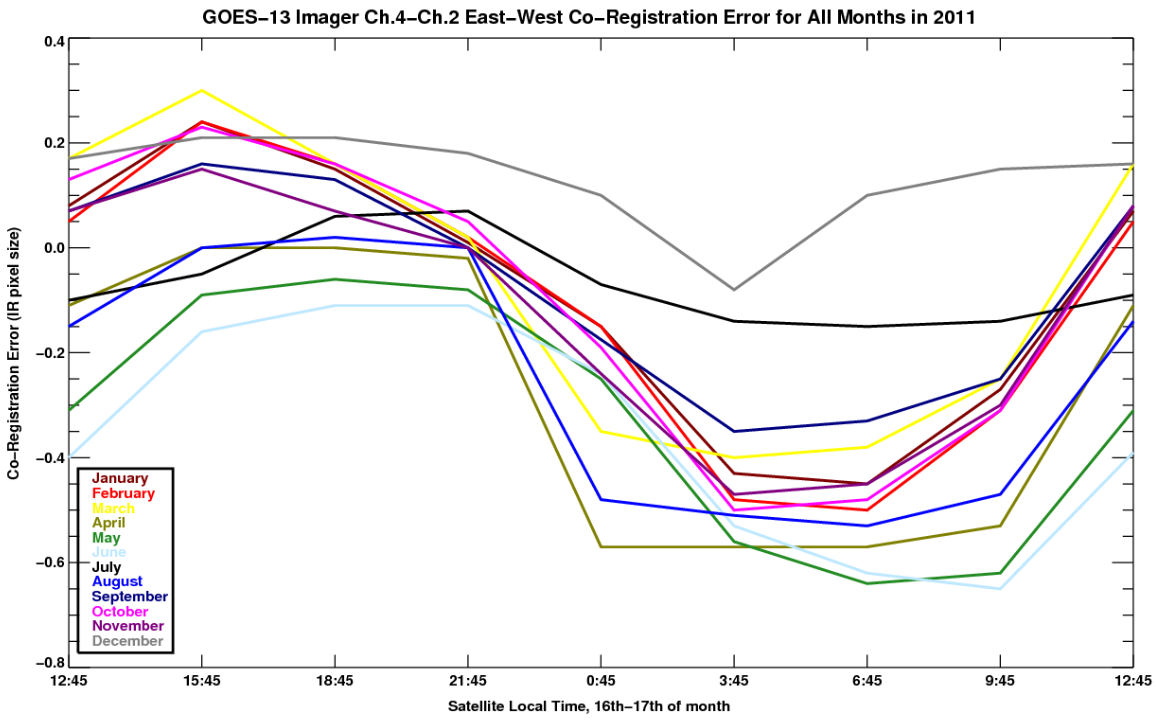


Figure 12. GOES-13 Imager Channel 4 to Channel 2 East-West co-registration monthly variation in diurnal cycles.

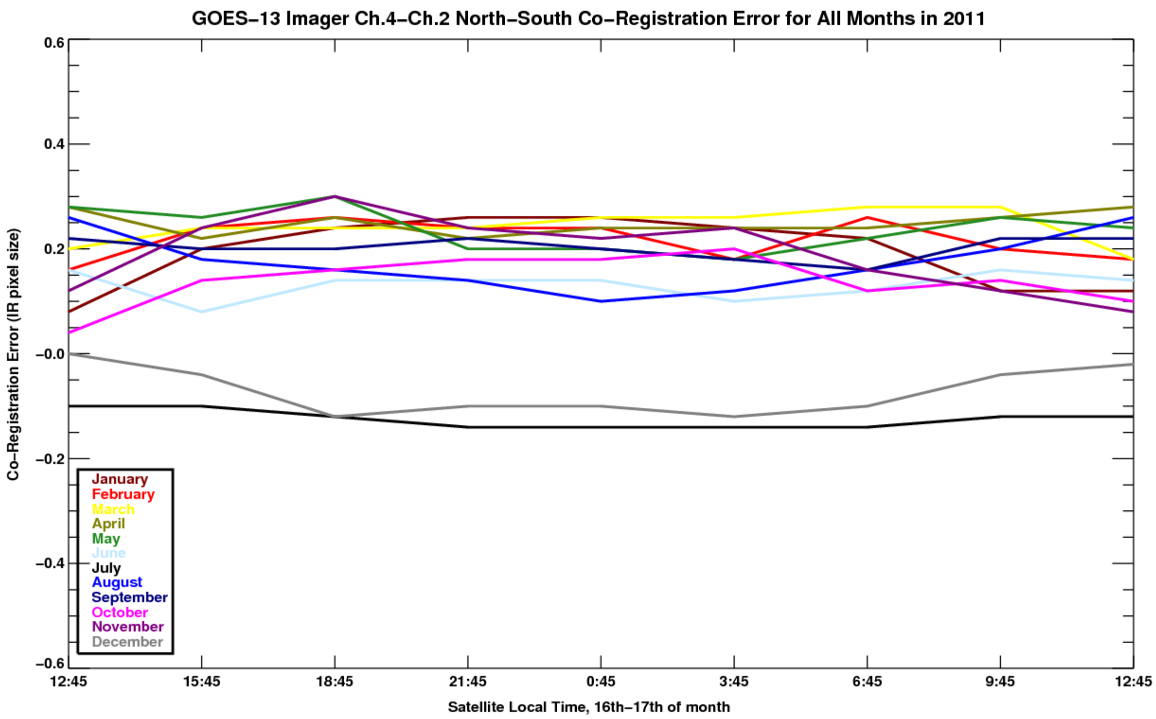


Figure 13. GOES-13 Imager Channel 4 to Channel 2 North-South co-registration monthly variation in diurnal cycles.

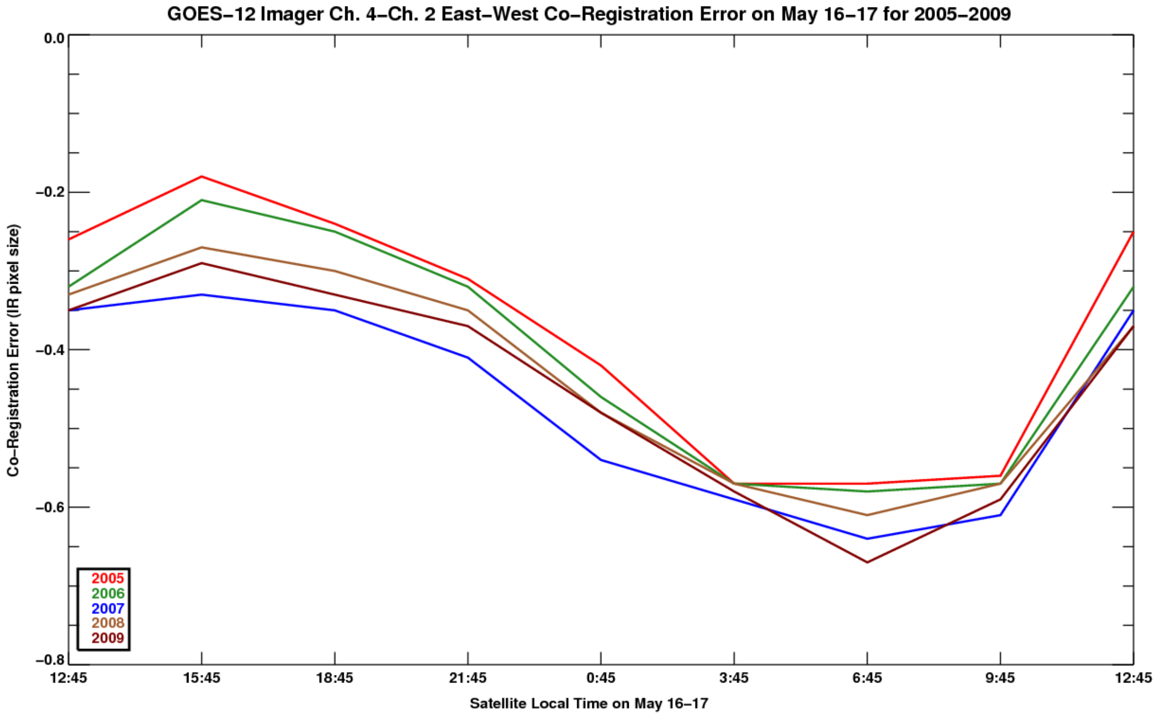


Figure 14. GOES-12 Imager Channel 4 to Channel 2 East-West co-registration error diurnal pattern on May 16-17 for years 2005-2009.

Because there is more historical data with GOES-12 than GOES-13, it was used to analyze the year-to-year variation in the co-registration error diurnal pattern. Figure 14 shows the GOES-12 Imager Channel 4 to Channel 2 East-West co-registration error diurnal pattern on May 16-17 for 2005-2009. The pattern is consistent. Figures 15 and 16 show the GOES-12 Imager East-West/North-South long-term behavior for the IR channel pairs, using data from the 16th of every month at the same time of day. There is no long-term pattern present. In looking at Figures 17 and 18, the East-West/North-South long term behavior of the GOES-13 Imager, there is a noticeable discontinuity that appears in the December 2011 – January 2012 timeframe. The cause of this discontinuity is unknown. Otherwise, like the GOES-12 Imager, the GOES-13 Imager exhibits no noticeable long-term co-registration pattern.

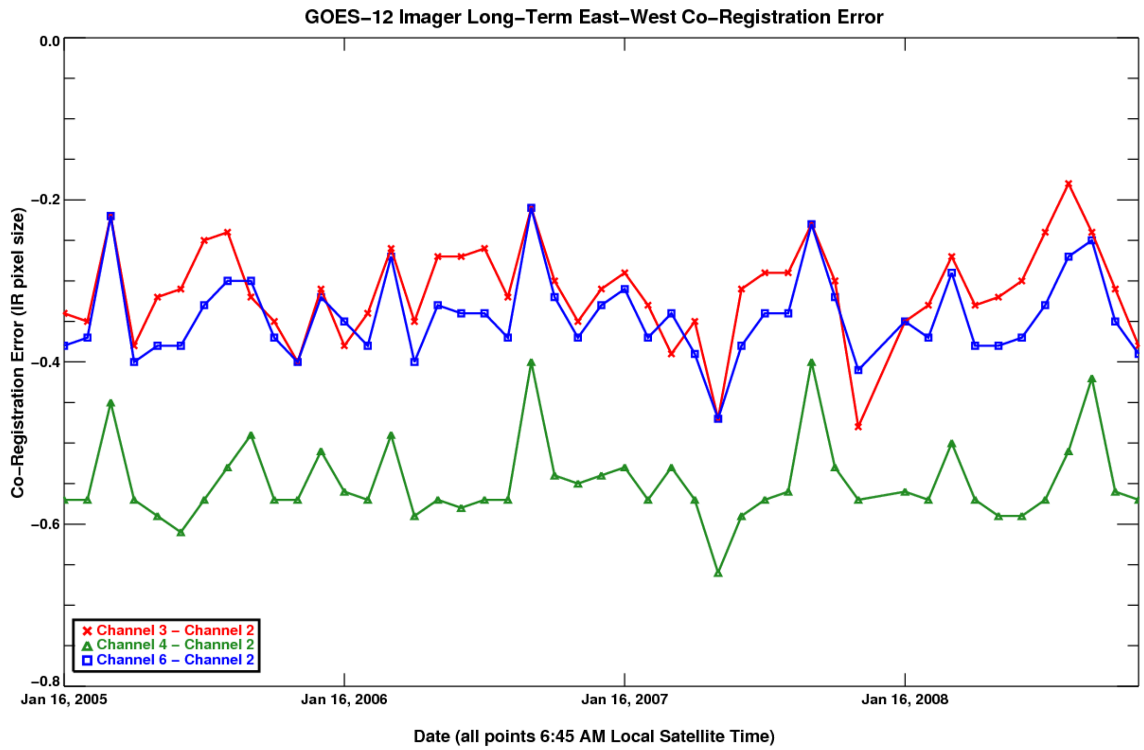


Figure 15. GOES-12 Imager long-term East-West co-registration error trend.

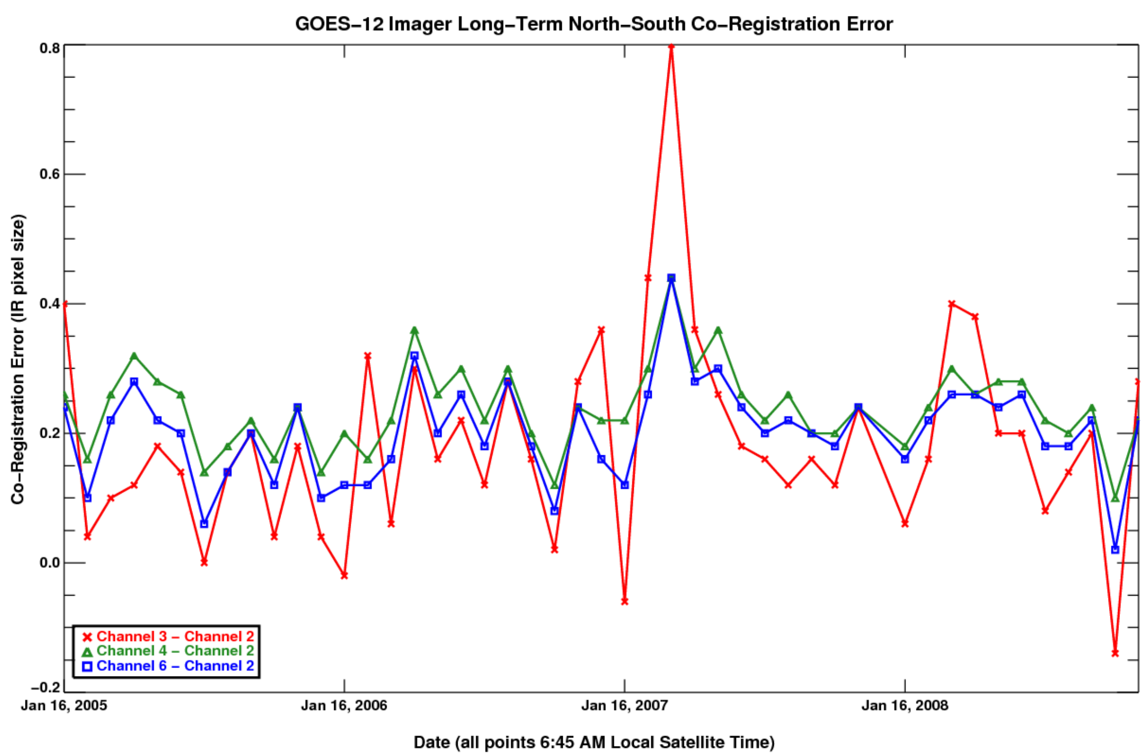


Figure 16. GOES-12 Imager long-term North-South co-registration error trend.

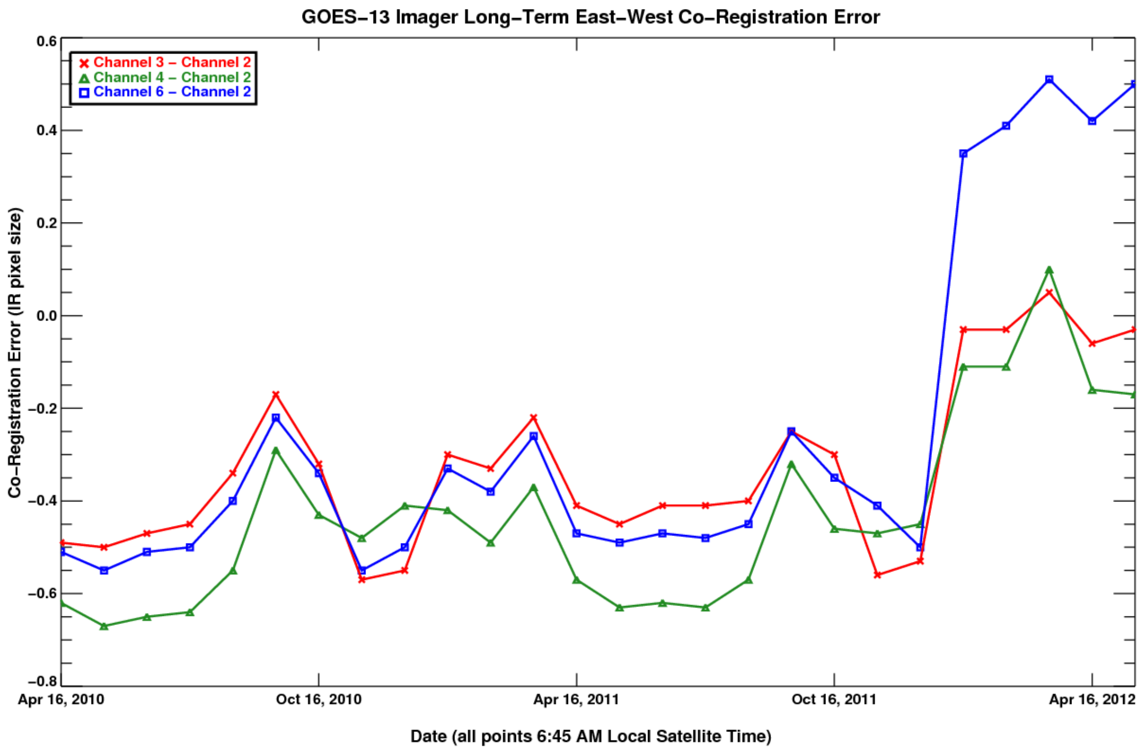


Figure 17. GOES-13 Imager long-term East-West co-registration error trend.

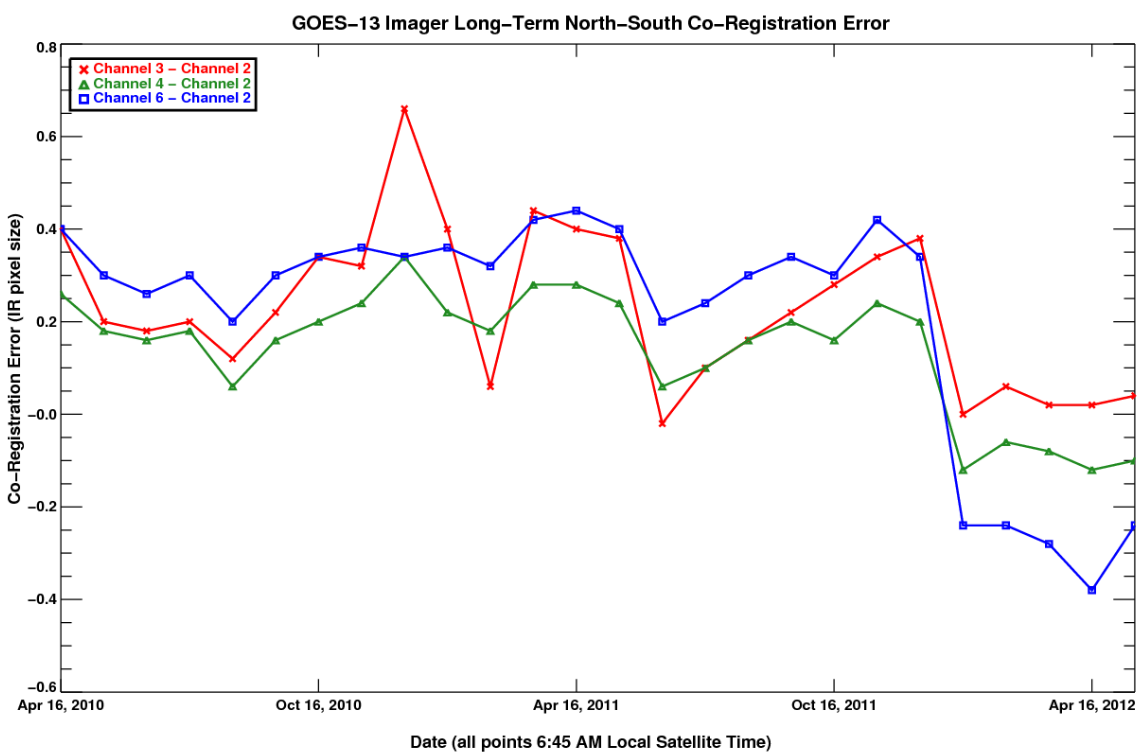


Figure 18. GOES-13 Imager long-term North-South co-registration error trend.

4. SUMMARY AND CONCLUSION

On May 16, 2012, CIMSS at the University of Wisconsin, along with the NOAA NESDIS group co-located there, reported that an erroneous fog product had led to the discovery that the GOES-13 Imager Channel 2 to Channel 4 co-registration exceeded specifications. To validate, using two novel methods, we characterized the GOES Imager channel-to-channel co-registration. One method utilized spatial-spectral brightness temperature gradients while the other used a statistical approach. A time series analysis showed that the two methods produced similar results, and thus validated each other as well as the CIMSS findings. Because it is computationally faster and exhibits less noise, the "Statistical Correlation" method was used for the co-registration characterization.

In the East-West direction, most of the GOES Imagers exhibit a strong sinusoidal diurnal pattern. This is suggestive of an underlying thermal cause, though proving this conclusively is beyond the scope of this paper. The diurnal patterns of the GOES-10, 11, 12, and 13 Imagers exhibit out-of-specification behavior at least some of the time when considering both the East-West and North-South directions in concert.

The GOES-13 Imager Channel 4 to Channel 2 co-registration diurnal cycles for the 16th and 17th of every month of the year 2011 were characterized. Ten out of twelve months showed a sinusoidal diurnal pattern, with some correlation between adjacent months. However, the cycles for July and December exhibited a very flat behavior with less error overall. The reason for this is unknown.

The GOES-12 and 13 Imagers showed no consistent long-term co-registration pattern. However, GOES-13 showed a large discontinuity in the December 2011-January 2012 timeframe, the cause of which is unknown.

The next GOES satellite to launch will be of the R-series. All of the satellite instruments onboard represent a marked improvement from their predecessors, or are entirely novel for GOES. Like the current GOES, the GOES-R series satellites will be subjected to an extensive post-launch engineering checkout and Post-Launch Science Test after launch and before operation. Because of the findings in this paper that the co-registration of previous GOES Imagers have exceeded specifications, we suggest including a co-registration test of the GOES-R Advanced Baseline Imager (ABI) during the GOES-R post-launch tests (PLTs). Further, because of the finding that the co-registration is subject to seasonal variations where some months exhibit much smaller errors than others, we recommend several co-registration tests during the PLT period. For the same reason and because of the novelty of the GOES-R instruments, we recommend the combination of the PLT test and any following 'commissioning phase' (after the hand-over to NOAA) to be at least a year.

The staff at NOAA's Center for Satellite Applications and Research, the science arm of NOAA's National Environmental Satellite, Data, and Information Service, are developing the Integrated Calibration/Validation System (ICVS) that includes instrument performance monitoring for a host of NOAA satellite instruments. As part of the ICVS, we plan to include an operational monitoring of the GOES Imager and future GOES-R ABI channel-to-channel co-registration. This will be especially useful following any co-registration error mitigation efforts to validate within-specification behavior.

5. FUTURE WORK

There are a number of techniques that might improve upon the methodology presented here that were not included but may be implemented in the future. The authors encourage any outside parties to attempt to improve the co-registration characterization effort for GOES or other Earth-observing systems using the ideas that follow. First, it is presumed that greater variablility within the images can improve the uncertainty. The PSF/MTF essentially reduces image variability, and therefore deconvolution may mitigate this effect. Also, the GOES imager oversamples in the East West direction, so East-West neighboring pixels "overlap". Skipping every other pixel might increase image variability.

To create a high-resolution pixel grid, the methods described in this paper used linear interpolation. This was intentional, because linear interpolation only uses the nearest nominal pixel locations, and pixels that are farther away should be less important due to the point-spread function. Still, other methods of interpolation may improve uncertainty, as they do not reduce image variability as linear interpolation does. A possible alternative is to use a point-spread function-weighted polynomial.

This paper dealt with the East-West and North-South directions separately. Using the "Statistical Correlation" method, one could perform the characterization on a two-dimensional grid directly (this cannot be done with the "Linear Fit" method because the difference in the imaging in the East-West and North-South directions causes different nominal linear correlation values in the two directions). A preliminary analysis indicated good agreement between a direct 2-dimensional measurement and separate measurements in each direction.

Finally, another means for co-registration characterization is to use the lunar edge. Differences in the position of the edge between channels is clearly due to co-registration error. The lunar surface does reach higher temperatures than the Earth's surface, so the IR channels of Earth observing systems can saturate when imaging the Moon. However, in some cases (i.e. full moon), while the interior of the moon may saturate, the edge does not. Using the lunar edge is important when considering non-IR channels, as the methodology presented in this paper is only useful in the infrared.

ACKNOWLEDGEMENTS

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