A Stellar Calibration Technique –
Application to GSICS Inter-Calibration of Solar Channels of Satellite Radiometers

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1 Introduction

Techniques that are currently in use to monitor the degradation rate of the responsivity in the visible (solar) channel of the Imagers carried by NOAA's Geostationary Operational Environmental Satellites (GOES) can be employed to support the inter-calibration efforts of the GSICS. In this outline our goal is to describe how star-sensing data can be acquired and processed to derive estimates on the rate of degradation in the responsivity of an Imager visible channel. Brightnesses of selected stars can be assumed to be almost invariant over a long period of time. Thus we are using a change in the measured brightness of a star to estimate a change in the instrument's responsivity.

2 Basic features of a detector array on a GOES I–M Imager visible channel

The Imager on a GOES satellite observes stars at regular time intervals as a part of the operational process for determining the Imager's orbit and attitude. The Imager's field of view is commanded to dwell at a location on space just to the east of the star being observed, and the diurnal rotation of the satellite then carries the image of the star across the Imager's detector arrays. Figure 1 illustrates the crossing of a star image over the detectors of a visible channel in a star sensing operation. The visible channel is equipped with a linear array of eight detectors oriented essentially in the north–south direction. In Figure 2, the two plots show the intensity of the star light measured by Detector 3 and Detector 4 as each detector registered the crossing of a portion of the star image. Each data point shown is actually a sum of 400 incoming pixels from the detector – a process to compact the volume of Imager data to a manageable size. We call each such data point a superpixel. The original individual samples are received at 21,800 pixels per second. The units on the abscissa are Detector Time Units (DTU), where one DTU is 400/21800 second. The units on the ordinate are Detector Pixel Units (DPU), where one DPU is a one (digital) count output (after summing over the 400 samples) of the channel. For each star look, we shall refer to the stream of superpixel data acquired from each detector as the detector

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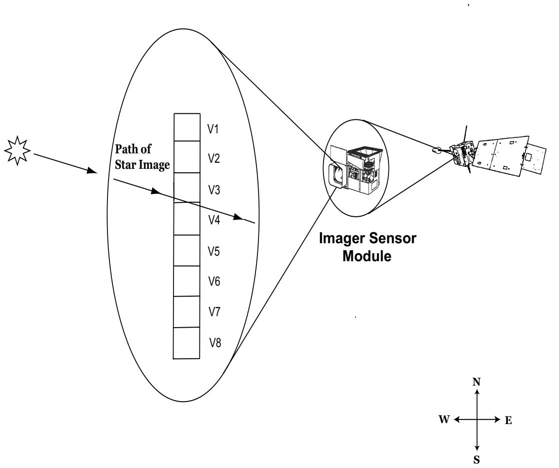

Figure 1: The eight detectors of the visible channel of an Imager conducting a star look.

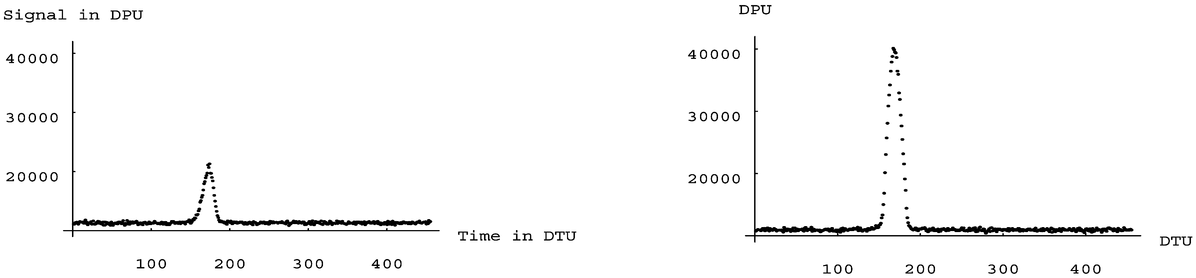

Figure 2: Measurements received from Detector 3 (left) and Detector 4 (right) of the visible channel of the Imager of GOES−12, in a star look of α−Aql, conducted on November 4, 2004. One Detector Time Unit (one DTU) is 400/21840 second. One Detector Pixel Unit (one DPU) is one count in a pixel value.

signal profile. The eight detector profiles of each star look, together with the time tag of the star look and the identification number of the star, are the principal required input data in our calibration work.

3 Detection of a star image and definition of the signal magnitude

For the detection of a star image from the signal profile of a detector, we adopted the operational detection algorithm implemented on the GOES Sensor Processing System (SPS) (see NOAA/NESDIS publication [1], page 176). In this procedure, a detector profile is scaled to the original pixel size by dividing each superpixel magnitude by 400. Then the profile is smoothed by replacing it with 12-point moving averages. Call this new profile a *doubly-averaged profile*. A group of consecutive pixels in a doubly-averaged profile is declared to be that of a star image if the magnitudes of the pixels are above a certain threshold level and the number of pixels in the group is larger than certain lower bound. If s is the magnitude of a pixel in a doubly-averaged profile and a is the average of all the pixel values, the threshold requirement for a pixel to be a star pixel is that $s - a > 0.5$. The threshold value of 0.5 is used on all the GOES satellites in the I to M series. The lower bound on the count of star pixels is 9. We found that a comparable signal threshold value can be obtained by examining the detector profiles that do not contain star signals – profiles of the background space signals and instrument noise. The standard deviation of the signals of such a profile (a doubly–averaged profile) has consistently been approximately one-quarter of the threshold value provided by the instrument manufacturer.

If star images have been detected on some of the detectors, we return to the superpixel profiles of the detectors and compute a star signal. We regard the linear array of eight detectors (Figure 1) as one integral detector where the image of the star moved across this single detector. We first combine the superpixel profiles that contain star images into one composite signal profile by summing at each time mark the measurements from each such profile. Numerical weighting factors (multiplicative factors) for the summands are allowed in this step of summing. The factors will be database constants whose default values are 1.0. The data in this sequence of sums are then rendered absolute by subtracting the baseline (space signal) from them. The baseline level here is computed as the result of a median filter applied to this sequence of sums. Finally, each shifted sum in the sequence is divided by 400 to transform the pixel amplitude from that of a superpixel to that of an original pixel measured on a detector. Figure 3 shows such a composite star-signal profile obtained from the two individual profiles of the star event of Figure 2. In this star event, only Detector 3 and Detector 4 registered star crossings.

Once a composite profile has been computed, a search to estimate the peak value is carried out. A sequence of moving averages across the profile is computed. The number of pixels included in the average is a predetermined parameter with the default value of 8. Calling the maximum value in this set of averages the peak value, we define this peak value to be the signal of the star.

Throughout the process of detecting a star image and computing a star signal, we conduct at different points of this process certain checks to determine whether the process should be continued. The major conditions for rejecting a star look are: (i) No crossing of a star image has been detected on any detector. (ii) A star image crossed over Detector 1 or Detector 8, allowing a part of the star image to fall outside of the detector array. (iii) A star image crossed over more than four detectors. (iv) Star images were registered on noncontiguous sets of detectors. (v) The time intervals where star images crossed over detectors do not form a continuously-joined sequence. (vi) More than one star image entered a detector. (vii) A detector profile contains point-spikes that have amplitudes higher than certain statistically computed upper bound. (viii) The estimated star signal is higher or lower than certain statistically determined upper bound or lower bound, respectively.

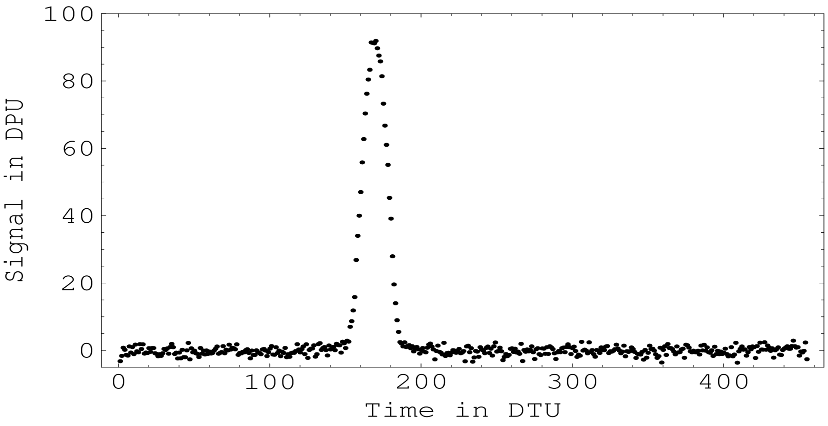

Figure 3: A Composite Profile computed for the star crossing of α–Aql in Figure 2. This profile (signal versus time) is the sum of the two individual profiles shown in Figure 2.

4 Constructing a time series of star signals and estimation of instrument responsivity degradation rate

In estimating an annual rate of change in the responsivity of the channel, one approach we use is to fit exponential functions to the star-signal time series of a chosen group of stars. Each exponential fit is of the form

$$Be^{-At} .$$

The time t is measured in days. The time $t = 0$ corresponds to the launch date of the satellite or the date when the satellite started its regular operation. We construct the fitting exponential function for a time series of a star by using all the admissible star signals, with only one important exclusion rule. The exclusion rule is that the star signals obtained within five hours on each side of the local midnight are not to be included. Signals measured in this period are usually low in value, due to distortion of the scan mirror caused by increased heating by the sun (see Bremer, et al., [2], pp.150–151). Figure 4 shows the plot of a 13–month time series of star signals of the star β-Cnc, observed by the Imager on GOES–13, together with the graph of the exponential fitting function. The exponential fit gives an annual degradation rate $A = 5.06\%$. The average annual degradation rate computed from 45 chosen stars over approximately the same period yields a rate of $\hat{A} = 6.32\%$, with a standard error of the mean of 0.40%.

As the period of a time series lengthens, an exponential function does not always fit the data well, especially at the starting and ending portions of the time series. A more flexible function $S(t)$, such as a polynomial function, can be used in place of an exponential function. An estimate of the relative degradation rate at time t is then the quotient $A(t) = \frac{S'(t)}{S(t)}$, where S' indicates the time derivative. Preliminary tests indicate that a cubic polynomial function for $S(t)$ serves such purpose.

5 A predecessor technique

The method described in this report evolved from several earlier star calibration methods that have continued to serve as robust and stable visible–channel methods for monitoring degradation. In particular, a method we call Method 2 (see Chang, et al., [3]) has been providing regular degradation estimates since the early

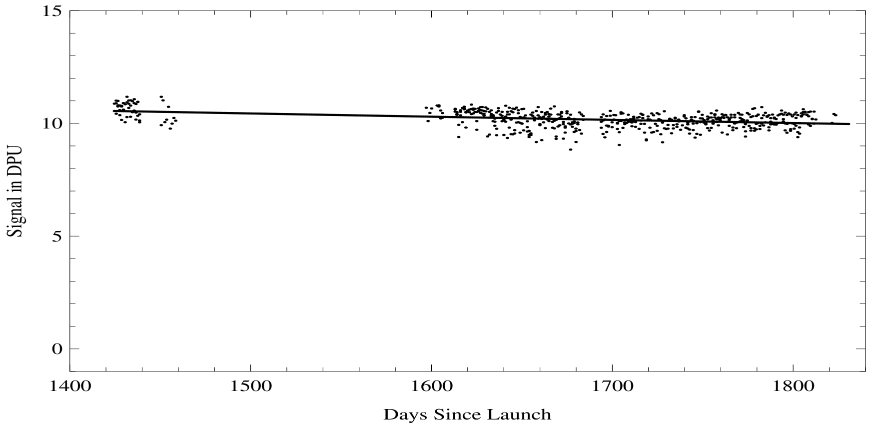

Figure 4: A time series of star signals of β-Cnc from GOES–13 and the exponential fit for this time series. Data of the time series were obtained over the period April 16, 2010, to May 20, 2011. Star signals collected before this period have been excluded because we are interested in the degradation in the responsivity of the Imager visible channel since the start of the operation of GOES–13, which is April 14, 2010. Day 1 is the launch date of GOES–13: May 24, 2006.

2000's. In this method, we depend on the operational GOES Orbit and Attitude Tracking System (OATS) to detect the presence of stars and compute the star signals from the data of the star looks. After quality screening the star signals, we fit the exponential functions to their time series to estimate the degradation rates. However, the OATS algorithm is not optimized for calculating the star signals, as it had been developed to determine pixel location of the star, not the pixel magnitude. Therefore, in the mid-2000's, motivated by our wish to be independent of the OATS processing and improve the accuracy of the computed star signals, we developed the current method. Method 2, however, continues to provide the degradation–rate reports that we disseminate to users. The following table shows results of monitoring the Imager visible channel of GOES–12 using Method 2. These results are the ones posted on our star-calibration web site http://www.star.nesdis.noaa.gov/smcd/spb/fwu/homepage/GOES_star_cal.php. Note that the degradation rate slows with time, a characteristic apparently shared by the Imagers on all NOAA's GOES satellites. This means that the time series do not strictly follow the form of an exponential decay.

6 Sources of uncertainty and some estimates of data scatter

There are certain sources that in general can cause uncertainty in our degradation estimates. We have also observed from GOES–8 through GOES–13 that certain factors have influenced the stability and reliability of our computed results. We list here four sources:

1. Our current star calibration techniques are based on the irradiance of a point source rather than the radiance of an extended source; therefore the degradation trends concluded from star observations may be slightly different from the degradation trends inferred from observing Earth scenes.

2. Although the detectors used for Earth imaging are the same as those used for star observations, the star observations employ an additional stage of amplification in the electronics. We believe, but cannot be certain, that the gain of the additional stage is constant in time.

Table 1: Estimated Imager visible–channel degradation rates for GOES–12 using Method 2. The rates are published on the GOES Star-calibration web site http://www.star.nesdis.noaa.gov/smcd/spb/fwu/homepage/GOES_star_cal.php. Each estimated rate $\hat{A}$ is the average of the A-coefficients of approximately 40 stars. The stated error is the usual standard error of the mean.

GOES–12 Update Date	**$\hat{A}$(annual rate)**	**Length of Time Series**
July, 2005	5.68 ± 0.30%	January 22, 2003 to January 23, 2005
June, 2006	5.80 ± 0.20%	April 1, 2003 to April 1, 2006
April 19, 2007	5.27 ± 0.13%	April 1, 2003 to April 1, 2007
January 11, 2008	4.82 ± 0.07%	April 1, 2003 to December 27, 2007
July 11, 2008	4.83 ± 0.07%	April 1, 2003 to April 17, 2008
January 21, 2009	4.44 ± 0.05%	April 1, 2003 to December 17, 2008
September 24, 2009	4.24 ± 0.05%	April 1, 2003 to August 23, 2009
April 27, 2010	4.06 ± 0.04%	April 1, 2003 to March 9, 2010
September 14, 2010	4.03 ± 0.04%	April 1, 2003 to August 23, 2010
December 30, 2010	3.93 ± 0.04%	April 1, 2003 to November 30, 2010
March 31, 2011	3.90 ± 0.04%	April 1, 2003 to February 22, 2011

3. The diurnal temperature changes in components of the Imager's optical chain cause fluctuations in the measured star signals. The fluctuations introduce secondary oscillations in our time series of star signals. In Chang, et al., [4], we discussed this phenomenon and showed some methods we have been using to lessen the influence of such signal variations on the estimated degradation rates.

4. The computed intensity of a star signal is subject to errors from such sources as instrument noise, errors in the estimations of the background space signals, errors in the method of estimating the star signal, etc.

Despite the influence of factors such as temperature change (item 3 above) and computational errors (item 4), we are observing a now familiar behavior of stability when we fit exponential functions to the time series of star signals. The degradation rates of the star time series (approximately 40 time series) for a satellite continue to show less scatter as the lengths of the time series increase. In Table 1, for instance, we observe that the relative standard error of the mean of the A-coefficients diminishes as the data period lengthens from two years to near eight years : 5.3%, 3.4%, 2.5%, 1.5%, 1.4%, 1.1%, 1.2%, 0.99%, 0.99%, 1.0%, 1.0%. We are expecting Monte Carlo simulations to give support to such observed stability.

7 Conclusion

We conclude by pointing out that many stars are light sources with stable and well-quantified intensities. On a spacecraft where data from star-sensing are available, such light sources can provide reliable and economical data for conducting long-term monitoring of the responsivities of the sensing instruments.

References

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[2] Bremer, J.C., J. G. Baucom, H. Vu, M. P. Weinreb, and N. Pinkine, “Estimation of long-term throughput degradation of GOES 8 & 9 visible channels by statistical analysis of star measurements,” in *Earth Observing Systems III*, *Proc. SPIE* **3439**, pp. 145–154, 1998.

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