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Improving IPATS Channel-to-Channel Registration Assessment

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ABSTRACT

The Image Navigation and Registration (INR) Performance Assessment Tool Set (IPATS) is a primary tool for assessing INR performance of GOES-R series ABI images. IPATS assesses five INR metrics: navigation, channel-to-channel registration (CCR), frame-to-frame registration, within-frame registration, and swath-to-swath registration. It was discovered that CCR assessment results between Visible-Near-Infrared (VNIR) channels and Infrared (IR) channels exhibits an annual oscillation in the north-south (NS) direction and a diurnal oscillation in the east-west (EW) direction, with an amplitude of approximately 5 µrad and 2.5 µrad, respectively. However, differences of navigation assessment results between VNIR and IR channels do not exhibit the annual or diurnal oscillations observed in CCR results. This indicates that the observed oscillations are due to measurement errors. The characteristics of the oscillations imply that cloud shadows are a possible cause of these measurement errors. In this study, several methods are explored to minimize the impact of cloud shadows on VNIR to IR CCR assessments: a) assessment at landmark locations only; b) using navigation assessment results to filter CCR assessments; c) using the ABI clear-sky-ratio product as a cloud mask; and d) smaller CCR assessment windows. In this paper, each method and a combination of several methods are evaluated based on assessment accuracy and the number of successful assessments. The selected approach is then used to reprocess GOES-16 ABI CCR data to show reductions in the annual and diurnal measurement error oscillations.

Keywords: GOES-16, ABI, IPATS, CCR

1 INTRODUCTION

The first three of the four latest US Geostationary Operational Environmental Satellites (GOES), known as the GOES-R series, were launched on November 19th, 2016, March 1st, 2018, and March 1st, 2022. They were respectively designated GOES-16, GOES-17, and GOES-18 upon reaching geostationary orbit. GOES-16 was relocated to its operational location at 75.2 degrees west and officially became GOES East in December 2017. GOES-17 was relocated to 137.2 degrees west and officially became GOES West in February 2019. GOES-18 replaced GOES-17 and became GOES West in January 2023. GOES-17 has been relocated to the storage orbit, serving as a backup to the operational GOES satellites.

The Advanced Baseline Imager (ABI) serves as the primary instrument on the GOES satellites, capturing images of Earth's surface and atmosphere for weather forecasts, climate change studies, and the detection and observation of bio-geophysical processes on the land surface, among other applications [1][2][3]. The ABI Level 1B (L1B) images are radiometrically calibrated, gridded, and navigated products. An increasing number of scientists employ ABI L1B products in their research, often involving multiple ABI L1B spectral channels [4][5]. Accurate Channel-to-Channel Registration (CCR) is crucial for such studies. CCR accuracy, along with other geometric metrics, is evaluated for the gridded GOES ABI data through Image Navigation and Registration (INR) assessments, which constitute a significant part of post-launch calibration and validation (Cal/Val) activities. The assessment results not only provide geometric accuracy information to data users but also offer in-depth analysis to aid engineers in enhancing geolocation algorithms, operational parameters, and future instrument design.

The INR Performance Assessment Tool Set (IPATS) was developed to independently verify ABI and Geostationary Lightning Mapper (GLM) INR for the GOES-R series [6] [7]. Three types of ABI images are available: Full Disk (FD), Continental United States (CONUS), and Mesoscale (MESO) [8]. IPATS continuously monitors the INR accuracy of all three types of ABI images since the GOES satellites' placement in the checkout location at 89.5 degrees west. This study aims to enhance CCR assessment accuracy. We first delineate the issues identified in the CCR assessment results. Subsequently, we introduce the data used in this study and outline potential methods for improvements. Next, we present

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the enhancements achieved through individual methods or the combination of multiple methods. Finally, we present reprocessed GOES-16 ABI annual CCR assessment results to demonstrate the improvements.

2 DATA, PROBLEMS AND METHODOLOGY

2.1 Data

This study utilizes two GOES data products from 2022. The first one is the ABI L1B FD data, which contains 16 spectral channels [8]. The operational IPATS generates CCR results for all 120 channel pairs. However, for the purpose of this study, we focus on the channel pair consisting of channels 13 and 2. This example is used to illustrate the issues and improvements in CCR assessments of channel pairs involving Visible-Near-Infrared (VNIR) and Infrared (IR) channels.

The second data product employed is the ABI L2 Clear Sky Mask (CSM) [9]. Within the L2 CSM product, each GOES pixel falls into one of four possible categories: confidently clear, probably clear, probably cloudy, or confidently cloudy. The cloud information within the CSM product can be utilized as a filter to eliminate CCR measurements that are influenced by cloud shadows.

2.2 Problems

It has been observed that the CCR assessment results between VNIR channels and IR channels exhibit an annual oscillation in the north-south (NS) direction and a diurnal oscillation in the east-west (EW) direction, with approximate amplitudes of 5 µrad and 2.5 µrad, respectively. Figure 1 depicts the GOES-16 ABI CCR results of channel 13 with respect to channel 2 in the NS direction, as assessed by the operational IPATS. The evaluated NS offset shifts towards the north during winter and towards the south during summer. These oscillations intersect the midline around the spring/fall equinox.

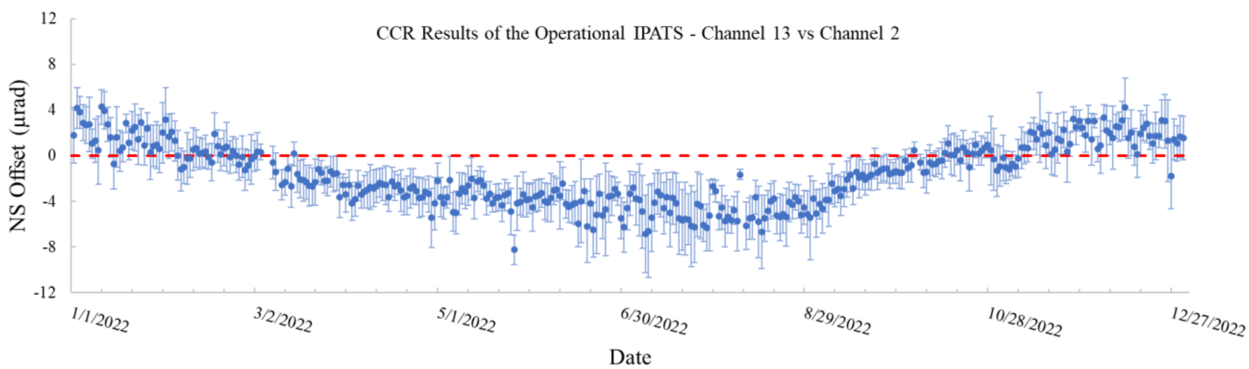

Figure 1. The G16 ABI CCR results of channels 13 and 2, as assessed by the operational IPATS. The blue dots represent the 24-hour mean CCR values derived from all FD scenes. The error bars denote one standard deviation of the 24-hour measurements.

However, the difference in navigation (NAV) assessment results between two channels does not display the same annual or diurnal oscillations as observed in the CCR results (Figure 2). Although not shown here, the oscillations are also not observed in the visible and IR star measurements. These observations suggest that the oscillations stem from measurement errors. The nature of these oscillations implies that this type of measurement error is linked to the sun's azimuth angle. It is highly likely that cloud shadows are the primary cause of these oscillations.

2.3 Methodology

There exist several potential methods to mitigate the influence of cloud shadows on CCR assessments of VNIR and IR channel pairs:

a) Limiting assessments to landmark evaluation locations exclusively.

b) Employing NAV assessment results for CCR assessment filtering.

c) Utilizing the ABI CSM product to construct a mask for CCR assessment filtering.

d) Employing smaller CCR assessment windows.

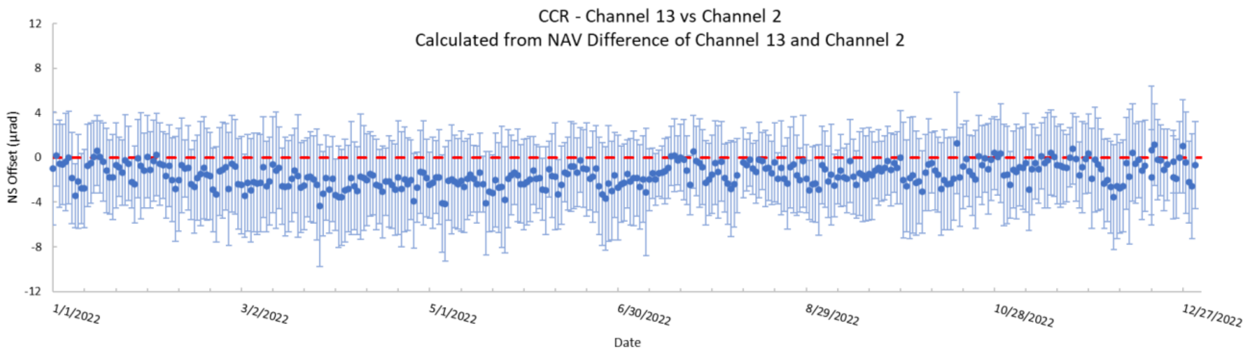

Figure 2 IPATS NAV assessment difference between channel 13 and 2 for GOES-16 ABI. The blue dots represent the 24-hour mean CCR values derived from all FD scenes. The error bars denote one standard deviation of the 24-hour measurements.

It should be noted that the mission requirement of CCR between VNIR and IR channel pairs is 11.2 µrad for |mean|+3*STD, where the mean and STD are the average and the standard deviation of the measurements in 24 hours. The goal of this study is to minimize systematic measurement errors (the observed oscillations) while limiting any increase in random measurement errors.

2.3.1 Evaluation locations

The assessment of ABI CCR involves comparing subset windows of two spectral channels [10]. These subset windows are centered at evaluation locations. For CCR assessments in the operational IPATS, the dimensions of ABI subset windows are standardized to 256 by 256 pixels. In cases where the spatial resolutions of the two channels differ, the subset window dimensions are set to 256 by 256 pixels of the coarser resolution channel.

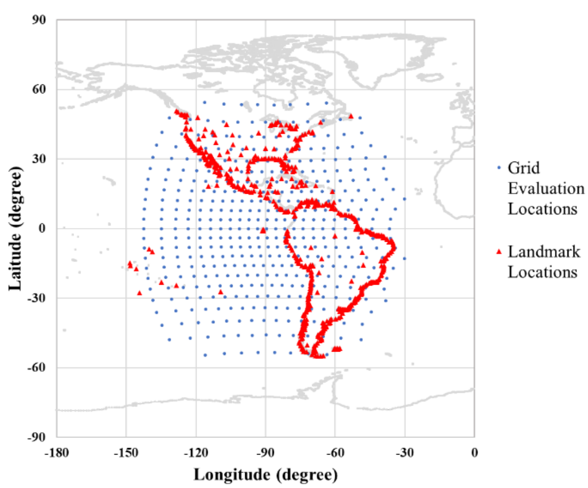

Figure 3. The CCR evaluation locations for the checkout location (89.5 degrees west) consist of both grid evaluation locations and landmark evaluation locations.

Two types of evaluation locations exist: grid evaluation locations and landmark evaluation locations (Figure 3). Grid evaluation locations are evenly distributed points within the ABI fixed grid coordinate system. Landmark evaluation locations are predominantly situated along the shorelines of North and South America (Figure 3). Shorelines are emphasized due to their tendency to exhibit high contrast, low spatial frequency image features that are well-suited for image registration at the spatial scale of ABI images.

In the process of registering image pairs across grid evaluation locations, the utilization of 100% cloud or cloud shadow features is a common outcome over oceanic regions. Findings from research conducted during the development of IPATS indicated that cloud textures offer substantial advantages in image registration when both images originate from VNIR or IR channels. However, the presence of cloud shadows introduces notable artifacts in CCR assessments, particularly when one channel is a VNIR channel and the other is an IR channel. Consequently, operational IPATS assessment results are exclusively derived from CCR assessments conducted at landmark evaluation locations. The grid evaluation locations are also excluded from the analysis in this study.

2.3.2 Filtering with NAV Assessment Results

NAV assessment involves comparing ABI subset images with reference images to evaluate the relative offsets between the two images. These reference images are derived from cloud-free Landsat images. The application of a measurement uncertainty (MU) filter guarantees the similarity between ABI subset images and their corresponding Landsat subset images. The MU filter plays a pivotal role within IPATS, as it effectively eliminates poor-quality image registration outcomes [6]. This filter is implemented across all five INR metrics produced by IPATS: NAV, CCR, Frame-to-Frame Registration (FFR), Within-Frame Registration (WIFR), and Swath-to-Swath Registration (SSR).

The values of computed MU can vary based on changes in image pair characteristics, such as image dimensions and radiometric calibration. Consequently, MU thresholds must be adjusted accordingly when these characteristics change. Since Landsat subset images are devoid of clouds, the MU filter employed within IPATS NAV assessment indirectly ensures minimal cloud coverage over corresponding ABI subset images. Therefore, restricting CCR assessment to locations where NAV measurements pass the MU filter should reduce the influence of cloud features and shadows on CCR results.

2.3.3 Filtering with the Cloud Mask

The GOES Level 2 CSM product enables the creation of a cloud mask to eliminate evaluation locations with substantial cloud coverage. Within IPATS, the Clear-Sky-Ratio (CSR) for an evaluation window is computed using the CSM product. The CSR is determined by calculating the ratio of the sum of confidently and probably clear pixels to the total number of pixels within the evaluation window. Using CSR as a measurement filter for CCR diminishes the influence of cloud shadows on CCR results.

2.3.4 Using Smaller Assessment Windows

The final approach involves reducing the dimensions of the evaluation windows. Cloud features and shadows typically span a significantly larger spatial range than ground features. On a smaller scale, clouds and cloud shadows appear more homogeneous compared to ground features. Therefore, employing evaluation windows of appropriate dimensions enables coverage of only a small portion of cloud textures and shadows. This reduces the likelihood of these features dominating the small-scale ground features during image registration.

(a) (b)

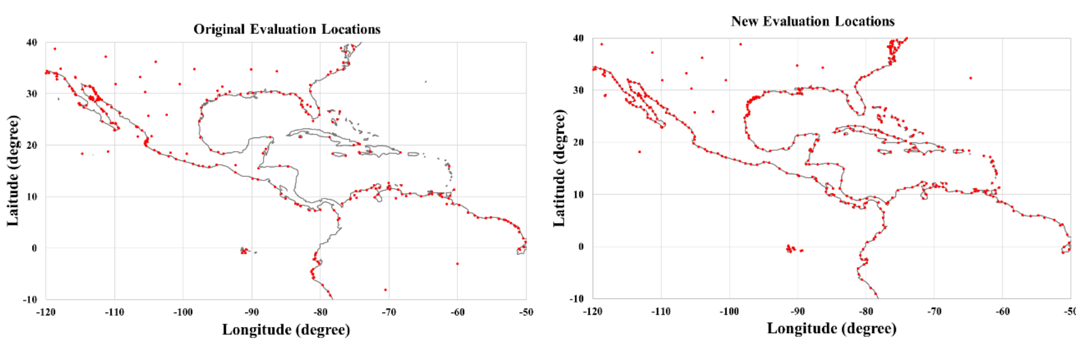

Figure 4. (a) The original evaluation locations and (b) the new evaluation locations.

Figure 4 showcases both the original and new evaluation locations across the Central America region. The original evaluation locations correspond to NAV assessment points, which rely on the availability of Landsat reference subsets. The original locations exhibit certain issues for CCR assessment: 1) frequent overlap, 2) uneven spatial distribution, and 3) absence of evaluation locations in certain regions. In contrast, the new locations are more uniformly distributed and capture key turning points along shorelines. The count of new locations (1369) is slightly lower than that of the original locations (1387) due to the removal of overlapping locations.

2.3.5 Model the Annual and the Diurnal Oscillations

To quantitatively describe the annual oscillation of the 24-hour mean CCR NS offsets, which are attributed to cloud shadows, a periodic function is employed:

$$y = A * \sin\left(B * \frac{x}{183} * \pi + C\right) + D \qquad (1)$$

Where *y* is the daily mean CCR NS offsets,

x is the calendar day of a year,

A is the amplitude,

B is the scale of the period. The period is 366 days when B equals to 1,

C is the phase shift,

D is the systematic bias.

In this study, the focus lies on the amplitude, denoted as "*A*", which serves as a measure of the influence of cloud shadows. The amplitude for the model of the data plotted in Figure 1 (G16 channel 13 versus 2 NS offset for all of 2022) is 3.77 μrad and serves as a baseline value for this study.

Likewise, a linear function is utilized to model the daily fluctuations in the mean CCR values of the scenes over a 24-hour period:

$$y = A * x + B \qquad (2)$$

Where *y* is the scene mean CCR EW offsets,

x is the time of day, ranging from 0 to 1,

A is the slope of the fitted linear model,

B is the intercept of the fitted linear model.

This study primarily centers on the slope, designated as "*A*", which functions as a metric for evaluating the impact of cloud shadows.

3 RESULTS AND DISCUSSIONS

3.1 Filtering with NAV Assessment Results

Figure 5 presents the reprocessed GOES-16 ABI CCR temporal plots for the channels 13 versus 2 in the NS direction for the year 2022. In this plot, only the CCR measurements at locations with successful high-quality NAV measurements taken at the same time are included. Despite this filtering, the annual variation cycle remains significant. The amplitude of the periodic model (Eq. 1) is determined to be 2.34 µrad. When compared to the operational IPATS CCR results discussed in Section 2.2, the observed amplitude improvement is approximately 1.4 µrad. This improvement is relatively modest due to the difference in evaluation window sizes between NAV and CCR assessments.

The evaluation window dimensions for NAV are determined by the size of Landsat subset images. A full Landsat 8 scene measures 180 by 180 km, while the Landsat subset images utilized in GOES ABI NAV are approximately 150 by 150 km. These dimensions correspond to 75 by 75 pixels of ABI IR channels with a spatial resolution of 2 km at nadir. The size of NAV evaluation windows diminishes towards the Earth's limb where the spatial resolution of ABI images coarsens. NAV evaluation windows can be as small as 10 by 10 ABI pixels near the limb. Conversely, the dimensions of CCR evaluation windows remain constant at 256 by 256 pixels in the operational IPATS. This disparity in evaluation window dimensions renders the NAV filter less effective, as it can result in cloud-free conditions within the NAV assessment window while encountering substantial cloud coverage within the larger CCR assessment window.

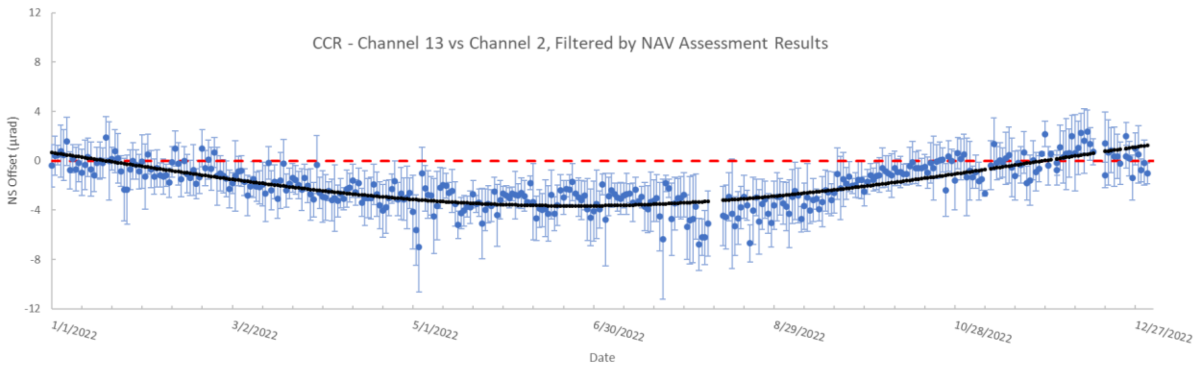

Figure 5. GOES-16 ABI CCR assessments results of the channels 13 and 2 in 2022. The blue dots are 24-hour mean CCR assessments and the error bars represent one standard deviation of CCR measurements in 24 hours. The black curve line is the periodic model.

3.2 Filtering with the CSR Mask

To examine the impact of the CSR mask, we explored five different CSR thresholds: 0%, 25%, 50%, 75%, and 90%. CCR measurements with a CSR value below the specified threshold were disregarded due to being categorized as poor quality.

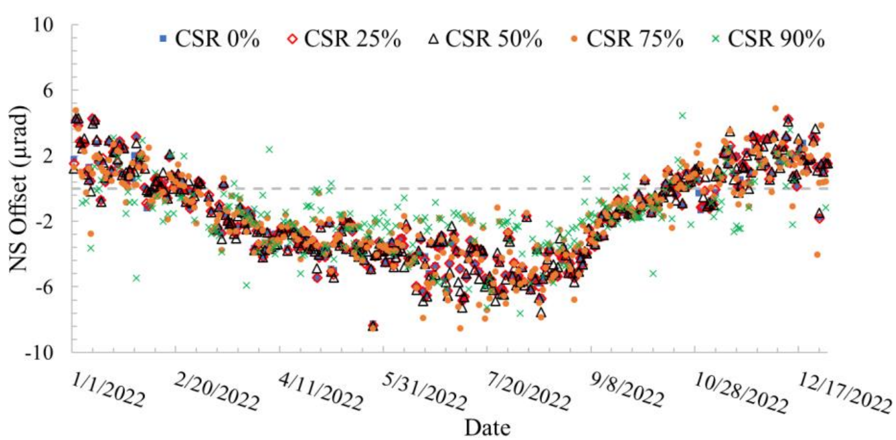

Figure 6: 24-hour mean CCR assessments in the NS direction for GOES-16 ABI in 2022. The CCR results are sourced from operational IPATS and filtered using CSR thresholds of 0%, 25%, 50%, 75%, and 90%, respectively.

Figure 6 illustrates the 24-hour mean CCR assessments using these five tested CSR thresholds for the year 2022. The amplitudes of the periodic model are recorded as follows: 3.77 µrad, 3.76 µrad, 3.74 µrad, 3.17 µrad, and 1.98 µrad, corresponding to the CSR thresholds of 0%, 25%, 50%, 75%, and 90%, respectively (Figure 7). The amplitudes of the periodic model remain relatively consistent until the CSR threshold reaches 90%. However, there is a substantial correlation between the average number of high-quality CCR measurements within 24-hour periods and the CSR threshold. This number decreases from 328 per 24 hours to 23 per 24 hours as the CSR threshold is increased from 0% to 90% (Figure 7). It is important to note that with a CSR threshold of 90%, there are no high-quality measurements at all during approximately 30% of the 24-hour periods in 2022.

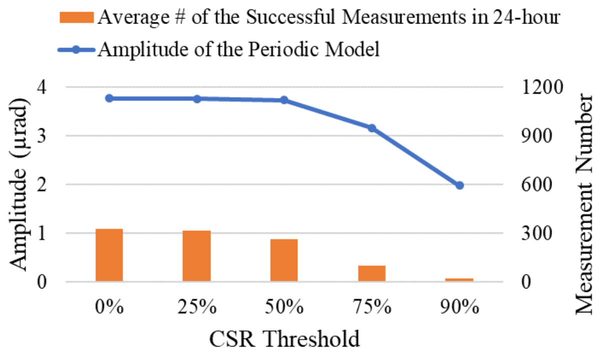

Figure 7: Variation of periodic model's amplitude and average 24-hour high-quality measurements with CSR threshold. The analysis pertains to GOES-16 ABI CCR for channel 13 versus channel 2 during the year 2022.

There are a couple of possible factors that undermine the effectiveness of the CSR mask filter. First, the percentage of cloud coverage may not be directly proportional to the impact of the cloud shadow. Even if the cloud coverage ratio is low, the impact of the cloud shadow can still be significant when it obscures ground features. Second, uncertainties in the cloud mask product itself can contribute to the overall uncertainties in the cloud mask filter. Overestimation or underestimation of the cloud coverage within the cloud mask product can diminish the effectiveness of the cloud mask filter.

3.3 Using smaller evaluation windows

In the operational IPATS, the CCR evaluation windows have dimensions of 256 by 256 pixels. To explore the effect of window dimensions, three smaller evaluation windows were tested: 128 by 128 pixels, 50 by 50 pixels, and 20 by 20 pixels.

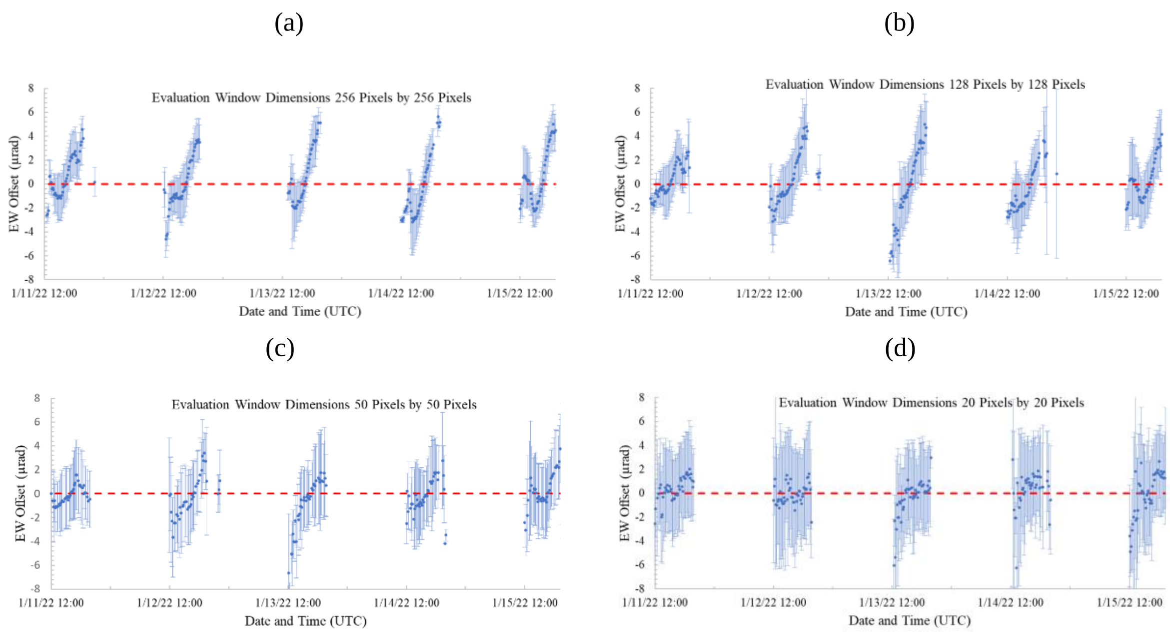

Figure 8. CCR assessments in the EW direction for G16 ABI scenes from January 11th to 15th of 2022. The dimensions of the CCR evaluation windows are as follows: a) 256 by 256 pixels, b) 128 by 128 pixels, c) 50 by 50 pixels, and d) 20 by 20 pixels.

As depicted in Figure 8, the diurnal variation of CCR EW offsets decreases as the evaluation window dimensions decrease, which aligns with expectations. However, concurrently the measurement uncertainty, represented by STD of the scene, increases. This increase in STD is attributed to the reduced number of image features within the smaller evaluation window, making the image registration process more challenging. A linear function (Eq. 2) is used to model the CCR results of each day to quantitively assess the diurnal variation in the EW direction. The larger slope of the linear model corresponds to a larger diurnal variation.

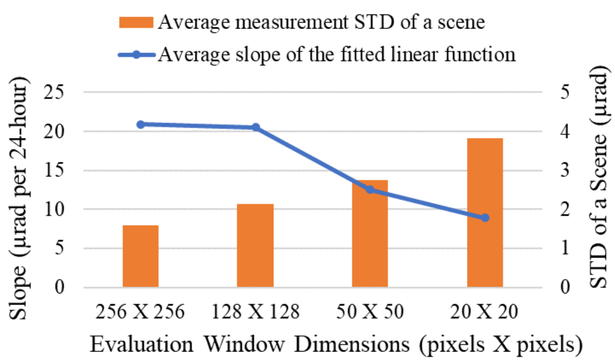

Figure 9. The changing of the slope of the linear model and the average measurement STD of a scene against the evaluation window dimensions

Figure 9 shows the changing of the slope of the linear model and the average measurement STD of a scene against the evaluation window dimensions. Among the three candidates, an evaluation window of 50 by 50 pixels emerges as the most suitable choice. The largest slope decrease, from 20.5 µrad/24-hour to 12.5 µrad/24-hour, happened when the evaluation window dimensions decreased from 128 by 128 pixels to 50 by 50 pixels. The average measurements STD of a scene increased most, from 2.75 µrad to 3.82 µrad, when the evaluation window dimensions decreased from 50 by 50 pixels to 20 by 20 pixels. Selecting 50 by 50 pixels strikes a favorable balance between reducing diurnal variation and limiting measurement uncertainty.

3.4 Integration of multiple methods

The effectiveness of the CSR filter was limited in the operational IPATS CCR results due to the dimensions of the CCR evaluation windows. However, its performance significantly improves with smaller evaluation windows and the improved distribution of evaluation locations depicted in Figure 4(b). Figure 10 presents the temporal plots of 24-hour mean CCR assessments with five tested CSR thresholds for 2022. CCR is assessed over the new evaluation locations with 50 by 50 pixel evaluation windows. The amplitudes of the periodic models are 2.60 µrad, 2.70 µrad, 2.68 µrad, 2.32 µrad, and 0.68 µrad for the thresholds 0%, 25%, 50%, 75%, and 90%, respectively. As the CSR threshold increases from 0% to 90%, the average number of high-quality CCR measurements in 24-hour periods drops from 1081 to 366 (Figure 11). Notably, only two 24-hour periods in 2022 lack high-quality measurements when the CSR threshold is set at 90%.

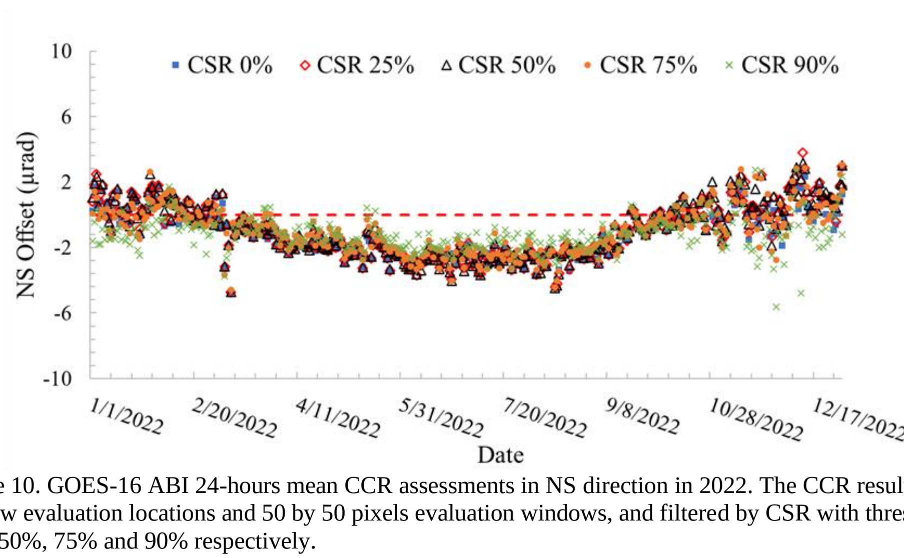

Figure 10. GOES-16 ABI 24-hours mean CCR assessments in NS direction in 2022. The CCR results are from the new evaluation locations and 50 by 50 pixels evaluation windows, and filtered by CSR with thresholds 0%, 25%, 50%, 75% and 90% respectively.

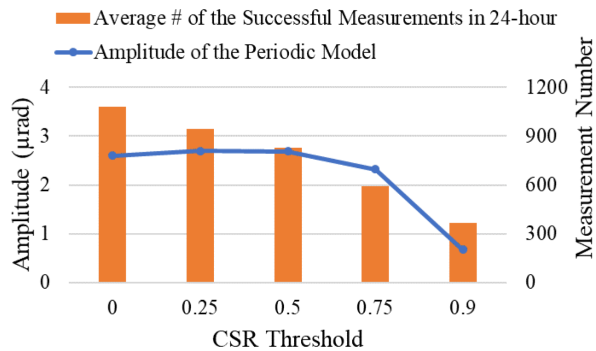

Figure 11. The amplitude and average 24-hour high quality measurements vs CSR threshold. The results are for GOES-16 ABI CCR of channel 13 versus 2 for all of 2022. The CCR is assessed with the new evaluation locations and 50 by 50 pixels evaluation windows.

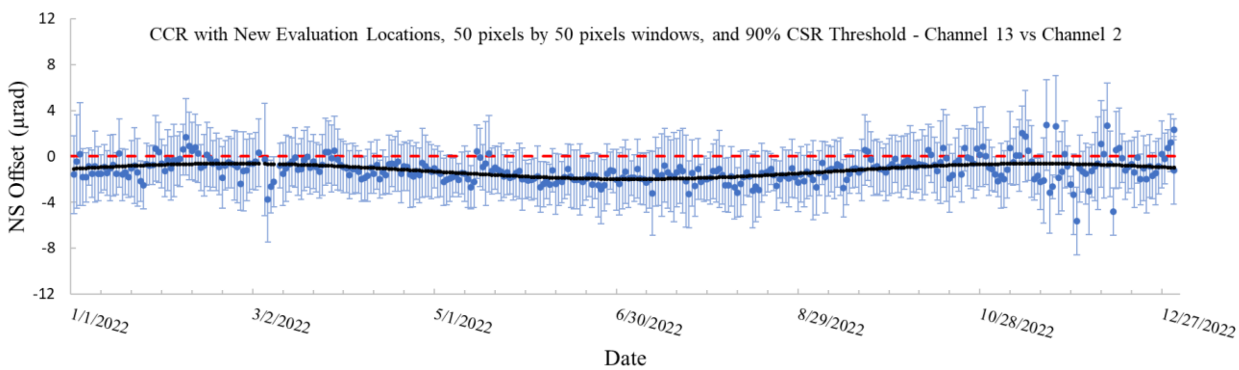

Figure 12. GOES-16 ABI CCR assessment results of the channels 13 and 2 in 2022. The blue dots are 24-hour mean CCR assessments and the error bars represent one standard deviation of CCR measurements in 24 hours. The black curve line is the periodic model. The CCR is assessed with the new evaluation locations and 50 by 50 pixels evaluation windows.

Figure 12 shows GOES-16 ABI CCR temporal plots of channel 13 versus channel 2 for the new evaluation locations with 50 by 50 pixels evaluation window dimensions. Compared to the operational IPATS CCR results (Fig.1), the amplitude of the periodic function decreases from 3.77 µrad to 0.68 µrad, indicating a significant reduction of cloud shadow effects. On the other hand, the average standard deviation of 24-hour high-quality measurements for 2022 increases from 1.71 µrad to 2.47 µrad.

4 CONCLUSIONS

The presence of cloud shadows introduces a periodic fluctuation in the accuracy of CCR assessments between GOES-R ABI VNIR and IR channel pairs, with an amplitude of approximately 3.77 µrad. Various strategies were explored to mitigate this impact. Filtering the results by NAV assessment led to a moderate reduction in amplitude of approximately 1.4 µrad. The CSR mask filter showed limited improvement until a CSR threshold of 90% was applied. However, the most effective approach to minimize the cloud shadow impact was by reducing the dimensions of the evaluation windows to focus more on ground features rather than cloud shadow features. Through the combination of reduced evaluation window size, evenly distributed evaluation locations, and the CSR filter, the NS CCR annual oscillation amplitude decreased from 3.77 µrad to 0.68 µrad.

This study highlights the often-overlooked significance of evaluation window size in image registration. Future research in this area should delve deeper into this topic. For instance, the evaluation window size for CCR/FFR assessments could be adaptive, adjusting based on actual image resolution. Additionally, to represent the same spatial ground cover, the window size could increase as view angles become larger.

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