

Optical Navigation Attitude Estimation and Calibration Performance Improvement using Outlier Rejection

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Spacecraft optical navigation (OpNav) systems process a sequence of images of celestial bodies against a star field background to estimate the position and velocity of the vehicle. While attitude is sometimes available from an onboard star tracker, it is often desirable to recognize the background stars in the OpNav images to better align the image. While many image processing algorithms exist for finding stars, efficiency and reliability remain key issues in the presence of extended bodies (e.g. the Moon, Earth), especially when attempting to solve the full lost-in-space problem. Some star outliers (stars identified with high residuals) could appear in the camera field of view, however using them in the attitude estimation or camera calibration would lead to less accurate results. Therefore, we require new and robust approaches to remove these outliers before any further processing.

The emphasis of the work is on developing a simple and robust iterative technique to detect and reject the outliers which could be found in any frame during the lost in space attitude determination or during the camera calibration. These outliers are determined based on the residuals of the centroids of the detected stars and the corresponding location using the star catalog. If the residuals exceed a predetermined threshold value, the object will be detected as an outlier and will be removed before another attitude determination and calibration iteration is performed.

The performance for both attitude determination and on-orbit camera calibration are improved by an almost two-fold increase in accuracy when applying this outlier rejection technique.

INTRODUCTION

The optical navigation (OpNav) camera measurement will be used mainly to provide vehicle position and velocity navigation information when the Moon/Earth is in the camera field of view (FOV). The attitude of the vehicle will be estimated using identified stars in the OpNav FOV. Therefore, a robust and accurate technique is required to estimate the attitude as well as the camera calibration from the imaged stars.

The outlier rejection introduced in this paper is a novel technique to remove the stars which have residuals greater than a certain predefined pixel threshold. This technique will ensure more

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accurate calibration parameters as well as more accurate star tracking attitude estimates from the stars with lower residuals. The star residuals are calculated after the first lost-in-space attitude is estimated.

When a star image is captured for both lost-in-space attitude determination and on-orbit camera calibration, star catalog data is used in conjunction with the camera's inertial attitude to determine which stars are expected to be in the camera's field of view. The pixel coordinates (u , v) of these expected catalog stars are then compared to the centroids of candidate stars from a starfield image. The difference in the pixel location of a candidate star and its matching catalog star results in two measurement residuals – a difference in the u (column) coordinate and a difference in the v (row) coordinate. A collection of measurement residuals for all matching candidate stars and catalog stars is then used to evaluate the quality of the attitude determination or camera calibration. Extending this measurement residual evaluation to include the identification of outliers offers the opportunity to increase the robustness and accuracy of these attitude determination and camera calibration algorithms.

For camera calibration a set of starfield images are taken with each image at a different attitude. The inertial attitude of the camera for each image is calculated and then used to determine which centroids within these images are likely identifiable stars. When a minimum number of stars for an image have been matched to a catalog star a data structure is then populated with that starfield image's attitude, number of matched stars, and catalog data for each matched star. After the full set of starfield images have been analyzed an array of starfield image structures is passed to a function that determines camera calibration parameters using an iterative Levenberg-Marquardt Algorithm.

The newly found camera calibration parameters are then used to compare expected catalog star locations to their respective matched image centroids. The difference in pixel coordinates of catalog stars and image centroids are collected in a measurement residual array. The residual array is then analyzed, and if a residual exceeds a predetermined threshold then the new camera calibration parameters are considered unusable. Unusable calibration parameters would at this point necessitate the collection of a whole new set of starfield images.

However, modifying the camera calibration process to include outlier identification and rejection prevents the need for collecting a completely new set of starfield images. This modification occurs after measurement residuals have been calculated by an initial calibration. Here the measurement residual array is used to calculate the normalized residuals for each pair of matched catalog star, image centroid in each starfield image. If the normalized residual for a matched pair is above a predetermined threshold, the centroid of that matched pair is considered an outlier. Information for matched pairs that meet or are below the threshold are kept within their respective starfield data structure – otherwise their information is filtered out. If at any point an outlier is found, a flag is set to run a second calibration using the now refined array of starfield data structures. The end result of this outlier filtering and recalibration technique are final camera calibration parameters that better fit to the majority of matched star centroid pairs.

LOSS OF COMMUNICATION NAVIGATION

NASA's Orion Multi-Purpose Crew Vehicle requires regular radionavigation-derived state updates from the Mission Control Center (MCC) to maintain an accurate navigation state throughout the mission timeline [Ref. 1]. In the event of communication loss, the onboard navigation estimate will diverge from the true trajectory due to unmodeled perturbations and

sensor drift. The Optical Navigation (OpNav) system provides a backup onboard source for navigation state updates, thus mitigating this hazard. More specifically, it provides range and bearing to a given target with the additional features of self-attitude determination, and real-time self-calibration. The software processes images, removes dark frames, undistorts images in real-time, and can be commanded to self-calibrate. Optical navigation functionality is a required part of the Orion spacecraft system [Ref. 2,3].

Figure 1 illustrates the timeline of Orion navigation with communication loss. The same high-level procedural steps of the OpNav system are used throughout the remainder of the mission. First, still images of Moon or Earth are processed to find apparent angular diameter and centroid in camera focal plane. Next, this raw data is transformed into range and bearing angle measurements using planetary data and precise star tracker inertial attitude. Finally, the measurements are sent to the main flight computer's Kalman filter to update the onboard state vector. Images are collected over an arc (~2hrs) to converge the state and estimate velocity. The same basic technique was used by NASA's Apollo program to provide navigation in the event of lost communication, but Apollo used manual crew sightings with a sextant instead of autonomously processing optical imagery.

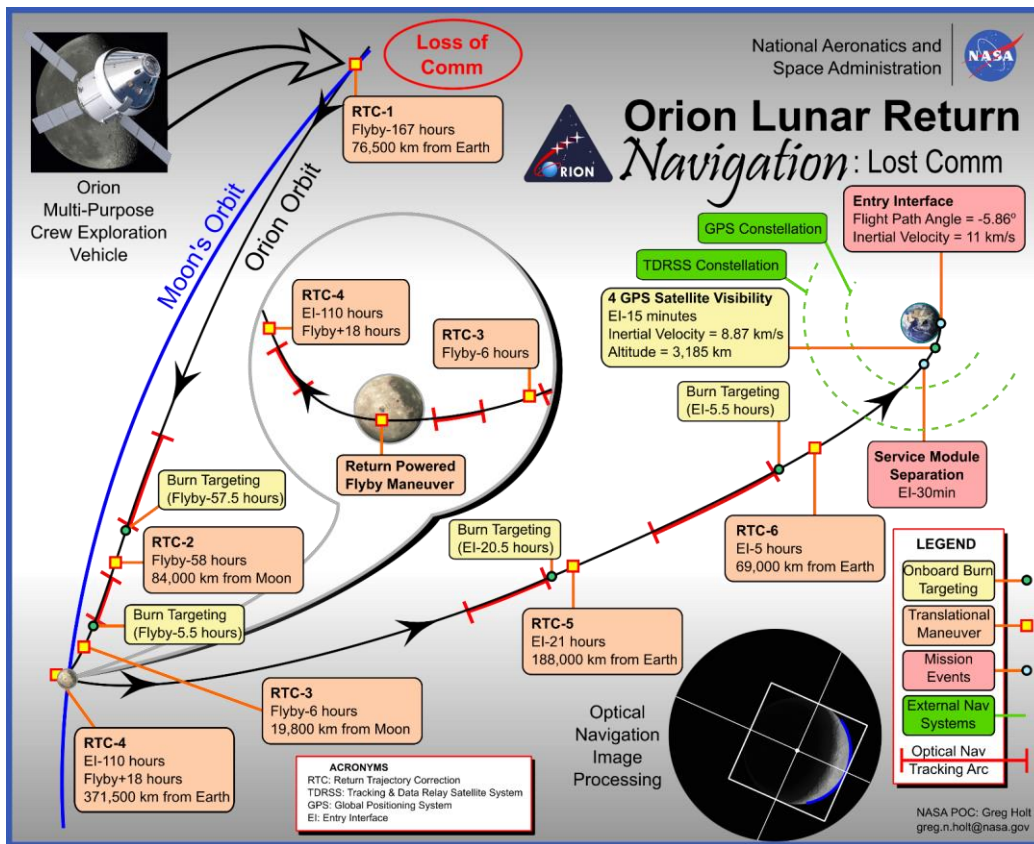


Figure 1. The outline of the Orion Spacecraft and the OpNav- Loss of Comm

OPNAV IMAGE CALIBRATION CONCEPT

The Orion OpNav image calibration capability analyzes an ensemble of starfield images to refine the estimates of the camera's geometric calibration parameters – five intrinsic parameters, five lens distortion parameters – and produce a distortion map. In addition, a corrected interlock angle (star tracker to camera) is determined if star trackers are used as a source to determine the camera attitude [Ref. 4-6].

Using star catalog data, a priori camera inertial attitudes, and the Brown distortion model, the calibration algorithm first identifies which stars will be projected onto the image and their expected pixel coordinates. The image itself is then processed beginning with dark frame removal. Next, centroids are identified and corrected for stellar aberration. Finally, the centroids and the expected catalogued stars are compared to determine which centroids are likely stars.

If there are enough images with a sufficient number of stars, the star centroid positions and their star catalog information are run through the iterative Levenberg-Marquardt Algorithm (LMA) [Ref. 7] to improve the intrinsic and lens distortion parameters, as well as the inertial camera attitude. Each image carries a separate alignment state, as such, these redundant attitude estimates are eventually combined using the QUaternion ESTimation (QUEST) algorithm [Ref. 8].

Measurement residuals are used to evaluate the quality of the calibration. Following the initial calibration, a check for any outlier centroids is performed. If an outlier is found, a second calibration with the filtered starfield image data will be run. The new camera calibration parameter estimates are used to generate a distortion map, and the inertial camera attitude correction is applied to the interlock angle.

OUTLIER REJECTION ALGORITHM

Outlier Rejection is a form of refinement made after an initial calibration. This refinement is done by removing star centroid data that skew the results of the initial calibration. A single outlier can cause the code to throw away an otherwise useful set of starfield images and necessitate the gathering of a whole new ensemble of images.

To deal with outliers, the Outlier Rejection algorithm normalizes measurement residuals obtained from the initial calibration and compares these residuals to a threshold. If the normalized residual is above the threshold, the corresponding centroid is considered an outlier. Outlier centroids and their associated data are then removed from the starfield data structure that fed into the initial calibration. This refined data structure is then used as input for a second calibration.

The algorithm is mainly comprised of two for-loops. The outer for-loop will iterate across every image in the ensemble, while the inner for-loop will iterate across every star in an image. During this process the starfield data structure used in the initial calibration is recopied. If an outlier is detected, the information for that outlier centroid is not copied to the data structure, and a recalibration flag is set to run a second calibration. A flowchart of the Outlier Rejection algorithm can be seen below in figure 2.

To ensure there are still enough valid centroids left for a second calibration, two checks are used. The first check makes sure that each image has at least the minimum number of valid centroids for a valid image. The second check makes sure that there are at least the minimum number of valid images for a valid ensemble. Both minimum number of centroid and minimum number of

image values are defined in an onboard configuration table. If an image is determined to have less than the minimum number of centroids, the image and its associated data is removed from the ensemble and data structure. If there are less than the minimum number of valid images left, then an error is set that there are not enough good images. If there is an error then a second calibration is not performed, and a whole new set of images will need to be collected.

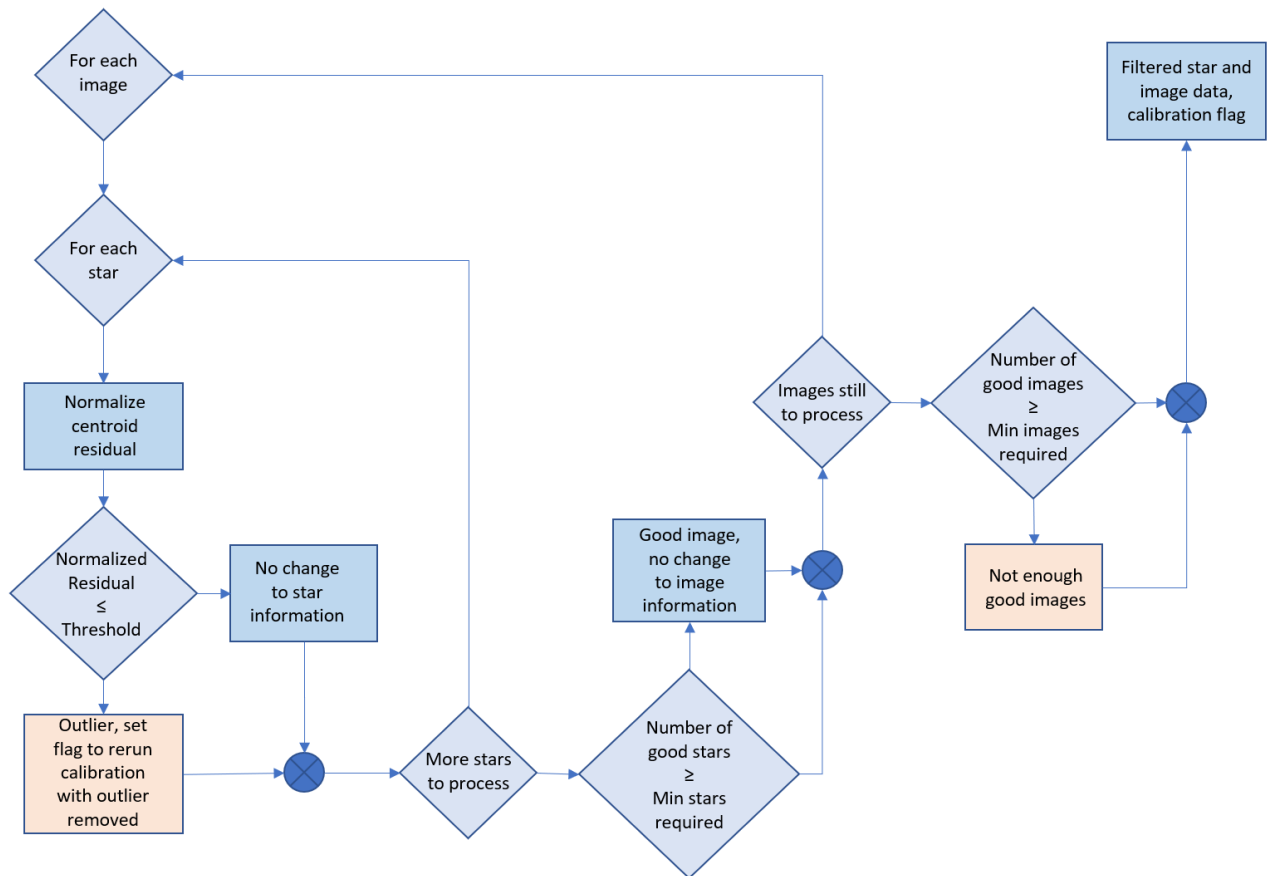


Figure 2. The Flowchart of the Outlier Rejection Technique

OUTLIER REJECTION MATLAB DRIVER

The outlier rejection technique described in the previous section was tested using several synthetic images created using NASA's Engineering Doug Graphics for Exploration (EDGE) package. These EDGE images are created using the OpNav hardware (Sensor/Lens) parameters and star catalog data similar to that which is loaded on the Orion spacecraft.

A MATLAB program is used to interface with the Lost in space algorithm (LISA) for the attitude determination. In this interface program, the outlier rejection may be either enabled or disabled. Additionally, the number of pixels to consider a rejected star is defined.

The program loads the simulated star image with an imager pixel size of $n_x=2592$, $n_y=2048$, a pixel size of 4.8 microns, and a field of view size of 16×20 degrees. Also, the associated true attitude is used for the quaternion error calculation.

Once the LISA has been performed and the estimated star quaternion, centroids, and inertial (cataloged) vectors are reported, the algorithm will execute the following steps:

1. The estimated attitude is used to calculate the projected star vectors in the camera FOV.

$$V_{proj} = A_{J2000}^{Cam} V_{inertial}$$

Where; V_{proj} is the projected star vector in the FOV, A_{J2000}^{Cam} is the direction cosine matrix that rotates a vector from the inertial frame to the camera frame, and $V_{inertial}$ is the star inertial (cataloged) vector.

2. Using the projected star vectors and the camera calibration parameters, calculate the projected stars in the FOV.

$$S_m = f/V(3)_{proj}$$

$$x_{proj} = \frac{n_x}{2} - S_m V(1)_{proj}/p_s$$

$$y_{proj} = \frac{n_y}{2} - S_m V(2)_{proj}/p_s$$

Where; x_{proj} and y_{proj} are the projected star location in the FOV, f is the focal length and p_s is the pixel size.

3. The residuals between the star centroids from LISA and the projected stars are then calculated.

$$Res_x = x_{proj} - x_{cent}$$

$$Res_y = y_{proj} - y_{cent}$$

Where; x_{cent} and y_{cent} , are the measured centroids of each star.

4. The norm of each star residual is calculated and compared against the predefined outlier rejection threshold (NumPixThre) for the number of pixel to consider a rejected star.
5. If any star has a norm of the residual greater than the NumPixThre, then this star will be rejected from further processing.
6. All the stars with less threshold are used for both the camera recalibration and attitude re-estimation using the The fast optimal attitude matrix (FOAM) for minimizing Wahba's loss function solves the optimal attitude matrix directly and efficiently [Ref. 9].

OPNAV ATTITUDE IMPROVEMENT RESULTS

The above Matlab driver is applied to test the outlier rejection technique and several EDGE simulated images are used to evaluate the performance of the proposed algorithm.

Figure (3) shows one of the OpNav star images with lens distortion and stellar aberration added to the simulated image. The associated results from the LISA are also projected on the simulated image. The star image has 18 centroided stars, shown as green circles, and 10 identified stars, shown as red stars. The total attitude error between the true attitude and the estimated attitude before applying the outlier rejection is about 48.17 arcsec.

Figure (4) shows the residuals between the measured star centroids and the projected star centroids in the FOV. Two candidate residual thresholds (NumPixThre) are shown. The red line is for NumPixThre equal to 2 pixels while the green line is for the NumPixThre equal to 3 pixels.

If the NumPixThre is 3 (green-line) pixels, then 1 star will be rejected from the list of the identified stars and only 9 identified stars will be used for the attitude estimation re-calculation, and the resulting attitude error will drop to 28.48 arcsec.

If the NumPixThre is 2 pixels (red-line), then 4 stars will be rejected from the list of the identified stars and only 6 identified stars will be used for the attitude estimation re-calculation, and the resulting attitude error will drop to 23.25 arcsec.

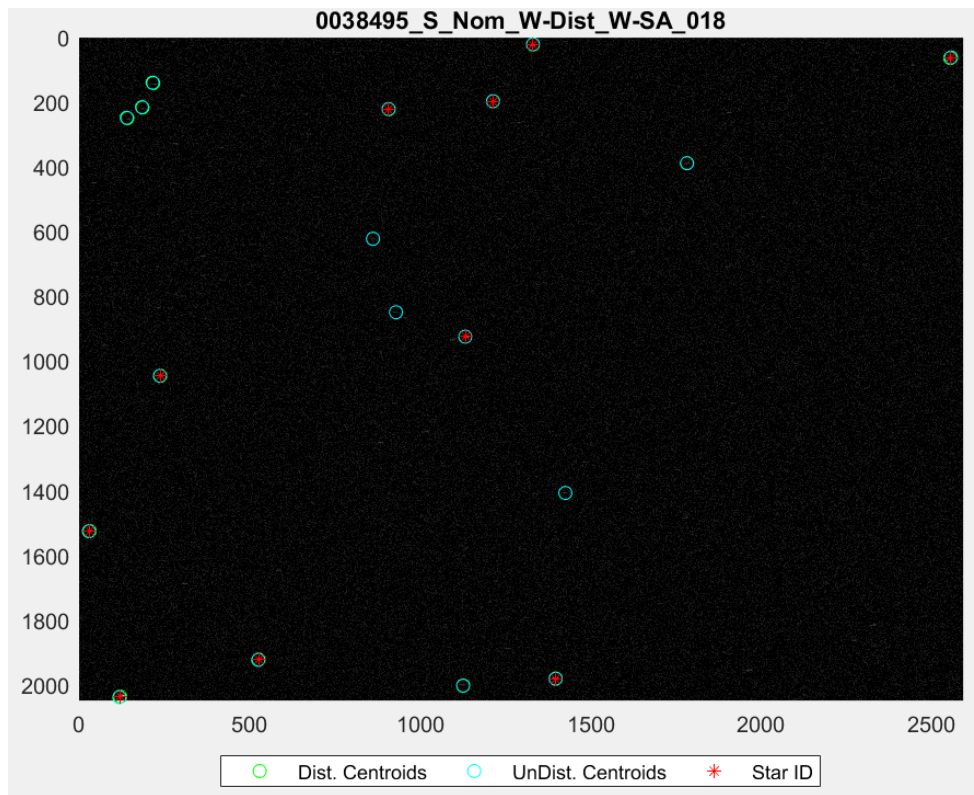


Figure 3. The image processing results for the OpNav star image

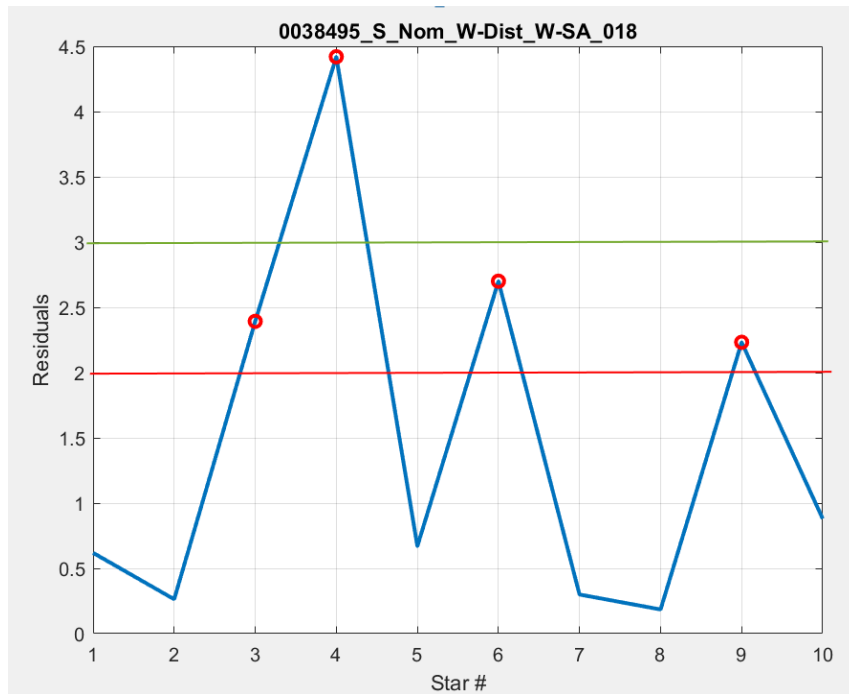


Figure 4. The Residuals of the star centroids in the FOV

The outlier rejection technique is also applied to 20 simulated images with a 0.18 deg/sec vehicle rotation rate. Figure (5) shows the true attitude of the simulated EDGE images. The resulting number of centroided stars as well as the identified stars for each image are shown in Figure (6). The attitude errors, the cross and about-boresight errors, and the total errors for each images are illustrated in Figure (7). The mean of total attitude errors is 24.88 arcsec, and the 3σ standard deviation is 28.7 arcsec. The 3σ for the cross/about-boresight errors are 14.09 arcsec and 28.74 arcsec respectively.

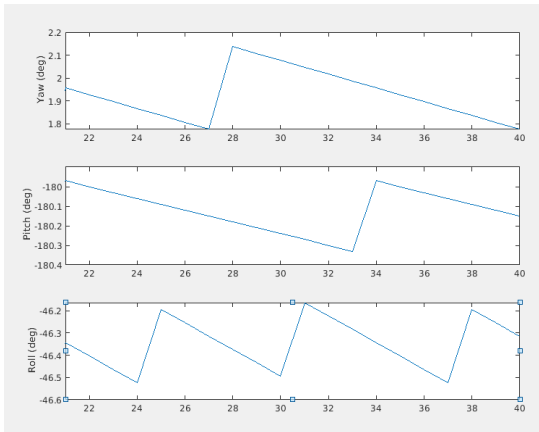


Figure 5. True attitude Yaw/Pitch/Roll (deg)

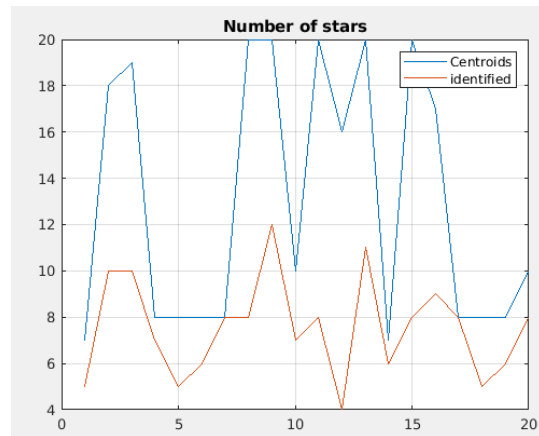


Figure 6. The number of centroided/identified stars

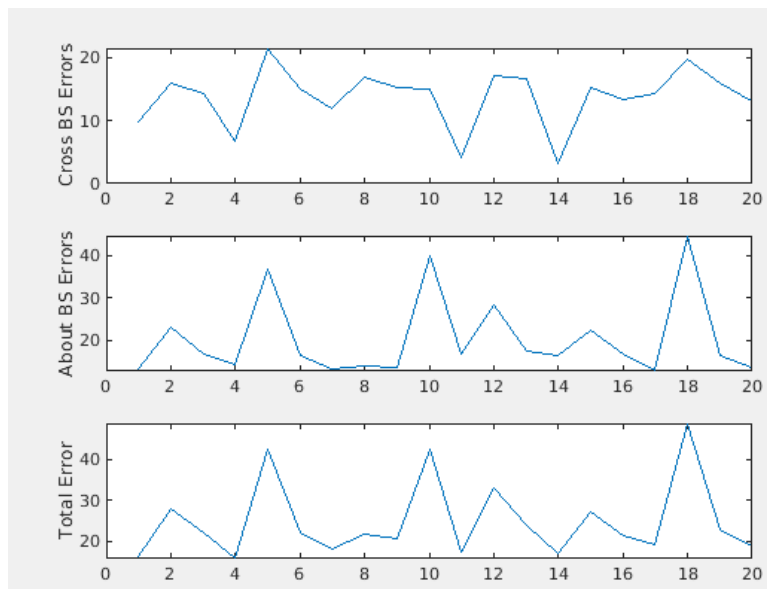


Figure 7. The attitude errors for each image

At least six images have one or two outlier objects for NumPixThre equal to 2 pixels. Figure 8 shows an example of one of these images that have 10 identified, with the two outlier stars near the corner of the image. If one of these stars is removed, the total attitude errors drops from 34.8 arcsec to 28.9 arcsec. If the other outlier star is also removed the total error drops to 24.03 arcsec.

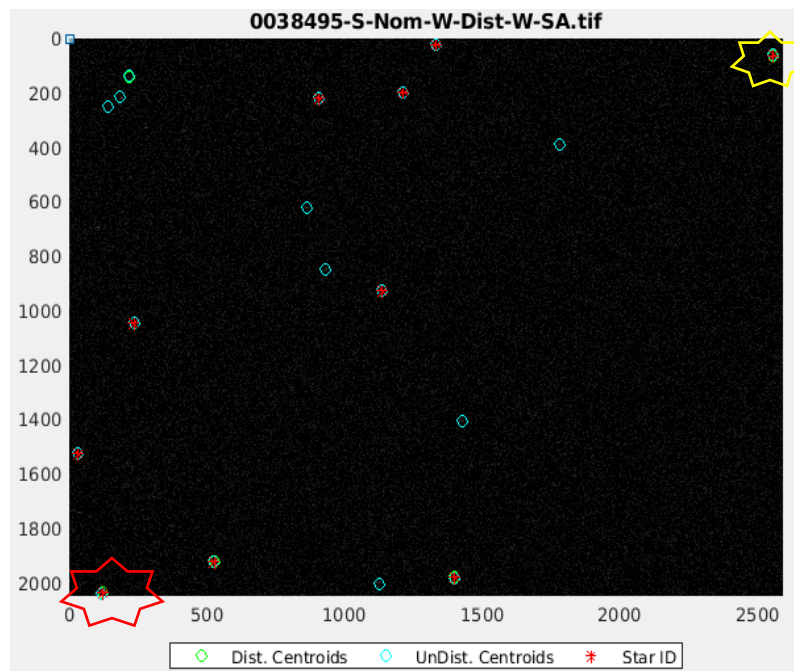


Figure 8. One of the star images with the outlier stars near the edges.

OPNAV CALIBRATION RESULTS: WITH AND WITHOUT OUTLIER REJECTION

One of the robustness tests for the Orion OpNav calibration software focuses on observing how it handles stars whose centroid location might be adversely affected by a non-stellar object near its Region-of-Interest (ROI). With the outlier rejection feature, the expectation is that such measurements will be dropped from the calibration data set, and calibration will be able to successfully complete.

Two cases were examined:

1. A non-stellar object overlapping a star (centroided as a single object)
2. A non-stellar object very close to a star, but not touching (centroided as two separate objects)

Case 1: Overlapping non-stellar object and star centroided as one

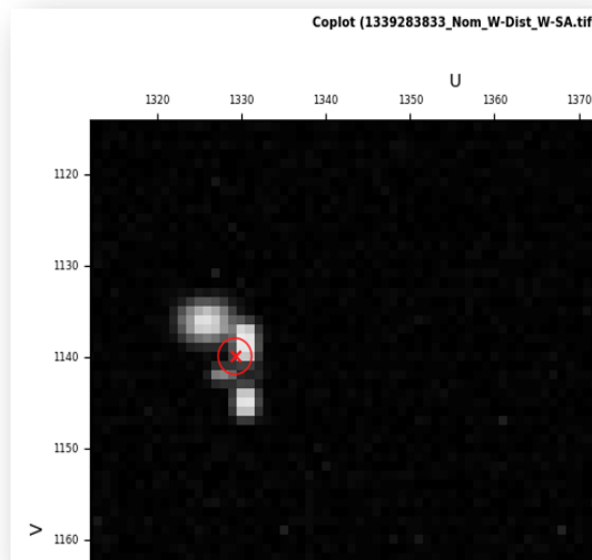


Figure 9. Overlapping object and star centroided as one

Figure 9 shows a non-stellar object, a star, and their centroided location as represented by the red “x”. Due to the non-stellar object, the star’s centroid is skewed away from it. Without the outlier rejection feature, calibration associates this centroid location with a star, and includes it in its calculations. This can be seen in Figure 10 where the green “x” marks represent centroids that have been identified as a star and used in the calibration. Ultimately, this causes the software to fail its measurement residual check. As such, the entire calibration is rejected, and a new set of images needs to be collected.

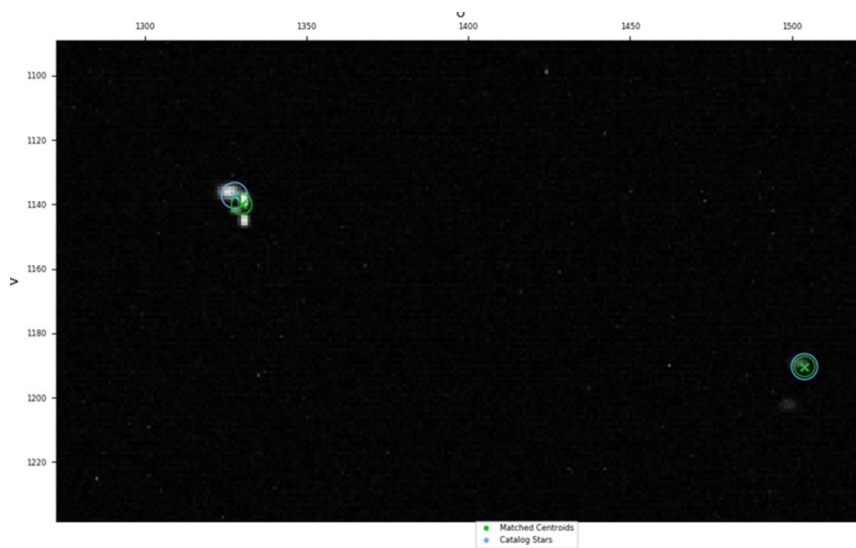


Figure 10. Zoomed-in view of the overlapping non-stellar object/star being identified as a star for calibration

Once outlier rejection is applied, however, the overlapping non-stellar object/star is discarded (see Figure 11), and the software is able to successfully complete and provide results within tolerance.

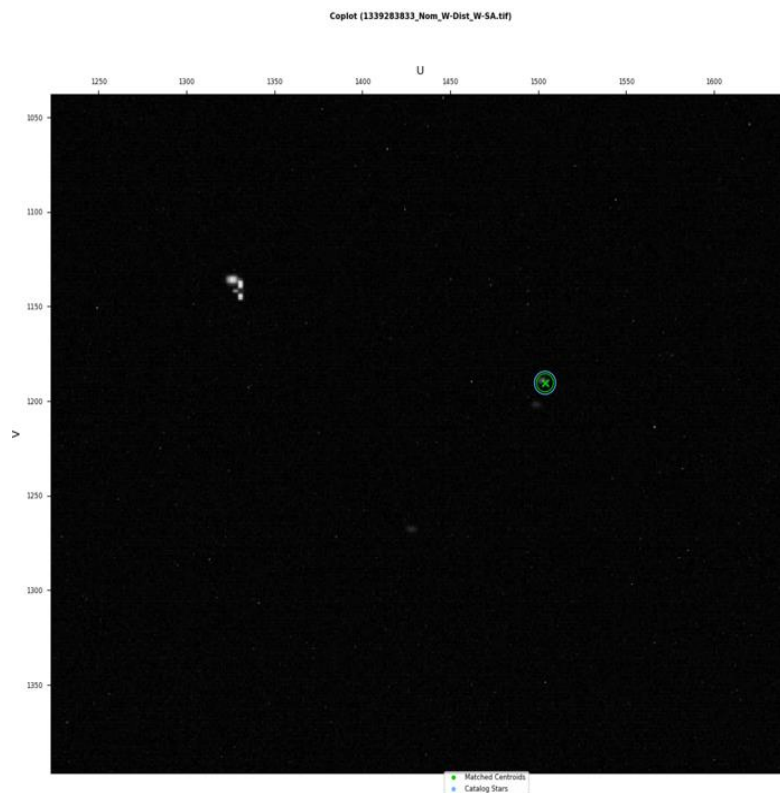


Figure 11. Zoomed-in view of the overlapping object/star not included in the calibration

Case 2: Non-stellar object within the ROI of a star, and centroided separately

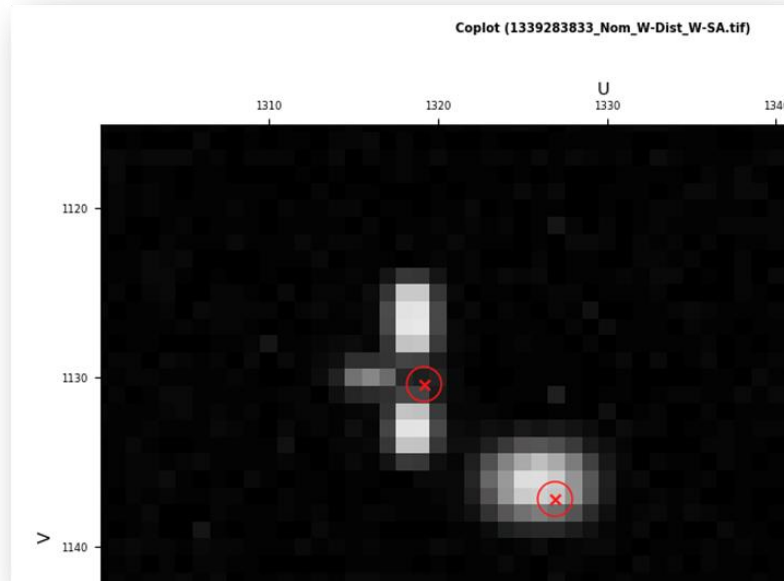


Figure 12. Non-stellar object near a star, and centroided separately

Figure 12 shows both a non-stellar object and a star, with their respective centroided locations represented by red “x” marks. With the non-stellar object being within a cataloged star’s ROI, both the non-stellar object and star are matched to the same cataloged star. This can be seen in Figure 13 where the green “x” marks show which centroids are identified as a star for use in calibration.

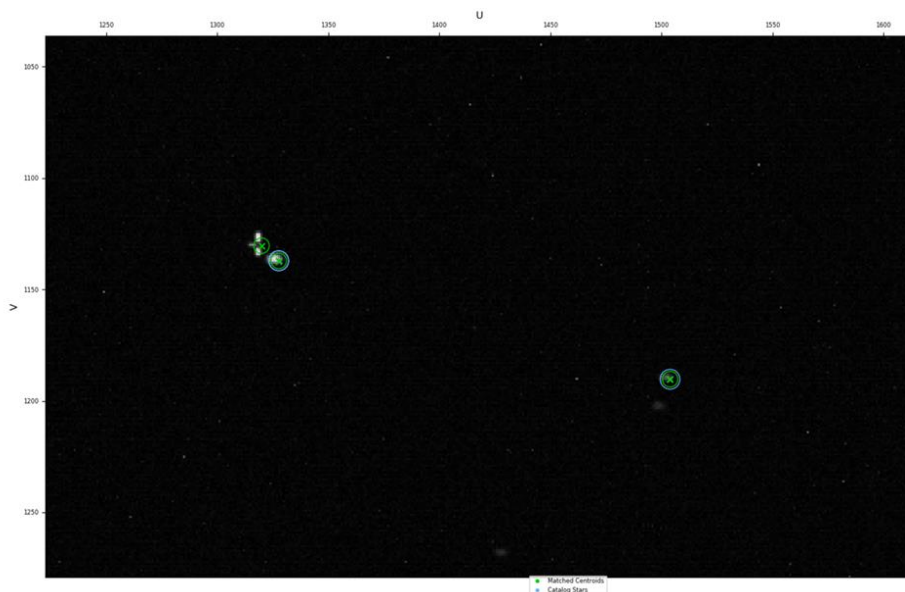


Figure 13. Non-stellar object and nearby star both matched to the (same) star

Similar to Case 1, the entire calibration routine would have failed due to the single high residual data point that the non-stellar object introduces, and a new set of images would be required. With the inclusion of the outlier rejection algorithm, however, that data point is dropped (see Figure 14), and calibration can complete successfully.

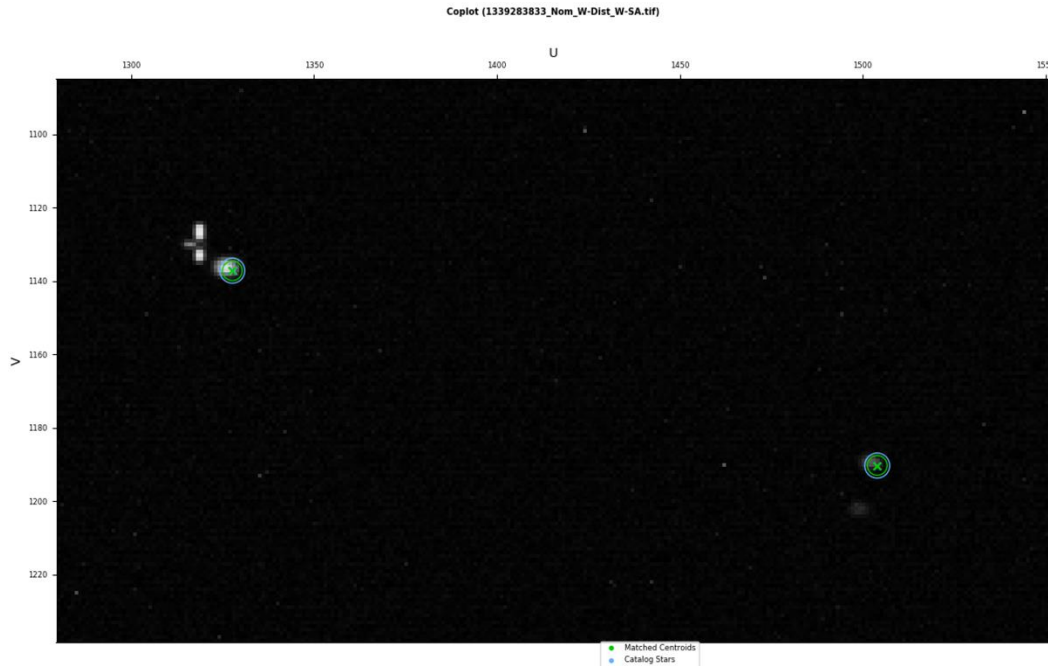


Figure 14. Non-stellar object is excluded from the calibration data set

As illustrated by these two test cases, the outlier rejection feature allows the calibration software to be robust against non-stellar objects in the field of view and, consequently, allows for a more efficient and simple concept of operations.

CONCLUSION

This paper introduces a new technique to detect and reject the outliers which could be found in any frame of the OpNav field of view during the lost in space attitude determination or during the camera calibration. This robust technique first determines the outliers based on the residuals of the centroids for the detected stars and their corresponding location using the star catalog. If these residuals exceed a predetermined threshold, the object will be detected as an outlier and will be removed before another attitude determination and calibration iteration is performed.

Several tests using single and multiple star images are carried out to test the performance for both the attitude determination and the camera calibration. These tests proved that the results are improved by an almost two-fold increase in accuracy when applying this outlier rejection technique.

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