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BACKUP OPTICAL NAVIGATION ATTITUDE FOR ARTEMIS-1 BACKUP ATTITUDE GROUND TOOL

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The Backup Optical Navigation Attitude (BONA) software was developed as a response to the Artemis1 Power Distribution Unit (PDU) hardware problems found early in 2021. The hardware problem, a capacitor installed incorrectly, removes the intended redundant path for which the PDU can relay its power and data to attached devices. Specific to the BONA context, the concern is that a failure of the single remaining path in this PDU would lead to an inability to communicate with one of the two-star trackers (STs) on Orion. By flight rule, being reduced to a single star tracker means an immediate turn around end-of-mission.

The BONA software is not intended to extend the mission, but instead act as a single star tracker attitude confirmation tool. Insurance, if you will, for the Orion project that a ground tool is available to compare the single remaining ST results with optical navigation images retrieved during the mission. Engineers operating BONA in the Mission Control Center (MCC) Mission Evaluation Room (MER) will analyze the downlinked star field images and based on the stars identified and known time of image, derive vehicle attitude estimates, which can be compared with the ST results. Potentially, in extreme situations, and with expert recommendation, the derivations could lead to navigation state updates being commanded to Orion.

INTRODUCTION

NASA's Orion Multi-Purpose Crew Vehicle requires regular attitude measurement updates from the onboard star trackers to maintain an accurate navigation state throughout the mission timeline [Ref. 1]. A backup optical navigation attitude tool is introduced in this paper in case of failure of the nominal navigation on-board Artemis-1. BONA is composed of two software components "***CORE***" and "***GUI***",

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both which are run in their own separate Linux based processes. The "CORE" process is a star-field to attitude computational software element. Given a suitable star field image from the optical navigation (OpNav) camera, image time, and various camera parameters, this software can derive quaternion values that can be used to define the vehicle's attitude. The "GUI" (Graphical User Interface) process is a python-based software that abstracts the task of properly executing the "CORE" process with the right inputs. Its purpose is to wrap the execution of the CORE process with a mouse-based interface intended to both ease and control the selection of user inputs, as well as post-process CORE output data further into a final usable product for the operators to analyze and assess.

Figure 1 depicts the full BONA software as it was intended to run in the MCC MER system, starting from the downlink of both starfield images, and existing vehicle attitude telemetry data. The images are analyzed by BONA, with the user selecting the proper images and camera configurations via the GUI. The GUI sets up and issues the commands for starting the CORE process, which derives an attitude solution. The GUI then further parses the output of the CORE process into easily readable tables for the operator to analyze and confirm. Finally, the GUI also provides the capability to interact with a pre-existing and well-known telemetry service provided by the MCC software environment called **OPS HISTORY**. From OPS HISTORY, the GUI requests vehicle navigated state telemetry which is also rendered to the operator for comparison and assessment with the CORE result.

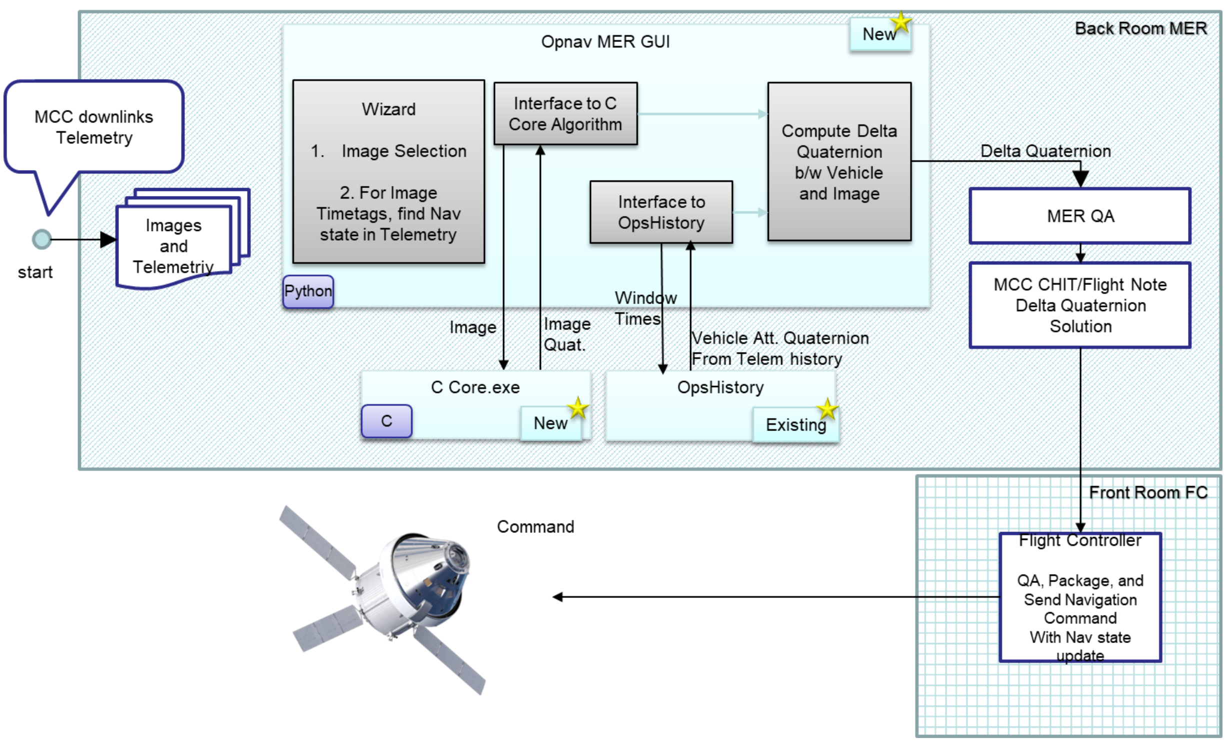

Figure 1. The Back Up Optical Navigation Tool System Diagram

OPNAV STAR TRACKER INTERLOCK ANGLE

Another related ground tool is the Star Tracker Interlock Angle Tool, which has the ability to calculate the ST to OpNav camera interlock angle. This tool takes OpNav [Ref. 2,3] camera star image attitude results from the CORE algorithm and measures the "interlock" or relative orientation of the star trackers relative to the OpNav camera.

Given CORE results, OPS HISTORY is queried at the appropriate time tag for ST telemetry, given as a quaternion representing the star tracker's attitude relative to ICRF.
The difference between the ST attitudes and the OpNav camera's attitude can then be calculated. These interlock quaternions are compared to the values last measured on-ground alignment during integration of the Orion vehicle. An angular difference between measured and expected is provided for each quaternion returned by the CORE.
Additionally, all the measured interlock quaternions are averaged for OpNav-ST1 and OpNav-ST2. The angular difference between this averaged value and the expected interlock is also provided.

The results of BONA tool for the delta quaternion as well as the interlock alignment will be supported and verified using both simulated images/data and on-orbit images/data downlinked during the Artemis 1 mission.

BONA MATHEMATICAL FORMULATION

The Backup Optical Navigation Attitude technique described in the previous section was developed based on the flowchart depicted in Figure 2.

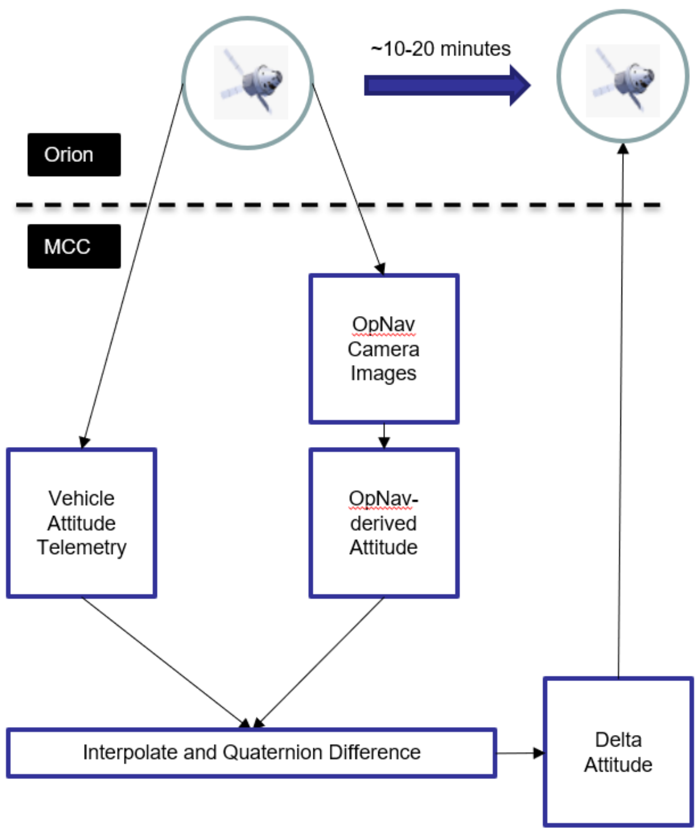

Figure 2. The flowchart of the BONA

During each walkthrough of BONA, the user can process several OpNav camera images at once. For each in this working set, BONA will walk the user through steps to compute a delta-attitude quaternion. All quaternions used in BONA are right-handed Hamiltonian convention.

BONA starts by processing the OpNav camera image with the CORE algorithm, which will output the camera inertial attitude. The CORE will report the estimated camera attitude $\boldsymbol{q}_{ICRF}^{Cam}$, as well as the observed star centroids in the image and the star vectors in the inertial frame. The locations of the star centroids and inertial vectors can be used by the user to visually confirm that centroids are being correctly computed. If the computed centroids do not pass visual inspection, then the image can be removed from the working set in BONA. This visual inspection is performed in addition to the internal error checks in the CORE algorithm.

Next, $\boldsymbol{q}_{ICRF}^{Cam}$ is rotated into the appropriate frame. The mission data book has the alignment values for the OpNav camera attitude with respect to the Orion Body frame, $\boldsymbol{q}_{Cam}^{OB}$. This is used to rotate the attitude as computed by the CORE algorithm. This gives us the first attitude that is used for the delta attitude computation.

$$\boldsymbol{q}_{ICRF}^{OB}{}^{ONV} = \boldsymbol{q}_{Cam}^{OB} \otimes \boldsymbol{q}_{ICRF}^{Cam}$$

Next, OPS HISTORY is used to extract the navigation channel’s attitude state at the same time tag as the OpNav image. From the Ops History query, BONA receives a time history attitude of the IMU with respect to the inertial frame, $\boldsymbol{q}_{ICRF}^{IMU}$ at a time range $\vec{t}_{OPS}$, where the image time tag t_i lies within $\vec{t}_{OPS}$. The time tags of the vehicle telemetry do not generally provide the attitude state at the exact same time tag as the OpNav image. So, a quaternion interpolation is used to interpolate the attitude of each channel at the OpNav image time to get the vehicle telemetry attitude at t_i. This gives $\boldsymbol{q}_{ICRF,i}^{IMU}$.

Next, $\boldsymbol{q}_{ICRF,i}^{IMU}$ is rotated into the appropriate frame. The mission data book has the alignment values for all of the IMUs with respect to the Orion Body frame, $\boldsymbol{q}_{IMU}^{OB}$. This is used to rotate the attitude as computed by the OPS HISTORY and the quaternion interpolation. This gives us the second attitude that is used for the delta attitude computation.

$$\boldsymbol{q}_{ICRF}^{OB}{}^{OPS} = \boldsymbol{q}_{IMU}^{OB} \otimes \boldsymbol{q}_{ICRF,i}^{IMU}$$

Finally, the delta attitude between both Orion Body inertial attitude is calculated using

$$d\boldsymbol{q}_{ICRF}^{OB} = \boldsymbol{q}_{ICRF}^{OB}{}^{OPS} \otimes \boldsymbol{q}_{ICRF}^{OB}{}^{ONV}$$

Note that the process above is performed for each image. After processing a set of *n* images, the user will have *n* corresponding delta attitudes. To compute the final delta attitude, the *n* delta attitudes are averaged together.

The average quaternion, given $\boldsymbol{q}_1$, $\boldsymbol{q}_2$, w_1, and w_2 (where w_1 and w_2 are the weights related to $\boldsymbol{q}_1$ and $\boldsymbol{q}_2$, respectively, and $w_1 + w_2 = 1$), is:

$$\boldsymbol{q}_{AVE} = \pm \frac{(w_1 - w_2 + z)\boldsymbol{q}_1 + 2w_2(\boldsymbol{q}_1^T\boldsymbol{q}_2)\boldsymbol{q}_2}{\|(w_1 - w_2 + z)\boldsymbol{q}_1 + 2w_2(\boldsymbol{q}_1^T\boldsymbol{q}_2)\boldsymbol{q}_2\|}, \qquad w_1 > w_2$$

$$= \pm \frac{2w_1(\boldsymbol{q}_1^T\boldsymbol{q}_2)\boldsymbol{q}_1 + (w_2 - w_1 + z)\boldsymbol{q}_2}{\|2w_1(\boldsymbol{q}_1^T\boldsymbol{q}_2)\boldsymbol{q}_1 + (w_2 - w_1 + z)\boldsymbol{q}_2\|}, \qquad w_2 > w_1$$

Where

$$z \triangleq \sqrt{(w_1 - w_2)^2 + 4w_1w_2(\boldsymbol{q}_1^T\boldsymbol{q}_2)^2}$$

The +/- signs in both above equations are selected according to the sign of $\boldsymbol{q}_1$.

For the special case where $w_1 = w_2 = \frac{1}{2}$,

$$\boldsymbol{q}_{AVE} = \frac{\boldsymbol{q}_1 + \boldsymbol{q}_2}{\|\boldsymbol{q}_1 + \boldsymbol{q}_2\|}$$

Over a set of *n* quaternions, a weighting scheme is introduced for *i* = 3, 4, …, n:

$$\boldsymbol{q}_{AVE}^{i} = QUAT\_AVE(\boldsymbol{q}_{AVE}^{i-1}, q^i, w_1^i, w_2^i)$$

with:

$$w_1^i = \frac{i-1}{i}$$

$$w_2^i = \frac{1}{i}$$

where q^i is the new quaternion to be average, and $\boldsymbol{q}_{AVE}^{i}$ is the previous averaged quaternion. Without this weighting scheme, a higher weight would be placed on the earlier average quaternion. This weighting scheme compensates for this.

The average delta attitude is computed using the methodology described above. This delta attitude will be used to correct the on-board attitude $\boldsymbol{A}_{ICRF}^{IMU}$in case of the loss of the star tracker attitude if its magnitude is within a certain threshold.

$$\boldsymbol{q}_{ICRF}^{OB^{corrected}} = d\boldsymbol{q}_{ICRF}^{OB} \otimes \boldsymbol{q}_{ICRF}^{OB^{onboard}}$$

BONA TEST RESULTS

The Backup optical navigation attitude tool was tested before and during the Artemis 1 mission using real OpNav Images along with the Star tracker data from the Ops History.

The tool GUI started with selecting the camera calibration parameters, which the image processing will be used later, as shown in Figure 3. The ground alignment of the Orion body to the OpNav camera is selected in this window as well.

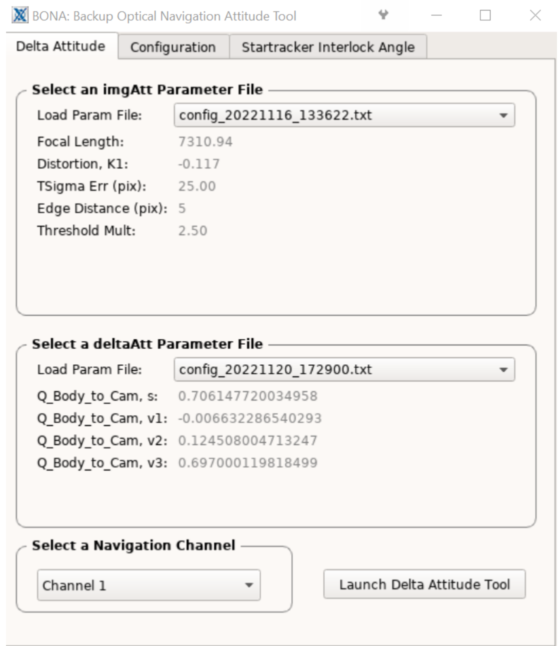

Figure 3. Selecting the imgAtt Calibration Parameters

After choosing the OpNav camera parameters and the alignment values for the camera body the GUI will ask to select a list of star images (up to 30 images) from a file list dialog to be processed through the imgAtt as shown in Figure 4.

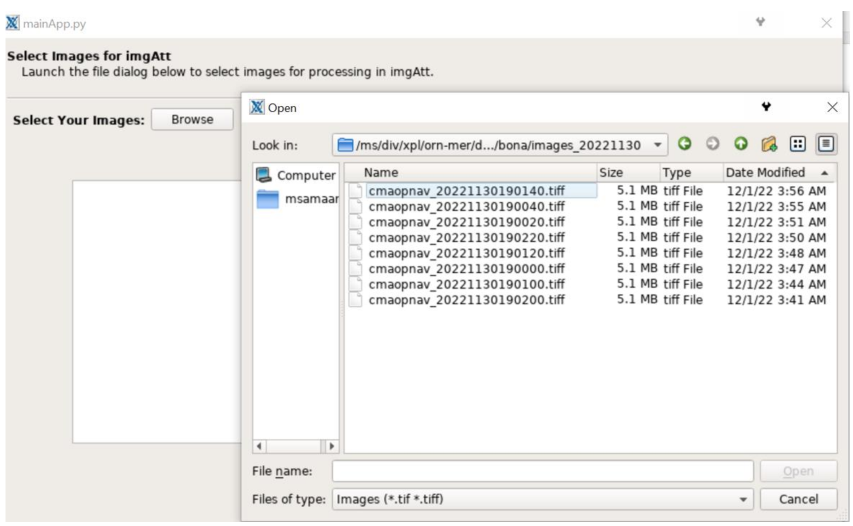

Figure 4. Selecting the OpNav Star Images

Once the OpNav star images are selected the tool will start with processing them using the imgAtt core algorithm. The GUI also will ask the user to select the dark frame option for the C core algorithm. The dark frame image is either selected from saved dark images or calculated using the average of the selected star images. The option to proceed without a dark image subtraction is the default selected option. The imgAtt algorithm outputs the quaternion and the status for each image as shown in Figure 5.

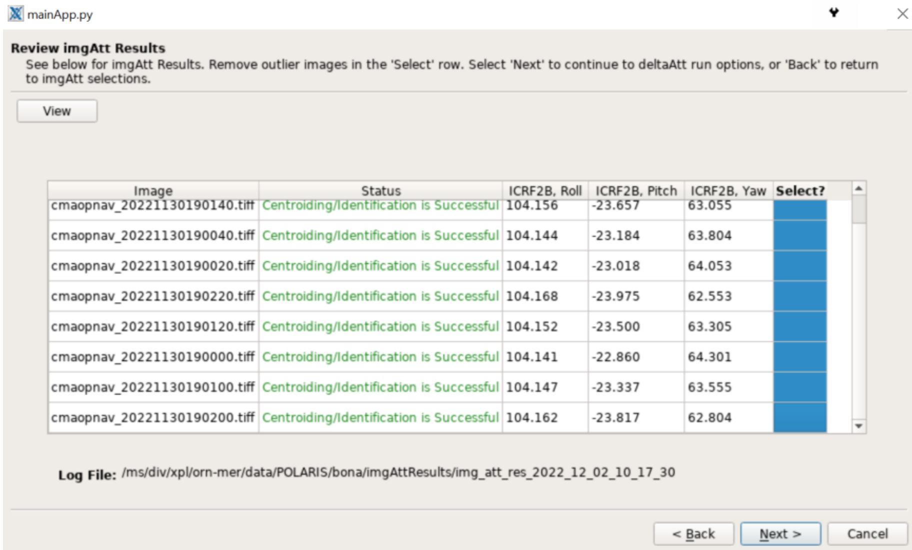

Figure 5. Review the imgAtt Results

The GUI user will have the option to view the resulting attitude and status message from the core algorithm and select/deselect images from the working set, if desired.
The user can also display and confirm the results each image with observed centroids with the 'View' button as depicts in Figure 6.

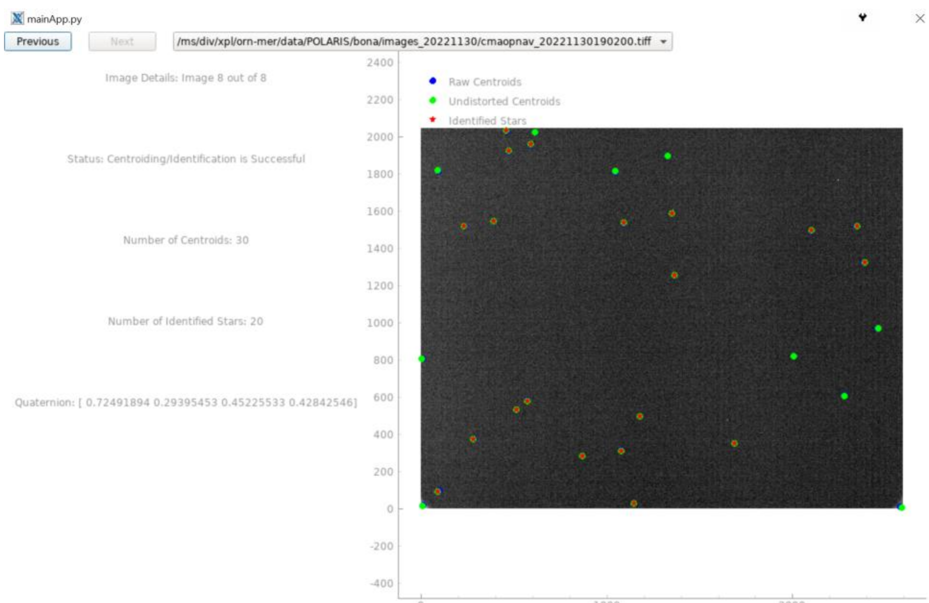

Figure 6. Review the Star Images with the Results

Finally, the GUI will extract the vehicle attitude telemetry from the three on-board channels and interpolate it at each time tag corresponding to each OpNav image. Furthermore, the resulting delta attitude for each image will be calculating and reported to the user to select/deselect the images which will be used for the final delta attitude calculation as shown in Figure 7.

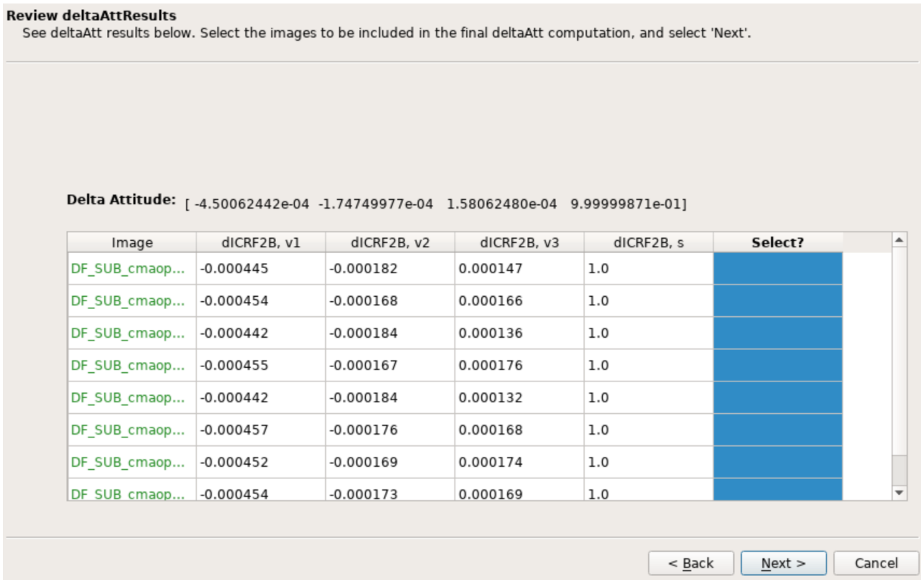

Figure 7. The Resulting delta Attitude for each Star Image

The rolling delta attitude average will be calculated based on the user selected images. The user will finally inspect the averaged delta attitude and choose either to send the command, using another MCC tool, to adjust the on-board attitude or repeat the whole process with new OpNav image set. Fortunately, we did not have to use the tool during Artemis-1 flight to adjust the on-board attitude but the whole tool was practiced several times to validate it's purposes. The total error of the delta attitude for the set of images used in Figures (5, 7) is about 292 arcsec if no dark image is used for the image attitude estimation while the error drops to 209 arcsec if a dark image is used for the attitude estimation algorithm.

INTERLOCK ANGLE RESULTS

Closely related to BONA is the Star Tracker Interlock Angle Tool (ST_Interlock), that has been used to calculate the Star Tracker (ST) to OpNav camera interlock quaternion.

ST_Interlock was planned to be used after launch of the Artemis 1 mission to determine if launch loads had significantly affected the alignment of the OpNav camera or star trackers. The ST-OpNav interlock quaternions are computed on-board as part of the OpNav calibration flight software, but the flight software requires an initial guess of the interlock that is very accurate (to within 200-300 arcseconds) [Ref. 4]. If launch loads perturb the expected alignments significantly, the OpNav calibration software could fail. ST_Interlock can be used to develop a configuration update to the OpNav calibration software that can allow recovery from such a situation.

Fortunately, the tool did not need to be used in flight for its intended purposes, but analyses are performed here using flight data to evaluate its performance.

First, a representative set of interlock quaternions was computed to establish a baseline for the as-flown interlock angles. The average of all the OpNav FSW-computed interlock quaternions was used as this baseline. The results of the ST_Interlock tool will be compared to these quaternions to evaluate performance of ST_Interlock.

The quaternion average here is computed using an eigenvector decomposition of a matrix containing the sum of the “projection operator” matrices for each quaternion, the projection operator being the outer product of the quaternion with itself (treating the quaternion as a 4x1 vector) [Ref. 5].

As part of the operation of the ST_Interlock tool, the images from each OpNav calibration pass were fed into BONA to produce CORE results files that contain the raw OpNav-ICRF quaternions for each image. The “Create Dark Frame” function was used for each calibration pass to produce the results. The ST_Interlock tool takes these results files and queries the OpsHistory database for star tracker telemetry data during the OpNav calibration pass. This telemetry is then searched and the individual Star Tracker-ICRF attitudes are interpolated using the SLERP algorithm to the exact time tag of the OpNav image.

Next, the ST_Interlock tool computes the interlock quaternions (OpNav-ST1 and OpNav-ST2).

Figures 8 and 9 show the results from the December 6, 2022 Artemis 1 calibration pass compared to the FSW average and the result from the ground calibration performed during vehicle integration [Ref. 4].

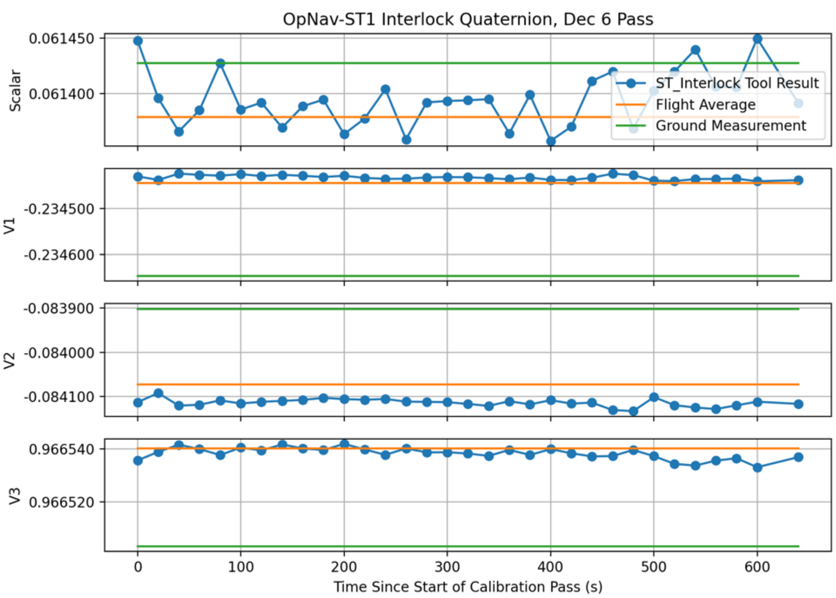

Figure 8. OpNav-ST1 Interlock Quaternion, Dec 6 Pass

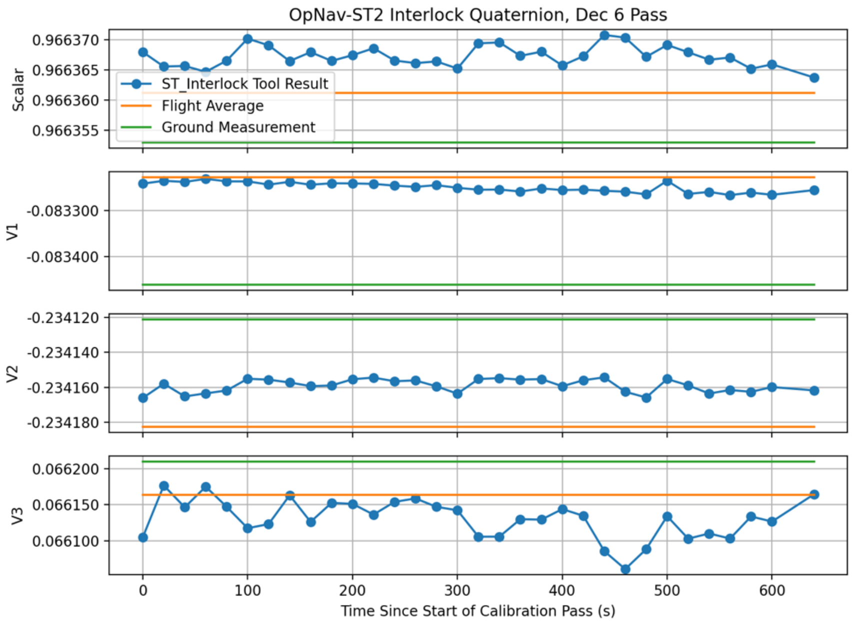

Figure 9. OpNav-ST2 Interlock Quaternion, Dec 6 Pass

Figure 10 and 11, show the differences between the interlock quaternions computed by the ST_Interlock tool and the FSW Average/Ground Calibration are shown below. Here we see that the ST_Interlock tool is providing results that closely align with the FSW-computed interlocks. This gives the team confidence that this ground tool works as designed.

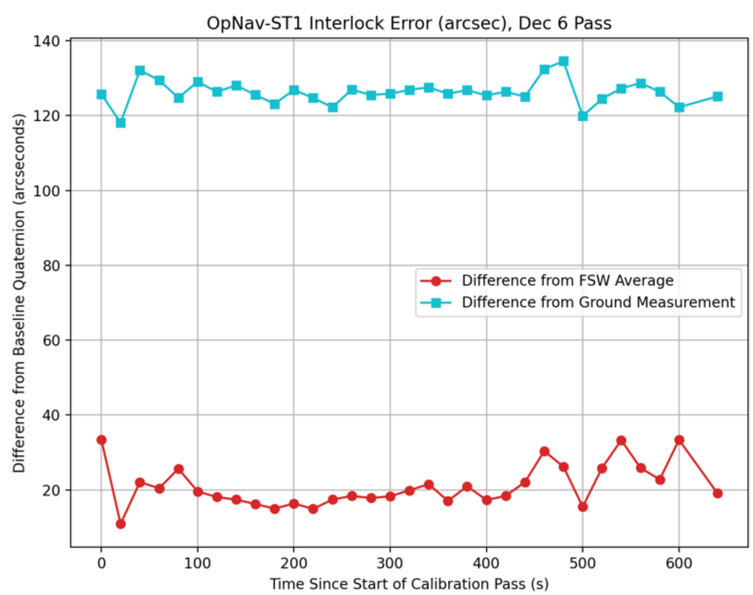

Figure 10. OpNav-ST1 Interlock Error, Dec 6 Pass

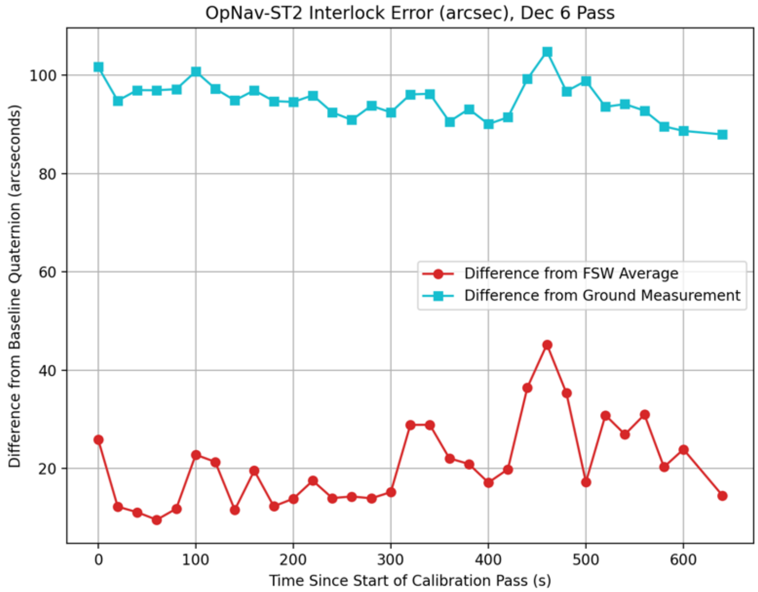

Figure 11. OpNav-ST2 Interlock Error, Dec 6 Pass

Next, for the purpose of this paper, the team has investigated any variance in computed interlock quaternions over the duration of the Artemis 1 mission. This analysis can give insight to potential structural shifting or reduction in performance of the OpNav Camera or star tracker hardware over the mission.

For this analysis, the average interlock quaternions for each OpNav calibration were computed and plotted in sequence as shown in Figures 12 and 13.

Also, the OpNav to both star trackers interlock angle errors as shown in Figures 14 and 15. With a few exceptions, the ~10 minute OpNav calibration passes were performed daily throughout the mission. The data has been organized to exclude data from passes where star tracker telemetry is incomplete due to "Loss of Signal" events or other issues with the ground processing of telemetry.

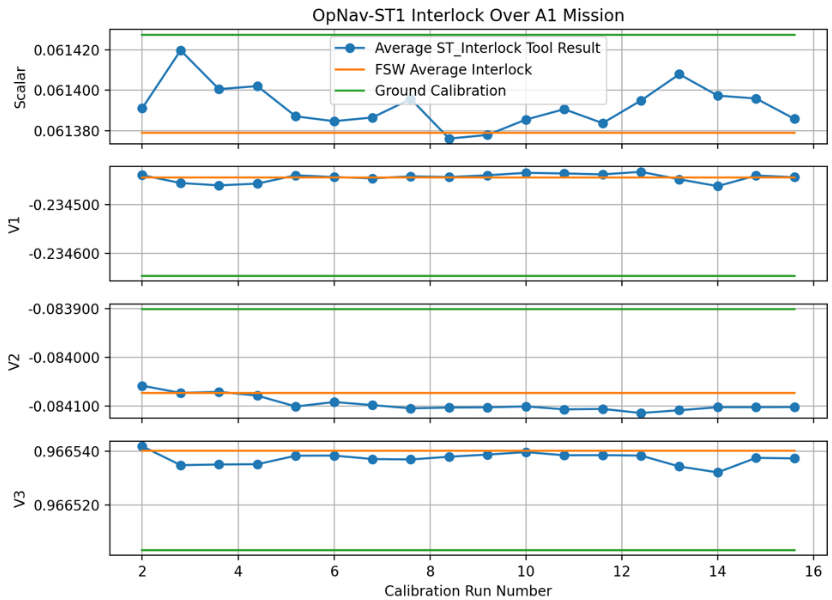

Figure 12. OpNav-ST1 Interlock Over Artemis-1

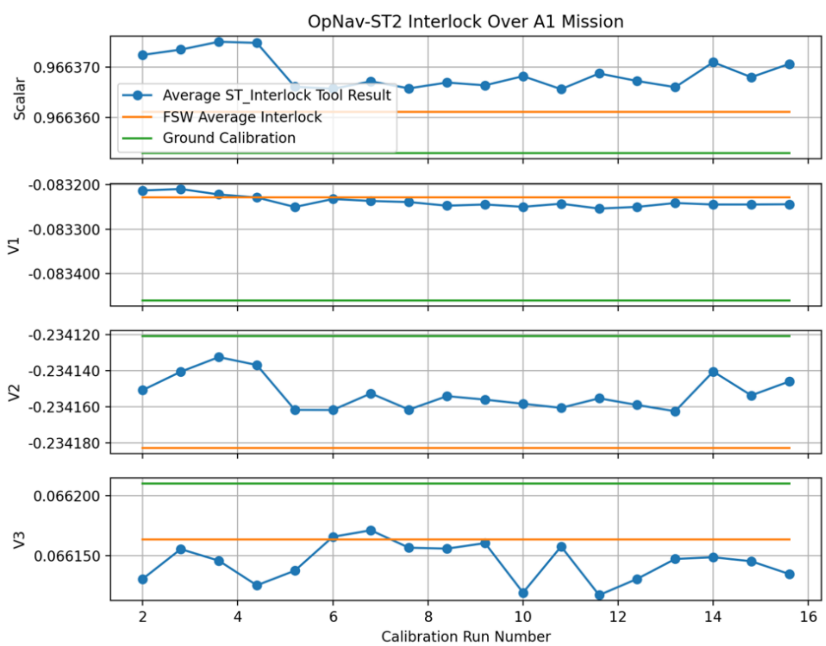

Figure 13. OpNav-ST2 Interlock Over Artemis-1

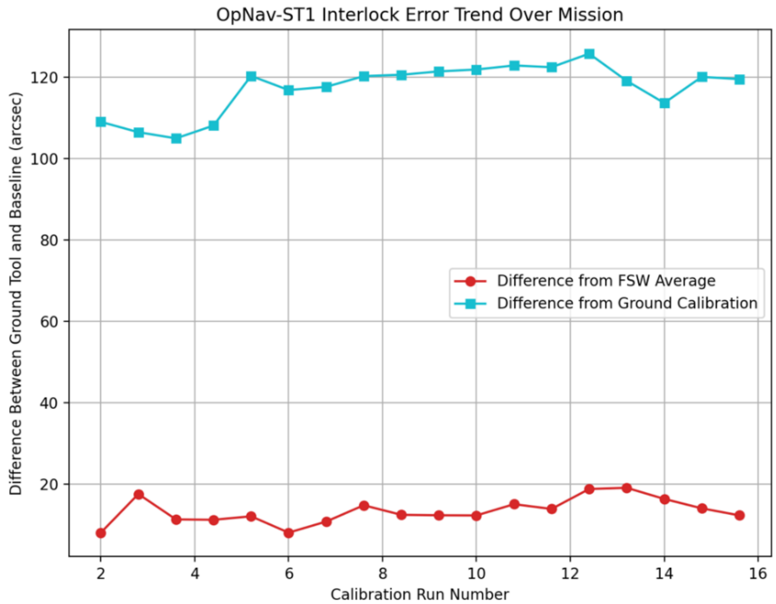

Figure 14. OpNav-ST1 Interlock Errors Over Artemis-1

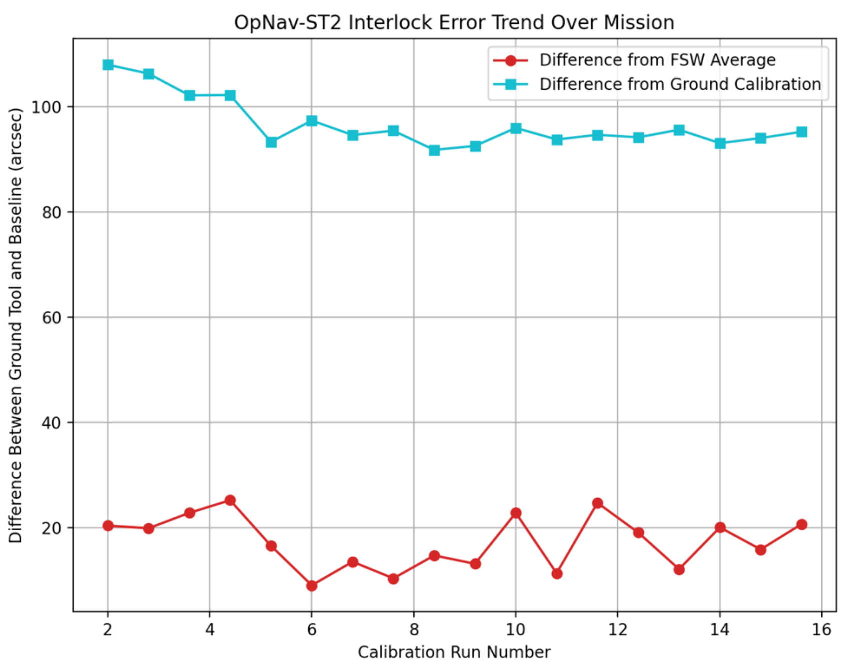

Figure 15. OpNav-ST2 Interlock Errors Over Artemis-1

While more in-depth analysis is planned to be performed with Artemis 1 flight data, the full-mission data largely matches the single-pass data previously shown. This gives the team further confidence in the performance of key ground tools and shows that there are no serious concerns with structural shifting or performance issues with star tracker or OpNav hardware that changed over the mission.

CONCLUSION

This paper introduces a new Backup Optical Attitude (BONA) tool to compute attitude and periodically provide delta attitude measurements to GNC in case the PDU S2 A fails during the Artemis-1 flight. While this situation never happened during Artemis-1, testing showed that with flight data, BONA computed a reasonable delta-attitude that could have been provided to GNC to update the state and rectify the IMU-based attitude error/drift.

Several successful tests before and during Artemis-1 are carried out to prove the purpose of BONA. To run BONA for testing, two pieces of data/information are required: the OpNav camera star field images and their time tags, and the vehicle attitude information at the image time tags from Ops History.

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