# CORRECTING FOR ROLLING SHUTTER DISTORTION IN DART OPTICAL NAVIGATION IMAGERY

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**Abstract.** *A key process in optical navigation (opnav) is the use of observed star centers, combined with a known camera model, to derive the pointing of a given picture*[1]*. This process typically produces attitude accuracies on the order of a tenth or hundredths of a pixel. However, as CMOS detectors become increasingly common in opnav cameras, so to does the use of a rolling shutter, as is the case for the Double Asteroid Redirection Test (DART) Didymos Reconnaissance and Asteroid Camera for Opnav (DRACO). A rolling shutter means that as the spacecraft deadbands, each readline is exposed at a slightly different attitude, thus distorting the resulting star pattern, and potentially inducing error to the process of estimating picture attitude. This paper details these effects on DRACO imagery, and the techniques developed to counteract them.*

**Introduction.** The DART spacecraft impacted Dimorphos, the smaller 180-meter diameter moon of the 65803 Didymos binary asteroid system, at 6.6-km/s on September 26th 2022[2]. The resulting change in the binary orbit period is now being measured to assess the effectiveness of a kinetic impactor for asteroid deflection. To accomplish this, an opnav campaign with 240 image sets taken every 5 hours starting 30-days from impact was designed to refine the Didymos-Barycenter ephemerides and enabled delivery of DART. This was accomplished with such accuracy, that given no thrusting, DART had a >99.7% chance of impacting Didymos instead. All opnavs were be taken with DART's only science instrument DRACO.

**DRACO.** DRACO is a modification of the Long Range Reconnaissance Imager (LORRI), flown first on the New Horizons spacecraft and now also on the Lucy spacecraft. The camera has a 0.29º x 0.29º field of view (FOV) with a CMOS detector. The detector produces 1024x1024 images with effective 13-µm pixels and an IFOV of 4.95 µrad. The full width at half maximum (FWHM) of the DRACO point spread function (PSF) is approximated by a gaussian with FWHM = 7.232/7.552-µm in x/y. This results in under-sampled PSFs, where the signal of a star can almost entirely fall into one pixel.

DRACO has two possible settings: global shutter and rolling shutter. While using global shutter avoids all the following outlined challenges, the global shutter is limited to low gain settings and suffers from higher read noise and popcorn pixels. The global shutter also has a built in background subtraction feature that is required for SMARTNav but would erase Didymos and stars on approach. The rolling shutter, with a gain 15 times the global, was thus required in order to image Didymos for most of approach.

**Rolling Shutter.** With a rolling shutter the exposure start time of each line is slightly offset and "rolls" from one end of the detector to another to complete an image, as depicted in Fig 1. In DRACO's case, the first lines exposed and read-out are the middle two lines 512 and 513. The shutter is then readout from these lines up and down at the same time, with 88 µs between the start of the current readline pair and the next. It takes 96.2-ms to readout the entire detector.

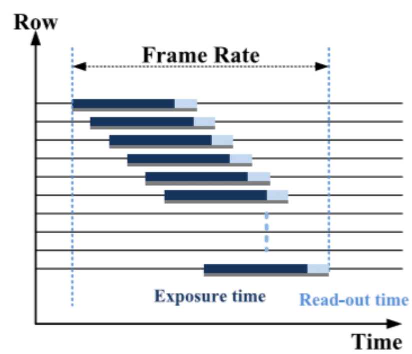


***Figure 1. Rolling shutter schematic***[3]

Critically, DART has thruster-controlled attitude and deadbands about a 0.07º box, at rates often greater than 10 pixels/sec. This attitude rate means that from the start of the first readline exposure to the last readline exposure, the attitude of DRACO will have shifted by 1 pixel. While typically a small distortion for the human eye, has the potential to significantly degrade opnav measurements which typically have accuracies on the order a tenths or hundredths of a pixel. For example, in a worst-case scenario, if Didymos is located at the first readline, and all the stars in the fields are clustered in the last readlines, the resulting attitude measured based on the stars can be around 1 pixel offset from the attitude of Didymos' readline, a 10x reduction in measurement accuracy.

**Pre-Flight Analysis.** Using attitude profiles simulated by GNC we modeled the rolling shutter distortion on images and developed techniques pre-flight to counter the expected effects. A few example attitude profiles are plotted in Fig 2. Using these profiles, we "distorted" stars and Didymos by adjusting their simulated locations by the appropriate amount given the drift rate and star readlines. We then registered these images with a basic gaussian centerfinder and compared the resulting attitude to the attitude of Didymos' readline. The worst-case resulting error introduced to a given 240 batch of simulated images on the measurement of Didymos is plotted in Fig 3. Depending on the deadband and resulting drift rate, there are clear clusters of biased data where the star field's distortion induces a consistent offset. The readlines that have the most stars have the most weight, and that can pull the attitude solution away from Didymos' readline.

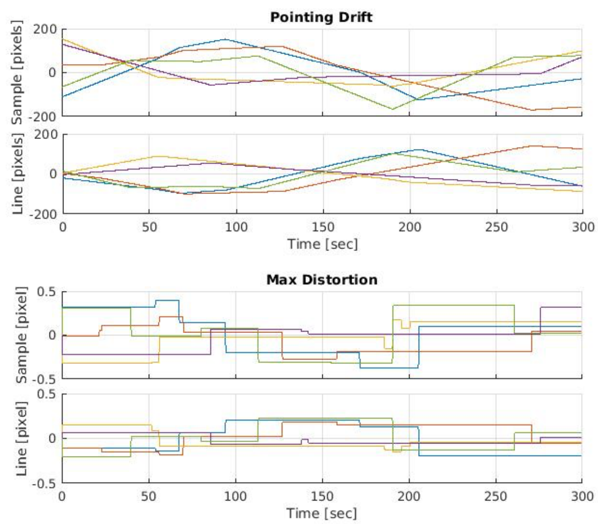


***Figure 2. GNC predicted attitude motion***

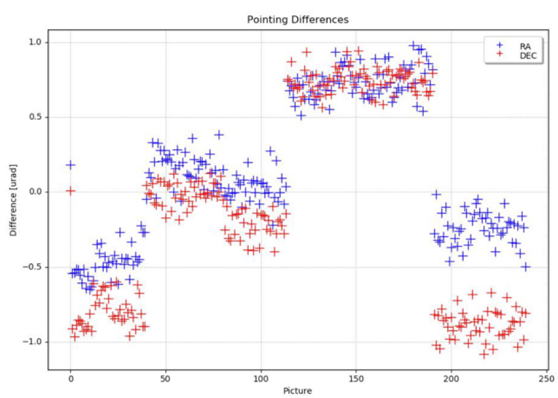


***Figure 3. Resulting measurement error with typical pointing estimation technique***

**Correction.** To limit these errors, we implemented two techniques, first a custom star weighting scheme, and then a distortion estimation step. The first step is a simple tweak of the standard pointing solution step. By weighting the stars closer to Didymos' readline more, we can skew the pointing solution toward those readline attitudes and reduce the effect of stars in readline attitudes that have drifted away from Didymos'. The weighting scheme implemented is outlined in Eq 1,2 and the result of this technique on the same data set is plotted in Fig 4. The errors are clearly reduced but still some effect is clear. Outliers also still clearly pop up as the distortion can get absorbed into erroneous twist estimates.

$$offset = readline_{didymos} - readline_{star} \quad \text{Eq. 1}$$

$$sigma_{star} = offset/(512) * 3 + 0.05. \quad \text{Eq. 2}$$

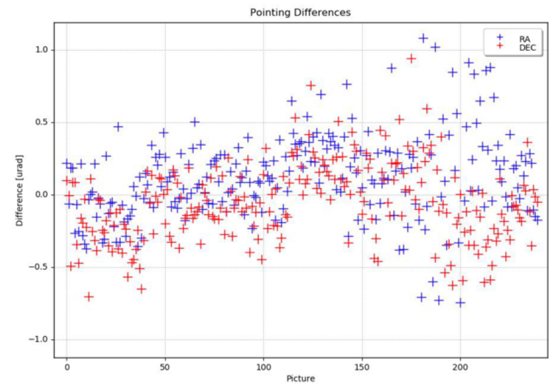


***Figure 4. Resulting measurement error with readline weighting pointing estimation technique***

The second step technique we implemented to minimize these errors was to estimate the distortion from directly from the residuals and attitude motion. Assuming a constant drift rate across a single image readout we can fit lines to the sample/line residuals vs readline. The slope of the lines is then the drift rate in pixels/second. Example fits to these simulated images are shown in Fig 5.

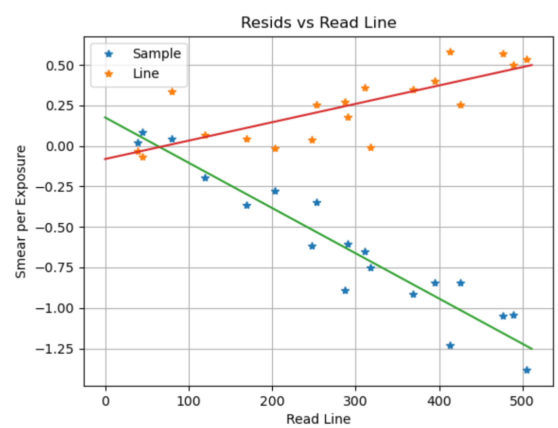


***Figure 5. Pointing solution residuals versus readline for a single image.***

Unfortunately, due to DRACO's undersampled PSF the individual centroiding on stars is only accurate to ~0.25 pixels and so the drift rate line fits in individual images can be noisy. To help correct this we identify different deadband drift regions and can average the fit slopes across multiple images to increase accuracy. With this measured the observed centers of stars and Didymos are simply adjusted by adding the sample, line drift rates times readline. We then re-run the pointing solution with the corrected star centers to give the complete measurement. The errors remaining after this step are plotted in Fig 6. After this step the signature originally shown in Fig 3 is nearly completely eliminated.

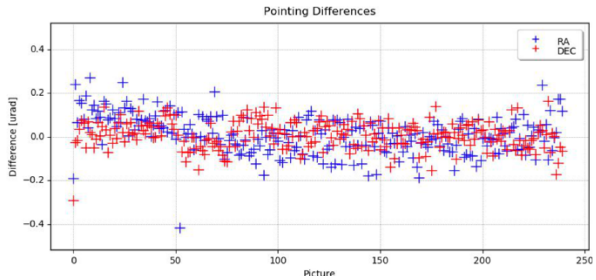


***Figure 6. Resulting measurement error with rolling shutter distortion estimation***

**In-Flight Application.**

While we prepared for the rolling shutter as much as possible pre-flight, in-flight was much more challenging. For the first half of approach, attitude drift rates were often 10x faster compared to the worst case GNC simulated profiles. Previously the worst-case drift rates produced roughly 0.5 pixel of distortion between first and last readline. In flight that max distortion was up to 5.0 pixels, making it very challenging to correctly estimate the attitude of Didymos' readline. An example attitude profile across 5 different image batches is shown in in Fig 7.

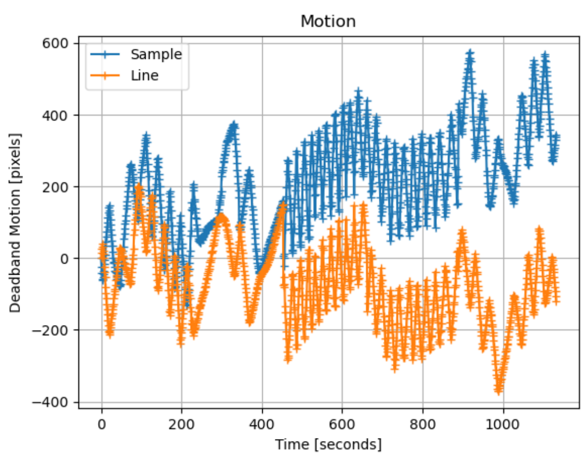


***Figure 7. In flight attitude motion in sample/line.***

Not only does this rapid deadbanding increase distortion, it reduces the number of images within each deadband regime, reducing our ability to average the estimated distortions. The chattering also induces additional vibration effects that add further noise to the observed star locations. While our process to estimate the deadband effects is able to improve the star residuals by ~50%, the added error is still evident as shown in Fig 8.

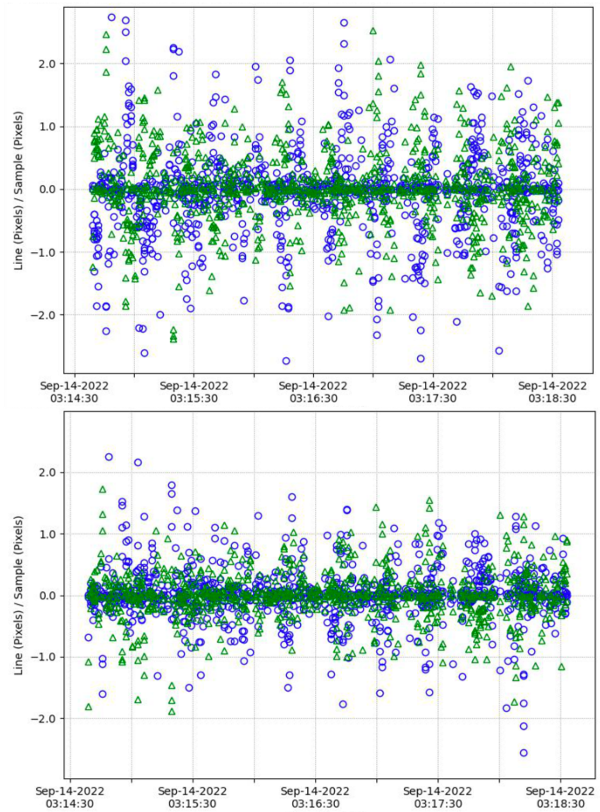


***Figure 8. Pointing solution star residuals. Top shows custom weight centerfinder results, bottom shows rolling shutter estimation results.***

The high drift rates not only made the rolling shutter estimation more complex, but also introduced smear that significantly reduced the SNR of Didymos. Ultimately our efforts to estimate the rolling shutter in the individual images had little effect in the final measurement as the dim Didymos signal required coaddition of large images batches via median filter subsampling[4]. These large batches of ~40-80 images include multiple different deadband regimes and so are combining fundamentally different images.

Even with this imperfect coadding, with such large sets we were still able to amplify star signals and reduce noise enough to increase our detectable star magnitude from roughly 13.5 to 14.5. The deeper fields then give more power to the custom weighting scheme as there will naturally be more stars with readlines near Didymos'. This handles any residual distortion that remains in the imperfect coadd output. With this process, even with 5-pixel distortions, our Didymos observations consistently fit with a standard deviation of less than 0.15 pixels 1-sigma during the first half of approach.

This measurement accuracy was sufficient to satisfy navigation requirements, however the rapid deadbanding also had the negative effect of introducing a large biased delta-v. While the general bias in the trajectory could be estimated and predicted out, the increased accelerations overall added uncertainty and so 11 days before impact, GNC successfully implemented a fix to reduce the deadbanding rates. As seen by the opnav attitude data, this resulted in 2x to 5x decreases in the drift rates. An example attitude profile is shown in Fig 9 which only has 4 significant deadband events across the image set.

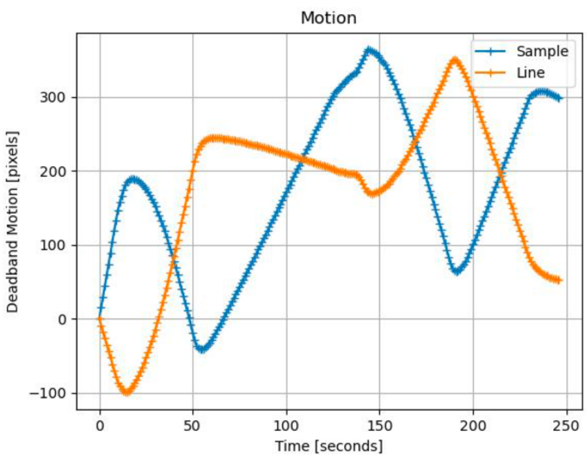


***Figure 9. In flight attitude motion in sample/line post GNC update.***

The reduced drift rates improved the opnav measurement quality significantly. High-end drift rates now distorted images by a max of only 1-2 pixels, smear was reduced, and the different deadbands could be clearly grouped and estimated. Fig 10 shows how Didymos' measurement quality changes when using a standard registration method versus the custom readline weighting versus estimating and correcting the distortion from the star residuals.

Without any mitigation steps the Didymos measurements have a clear profile that follows the different deadbands. By applying the custom weighting scheme, the bulk of the non-random signature is eliminated. After estimating the distortion, the last remnants of the deadbanding signature are flattened and the noise is random with a standard deviation of 0.07 pixels. These final observations can then be grouped and averaged to produce even more accurate observations.

Ultimately, with all these techniques, in the final week of approach we were able to derive measurements of Didymos with an accuracy of 0.01 to 0.03 pixels 1σ (4.95e-8 to 1.49e-7 urad), even with star fields distorted over a pixel. The final approach opnav residuals are plotted in Fig 11 highlight this performance.

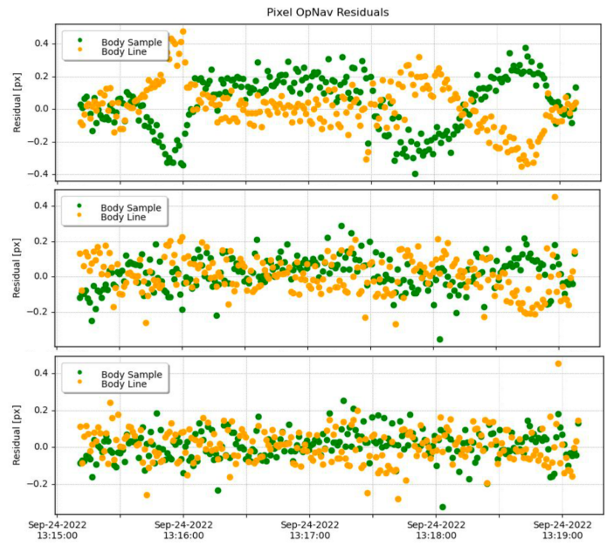


***Figure 10. Top, basic registration with centroid weights defined by star SNR. Middle, readline based star weighting. Bottom, distortion estimated and corrected from star residuals.***

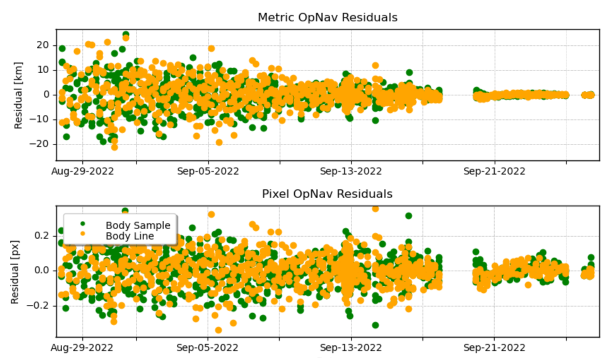


***Figure 11. Approach opnav residuals in metric and pixel space.***

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**References.**

[1] W. M. Owen, Jr, "Methods of Optical Navigation at JPL," AAS paper 11–215, Feb. 2011

[2] B. Kantsiper, A. Cheng and C. Reed, "The Double Asteroid Redirection test mission," *2016 IEEE Aerospace Conference*, 2016, pp. 1-7, doi: 10.1109/AERO.2016.7500625.

[3] Z. Liu,W.P., G. Weipeng, W. Shangsheng, "Improved Target Signal Source Tracking and Extraction Method Based on Outdoor Visible Light Communication Using an Improved Particle Filter Algorithm Based on Cam-Shift Algorithm," *IEEE Photonics Journal*, PP. 1-1. 10.1109/JPHOT.2019.2940773.

[4] "D. Mages, W. Owen, J. Riedel, "The benefits of subsampling optical navigation images as applied to the New Horizons flyby of 2014MU69", Paper presented at the 2nd RPI Space Imaging Workshop, Saratoga Springs, NY , 28-30 October 2019.