OSIRIS-REx
ASTEROID SAMPLE RETURN MISSION

Transition From Centroid-based to Landmark-based Optical Navigation during OSIRIS-REx Navigation Campaign at Asteroid Bennu

2nd RPI Space Imaging Workshop

Coralie D. Adam[1], OSIRIS-REx Optical Navigation Lead

Leilah K. McCarthy[1], Eric M. Sahr[1], Derek S. Nelson[1], John Y. Pelgrift[1], Erik J. Lessac-Chenen[1], Jason M. Leonard[1], Peter G. Antreasian[1], Eric E. Palmer[2], John R. Weirich[2], Robert W. Gaskell[2], Olivier S. Barnouin[3], Michael C. Moreau[4], and Dante S. Lauretta[5]

KinetX Aerospace
Space Navigation and Flight Dynamics Practice

NASA GSFC
Navigation and Mission Design Branch

[1]KinetX, Inc., Space Navigation and Flight Dynamics Practice, Simi Valley, CA 93065, USA.
[2]Planetary Science Institute, Tucson, AZ 85705, USA.
[3]The Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA.
[4]NASA/GSFC Navigation and Mission Design Branch, Greenbelt, MD 20771, USA.
[5]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85705, USA

UNIVERSITY OF ARIZONA NASA'S GODDARD SPACE FLIGHT CENTER LOCKHEED MARTIN

Outline

- Introduction to the Navigation Campaign
  - Activity schedule and shape model development plan
  - Orbital A OpNav imaging concept of operations
- OpNav Techniques
  - Shape model development via Stereophotoclinometry
  - Centroid-based observables
  - Landmark-based observables
- Landmark Transition ConOps and Success Criteria
- Centroid OpNav Results and Performance
- Landmark OpNav Results and Performance
- Conclusions

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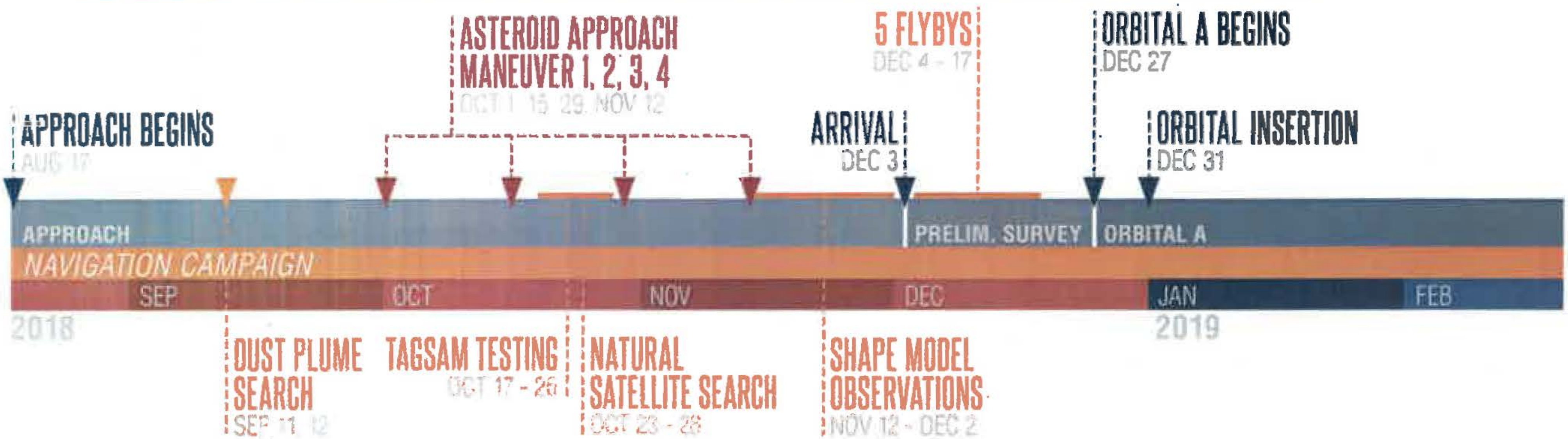
Navigation Campaign Overview

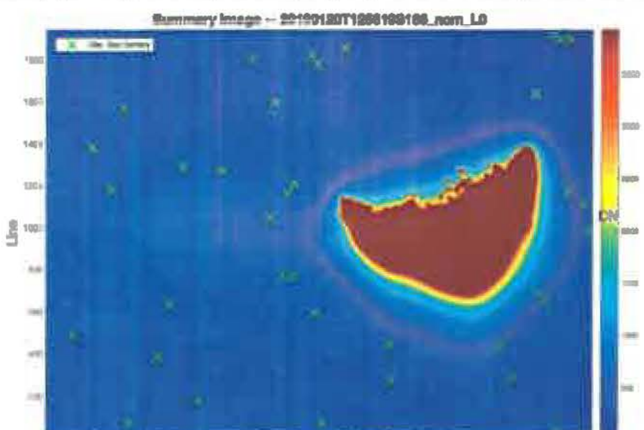


- Centroid-based OpNav utilized throughout Nav Campaign
- Landmark-based OpNav begins officially in Orbital A, with some preliminary work during Preliminary Survey
- Shape model development during Orbital A:
  - spc075draft.v1 delivered on 12/27
  - spc075draft.v7 delivered on 1/10 after first iteration with FDS
  - spc075draft.v9 delivered on 1/20 after second iteration with FDS

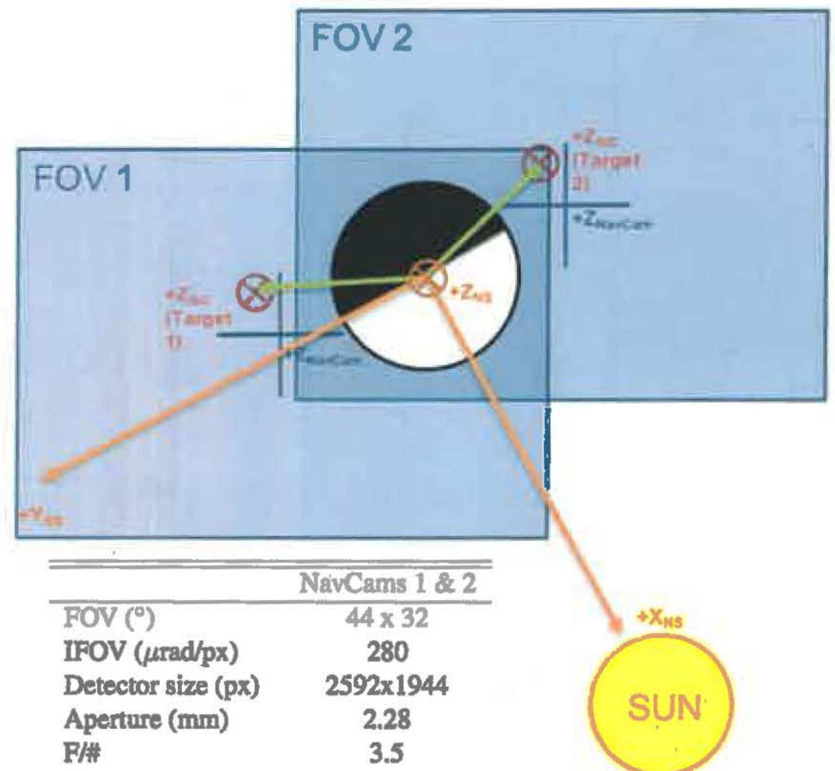
Orbital A OpNav Imaging Plan

- Two-hour imaging cadence
- 2 long-short image pairs at each 2x1 mosaic target
  - Ephemeris-relative targeting along spacecraft's down-track direction (largest predictive uncertainties)
  - GNC enables gyro-only propagation mode to minimize noise in attitude data sampling
- Attitude is
  - estimated from stars in long exposure
  - propagated via reconstructed attitude to short exposure image (~7 seconds earlier)
- OpNav observables computed from short exposure

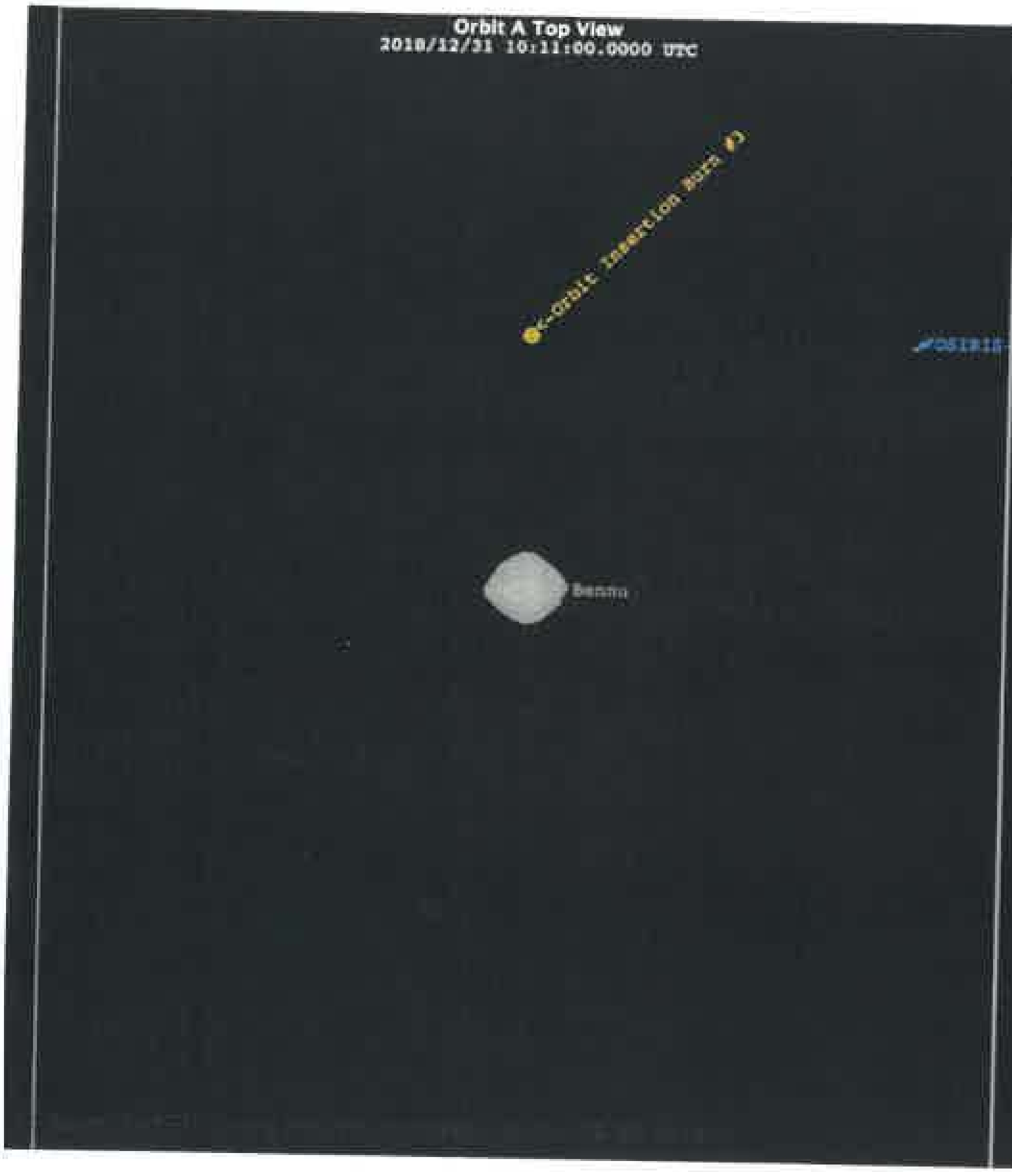
Long Exposure image of Bennu and Stars

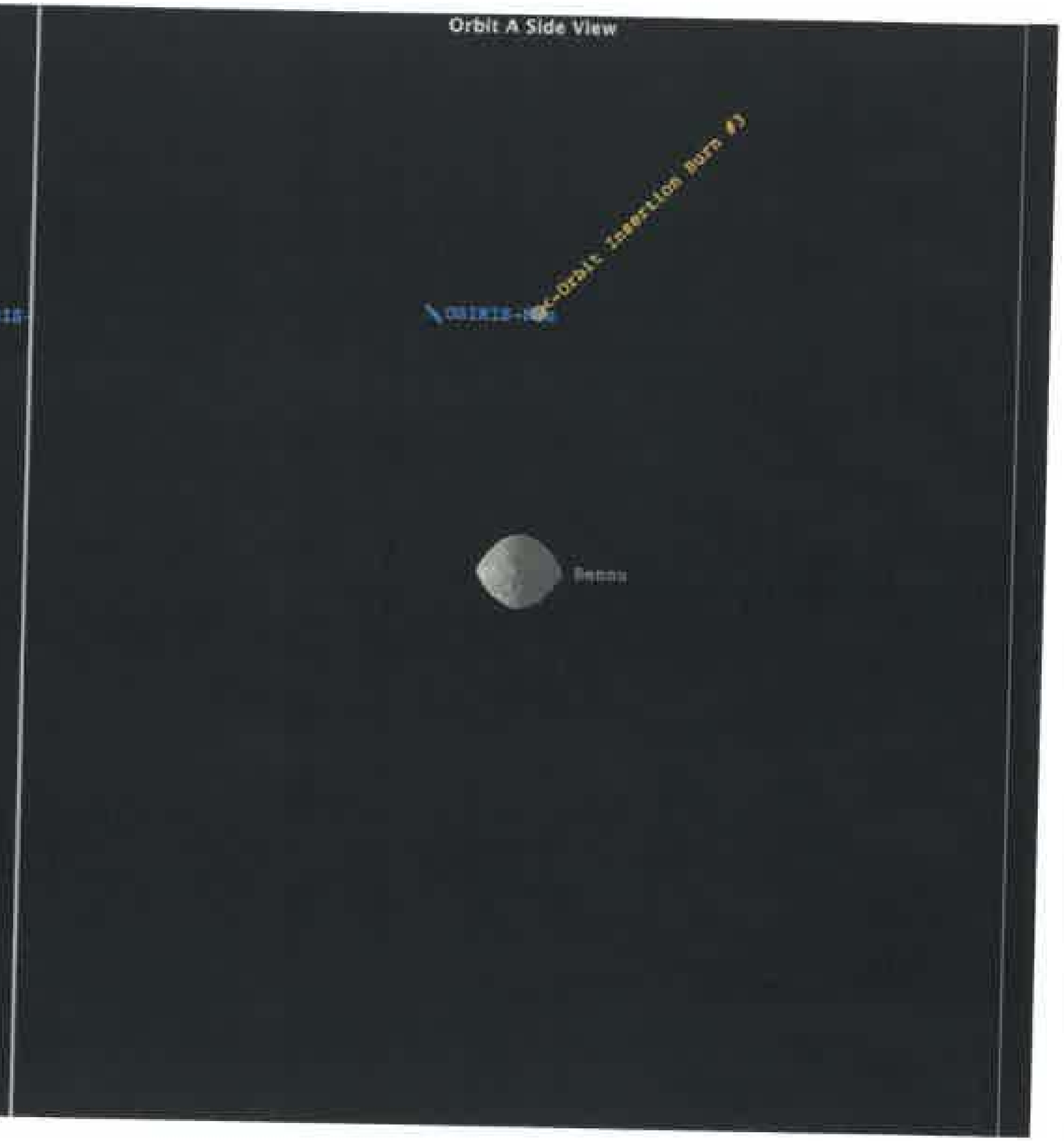


2x1 Mosaic Schematic



	NavCams 1 & 2
FOV (°)	44 x 32
IFOV (μrad/px)	280
Detector size (px)	2592x1944
Aperture (mm)	2.28
F/#	3.5
Focal length (mm)	7.6
Pixel size (microns)	2.2x2.2


Orbit A Top View
2018/12/31 10:11:00.0000 UTC
<-Orbit Insertion Burn #3
Bennu


Orbit A Side View
<-Orbit Insertion Burn #3
Bennu

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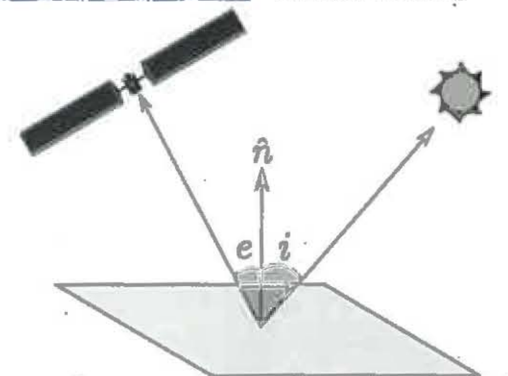
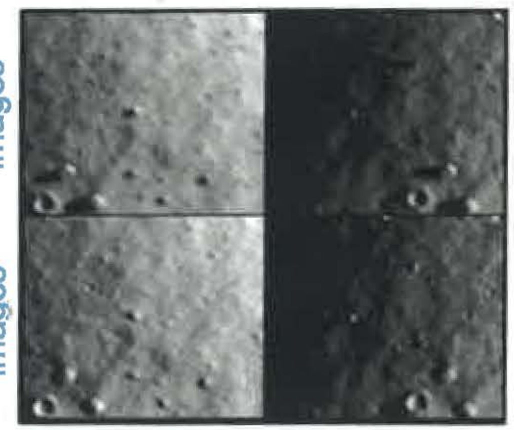
SPC Overview

- Stereophotoclinometry (SPC) is a technique for performing relative navigation using terrain features of a body (e.g., Bennu)
  - **Stereo** refers to the use of multiple images to determine a feature location
  - **Photoclinometry** refers to the method of “shape through shading”, i.e., determining topographic features through apparent brightness, slopes, and albedo
- Shape model developed by OSIRIS-REx Altimetry Working Group
- FORTRAN utilities used to compare simulated and actual images in order to construct 2D bearing measurements (expressed in the camera frame) to known landmark locations



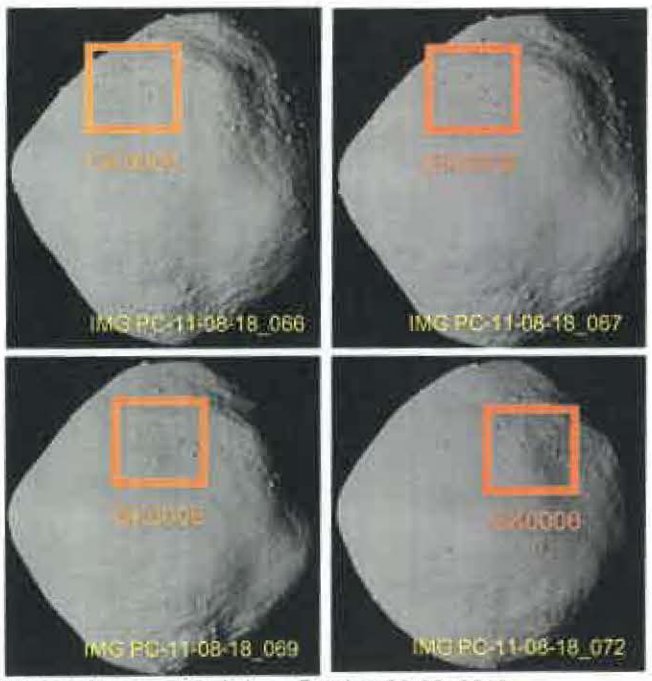
$$I_{jk} = a_k \left[(1-\beta)\cos i_{jk} + 2\beta \frac{\cos i_{jk}}{\cos i_{jk} + \cos e_{jk}}\right]$$

$$\beta = e^{-\alpha/\alpha_0}$$

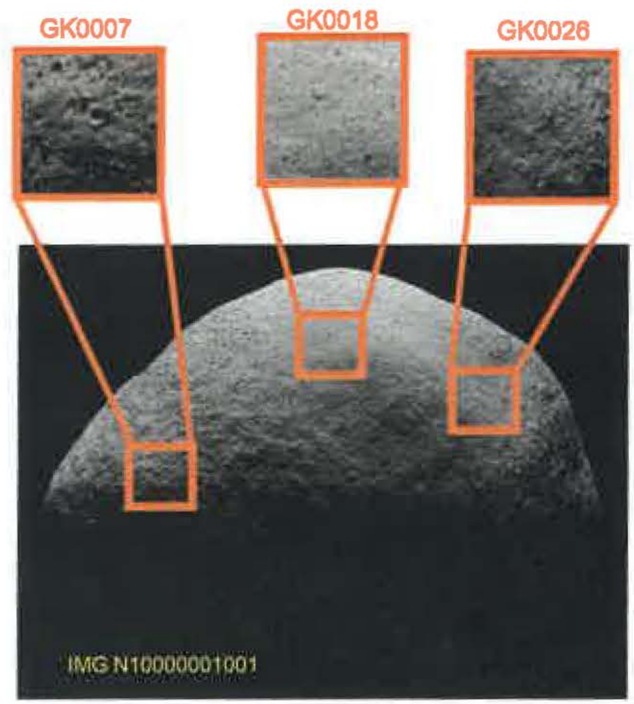


SPC Processes

- **Step 1: Maplet Construction**
  - ALTWG Team builds a set of maplets using <u>multiple images per maplet</u>

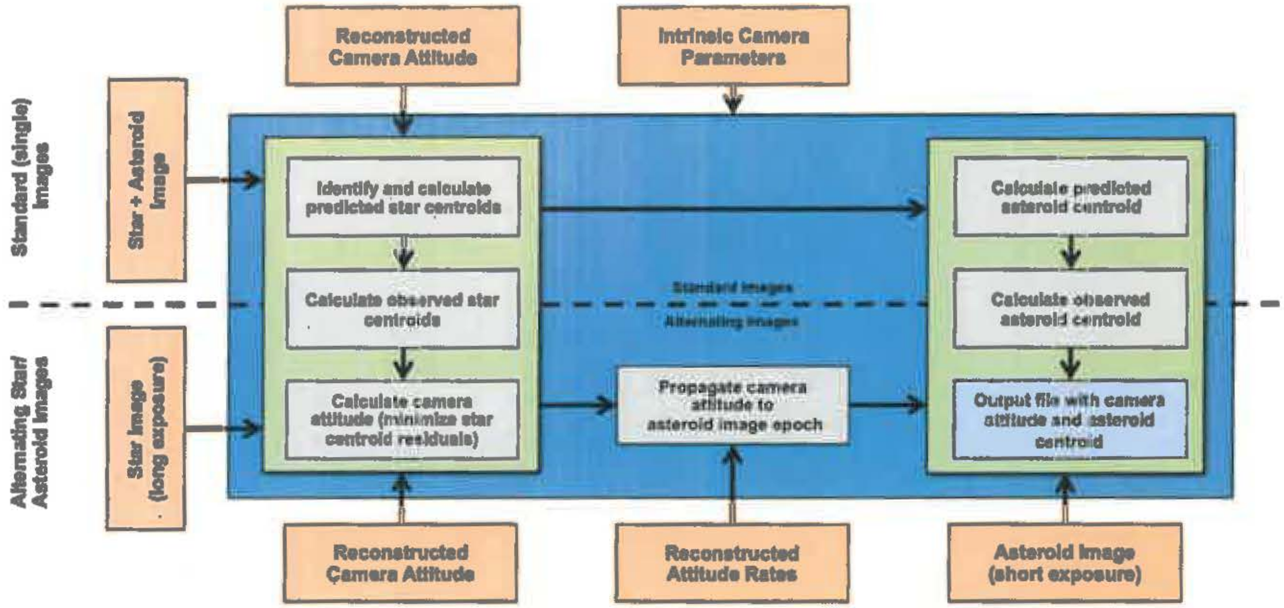


- **Step 2: Using Maplets for Navigation**
  - Navigation Team identifies and precisely locates <u>multiple maplets in a single image</u>



Centroid-based Optical Navigation Techniques

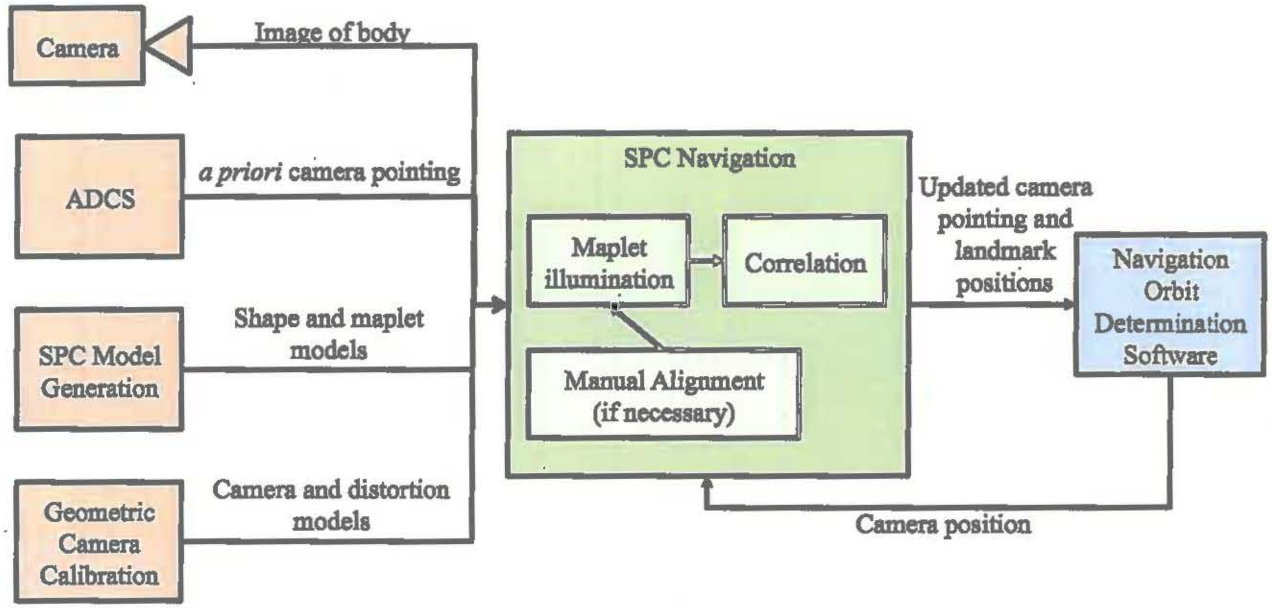
- Centroid-based optical navigation
  - Centroids of stars are calculated and used to determine inertial attitude of the camera at the image epoch
  - Observed centroid of the target is calculated using centerfinding algorithm
  - Camera attitude and residual between the predicted and observed target centroid are then used to estimate a solution for the body-relative spacecraft state
- KinetX Image Processing software suite (KXIMP)
  - Consists of a suite of MATLAB functions and scripts used to calculate centroid-based OpNav observables
  - KXIMP ingests images of the target and background stars, determines centroids of visible stars and targets in the field, calculates the inertial camera attitude, and packages the relevant data into an output file that is passed to the primary OD filter software



KinetX KXIMP OpNav Software Processing Flow

Landmark Optical Navigation Techniques

- Landmark Optical Navigation
  - The use of landmarks on the body to solve for both the body and spacecraft position in the presence of pointing knowledge errors.
  - If the pointing knowledge uncertainties are large, it requires a large FOV to capture large enough span of landmarks in the image to break the degeneracy between pointing and position errors.
- SPC (Stereophotoclinometry) Software
  - Landmark OpNav processing tool developed by Bob Gaskell that is used during Orbital A through TAG
  - Identifies and estimates landmark positions and pointing in OpNav images
  - Generates optical regres file to be incorporated into OD process
  - Also used by science team to generate shape model and terrain maps



SPC Landmark OpNav Software Processing Flow

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ALTWG-FDS Shape Model-Landmark Iteration

1. FDS processes NavCam OpNav images with both KXIMP and SPC for first week in orbit

2. FDS performs statistical OD and provides parameter estimates below to ALTWG

Bennu Pole, spin, PM, cf-cm vector, shape scale

3. ALTWG updates shape model based on FDS estimates of pole, scale, etc. and delivers back to FDS

4. FDS ingests new ALTWG landmarks, re-processes previous NavCam OpNav arc, adds another week of OpNavs to data arc.

Repeat steps 2-4 until convergence

- The Altimetry working group (ALTWG) is responsible for developing and delivering the asteroid shape model and DTMs at various resolutions.
- Iteration between FDS and ALTWG will be required to:
  - Ensure shape model development is closely tied to best OD solutions
  - Resolve coordinate frame, pole offsets and spin rate
  - Ensure shape mode is properly scaled
  - Identify and fix problem landmarks/regions
  - Successfully complete transition to landmark-Nav
- Two iterations were required during Orbital A during the 3-week transition period
- Shape model/landmarks developed by JPL Nav Team provided independent source of landmark data that was also assessed by the FDS team

Transition to Landmark Navigation

- Orbit A is the best time to perform the transition from centroid-based to landmark OpNav.
  - Operationally less intensive with fewer maneuvers and ephemeris updates
  - Orbital phase transition period allows overlap comparisons between the two OpNav techniques
- Landmark Transition Success Criteria:
  - Predicted trajectory state errors meet the accuracies required for Detailed Survey science observations
  - Reconstructed OD accuracy
    - Landmark-based-reconstructed trajectories improved over star-based-reconstructed solutions
  - Predictive OD accuracy
    - Predictions from landmark based OD solutions improved over centerfinding
  - Landmark residuals have converged and consistent with shape model requirements
  - Bennu geophysical parameters have converged to within expected uncertainties

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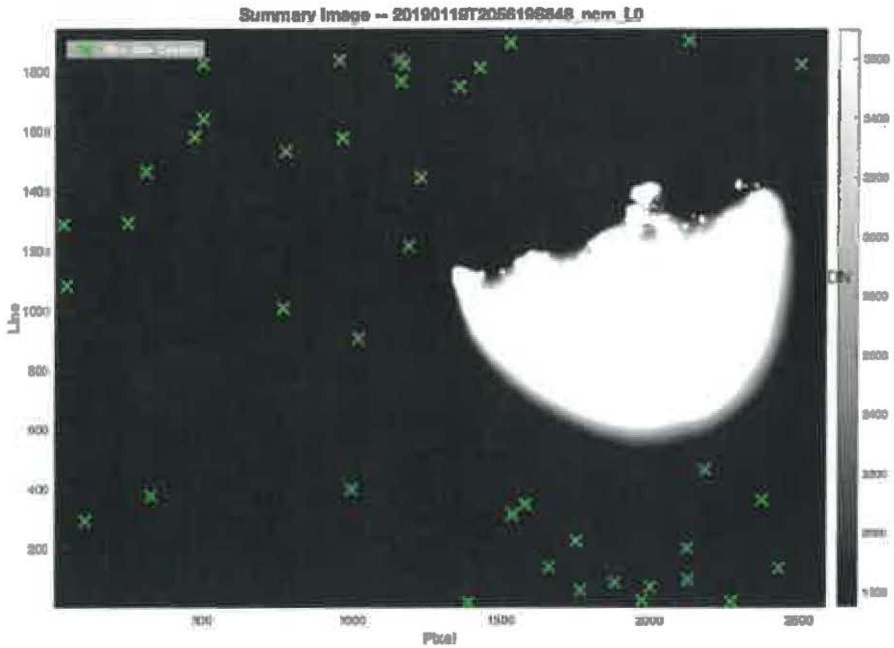
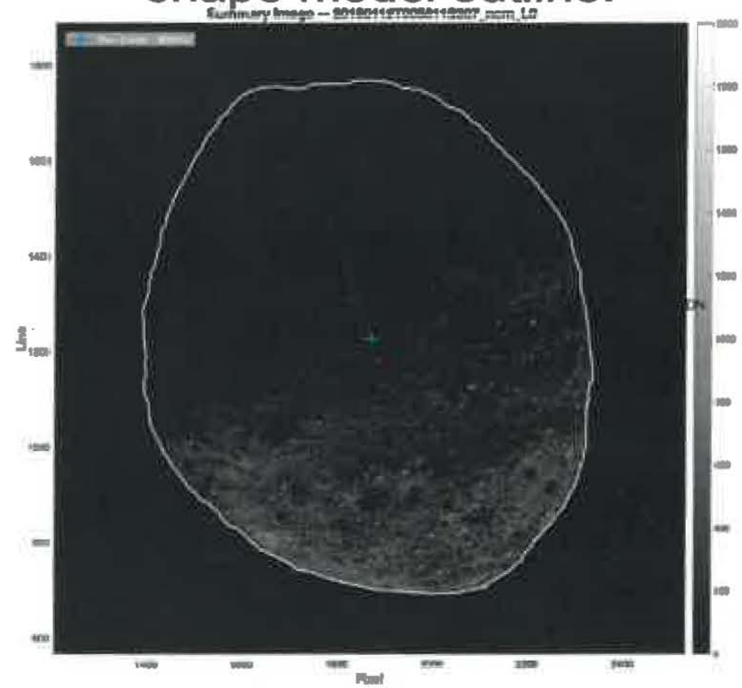
Exceptional KXIMP Centerfinding Performance

KXIMP star solution results

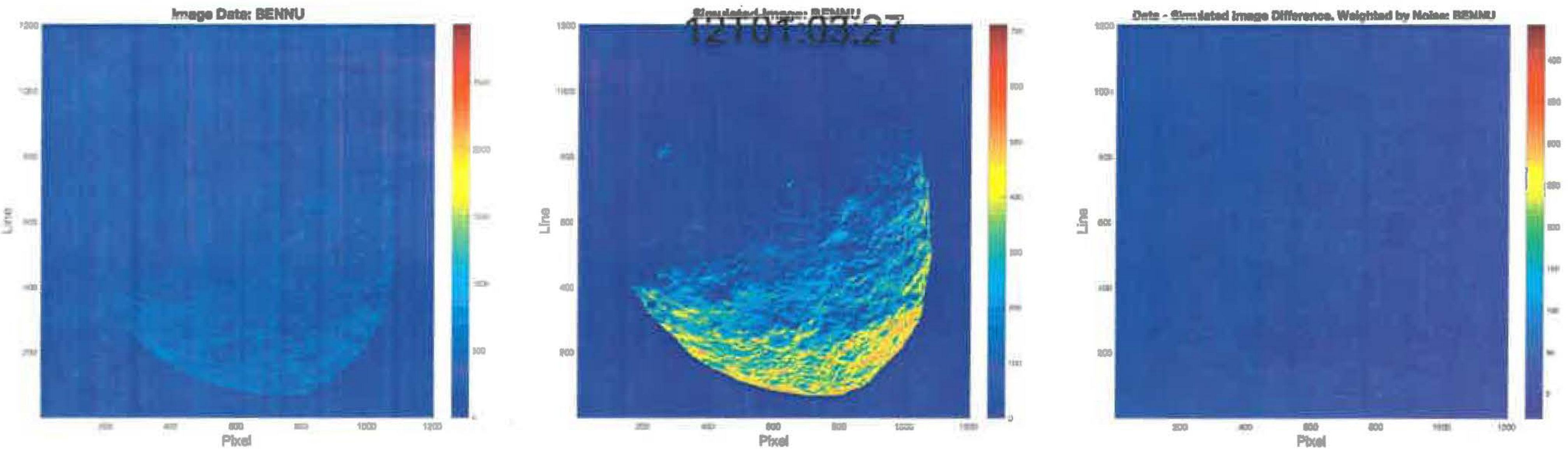


KXIMP centroid results with shape model outline.



Exceptional KXIMP Centerfinding Performance

2019-01-12T01:03:27



Exceptional KXIMP Centerfinding Performance

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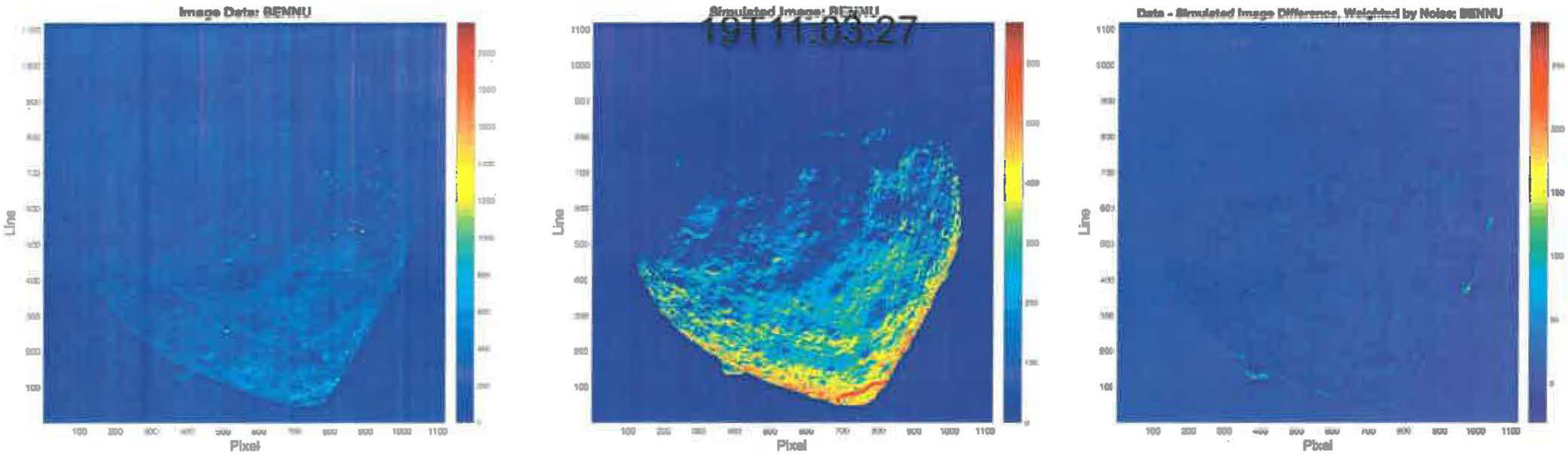
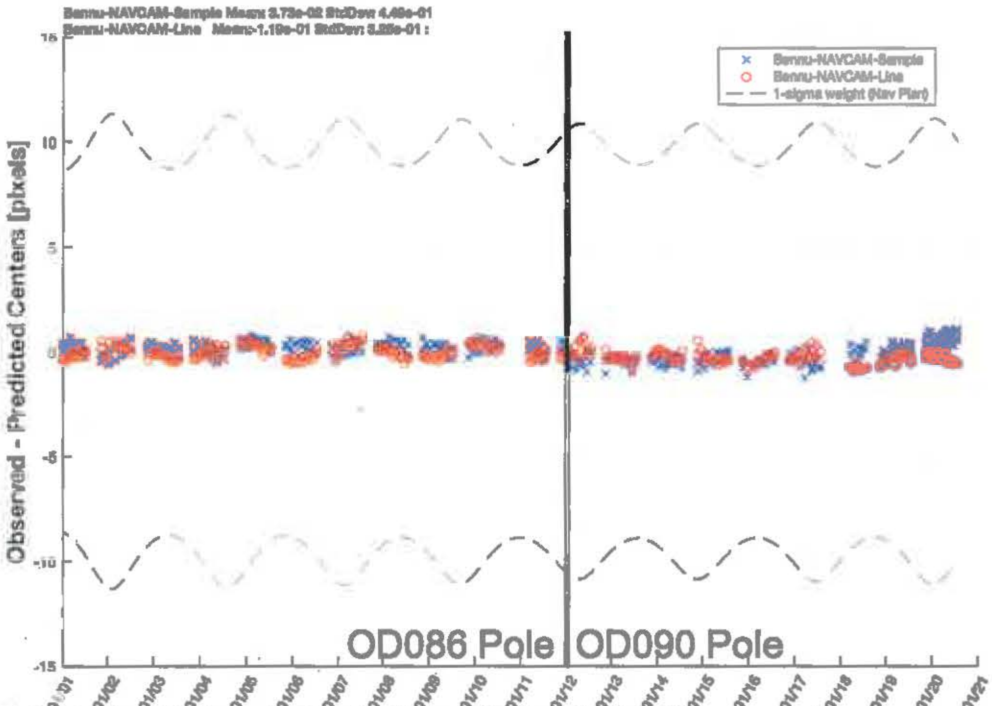
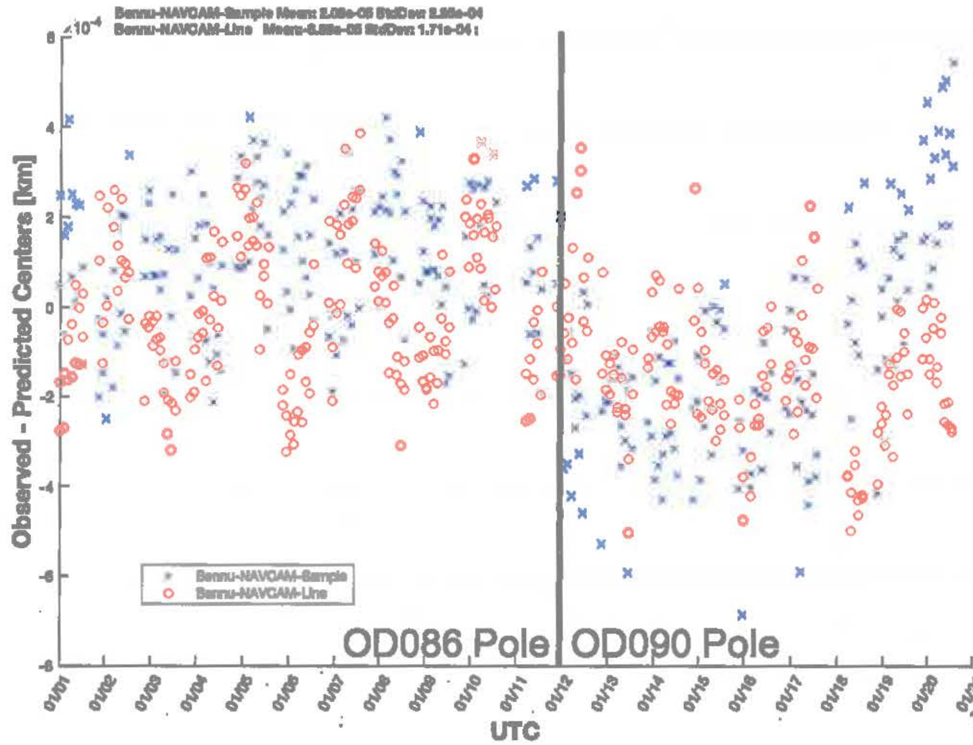


Exceptional KXIMP Centerfinding Performance

- Analysis assumed ~10px, 1-sigma (1px + 1% of Body Diameter).
- Residual performance has been <0.5px or <30cm, 1-sigma (**<u>0.06% of Body Diameter</u>**).





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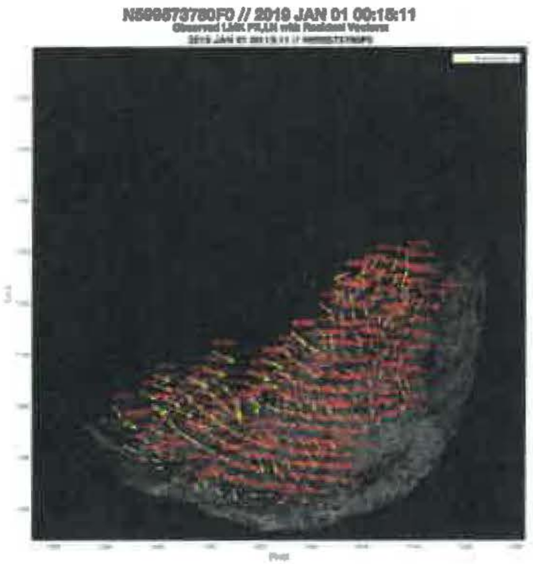
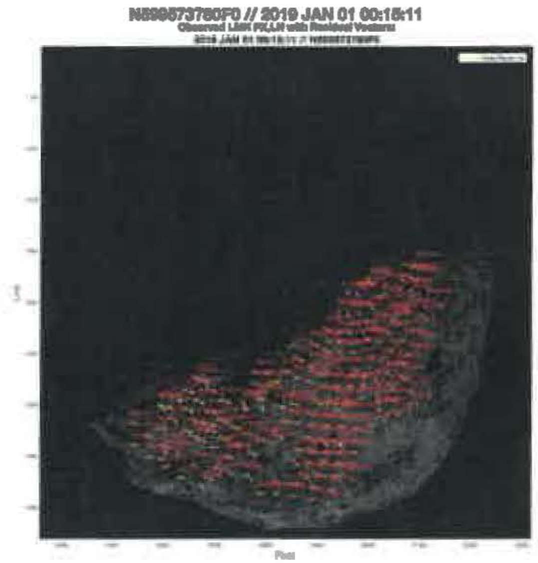
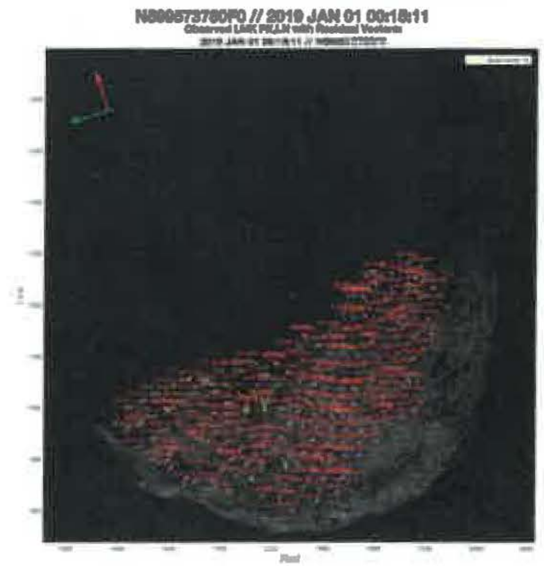
Residual Quiver Plot Comparison between 3 delivered ALWTG models (two iterations with FDS)



Model: spc075draft.v1
delivered 12/27

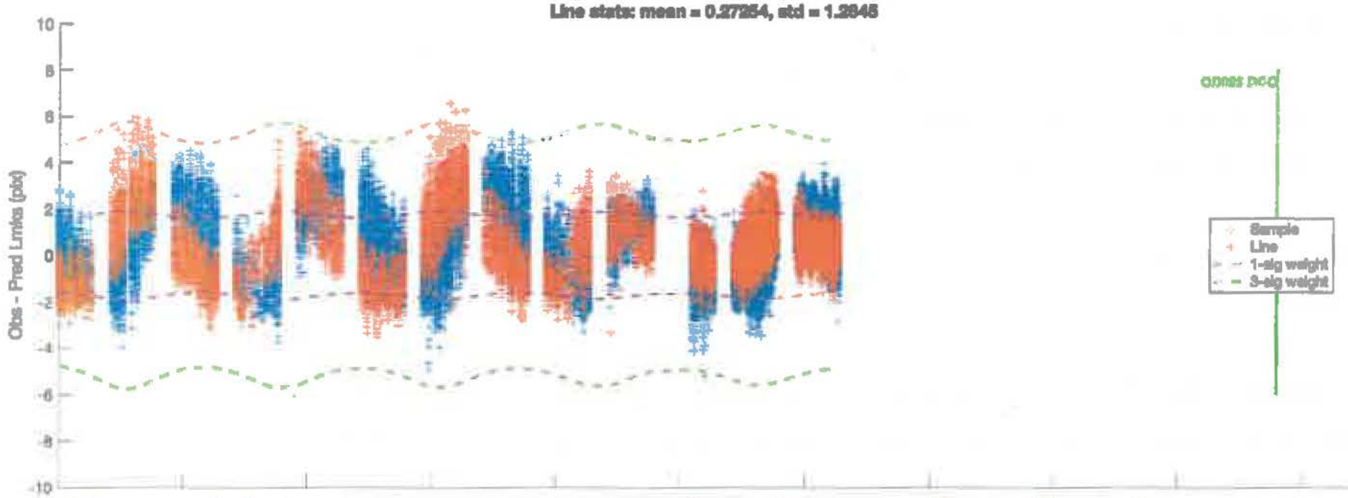


Model: spc075draft.v7
delivered 1/10

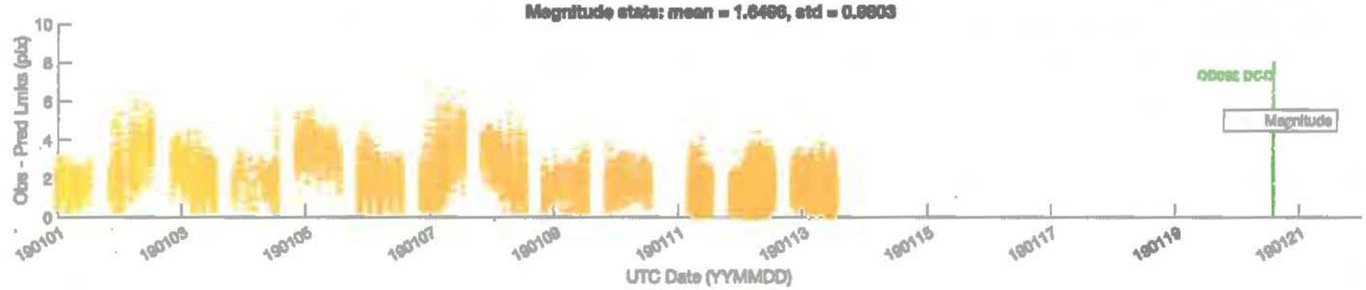


Model: spc075draft.v9
delivered 1/20

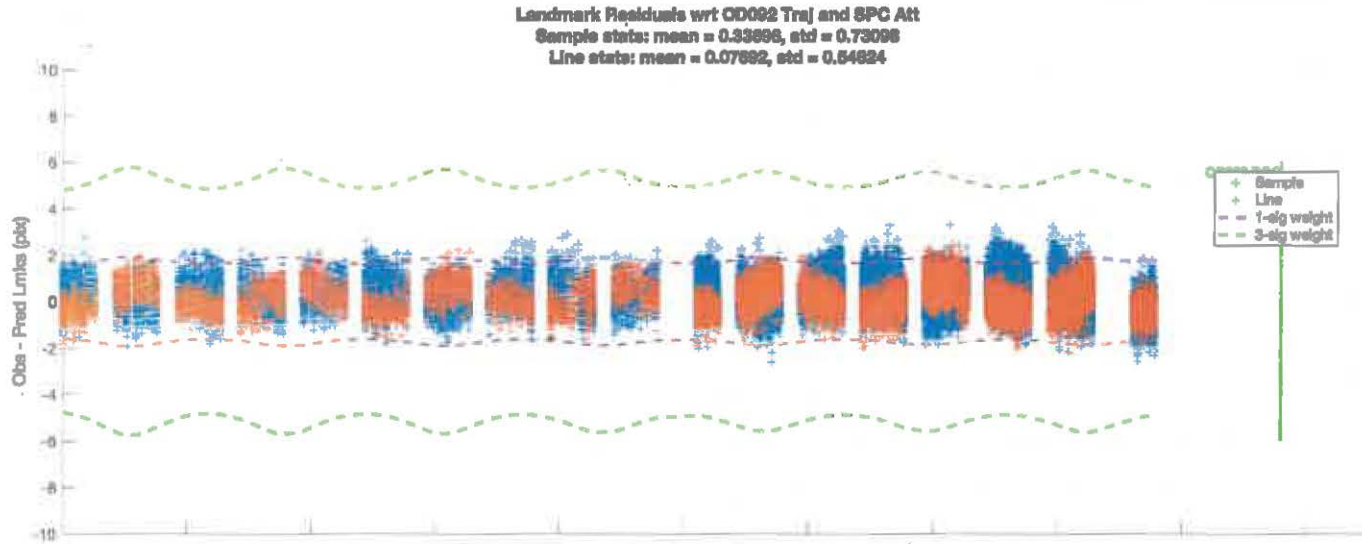
OLM001_spc075draft.v1 Px/Ln Residuals w.r.t OD092



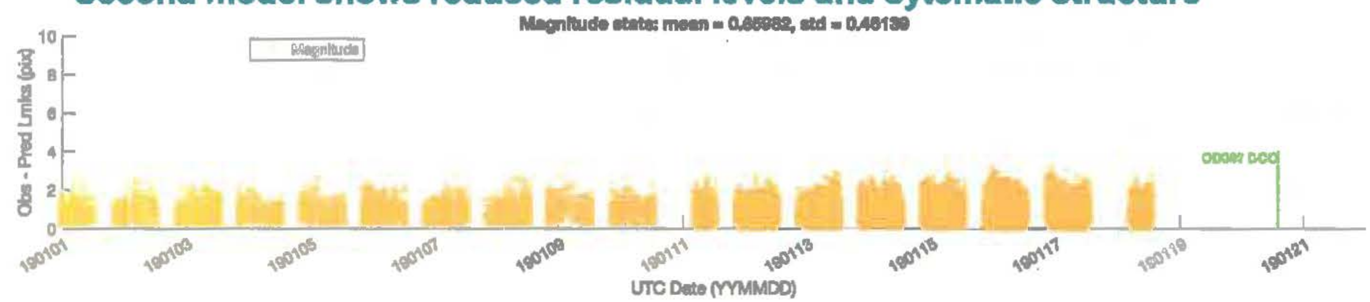
First model shows structure due to pole and center of coordinate frame errors



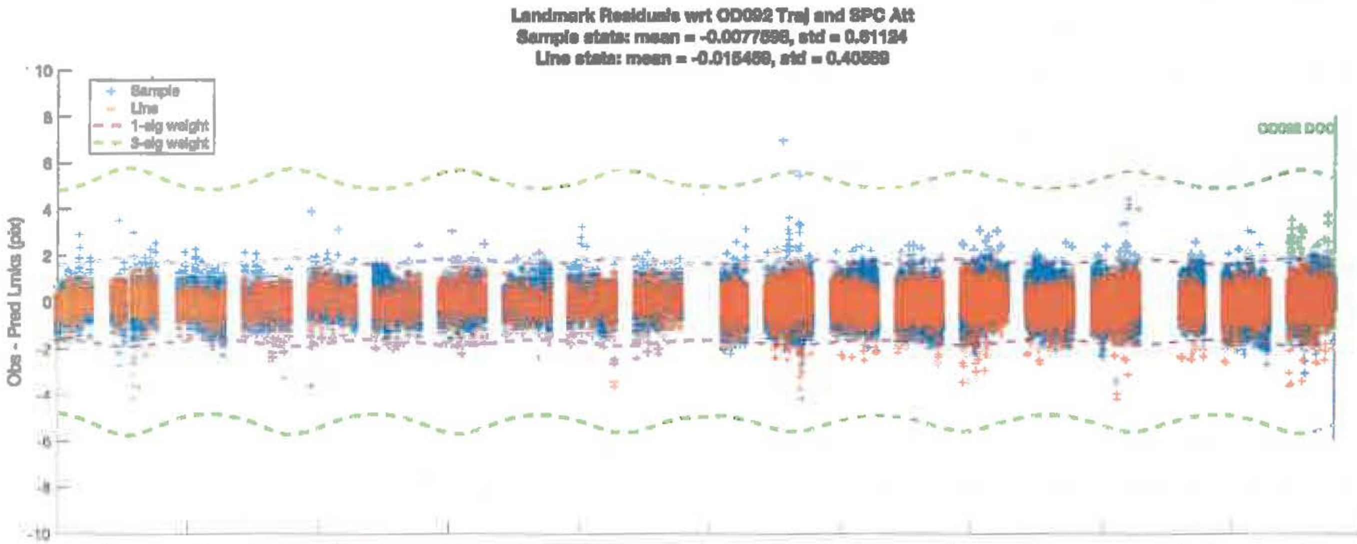
OLM004_spc075draft.v7 Px/Ln Residuals w.r.t OD092



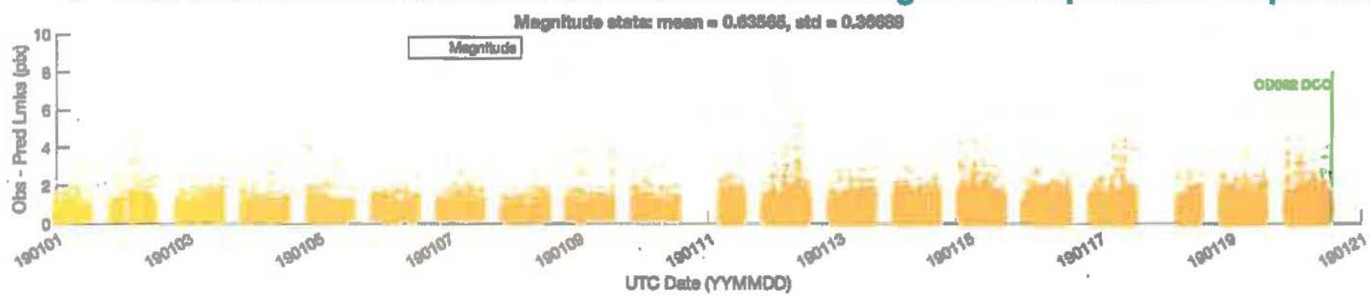
Second model shows reduced residual levels and sytematic structure



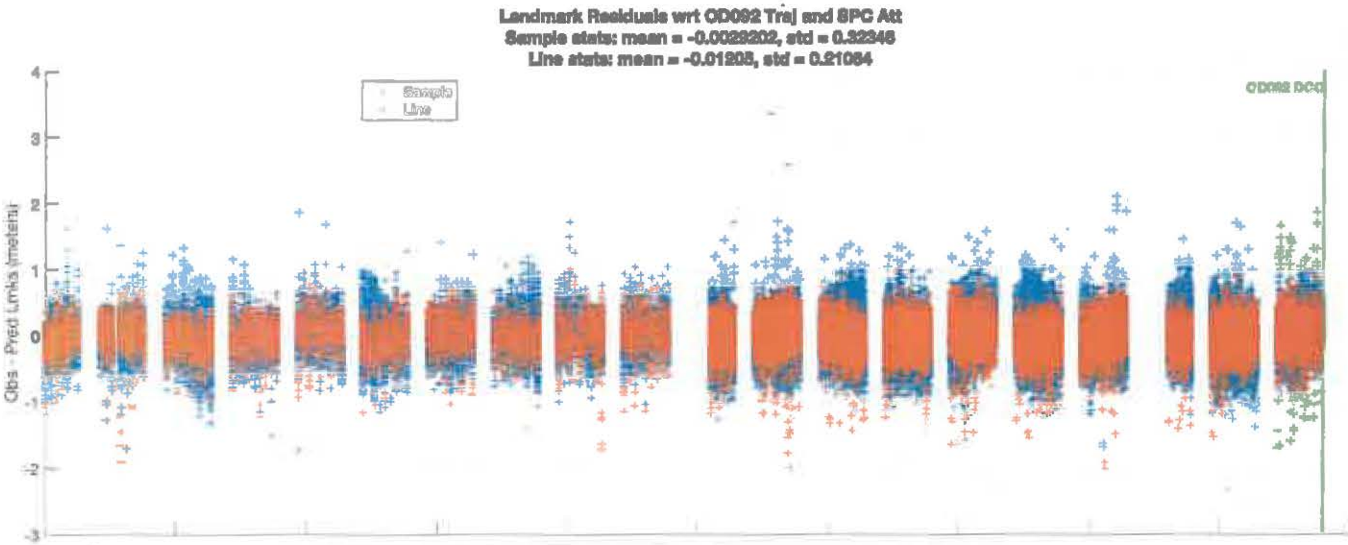
OLM001_spc075draft.v9 Px/Ln Residuals w.r.t OD092



3rd and final model landmark residuals have converged to shape model requirements



OLM001_spc075draft.v9 Px/Ln Residuals w.r.t OD092



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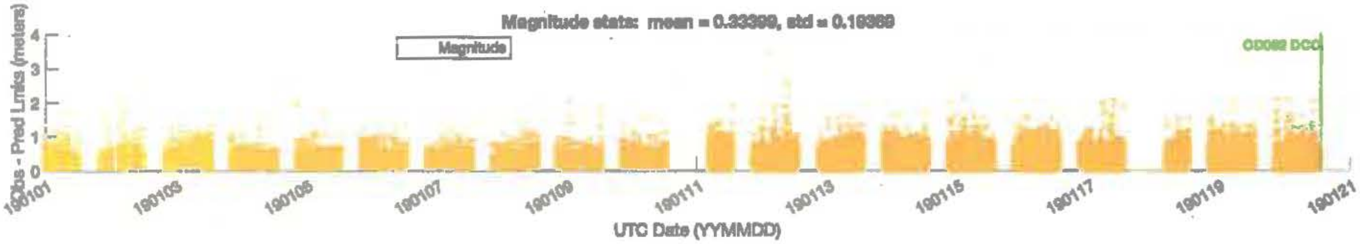

Conclusions

- Centroid-based OpNav performance was exceptional throughout Approach, PS, and Orbit A
  - This performance was enabled due in part to the exceptional fidelity of the Nolan model early in approach, and the early limber and SPC models delivered by ALTWG
  - Early shape model deliveries helped improve the OpNavs and OD on Approach and Preliminary Survey which fed back into the shape model building. Alleviated trajectory errors which fed back into better shape formulation.

- Landmarks from ALTWG are meeting the primary 75 cm requirement
  - ALTWG model landmarks are good to ~52 cm 1-sigma. When corrected, landmarks are good to ~16 cm 1-sigma (2 iterations between ALTWG and FDS)

- Orbit determination performance in Orbital A exceeded pre-mission expectations, due in part to:
  - Centroid-based OD solutions performing as well as Landmark-based solutions
  - Landmarks allowed for better estimation/convergence of Bennu geophysical parameters than centroid solutions (CF/CM offset, Pole, rotation rate)
  - Landmarks allowed us to identify small errors in the centroid models and when corrected produce consistent trajectories and parameter estimates

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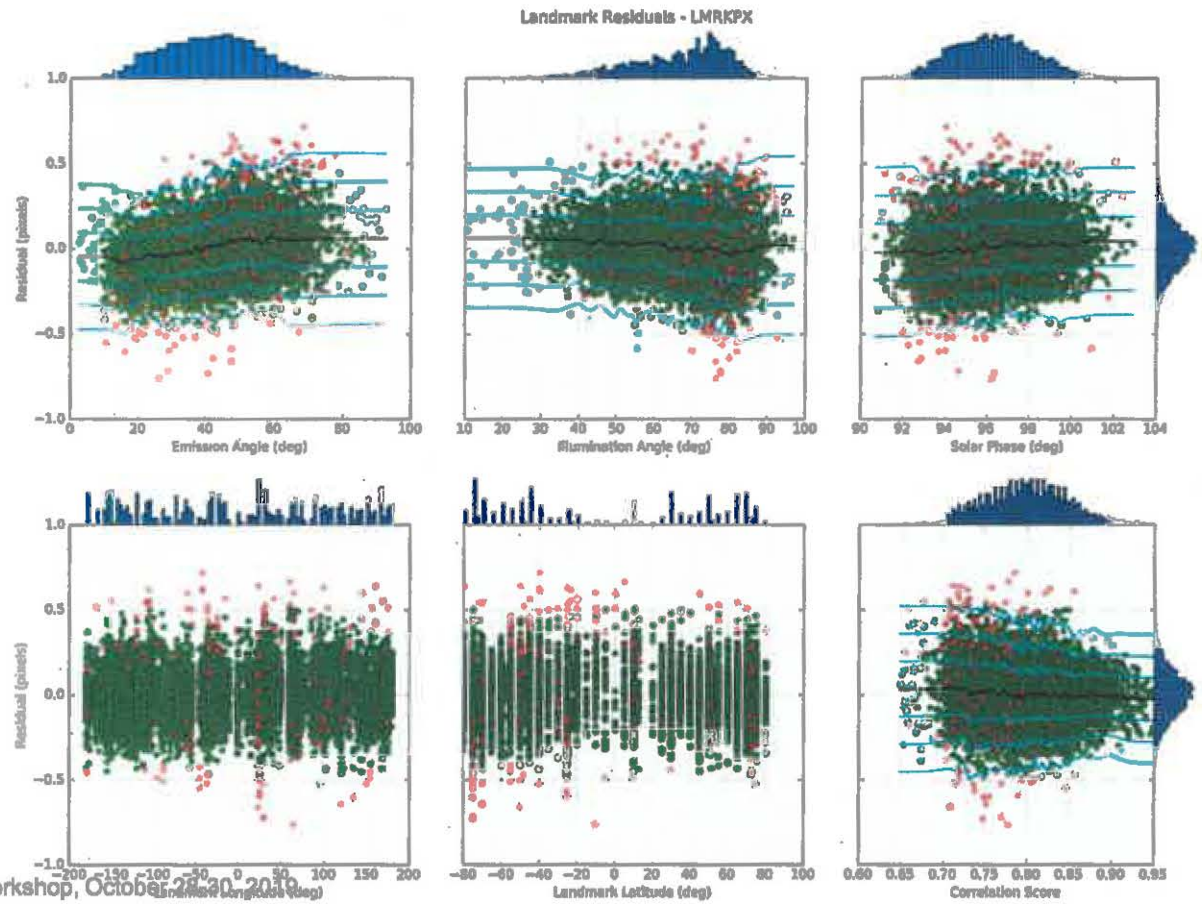
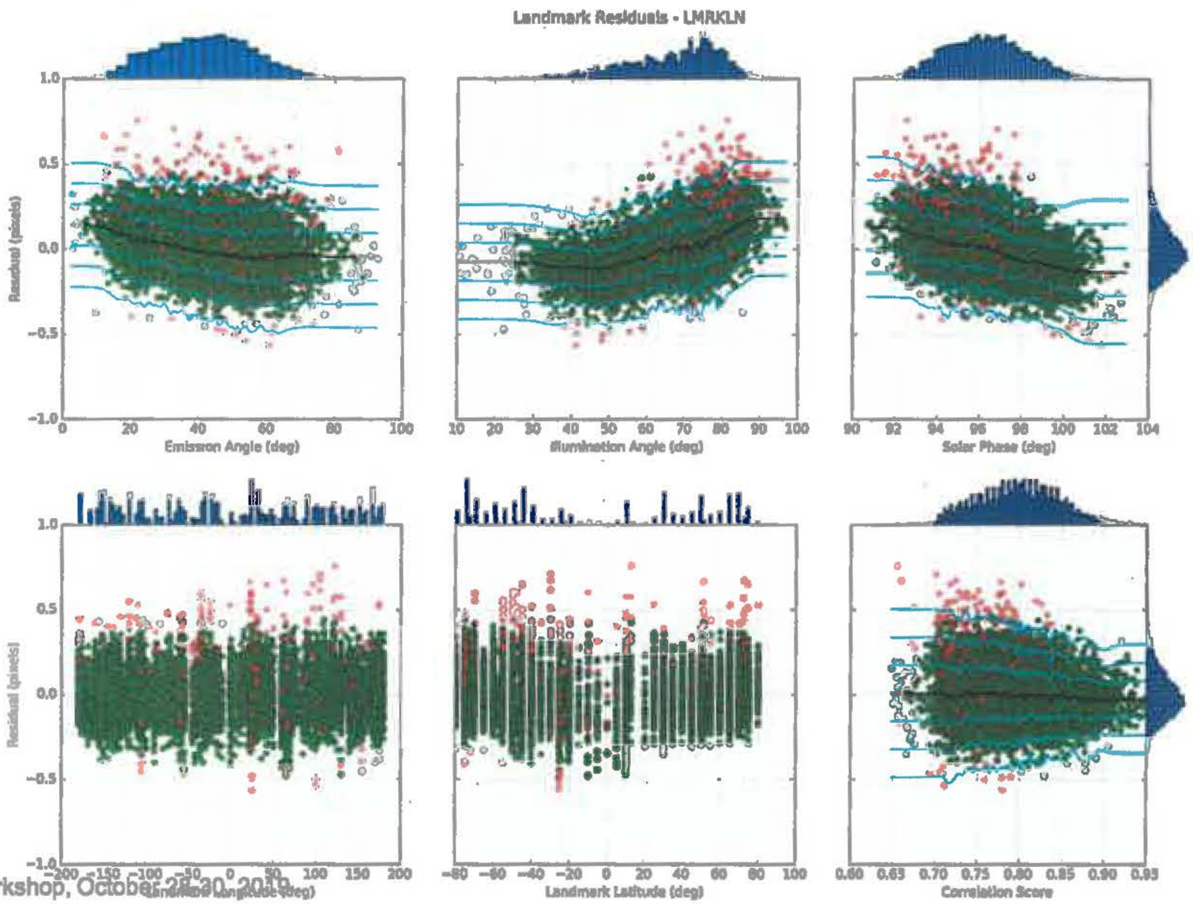
BACKUP

Landmark Residuals - Pixel

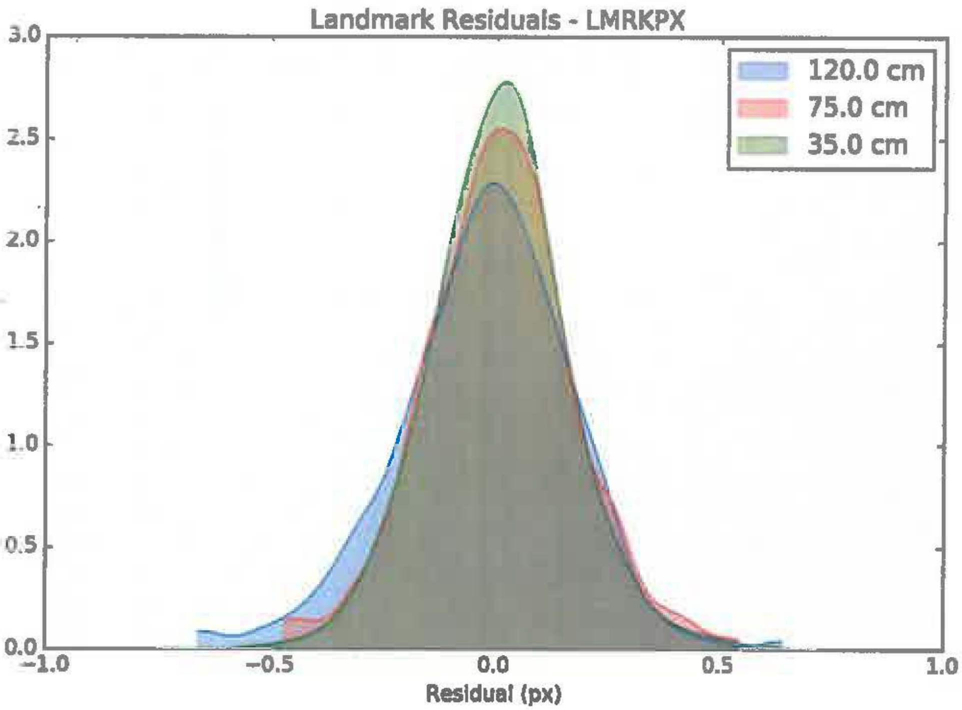


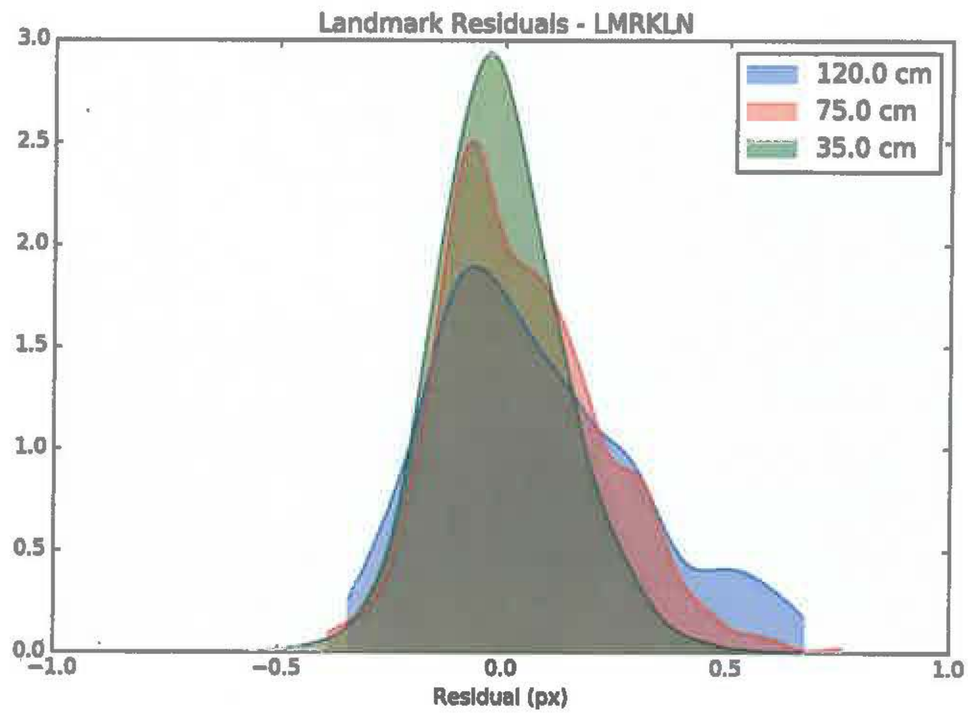
Landmark Residuals - Line



Shape Model Resolution

- FDS is not seeing a significant difference in the landmark residuals based on maplet resolution when landmarks locations are corrected





ALTWG Global Altitude Correction