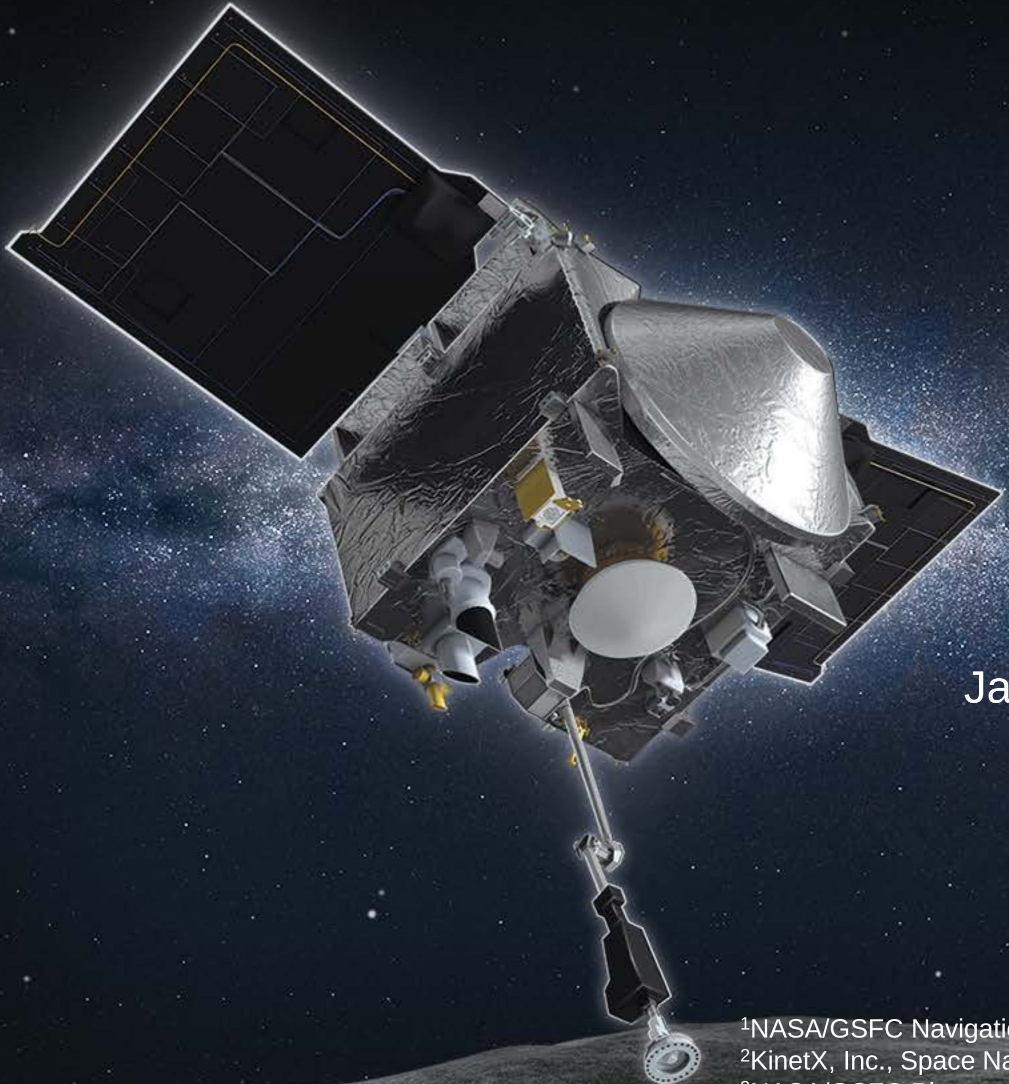
OSIRIS-REx
ASTEROID SAMPLE RETURN MISSION



The Image Constraint Measurement Type for Orbit Determination & Geophysical Parameter Estimation

2nd RPI Space Imaging Workshop

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Outline

- Brief History
- Measurement Specification
- Constructing the Observables
- Results from Orbital A
- Alternative Approaches to Observable Construction
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Brief History of Image Constraints (ICs)

- Originally published in Mazarico, et. al. (2014)
  - Developed as an alternative to direct landmark processing
  - Processed image constraint measurements for NEAR at Eros
- Implemented in GSFC’s GEODYN precision orbit determination and geophysical parameter estimation software
- Further improved and tested for Dawn at Vesta (see Centinello, et. al, 2015)
- Recently implemented in the MIRAGE operational navigation software suite for the OSIRIS-REx mission at Bennu
  - Used to supplement traditional direct-landmark measurements

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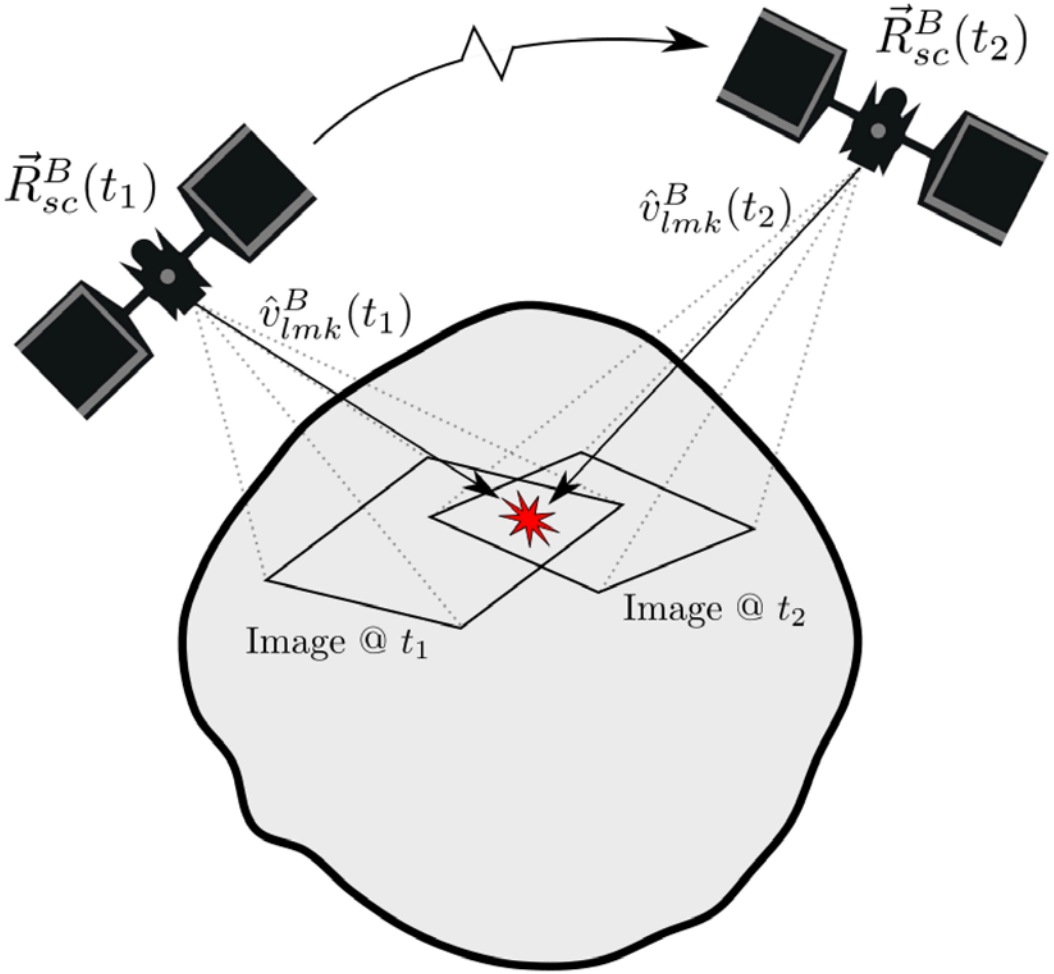
Measurement Specification (1/X)



- Consists of observations of a single surface feature (or landmark) in two different images
- The unit vectors corresponding to each observation must, by definition, intersect in the target body's fixed frame
- Constrains the relative position and orientation of the spacecraft at the time of the two exposures
- Similar to visual odometry but at much longer baselines

Measurement Specification (2/X)

- Start with observed sample/line location of landmark, $[s, l]$ (in pixels) for each image
  - Extracting $[s, l]$ for each landmark is addressed later…

- $\hat{v}_{lmk}^{C}(t)$ - find by inverting an appropriate camera model (OpenCV for OSIRIS-REx):

$$\begin{bmatrix} s \\ l \end{bmatrix} = g(\hat{v}_{lmk}^{C}, f_{x,y}, k_{0-6}, p_{1-2,}\, c_{x,y})$$
$$\hat{v}_{lmk}^{C} = g'(s, l, f_{x,y}, k_{0-6}, p_{1-2,}\, c_{x,y})$$

- Rotate $\hat{v}_{lmk}^{C}(t)$ from the camera frame to the spacecraft-fixed frame:

$$\hat{v}_{lmk}^{S}(t) = C_{B}^{I}(t)\delta C C_{S}^{C}\hat{v}_{lmk}^{C}(t)$$

- Rotate $\vec{R}_{sc}^{I}(t)$ and $\hat{v}_{lmk}^{I}(t)$ to target-body fixed frame using IAU rotation parameters:

$$\vec{R}_{sc}^{B}(t) = C_{B}^{I}(t)\vec{R}_{sc}^{I}(t)$$
$$\hat{v}_{lmk}^{B}(t) = C_{B}^{I}(t)\hat{v}_{lmk}^{C}(t)$$
$$C_{B}^{I}(t) = f(t, \alpha, \delta, \omega_0, \omega, \ldots)$$

Measurement Specification (3/X)

- **Minimum intersect distance** of two rays with origins $\vec{R}_{sc}^{B}(t_1)$, $\vec{R}_{sc}^{B}(t_2)$ and directions $\hat{v}_{lmk}^{B}(t_1)$, $\hat{v}_{lmk}^{B}(t_2)$:

$$d = \left[\vec{R}_{sc}^{B}(t_1) - \vec{R}_{sc}^{B}(t_2)\right]^T \left[\frac{\hat{v}_{lmk}^{B}(t_1) \times \hat{v}_{lmk}^{B}(t_2)}{\left|\hat{v}_{lmk}^{B}(t_1) \times \hat{v}_{lmk}^{B}(t_2)\right|}\right]$$

- By definition, d is nominally zero: $\delta y = 0 - d = -d$

- Image constraints are a **differenced measurement**:
  - No dependence on landmark locations/shape model (except during processing)
  - Some 1st order errors in location/shape cancel
  - Still susceptible to shape/orbit scale errors

Information Content

- Provides relative state information ($\Delta\vec{R}_{sc}^{B}$) perpendicular to the baseline:

$$\frac{\partial d}{\partial \Delta\vec{R}_{sc}^{B}} = \left[\frac{\hat{v}_{lmk}^{B}(t_1) \times \hat{v}_{lmk}^{B}(t_2)}{\left|\hat{v}_{lmk}^{B}(t_1) \times \hat{v}_{lmk}^{B}(t_2)\right|}\right]^{T}$$

- Alternate formulation for epoch-state filters (in terms of $X^{I}(t_0)$):

$$d = X^{I}(t_0)^{T}\left[C_{B}^{I}(t_1)\Phi(t_0,t_1) - C_{B}^{I}(t_2)\Phi(t_0,t_2)\right]^{T}\left[\frac{\hat{v}_{lmk}^{B}(t_1) \times \hat{v}_{lmk}^{B}(t_2)}{\left|\hat{v}_{lmk}^{B}(t_1) \times \hat{v}_{lmk}^{B}(t_2)\right|}\right]$$

$$\frac{\partial d}{\partial X^{I}(t_0)} = \left[\frac{\hat{v}_{lmk}^{B}(t_1) \times \hat{v}_{lmk}^{B}(t_2)}{\left|\hat{v}_{lmk}^{B}(t_1) \times \hat{v}_{lmk}^{B}(t_2)\right|}\right]^{T}\left[C_{B}^{I}(t_1)\Phi(t_0,t_1) - C_{B}^{I}(t_2)\Phi(t_0,t_2)\right]$$

- Also provides information for:
  - Camera Pointing Correction - δC
  - Target Body Orientation - α, δ, ω (not ω_0!)

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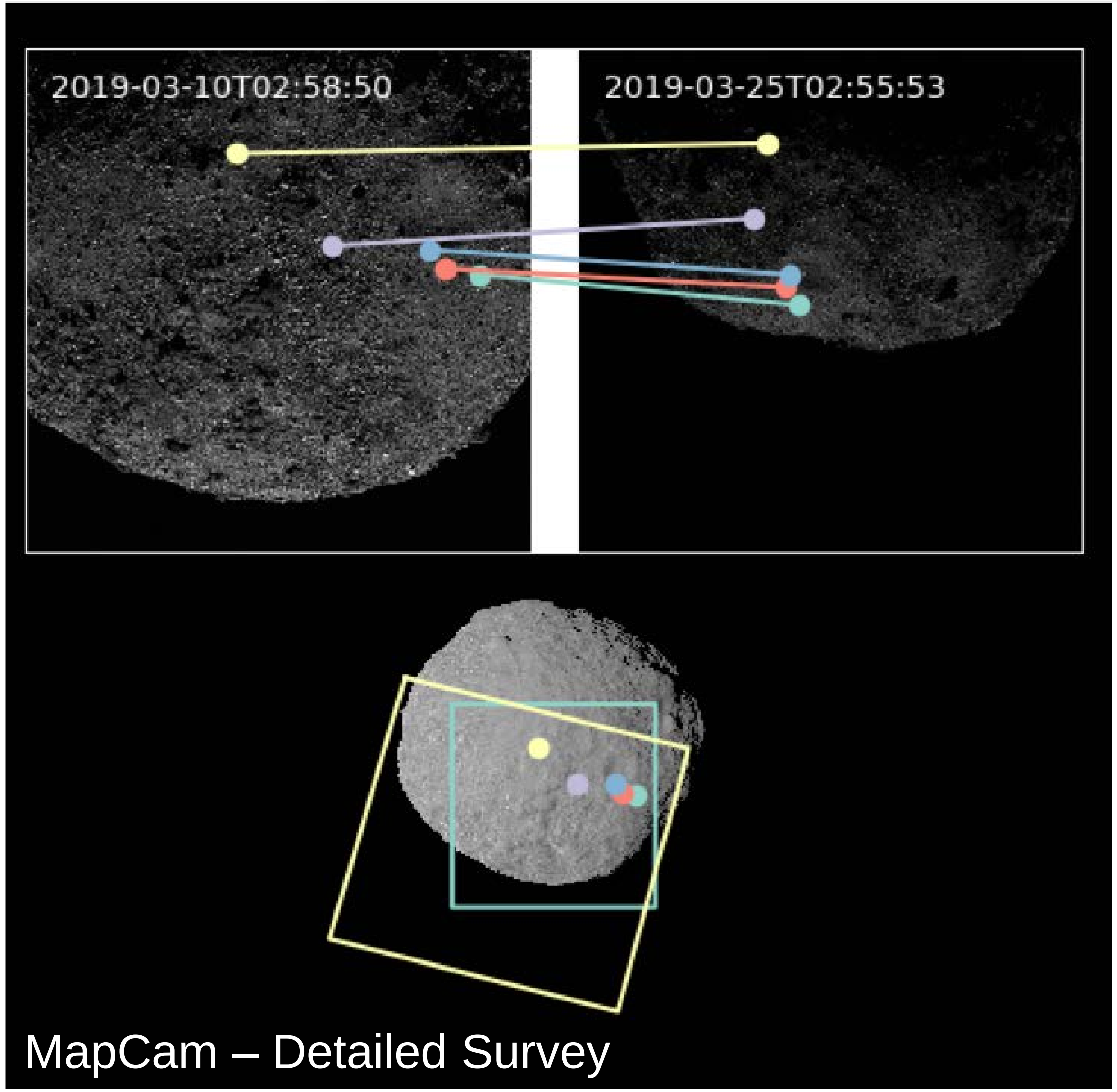
Constructing the Observables



- Need to identify common landmarks between two images
  - Usually from the same imager, but can be different
- Convenient by-product of traditional SPC (or similar) terrain-relative navigation
  - Requires a full shape model
  - See subsequent slides for alternative approaches…
- Commonly constrain:
  - Min/Max time between landmarks
  - Number of “appearances” of each landmark
- Ideal to select combinations that vary the baseline direction

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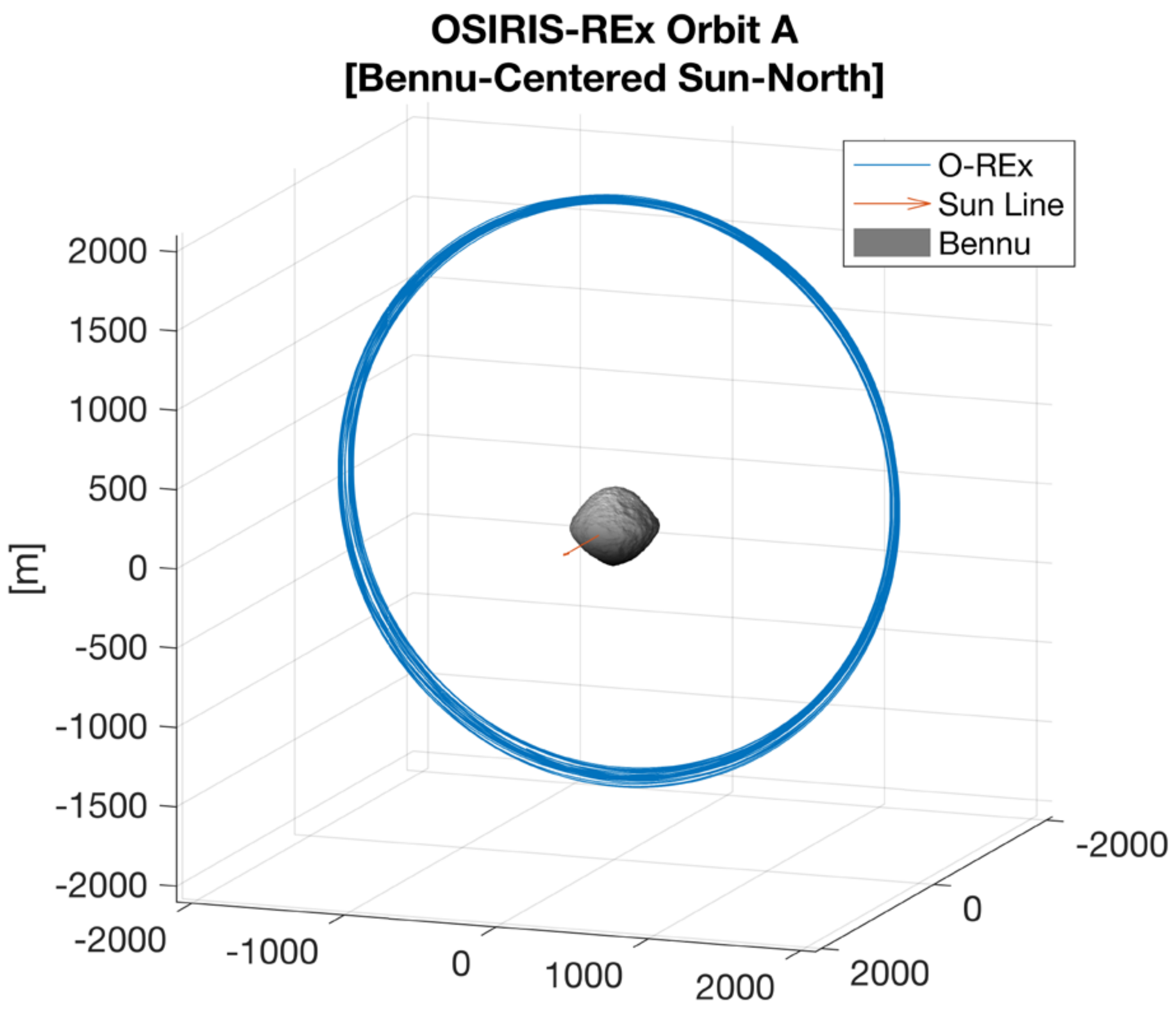
Example: OSIRIS-REx Orbital A



- Processed Direct Landmark and IC data from Orbital A in GEODYN
  - *Representative example – do not replace official results from FDS and other science working groups*
- 2.1 x 1.6 km "Frozen" terminator orbit
  - January 1st to February 28th
- Long and Short NavCam Exposures
  - Precise camera pointing
- Shape Model: 75 cm GSD
  - From Altimetry Working Group (iterated)
  - Sub-sampled to ~1000 landmarks

Orbital A Image Constraints

- Total number of Direct Landmark Observables: **91,999**
  - From 1757 images and 992 Landmarks
- Filter Criterion:
  - Minimum Time Between Image Pairs: 60 hours (~1 orbit period)
  - Maximum Time Between Image Pairs: None (entire arc, ~2 months)
- Total number of Image Constraint Observables: **107,573**
  - Most “appearances” by a single landmark: 23
- Also looked into filtering landmark pairs by baseline direction to maximize information content (J. Leonard/KinetX)

Orbital A Filter Cases

- Case 1:
  - Direct Landmarks Only (1 pixel weight)
  - No scale or COM-COF estimation
- Case 2:
  - Direct Landmarks Only (1 pixel weight)
  - Estimate scale and COM-COF
- Case 3:
  - Direct Landmarks Only (3 pixel weight)
  - Estimate scale and COM-COF
- Case 4:
  - Image Constraints Only (10 cm weight)
- Case 5:
  - Image Constraints Only (75 cm weight)

Orbital A Filter Cases

- Solve-For Parameters:
  - Spacecraft:
    - Position/Velocity at Epoch
    - Impulsive Momentum Desaturations
      - Twice-per-week
    - Stochastic Accelerations
      - 1-day Batches
    - Per-Pass DSN Range Biases
  - Bennu:
    - GM and J2
    - Spin Pole & Rate
    - Shape Model Scale (Cases 2 & 3)
    - COM-COF Offset (Cases 2 & 3)

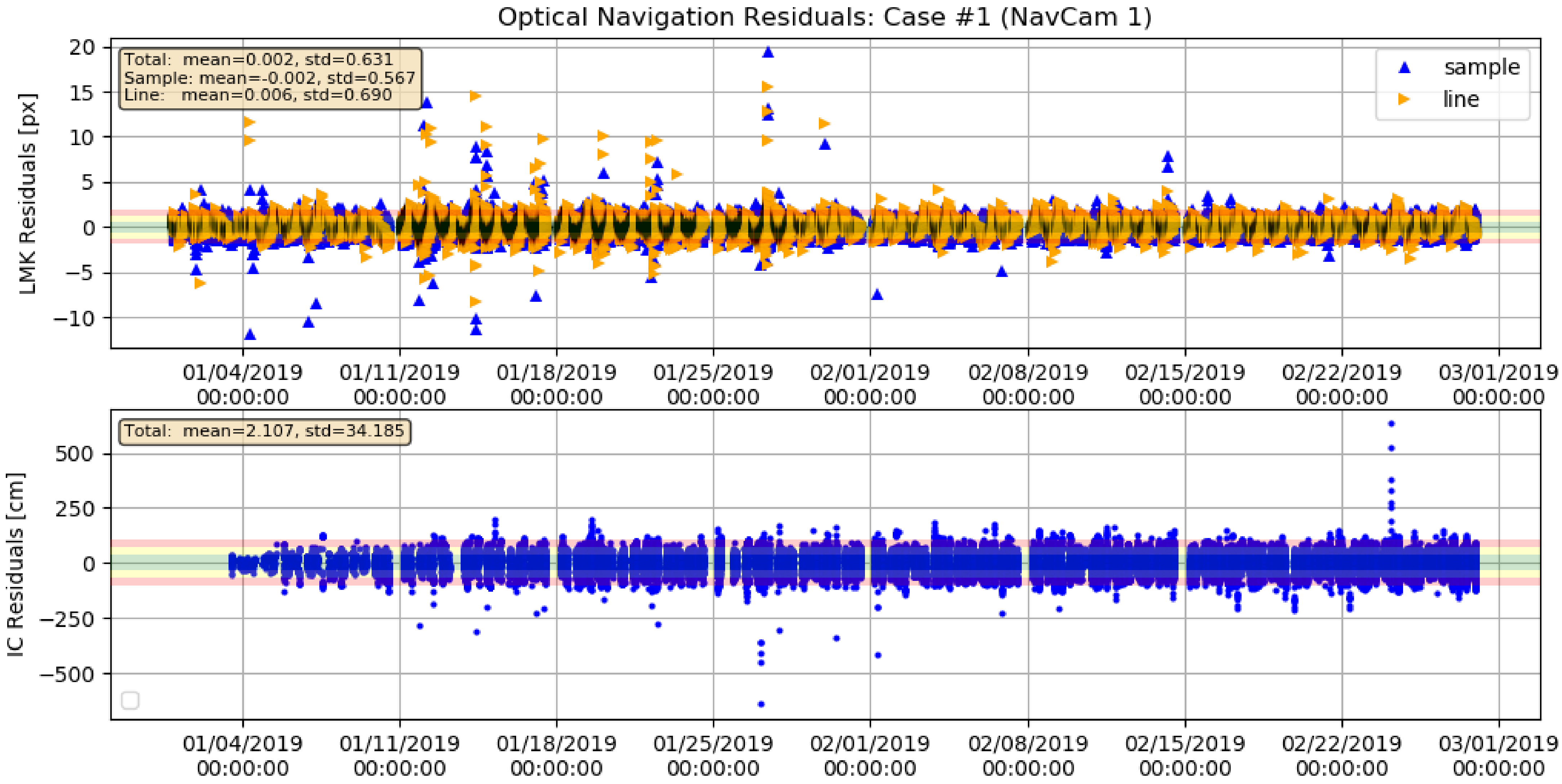
- Measurements (Weight)
  - DSN Range (21 RU)
  - DSN Doppler (5.5 mHz)
  - Direct Landmarks (1 or 3 pixels)
  - Image Constraints (10 or 75 cm)

Residual Comparison

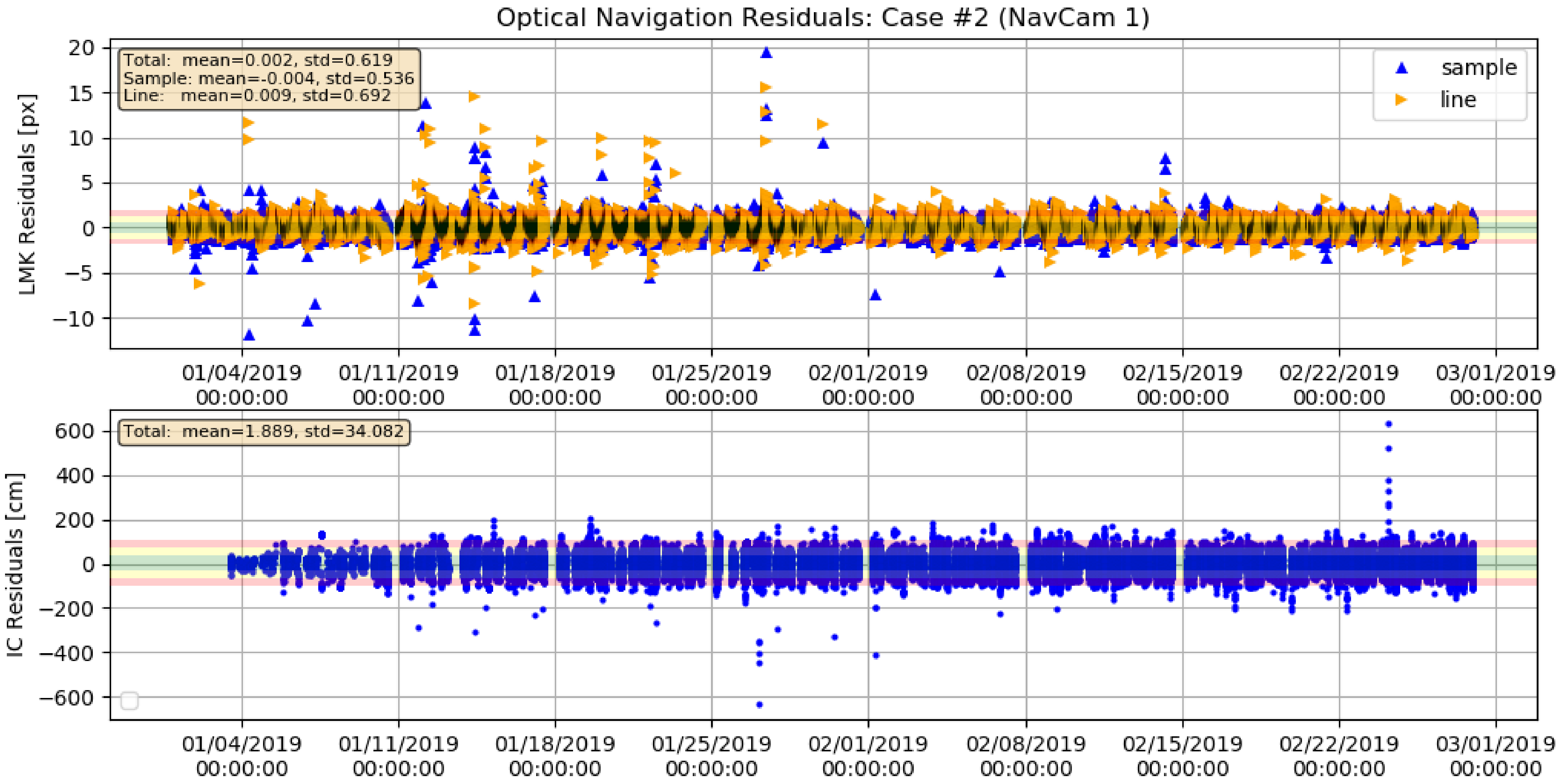
	Direct Landmarks		Image Constraints	
	Mean (pix)	RMS (pix)	Mean (cm)	RMS (cm)
Case 1: DL (1 px), no Scale or COM-COF	0.0019	0.6315	2.11	34.25
Case 2: DL (1 px), Scale & COM-COF	0.0021	0.6187	1.89	34.13
Case 3: DL (3 px), Scale & COM-COF	0.0025	0.6402	2.38	34.52
Case 4: ICs Only (10 cm)	0.2293	1.516	-0.64	29.29
Case 5: ICs Only (75 cm)	0.1665	1.0856	-0.67	29.74

- **Fit / Passthru**
- Residuals are similar for DL-only and IC-only cases

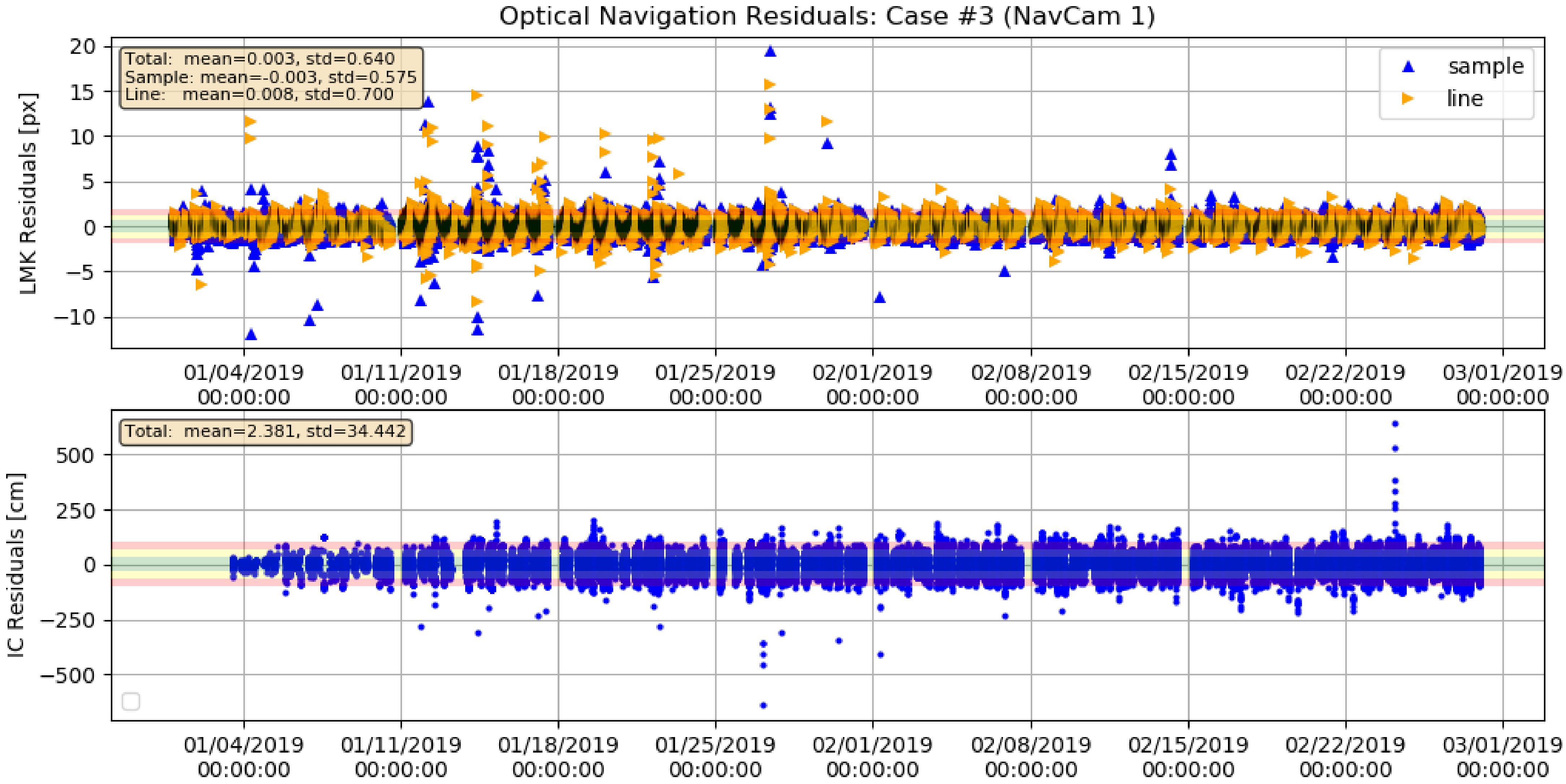
Residuals: Case 1
Direct Landmarks Only (1 px), No Scale/COM-COF



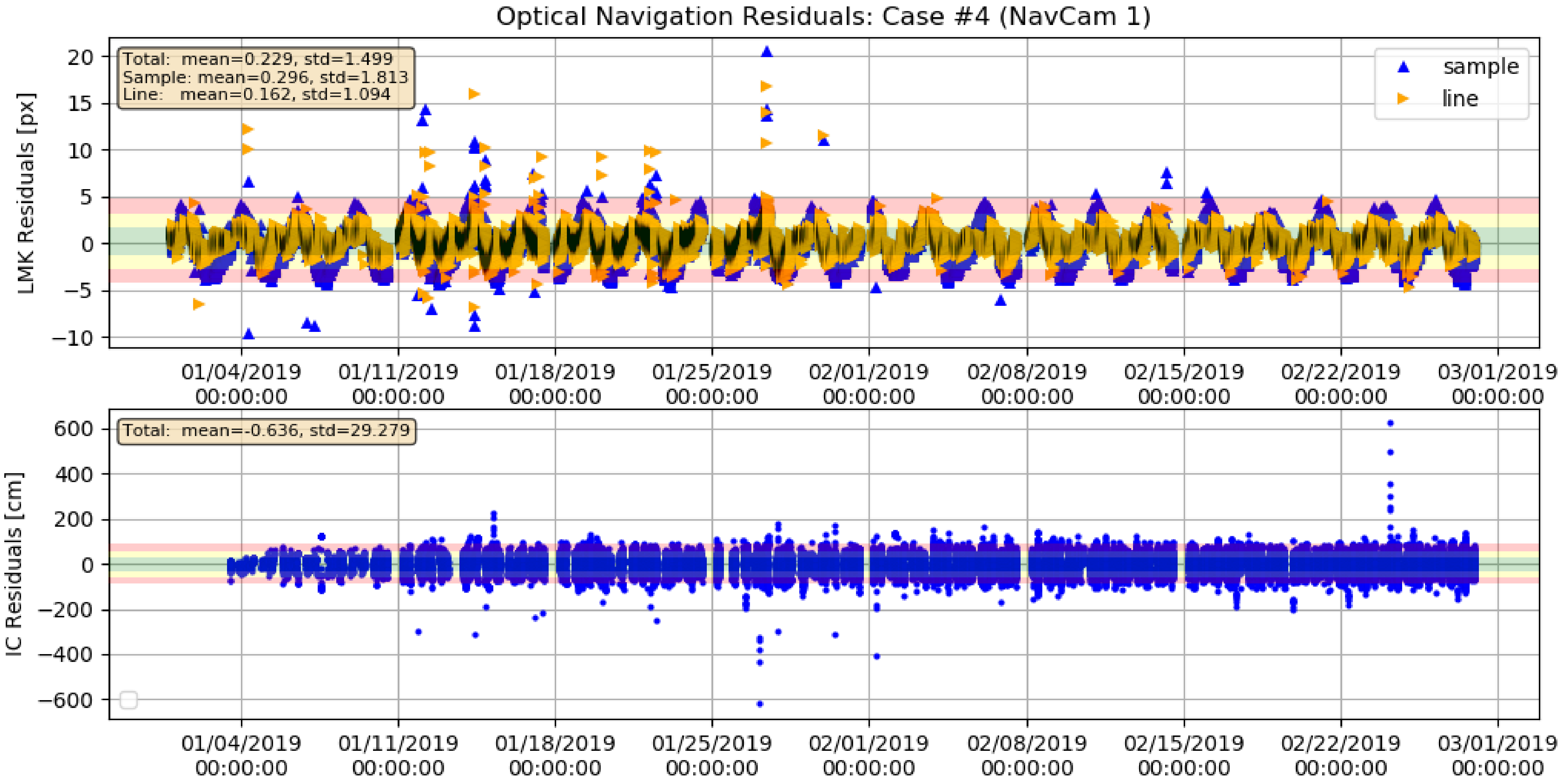
Residuals: Case 2
Direct Landmarks Only (1 px), With Scale/COM-COF



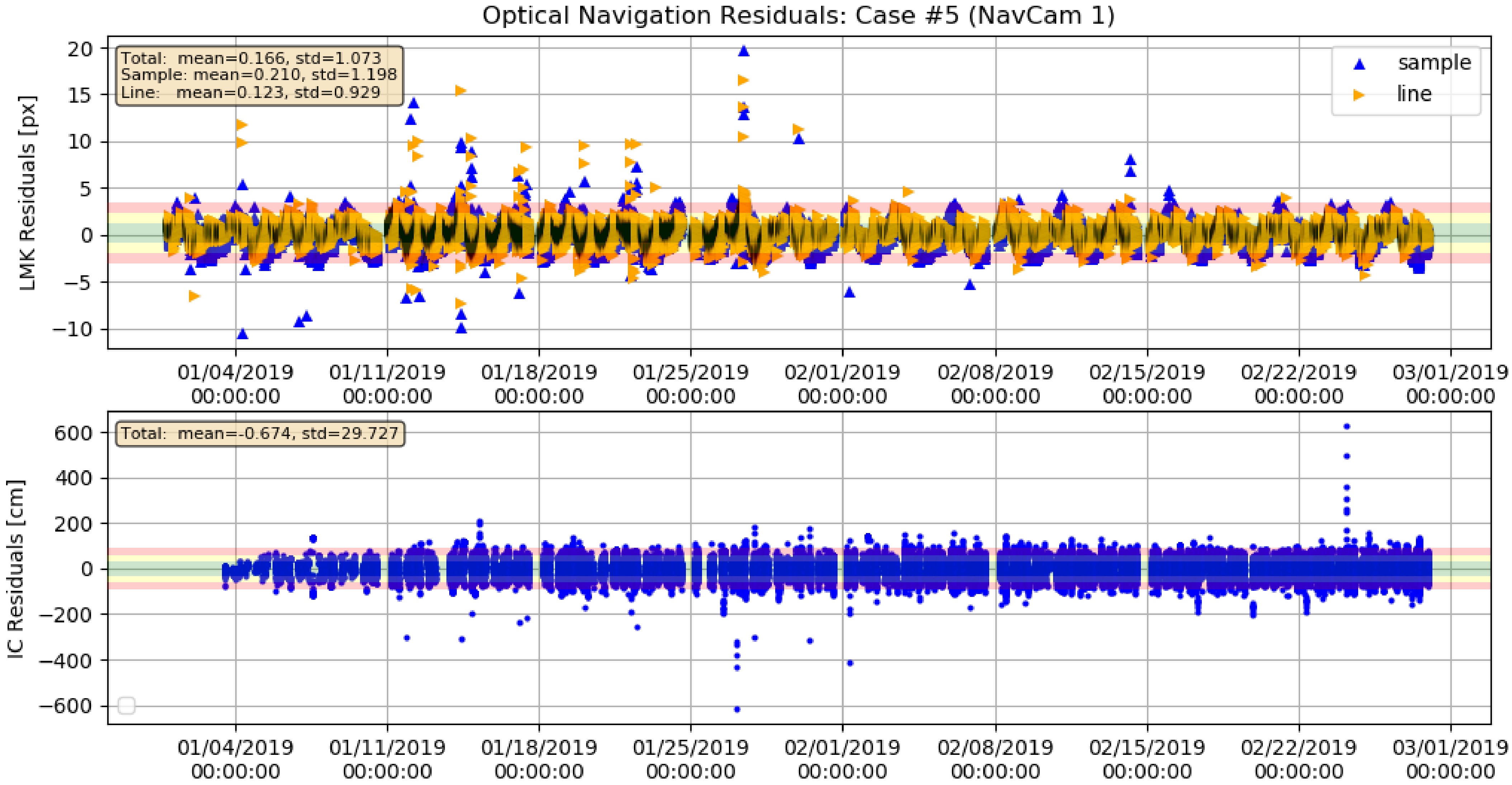
Residuals: Case 3
Direct Landmarks Only (3 px), With Scale/COM-COF



Residuals: Case 4
(Image Constraints Only, 10 cm)



Residuals: Case 5
(Image Constraints Only, 75 cm)

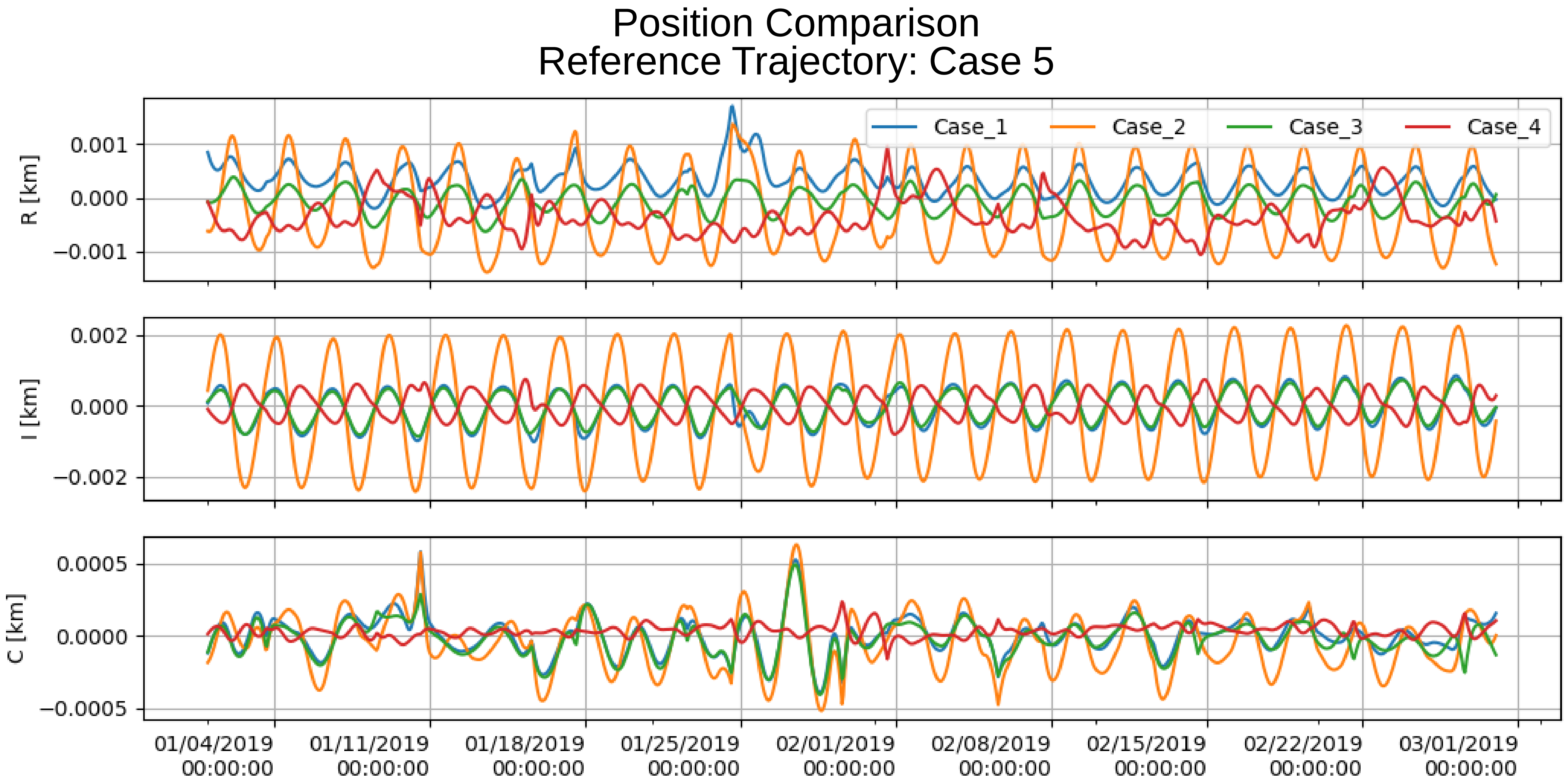


Spin State Sensitivity

	α	δ	ω_0	ω
Case 1	85.5039° ± 0.223°	-60.2974° ± 0.070°	27.3665° ± 0.298°	0.02328 ± 4.6e-8°/sec
Case 2	85.5036° ± 0.223°	-60.2905° ± 0.071°	27.3642° ± 0.298°	0.02328 ± 4.6e-8°/sec
Case 3	85.4991° ± 0.583°	-60.2969° ± 0.209°	27.3599° ± 0.842°	0.02328 ± 1.4e-7°/sec
Case 4 (w/ω_0)	85.4437° ± 0.052°	-60.3767° ± 0.019°	16.6103° ± 12.98°	0.02328 ± 4.6e-8°/sec
Case 4 (w/o ω_0)	85.4435° ± 0.052°	-60.3767° ± 0.019°	27.3118° (Fixed)	0.02328 ± 7.5e-9°/sec
Case 5	85.4503° ± 0.363°	-60.3760° ± 0.137°	27.3118° (Fixed)	0.02328 ± 5.5e-8°/sec

- Spin State Epoch: December 1st, 2018 00:00:00.000
- All parameters are within family **except** for ICs-only with ω_0 estimation

Trajectories Compared to Case 5



Iterating IC Solutions with Direct Landmarks

- Case 6:
  - Held Case 4 trajectory fixed (ICs only, 10 cm weight)
  - Re-estimated Spin Pole/Rate, Shape Model Scale, and COM-COF offset using Direct Landmarks
  - Direct Landmark Residuals: **-0.0147 px mean, 0.6952 px RMS**

- Case 7:
  - Held Case 5 trajectory fixed (ICs only, 75 cm weight)
  - Re-estimated Spin Pole/Rate, Shape Model Scale, and COM-COF offset using Direct Landmarks
  - Direct Landmark Residuals: **-0.0046 px mean, 0.6973 px RMS**

	SCALE	COM-COF X	COM-COF Y	COM-COF Z
Case 1	1.0 (Fixed)	0.0 (Fixed)	0.0 (Fixed)	0.0 (Fixed)
Case 2	0.9995 ± 2.07e-5	0.3599 ± 0.17 cm	1.235 ± 0.17 cm	146.6 ± 3.68 cm
Case 3	0.9996 ± 8.97e-6	0.2048 ± 0.52 cm	1.266 ± 0.51 cm	-62.80 ± 5.3 cm
Case 6	0.9997 ± 8.97e-6	0.1454 ± 0.17 cm	1.249 ± 0.17 cm	-119.2 ± 0.24 cm
Case 7	0.9998 ± 8.97e-6	-0.0885 ± 0.17 cm	1.427 ± 0.17 cm	-67.87 ± 0.24 cm

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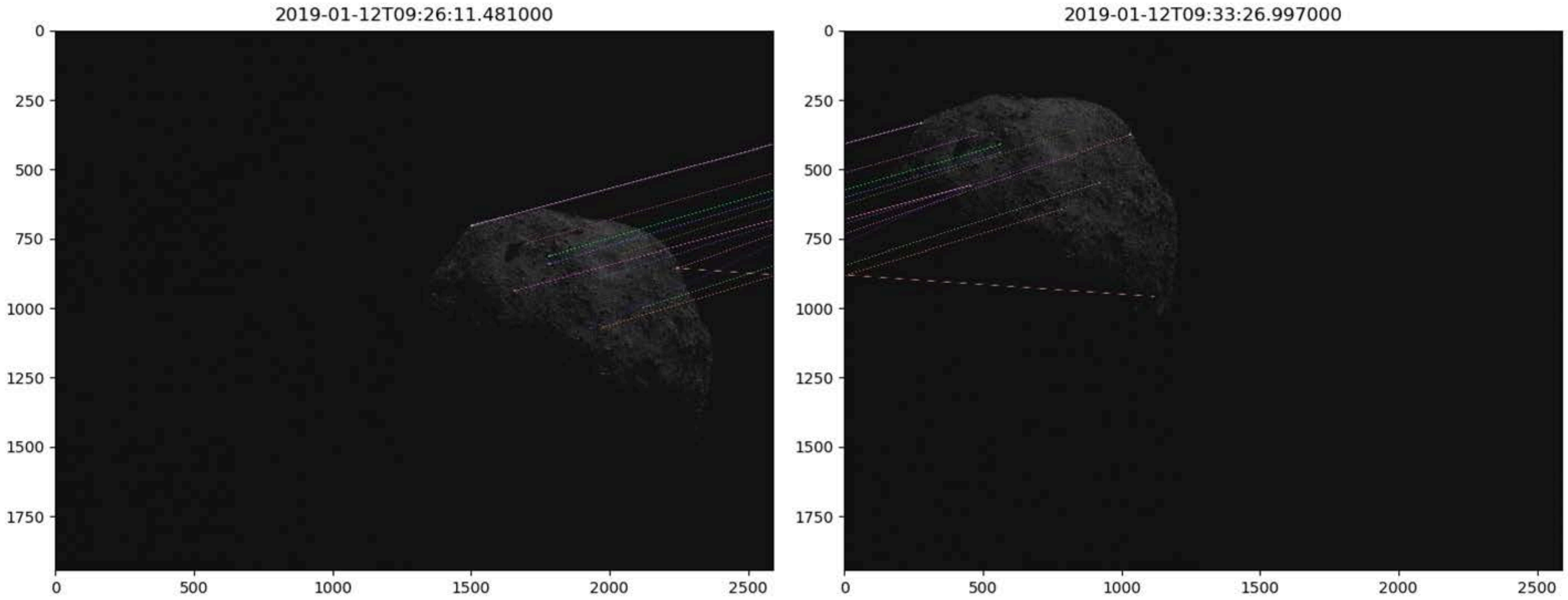
Alternatives Methods to Identify Constraints

While SPC provides an opportunity to easily extract the location of the same feature in numerous images, it requires having a pre-built shape model, nullifying one of the benefits of this measurement type.

We are currently investigating alternative methods of matching features between images using just image processing.

- Feature Descriptors (shown)
- RANSAC based Keypoint
- Template Matching
- Mutual Information Correlation



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Conclusions & Future Work

- ICs are an alternative to Direct Landmark observables in orbit determination and provide an additional metric to evaluate solutions
  - Demonstrated with NEAR, Dawn, and OSIRIS-REx data
- The IC measurement model does not depend on a shape model or pre-defined landmarks
  - Some 1^{st} order errors cancel (not scale)
  - Potential to generate ICs without prior shape model development
- Orbital A results are consistent with one-another, depending on the weighting scheme
- Future Work:
  - Continue analyzing OSIRIS-REx data in other mission phases (Surveys, Orbit B, etc.)
  - Refine IC alternative construction techniques that do not require a shape model and test with OSIRIS-REx imagery
  - Compare with other complimentary data types: Direct and Differenced Altimetry

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