Orbit Determination from Two Line Element Sets of ISS-Deployed CubeSats

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JSpOC Disclaimer

Please refer to space-track.org on the use of TLEs:

TWO-LINE ELEMENT (TLE) SET IS THE MEAN KEPLERIAN ORBITAL ELEMENT AT A GIVEN POINT IN TIME FOR EACH SPACE OBJECT REPORTED. A TLE IS GENERATED USING THE SIMPLIFIED GENERAL PERTURBATIONS THEORY AND IS REASONABLY ACCURATE FOR LONG PERIODS OF TIME. A TLE AVAILABLE TO THE PUBLIC SHOULD NOT BE USED FOR CONJUNCTION ASSESSMENT PREDICTION. SATELLITE OPERATORS ARE DIRECTED TO CONTACT THE JOINT SPACE OPERATIONS CENTER AT 805-605-3533 FOR ACCESS TO APPROPRIATE DATA AND ANALYSIS TO SUPPORT OPERATIONAL SATELLITES.

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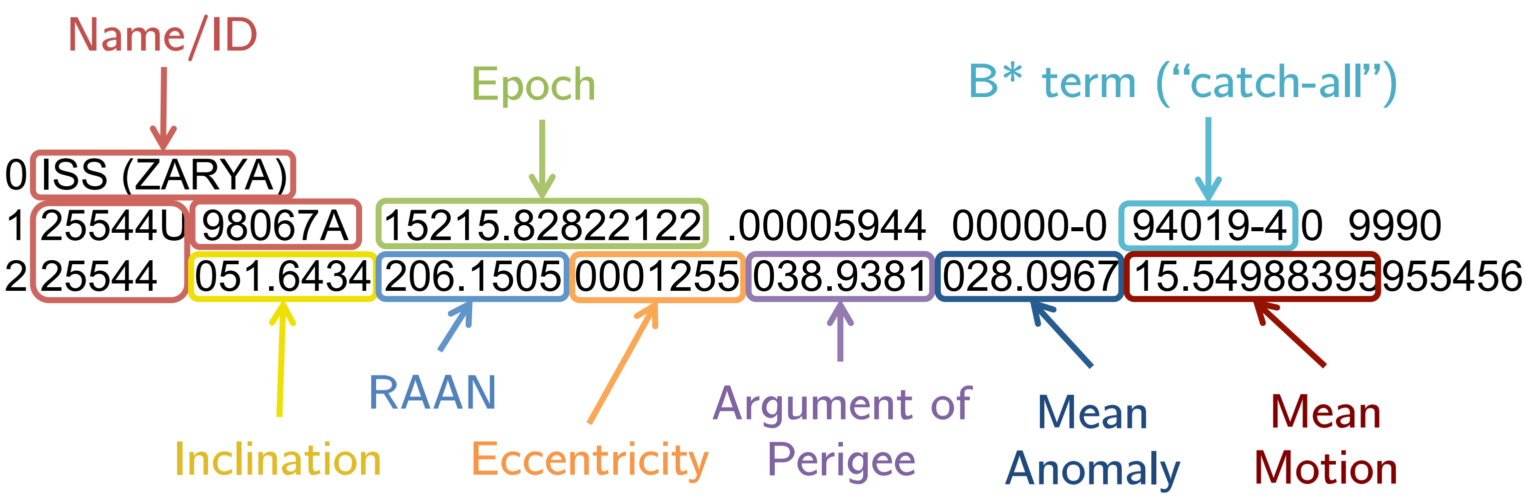
Outline

- Introduction
  - Importance of TLE Accuracy
  - ISS-deployed CubeSats
- Analysis of TLE Accuracy
  - Dataset & Methods
  - Statistical Results
  - TLE Self-Consistency
- Estimation Techniques
  - Least Squares Method & Application
  - TLE Improvement
- Conclusion & Future Work

Background & Motivation

- Joint Space Operations Center (JSpOC) tracks 23,000 objects in space → made public as TLEs
  - No accuracy statistics provided
  - Intended for use with SGP4
- Uses of TLEs
  - Conjunction assessments[1,2]
  - Orbit determination for small satellites[3]



ISS-deployed CubeSats

- Recent growth: 61 CubeSats deployed since 2014[4]
- Prior studies on CubeSats in LEO indicate TLE accuracy within 1 km[5,6]
- However, ISS orbit is unique
  - Low altitude at ~410 km
  - High drag environment
  - Atmospheric variability
  - Many CubeSats in similar orbits

Image of MicroMAS and Lambdasat deployments.

Objective #1: Provide statistics regarding JSpOC TLE accuracy for ISS-deployed CubeSats.

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Dataset & Method

- Analysis conducted on 10 satellites of Planet Labs Flock 1B during September 2014
  - 634 JSpOC TLEs across all satellites
  - "Truth set" is orbital ephemerides from Planet Labs based on two-way ranging
- JSpOC TLEs are propagated forward in time and compared to truth in 20 minute intervals

Image of Dove deployments from NASA.

Planet Labs' data is used with their approval and is publicly available at: http://ephemerides.planet-labs.com/

Reference Frame

Radial error, $\hat{R}$

In-track error, $\hat{S}$

For circular orbits, $\hat{S}$ is aligned with the velocity vector

Cross-track error, $\hat{W}$

Perpendicular to orbital plane

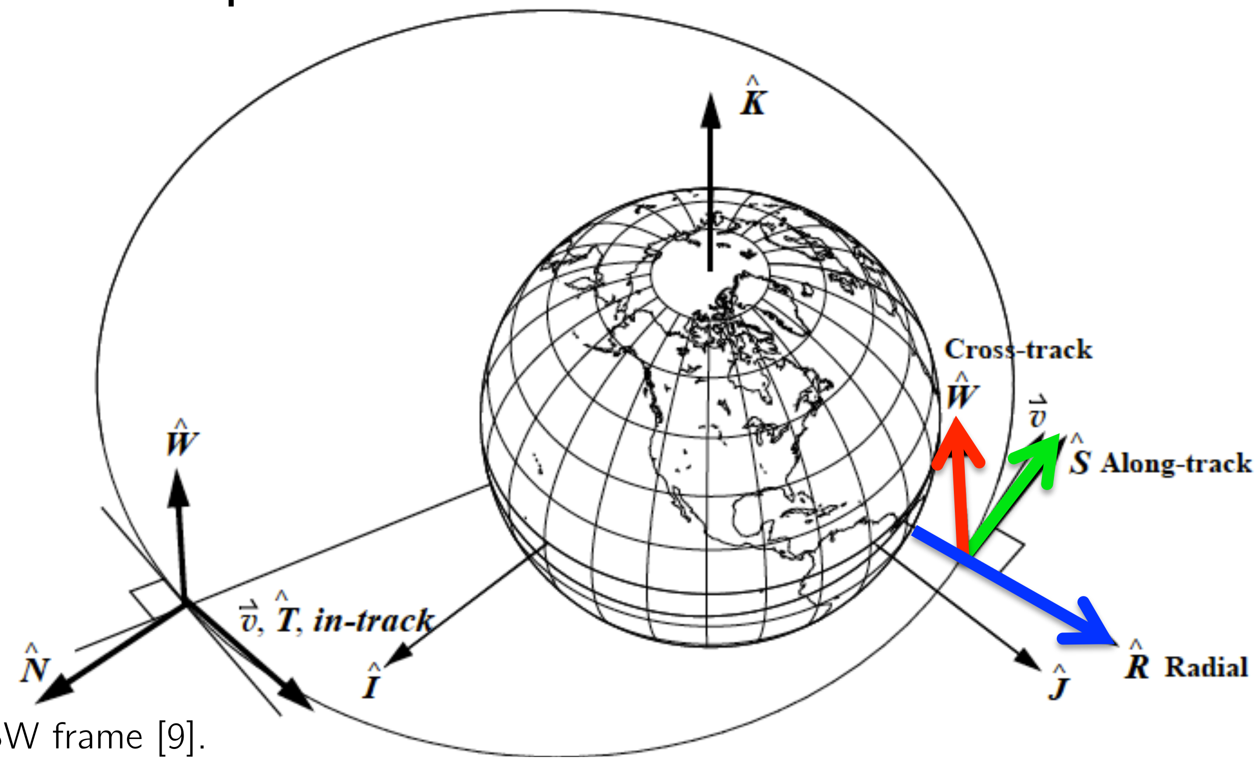
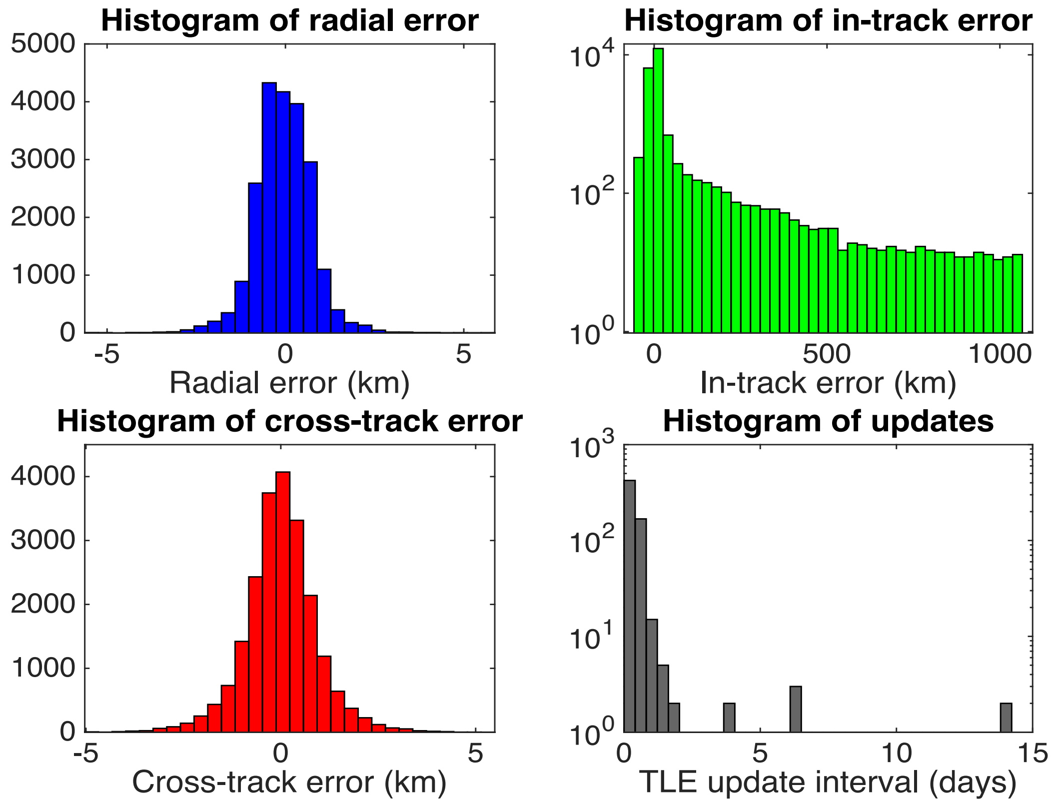


Image of RSW frame [9].

TLE Accuracy Statistics

- 25% of time, total error is >10 km
- In-track error dominates
- Median update time of 8 hours between epochs
- Occasional week-long update gaps



Error	Q1 (km)	Median (km)	Q3 (km)
Radial Error	-0.54	-0.07	0.45
In-track Error	-3.45	0.32	6.26
Cross-track Error	-0.50	0.00	0.51
Total Error	2.01	4.52	10.60

TLE Self-Consistency

- Given a set of TLEs, can use self-consistency check to estimate propagation error[7]
  - Treat each TLE as “truth” at its epoch
  - Propagate a TLE with epoch t_i to a second TLE with epoch t_j to estimate error as a function of propagation time

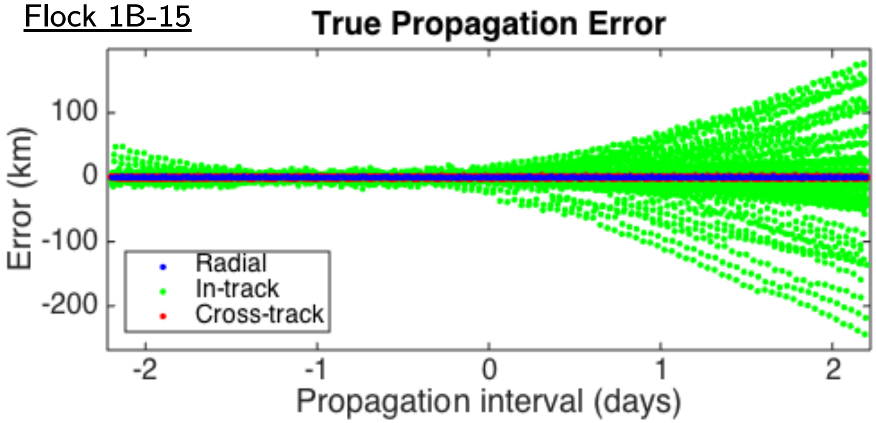
- Chronological TLE comparison can alert operator to error spikes

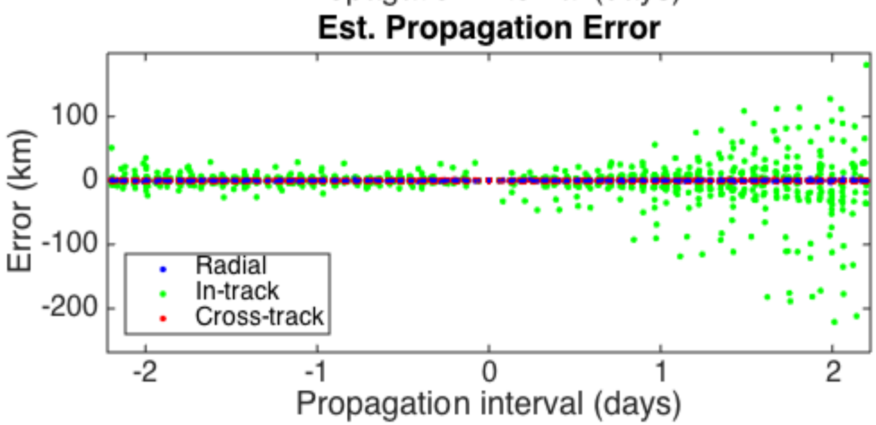
Objective #2: Determine if self-consistency checks provide a good estimate of propagation error.

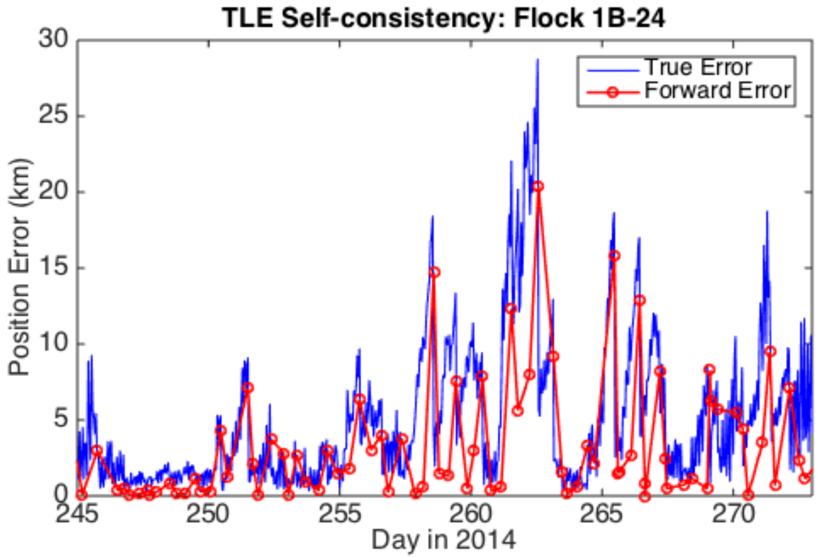
Self-Consistency & Propagation Error

- Self-consistency metric can accurately estimate 1-σ error to within 10%
- Chronological self-consistency checks can reveal error spikes

Flock 1B-15







1-σ propagation error:
After 1 day → 10-30 km
After 2 days → 20-70 km

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Objective #3: Apply least squares estimation techniques to improve current TLE based only on prior TLEs.

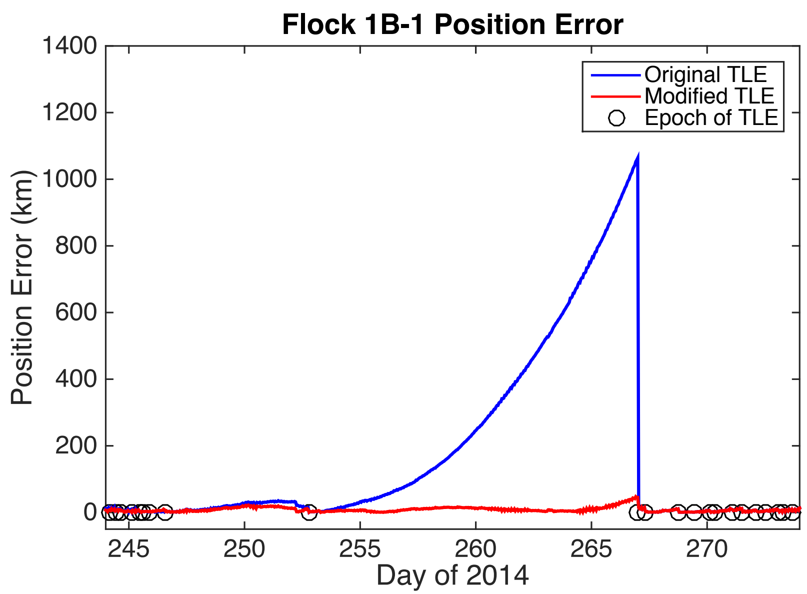
Least Squares Method & Application

• State vector is 6 orbital elements and B*
• Two cases: "poorly-tracked" vs. "well-tracked"
  – Criteria: Are there 5 TLEs in past 36 hours?
  – If well-tracked, conduct full state estimate
  – If poorly-tracked, only estimate B*
	State Vector: $\boldsymbol{X} = \begin{bmatrix} i \\ \Omega \\ e \\ \omega \\ M \\ n \\ B^* \end{bmatrix}$

• Pseudo-observations consist of position and velocity of prior TLEs	Observations: $\boldsymbol{y_i} = \begin{bmatrix} \boldsymbol{r_i} \\ \boldsymbol{v_i} \end{bmatrix}$
• Current TLE is propagated to pseudo-observations and residuals are formed • Jacobian is estimated with finite differencing	Jacobian: $A = \frac{\delta\ observations}{\delta \widehat{\boldsymbol{X}}_0}$ $\delta_i = \widehat{\boldsymbol{X}}_{\boldsymbol{mod_i},\boldsymbol{0}} - \widehat{\boldsymbol{X}}_{\boldsymbol{nom},\boldsymbol{0}}$ $A \approx \frac{obs_{mod} - obs_{nom}}{\delta_i}$
• Least squares correction is applied repeatedly until tolerance is met[8]	LS Correction: $\delta\widehat{\boldsymbol{X}} = (A^T W A)^{-1} A^T W \boldsymbol{b}$

Estimation Results: Poorly-tracked

- Worst-case scenario: Flock 1B-1
  - TLE update gap of over 2 weeks
  - Propagation error grows to 1100 km
- Estimation of B* term → propagation error reduced by 95%
- Poorly-tracked cases show significant improvement



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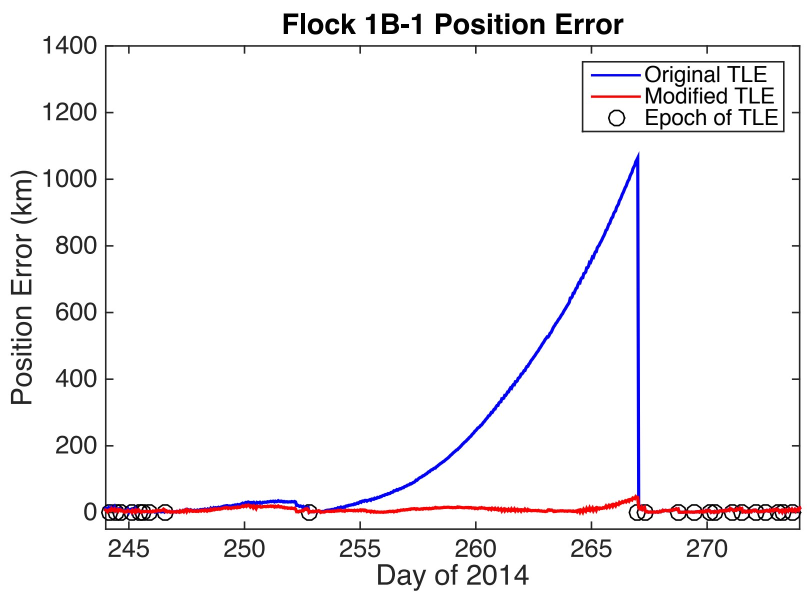
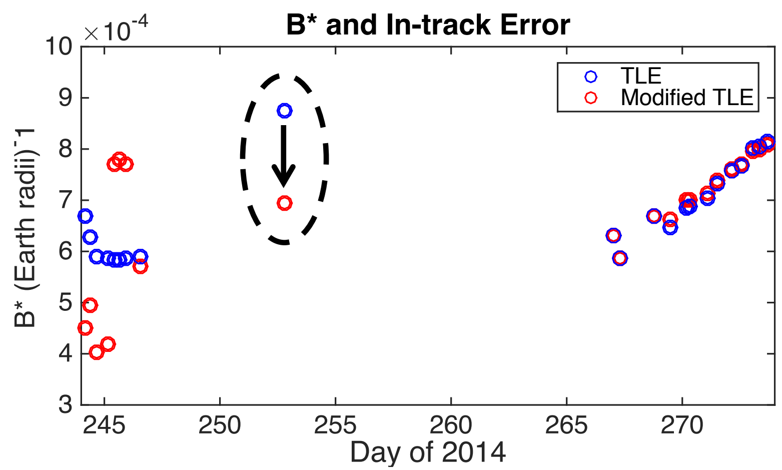
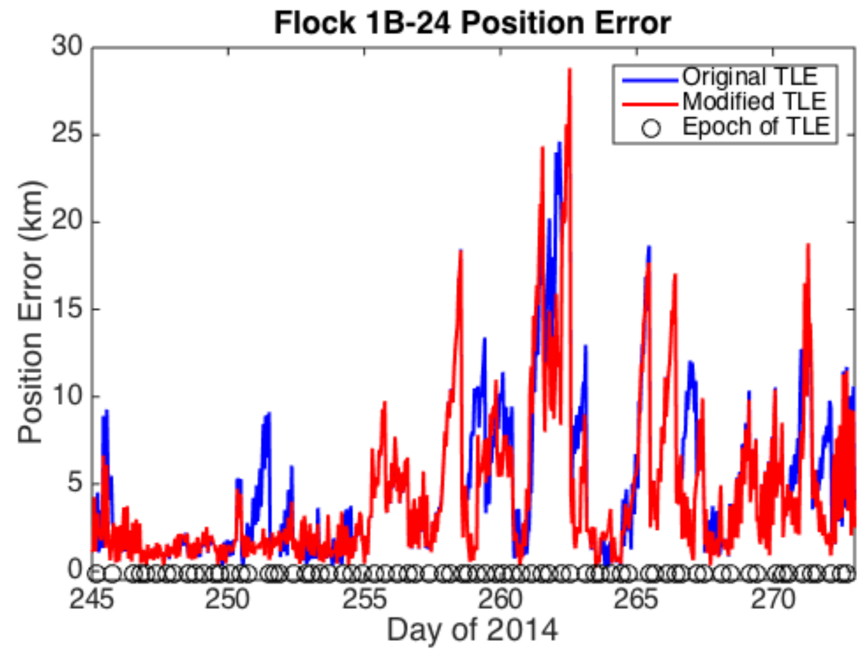




Estimation Results: Well-tracked

- Best-case scenario: Flock 1B-24
  - Consistent tracking over entire month
  - Highest error is 25 km



- Estimation of full state → propagation error reduced by 15%

- Well-tracked cases show modest improvement

Combined Estimation Results

- 9/10 satellites show reduction in propagation error with estimation technique
- Greatest improvement in cases with sparse TLE updates

Sat. ID	Mean Propagation error in position		
	Orig. TLE (km)	Mod. TLE (km)	% Improvement
1B-1	165.2	8.6	95%
1B-2	23.7	23.2	2%
1B-7	11.9	13.3	-11%
1B-8	73.1	43.8	40%
1B-15	8.2	7.3	10%
1B-16	4.3	3.9	9%
1B-23	5.0	4.3	15%
1B-24	5.1	4.3	15%
1B-25	8.1	7.1	13%
1B-26	5.5	5.0	6%

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  - Median error is 4.5 km
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- Least squares estimation techniques can improve accuracy, particularly with sparse TLE updates
- Results are specific to ISS-deployed CubeSats, so future work aims at an analysis of other orbits

Acknowledgements

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Questions?

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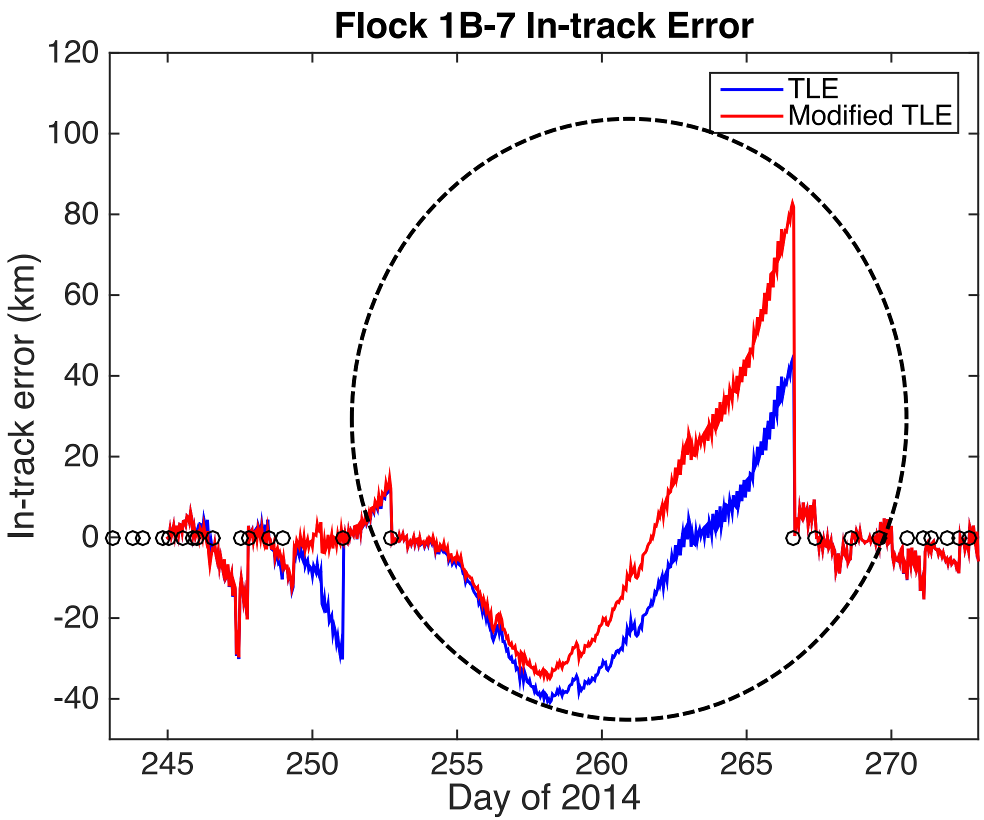
Backup Slides

Flock 1B-7 Case

- Falls into "poorly-tracked" category
- Unusual behavior: in-track error goes from negative to positive
  - Estimation of B* term is insufficient to resolve behavior



Why estimation of B*?

- B* is highly coupled to in-track error, so it has the greatest effect in reducing this error

$$B = C_d A/m$$

$$B^* = B\rho_0/2$$

- B* is used as a "catch-all" term for unmodeled effects

Planet Labs Dove