CCAR

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AVS Laboratory

Methods to Detect Impact-Induced Orbit Perturbations Using Spacecraft Navigation Data

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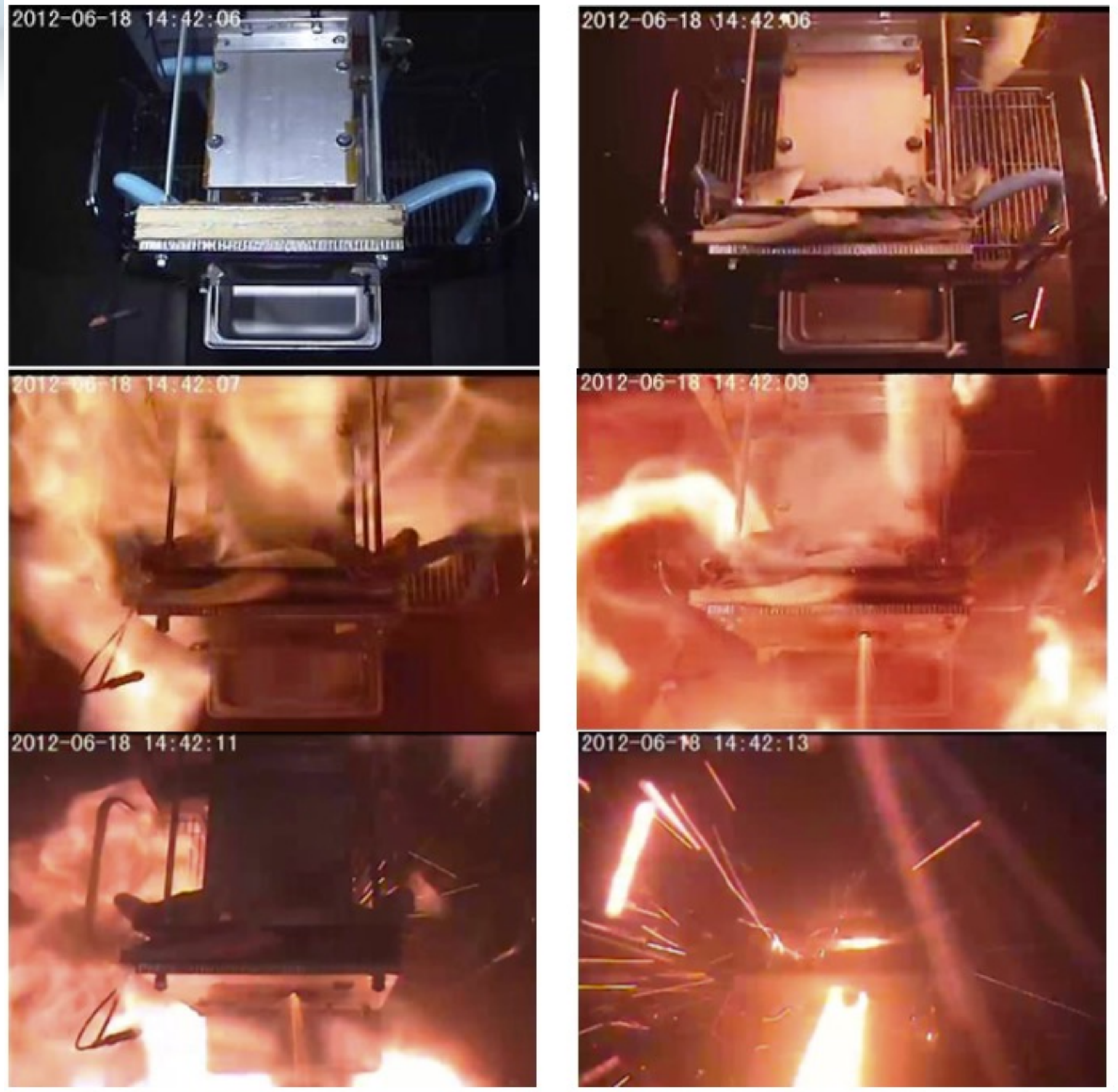
Hazardous Non-Trackable Orbital Debris

- Fragmentation events produce clouds of small debris as well as larger trackable debris pieces
  - Space Surveillance Network tracks down to ~10 cm in LEO, ~70 cm in GEO **(<10% of hazardous debris**)
  - Debris 1 cm or smaller can cause mission-ending damage
- Sample return missions indicate 100s-1,000s of impacts
  - LDEF, Hubble solar arrays, etc.
- Recent events
  - Sentinel-1A, DigitalGlobe's WorldView-2 (debris strikes – nominal operations)
  - NASA's MMS Constellation (multiple particle strikes – nominal operations)
  - Telkom-1, AMOS-5, maybe Intelsat-29e (satellites lost in abrupt anomalies, debris plausible)

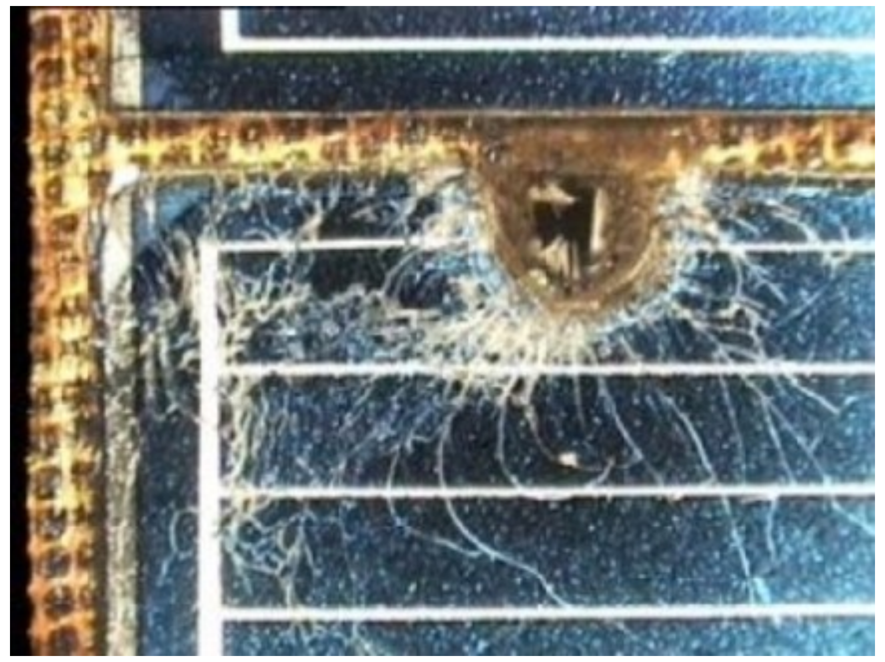
NASA test of 1 cm Aluminum sphere impacting battery at ~7 km/s

"This test resulted in a visible deflagration as the impacted cell contents are energetically ejected…"

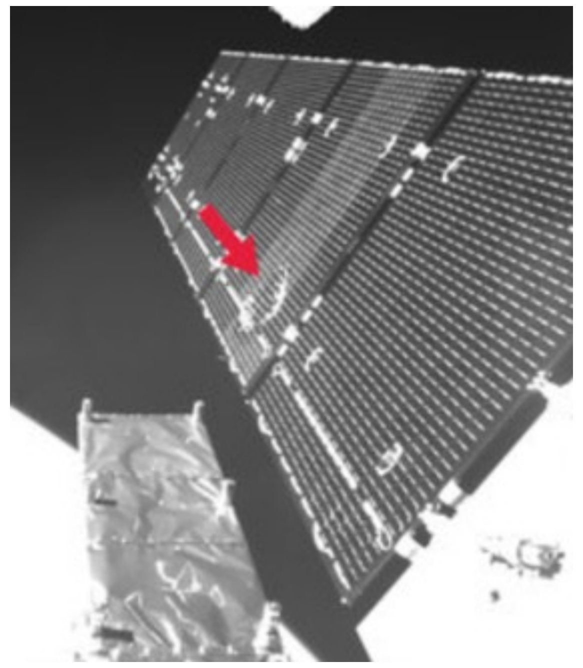


Source: Orbital Debris Quarterly News, Feb 2017

Debris Strikes on Hubble and Sentinel-1A Solar Arrays



Source: ESA website

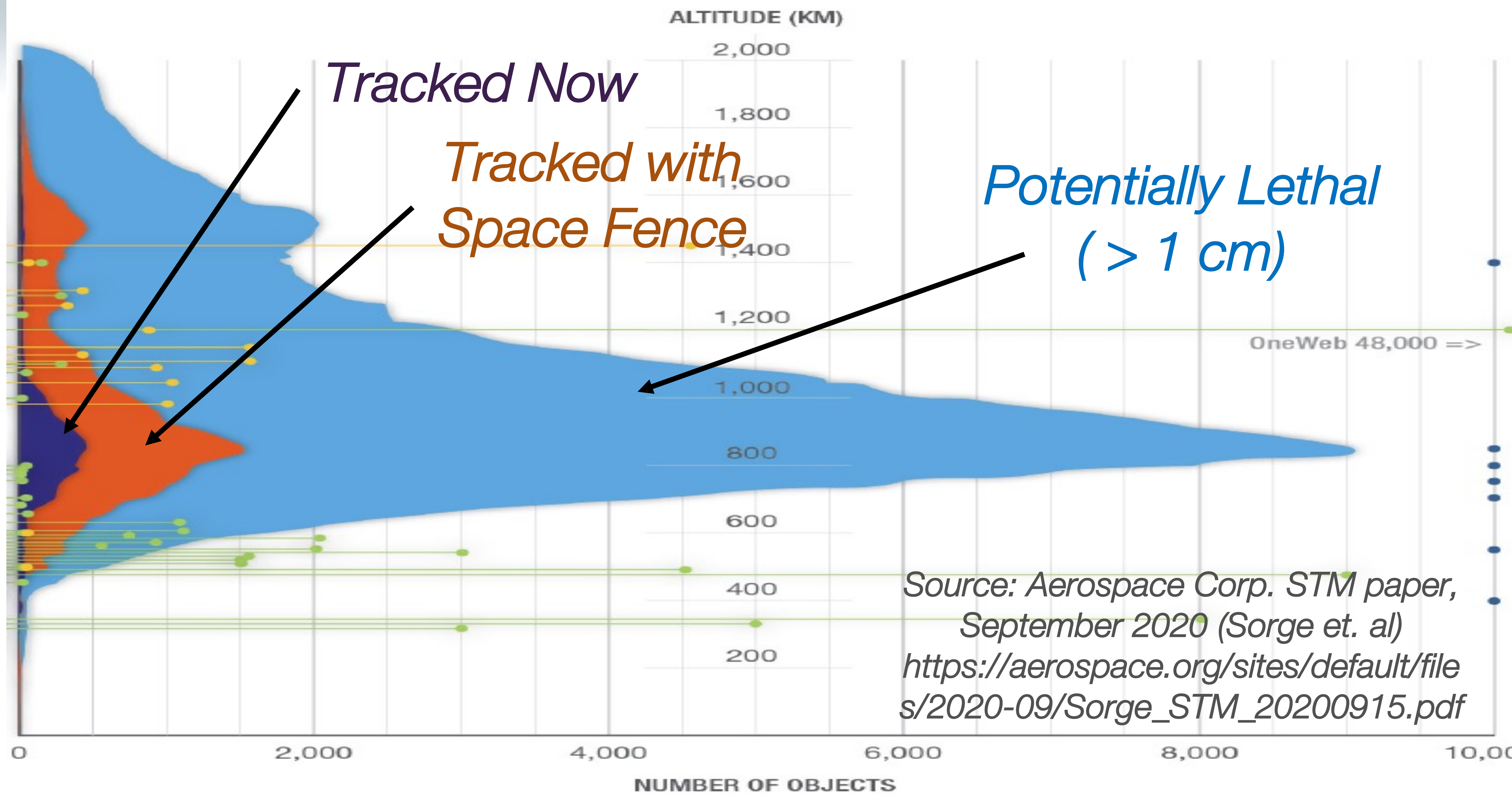


Source: ESA website

Untrackable strikes can be benign, or can be catastrophic

Challenges in Predicting Risks from Untracked Debris

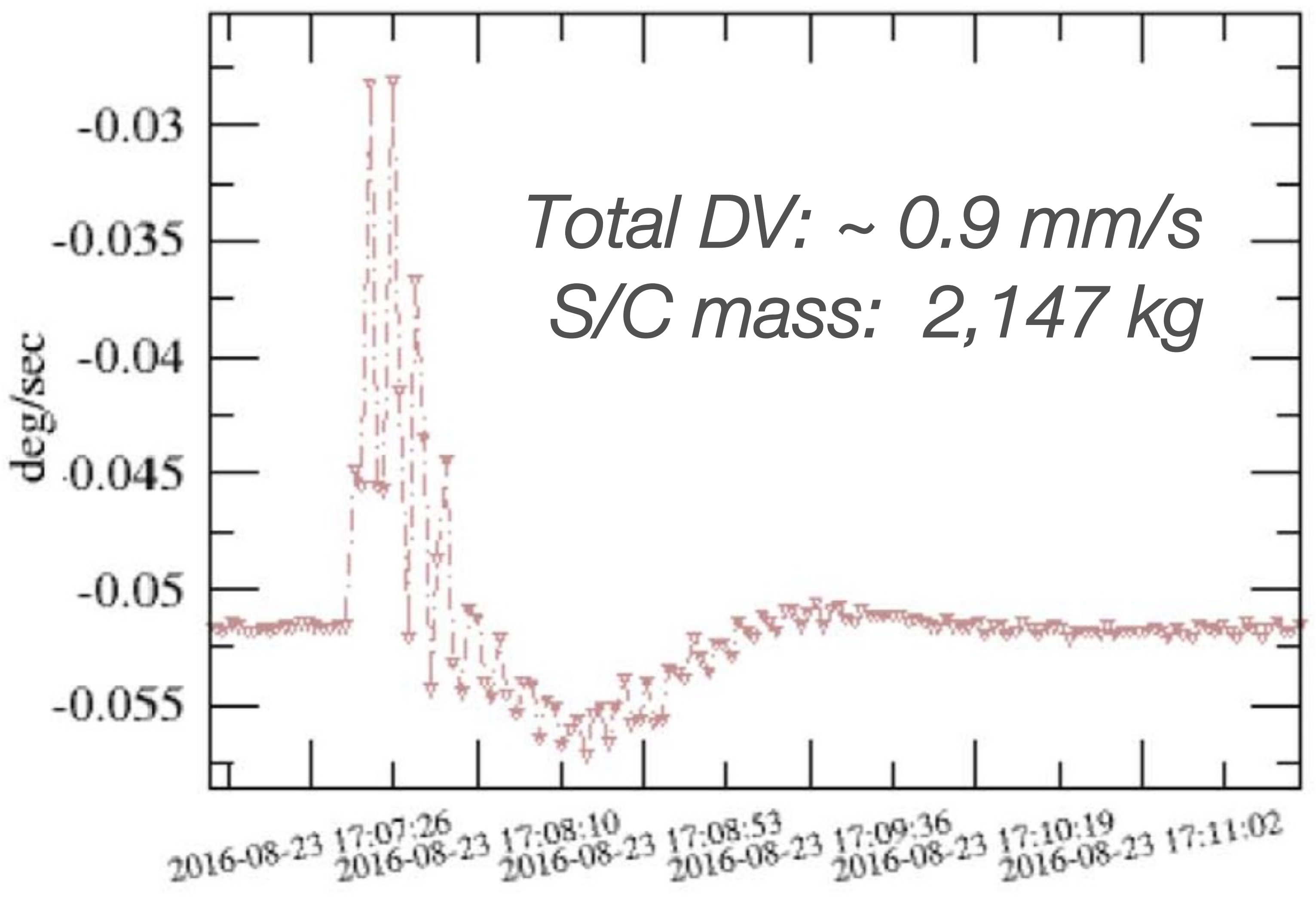
- ORDEM is used to predict expected debris flux
  - Fundamentally limited by data collection systems
  - 2017 NESC report evaluates predicted vs. reported anomalies
    - Found significant inconsistencies (vs. ORDEM3.0)
    - Far **fewer** anomalies reported than predicted in multiple studies
    - One study: Predicted 24-160 perturbations, experienced 7
    - **Recommendation: collect additional data to validate models**



Source: Aerospace Corp. STM paper, September 2020 (Sorge et. al) https://aerospace.org/sites/default/files/2020-09/Sorge_STM_20200915.pdf

- Typical spacecraft operations:
  - Anomalous behavior => full review (Significant time + $$$)
    - Sentinel-1A: DV estimated by ESA FD (1st order), ESA Nav POD, and GSOC
  - No anomalous behavior => not assessed/investigated/cataloged?
    - **Indications of debris strike often subtle**
- Emerging space era: more satellites, more autonomy

Sentinel-1A telemetry



Source: DOI http://dx.doi.org/10.1016/j.actaastro.2017.05.010, Acta Astronautica

Can subtle strike effects be sensed in spacecraft nav data?

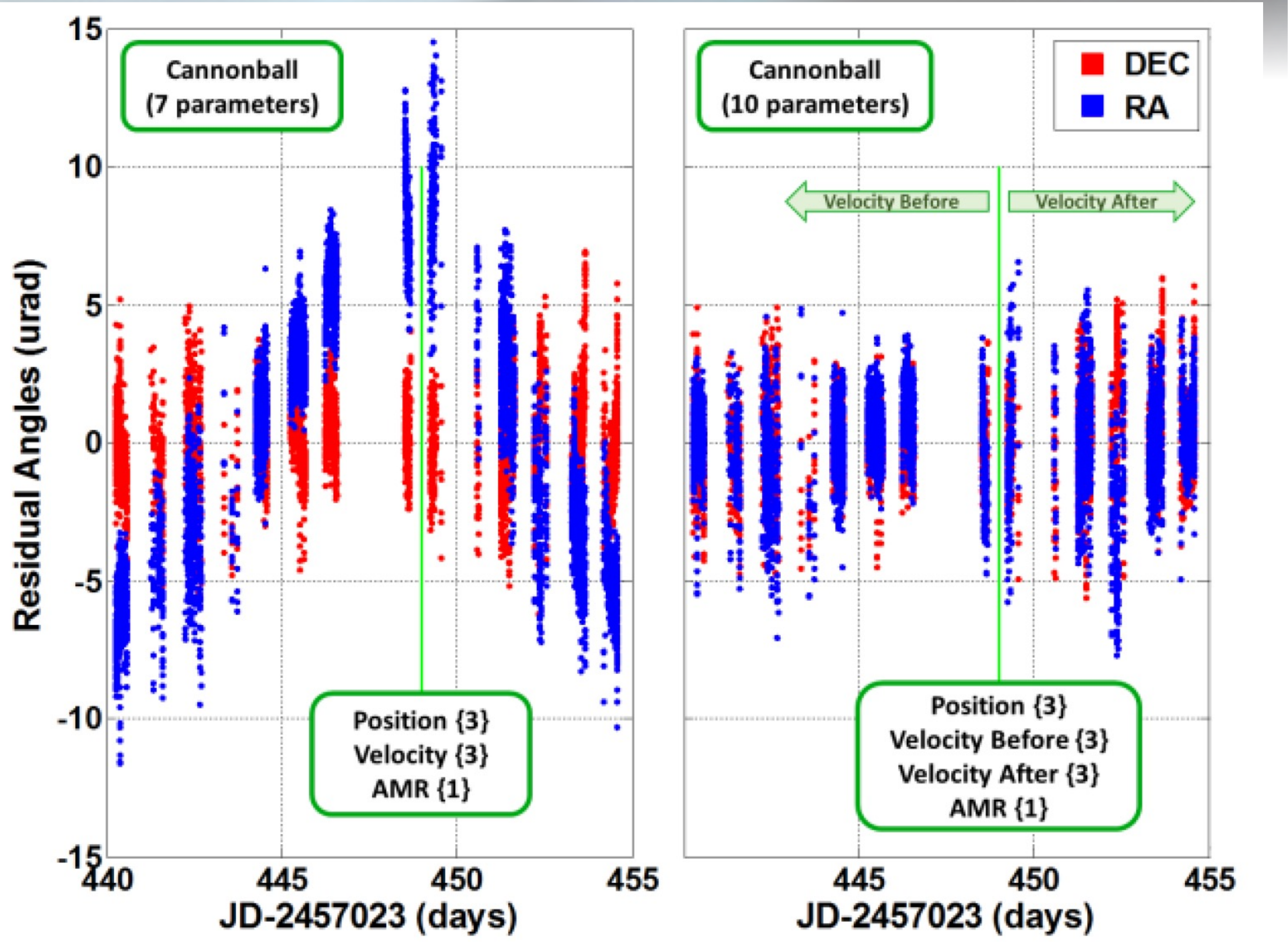
Initial Methods Development Approach

- Research Goal:

  Develop techniques to identify minor debris strikes in spacecraft nav data

- Debris strike changes orbit abruptly
  - Can small, abrupt deviations be distinguished from typical orbit perturbations?
  - Semi-autonomous routine identification vs. waiting for anomaly

- Initial development: methods to accentuate abrupt, subtle orbit changes
  - ‘You don’t need to re-invent precision orbit determination’



Source: Exoanalytic Solutions, Proc. 7th European Conference on Space Debris, Darmstadt, Germany, 18–21 April 2017, published by the ESA Space Debris Office (http://spacedebris2017.sdo.esoc.esa.int, June 2017)

Unexpected ‘Momentum Impulse Transfer Event’ on GEO spacecraft, detected by ground-based sensors. In-track DV approximately 0.7 mm/s

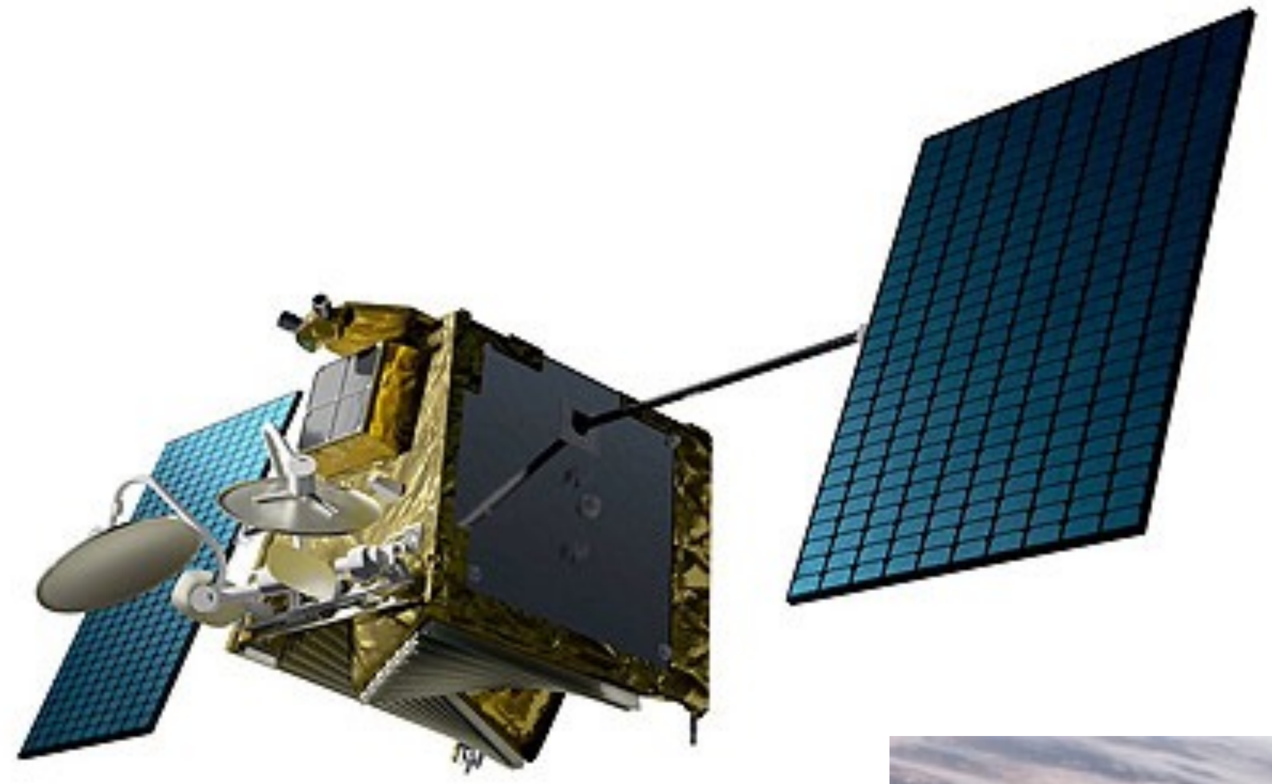
Simulation Scenario

- 200 kg LEO satellite with COTS GPS (gaussian noise)
- Apply debris strike as instantaneous DV

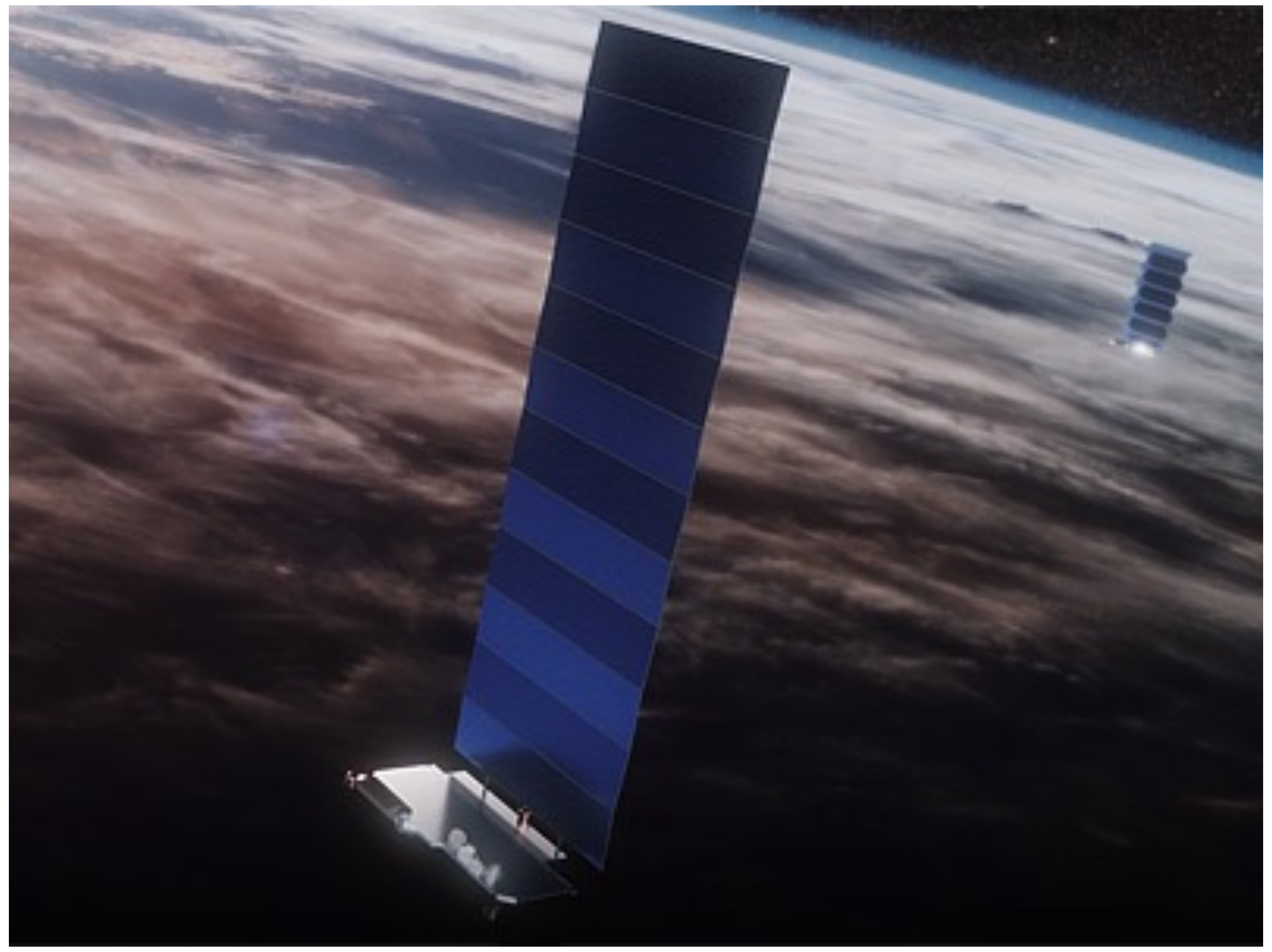
$$\Delta \boldsymbol{p} = \beta m_d \boldsymbol{v}_d \qquad \Delta V = \frac{\Delta \boldsymbol{p}}{m_s}$$

- Develop filtering methods
  - Simulate orbit, apply abrupt DV, generate GPS data
  - Apply EKF with DMC to estimate state & unmodeled accels
  - Run EKF with DMC backward and apply smoother
  - Calculate various test statistics to accentuate subtle strike
  - Tune and characterize performance
    - Trade study, Monte Carlo
  - Add orbit perturbations, assess effects

~1/5th U COTS GPS
Source: cubesatshop.com



OneWeb: ~150 kg
Source: OneWeb



Starlink: ~260 kg
Source: spacenews.com

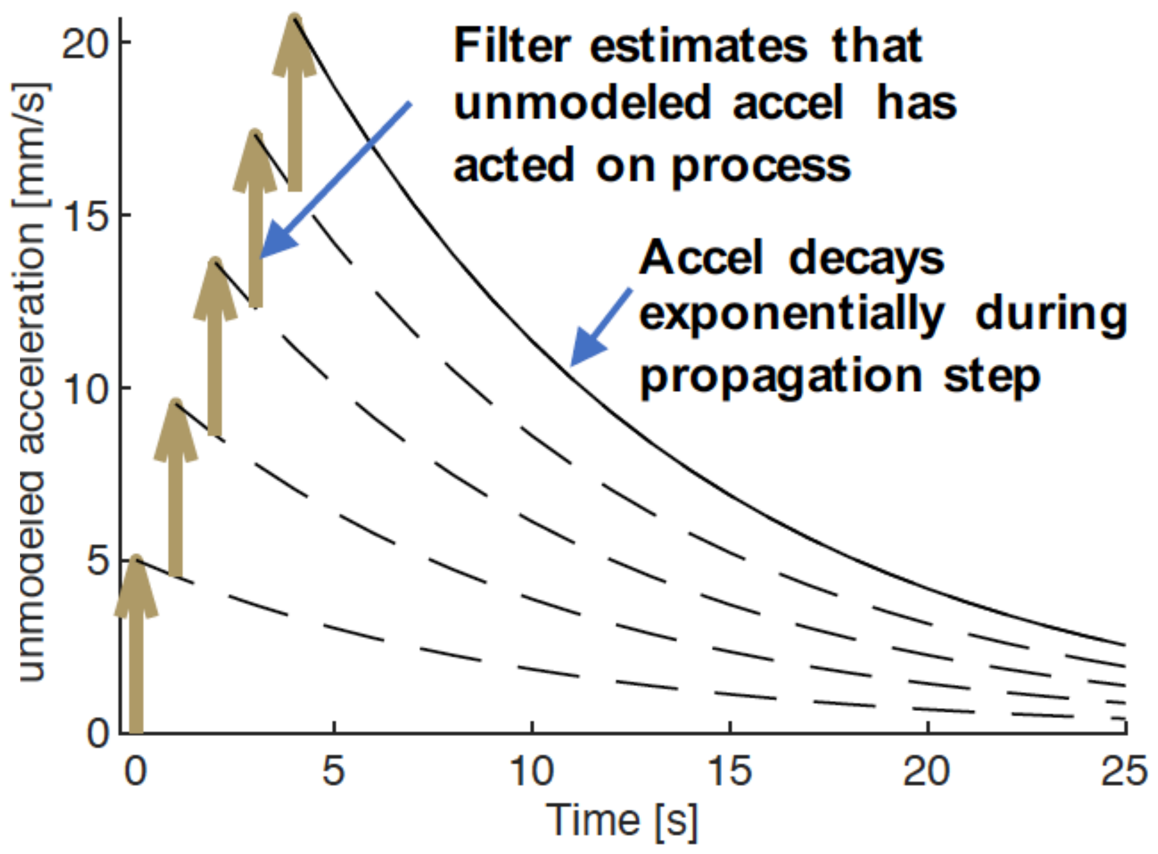
EKF w/ Dynamic Model Compensation

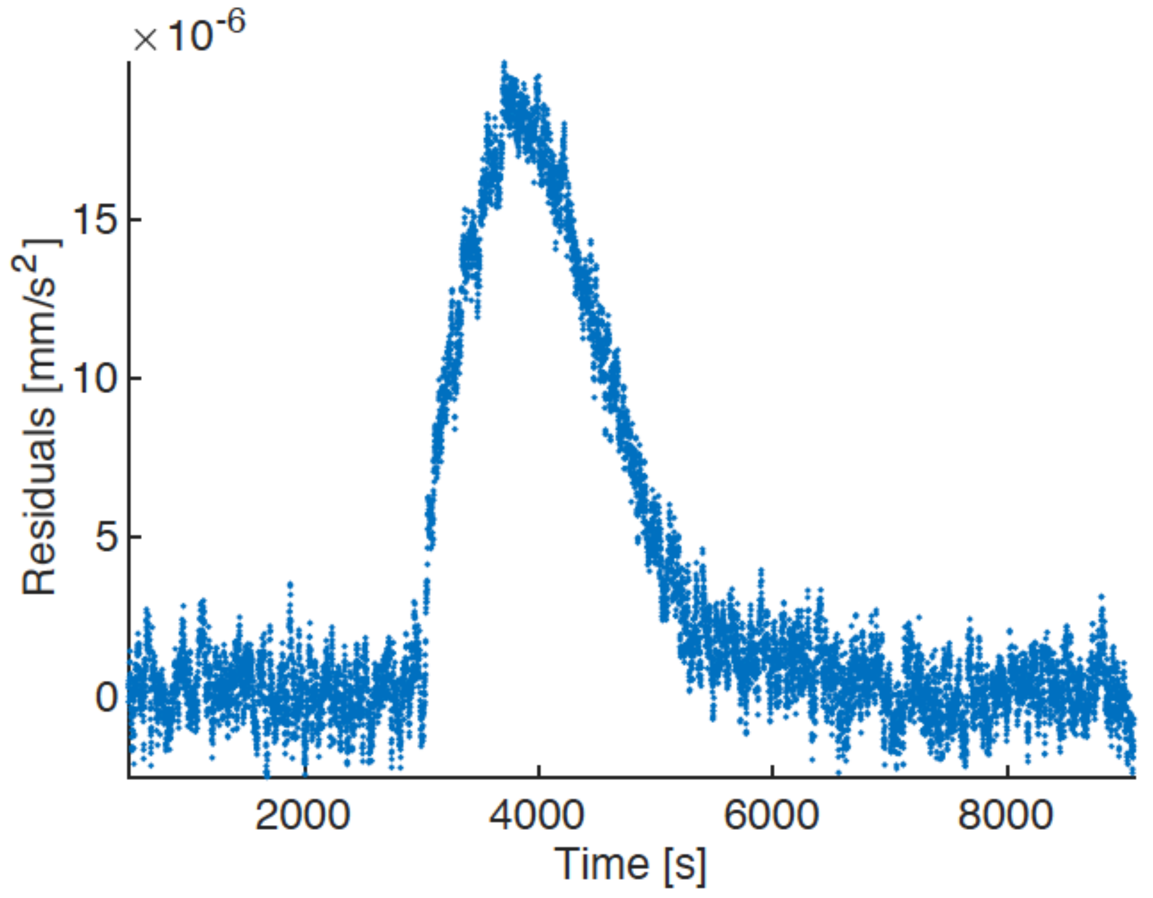
- Estimate unmodeled accelerations as first-order Gauss-Markov

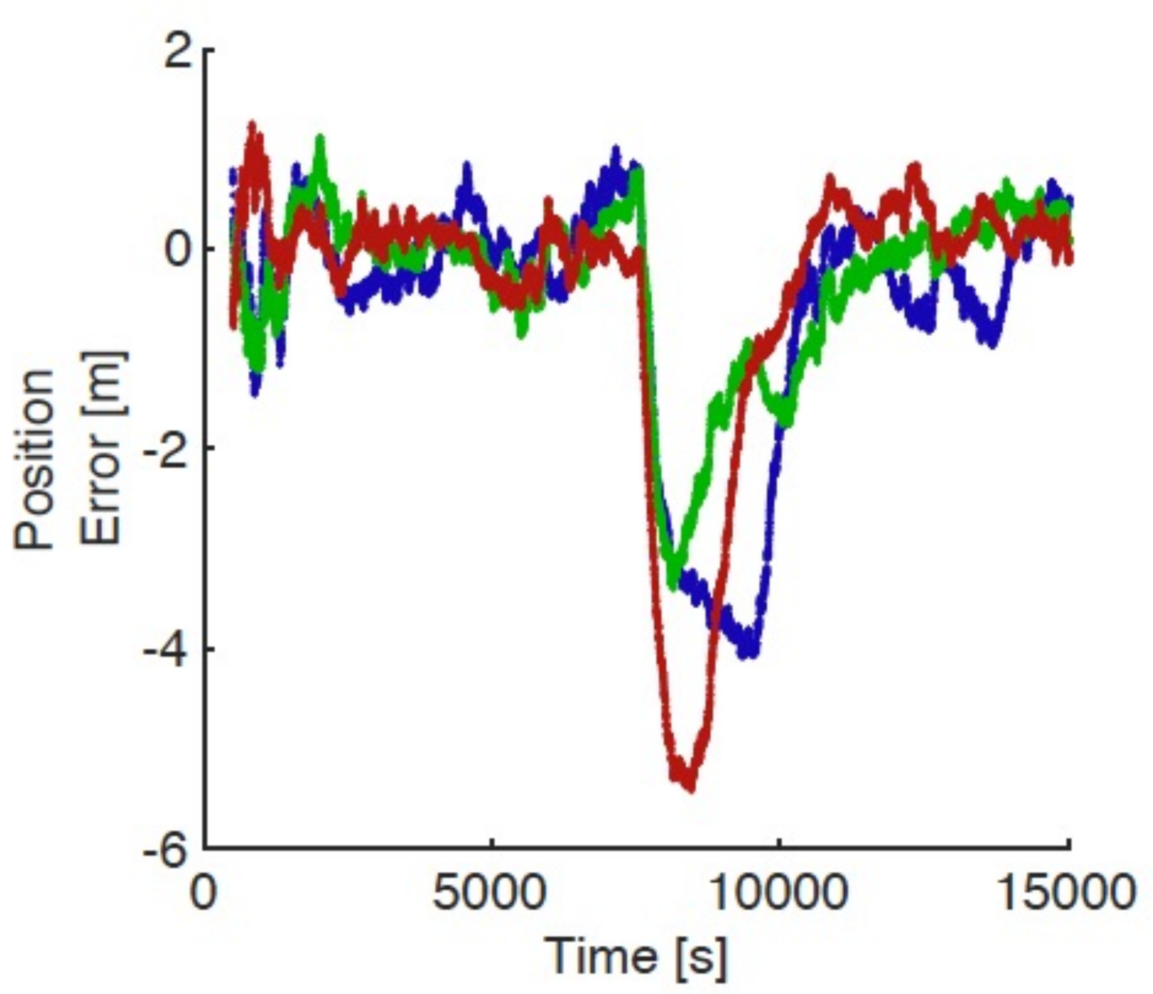
$$\dot{\mathbf{X}} = \begin{bmatrix} \boldsymbol{v} \\ \boldsymbol{a} \\ \dot{\boldsymbol{w}} \end{bmatrix}$$

$$\boldsymbol{a} = -\frac{\mu}{r^3}\boldsymbol{r} + \boldsymbol{w}$$

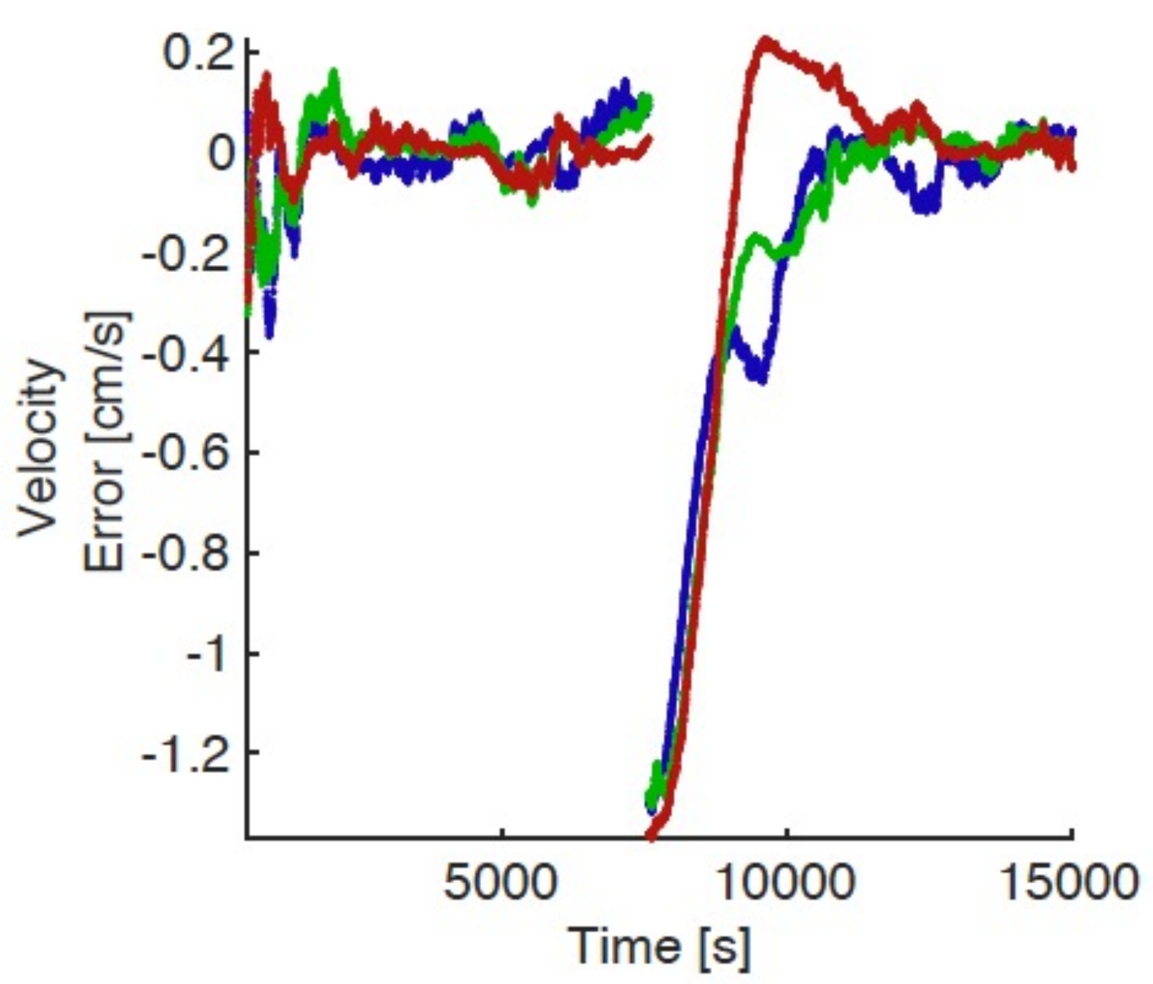
$$\dot{\boldsymbol{w}} = -\frac{1}{\tau}\boldsymbol{w} \qquad \boldsymbol{w}(t+\Delta t) = \boldsymbol{w}(t)e^{-\frac{\Delta t}{\tau}}$$



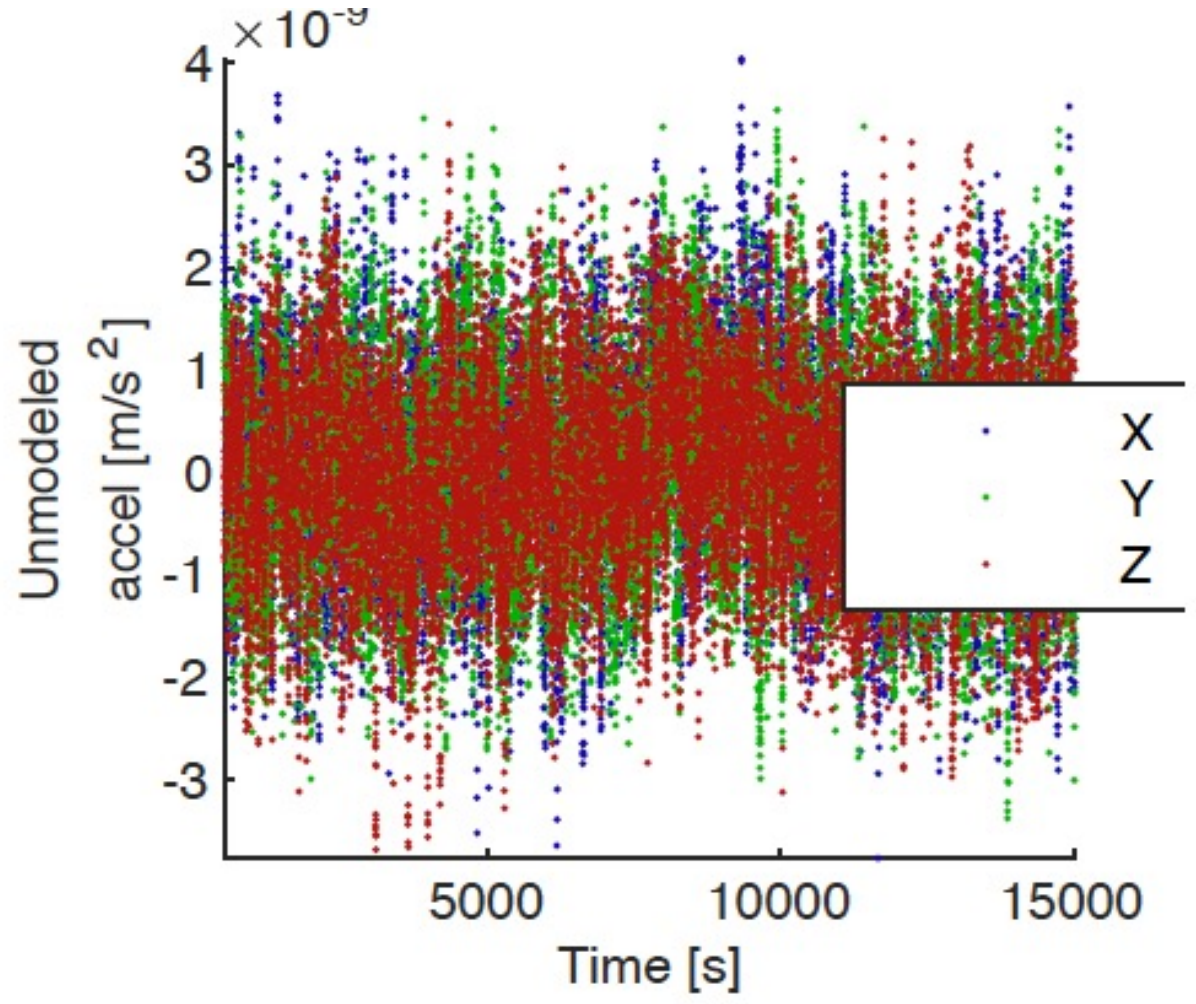




(a) Position Error



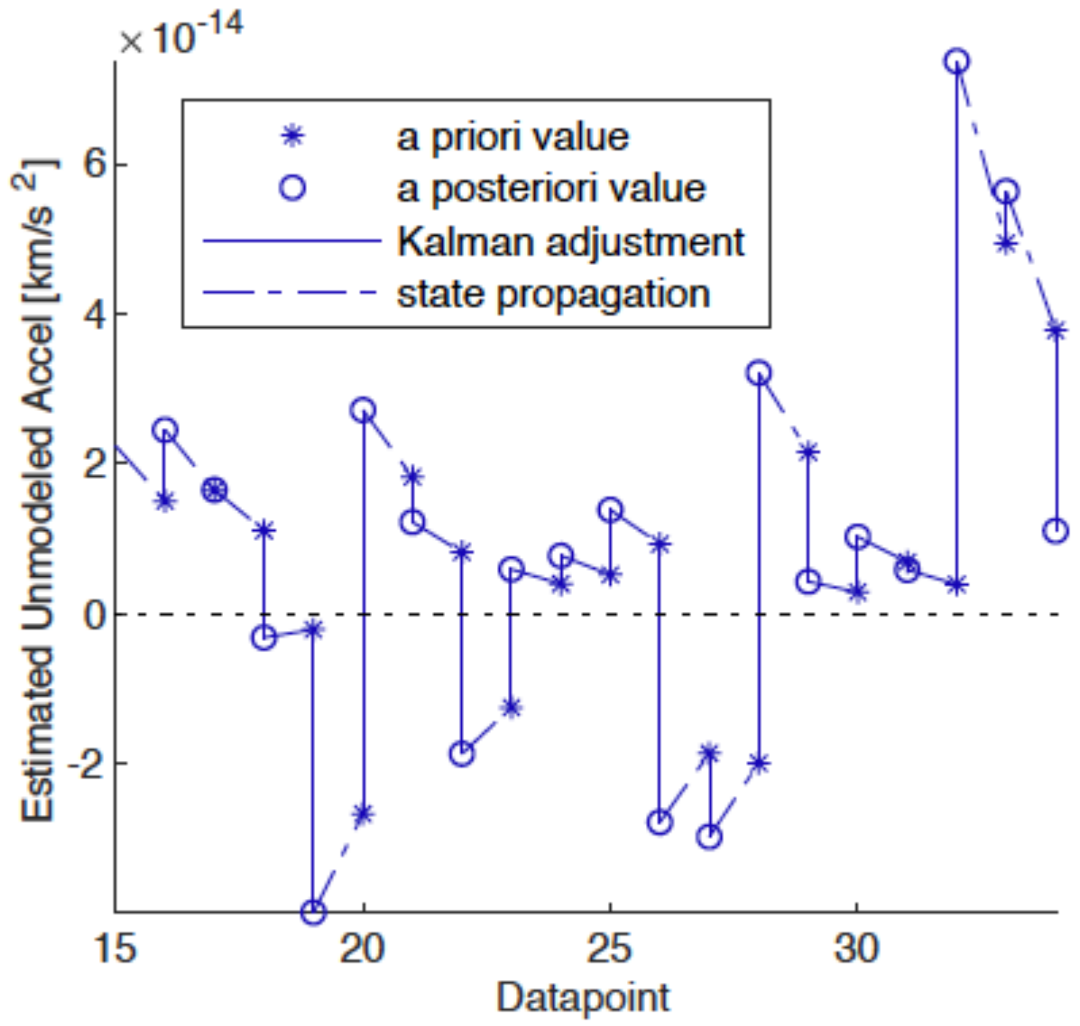
(b) Velocity Error



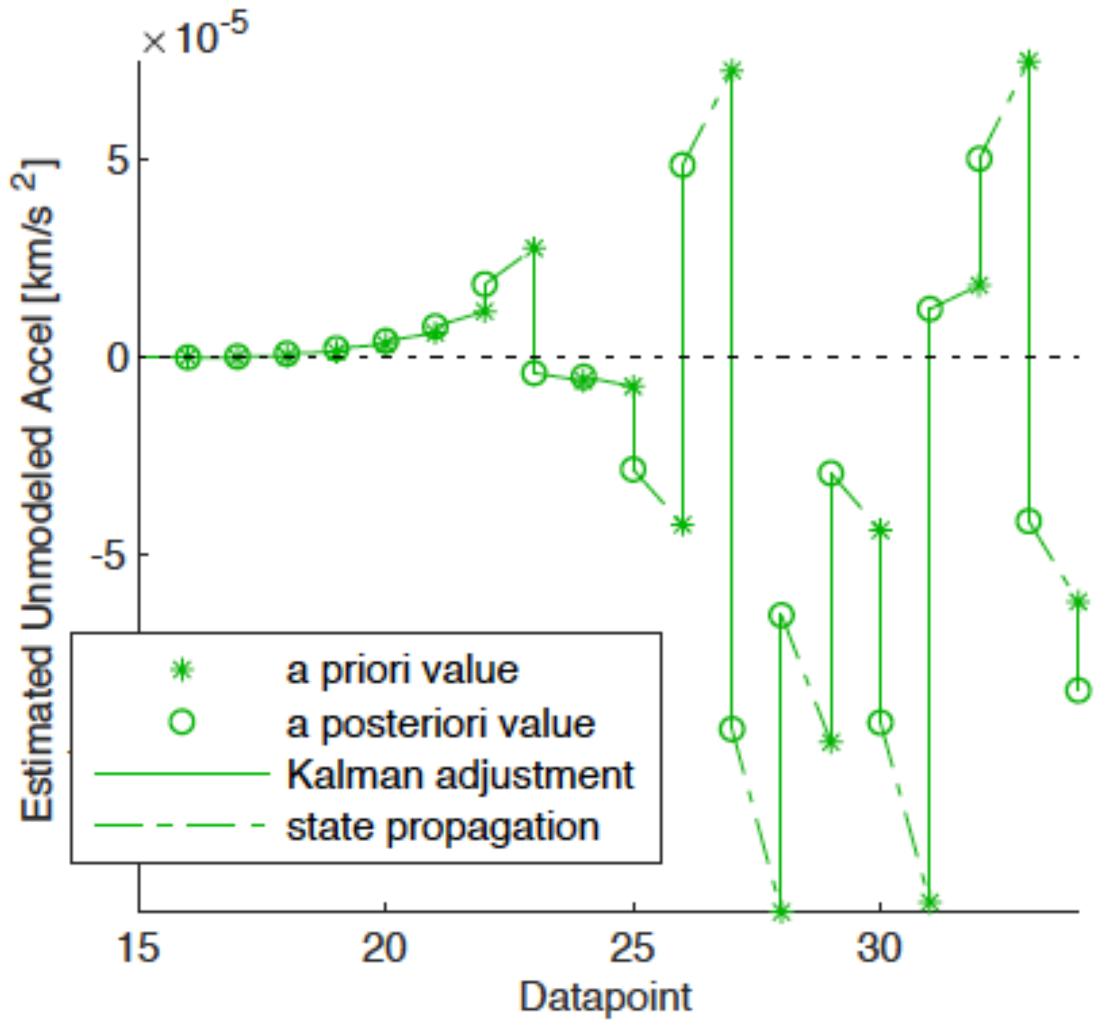
(c) Estimate of Unmodeled Accel

Backward Filtering

- Issue: short time constant causes unmodeled accels to grow in backward propagation

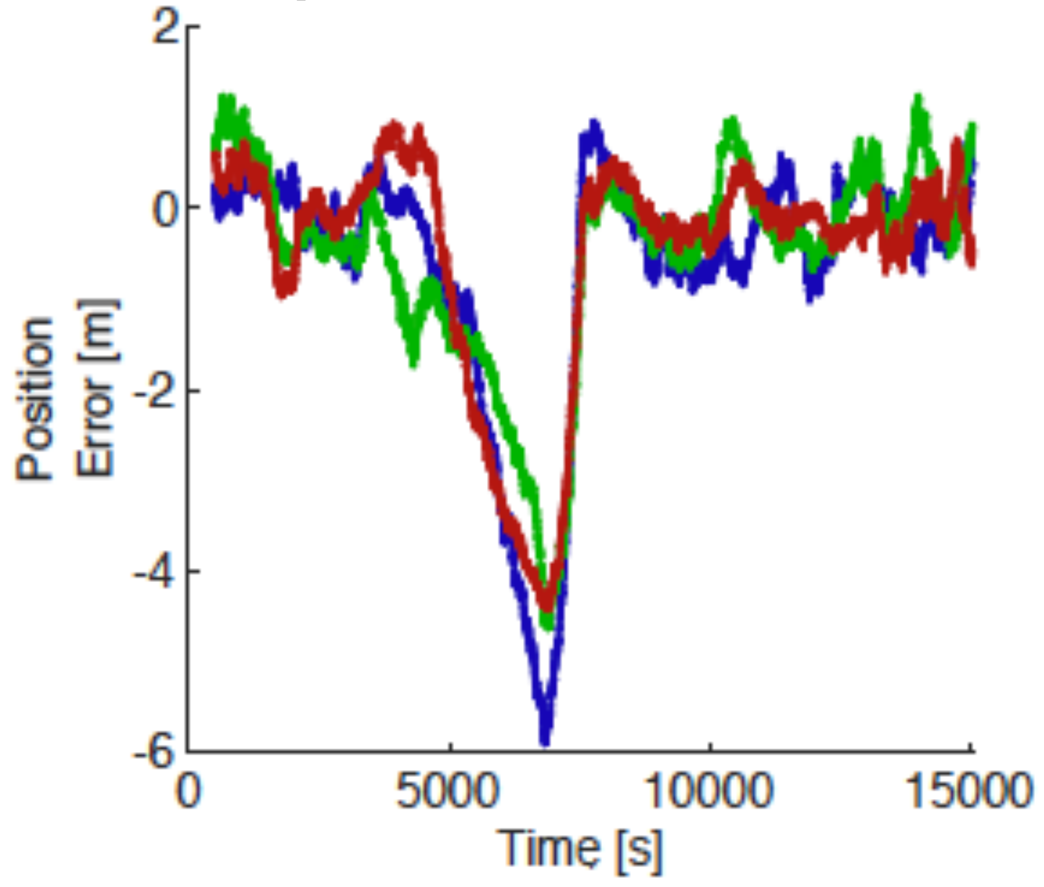


(a) Forward filter initialization

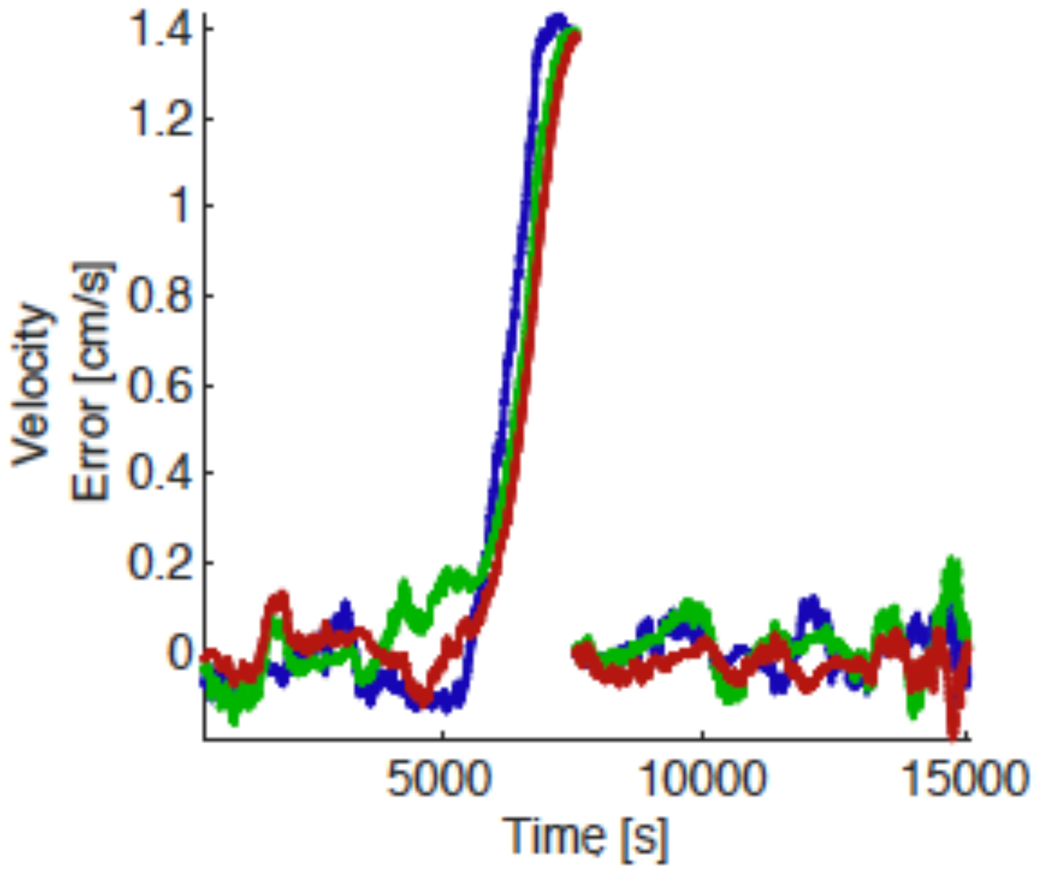


(b) Backward filter initialization (no changes from forward)

- Result: backward filter performs like forward filter



(a) Position Error

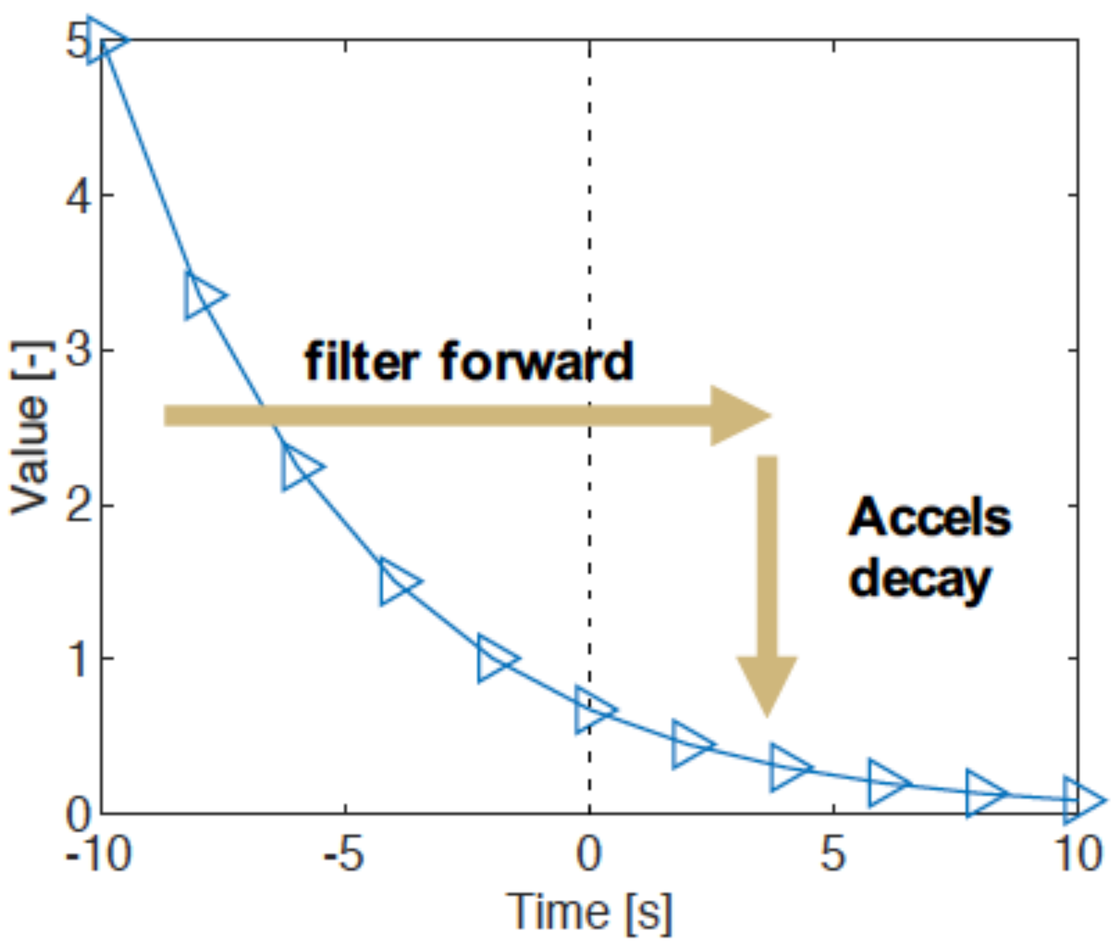


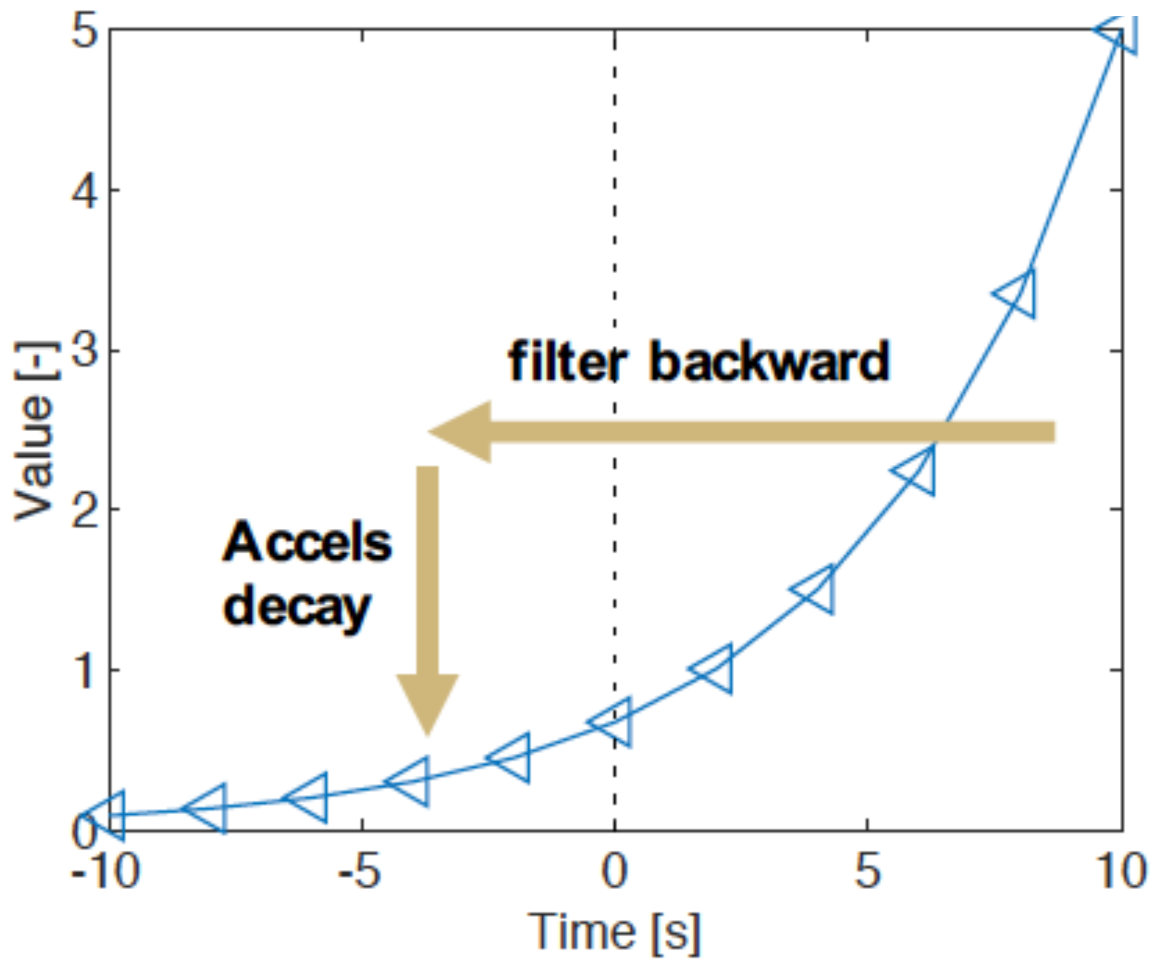
(b) Velocity Error

- Correction: use alternate FOGM in backward propagation

$$w(t+\Delta t) = w(t)e^{\frac{\Delta t}{\tau}}$$

$$\dot{w}(t) = \frac{1}{\tau}w(t)$$





Smoothing

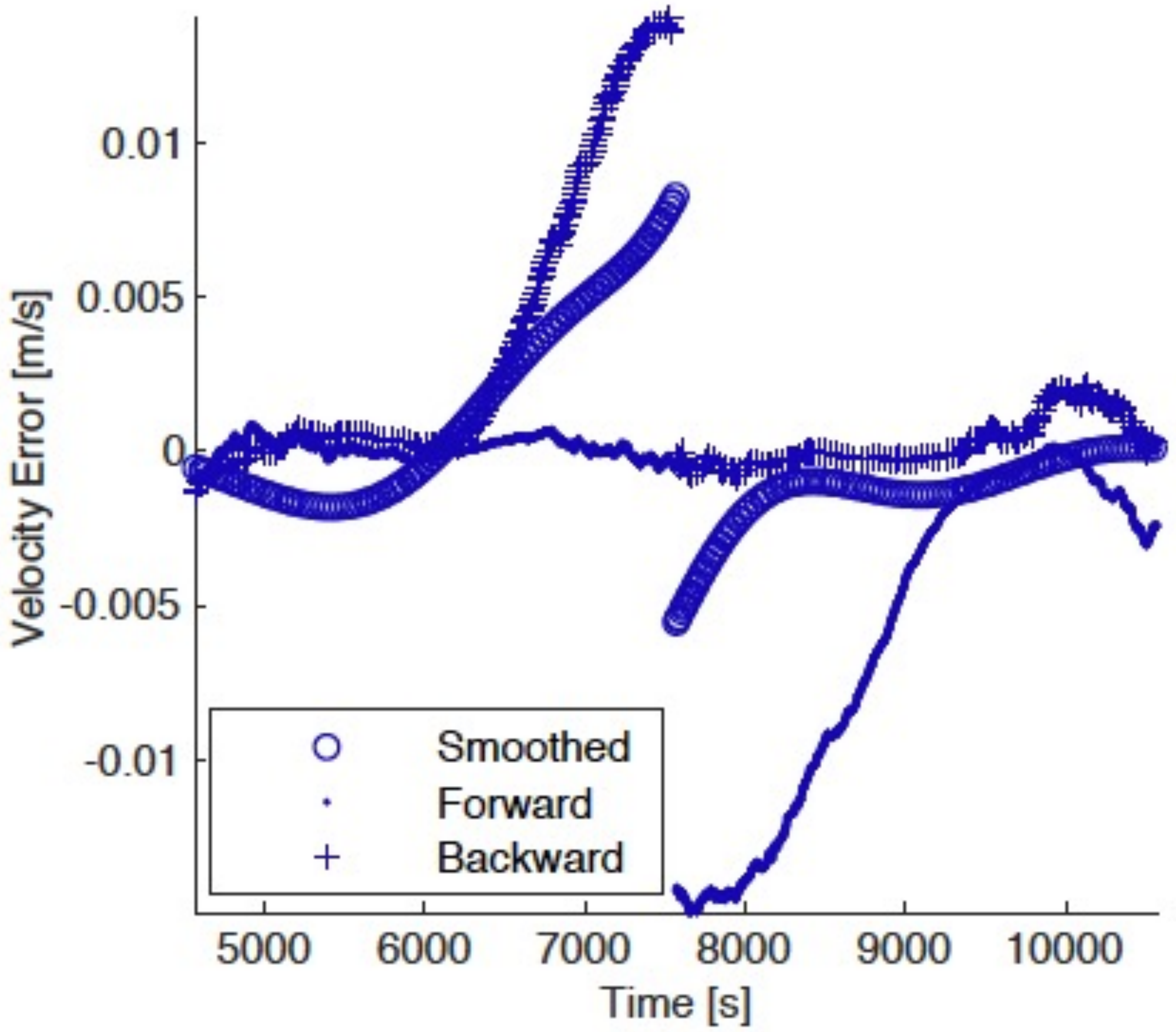
- Fuse forward and backward state estimates to improved state estimate
  - Smoothing produces MUCH larger feature in unmodeled accelerations!

$$\mathbf{X}_{S,i} = \mathbf{W}_{F,i}\mathbf{X}_{F,i} + (\mathbf{I} - \mathbf{W}_{F,i})\bar{\mathbf{X}}_{B,i}$$

$$\mathbf{P}_{S,i} = \mathbf{W}_{F,i}\mathbf{P}_{F,i}\mathbf{W}^{\mathrm{T}}_{F,i} + (\mathbf{I} - \mathbf{W}_{F,i})\bar{\mathbf{P}}_{B,i}(\mathbf{I} - \mathbf{W}_{F,i})^{\mathrm{T}}$$

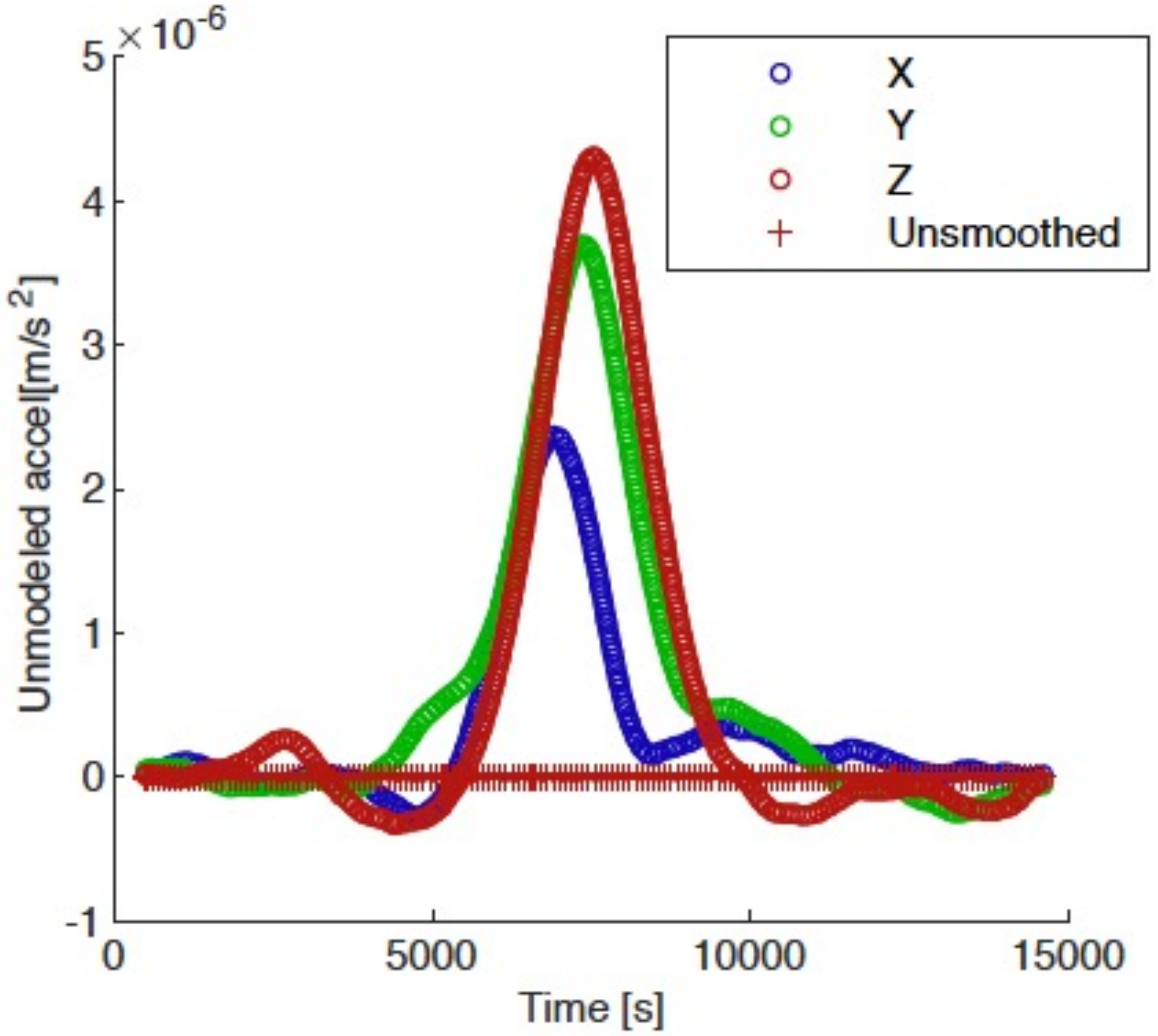
$$\mathbf{W}_{F,i} = \bar{\mathrm{P}}_{B,i}/(\mathrm{P}_{F,i} + \bar{\mathrm{P}}_{B,i})$$

- Velocity: smoothing takes average between state estimates (expected)



(a) Smoothed velocity (X only)

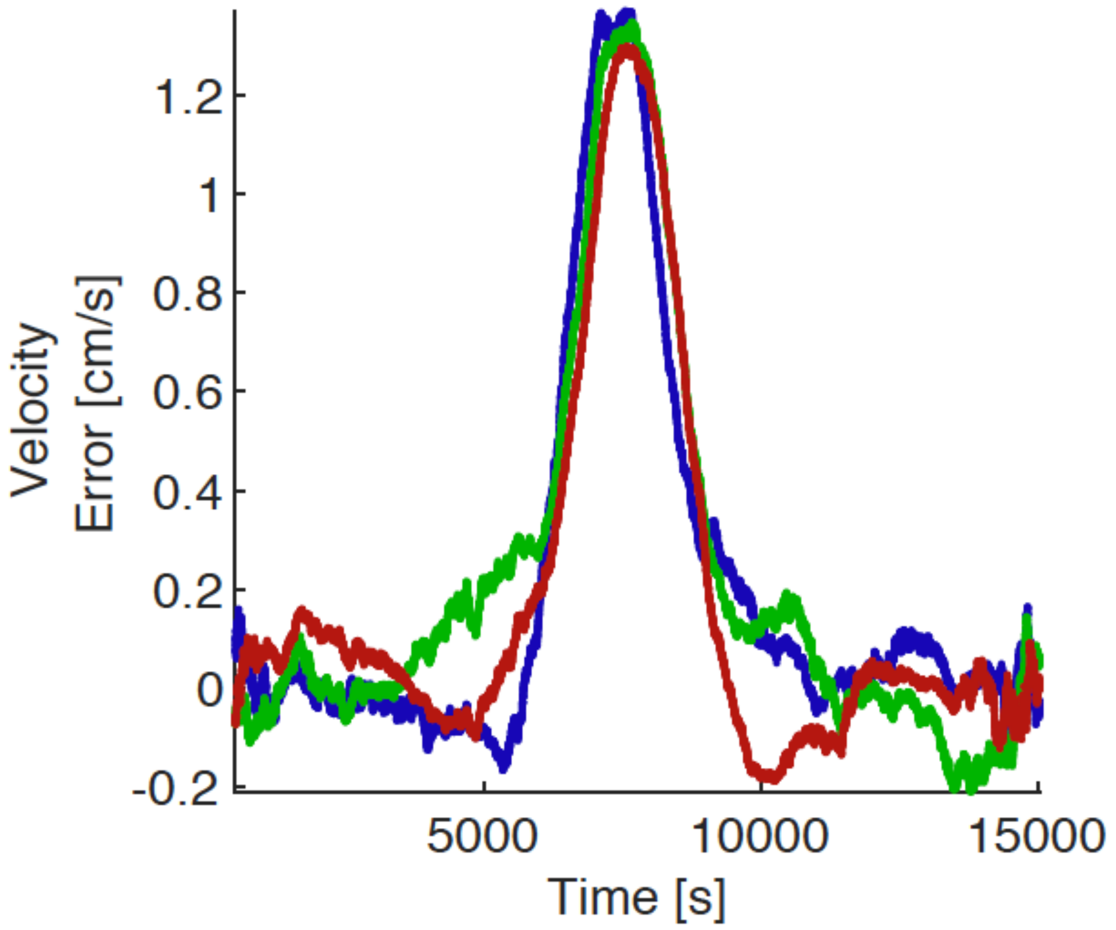
- Acceleration: smoothed accel creates strong feature where none is visible in unsmoothed accel (unexpected)



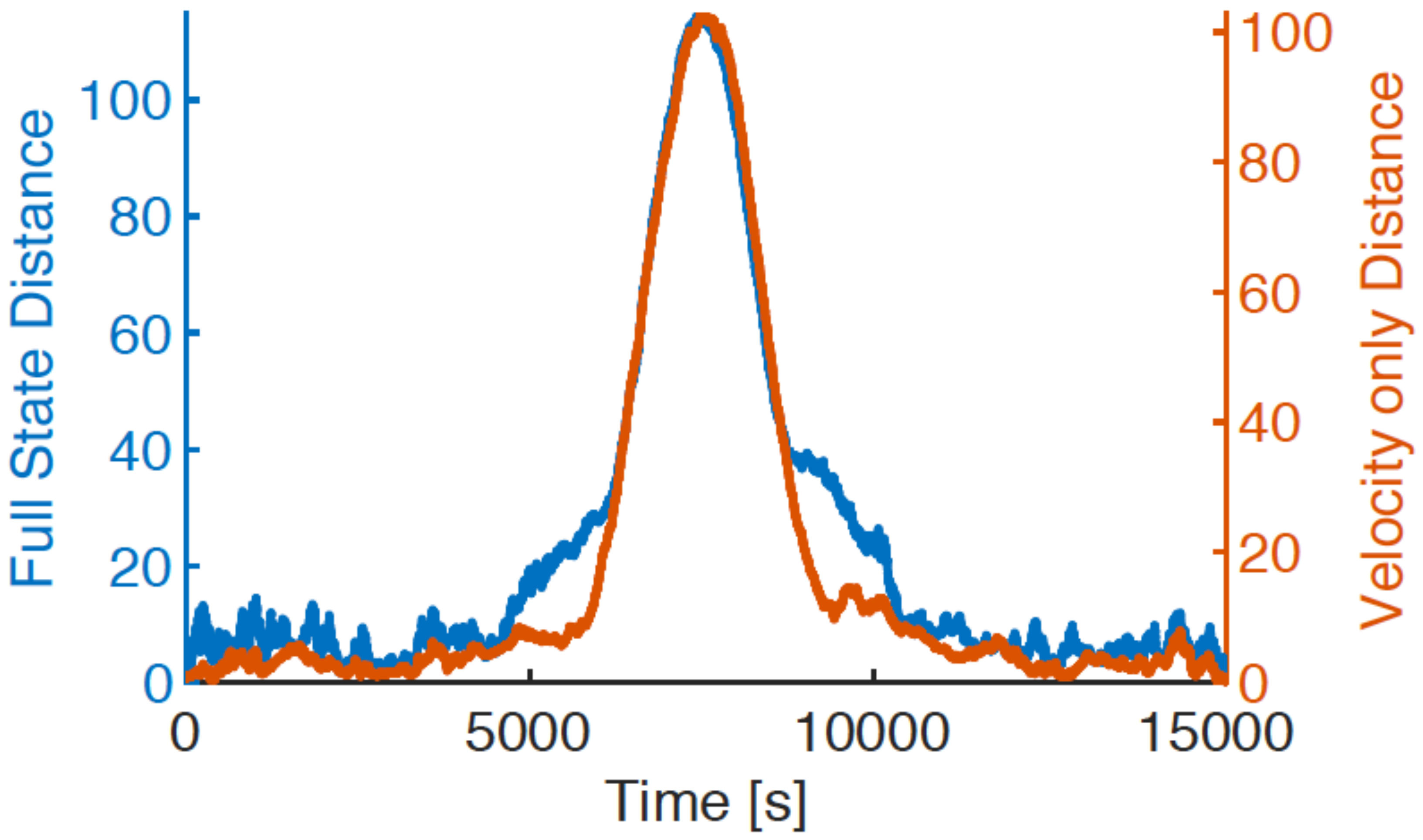
(b) Smoothed acceleration

Test Statistics

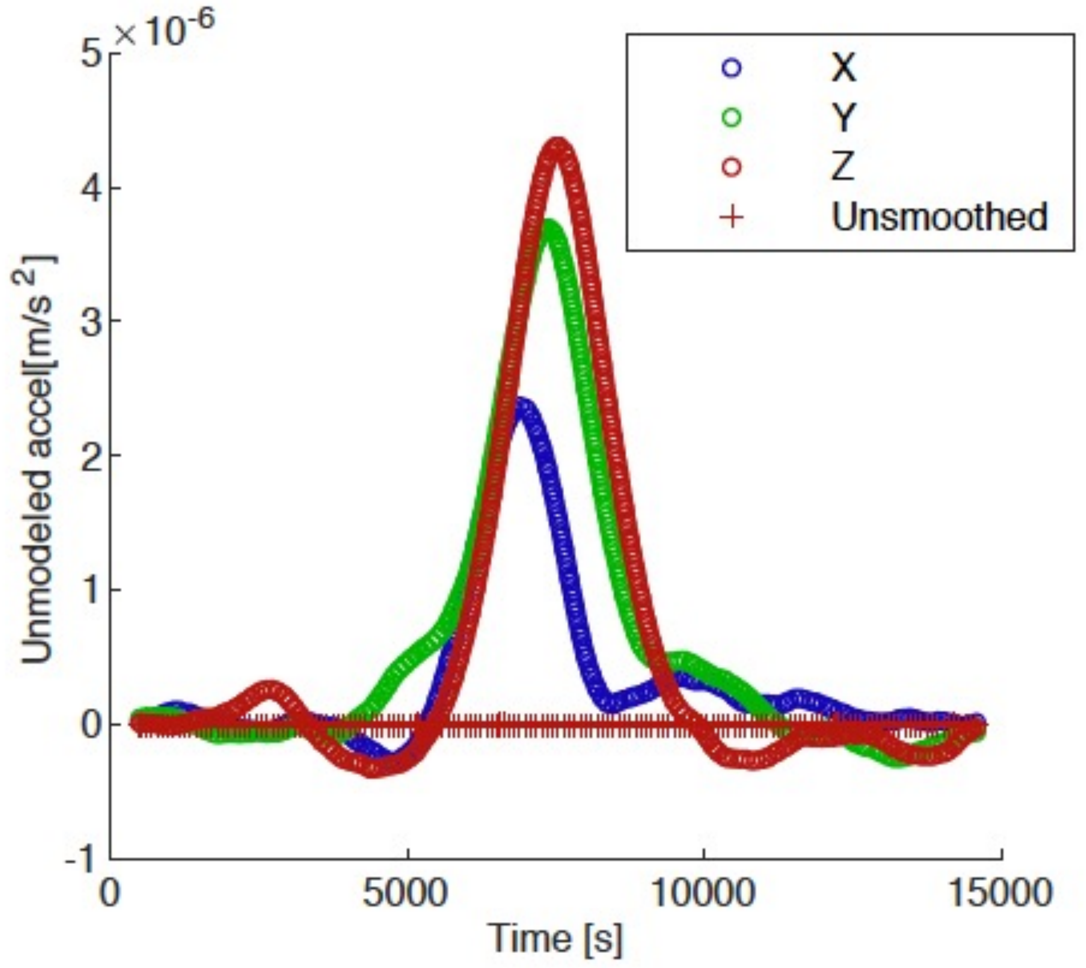
- Difference between fwd bkwd states (estimates velocity)



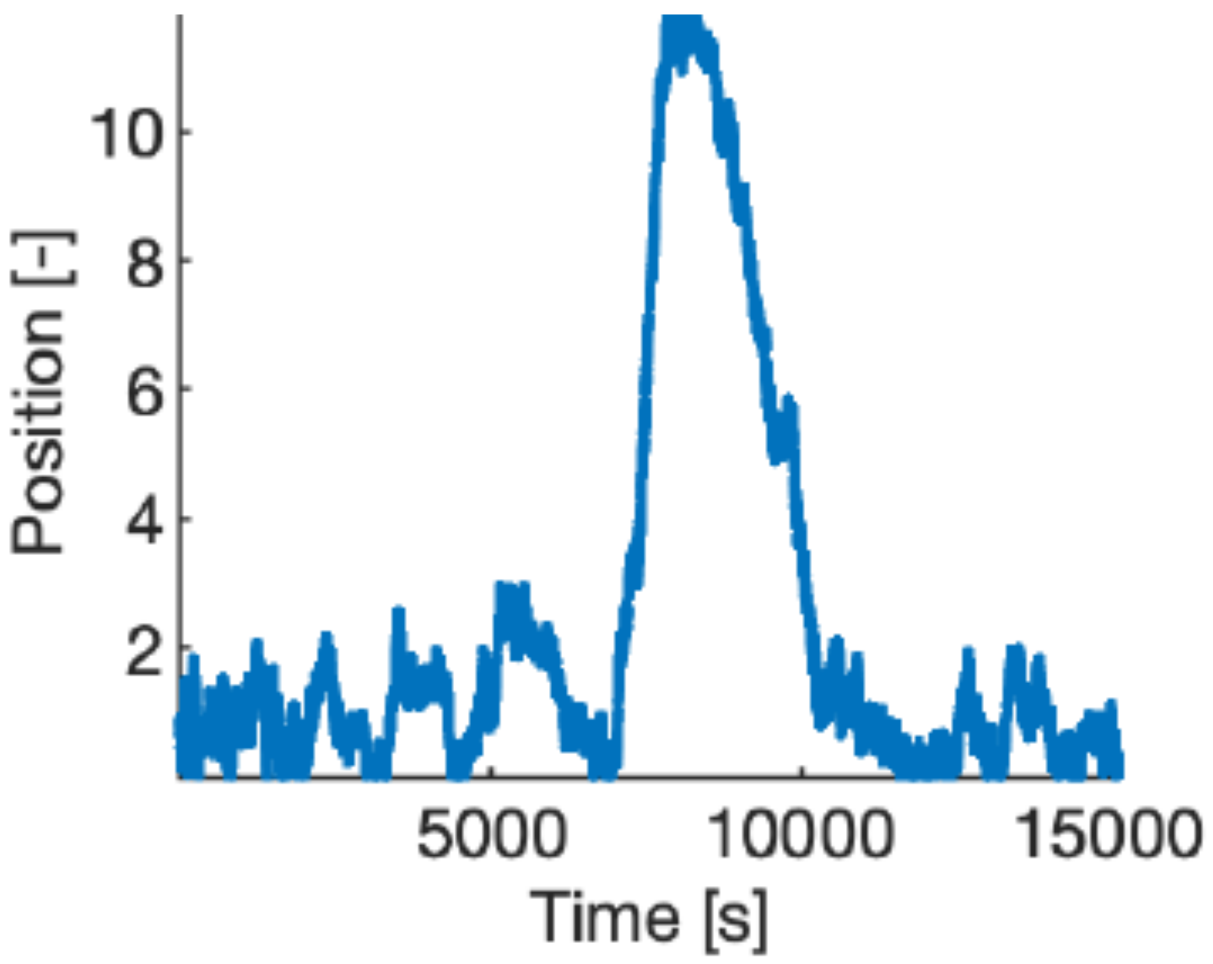
- Mahalanobis distance between fwd and bkwd states

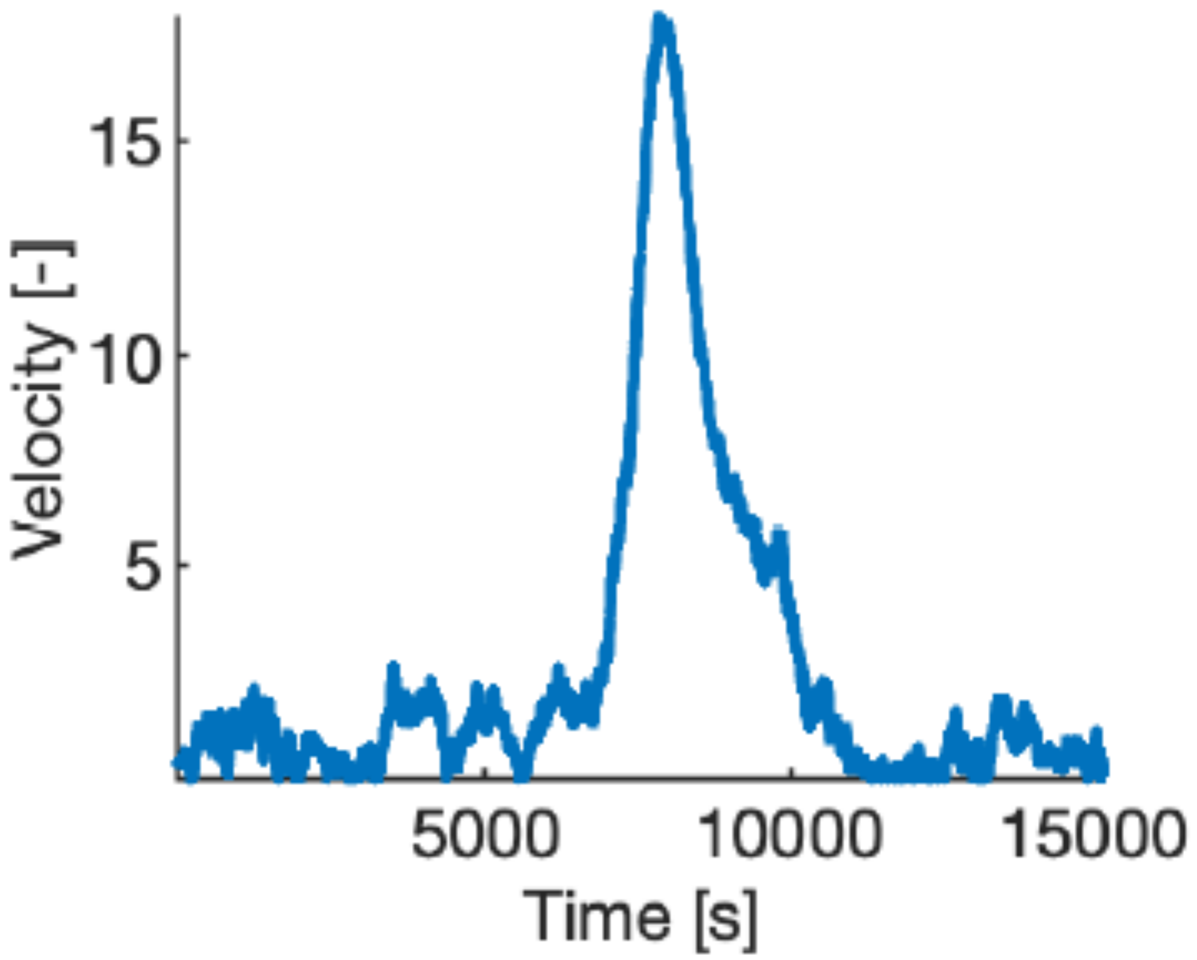


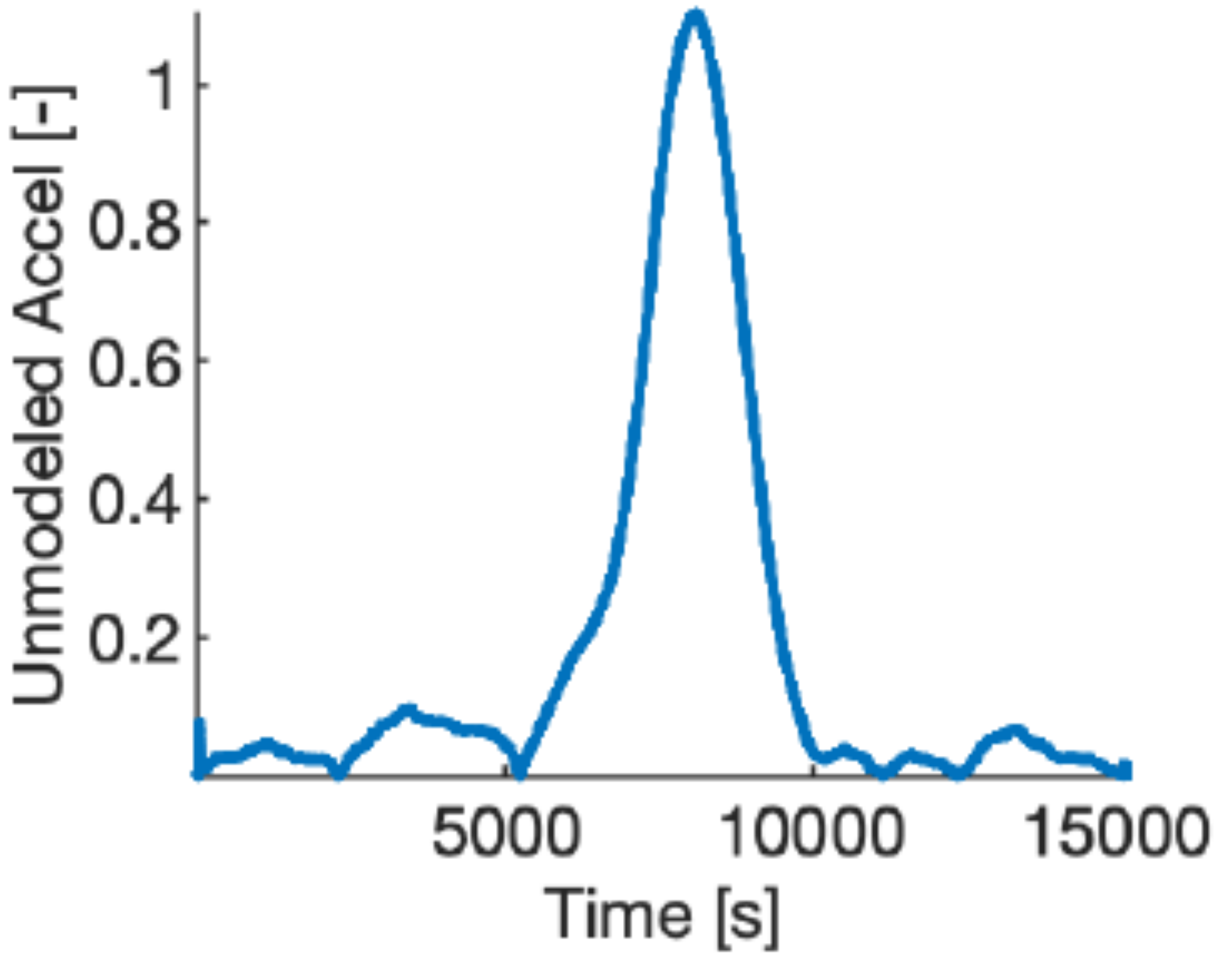
- Smoothed accelerations



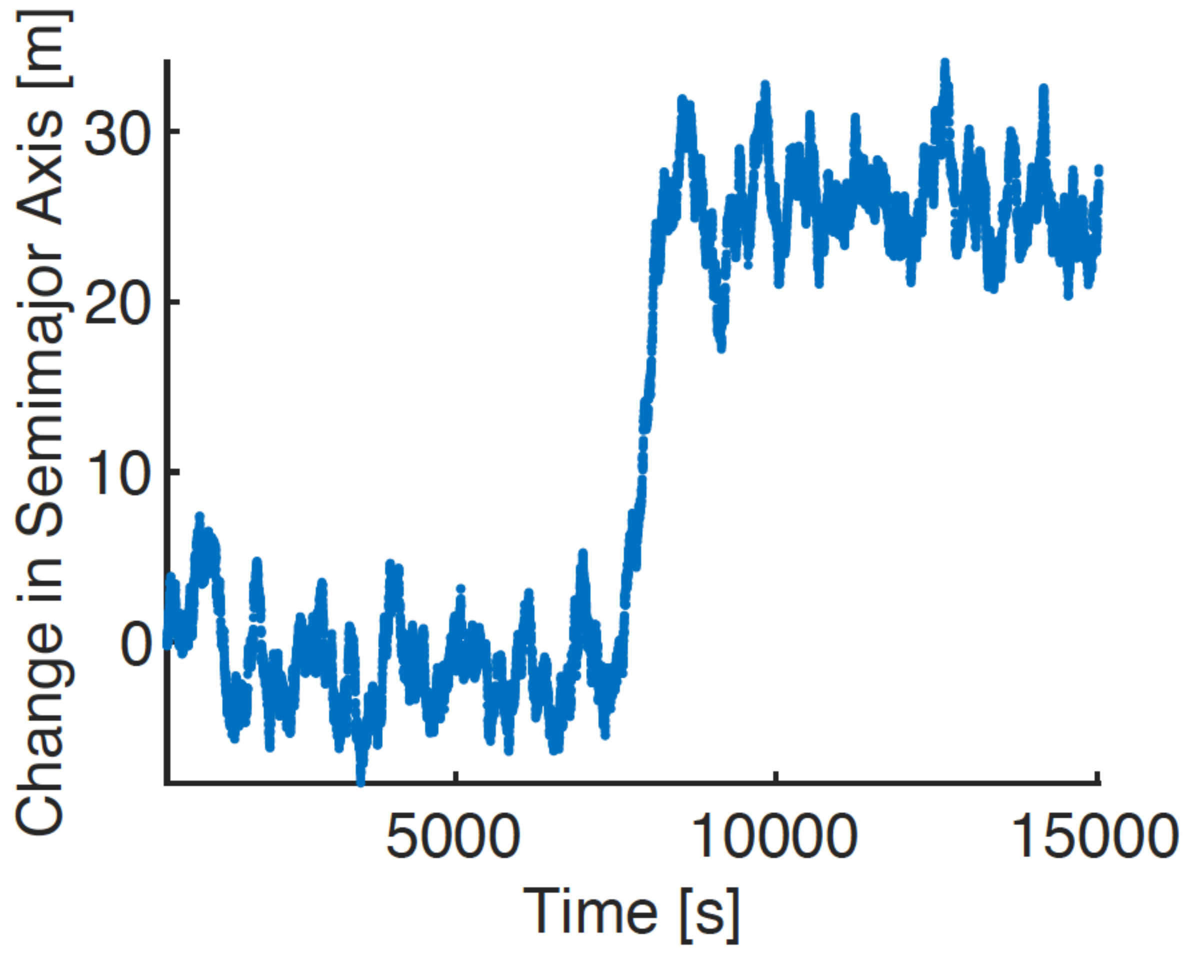
- McReynold's filter-smoother consistency test





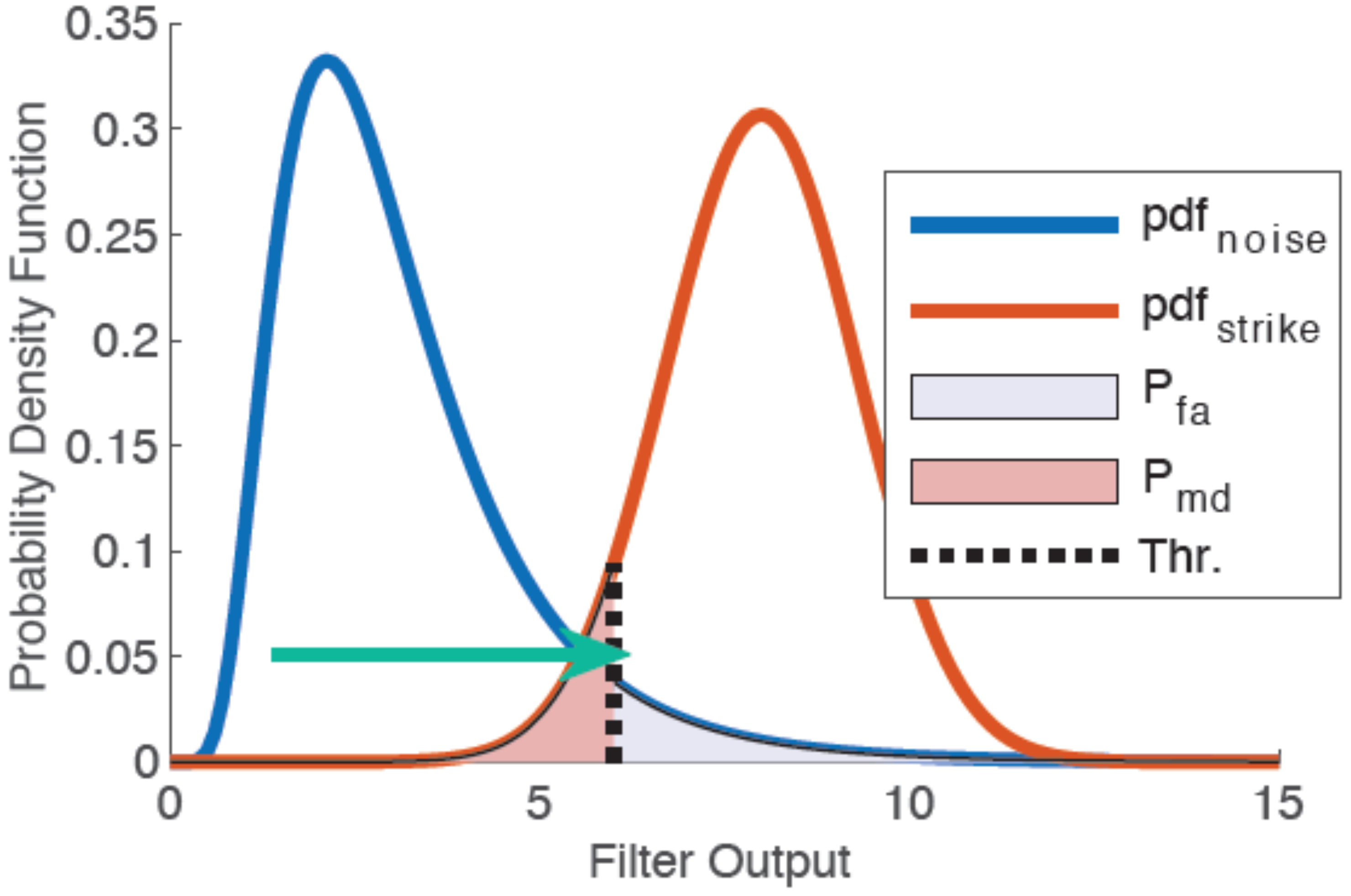


- Change in orbital constants

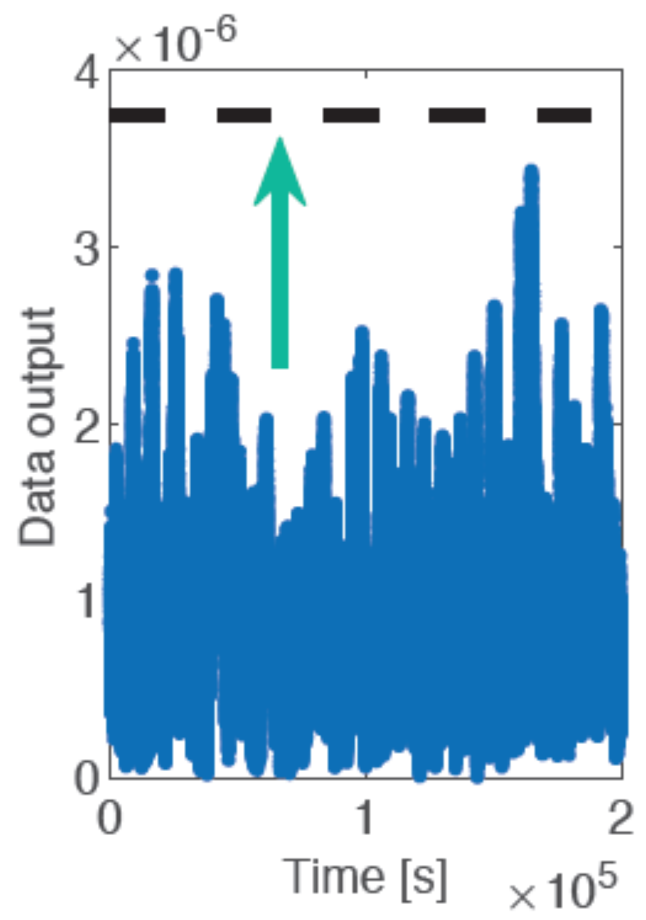


Tuning FOGM Parameters

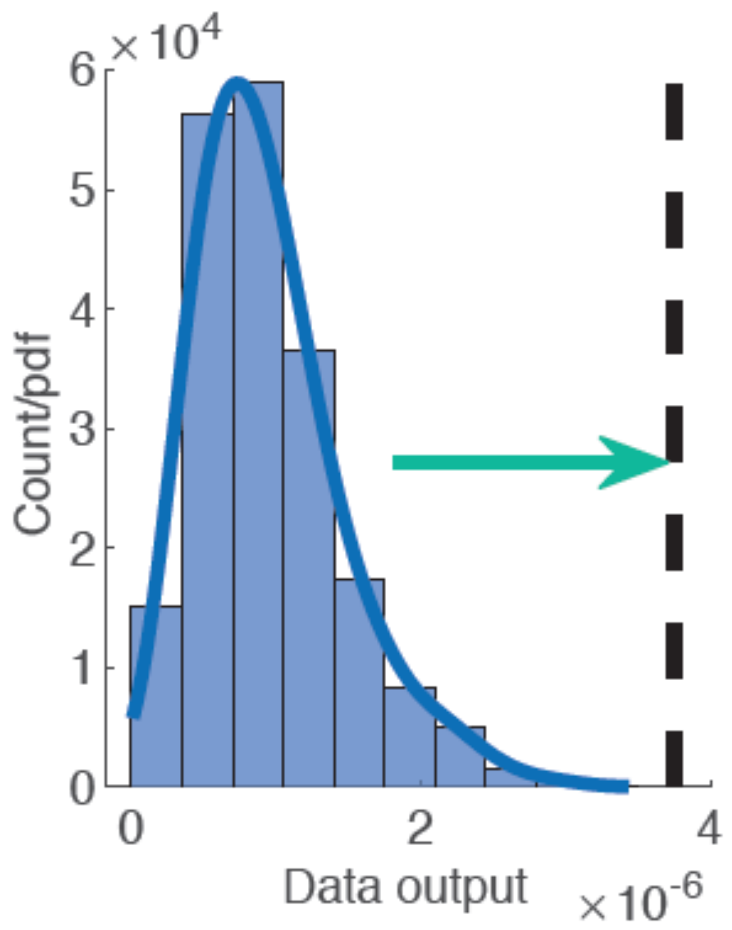
- Setting detection thresholds, trading tau and sigma to compare SNRs



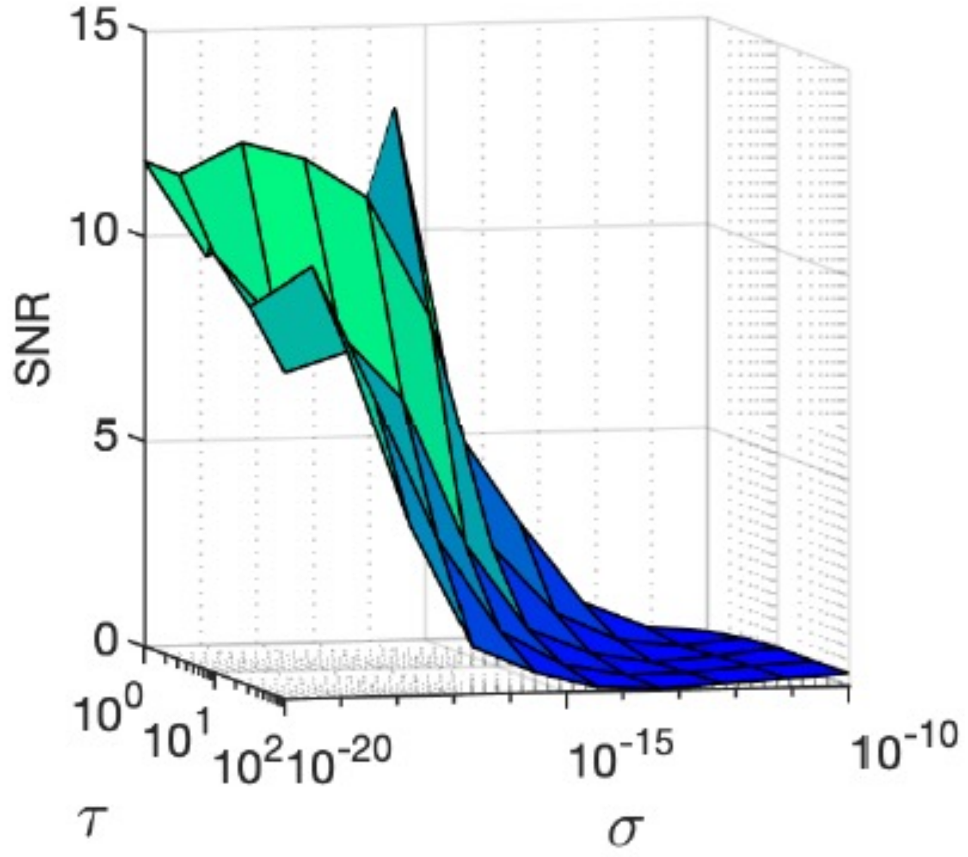
(a) Concept for setting thresholds



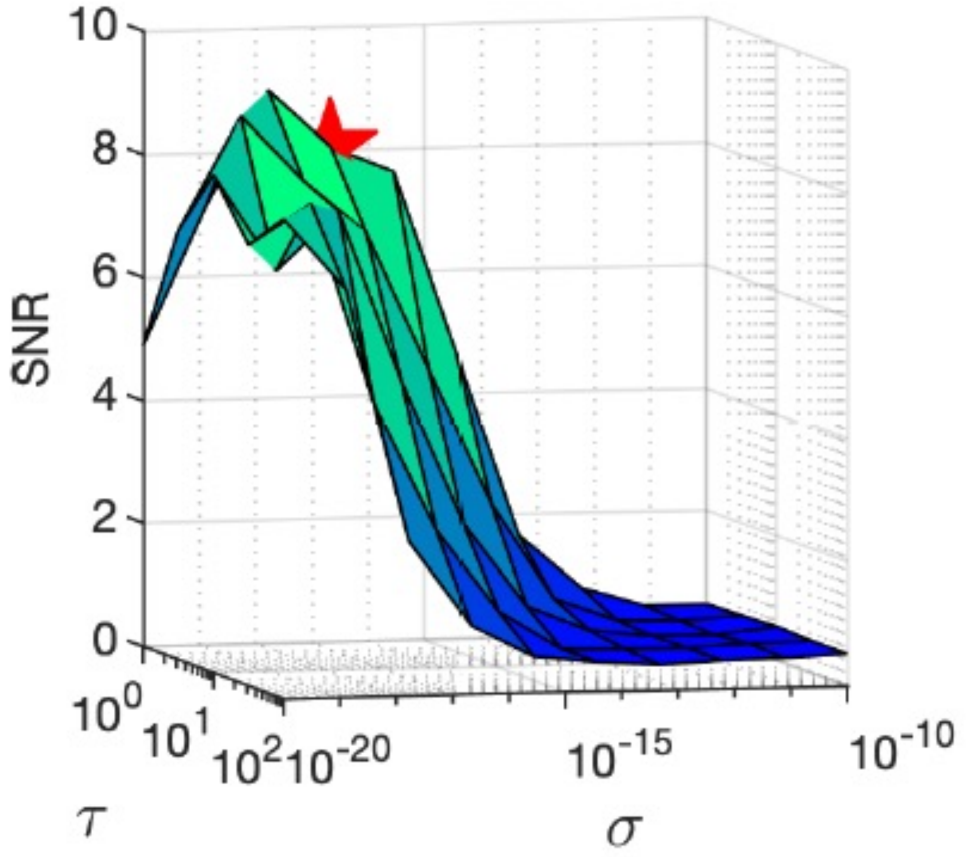
(b) Data with threshold



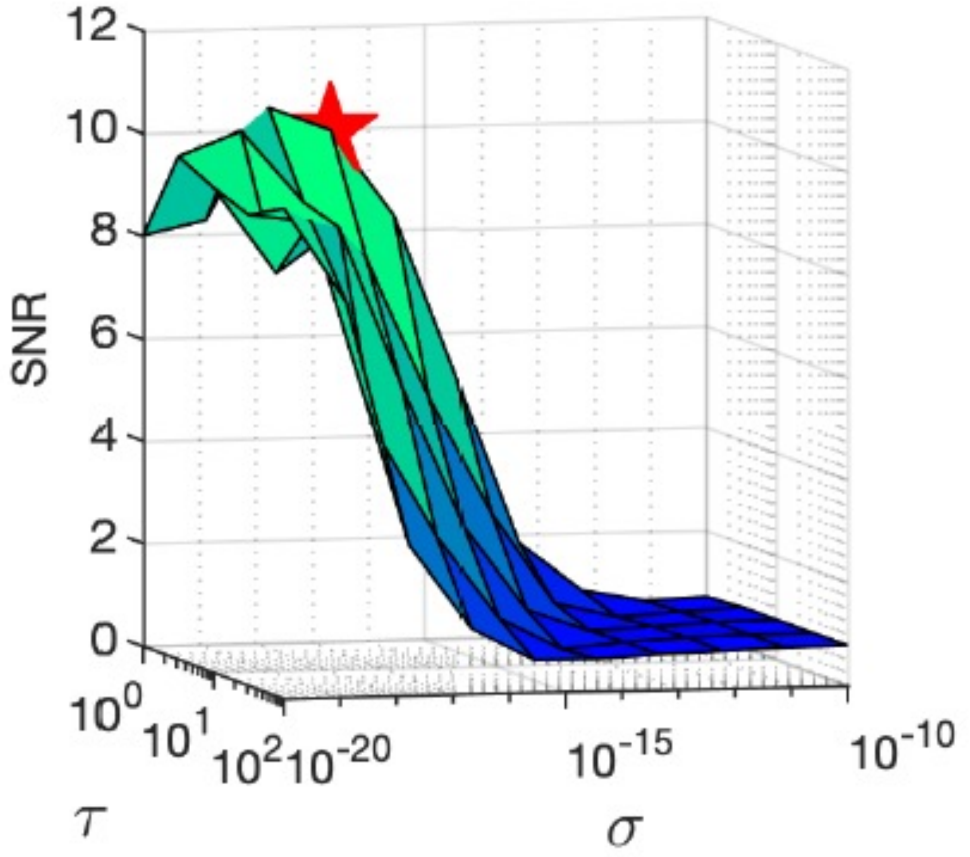
(c) Histogram and pdf



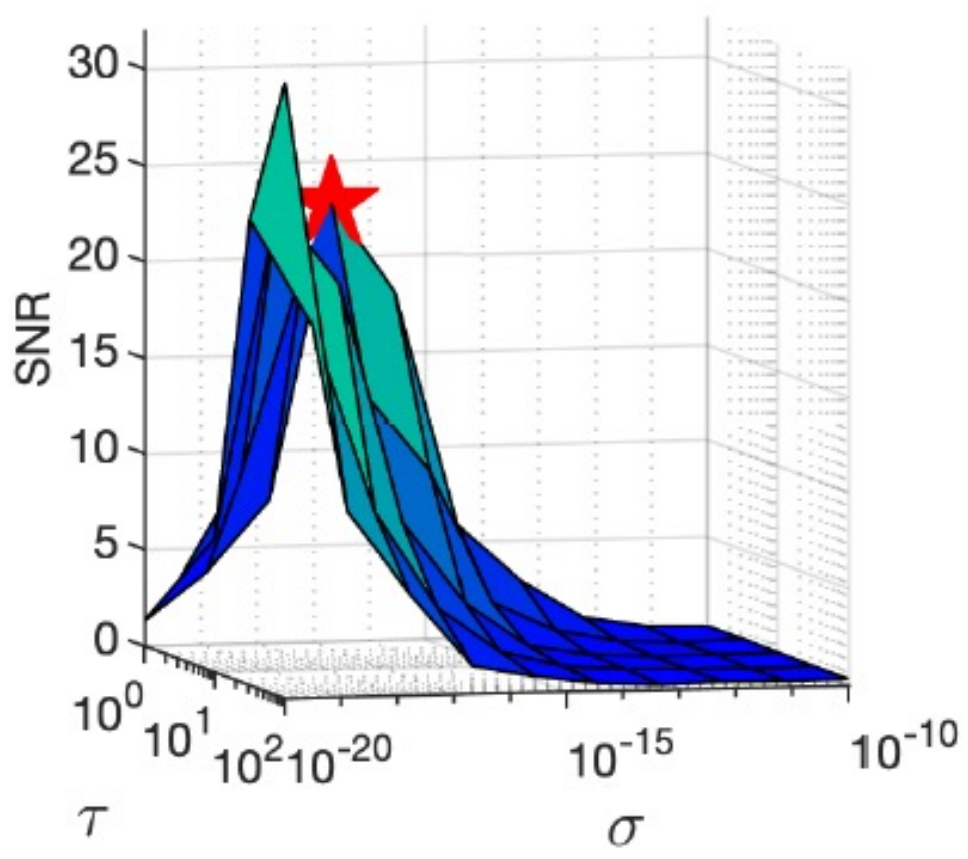
(a) TS1: Difference in Velocity



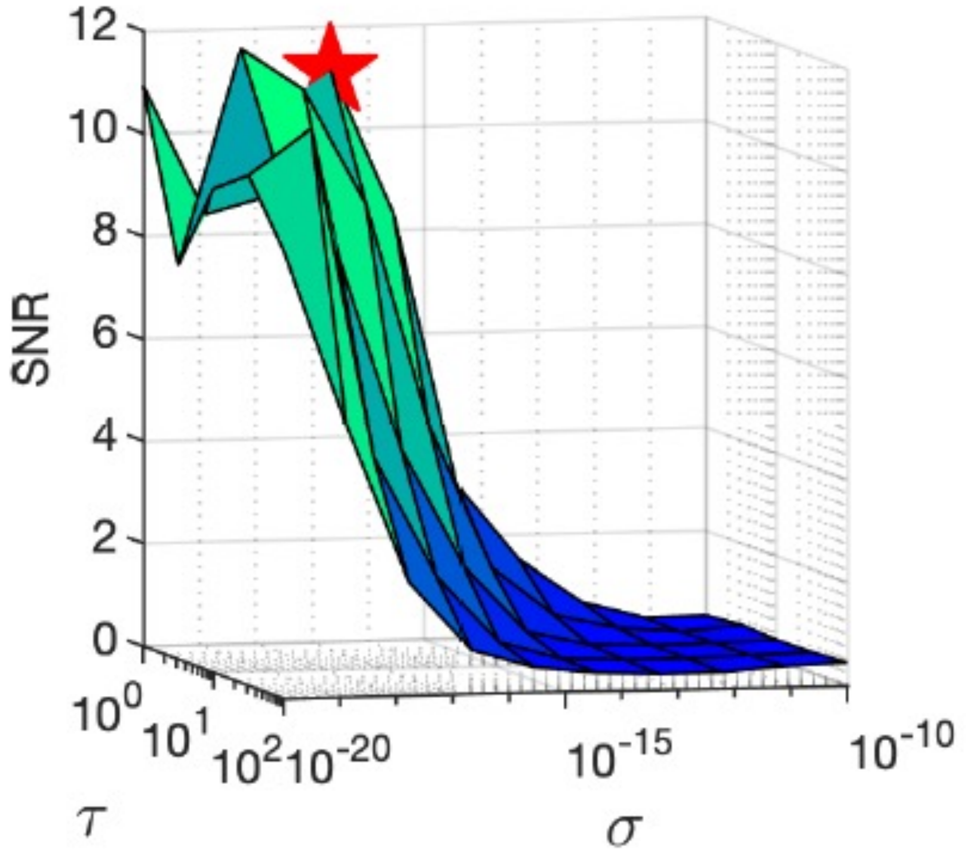
(b) TS2a: Mahalanobis dist., peak value



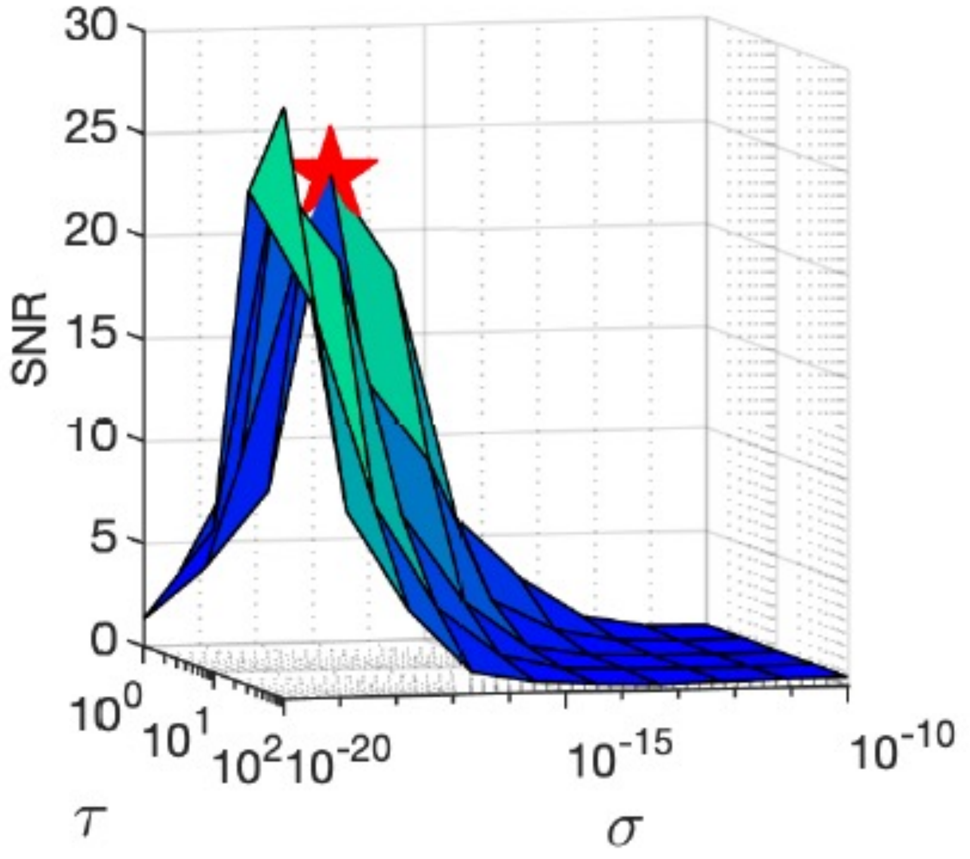
(c) TS2b: Mahal. dist., integrated value



(d) TS3a: Smoothed accel peak



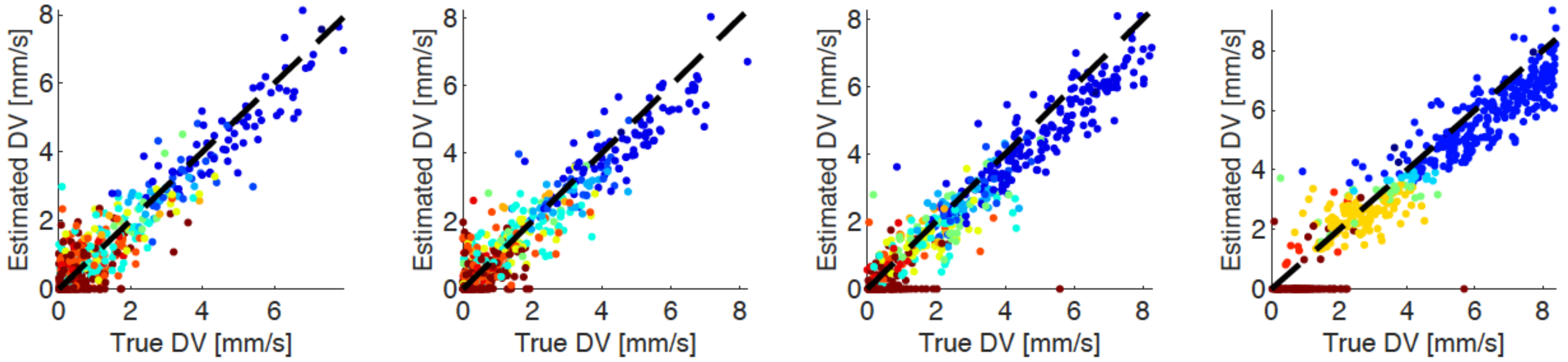
(e) TS4a: McReynold's peak vel.



(f) TS4b: McReynold's peak acc.

Monte-Carlo Analysis

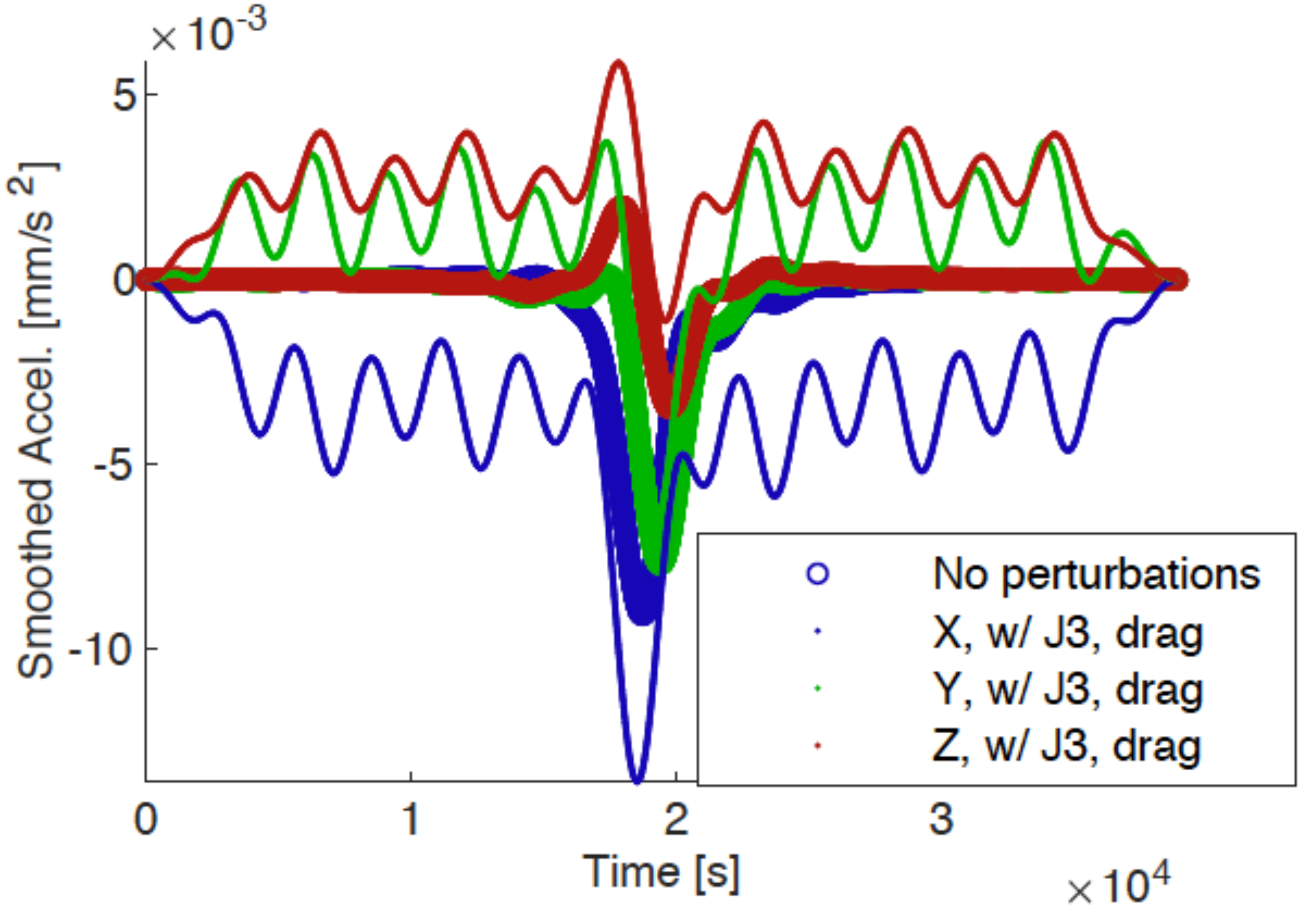
- Monte-Carlo strike size and direction, determine if detected
  - Strikes >1 mm/s rarely detected
  - Most test statistics detect strikes > 4 mm/s
  - Reminder: Sentinel-1A is large S/C. Similar strikes => much larger DV on smaller S/C



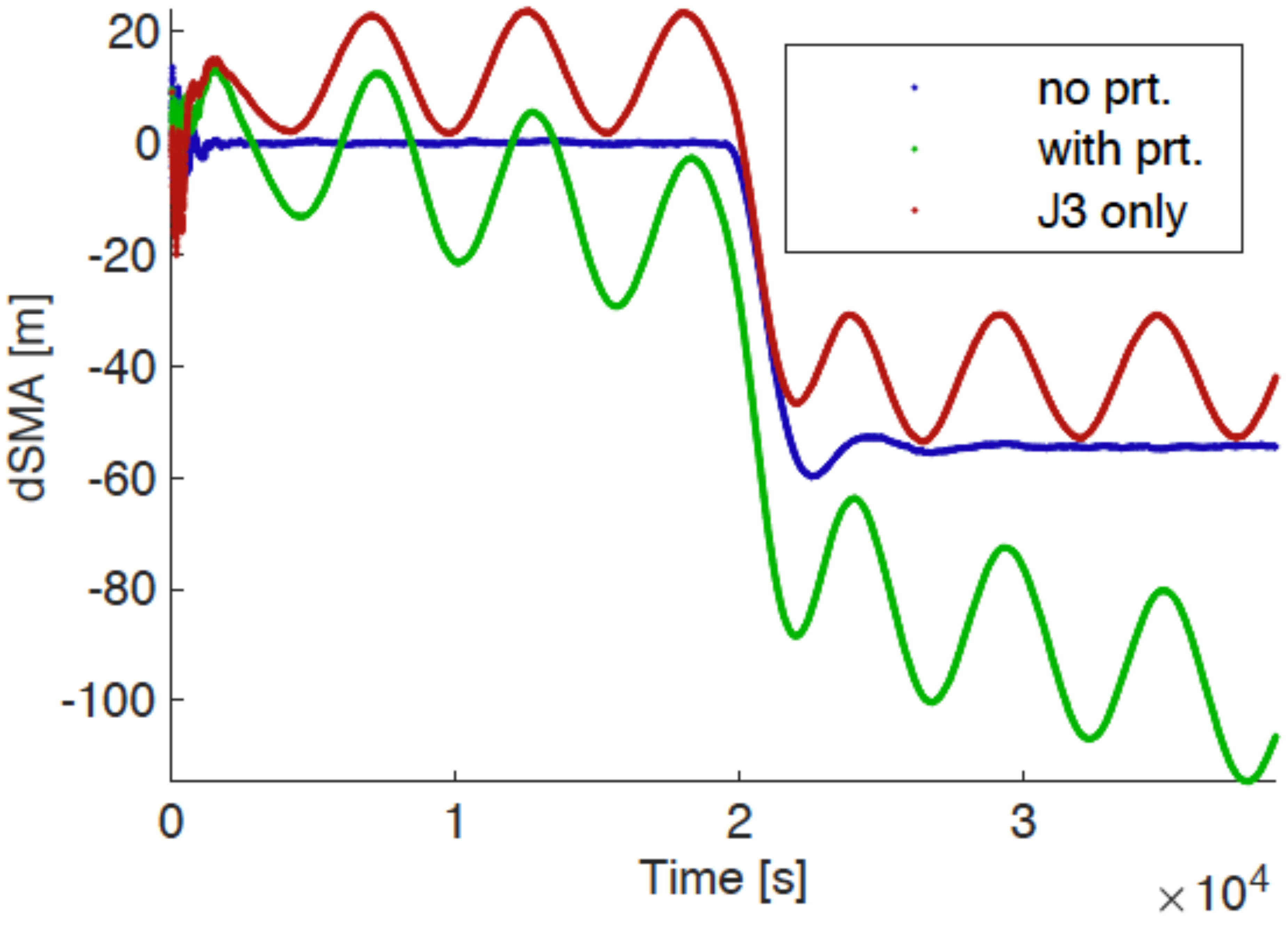
(a) Strike size estimate in X-axis (b) Strike size estimate in Y-axis (c) Strike size estimate in Z-axis (d) RSS magnitude

Adding Unmodeled Perturbations

- Add orbit perturbations to truth state but not to filter dynamics
  - Add J3 and drag perturbations (400 km orbit)
  - DMC responds to unmodeled dynamics, obfuscates expected strike
  - 2X strike magnitude produces signal which is still detectable
  - J3 and drag not too hard to include in filter dynamics => this is likely worse than most S/C stat OD can attain



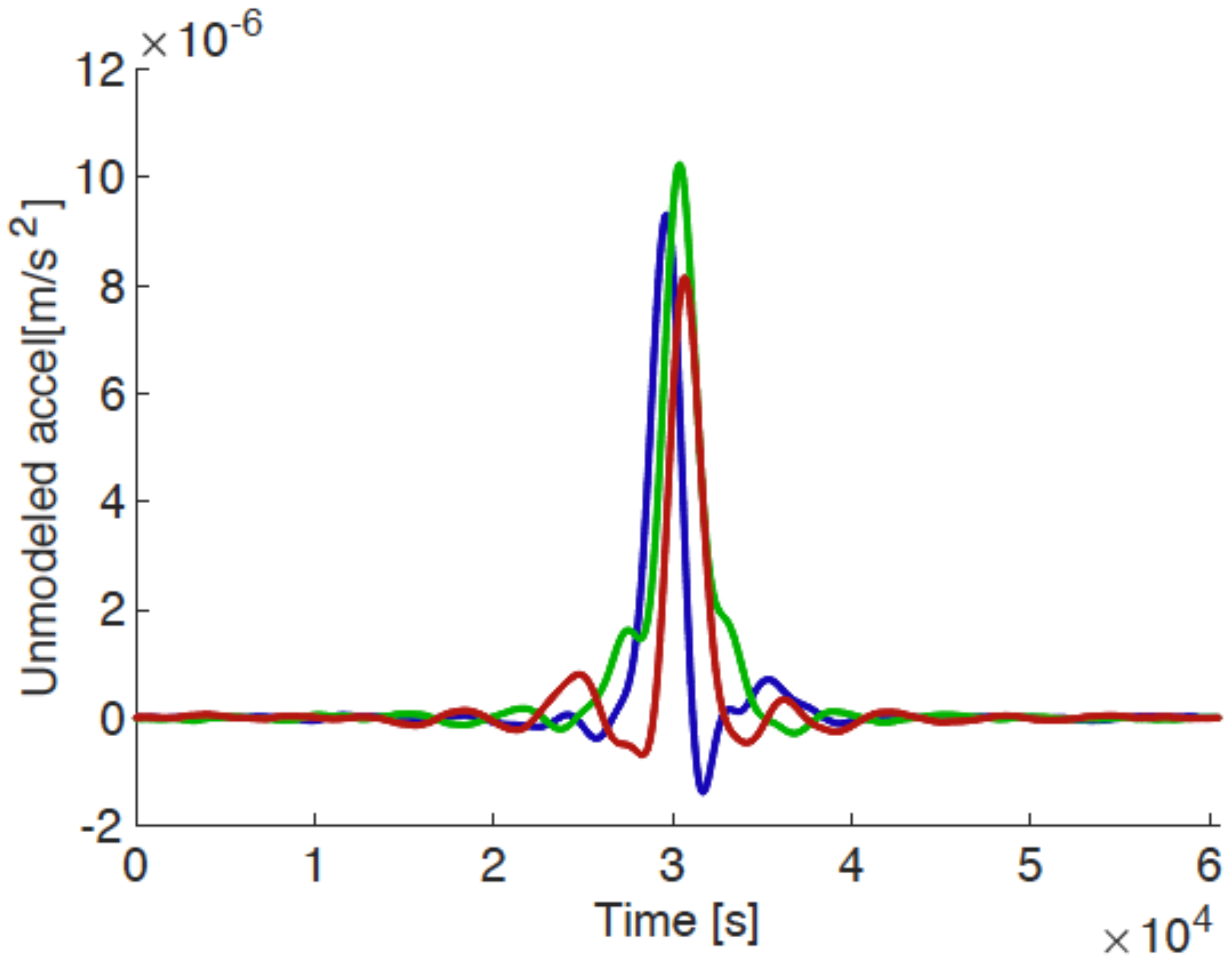
(a) Smoothed Acceleration



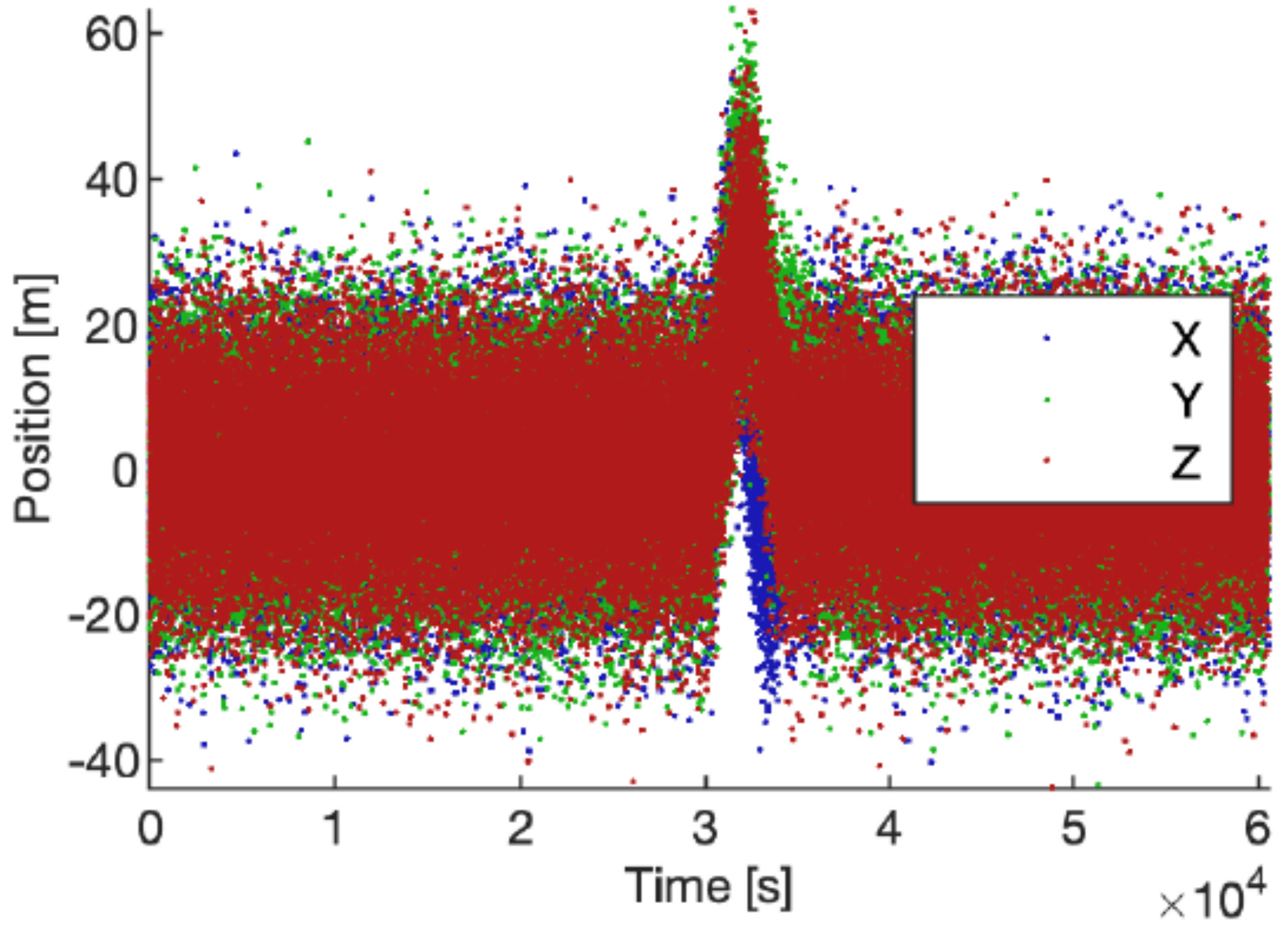
(b) Change in semimajor axis

Detection w/ Filter vs. Traditional Residuals

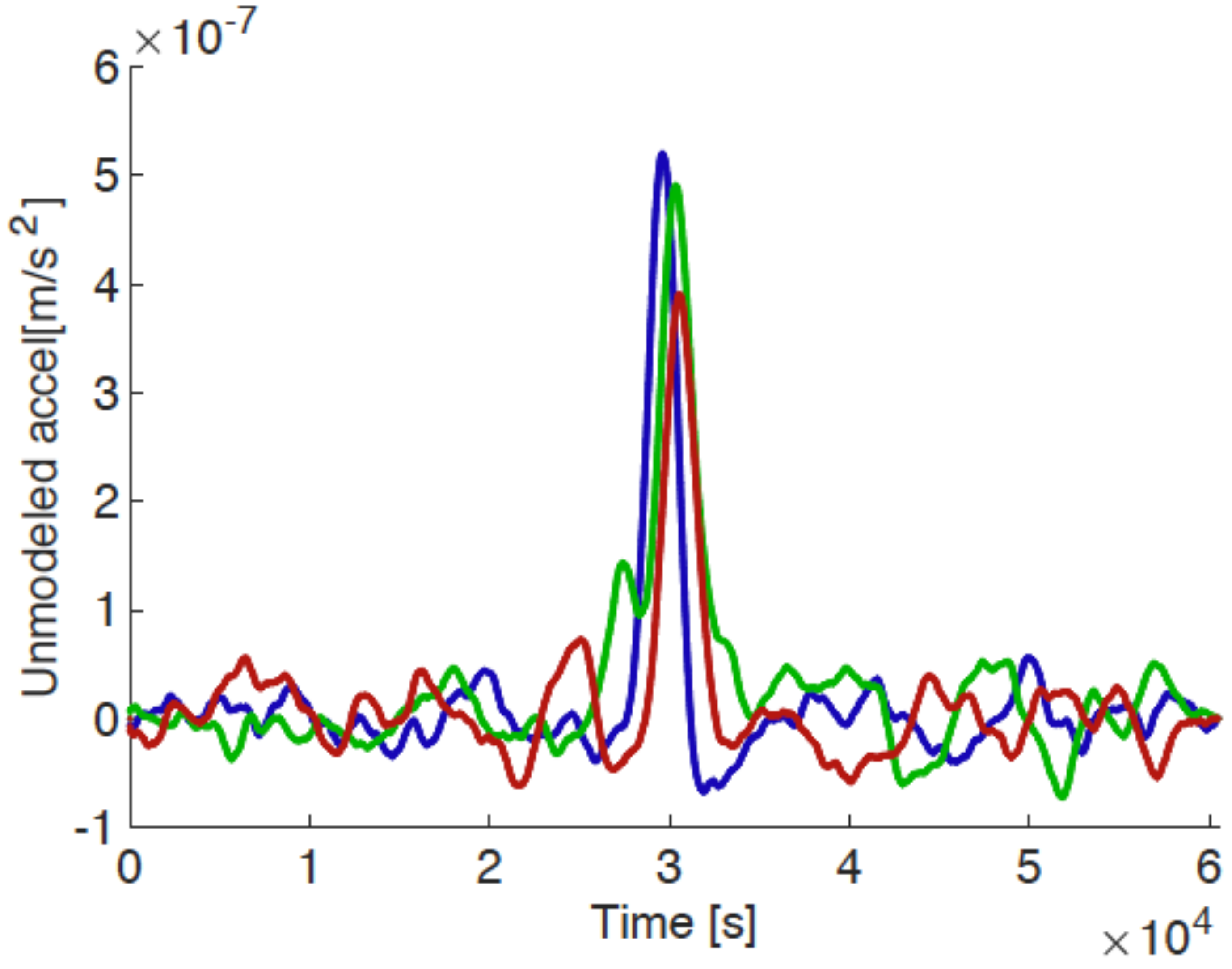
- Typical filter assessment: look at residuals for unexpected features
  - 2X strike shows small feature in residuals
  - 1/10th strike still easily detectable w/ modified filter
  - => Significant increase in detectability of minor, non-damaging strikes by applying dedicated filter



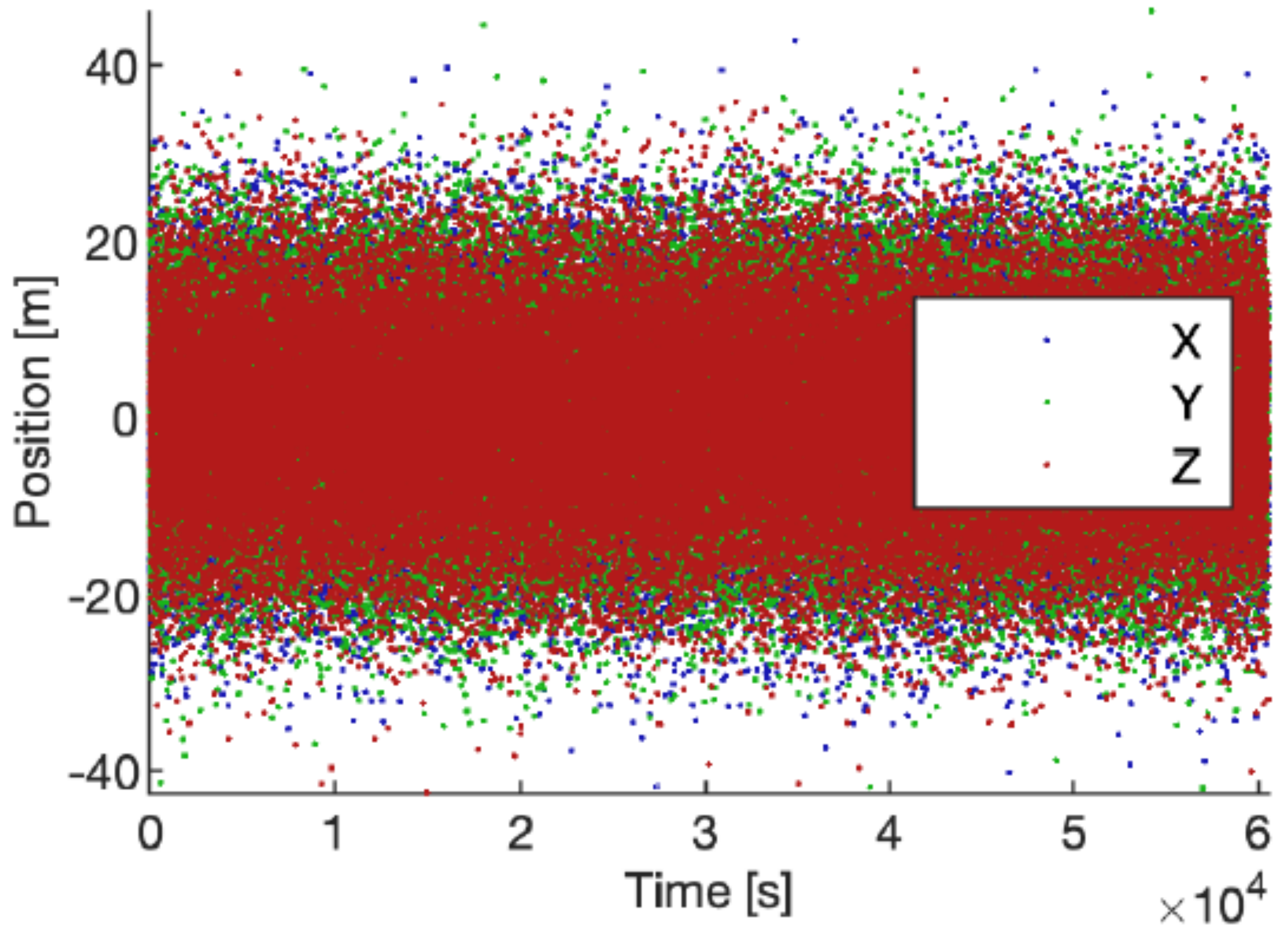
(a) Large strike (2X), smoothed acceleration



(b) Large strike (2X), position residuals



(c) Small strike (1/10th), smoothed acceleration



(d) Small strike (1/10th), position residuals

Conclusions

- Hazardous non-trackable debris is an ongoing challenge to safe space operations
  - Modeling risk is challenging, models suffer from limited data sources
  - Strikes can range from benign to mission-ending
- Appropriately designed filter can identify abrupt, subtle orbit perturbations
  - Substantially lower detection threshold than typical operations
  - Semi-autonomous detection of strikes which do not cause anomaly

				Densities, in g/cm^n:			2.7	8.05	0.04269	1.8	8.96
Regime	Scale	Mass S/C (kg)	Mass db (g)	velocity (km/s)	MEF	DV (cm/s)	Aluminum sphere diameter (cm)	Steel sphere diameter (cm)	Square of MLI (cm, on edge)	1 mm thick square CFRP (cm)	Length of 2 mm dia. copper wire (cm)
LEO	Default	200	0.2	12	2	2.4	0.52	0.36	2.16	1.05	0.71
LEO		100	0.1	12	2	2.4	0.41	0.29	1.53	0.75	0.36
LEO		10	0.01	12	2	2.4	0.19	0.13	0.48	0.24	0.04
LEO		1000	1	12	2	2.4	0.89	0.62	4.84	2.36	3.55
LEO	2X	200	0.4	12	2	4.8	0.66	0.46	3.06	1.49	1.42
LEO		100	0.2	12	2	4.8	0.52	0.36	2.16	1.05	0.71
LEO	5X	200	1	12	2	12	0.89	0.62	4.84	2.36	3.55
LEO		100	0.5	12	2	12	0.71	0.49	3.42	1.67	1.78
LEO	1/10th	200	0.02	12	2	0.24	0.24	0.17	0.68	0.33	0.07
LEO		1000	0.1	12	2	0.24	0.41	0.29	1.53	0.75	0.36
GEO	Default	200	6.857143	0.7	1	2.4	1.69	1.18	12.67	6.17	24.36
GEO		2000	68.57143	0.7	1	2.4	3.65	2.53	40.08	19.52	243.60

Key:	Likely too small to cause damage	Hazardous nontrackable	Potentially trackable

Classes of Debris Events

- Strikes too small for measurable effect
- Strikes which do not affect nominal operation, but do affect spacecraft
- Strikes which disrupt nominal operation, but are recoverable
- Strikes which disable spacecraft
- Strikes causing severe fragmentation events

Sentinel-1A: ~2.2 kg m/s

DV detected: ~0.9 mm/s

Questions and Discussion