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Identifying Minor Debris Strikes in Spacecraft Telemetry: Methods and Applications

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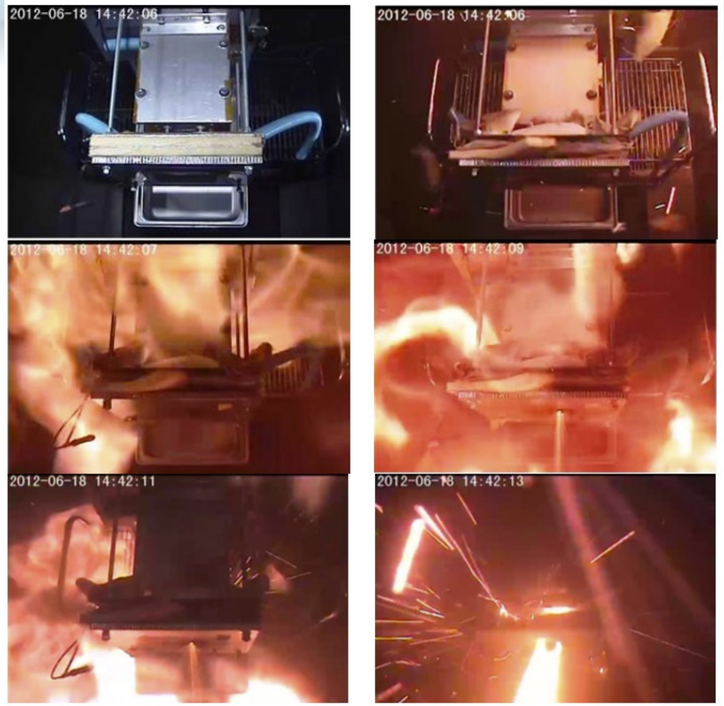
Hazardous Non-Trackable Orbital Debris

- 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)

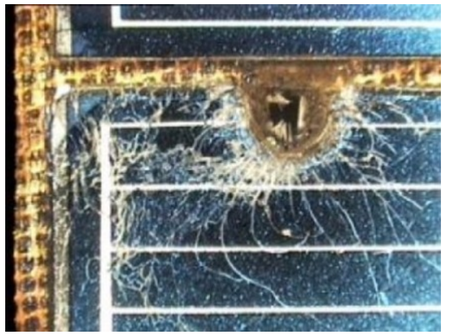
NASA test of 1 cm Aluminum sphere impacting battery at ~7 km/s



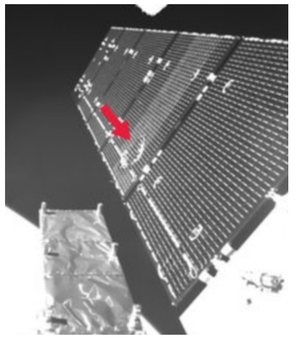
Source: Orbital Debris Quarterly News, Feb 2017

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

Debris Strikes on Hubble and Sentinel-1A Solar Arrays



Source: ESA website



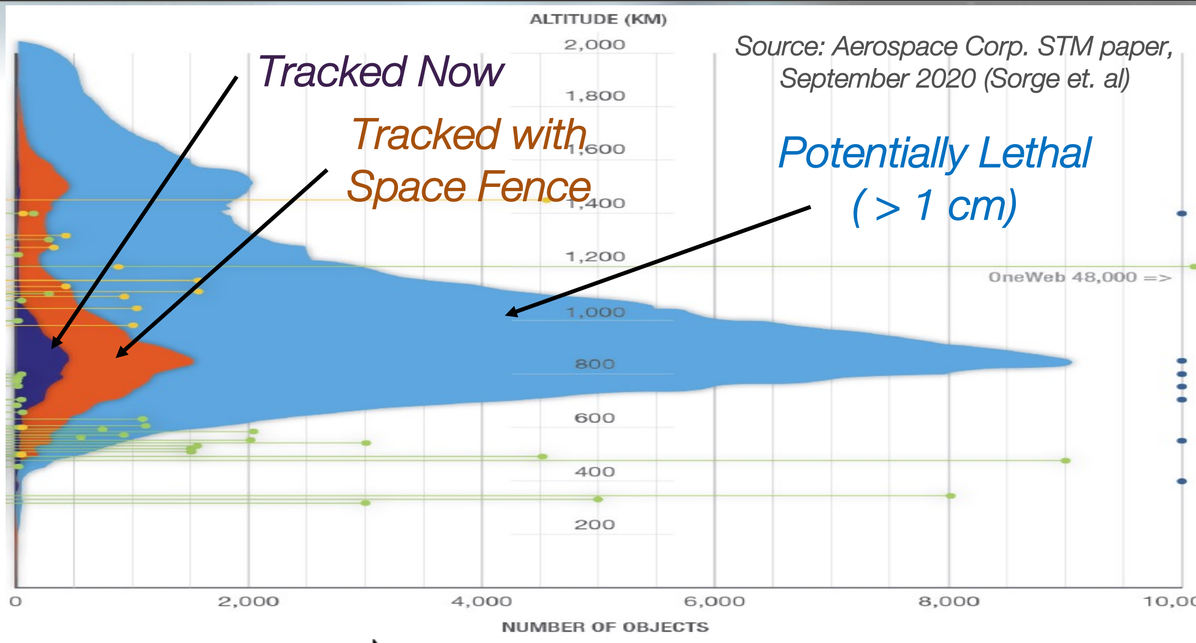
Source: ESA website

Untrackable strikes can be benign, or can be catastrophic

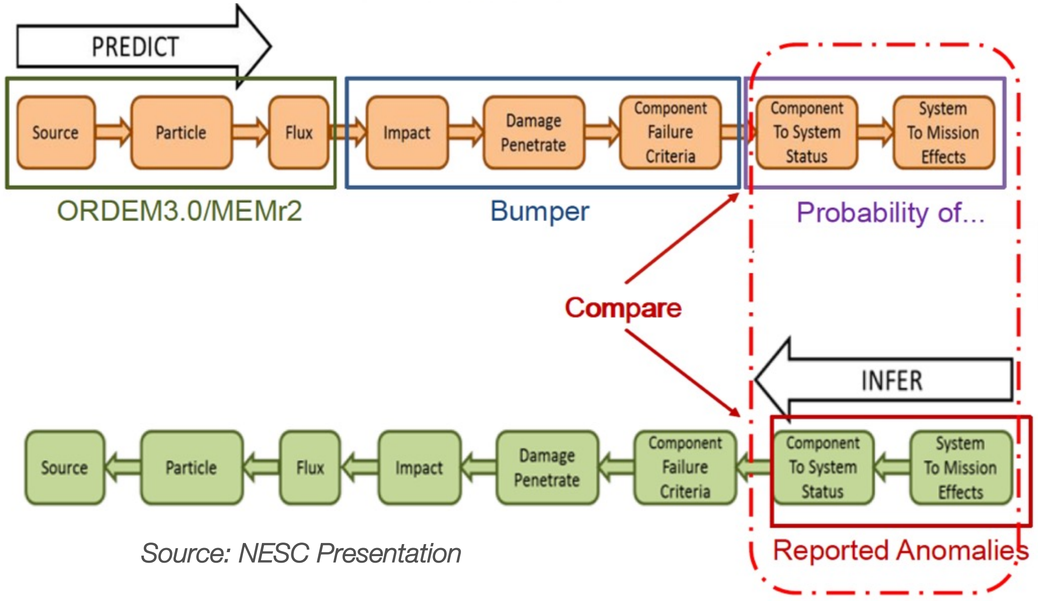
Challenges in Modeling Untrackable Debris

- ORDEM is used to predict expected debris flux
  - Fundamentally limited by data collection systems
  - Only models debris >10 cm in GEO, extrapolated from 30 cm data
  - 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
    - **<u>Recommendation: collect additional data to validate models</u>**
- Typical spacecraft operations:
  - Anomalous behavior => full review (Significant time + $$$)
  - No anomalous behavior => not assessed/investigated/cataloged?
    - **Indications of debris strike often subtle**
- NewSpace era: more satellites, more autonomy

Can subtle strike effects be sensed in spacecraft telemetry?



Source: Aerospace Corp. STM paper, September 2020 (Sorge et. al)



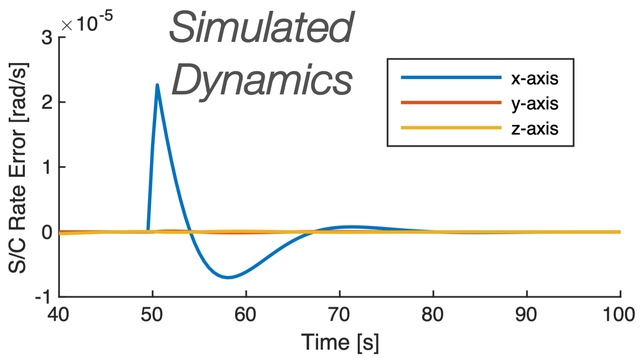
Source: NESC Presentation

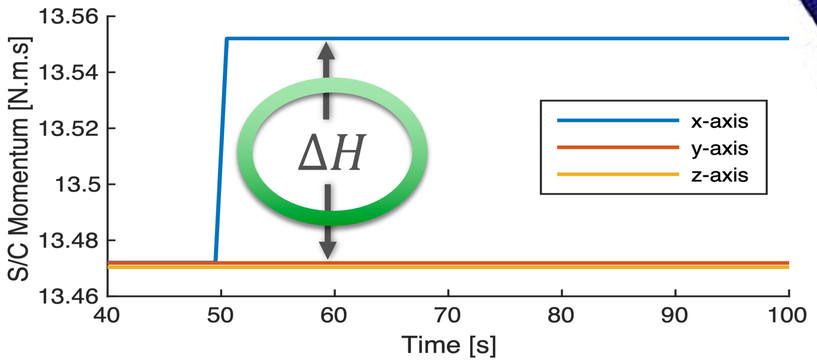
Spacecraft Dynamics Modeling

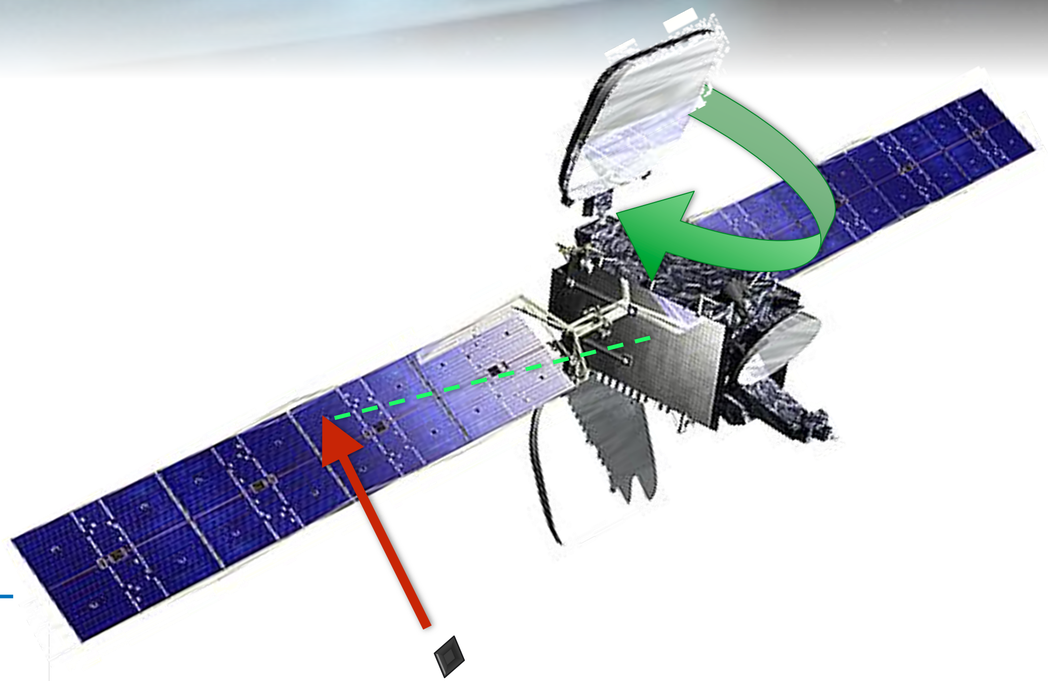
- Research Goal:

  Develop techniques to identify minor debris strikes in spacecraft telemetry

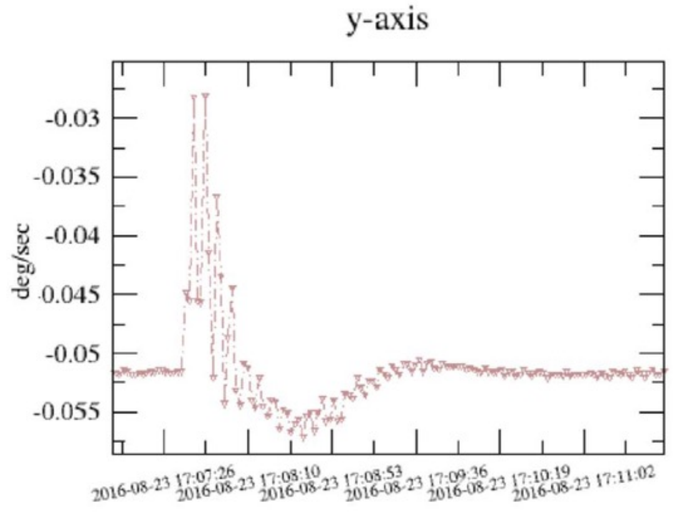
- Debris strike imparts rotation
  - Corrected by attitude control for most satellites
  - **Abrupt change in angular momentum of satellite**







- Outcomes
  - Can use most active spacecraft as *in situ* debris sensors
  - Acquire data to validate models and improve risk assessments
  - Monitor spacecraft state-of-health

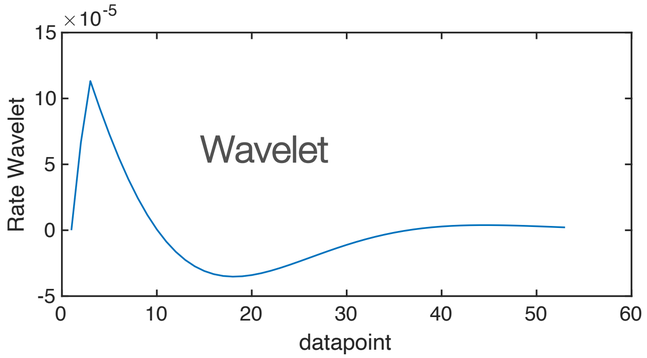


Telemetry from Sentinel-1A strike

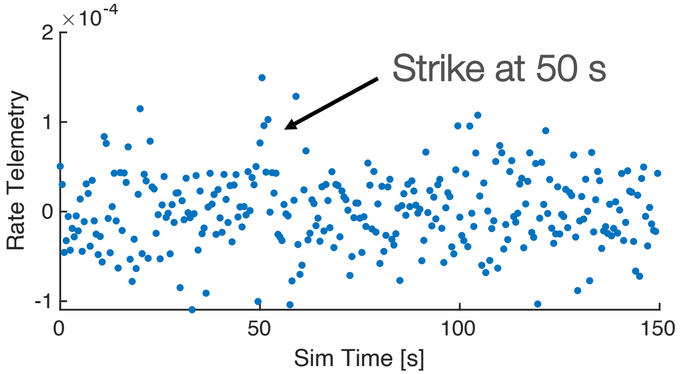
Source: Acta Astronautica 137 (2017) 434-443

Digital Signal Processing vs. Change Detection

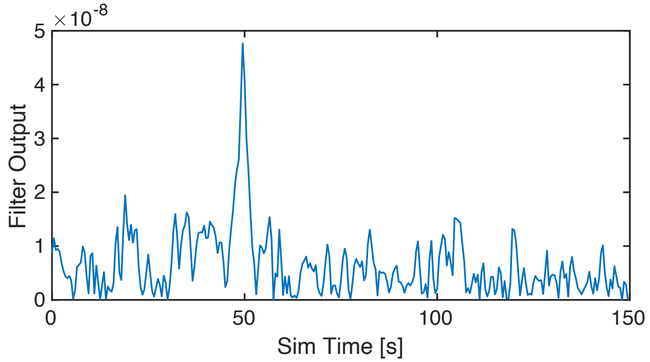
- Digital signal processing: Matched filter applied to rate telemetry



Find 'signal' produced by S/C response to strike



Noisy data obfuscates signal



Filter output shows clear spike

- Change detection algorithms: applied to angular momentum telemetry

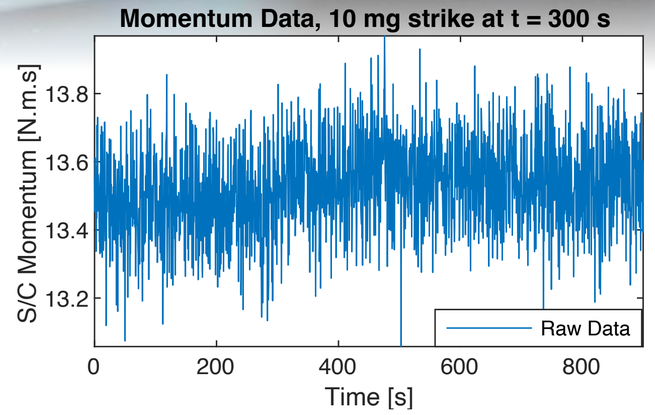
Inertial angular momentum changes abruptly when strike occurs

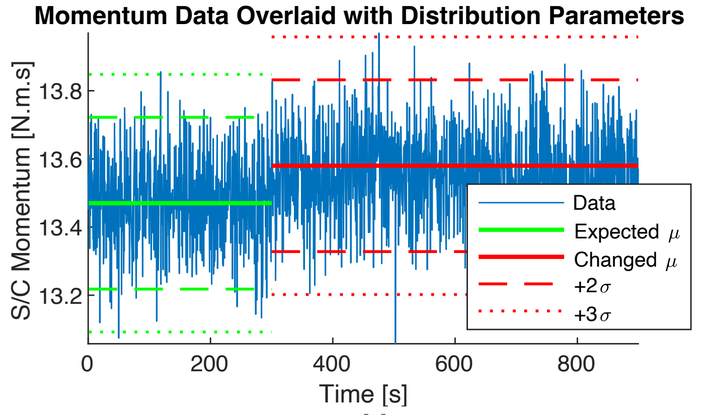
$$\mathcal{L}(\mathbf{y}) = \frac{\mathrm{p}\left(\mathbf{y}|\mathcal{H}_1\right)}{\mathrm{p}\left(\mathbf{y}|\mathcal{H}_0\right)}$$

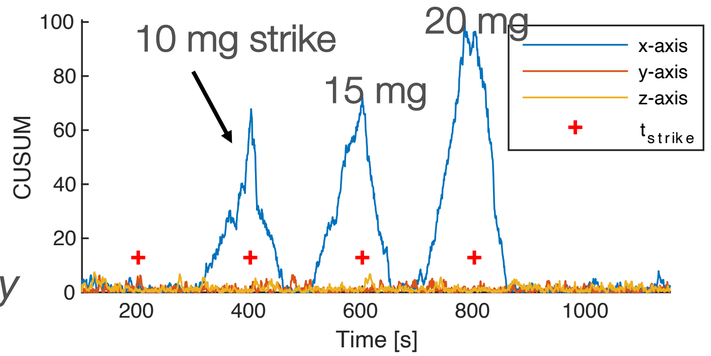
$$S_n = \sum_{k=1}^{n} \ln(\mathcal{L}(\mathbf{y}))$$

$$W_n = S_n - \min_{0 \leqslant \mathrm{k} < \mathrm{n}} S_k$$

Sequential probability ratio test applied in sliding window filter accentuates change dramatically

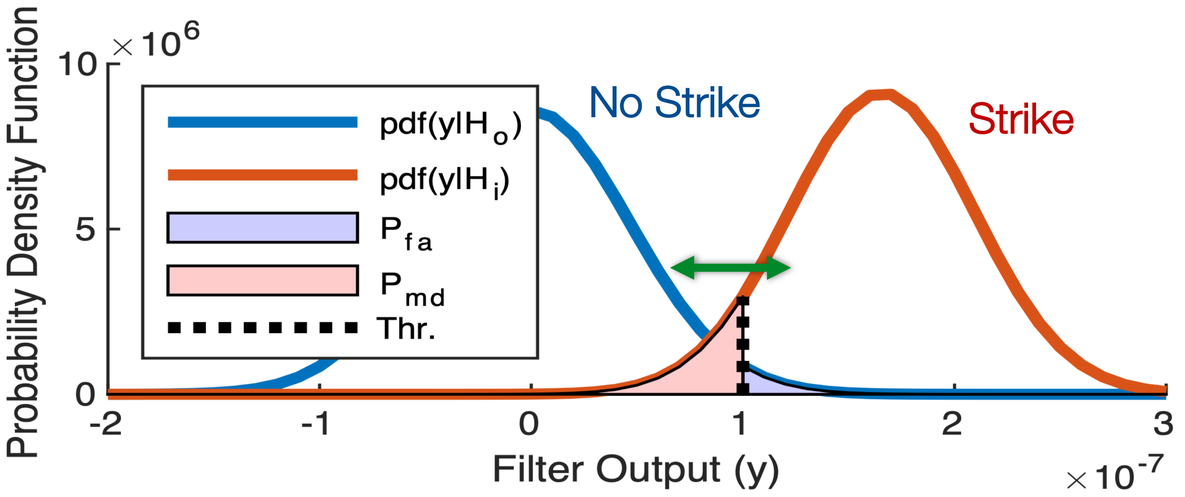


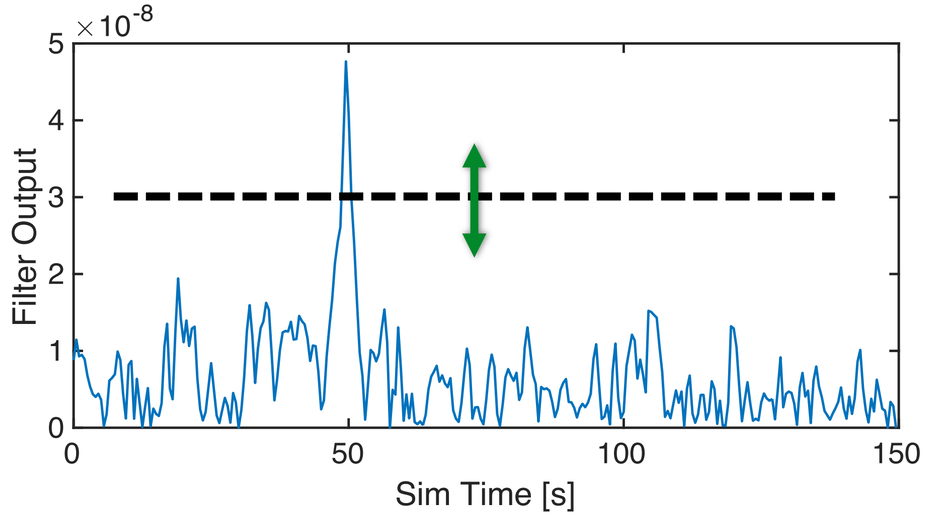


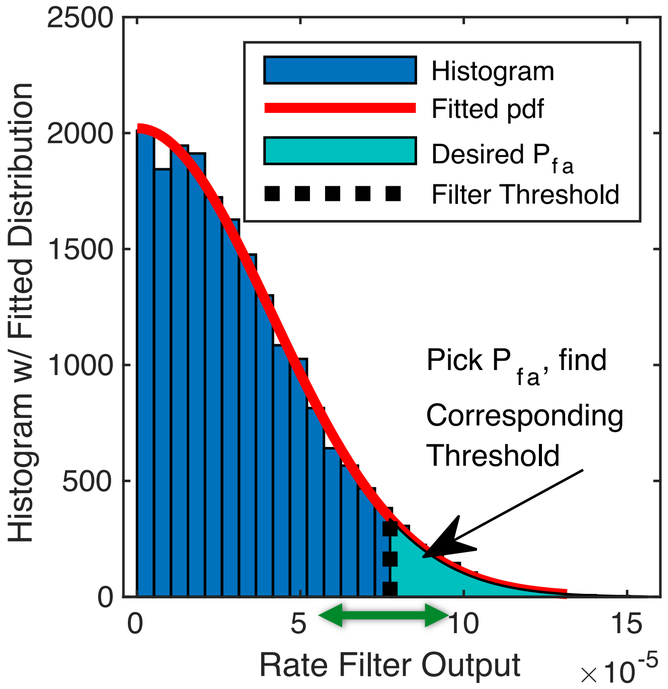


Setting Detection Thresholds

- Set threshold based on baseline filter noise
  - Depends on objective:
    - Low to catch lots of small questionable blips
    - High to only catch distinct features
- Determine strike detection thresholds
  - **Note: increasing P_D also increases P_{FA}**
  - What size strike can be detected with reasonable P_{FA}?



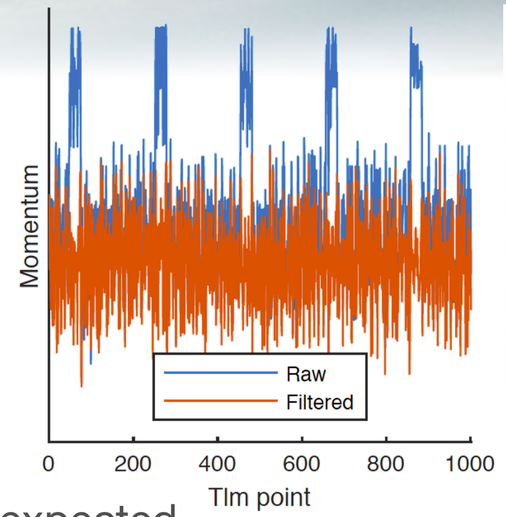


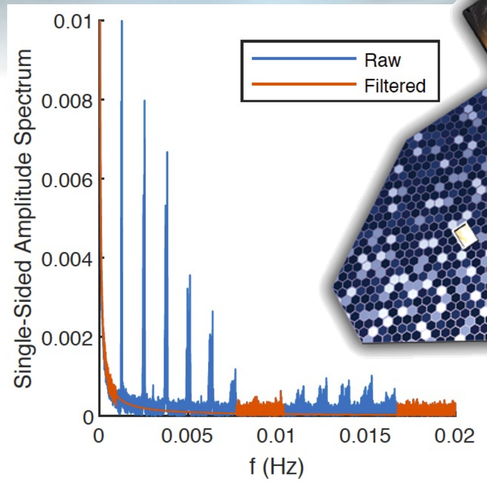


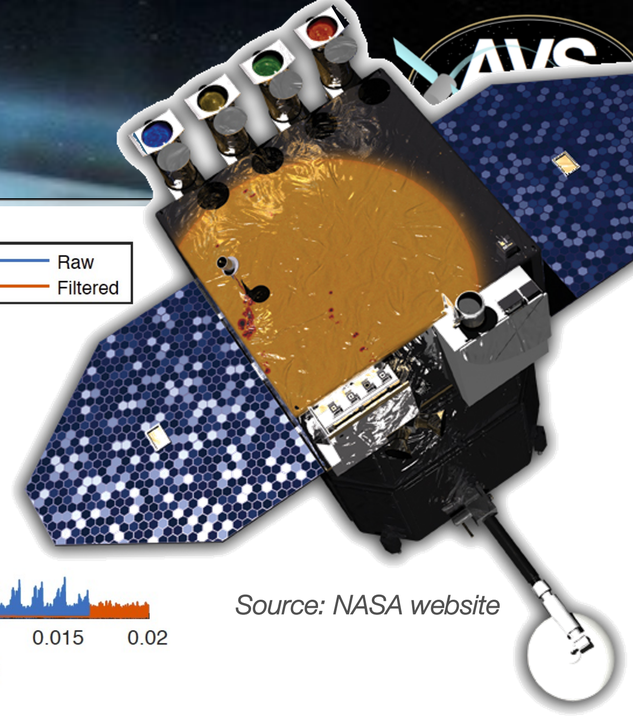
Applying to Real Telemetry: GEO Spacecraft

- NASA Solar Dynamics Observatory
  - Pre-filter to remove square wave from momentum

Preprocess data to remove square wave



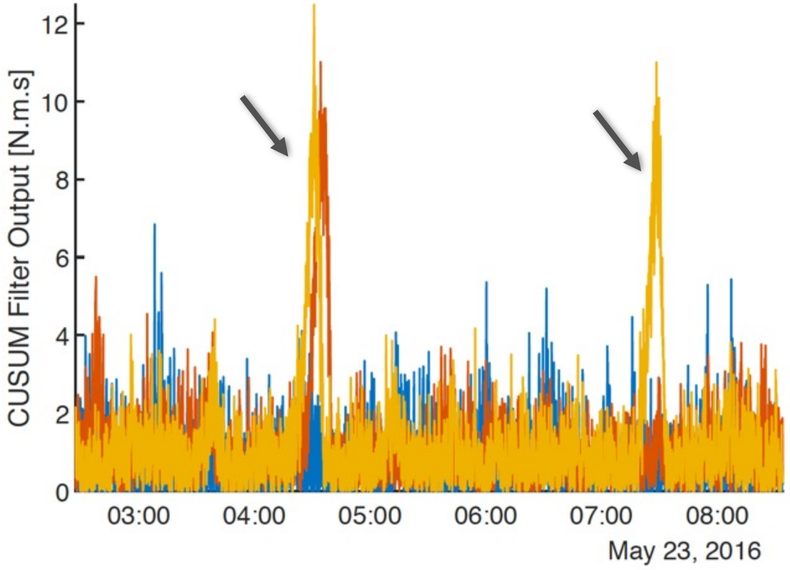




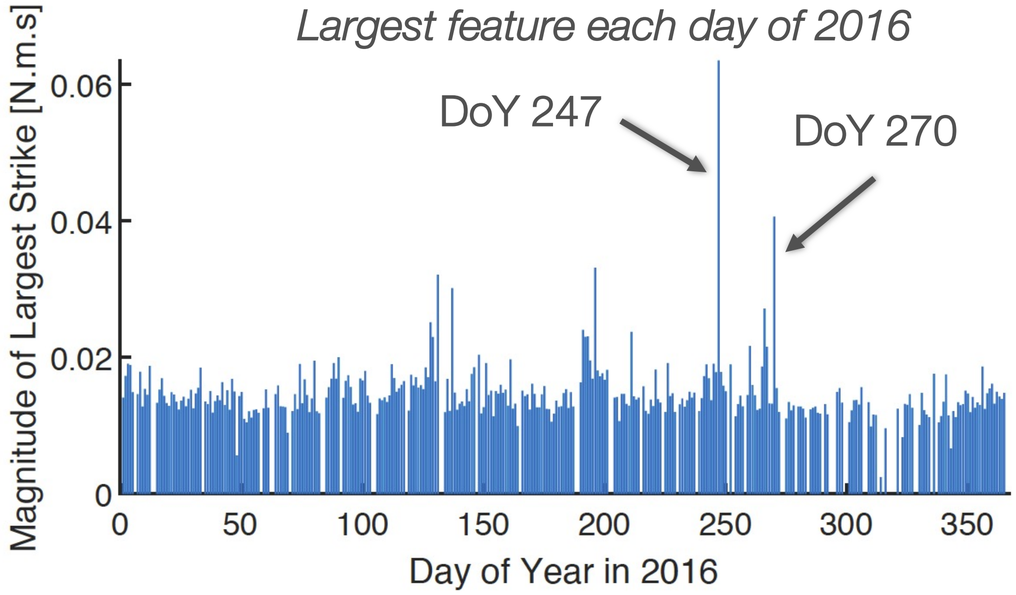
Source: NASA website

- Results
  - Frequent small blips
  - Some larger features
  - Low detection threshold – routine false alarms are expected

Example small blips in filter output



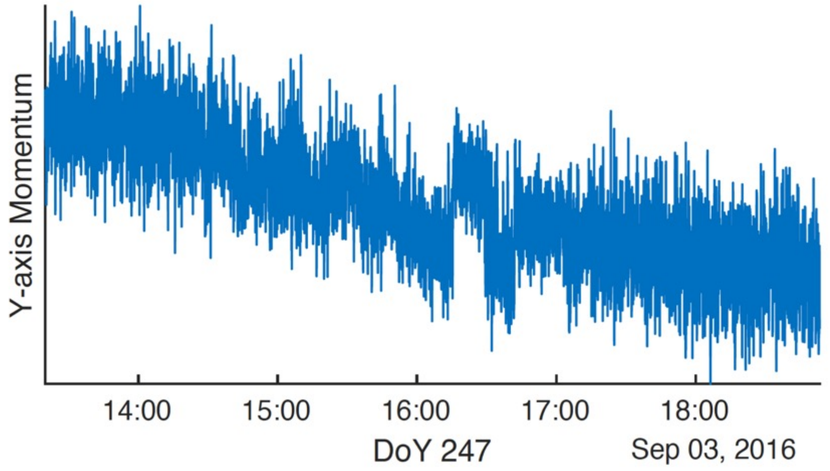
Largest feature each day of 2016

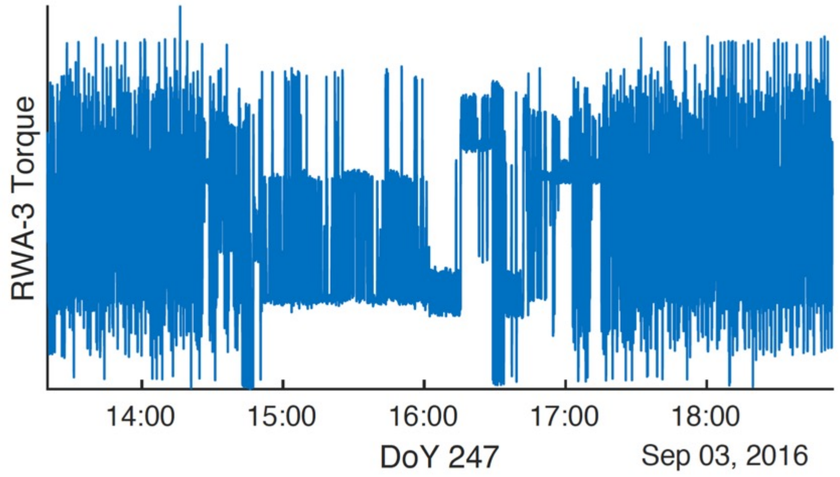


SDO Checkpointed Results

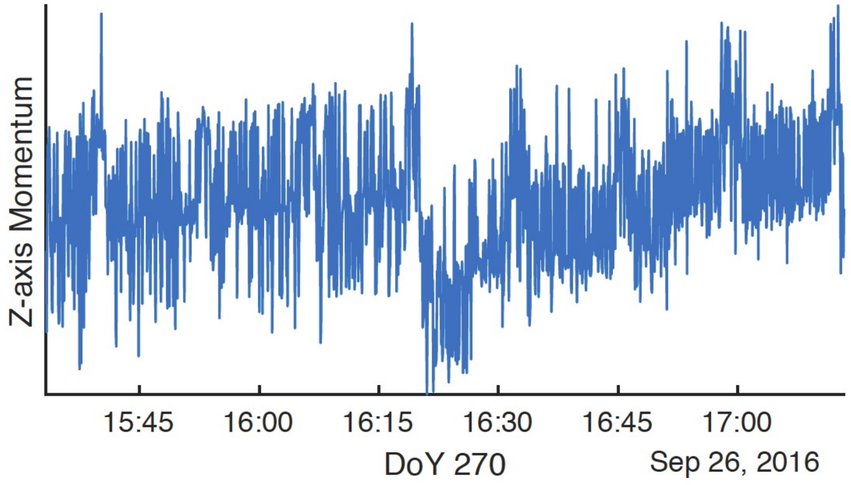
- Examine telemetry of large strikes

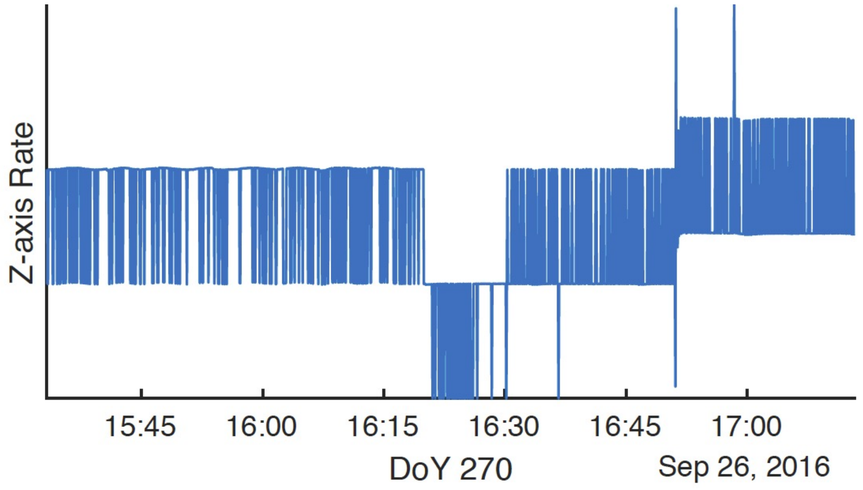
2016 DoY 247:
- Momentum oscillates
- RWA telemetry peculiar, leads strike by ~1 hr
- Likely not a strike, but interesting feature





2016 DoY 270:
- Abrupt change in momentum
- Rate shows interesting signature
- From ops team: IRU heaters were turned on at 1603, take 25-30 minutes to warm





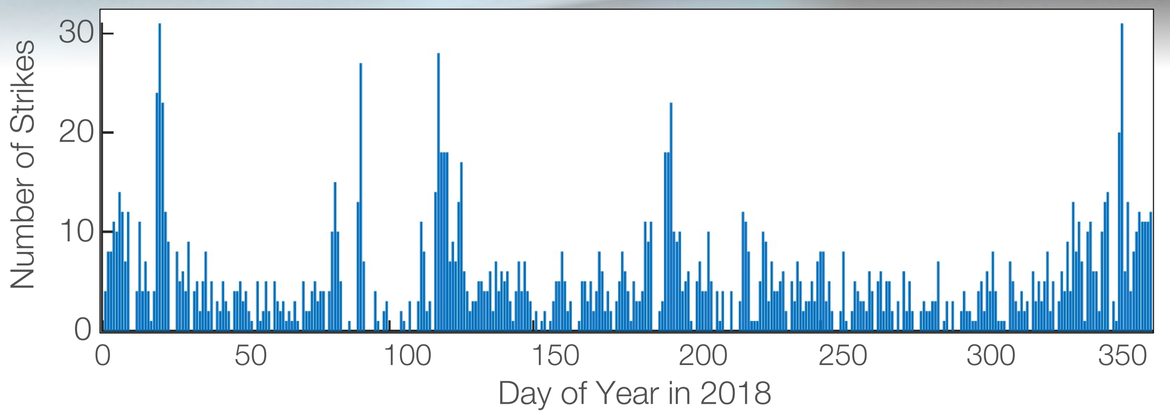
Algorithms identify momentum perturbations, but may be attributable to other sources

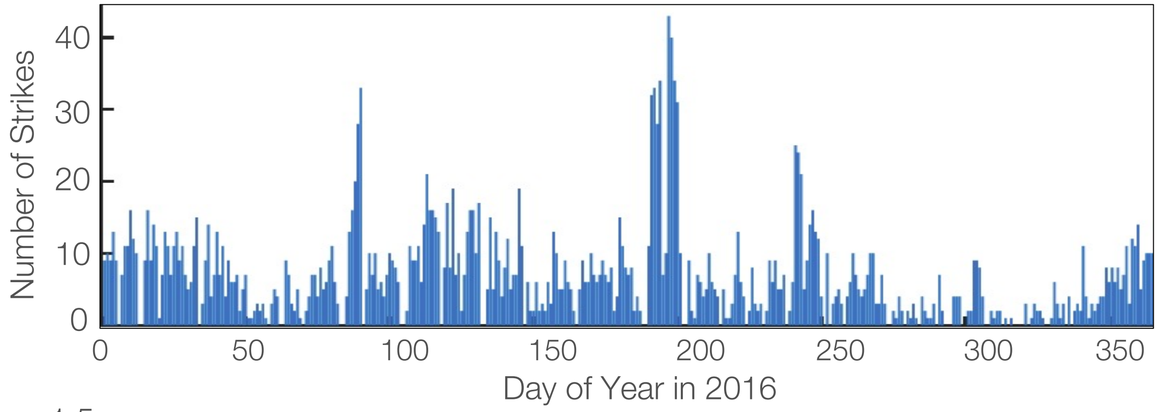
Blip Count Per Day Over Year vs. MM Flux Variation

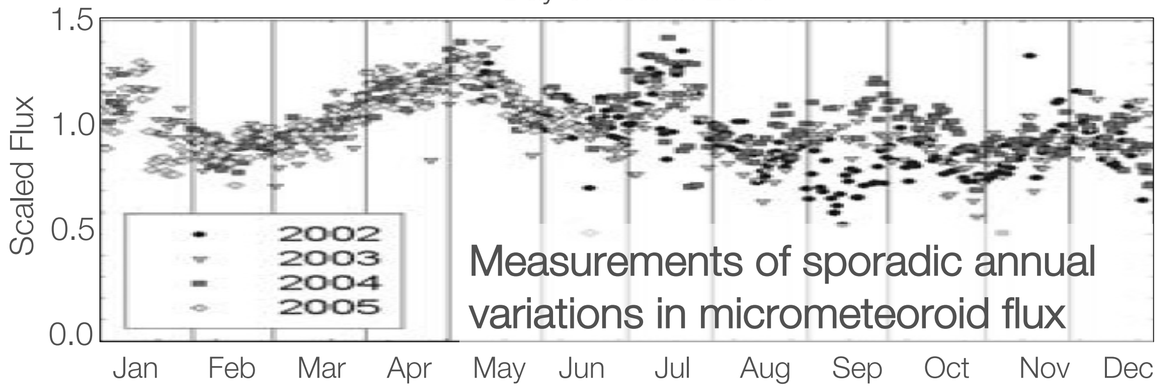
- At first assumed small detections were just noise
- But interplanetary spacecraft have measured dust impacts at rates of several times per day
- Interesting trends emerged with multiple years
- Even more interesting: Some correlation to annual sporadic variations in micrometeoroid flux
- Maybe these blips are real?
  - Initial model comparisons not supportive
  - MEM3 predicts a few per year
  - Momentum enhancement factor highly questionable in micrometeoroid size/velocity regime

MEF Test, Ernst-Mach-Institut

Hypervelocity test on thick, homogeneous target (1.2 cm al sphere, 6.8 km/s)



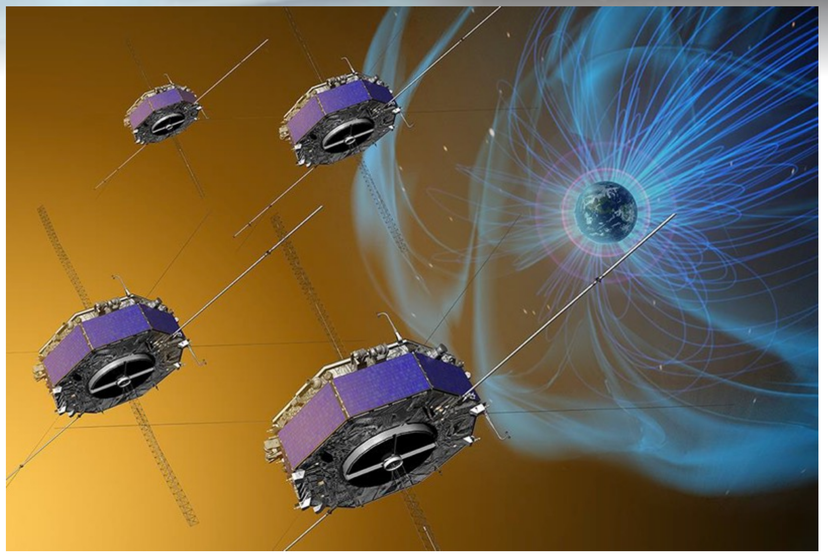




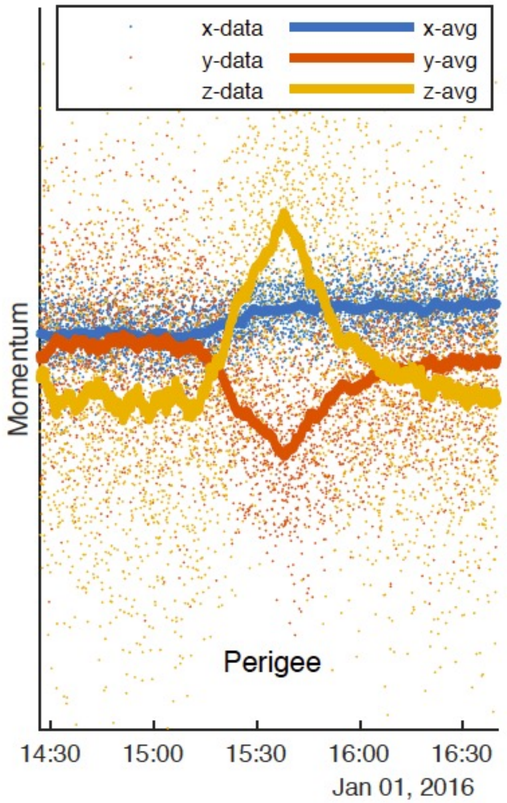
Campbell-Brown & Jones, Annual Variation of Sporadic Radar Meteor Rates

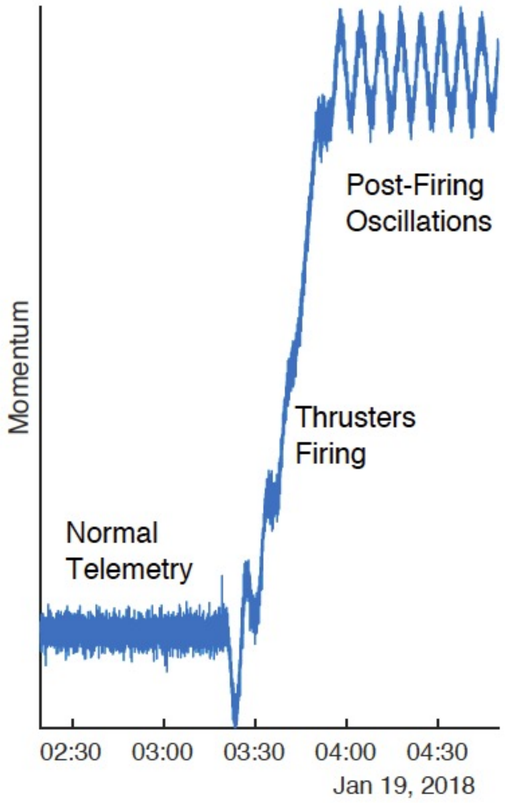
Processing MMS Data

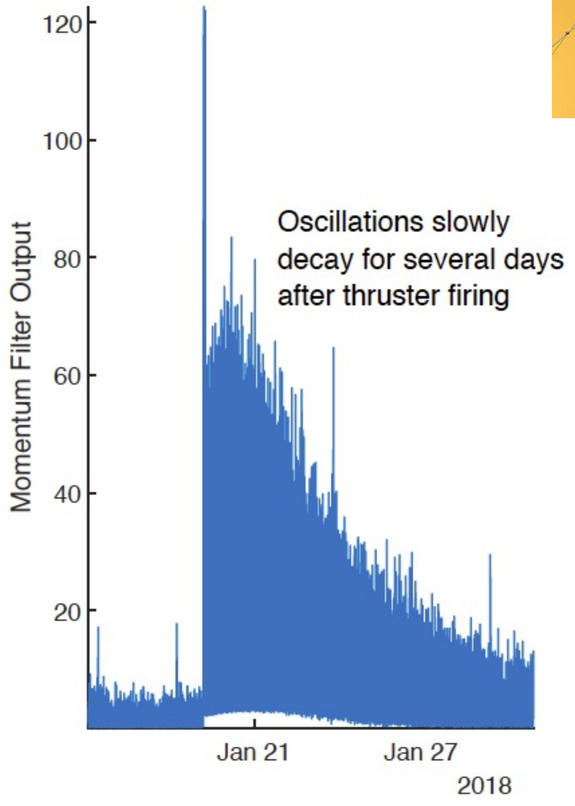
- Magnetospheric Multiscale (MMS)
  - 4 spacecraft in formation, highly elliptical orbit
  - Spin-stabilized, four 60 m wirebooms
- Calculate inertial angular momentum from S/C rate, inertia, and pointing (no RWAs)



Source: Wikipedia





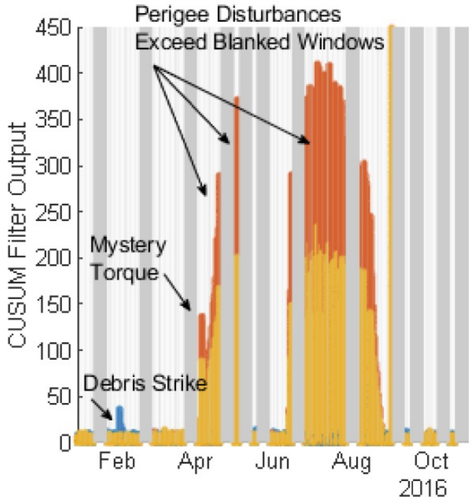


Blank perigees from results – gravity-gradient torques?

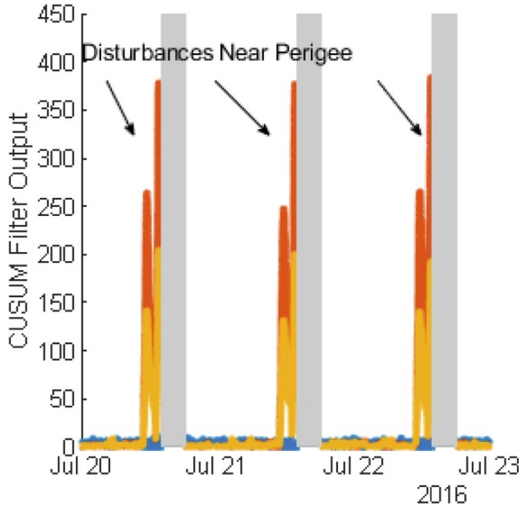
Blank 10 days (!) after firing thrusters – wirebooms oscillate, trip detectors

MMS Data Features

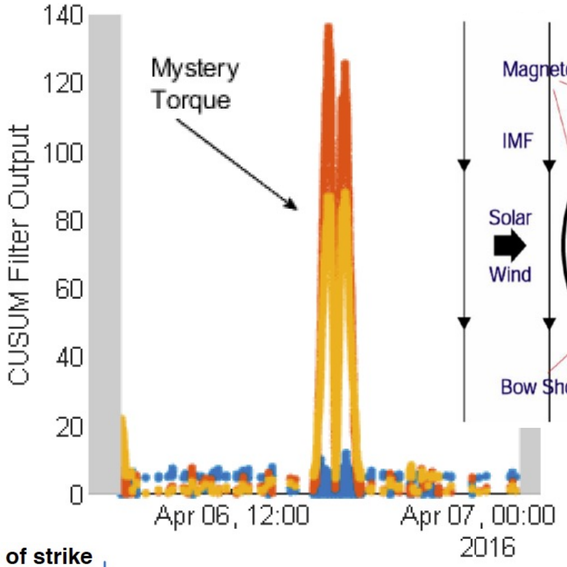
10 months of results: plot filter output above threshold



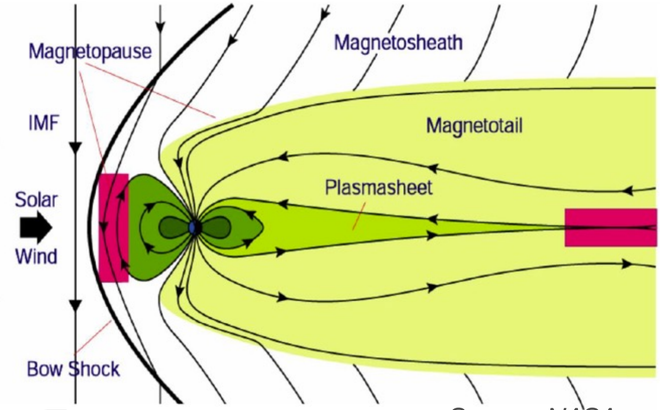
Blanked window insufficient: disturbance moves relative to perigee => not GG



Occasional mystery torques overwhelm results

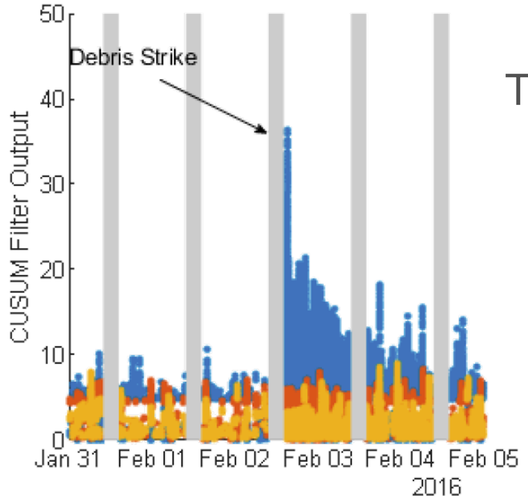


MMS mission regions of interest

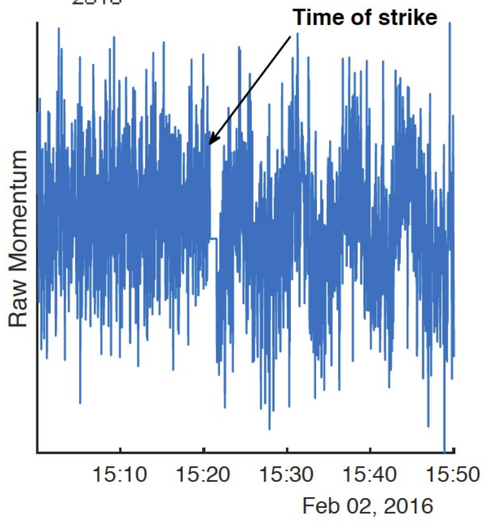


Source: NASA

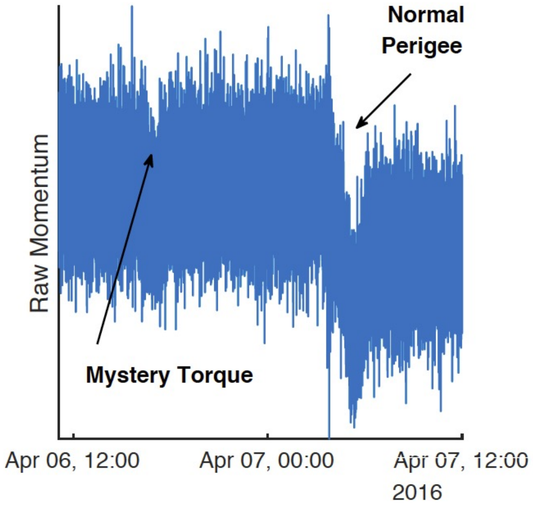
Known debris strike easily detected



Telemetry from debris strike shows wireboom oscillation

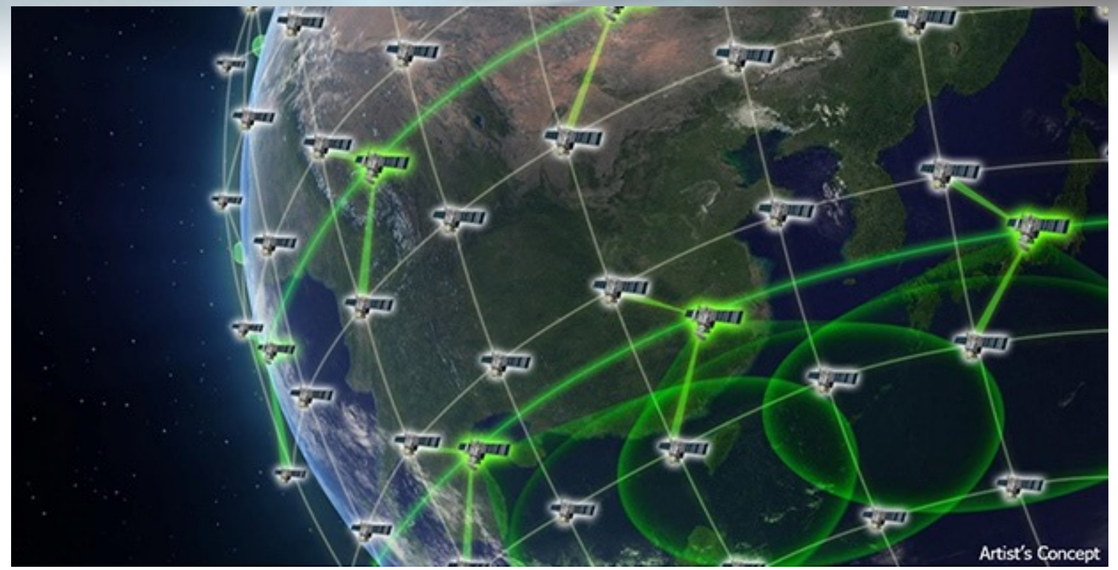


Telemetry from mystery torques shows change in angular momentum



Potential Applications: Anomaly Screening and Resolution

- State of health monitoring, anomaly attribution/response
  - Quicker response/resolution to immediate strike-induced anomalies
  - Monitor for anomalies that may not manifest immediately
    - Example: startracker baffle strike leads to straylight issues later
  - Monitoring momentum can show issues besides particle impacts
- Improve operator knowledge of local debris environment
  - Especially constellations



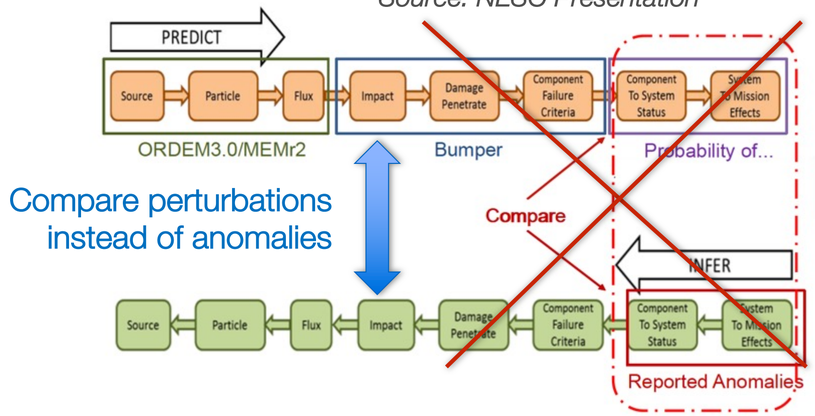
Source: DARPA website

- Concrete method for implementing ‘Satellite as a Sensor’ concepts
- Great fit for constellations and product line satellites
  - i.e., commercial GEO bus product lines
  - More satellites, more autonomy

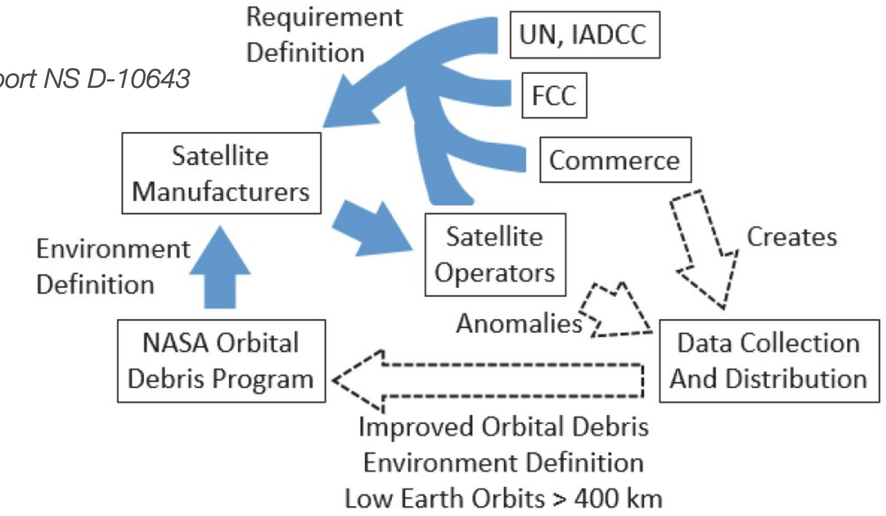
Potential Applications: Wider Adoption, Broader Impact

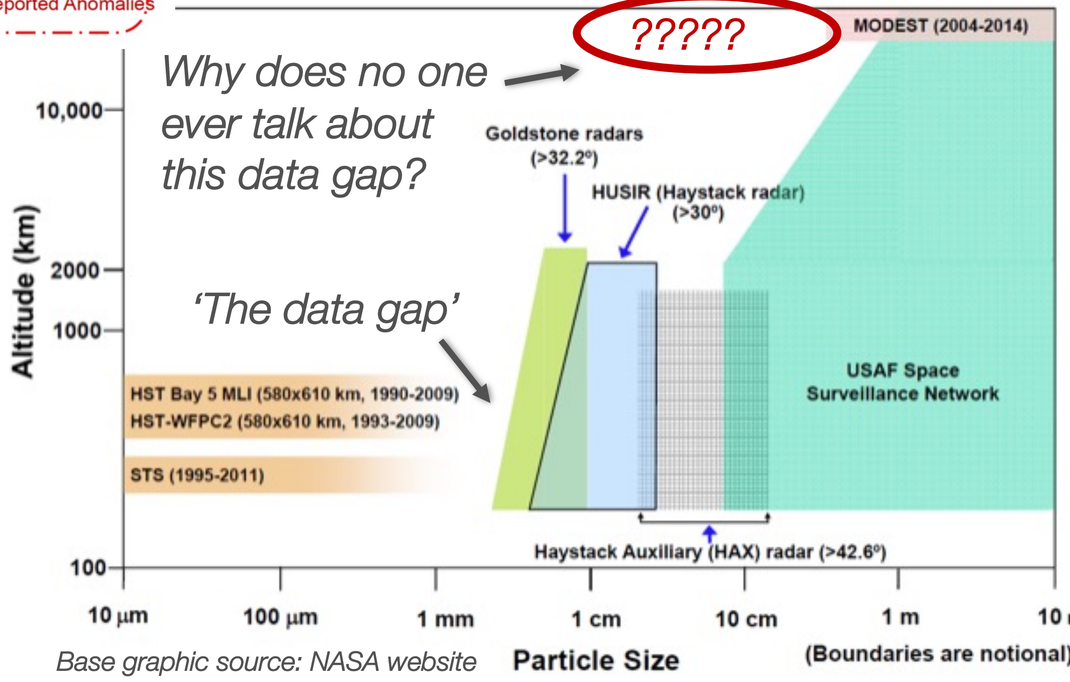
- Department of Commerce STM
  - Open architecture data repository for SSA info
  - Recent paper by IDA on orbit perturbations
  - Perturbations provide more data than anomalies, fewer barriers?
- Additional model validation
  - Data correlated to debris mass
  - Data collection in GEO (little to no data on small debris)
- Validated and/or improved debris risk assessments
  - Motivate appropriate behavior from New Space actors
  - Space insurers can assess risks more accurately
    - Insurers can provide <u>significant</u> incentives to commercial

Source: NESC Presentation



Source: IDA report NS D-10643

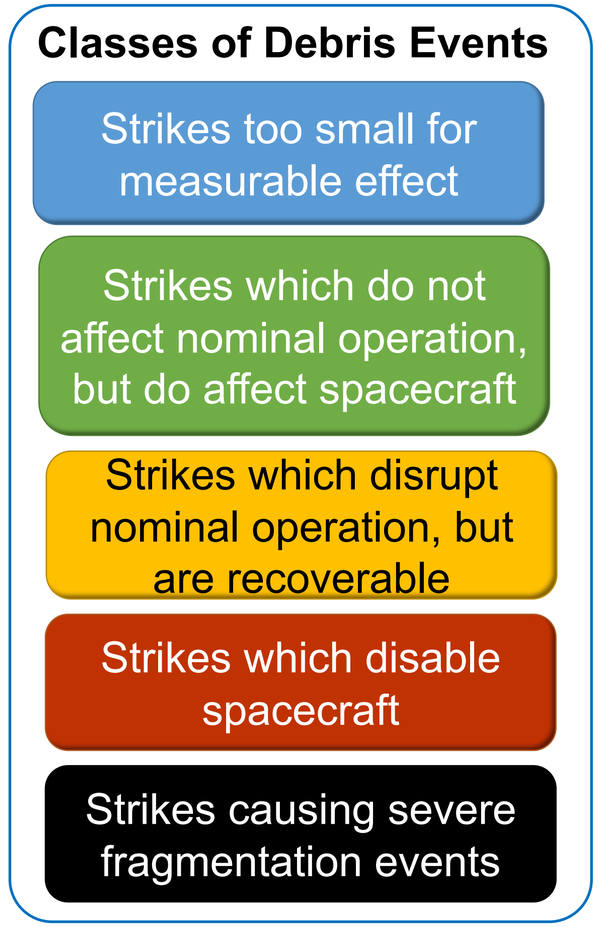




Base graphic source: NASA website

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
- Change detection algorithms can highlight unexpected perturbations in telemetry
- Running algorithms on spacecraft data turns up unexpected features
  - Con: obfuscate debris strikes
  - Pro: may be useful for monitoring general state of health
- Techniques have utility on both local and global scales
  - Monitor individual spacecraft for anomaly resolution
  - Contribute perturbations to database to validate and/or improve debris risk assessment methods



Questions and Discussion