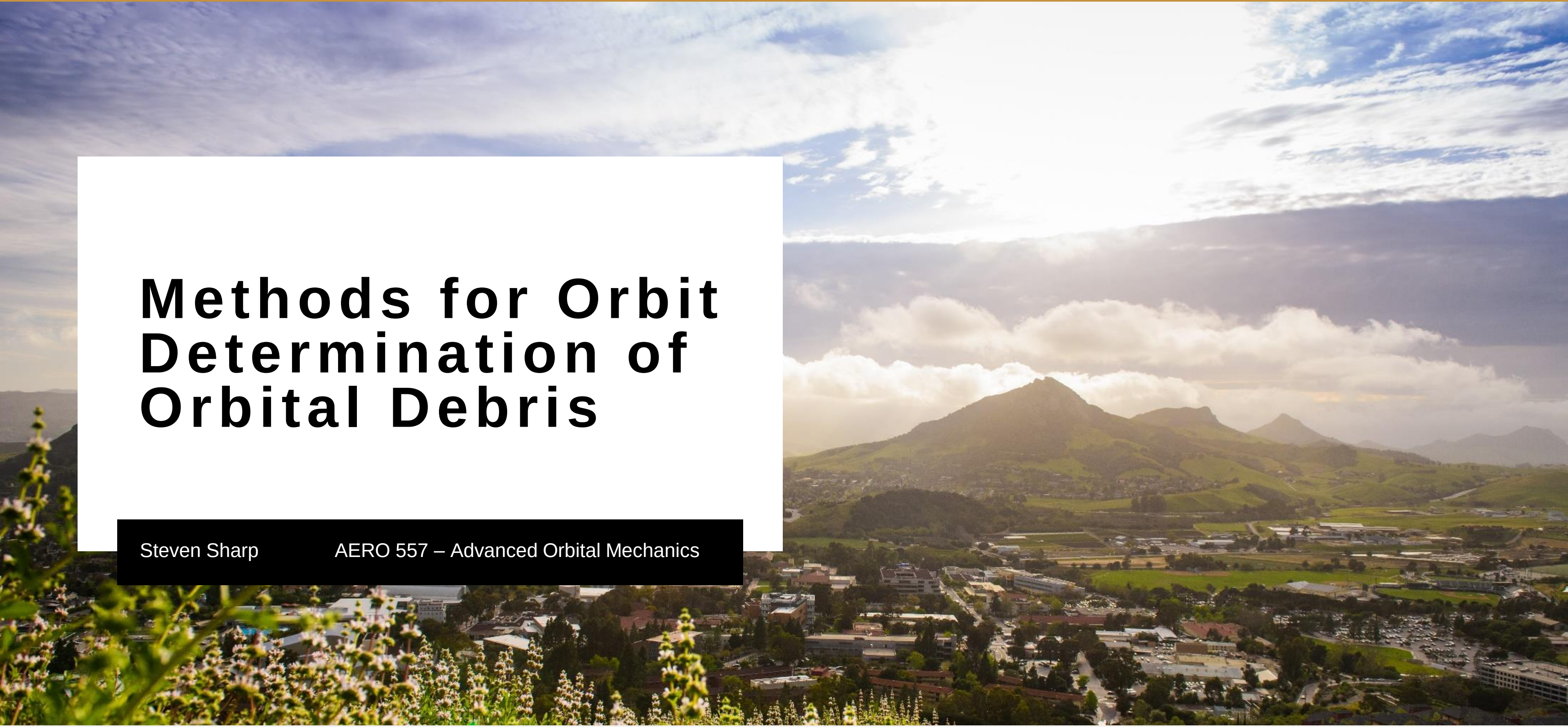

Methods for Orbit Determination of Orbital Debris

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AERO 557 – Advanced Orbital Mechanics

CAL POLY

Motivation

- As the frequency of multi-satellite launches and launches in general continues to grow, the amount of orbital debris increases exponentially and unexpected collisions become ever more likely
- Objects over 10 cm in diameter are well catalogued and tracked, but the sheer quantity of <10cm orbital debris fragments combined with the challenges presented to determine the orbit of such small objects make it difficult to track a significant portion of all debris fragments
- Debris also cannot communicate with Earth or other satellites and don't correct for perturbations, while also not being as bright as celestial objects


European Space Agency

Motivation

- Novel and unique methods for orbit determination are necessary to make a dent in the amount of untracked debris fragments
- We will discuss three methods for OD of orbital debris:
  - traditional optical and radar observation
  - laser ranging
  - in-situ observation

Optical and Radar Observation

- Observations of an unknown piece of orbital debris are generally very short and produce an uncorrelated trajectory or tracklet
- In order to perform orbit determination, there must either be a known breakup event that the object can be tracked from or there must be two or more tracklets that can be correlated together
- Analyzing the massive amount of observed tracklets naïvely is very computationally expensive, especially as the size of the observable population continues to grow

[1] Tommei G., Milani A., Rossi A., "Orbit Determination of Space Debris: Admissible Regions," Celestial Mechanics and Dynamical Astronomy, 1 April 2007

Optical and Radar Observation

- To simplify the computation of possible correlations, use a concept from OD for celestial objects: the admissible region
- The admissible region is defined by the following set of constraints that rule out impossible and highly improbable orbits:

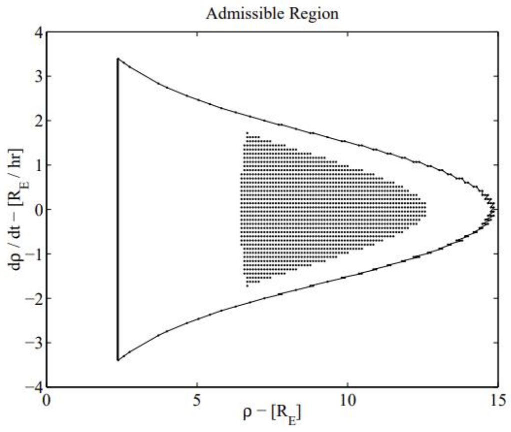
$$\mathcal{C}_1 = \{(\rho, \dot{\rho}) : E < 0\}$$

$$\mathcal{C}_2 = \{(\rho, \dot{\rho}) : 2\ \mathrm{R}_\oplus < \rho < 20\ \mathrm{R}_\oplus\}$$

$$\mathcal{C}_3 = \{(\rho, \dot{\rho}) : 1.03\ \mathrm{R}_\oplus < r_p\}$$

$$\mathcal{C}_4 = \{(\rho, \dot{\rho}) : r_a < 25\ \mathrm{R}_\oplus\},$$

$$\mathcal{C} = \bigcap_{i=1}^{4} \mathcal{C}_i.$$



Example admissible region for a specific observation vector

[2] J.M Maruskin, D.J. Scheeres, K.T. Alfriend, “Orbit Determination of Space Debris: Correlation of Optical Observations,” Proceedings of the Advanced Maui Optical and Space Surveillance Technologies Conference, Wailea, Maui, Hawaii, 19 September 2008

Optical and Radar Observation

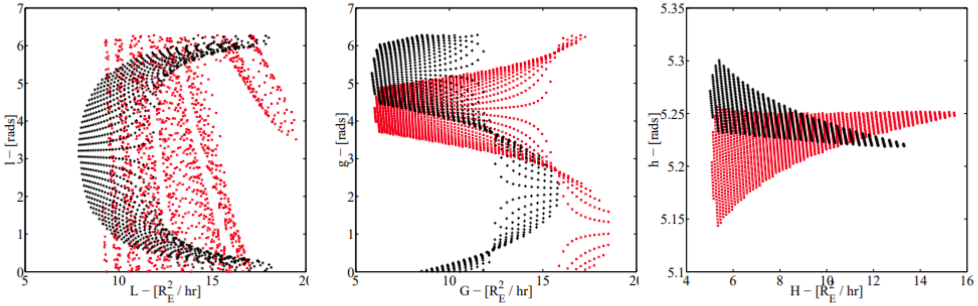
- To determine whether two tracklets are correlated, simply compare their respective admissible regions…
- It turns out that it's not that simple since both admissible regions are subsets of two different sets of topocentric coordinates from different times and locations in space
- So, instead we translate the slant range vector to orbital elements and set up Delaunay variables (ignoring singular cases which can instead use Poincaré canonical variables):

$$
\begin{aligned}
l &= M, & L &= \sqrt{\mu a}, \\
g &= \omega, & G &= L\sqrt{1-e^2}, \\
h &= \Omega, & H &= G\cos i,
\end{aligned}
$$

[2] J.M Maruskin, D.J. Scheeres, K.T. Alfriend, "Orbit Determination of Space Debris: Correlation of Optical Observations," Proceedings of the Advanced Maui Optical and Space Surveillance Technologies Conference, Wailea, Maui, Hawaii, 19 September 2008

Optical and Radar Observation

- We now use some multi-dimensional mathematical magic to map the two admissible regions into a six-dimensional Delaunay space and then propagate them to a common epoch
- Since the admissible regions are two-dimensional manifolds within a six-dimensional space, the likelihood of accidental intersection is very low, so the two tracklets are almost certainly correlated if it can be shown that the admissible regions in Delaunay space intersect at a single point
- A simple least squares method can then be used for the final orbit determination since the orbit is within the neighborhood of the point of intersection



Two admissible regions projected onto selected planes on the Delaunay space (one in black, the other in red)

[2] J.M Maruskin, D.J. Scheeres, K.T. Alfriend, "Orbit Determination of Space Debris: Correlation of Optical Observations," Proceedings of the Advanced Maui Optical and Space Surveillance Technologies Conference, Wailea, Maui, Hawaii, 19 September 2008

Laser Ranging

- Laser ranging is a promising alternative to traditional optical and radar observations
- When compared to radar, reduces inaccuracy from
  - Rayleigh scattering
  - Wave diffraction
  - Beam divergence
  - Atmospheric attenuation
- Optical measurement sites are generally cheaper and are much more widely available than radar detectors

[3] U. Hugentolber and C. Bamann, “Accurate Orbit Determination of Space Debris with Laser Tracking,” 7th European Conference on Space Debris, Darmstadt, Germany, 18–21 April 2017

Laser Ranging

- Mono-static ranging
  - Simple travel time estimate from short laser pulses emitted and received by a single ground station
- Bi-static ranging
  - One ground station emits the laser pulses and another ground station receives them
- Multi-static ranging
  - Multiple ground stations receive an emitted laser pulse and compare travel times

[3] U. Hugentolber and C. Bamann, "Accurate Orbit Determination of Space Debris with Laser Tracking," 7th European Conference on Space Debris, Darmstadt, Germany, 18–21 April 2017

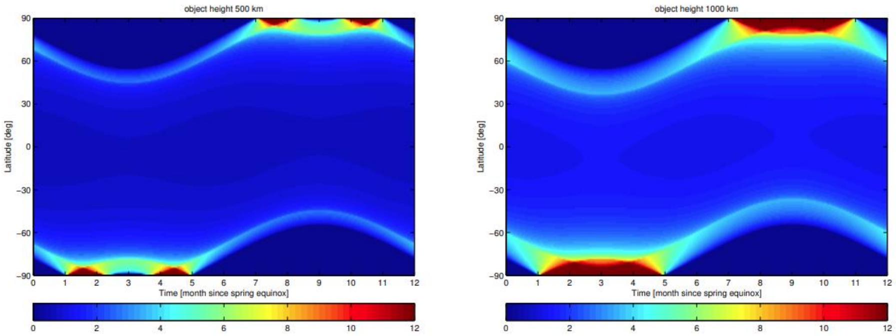
Laser Ranging

- Filtering
  - Received SNR is generally orders of magnitude smaller than optical measurements of large satellites
  - Latest TLE propagated to current time and compared to the single pass results of mono- or bi-static ranging
  - Residuals are filtered using an extended Kalman filter
  - Clock offsets need to be included in the filter for bi- and multi-static ranging

[3] U. Hugentolber and C. Bamann, "Accurate Orbit Determination of Space Debris with Laser Tracking," 7th European Conference on Space Debris, Darmstadt, Germany, 18–21 April 2017

Laser Ranging

- Limitations
  - Similar to optical tracking
    - Weather
    - Object illumination
    - Station illumination



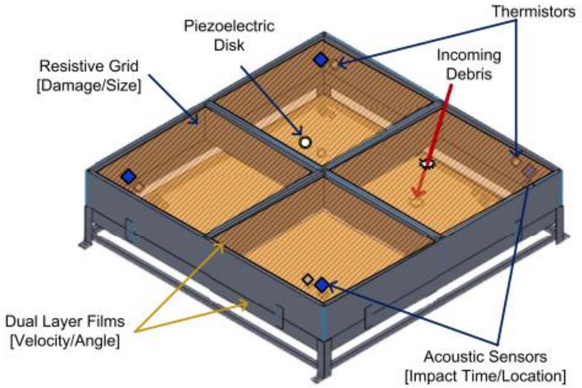
Observable period for each latitude, scale in hours

  - Tracking without being able to see the object is possible but it requires highly accurate TLE info that is recent enough to not be subject to significant perturbations
  - Alternatively, combining radar and laser measurements or using advanced CCD cameras could enable blind tracking

[3] U. Hugentolber and C. Bamann, "Accurate Orbit Determination of Space Debris with Laser Tracking," 7th European Conference on Space Debris, Darmstadt, Germany, 18–21 April 2017

In-situ Observation

- Collisions with orbital debris are inevitable with enough time, so satellites can implement impact sensors to measure the flux of smaller pieces of debris than ground stations are capable of detecting
- Radar observations are limited to around 2 mm debris size, but observations from debris impact sensors can determine the flux of sub-millimeter and even 100 μm objects
- Complete orbit determination is impossible with a single observation but at least the direction of the angular momentum of the debris can be determined

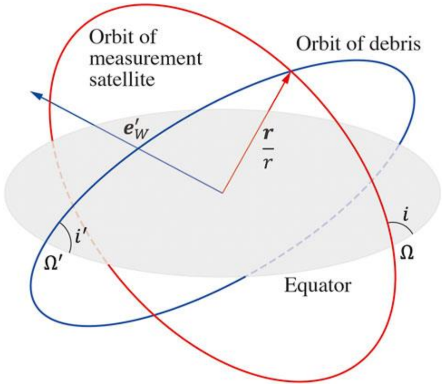


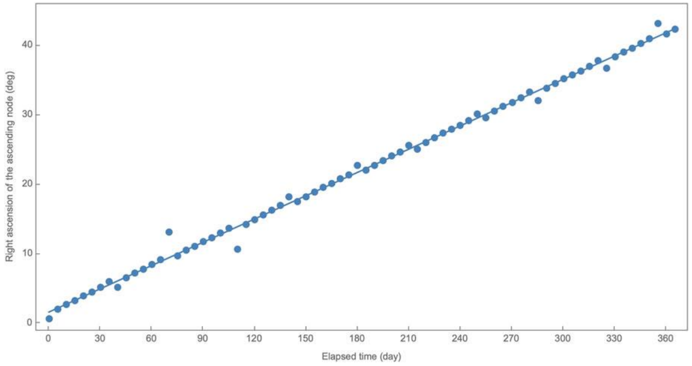
Example debris impact sensor

[4] Michael Tsao, H. Ngo, R. Corsaro, C. Anderson, “An In Situ Measurement System for Characterizing Orbital Debris,” IEEE International Instrumentation and Measurement Technology Conference, May 2012

In-situ Observation

- Assumptions
  - The detecting satellite and the piece of debris are both in circular orbits
  - The detecting satellite and the piece of debris share the same position vector at the time of impact
  - J_2 is the most significant perturbation, so the inclination and rate of change of the RAAN are approximated as constant
  - Orbital parameters are propagated from the time of breakup to the time of impact, while accounting for major perturbations

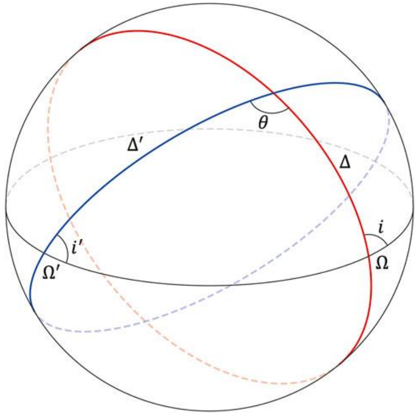




Example RAAN over time for a specific piece of orbital debris

[5] Toshiya Hanada, K. Fujita, Y. Yoshimura, "Estimation of Orbital Parameters of Broken-Up Objects from In-Situ Debris Measurements," Frontiers in Space Technologies Vol. 3, 11 April 2022

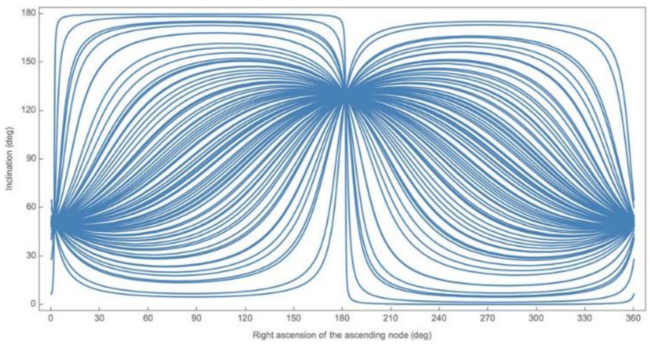
In-situ Observation



- The inclination and rate of change of the RAAN are then constrained with the following equations:

$$\left\{x(t)\sin\left[\Omega_0' + \dot{\Omega}'(t - t_0)\right] - y(t)\cos\left[\Omega_0' + \dot{\Omega}'(t - t_0)\right]\right\}\sin i' + z(t)\cos i' = 0$$

$$\sin\theta\frac{d\Delta}{dt} = \sin i'\cos\Delta'\left(\frac{d\Omega}{dt} - \frac{d\Omega'}{dt}\right) + \sin\Delta'\frac{di'}{dt} - \sin\Delta\cos\theta\frac{di}{dt}$$



Example RAAN vs. inclination for a specific piece of orbital debris

- This results in a set of possible relations between RAAN and inclination with two fixed points at and opposed to the point of collision

[5] Toshiya Hanada, K. Fujita, Y. Yoshimura, "Estimation of Orbital Parameters of Broken-Up Objects from In-Situ Debris Measurements," Frontiers in Space Technologies Vol. 3, 11 April 2022

In-situ Observation

- Limitations
  - The origin of the piece of debris needs to be able to be traced back to a known breakup event
    - Propagating the known pieces of debris from every recent breakup event and determining whether the momentum of a piece of debris from said event could possibly put it on an orbit that intersects the detecting satellite’s orbit at the time of a collision can provide some insight but is computationally expensive
  - Micrometeoroids may be falsely identified as pieces of orbital debris
  - Debris impact detectors have limited durability and the accuracy of measurements degrades with more impacts

[5] Toshiya Hanada, K. Fujita, Y. Yoshimura, “Estimation of Orbital Parameters of Broken-Up Objects from In-Situ Debris Measurements,” Frontiers in Space Technologies Vol. 3, 11 April 2022

References

[1] Tommei G., Milani A., Rossi A., “Orbit Determination of Space Debris: Admissible Regions,” Celestial Mechanics and Dynamical Astronomy, 1 April 2007

[http://eprints.adm.unipi.it/714/1/deb_admreg_eprint.pdf]

[2] J.M Maruskin, D.J. Scheeres, K.T. Alfriend, “Orbit Determination of Space Debris: Correlation of Optical Observations,” Proceedings of the Advanced Maui Optical and Space Surveillance Technologies Conference, Wailea, Maui, Hawaii, 19 September 2008

[https://amostech.com/TechnicalPapers/2008/Astrodynamics/MaruskinScheeres.pdf]

[3] U. Hugentolber and C. Bamann, “Accurate Orbit Determination of Space Debris with Laser Tracking,” 7th European Conference on Space Debris, Darmstadt, Germany, 18–21 April 2017

[https://conference.sdo.esoc.esa.int/proceedings/sdc7/paper/407/SDC7-paper407.pdf]

[4] Michael Tsao, H. Ngo, R. Corsaro, C. Anderson, “An In Situ Measurement System for Characterizing Orbital Debris,” IEEE International Instrumentation and Measurement Technology Conference, May 2012

[https://arxiv.org/ftp/arxiv/papers/1612/1612.03971.pdf]

[5] Toshiya Hanada, K. Fujita, Y. Yoshimura, “Estimation of Orbital Parameters of Broken-Up Objects from In-Situ Debris Measurements,” Frontiers in Space Technologies Vol. 3, 11 April 2022

[https://www.frontiersin.org/articles/10.3389/frspt.2022.867236/full]