Investigation into the rotational dynamics of the defunct satellite TOPEX/Poseidon

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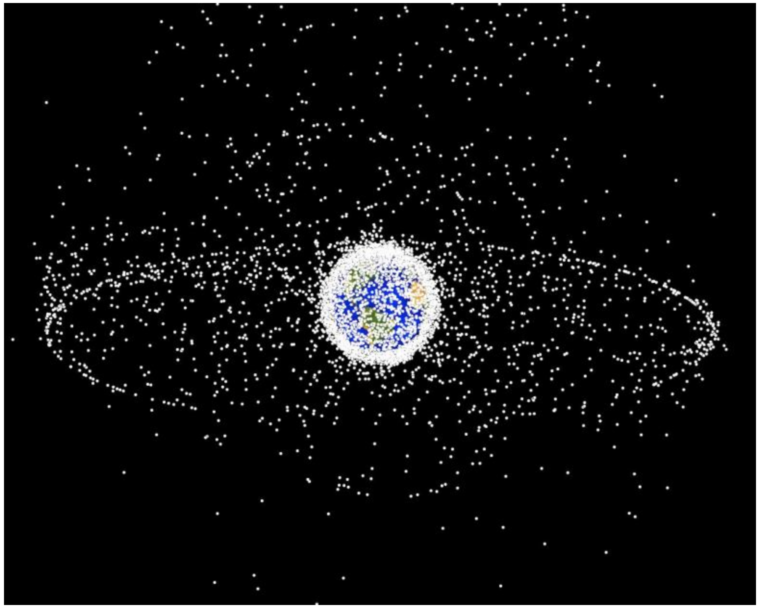
Outline

1) SPACE DEBRIS ATTITUDE DYNAMICS

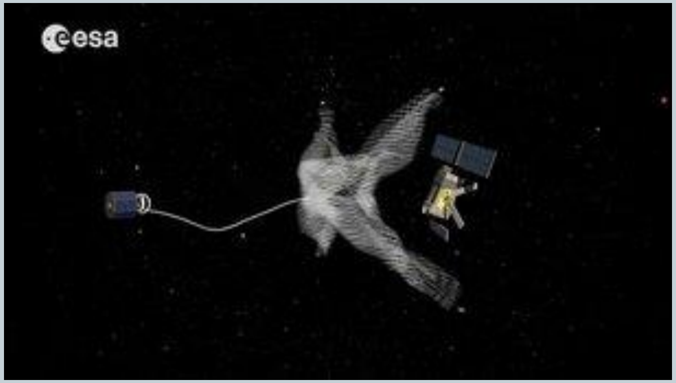
2) DEBRIS SPIN/ORBIT SIMULATION ENVIRONMENT (D-SPOSE)

3) TOPEX/POSEIDON ATTITUDE ANALYSIS



Active Debris Removal (ADR)

- Attempts to de-orbit critical targets being developed.
  - Launch removal spacecraft
  - Rendez-vous with target debris
  - Analyse target motion
  - Stabilize and capture
  - De-orbit and burn

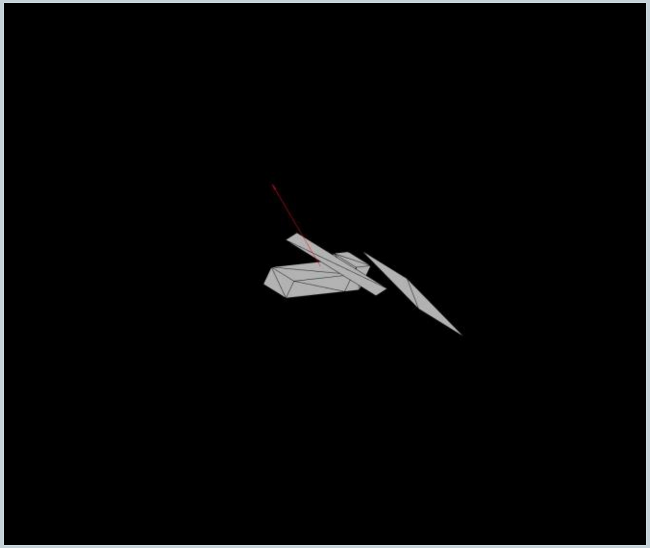


- Capture technologies include:
  - Robotic arm
  - Net
  - Harpoon

Rotational Motion of Space Debris

- Need to accurately know rotational motion of target debris for Active Debris Removal before launch of removal spacecraft

- Environmental torques:
  - Gravity gradient
  - Magnetic torques
  - Aerodynamic torque
  - Radiation torques
  - Particle bombardment



- Accurate attitude estimates also improve orbit predictions for conjunction analyses

Debris Spin/Orbit Simulation Environment (D-SPOSE)

- Can we build a flexible and comprehensive tool to analyze and predict the rotational motion of large space debris?

- Tool will be publicly available by the end of 2018 / early 2019

Model Equations and Perturbations

Orbit:

1) $$\ddot{\mathbf{r}}(t) = -\frac{\mu}{r(t)^3}\mathbf{r}(t) + \sum_j \mathbf{a}_j(t,\mathbf{r}(t))$$

Attitude:

2) $$\mathbf{I}\dot{\omega}(t) + \omega(t)^{\times}\mathbf{I}\omega(t) = \sum_j \boldsymbol{\tau}_j(t,\mathbf{r}(t))$$

3) $$\dot{\mathbf{q}}(t) = \frac{1}{2}\Omega(\omega)\mathbf{q}(t)$$

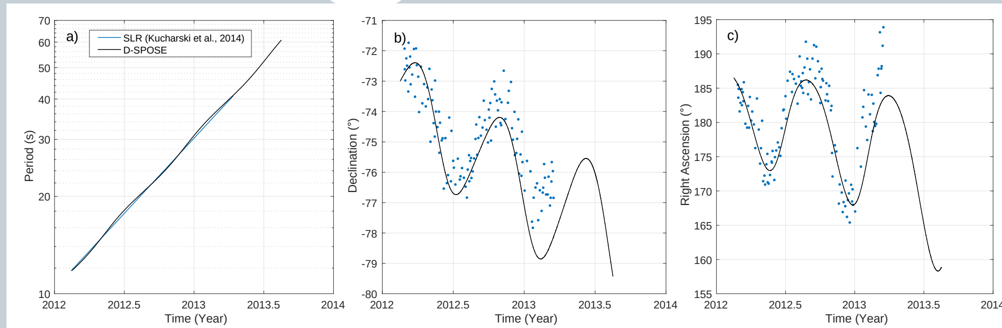
Perturbation	Environmental Model
Gravitational perturbations and gravity gradient torque	EGM2008
Third-body perturbations	Ephemeris
Aerodynamic drag and torque	DTM-2013; NRLMSISE-00; JB-2008; HWM14
Eddy-current torque	IGRF-12; WMM
Solar radiation pressure and torque	Montenbruck and Gill
Albedo and IR acceleration and torque	Stephens; CERES; ECMWF
Internal energy dissipation	Kane Damper
Hypervelocity impacts	Sagnières and Sharf; MASTER-2009

Model Input

- Spacecraft Geometry (list of triangular surfaces)
- Time Parameters (propagation length and time step)
- Spacecraft Parameters (inertia and magnetic tensors, surface optical coefficients)
- Initial Conditions (initial orbit, attitude and angular velocity)
- Model Parameters (selected perturbations, chosen environmental models)

Validation from SLR Observations and Light Curves

LARES



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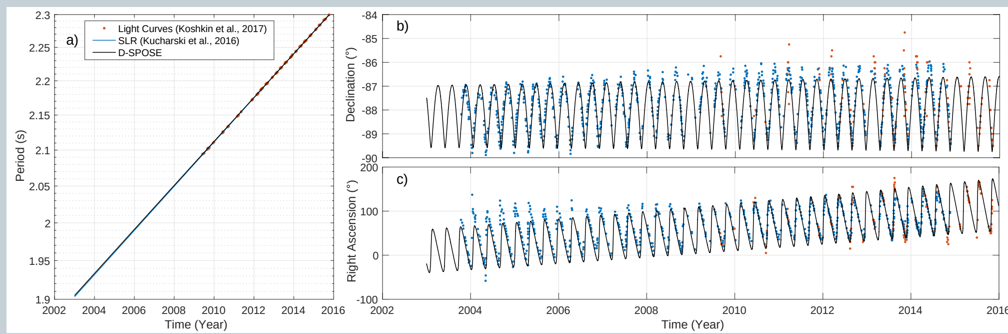
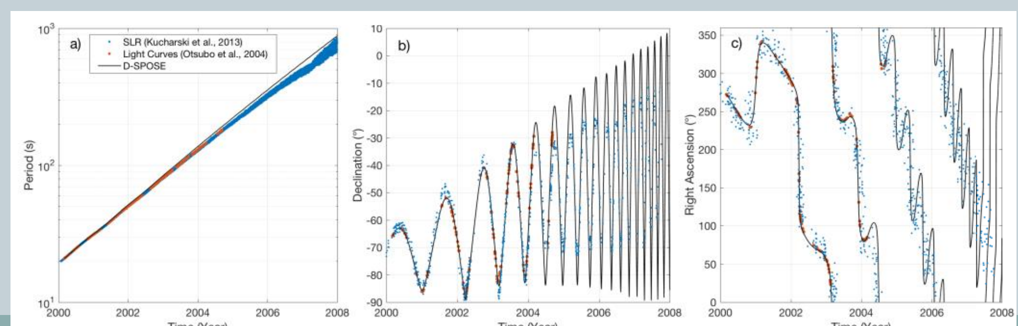


LAGEOS-2

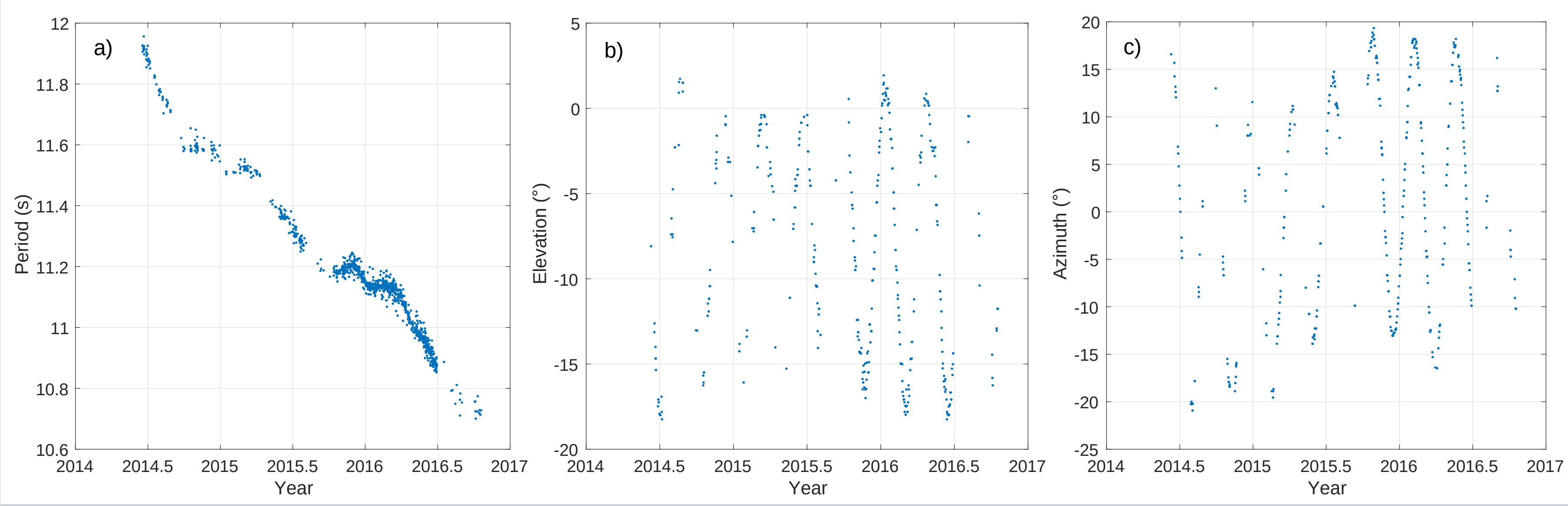


TOPEX/Poseidon Attitude Analysis

- Application of D-SPOSE to TOPEX/Poseidon in order to shed light on spacecraft rotational dynamics
- Possibility to investigate its unknown spacecraft parameters (moments of inertia, magnetic properties, etc…)

SLR Observations

- High repetition rate SLR observations show increase in spin period due to solar radiation pressure (Kucharski et al., 2017)
- Oscillations in spin axis elevation and azimuth are present
- Can D-SPOSE replicate these observations?
- Most important parameters, moments of inertia, are unknown



Moments of Inertia from Observations

- Gravity-gradient torque forces closed loop motion in reference frame precessing with the orbit (Holland and Sperling, 1969).

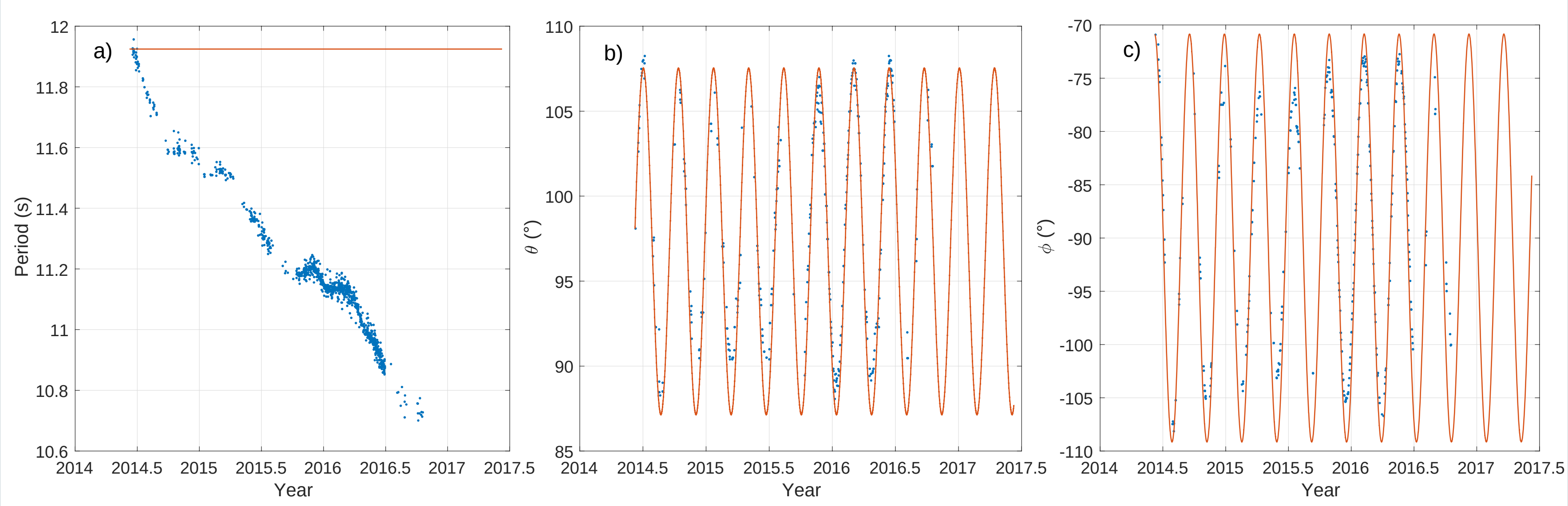
- From observation of spin axis (z-axis), we can obtain relationship between moments of inertia as a function of orbital parameters and spin axis orientation:

$$\frac{d\mathbf{L}}{dt} = \frac{3m}{4r^3}\frac{H}{L^2}L_z\begin{bmatrix} -L_y \\ L_x \\ 0 \end{bmatrix} - \omega \times \mathbf{L} \Rightarrow \frac{I_x + I_y - 2I_z}{I_z} = \frac{4r^3\omega}{3\mu}(-\dot{\Omega}\sin i \csc\theta \sin\phi + \dot{\Omega}\cos i \sec\theta)$$

  - From SLR observations, it was found that: $I_x + I_y = 2.83 I_z$
  - Spacecraft in a stable minor-axis spin?

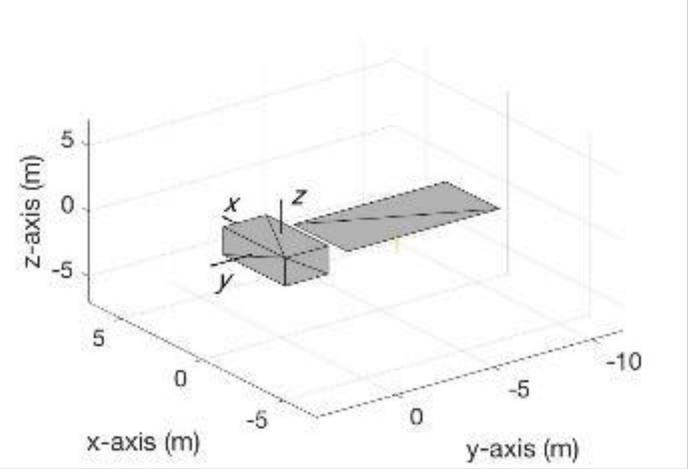
Gravity-Gradient Torque Only

- Using $I_x + I_y = 2.83 I_z$
- Results independent of I_x, I_y, and I_z as long as relationship holds



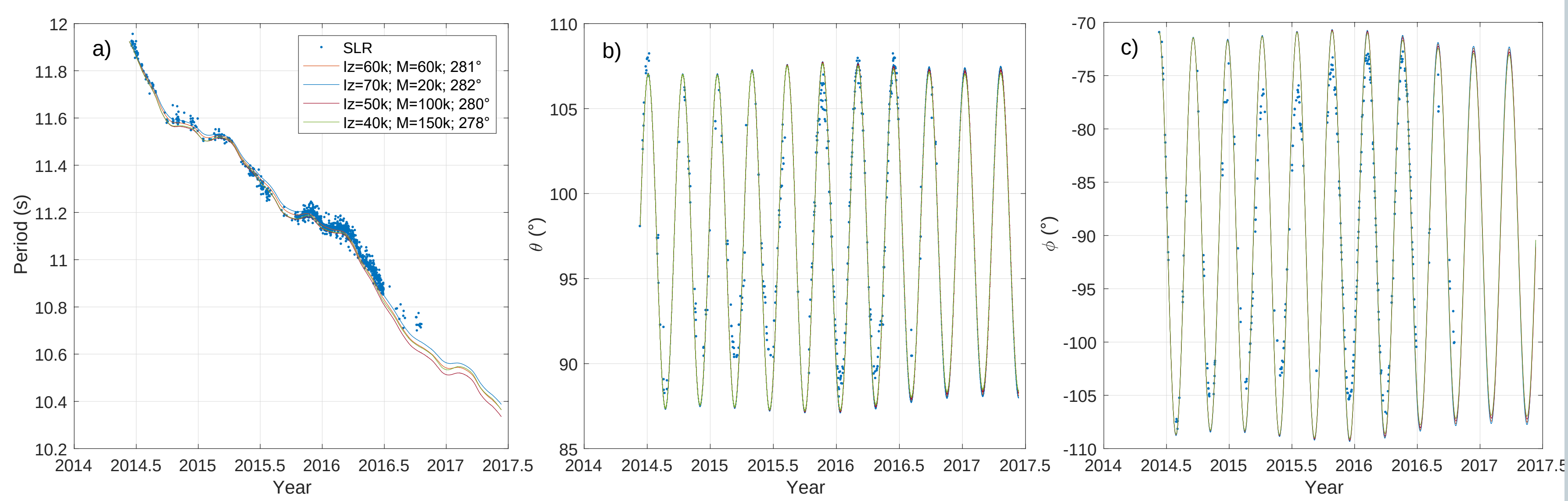
Propagator Input

- Other unknowns include the magnetic properties (eddy-current torque) and the spacecraft geometry (orientation of solar panel plays large role in effect of SRP)
- Spacecraft spinning counterclockwise about z-axis
- I_z was varied from 70k to 40k kg m^2
- Axisymmetry assumed (I_x=I_y); further tested afterwards
- Magnetic tensor and solar panel orientation (rotating about y-axis) were varied to fit observations



Simulation Results

- Spin evolution well captured by various simulations
- Amplitude of oscillations were found to vary due to radiation pressure
- Approx. linear relationship between I_z and M: $I_z = 75000 - 0.25M$
- Solar panel orientation close to Kucharksi et al. (2017) value
- Even with Kane damper, spacecraft in stable minor-axis spin (depending on damper characteristic: when dissipation is strongest, spacecraft eventually evolves into major-axis spin after a few years)



Conclusions

- From observations, a relationship between the moments of inertia was determined: $I_x + I_y = 2.83 I_z$
- A linear relationship exists between I_z and M: $I_z = 75000 - 0.25M$; relationship between I_x and I_y is unknown.
- Simulations show TOPEX/Poseidon is spinning in a stable manner about minor axis
  - Currently doing energy checks to validate this
  - Looking at effect of Kane damper characteristics on spin stability
- A maximum value of I_z is 75,000 kg m^2; obtaining a better estimate of the magnetic tensor will provide additional info on the moments of inertia, which, in turn, will provide more accurate estimate of solar panel orientation
- D-SPOSE will be publicly available by end of 2018 / early 2019 on the McGill Aerospace Mechatronics Laboratory GitHub: <https://github.com/McGill-AML>