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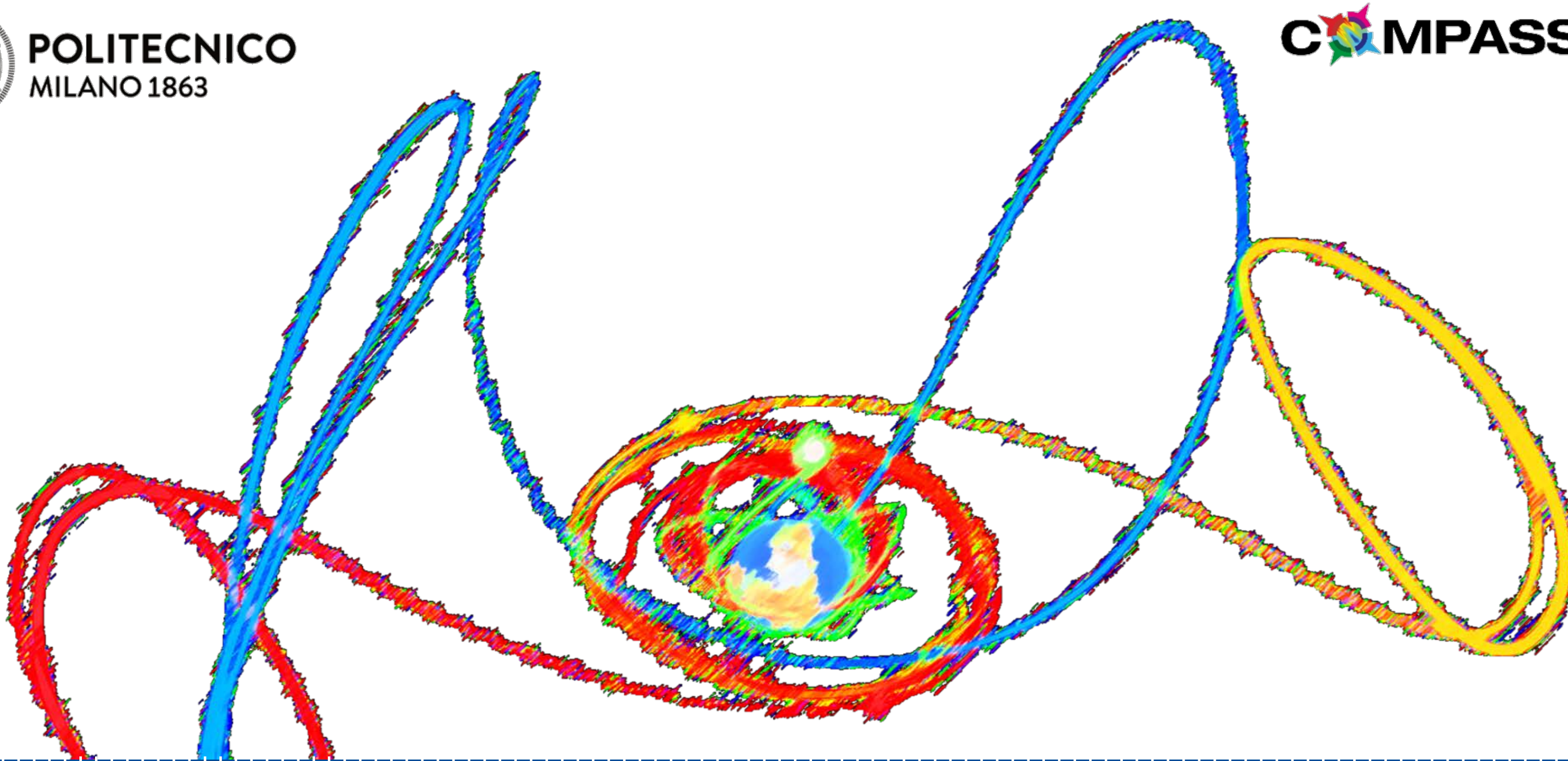


Numerical analysis of the effects of drag and its interaction with solar radiation pressure and Earth's oblateness

Mayeul Langlois d'Estaintot, Camilla Colombo - Politecnico di Milano

KePASSA – 2017 ESA/ESTEC

INTRODUCTION

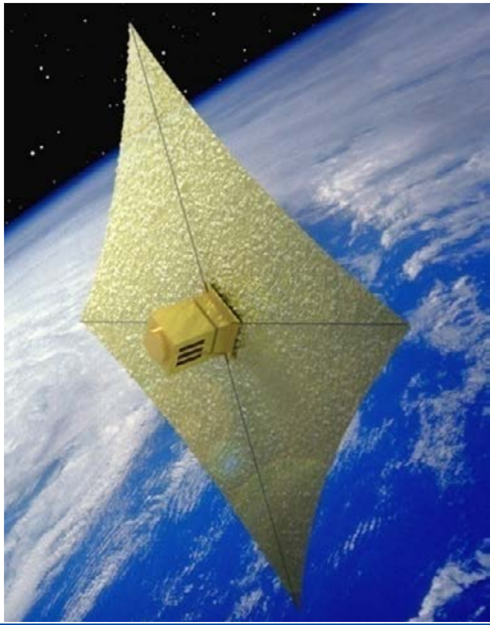
Introduction

End of life deorbiting with solar sail

- The increasing number of debris around the Earth has made **End-of-Life** of any spacecraft a major issue for every actor in the space field.

- **Solar sail** has been demonstrated as a viable option for passive disposal through re-entry.

- The area-to-mass-ratio of the satellite is augmented
  - Passive eccentricity increase until perigee enters in the drag region (from 650-800 km down depending on atmosphere model)
  - Drag affects the orbit too so the orbit energy is progressively decreased until re-entry.



Introduction

End of life deorbiting with solar sail

- Past work have computed the sail requirement for deorbiting considering only solar radiation pressure and Earth's oblateness
- How drag affects the deorbiting?

- In this work:
    1. Study and review of atmospheric models and their validation for evaluating the effects of atmospheric drag.
    2. Numerical analysis of the effect of drag + Solar Radiation Pressure (SRP) + Earth oblateness.

➢ Lücking & al. 2012, and 2013

REVIEW OF ATMOSPHERIC MODELS

Review of atmospheric models

State of the art

- The main models in use today can be divided into two families:
  - Empirical models
  - Exponential models

- Some examples are
  - US Standard Atmosphere (USSA76),
  - Variation of the Jacchia-Roberts 1977 (J77)
  - Mass Spectrometer Incoherent Scatter (MSIS)
  - The Drag Temperature Model (DTM)

Review of atmospheric models

Solar activity

- The solar activity is a major variable during the evaluation of the atmospheric density with an empirical model.

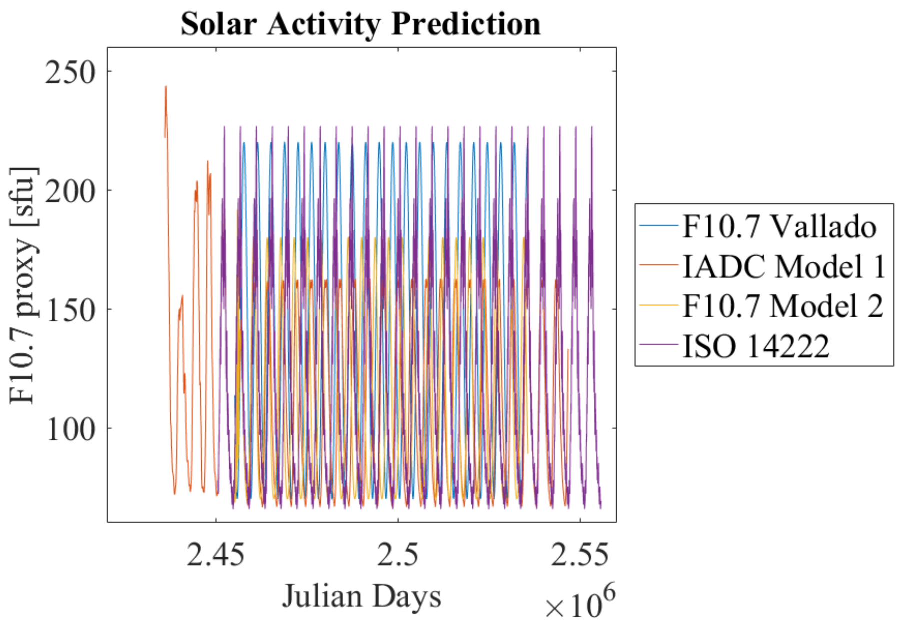
- The solar activity is approximated with several proxies, the most common is the $F_{10.7}$. It represents in sfu the activity of the sun.

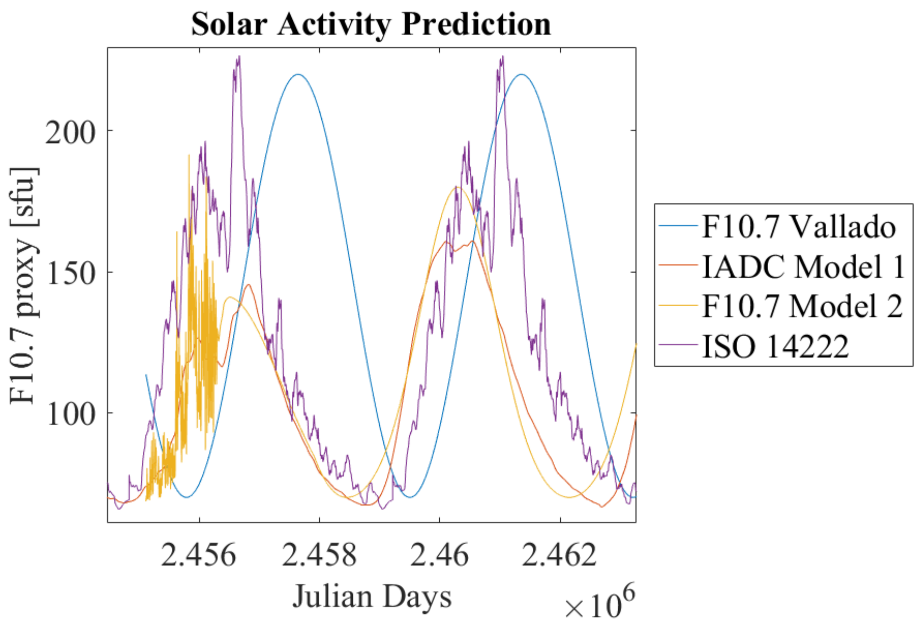
- Each proxy is usually used in two forms:
  - One day value
  - One 81-day running average centred to the atmospheric density evaluation date (commonly called “proxy-name bar” or “proxy-name 81”)

Review of atmospheric models

Solar activity

The solar activity is **not easily predictable**, different prediction models exist.





- Fundamentals of Astrodynamics, Vallado 4th Ed.
- NOAA data from ftp.ngdc.noaa server

Review of atmospheric models

Solar activity

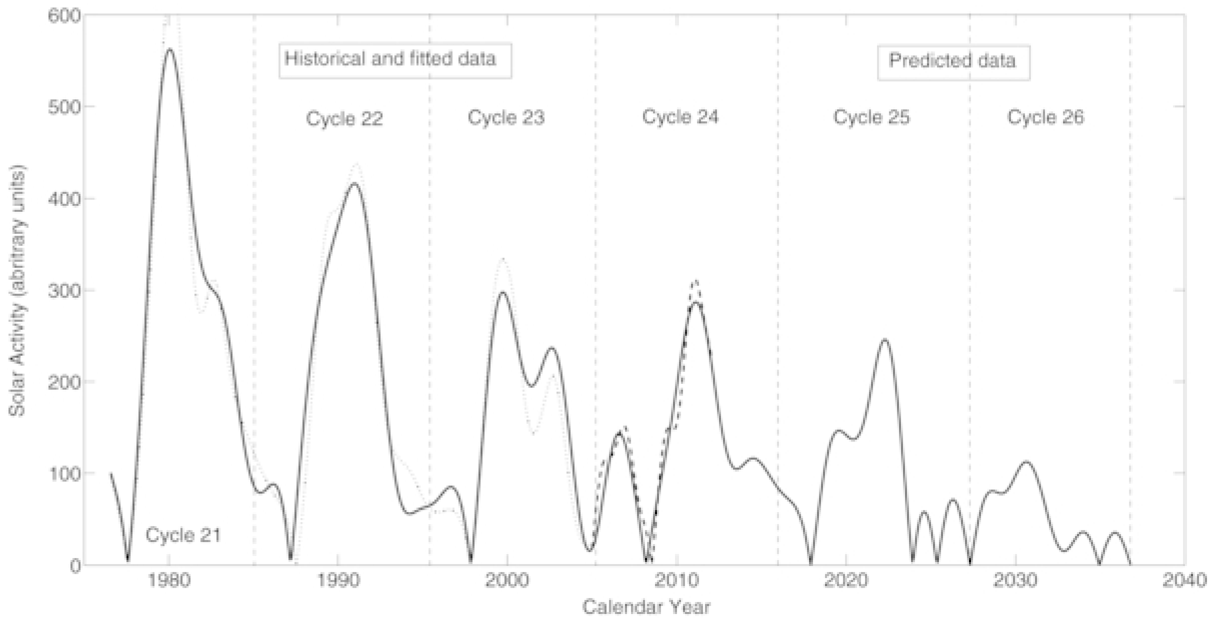


Figure 4 from Prediction of Solar Activity from Solar Background Magnetic Field Variations in Cycles 21-23
Simon J. Shepherd et al. 2014 ApJ 795 46 doi:10.1088/0004-637X/795/1/46

Low level of solar activity dictated by the observation of the last years lead us to assume that in the next decades the solar activity will be significantly lower than the average of the past two cycles.

- Anselmo L., private communication, 2017

Review of atmospheric models

Selection of an atmospheric model

- Models reviewed:
  - Jacchia 77
  - Jacchia-Bowmann (JB) 2008
  - Drag Temperature Model (DTM) 2013
  - Exponential Models
- Settings:
  - Different solar activity, max, min and average, with respect to the last solar cycle and the on-going (number 23-24)
  - One particular location lat: 45°N, lon: 0°
    (same as the one chosen for USSA76)
  - Altitude over 120-1000 km

Review of atmosphere models

Selection of an atmospheric model – Exponential models

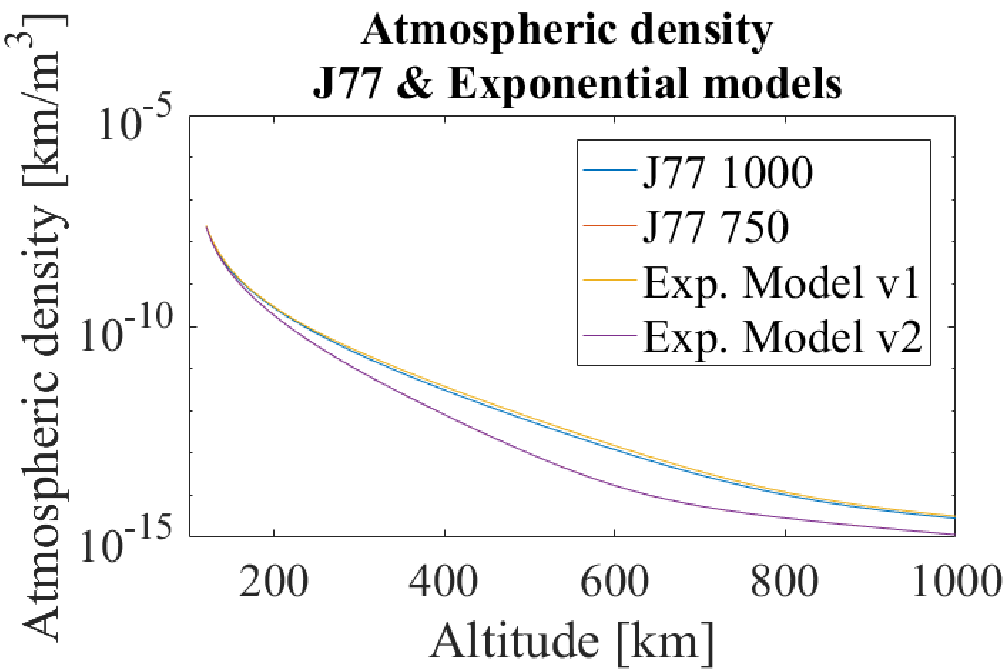
- Exponential model :
  - Input data: Altitude
  - Output: Atmospheric density

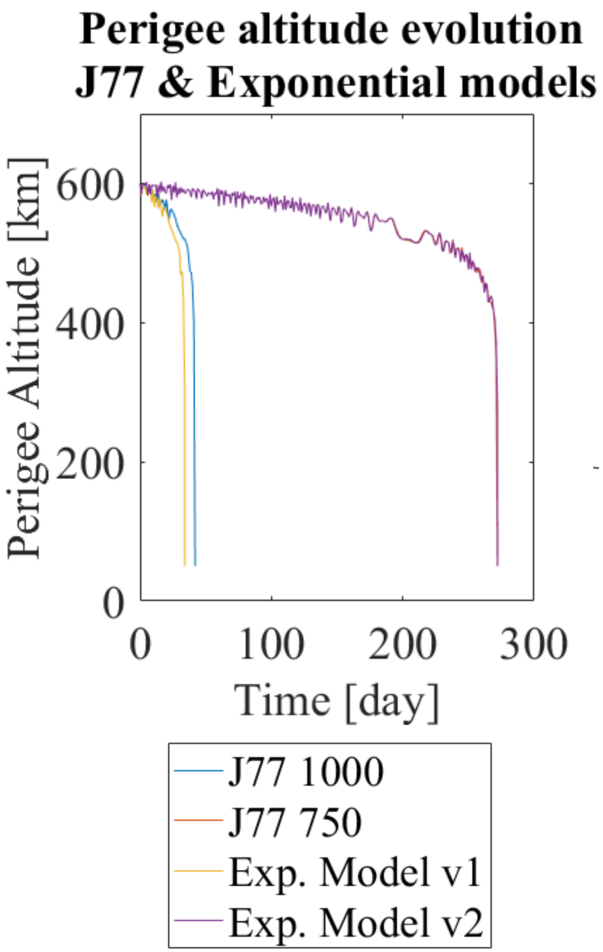
Pros	Cons
Easily implemented	Not an ISO model
Low ratio computational time over accuracy	v1: built upon the J77 with an exospheric temperature of 1000 K v2: built upon the J77 with an exospheric temperature of 750 K

- Exponential model v1: based upon Vallado's model
- Exponential model v2: see S. Frey presentation

Review of atmosphere model

Selection of an atmospheric model – Exponential models





Review of atmosphere models

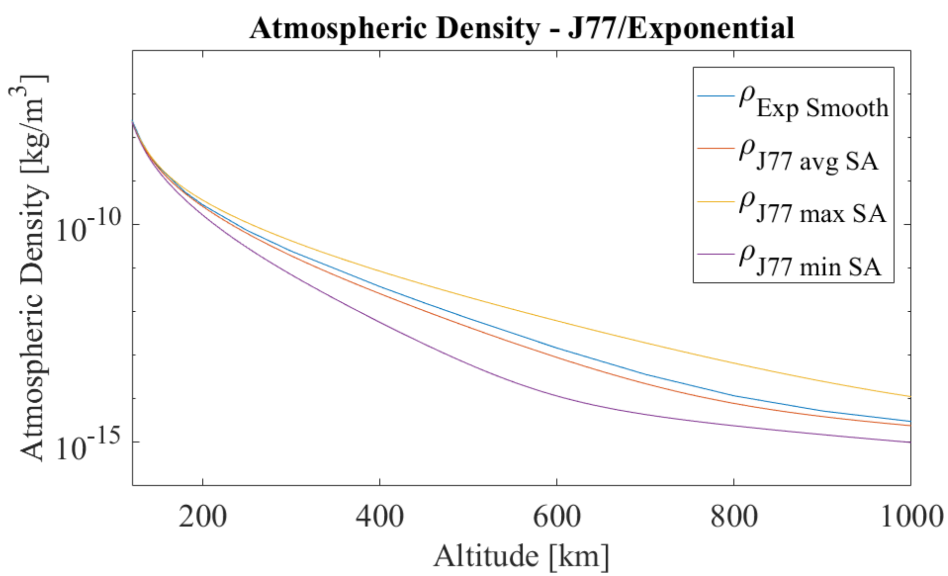
Selection of an atmospheric model – J77

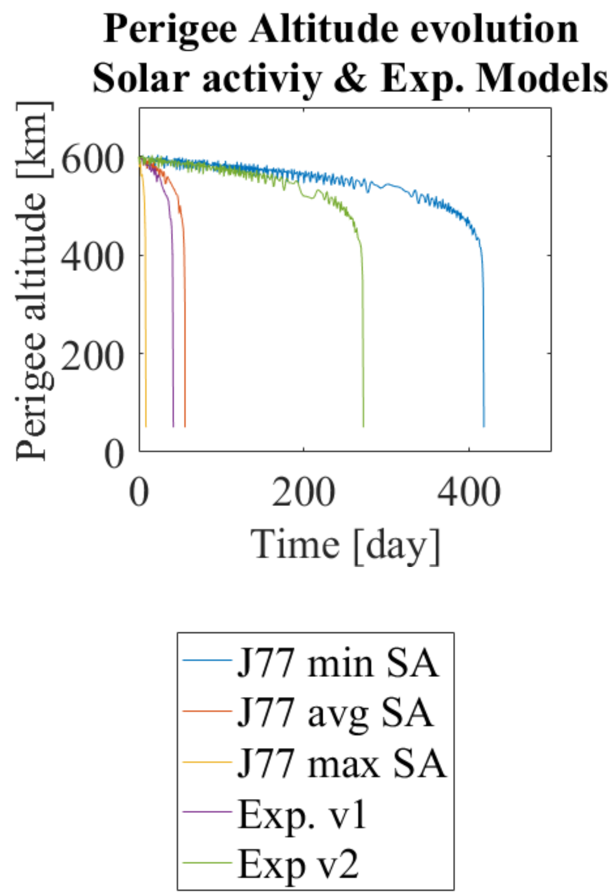
- Jacchia 77:
  - Input data:
    - Solar activity ($F_{10.7}$ & $\overline{F}_{10.7}$ proxies),
    - Altitude
  - Output:
    - Atmospheric chemical composition
    - Exospheric temperature
    - Atmospheric density

Pros	Cons
Easily implemented	Not an ISO model
Can use predicted Solar Proxy	Need of Solar Proxy
Low ratio computational time over accuracy	

Review of atmosphere models

Selection of an atmospheric model – J77





Review of atmosphere models

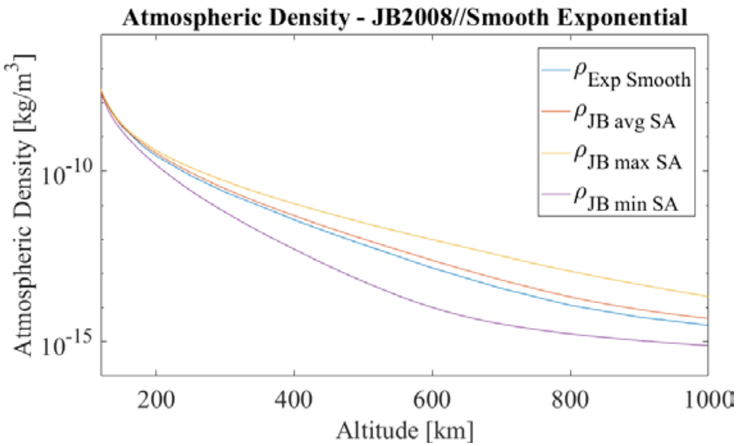
Selection of an atmospheric model – JB08 & DTM13

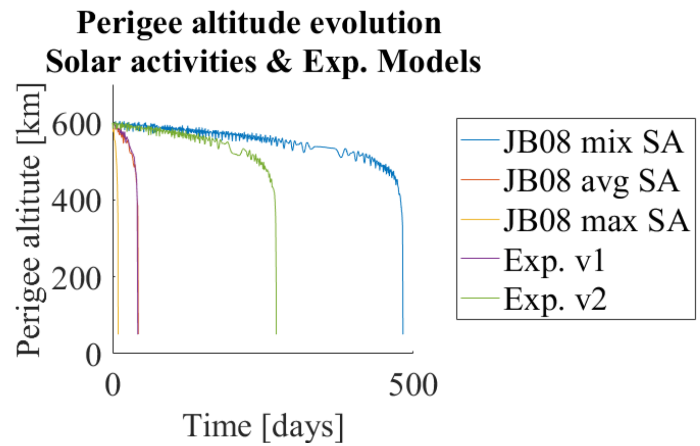
- Jacchia-Bowman 2008 & Drag Temperature Model 2013:
  - Input data:
    - Time
    - Spacecraft position
  - Output:
    - Atmospheric chemical composition (DTM13)
    - Exospheric temperature
    - Atmospheric density

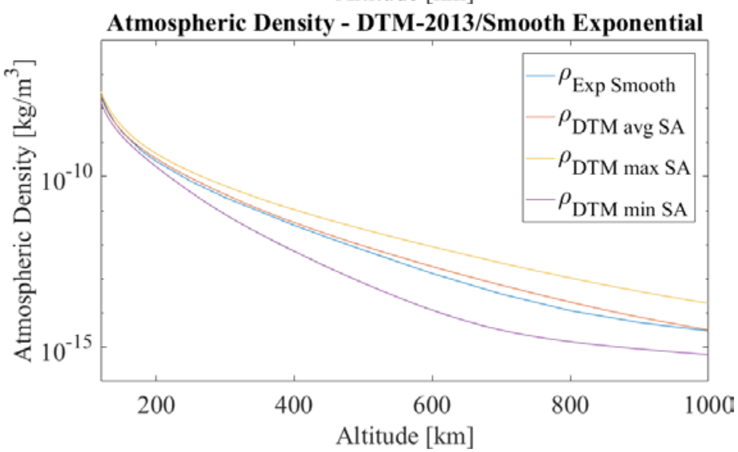
Pros	Cons
Easily implemented	High ratio computation time over accuracy
ISO Model	Need of heavy personal data tables

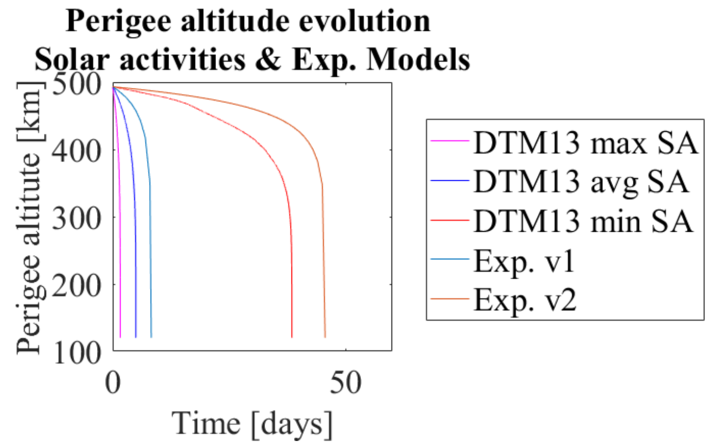
Review of atmosphere models

Selection of an atmospheric model – JB08 & DTM13









Review of atmosphere models

Atmospheric models - Uncertainties

- During the review, several uncertainties were studied.
  - Solar activity prediction
  - How do models take into account the following parameters:
    - Magnetic activity,
    - Solar weather (storm),
    - Spacecraft location.
- All those parameters are used to computed the exospheric temperature, thus the uncertainties bring by the solar activity are the more impactful compared to the other one.

Review of atmosphere models

Conclusion

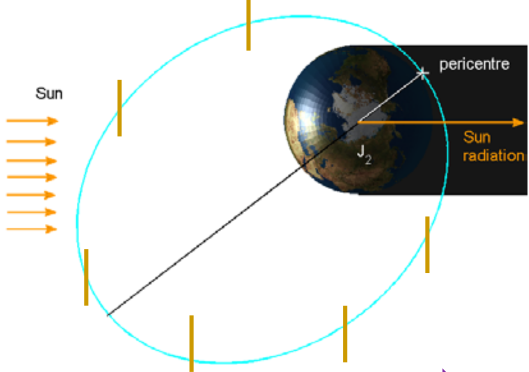
Many model exists for the atmosphere:

- As empirical models rely upon the exospheric temperature, thus the solar activity, they are not the best way to predict atmospheric density.
- Jacchia-77 model with a fixed exospheric temperature of 750 K is chosen to compute the atmospheric density for the second part of this study.
  - Exospheric temperature of 750 K creates a conservative approach with respect to the effectiveness of a de-orbiting done using area augmentation devices.
  - Exospheric temperature of 750 K also takes into account the prediction of lower activity solar cycles.

DRAG-SRP-J_2 INTERACTION

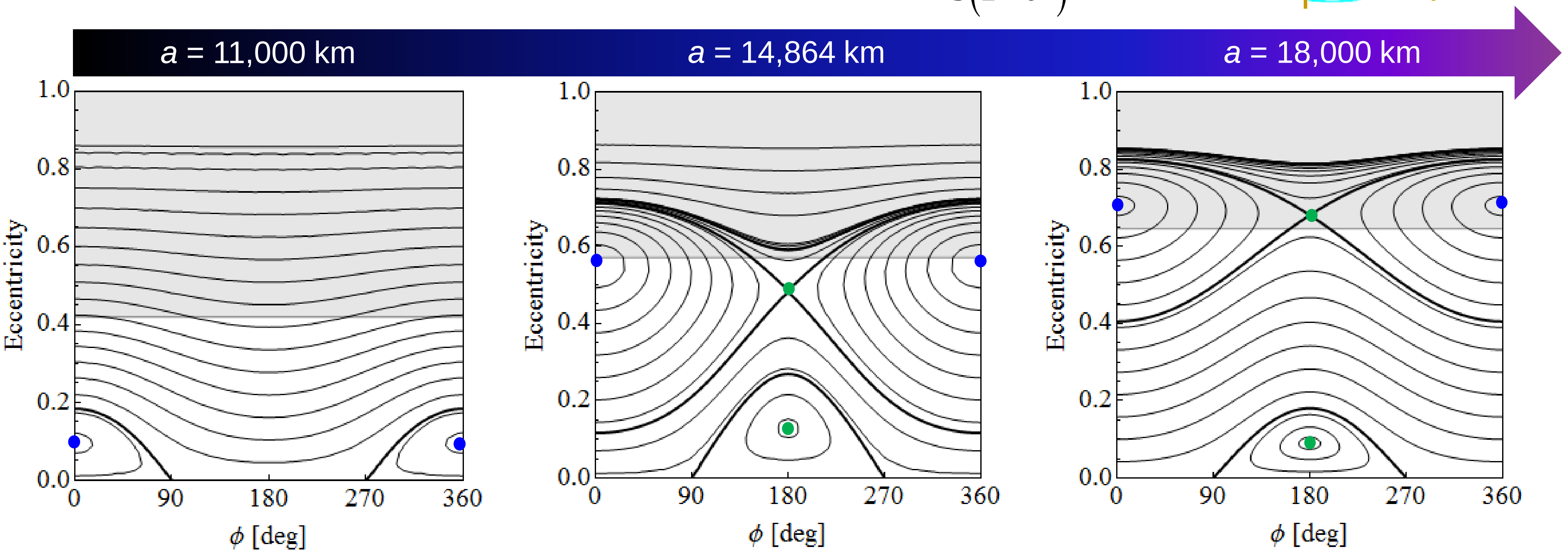
Drag-SRP-J_2 interaction

Phase space: SRP and J_2 only



Planar case

$$H = -\sqrt{1-e^2} + C\left(a, A/m\right) e\cos\phi - \frac{W\left(a, J_2\right)}{3\left(1-e^2\right)^{3/2}}$$



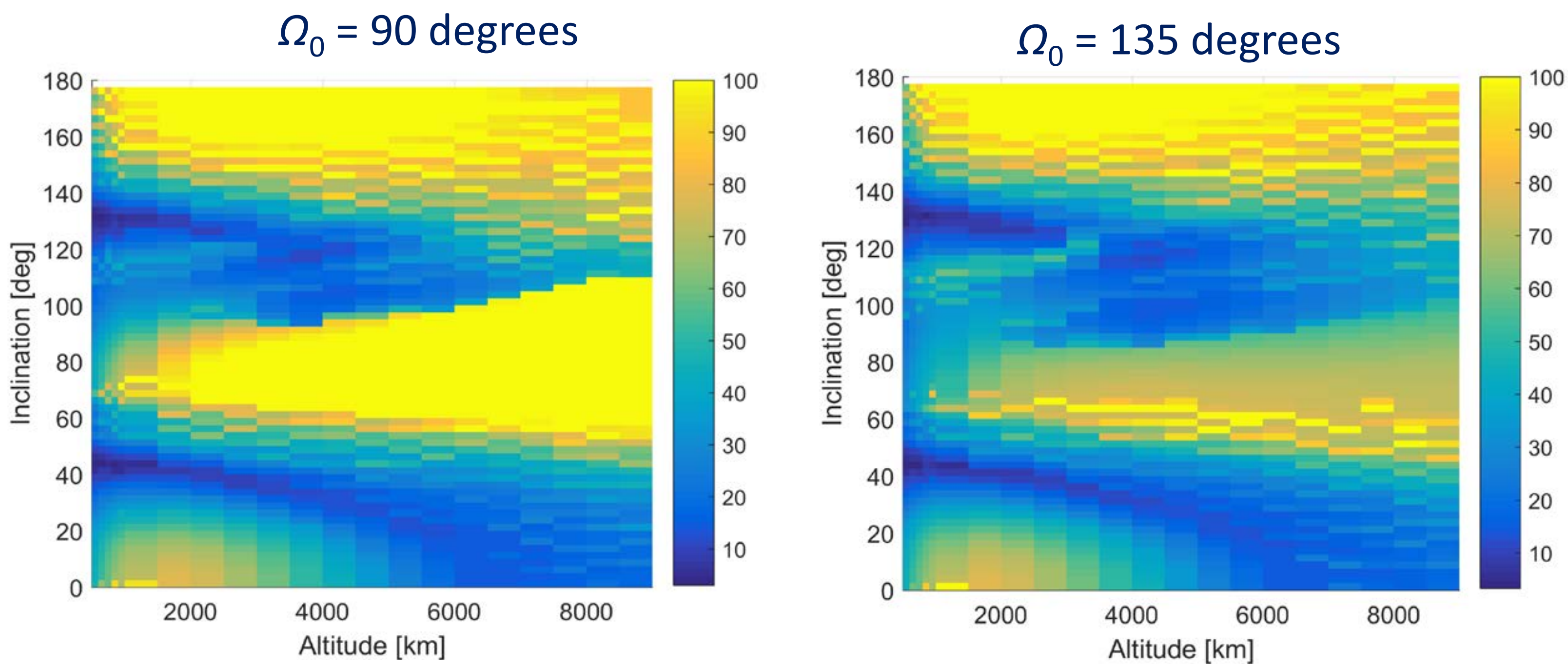
Eccentricity-perigee orientation evolution of a spacecraft of area-to-mass ratio of 5 m²/kg and c_R = 1.8 due to the effects of J_2 and solar radiation pressure.

➢ Colombo et al. 2012

Drag-SRP-J_2 interaction

Solar sail requirements (SRP+J_2)

Used as initial condition to determine the requirements for a deployable sail to deorbit in a given time.



Required effective area-to-mass ratio to deorbit in one year [m²/kg].

Drag-SRP-J_2 interaction

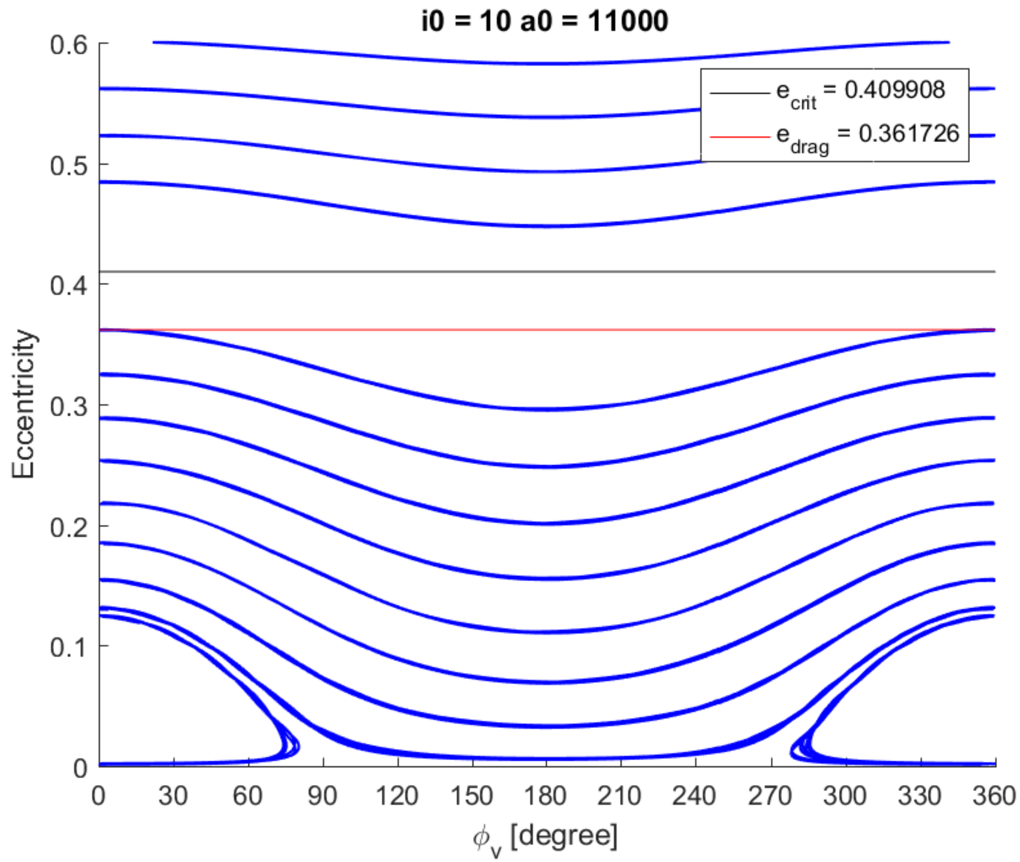
Initial conditions

Numerical study on interactions between solar radiation pressure and the Earth's oblateness and drag (exponential model based upon the J-77 with an exospheric temperature of 750 K).

Parameter	Value
AMR	[0.0012, 1, 2, 3, 5] m^2/kg
c_R	1.0
c_D	1.8
Ω_0	0.0 degree
ω_0	180.0 degrees
Inclination	[10-170] degrees
Eccentricity	[0.1-0.9]

Drag-SRP-J_2 interaction

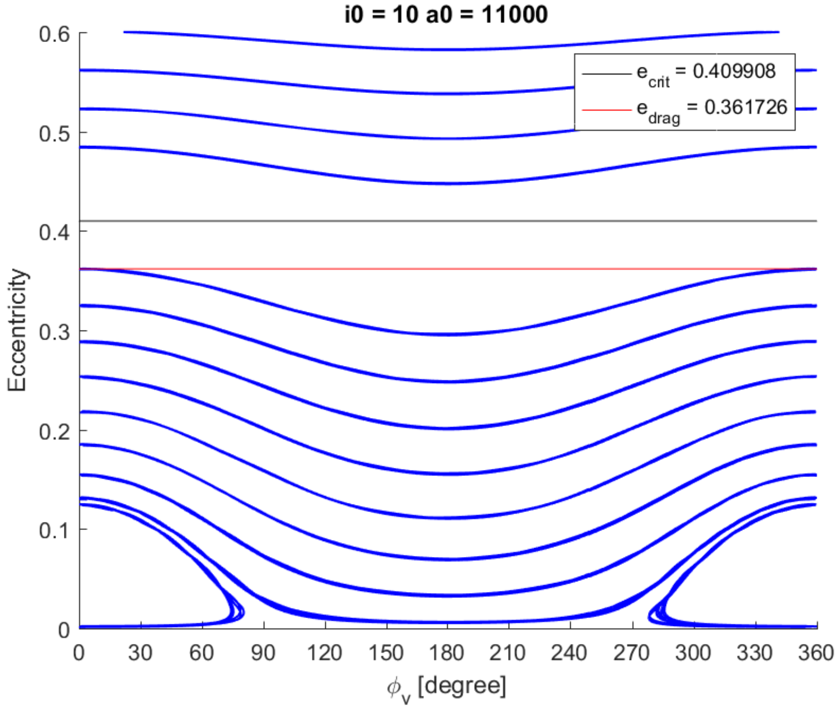
Phase space: SRP and J_2 only



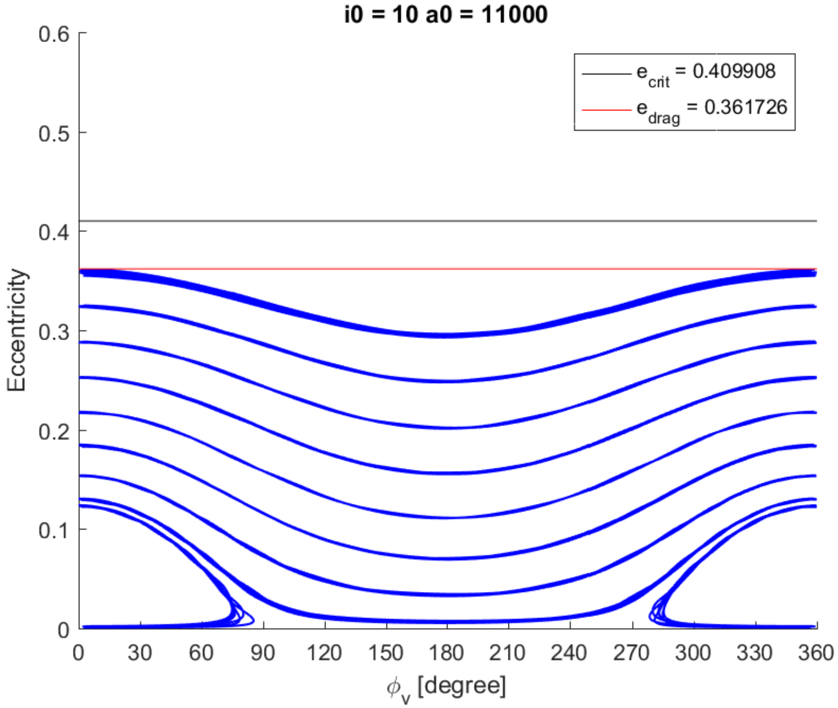
The initial inclination (i_0) is in degree, the initial semi-major axis (a_0) is in kilometres.

Drag-SRP-J_2 interaction

Phase space: SRP, J_2 and atmospheric drag



Propagation over 45 years without drag.



Propagation over 45 years with drag.

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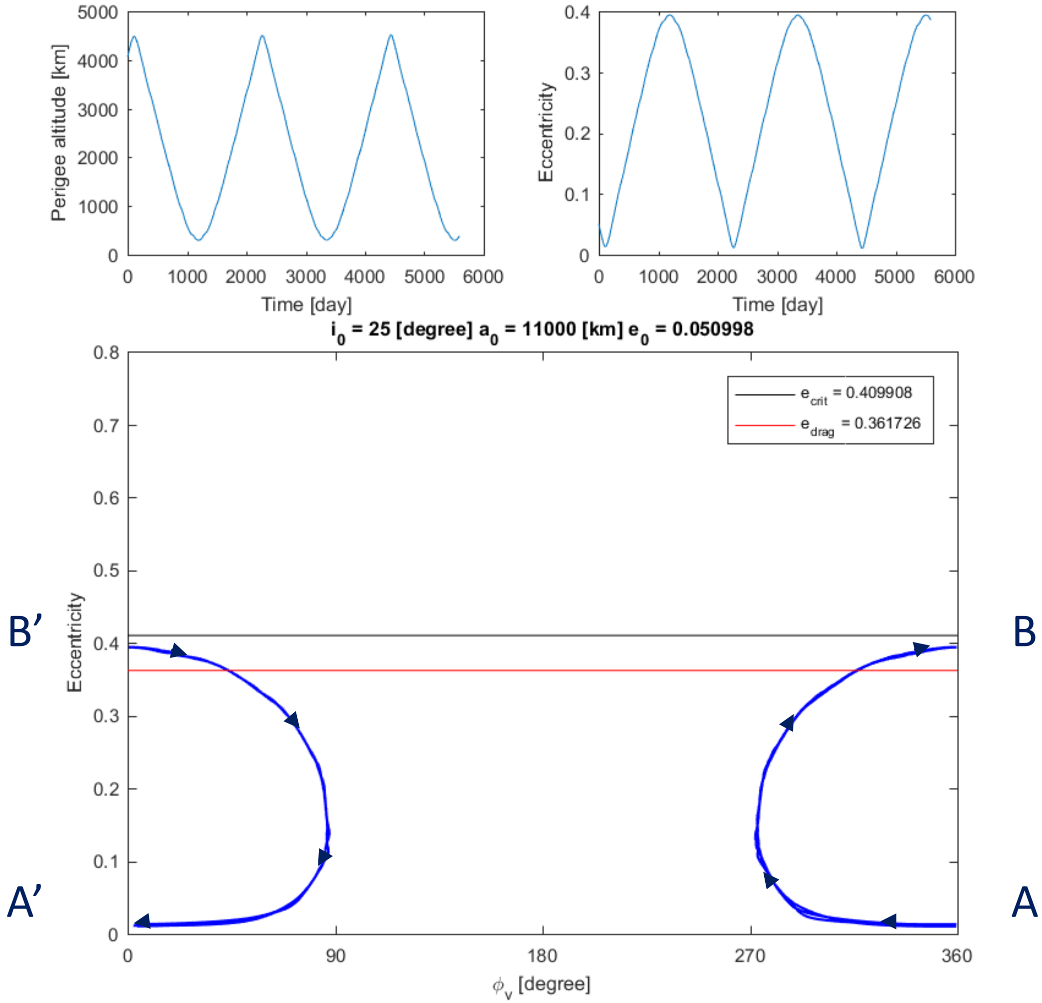
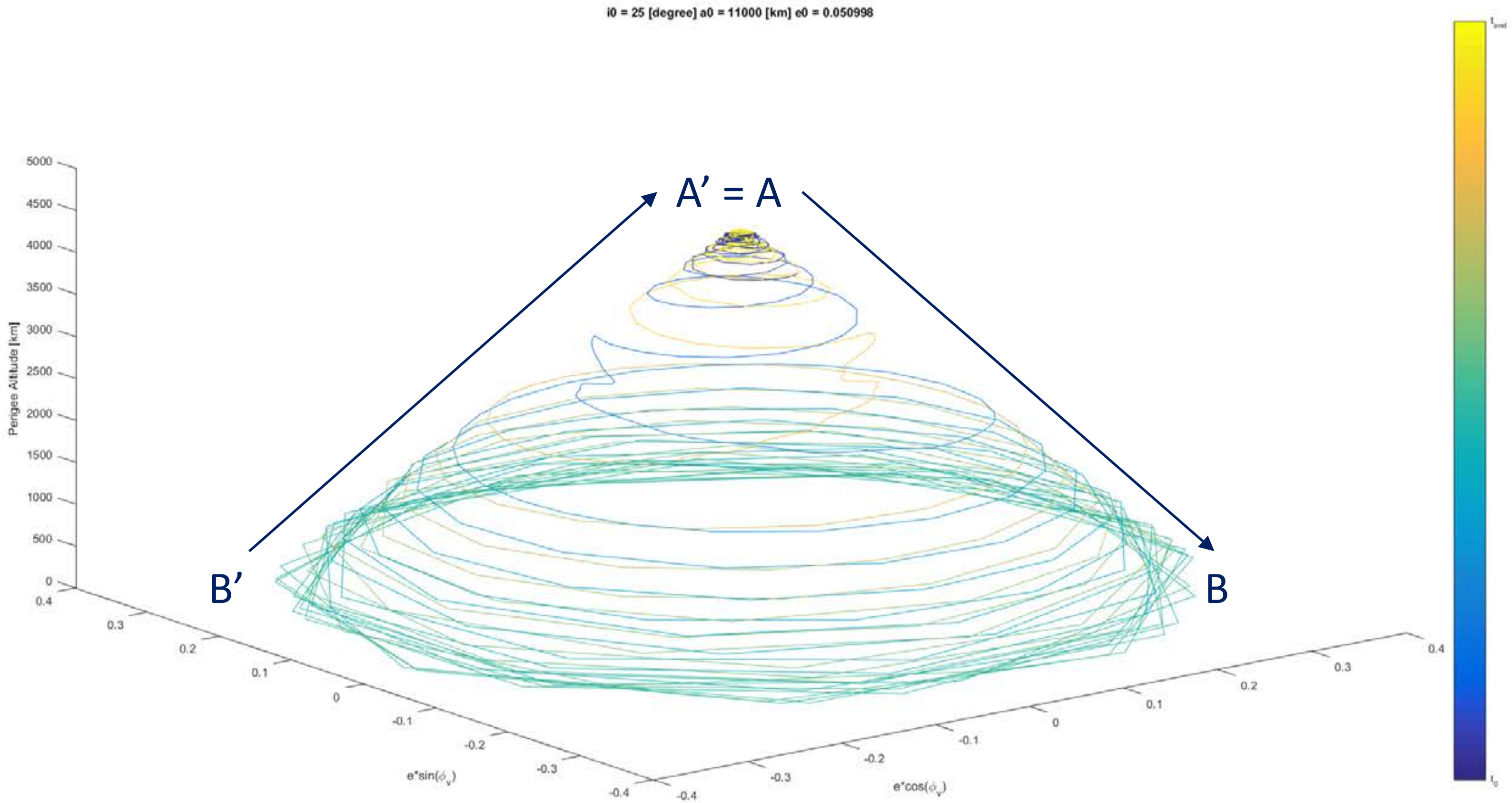
Drag-SRP-J_2 interaction

Preliminary results – SRP and J_2 only



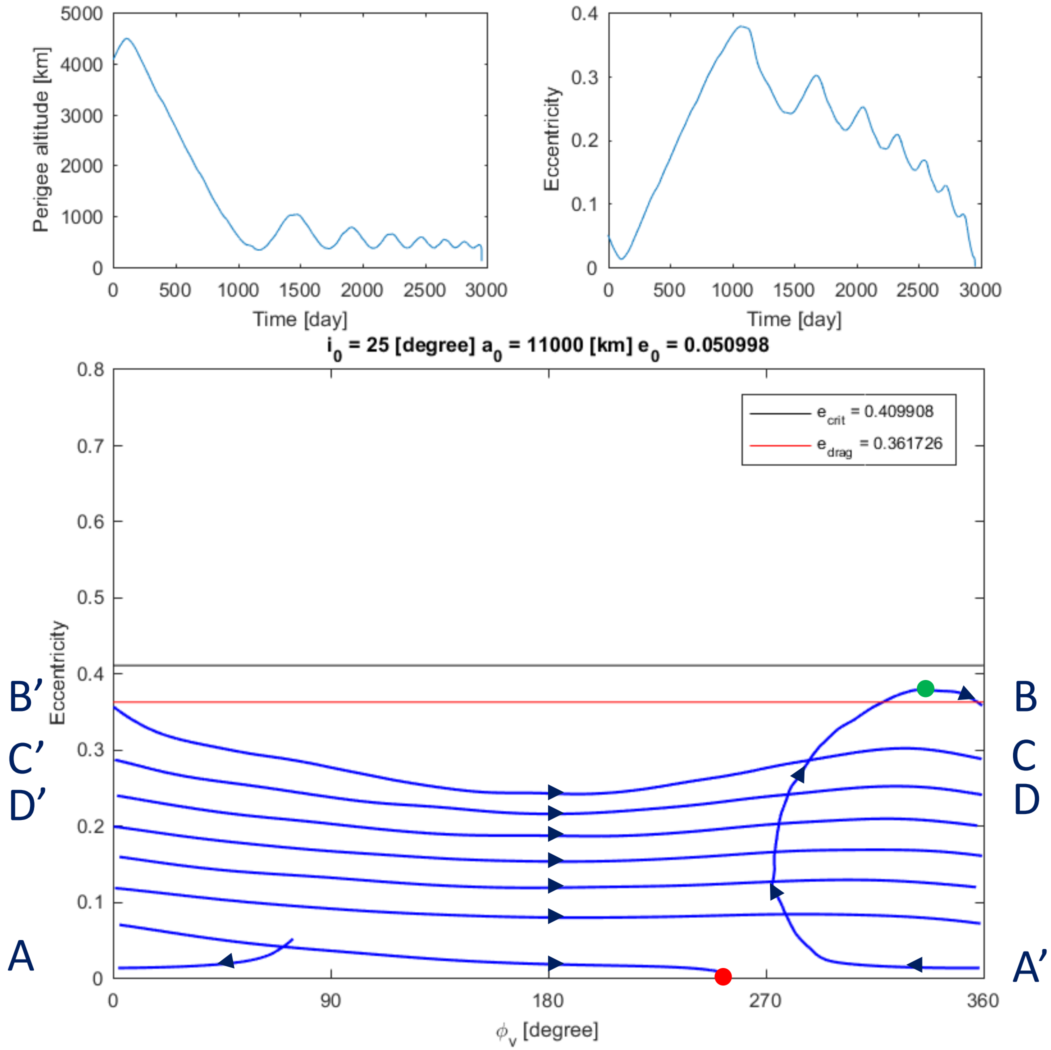
Drag-SRP-J_2 interaction

Preliminary results – SRP and J_2 only



Drag-SRP-J_2 interaction

Preliminary results – SRP, J_2 and atmospheric drag



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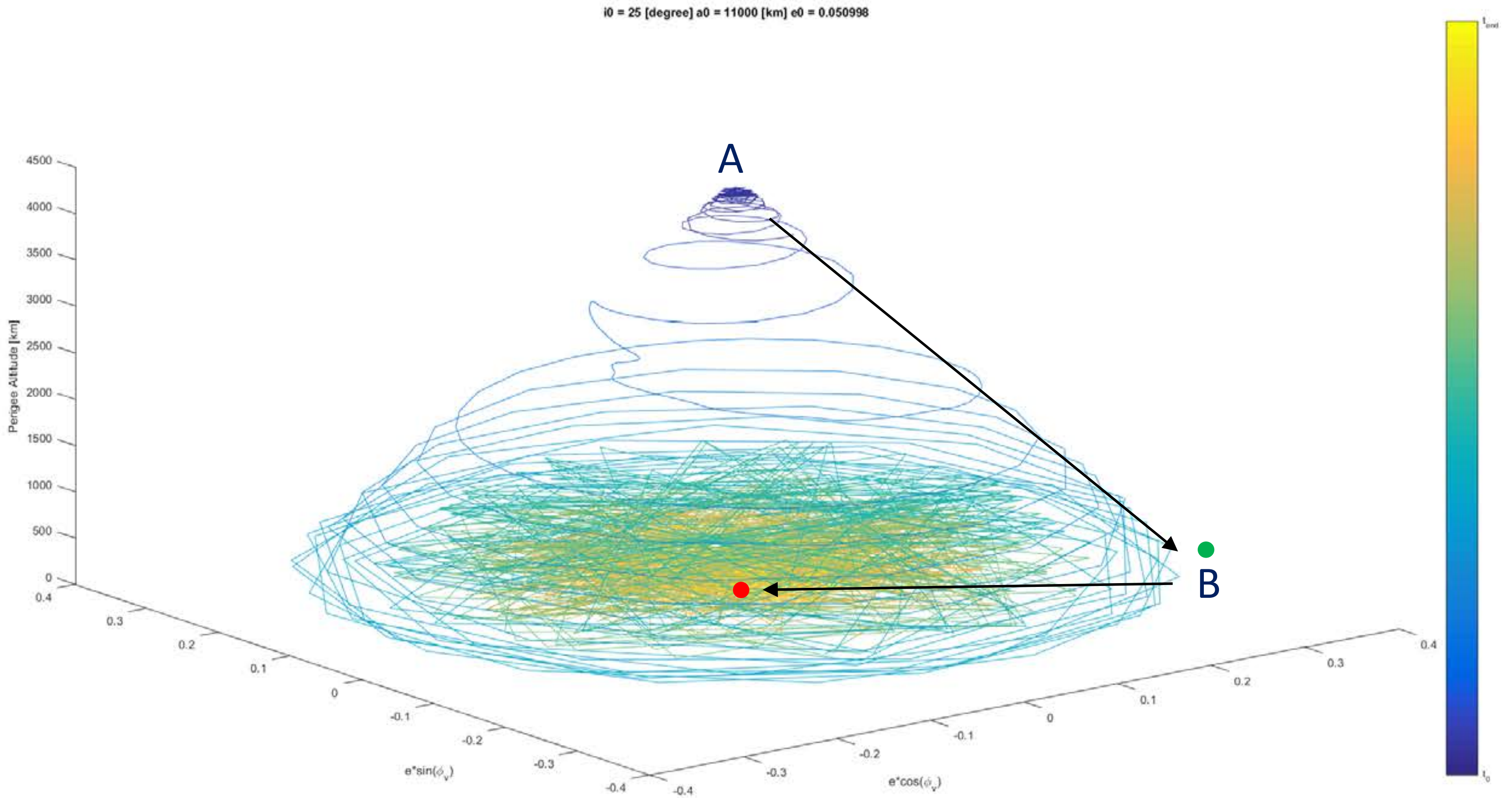

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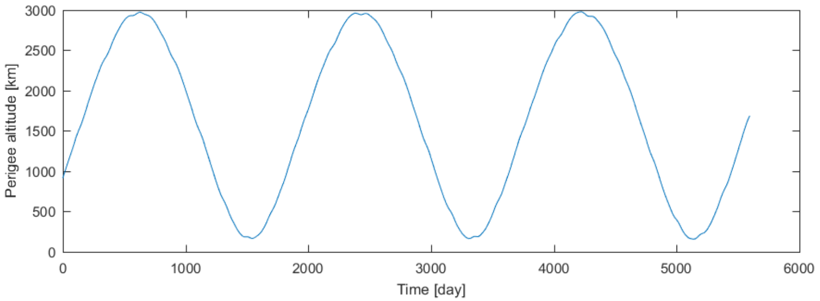
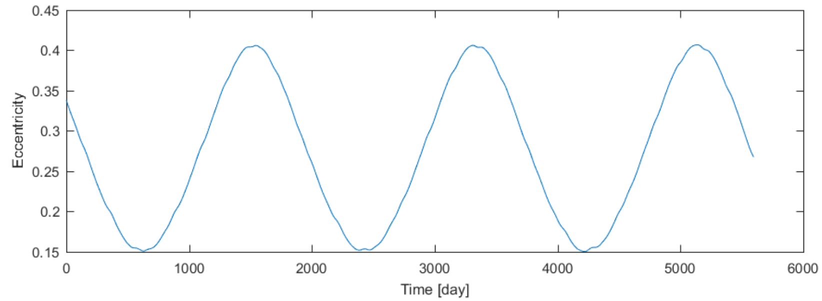
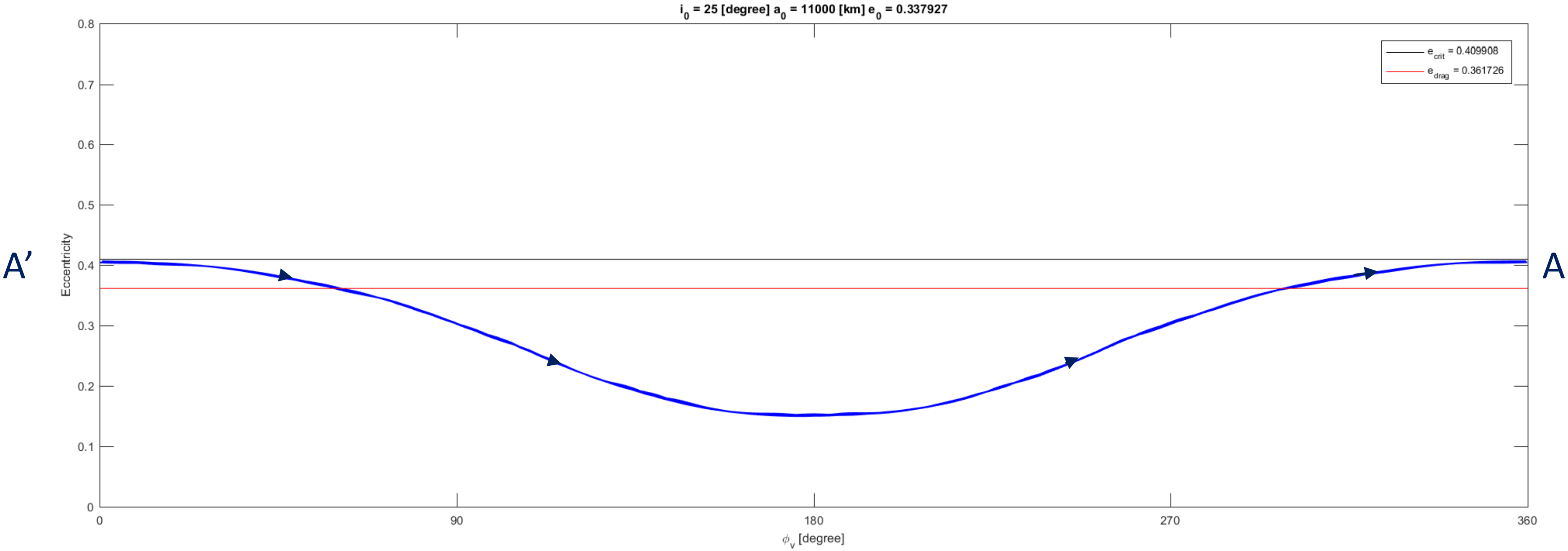
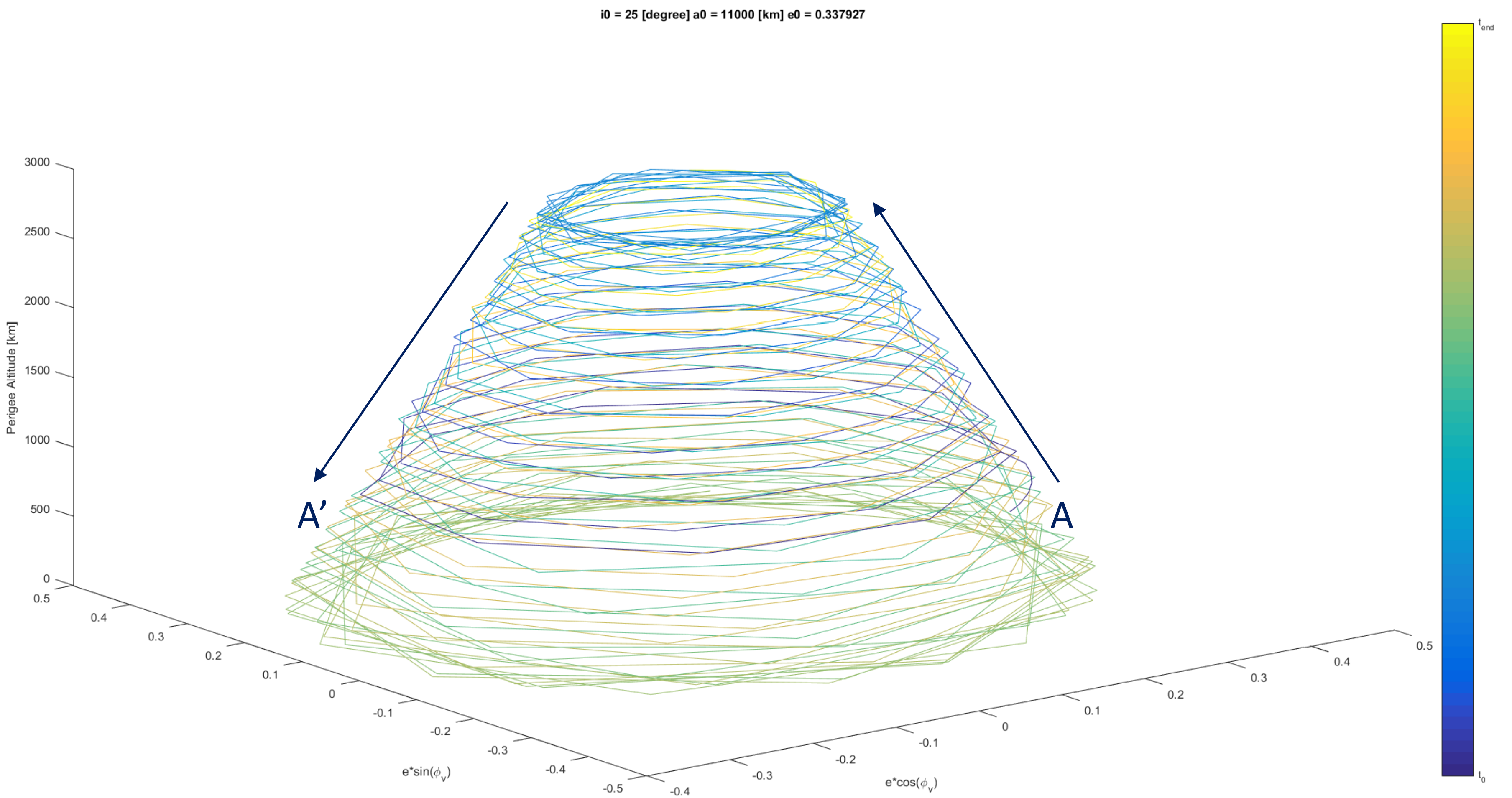






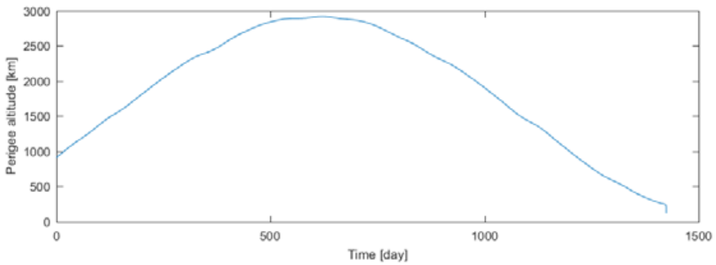
Drag-SRP-J_2 interaction

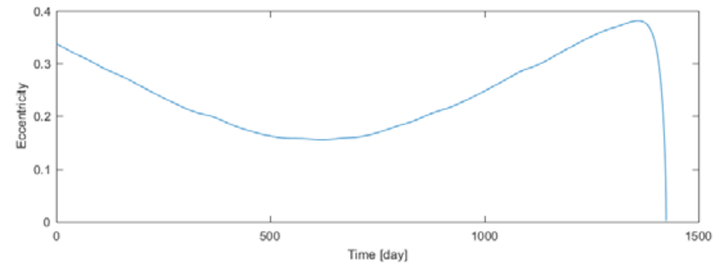
Preliminary results – SRP and J_2 only

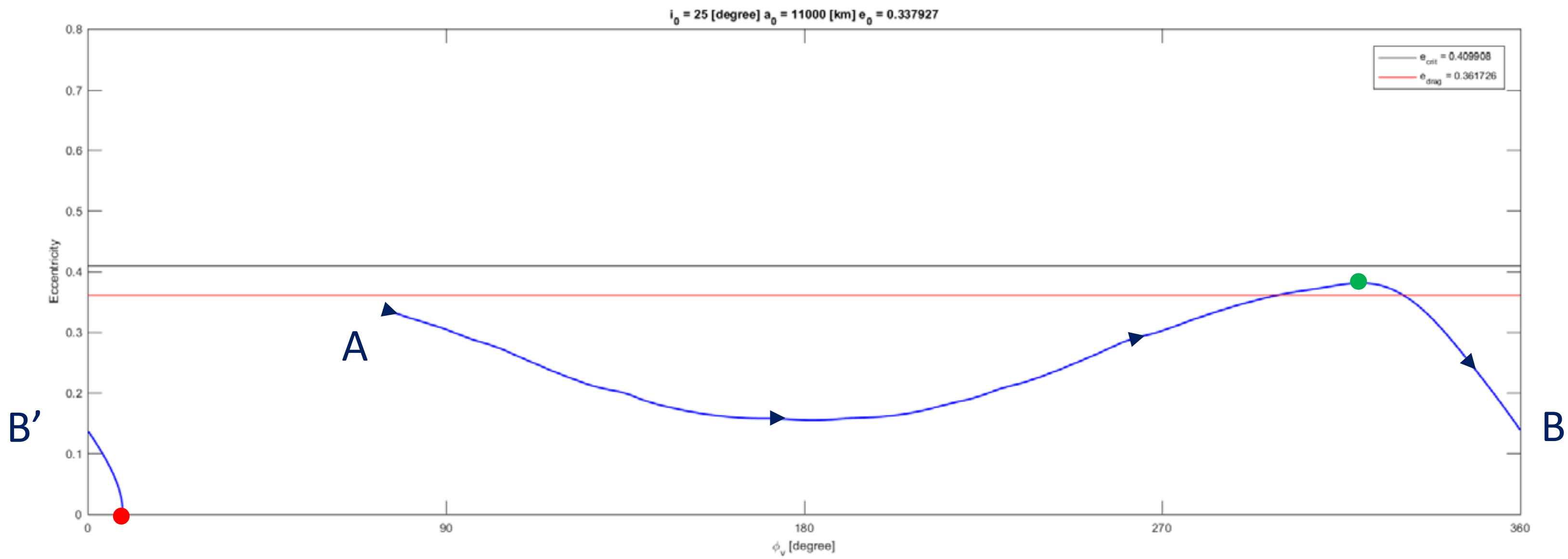


Drag-SRP-J_2 interaction

Preliminary results – SRP, J_2 and atmospheric drag

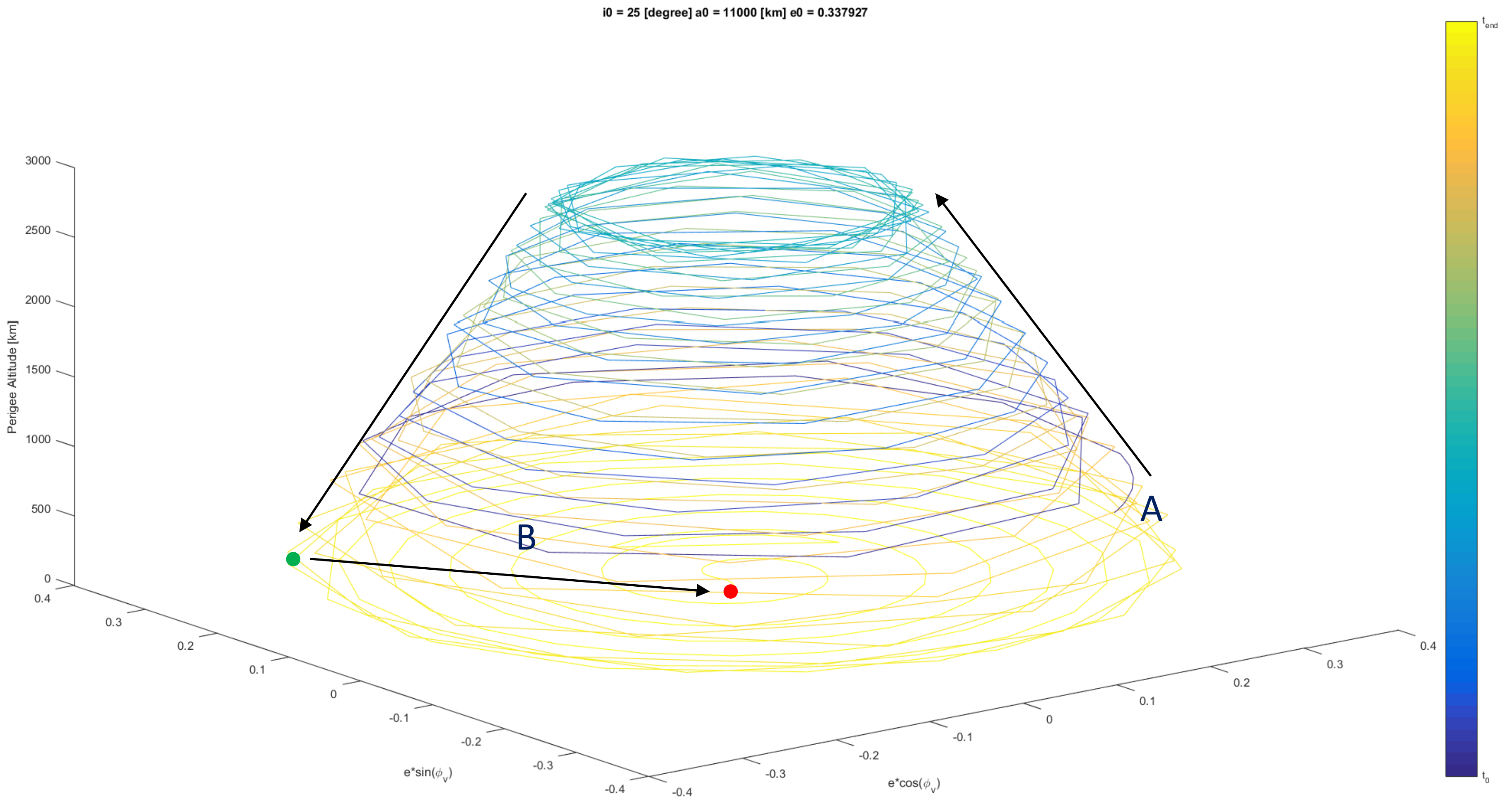






Drag-SRP-J_2 interaction

Preliminary results – SRP, J_2 and atmospheric drag



Conclusion

Application and future work

- Application:
    - Improvement of ATM requirement definition for a sail for deorbiting under the effects of these three perturbations only.
- Future work:
    - Go from numerical analysis to analytical.

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Numerical analysis of the effects of drag and its interaction with solar radiation pressure and Earth's oblateness

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