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Improved Design and Deployment Analysis for a HEO Tetrahedral Formation with Passive Deputy Nanosatellites

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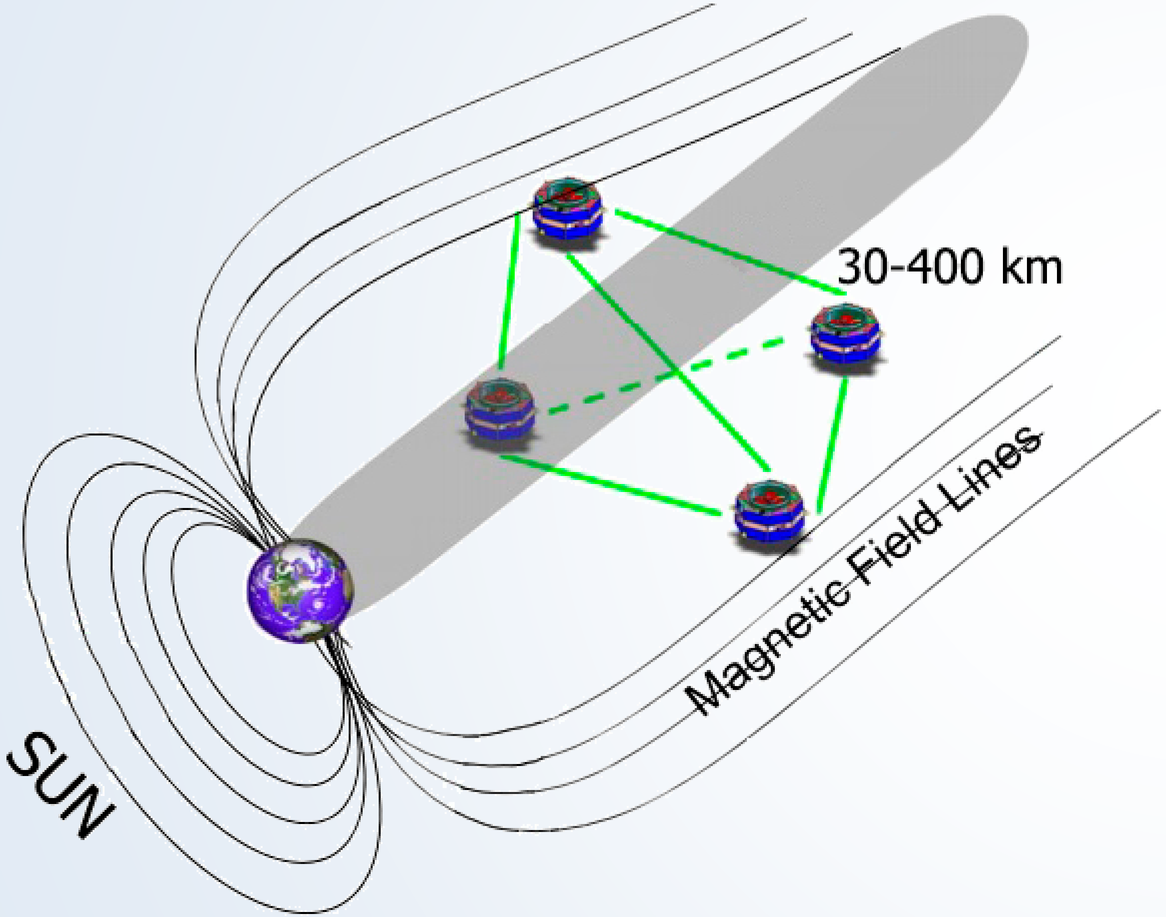
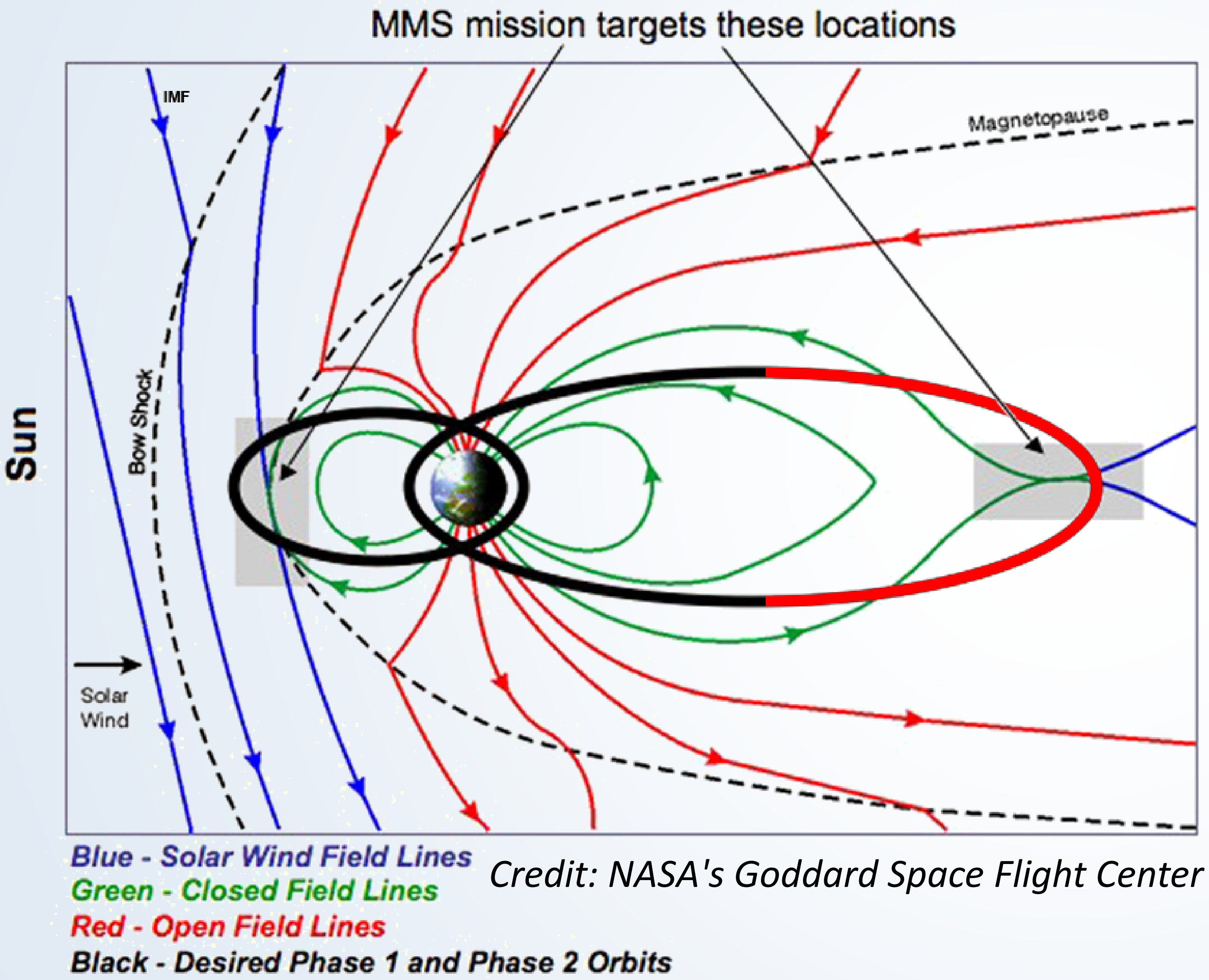
Introduction



Credit: NASA's Goddard Space Flight Center

- Small satellites able to perform complex missions
- NASA Magnetospheric Multiscale mission (MMS)
- Tetrahedral formation on HEO
- Maneuvers used to prevent drift
- Each spacecraft weighted 1360 kg

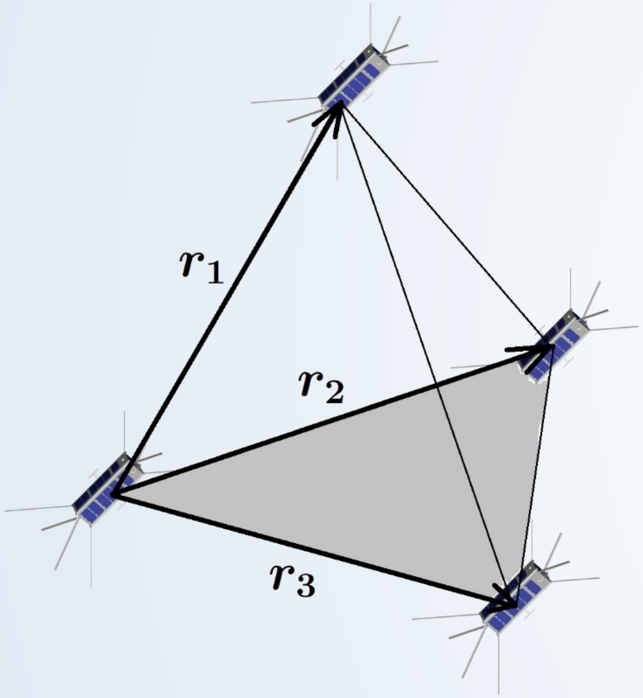
Reference orbit



Credit: NASA's Goddard Space Flight Center

- Highly Elliptical Orbit
- $R_\alpha = 200000\ \mathrm{km}$
- $R_\pi = 2000\ \mathrm{km}$
- $i = 51.6^\circ$, start from Baikonur
- $\Omega = \omega = 0^\circ$
- Region of Interest: $|\vec{r}| > 15R_E$
- Perturbations: J2, Lunisolar

Formation quality factor



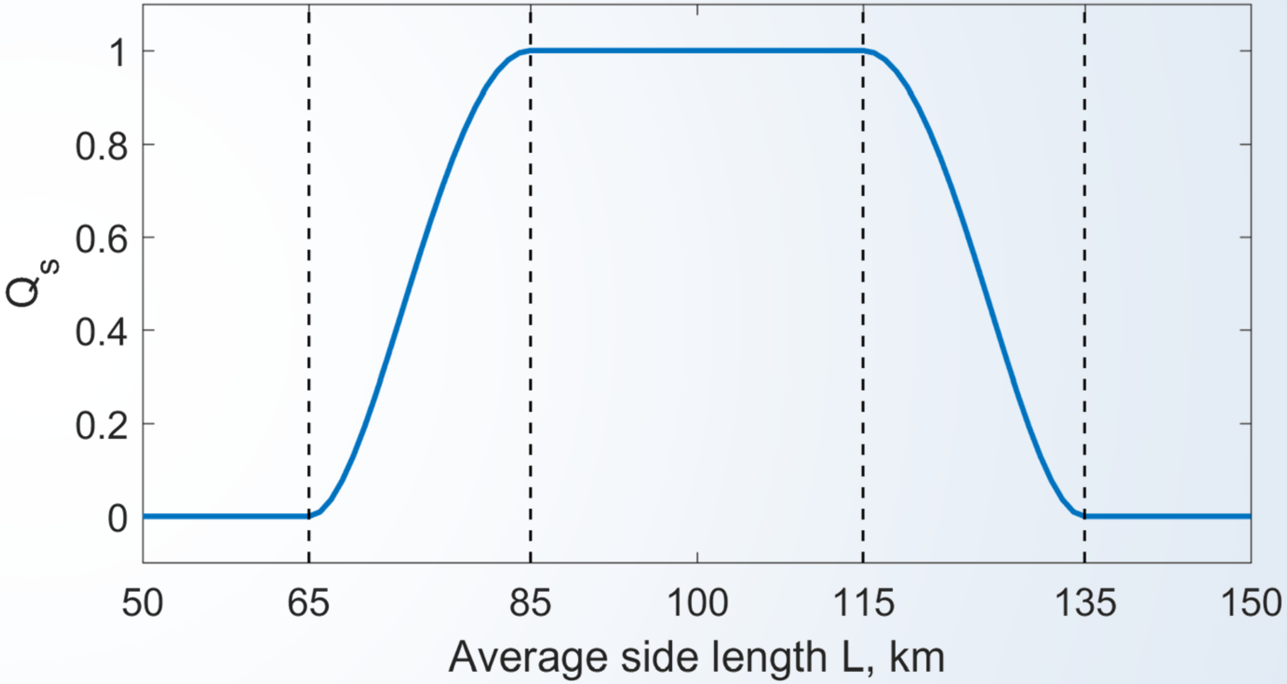
$$V_a = \frac{1}{6}|\vec{r_1} \cdot (\vec{r_2} \times \vec{r_3})|.$$

$$V_r = \frac{\sqrt{2}}{12}L^3$$

$$L = \frac{1}{6}\sum_{i=1}^{6} l_i$$

$$Q_v = \frac{V_a}{V_r}$$

Visualization of the scale factor Q_s



$$Q = Q_v \cdot Q_s \in [0;1]$$

$$Q_{int} = \frac{1}{t_2 - t_1}\int_{t_1}^{t_2} Q(t)dt$$

Problem statement

- Find optimal orbits for each of the four spacecraft near the reference orbit to maximize the number of orbital revolutions with acceptable formation quality ($Q_{int} > 0.7$ in RoI).
- Examine different options of formation satellites deployment in the orbits found.

Optimization Problem

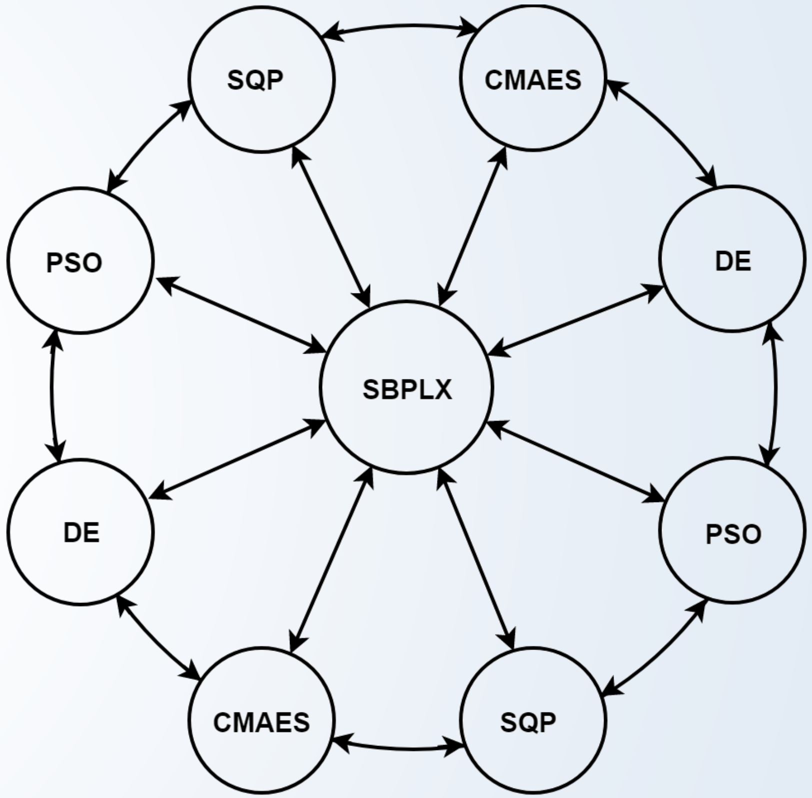
- The goal is to optimize the orbits of four satellites in the reference orbit vicinity
- Objective function:

$$\overline{Q}_{int}(x) = \frac{1}{N_{rev}} \sum_{i=1}^{N_{rev}} \hat{Q}^i_{int}(x) \longrightarrow max$$

- Unknown vector x: 6 orbital parameters for each of the four deputy satellites (24 variables in total)
- N_{rev} – number of revolutions
- $\hat{Q}^i_{int}$ – modified formation quality factor on *i*-th revolution

Supercomputer Optimization

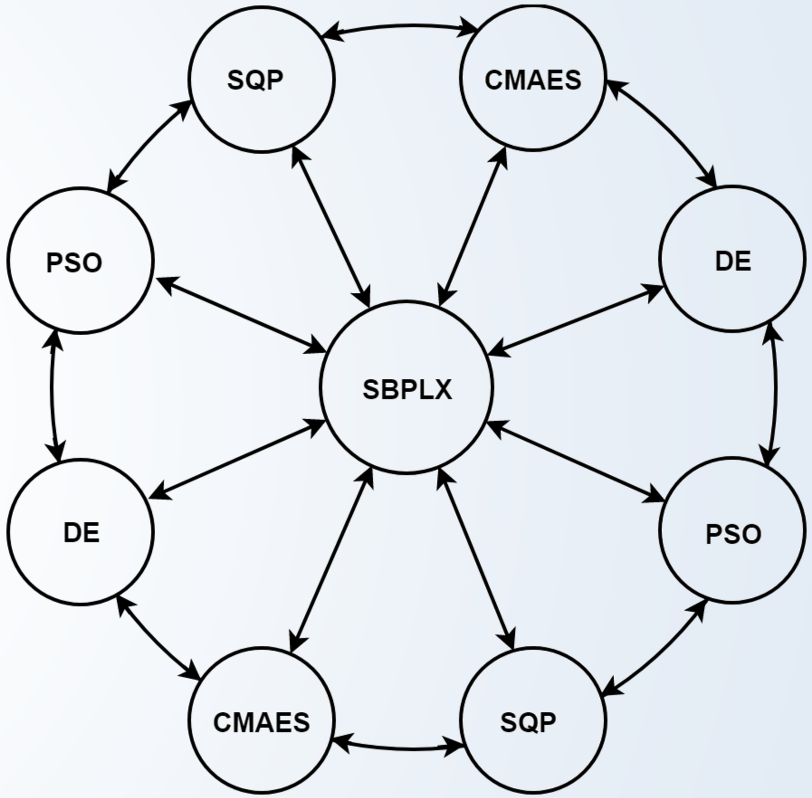
- Generalized Island Model from ***pagmo*** C++ library was used
- Developed by ESA to solve optimization problems in parallel
- Different optimization algorithms work on different islands (i.e. different CPUs)
- Islands asynchronously exchange information about best candidates to achieve better solutions
- The K60 supercomputer made it possible to operate with 361 islands



Island topology used in the optimization

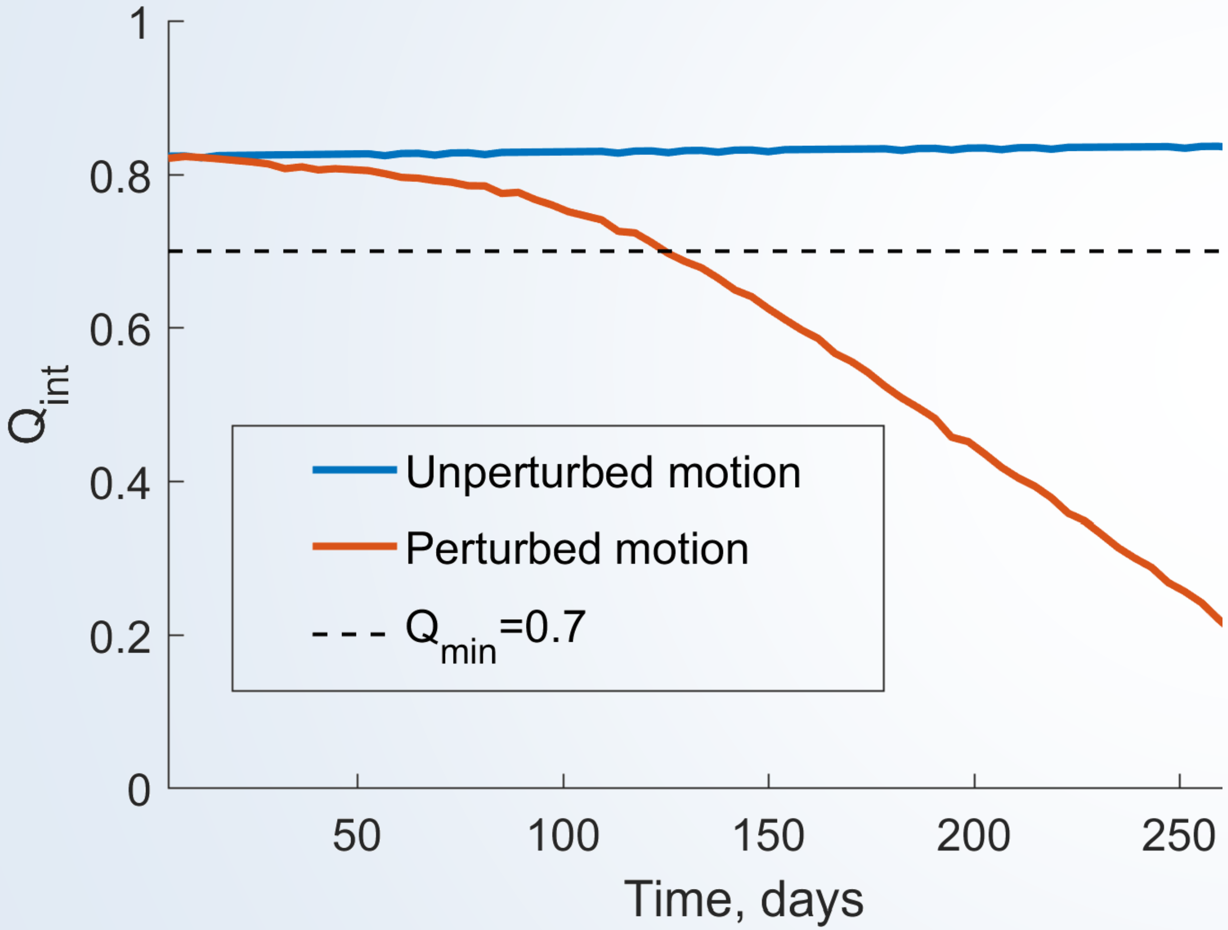
Supercomputer Optimization

- Benchmark problem was developed to choose algorithms
- Algorithms on the ring islands:
  - Differential Evolution (DE)
  - Covariance Matrix Adaptation Evolution Strategy (CMAES)
  - Particle Swarm Optimization (PSO)
  - Sequential Quadratic Programming (SQP)
- Central Island:
  - Subplex Method



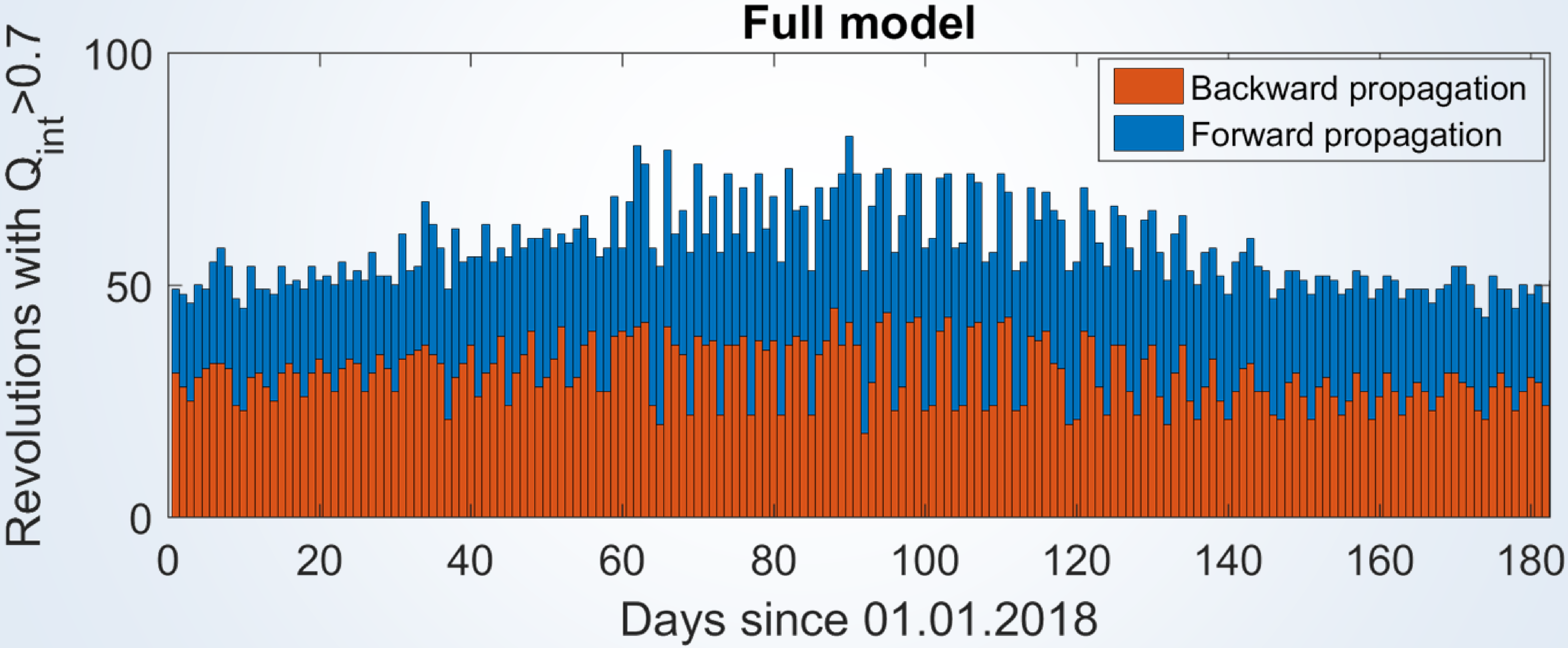
Island topology used in the optimization

Start date selection analysis (1)

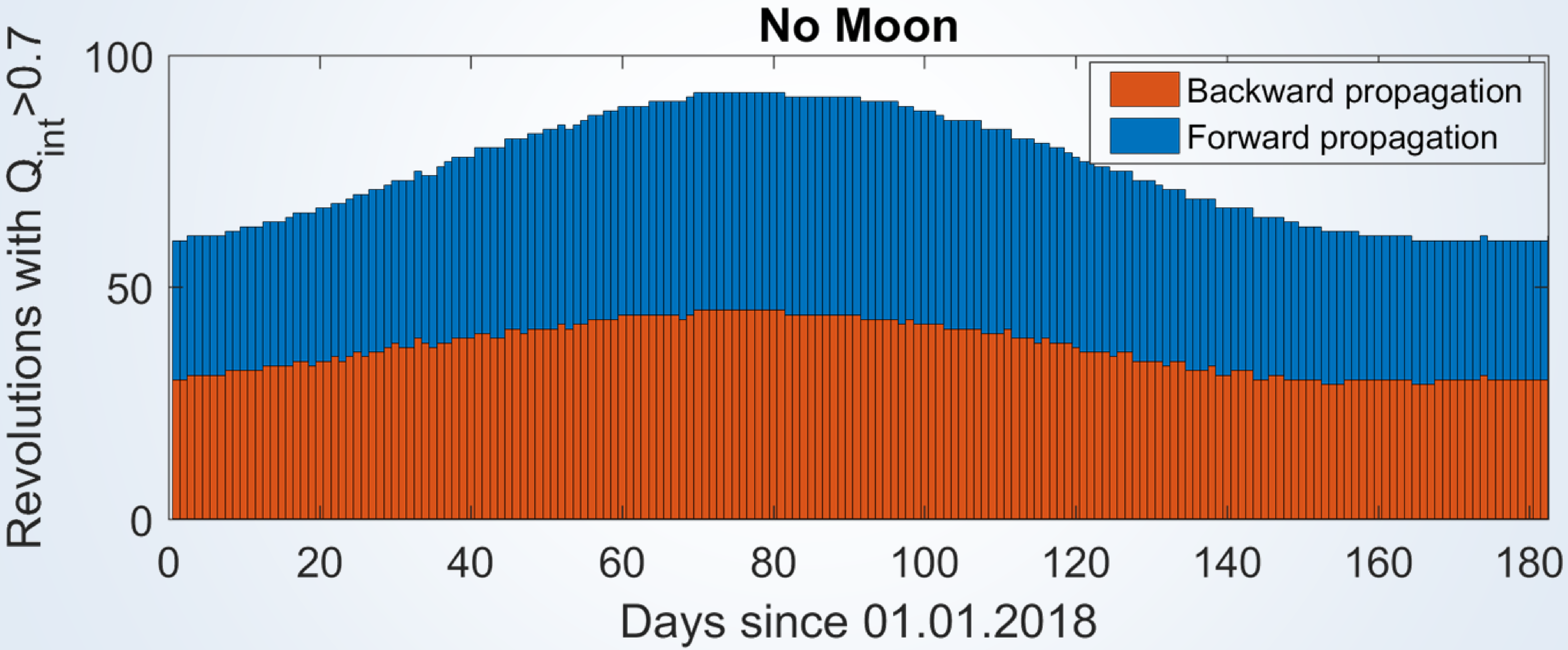


- Overall mission lifetime may depend heavily on the mission start date
- Same orbits should be propagated with various initial dates
- Such orbits were obtained by optimization in two-body problem

Start date selection analysis (2)

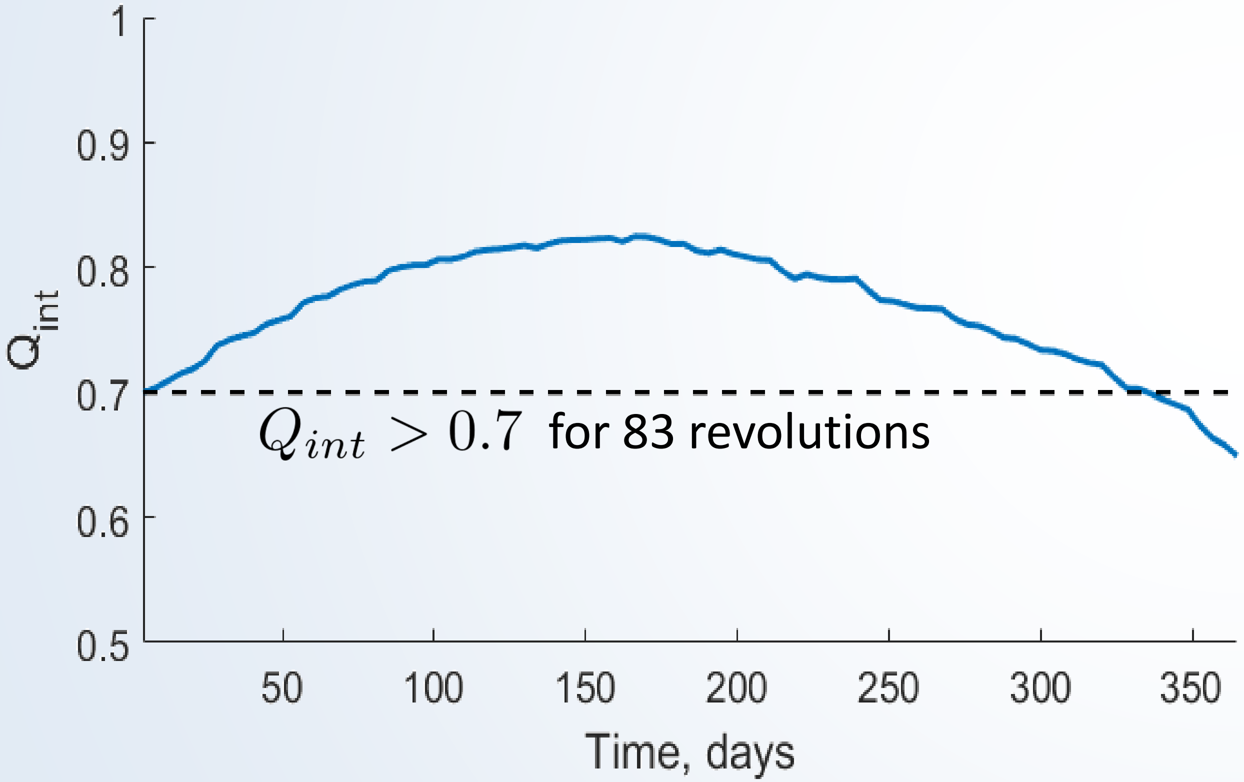


Start date selection analysis (3)

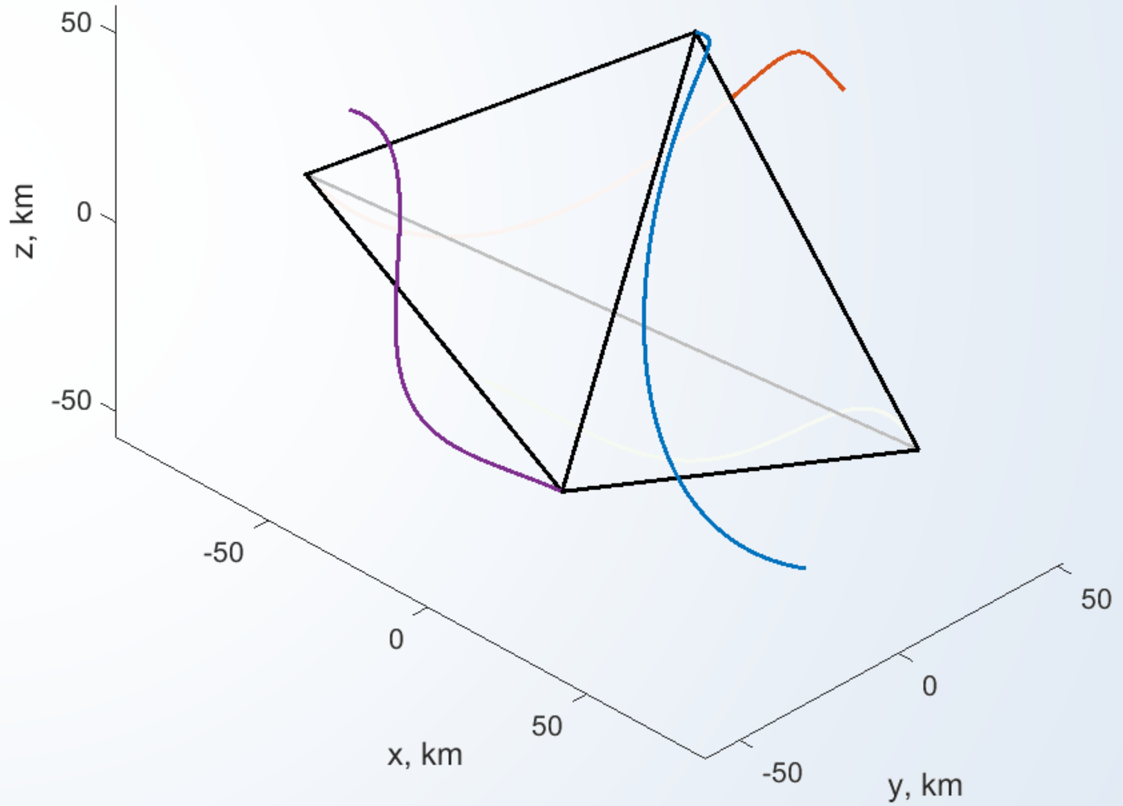


Optimization results

Evolution of Q_{int} with the optimized orbits



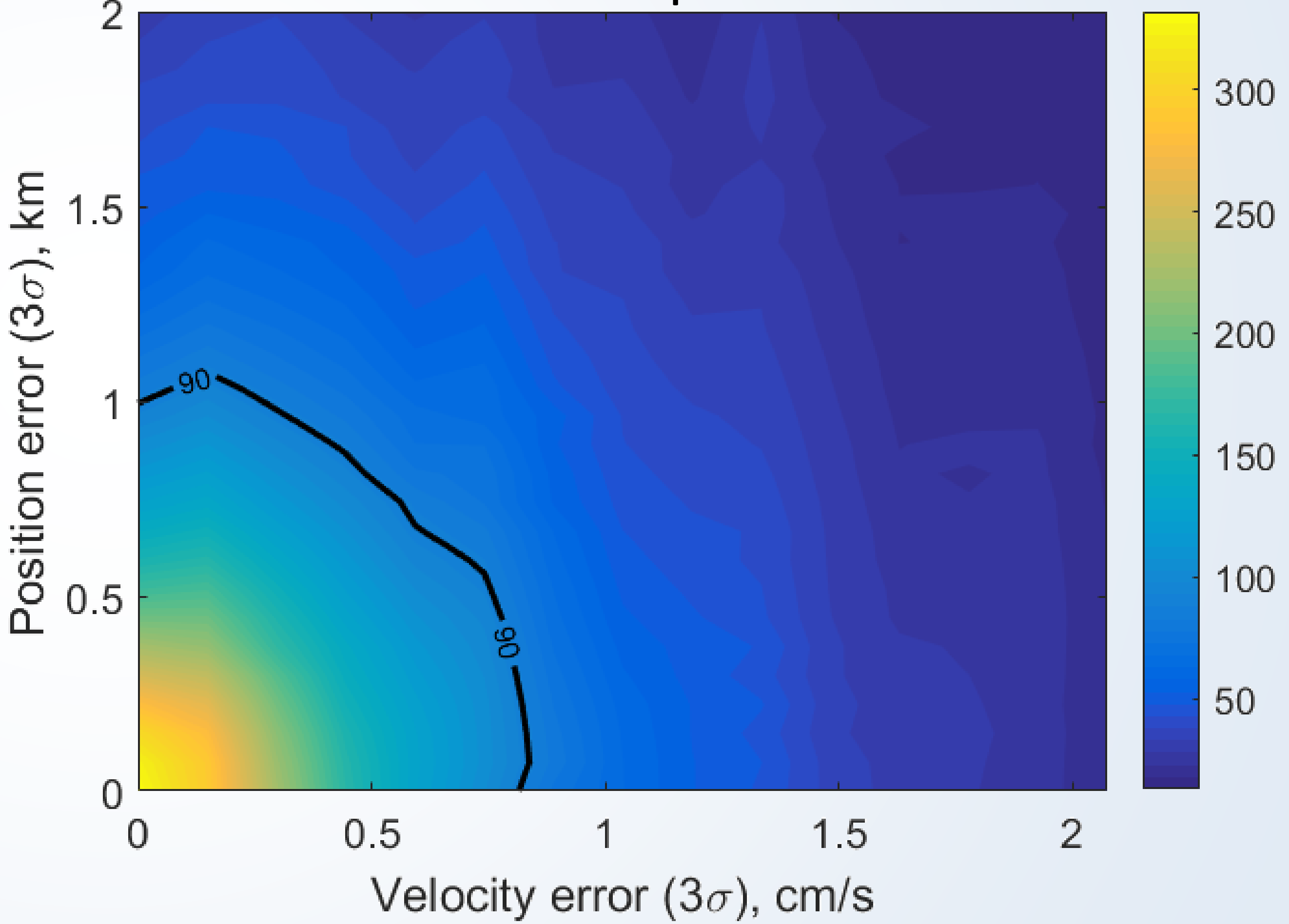
Tetrahedron on RoI of 40-th revolution



Orbital deployment

- Three deputy nanosatellites can be detached from the chief microsatellite
- The chief microsatellite has to be placed into the corresponding orbit by the launch vehicle
- Overall mission lifetime depends heavily on the deployment errors

Mission duration (in days) for different initial orbit perturbations



Deployment by means of standard spring pushers (1)

- Deployment happens within the three revolutions before the science phase of the mission begins
- Each revolution is reserved for the separation of one deputy satellite
- The chief satellite corrects its orbit between the separations
- Separation impulses are limited to 2 m/s and affects both Deputy and the Chief inversely proportionally to their masses
- Chief mass equals to 30 kg, Deputy mass is 5 kg

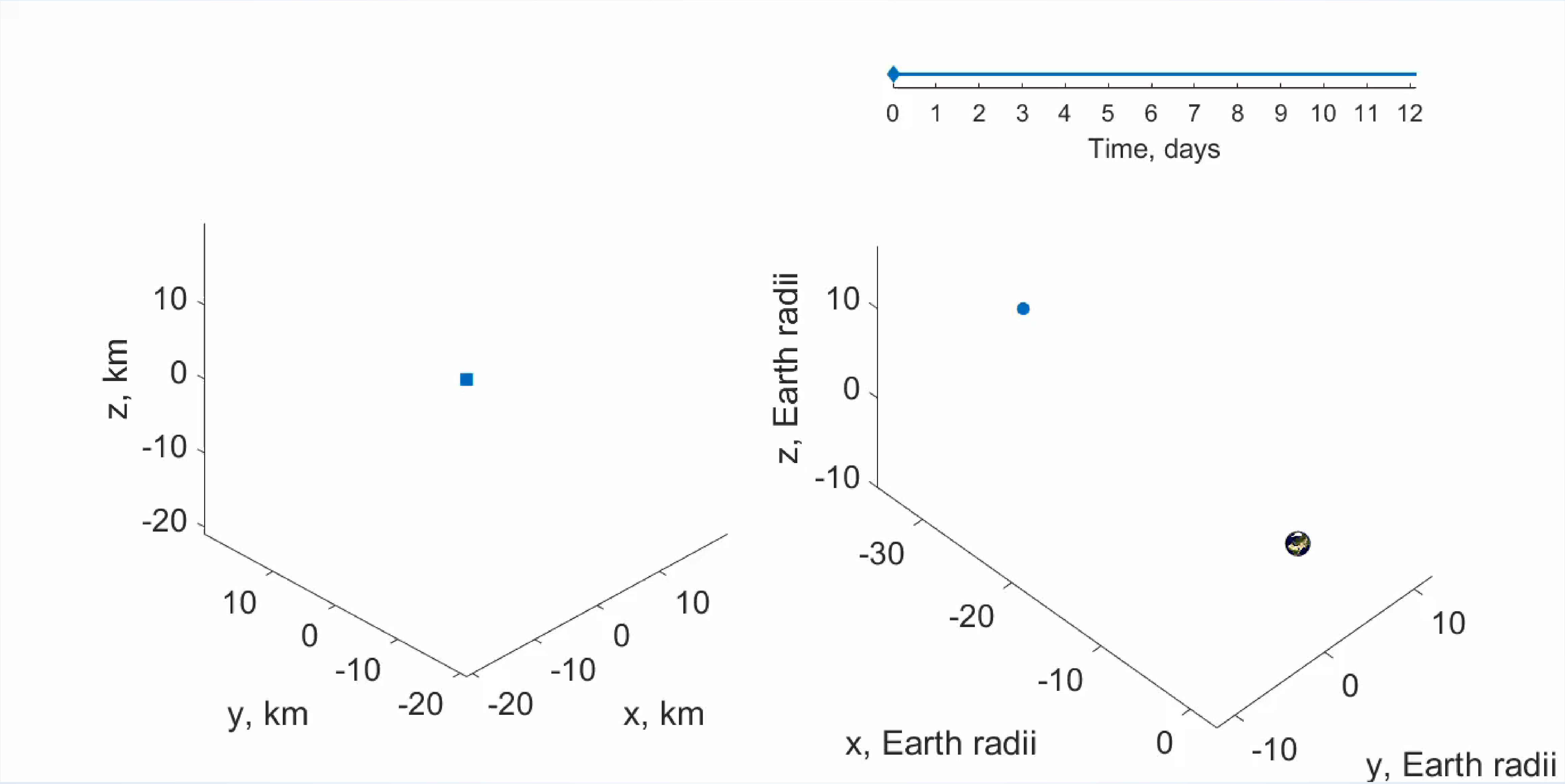
Deployment by means of standard spring pushers (1)

- 30-dimensional optimization problem:

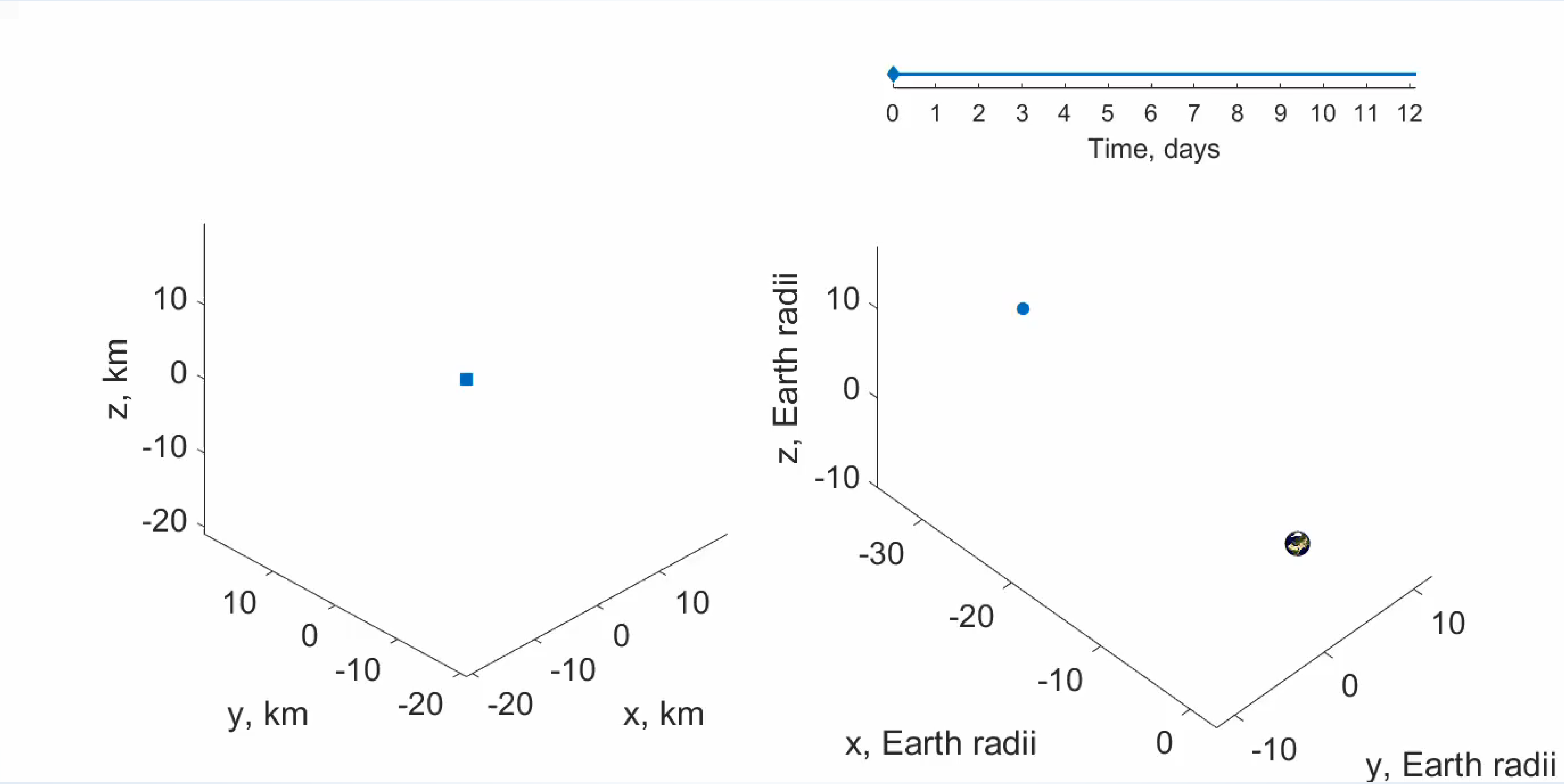
  - six elements for initial Chief orbit
  - three Chief correction impulses
  - three separation impulses
  - each impulse described by three velocity components and its execution time

- The sequential quadratic programming method has been used

Deployment process



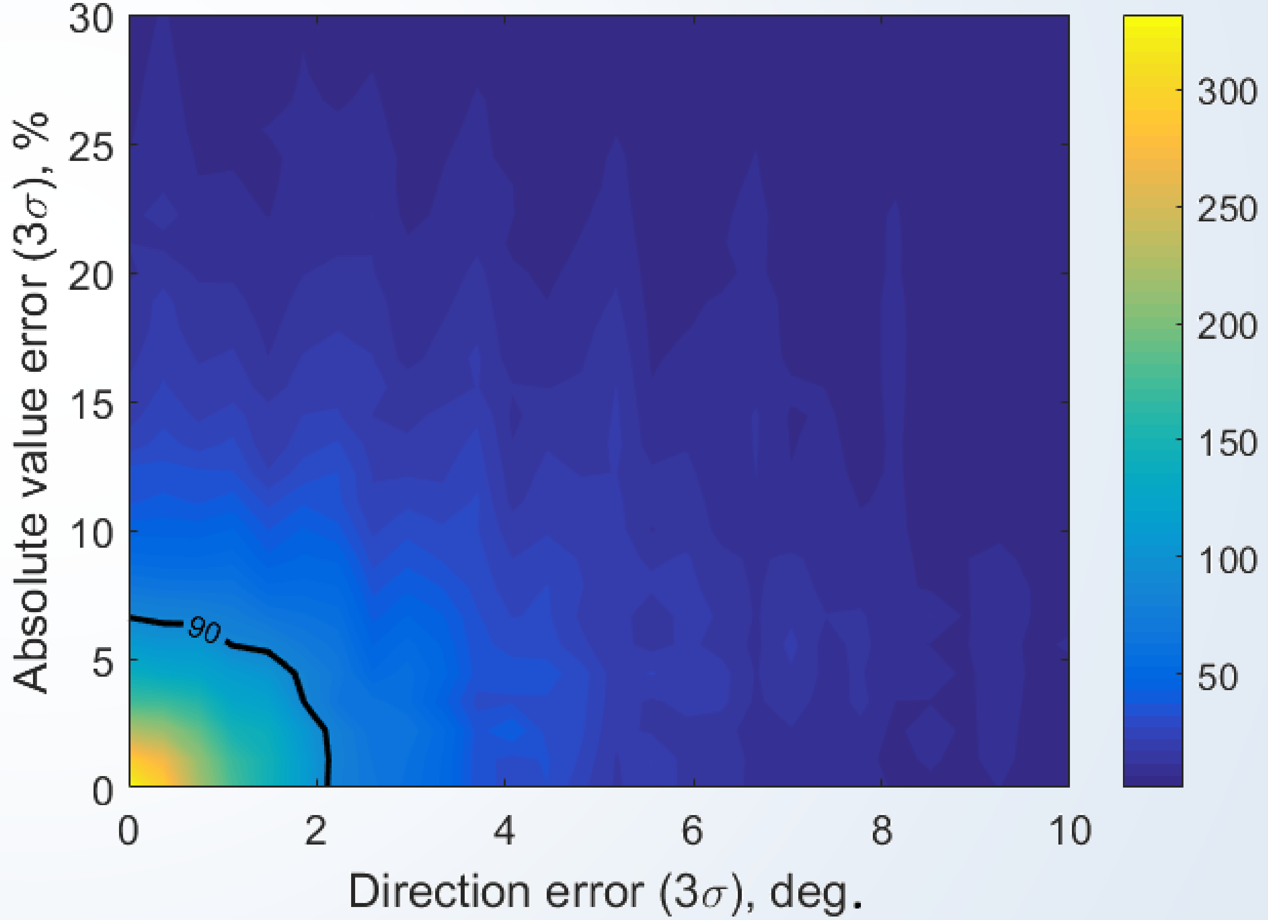
Deployment process



Deployment by means of standard spring pushers (2)

- Separation impulses found have magnitude up to 2 m/s
- Spring pushers are the source of large errors, up to 30% of impulse magnitude
- Typical errors in spring pusher impulses – 20% in magnitude and 5 deg in direction – cause a formation to degrade in less than a month

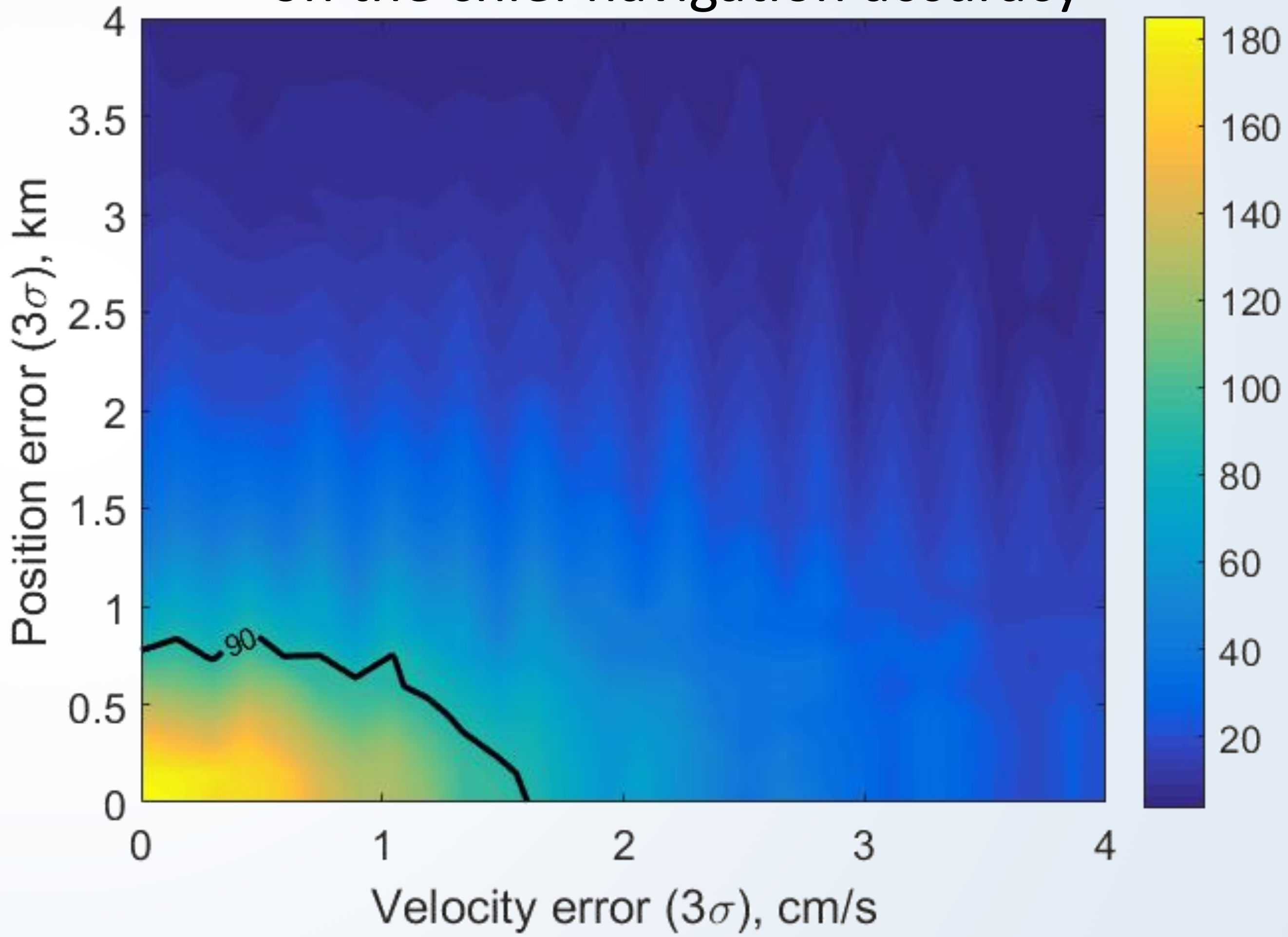
Mission duration (in days) dependency on the spring pusher errors



Deployment with low-velocity spring pushers

- Usage of low-velocity (5 cm/s) spring pushers is suggested to achieve better mission lifetime
- Separation impulses errors were fixed at 20% in magnitude and 10 deg in direction
- To maintain a mission for three months, chief accuracy of 0.8 km in position and 1.6 cm/s in velocity is required

Mission duration (in days) dependency on the chief navigation accuracy



Conclusions

- For the formation satellites, such orbits exist that tetrahedron quality is acceptable for 83 revolutions (approx. 340 days) of purely ballistic motion
- To solve the optimization problem in a parallel way, the generalized island model was launched on the K-60 supercomputer
- Standard spring pushers with an impulse up to 2 m/s have errors up to 30%, which leads to formation degradation in less than a month
- To keep the formation for 3 months, low-velocity separation is needed, with chief spacecraft navigation errors no worse than 0.8 km and 1.6 cm/s

Acknowledgements

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Thanks for your attention!