Rymdstyrelsen
Swedish National Space Agency

Ansökan för NRFP, omgång 3

Multi-spacecraft Formations

Sumeet Satpute
Luleå University of Technology,
Kiruna, Sweden

Main Supervisor
Prof. Reza Emami
Luleå University of Technology,
Kiruna, Sweden

Assistant Supervisor
Dr. Per Bodin
AOCS Department
OHB, Sweden

15-11-2018

LULEÅ UNIVERSITY OF TECHNOLOGY

OHB SWEDEN

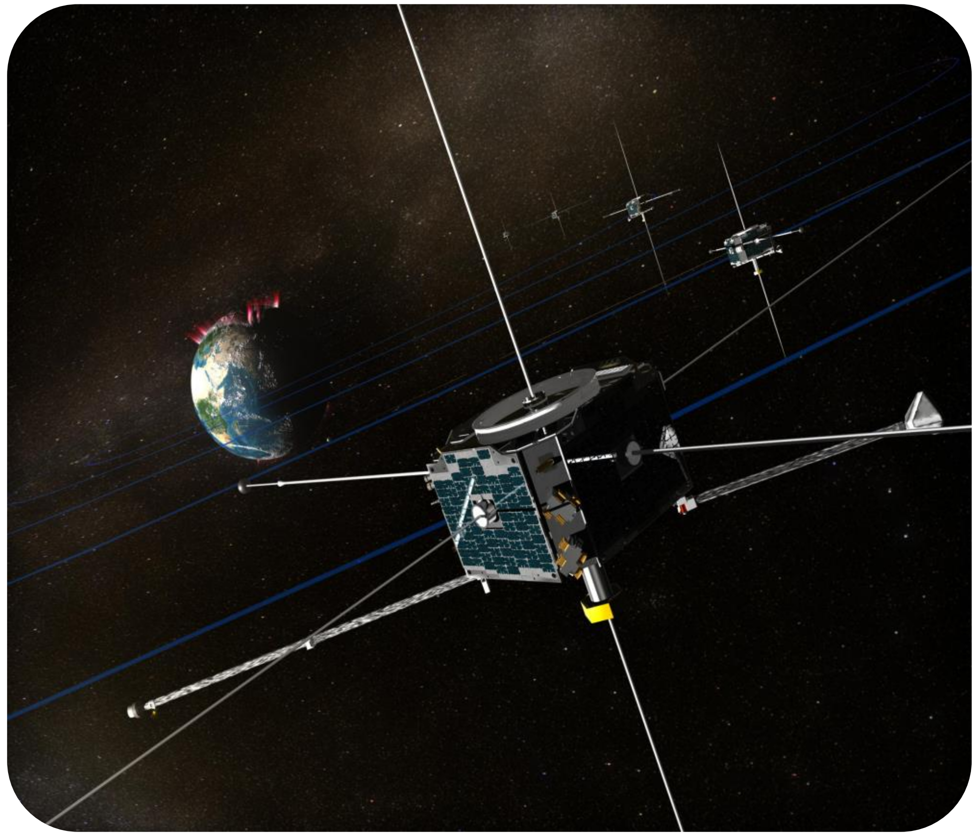
Outline

- Introduction
  - Work Packages
  - Research Focus
- Autonomous Co-location Of Geostationary Satellites
  - Project Requirements
  - Methodology
  - Simulation Results
- Multi-spacecraft Formation
  - Research Direction
- Work in Progress
- Publications
- Timeline

Introduction

- What?
  - *An autonomous system involving multiple spacecraft with an intelligent architecture*

- Why?
  - *Payload requirements*
  - *Redundancy*
  - *Economical*



Credits: NASA

Magnetospheric Multiscale (MMS) Mission

Work Packages

- WP1- Literature Survey
- WP2- Autonomous Co-location
- WP3- Distributed Fault-tolerant Control and Guidance Architectures
- WP4- Multi-agent Performance Enhancement Mechanisms
- WP5- Optimal and Robust Reconfiguration

Research Focus

- Autonomous co-location of geostationary satellites
  - How to design *station keeping maneuver plan autonomously* for a fleet of satellites in a geostationary slot

- Multi-spacecraft formation
  - How to advance the *real-world applicability* of spacecraft formation
    - *Reliability*: Task completion
    - *Fault tolerance*: Partial or complete hardware failure
    - *Adaptability*: Resource allocation or mission needs

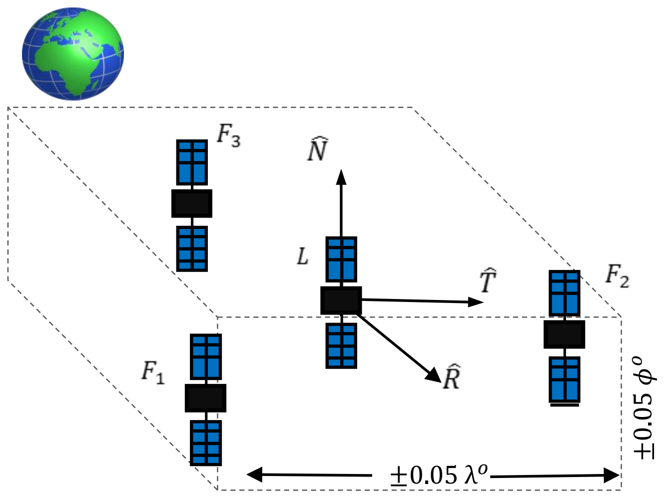
Autonomous Co-location of Geostationary Satellites

Credits: ESA

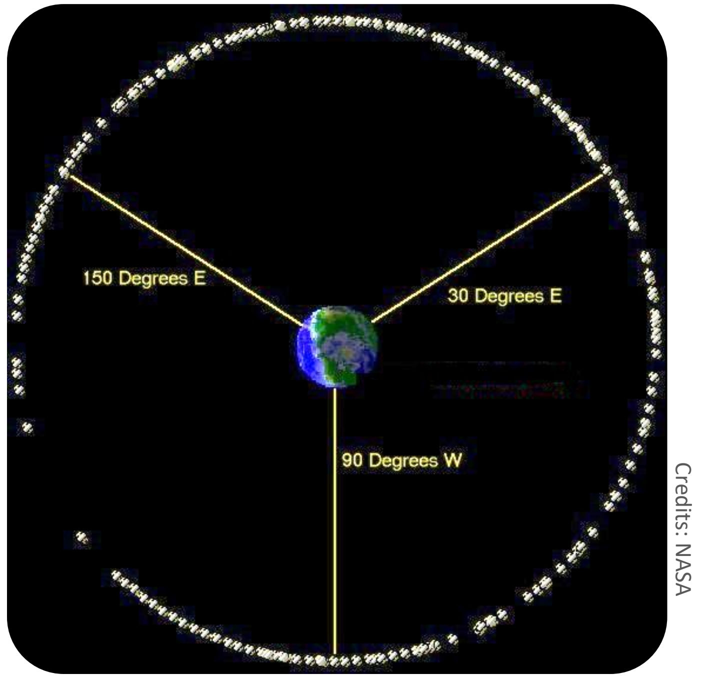
LULEÅ UNIVERSITY OF TECHNOLOGY

Satellite Co-location

- Sharing same longitudinal position with multiple satellites
- Maximize the slot capacity



a) Geostationary slot with co-located satellites



b) Satellite Population in Geostationary orbit

- Affecting Factors
  - Number of participating satellites
  - Characteristics of the propulsion system
  - Station Keeping period
  - Separation distance

Project Requirements

- *Eight* geostationary satellites
- Orbit determination using *onboard navigation system*
- Low thrust *electric propulsion*
- *Reduce* separation distance
- *Design* station keeping maneuvers
- *Minimize* the fuel consumption for each satellite

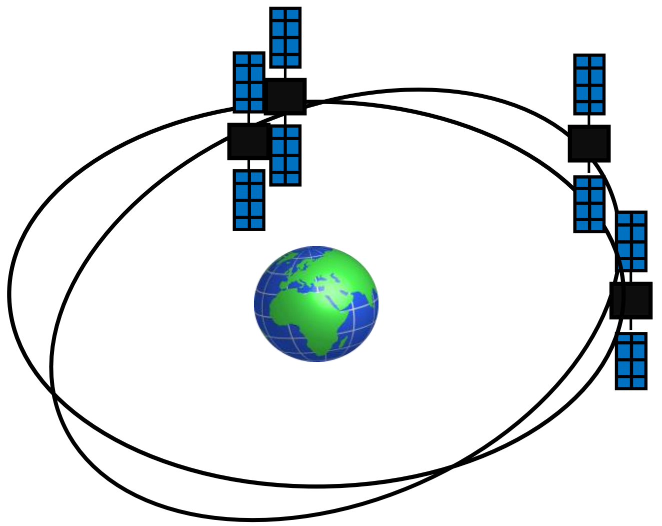
Motivation

- An optimal maneuver planning algorithm is proposed for a fleet of satellites to maintain :
  - Safe separation distance between the satellite pair
  - The Earth pointing attitude for each satellite.

LULEÅ UNIVERSITY OF TECHNOLOGY

Methodology

- Combined eccentricity and inclination vector separation
- A relative orbit control strategy is implemented using a leader-follower architecture.
- A dual rate predition model is proposed.
- A convex optimization problem is solved to obtain maneuver plans.

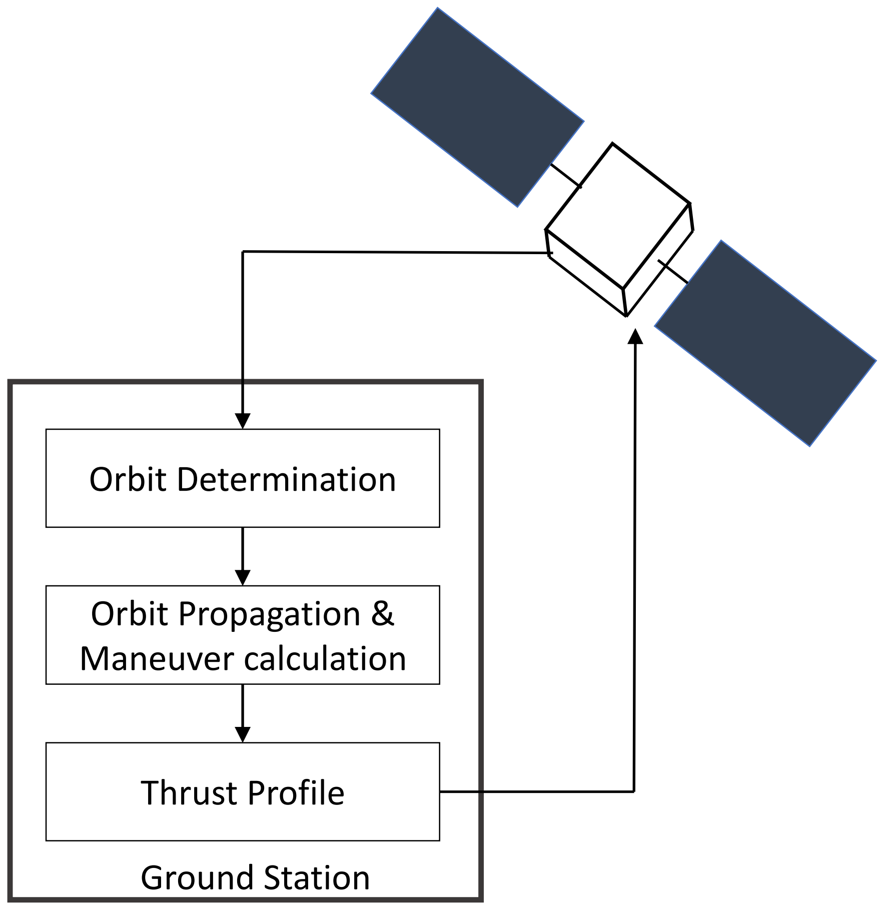


e/i vector separation strategy

LULEÅ UNIVERSITY OF TECHNOLOGY

Implementation

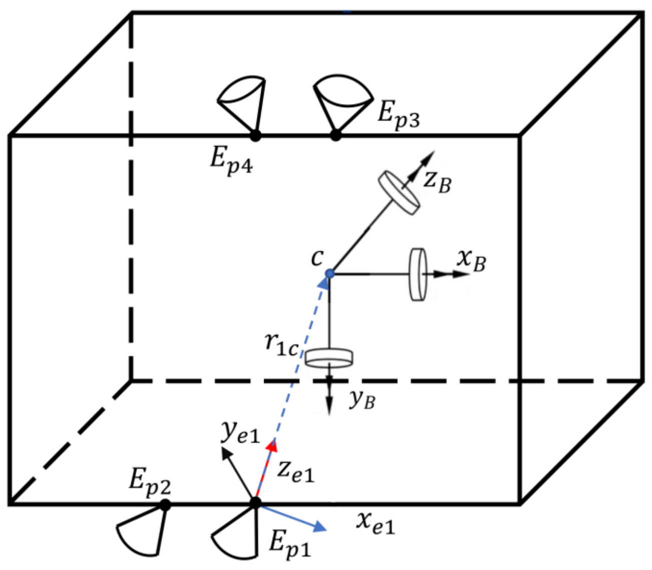
- Frequent maneuver planning is required
- The algorithm is implemented in a receding horizon control form
- Maneuver plans for each satellite are obtained with a prediction horizon of one day and replanning is done every 6 hours.



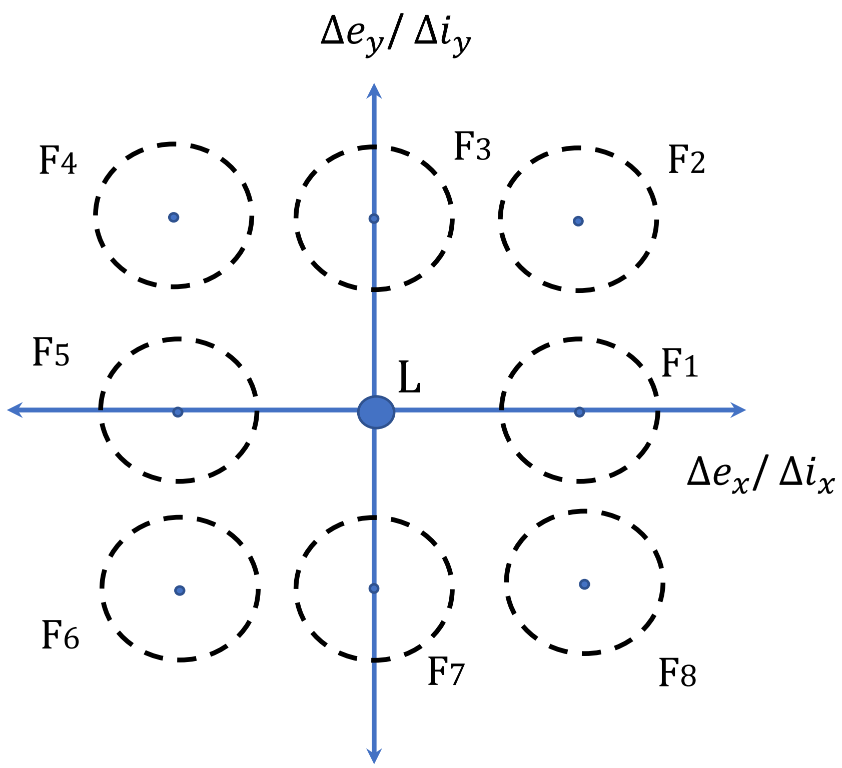
Simplified Station Keeping Scheme

Simulation Results

- A fleet of nine identical satellites are considered to stay within a GEO slot of size $\pm$ 0.06 deg.
- Each satellite is equipped with four on-off electric thrusters mounted on a bi-axial gimbal mechanism.
- The relative e/i vector are controlled in the circular tolerance windows.
- Estimated minimum worst case separation distance between satellite pairs is about 1.82 km.



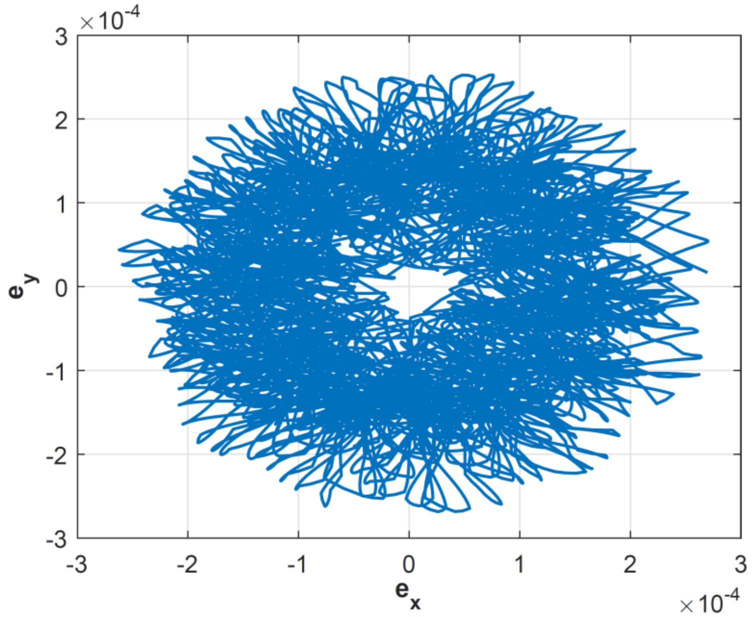
a) Schematic of the satellite



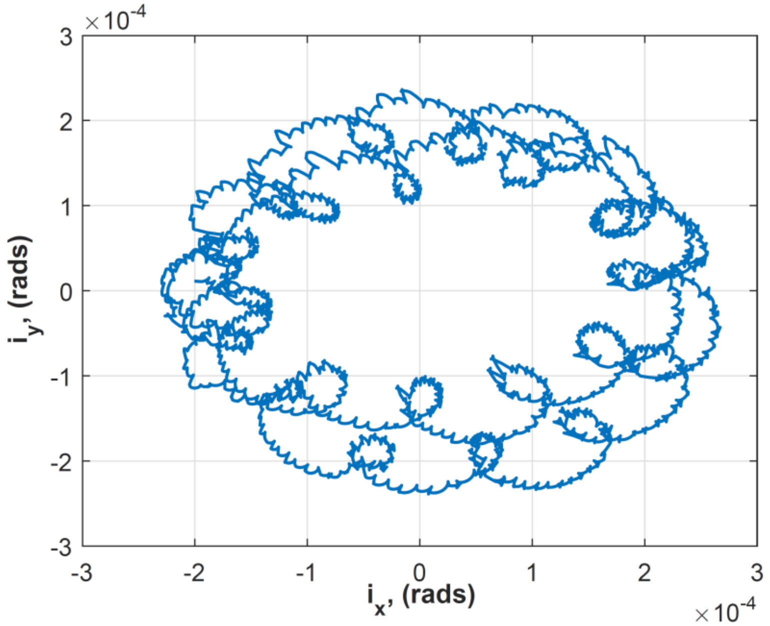
b) Relative eccentricity/inclination plane

LULEÅ UNIVERSITY OF TECHNOLOGY

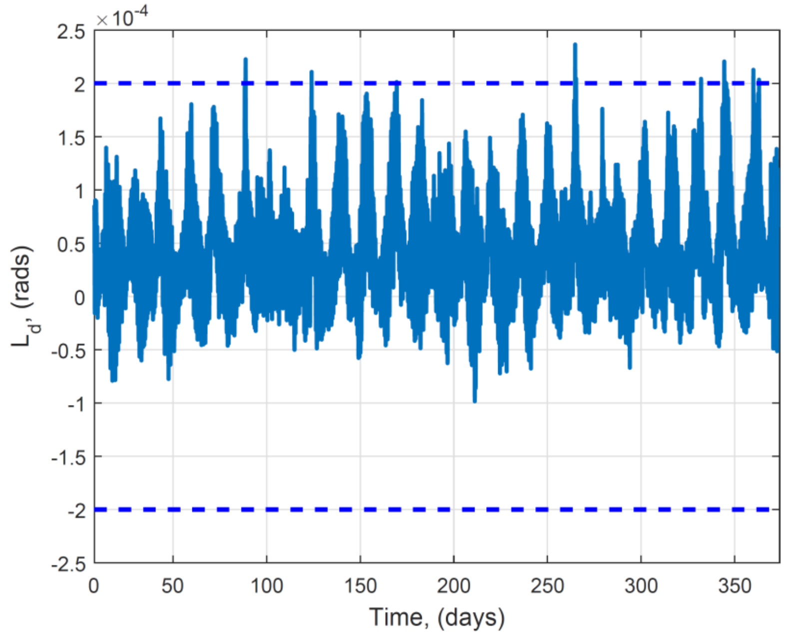
- Leader satellite states



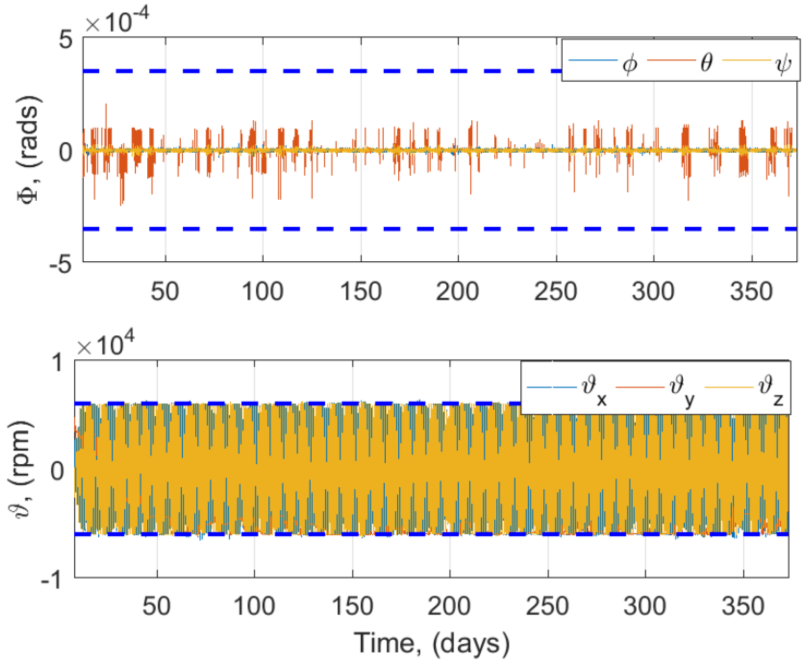
a) Osculating eccentricity vector



b) Osculating inclination vector

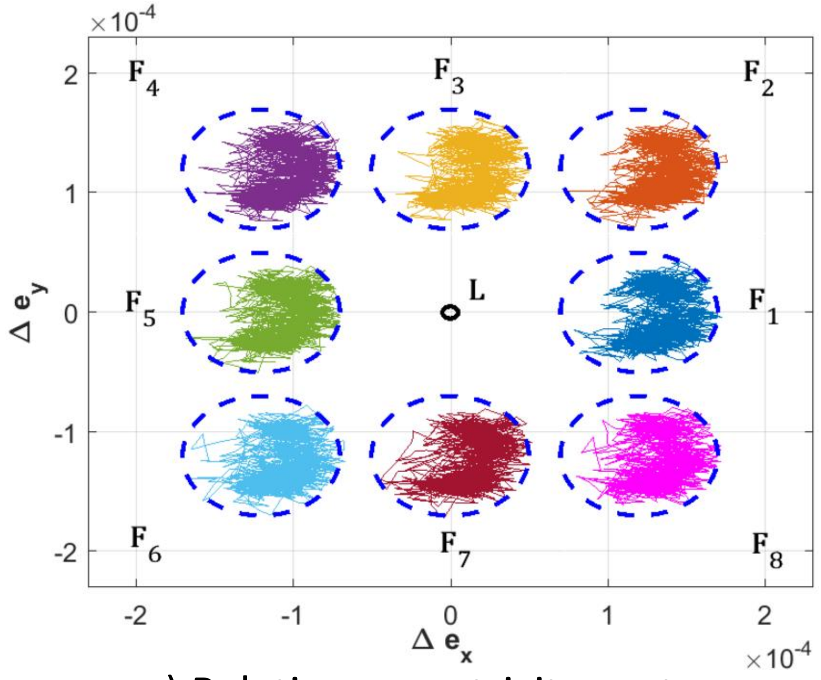


c) Mean longitude difference

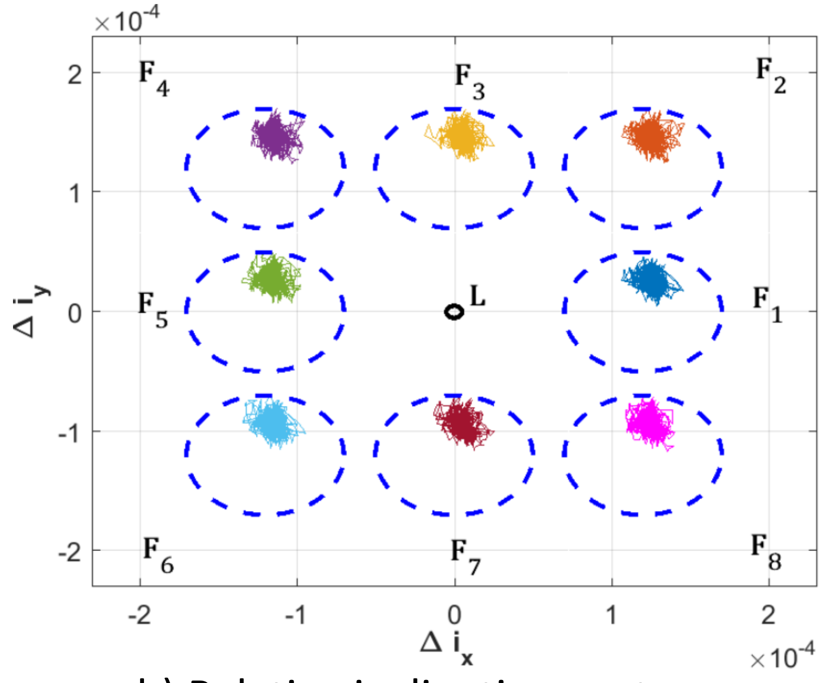


d) Attitude states

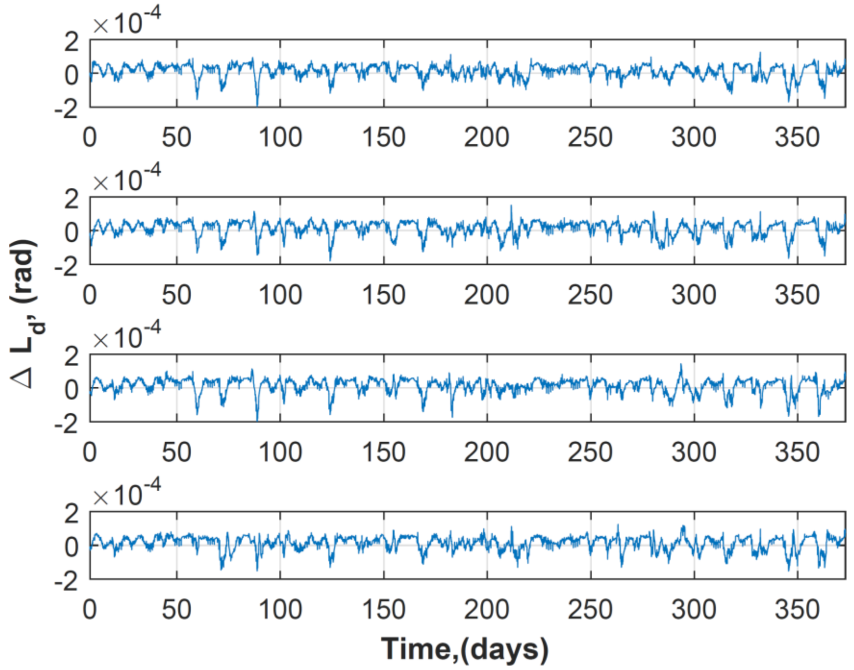
• Follower satellites’ relative orbital states



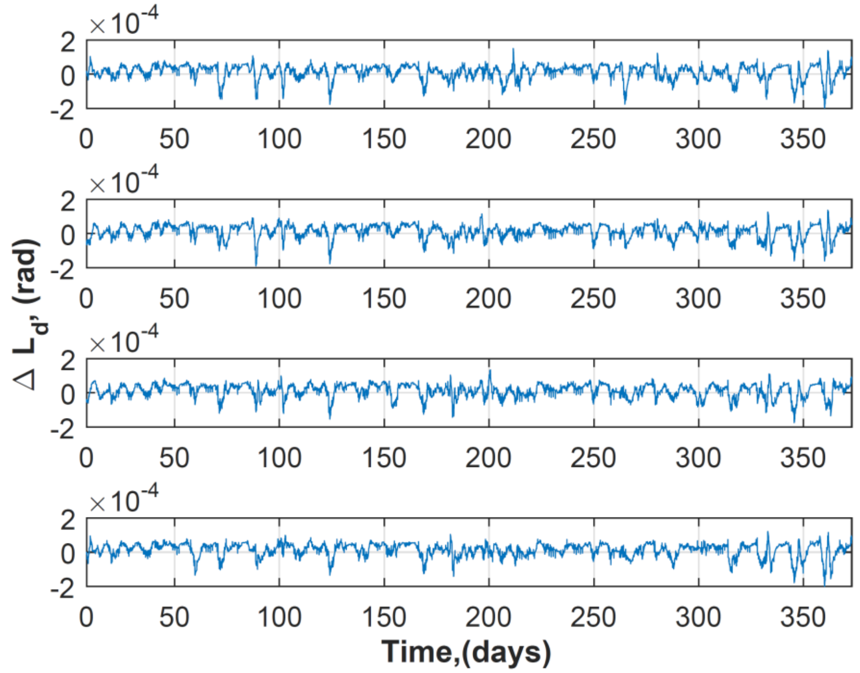
a) Relative eccentricity vector



b) Relative inclination vector

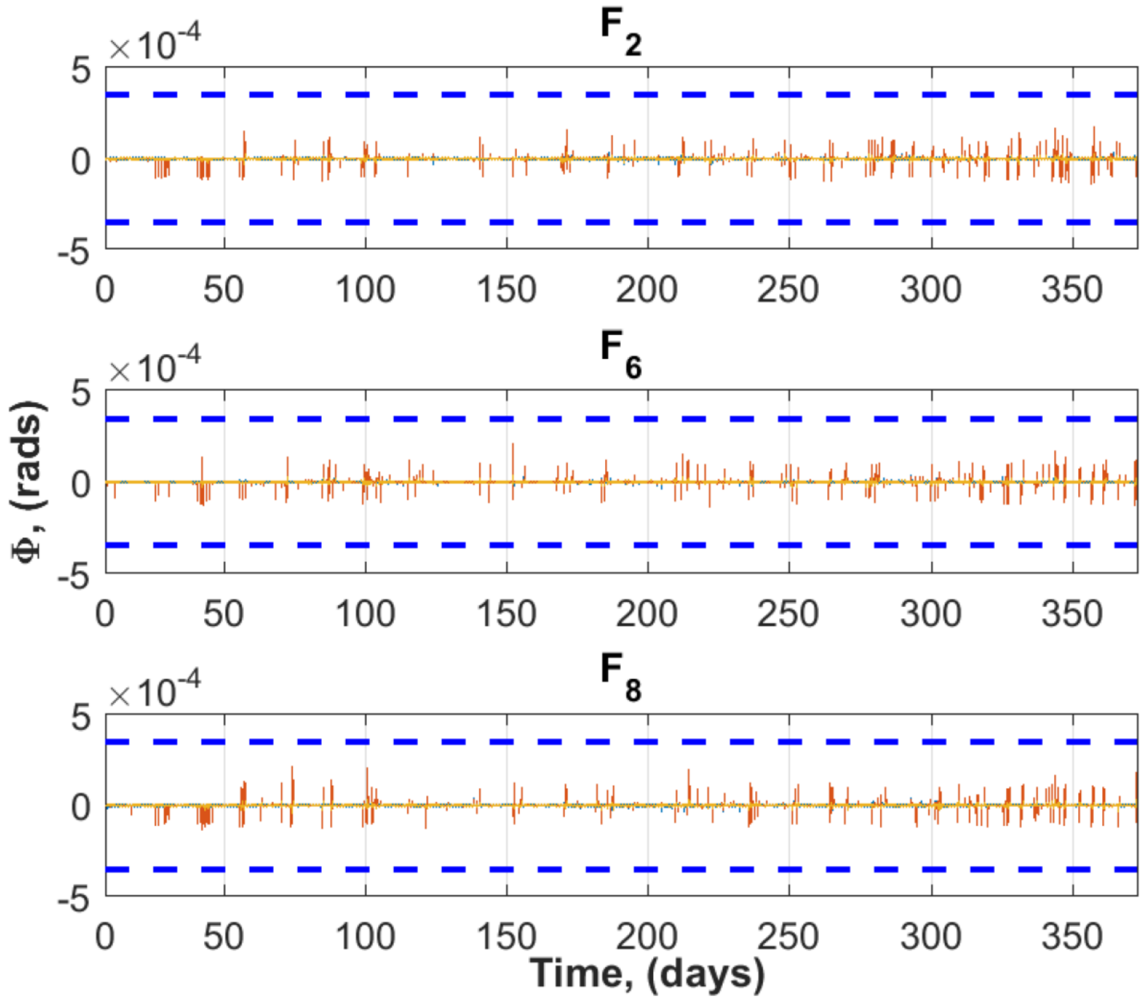


c) Relative mean longitude difference $(F_1 - F_4)$

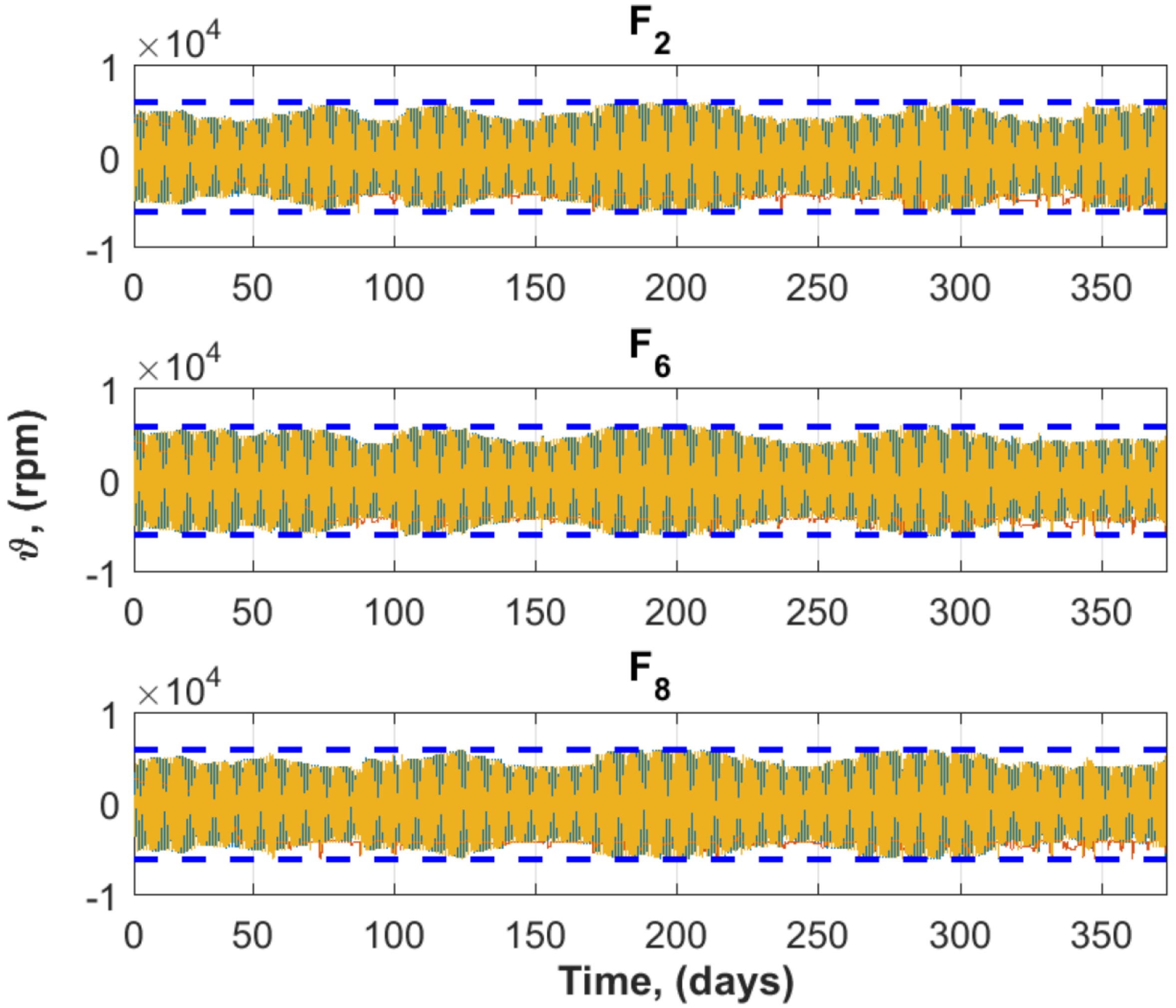


d) Relative mean longitude difference $(F_5 - F_8)$

- Follower satellites' attitude states

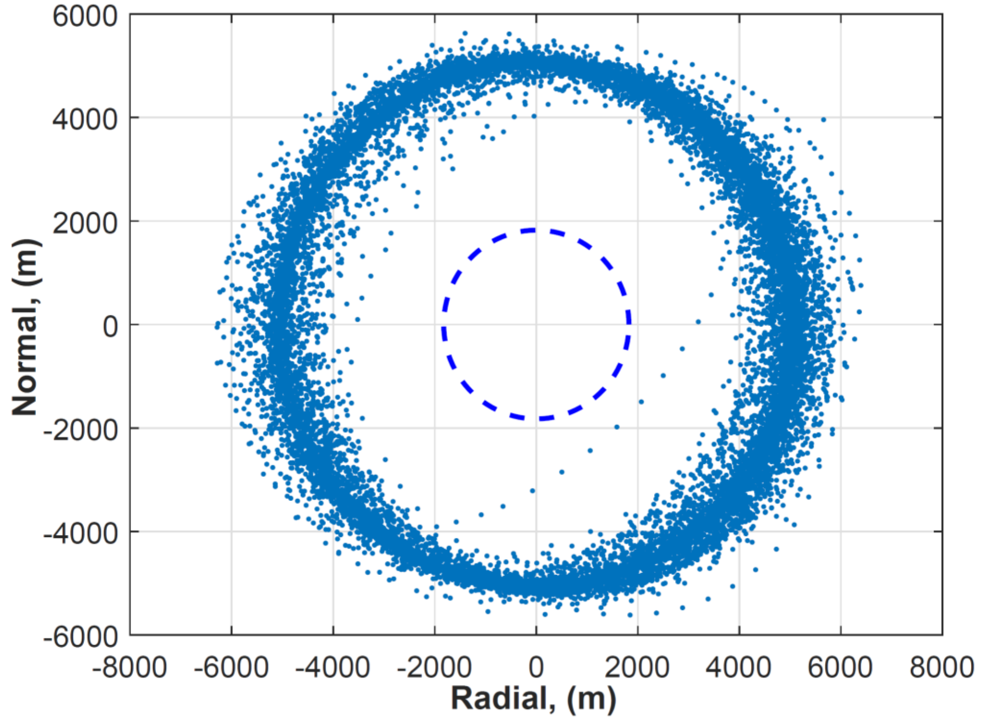


a) Euler angles



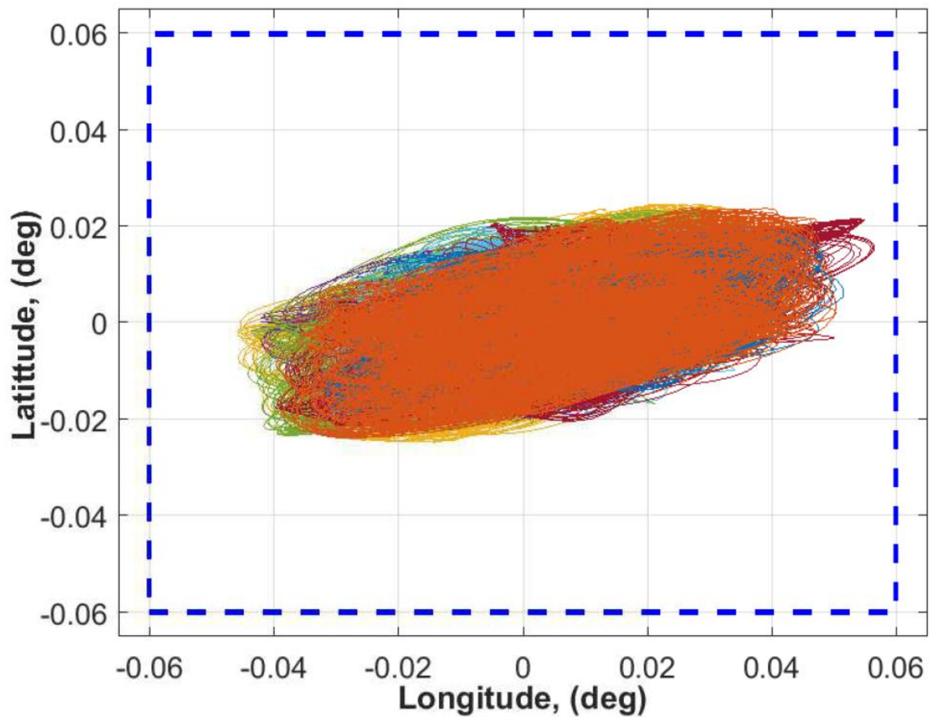
b) Reaction wheels angular velocity

- Radial-Normal separation distance



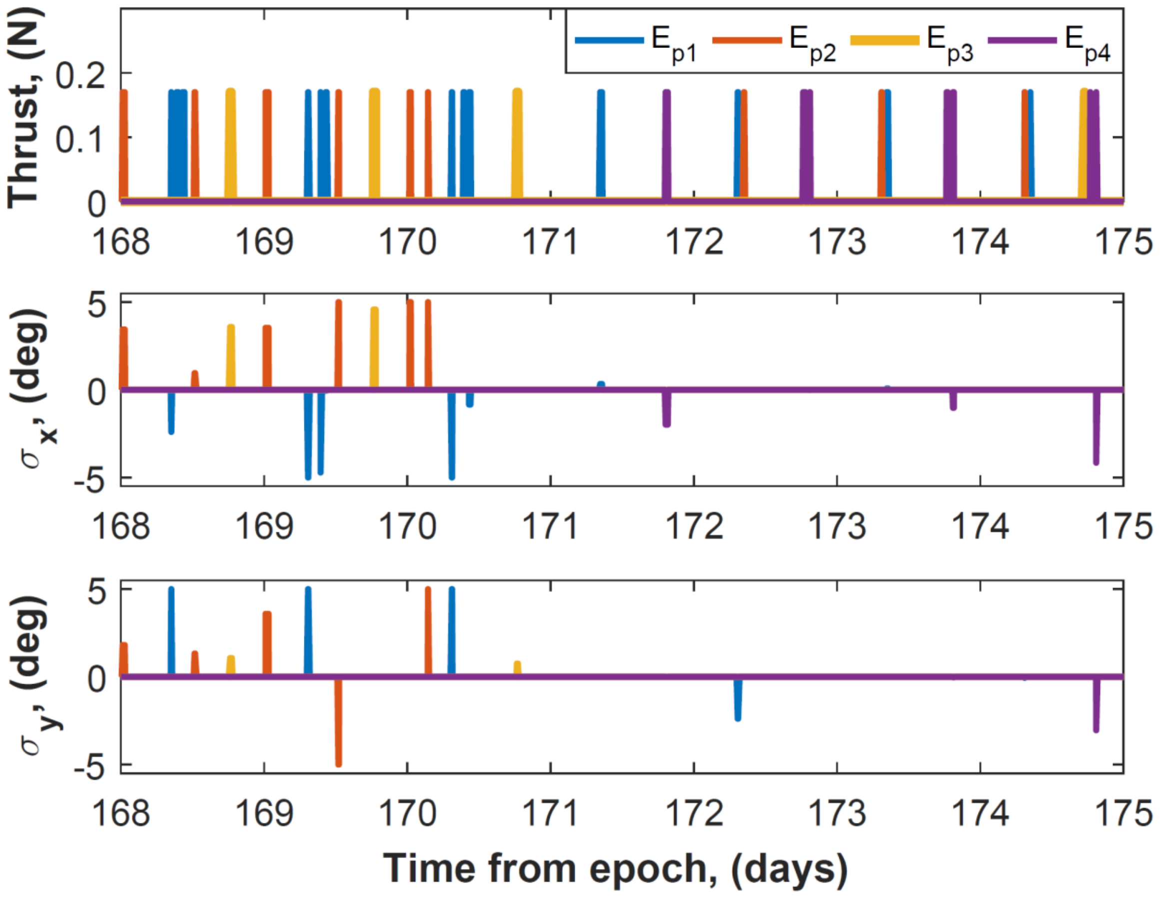
Separation between follower satellite pair F_3 and F_4

- Longitude-Lattitude window

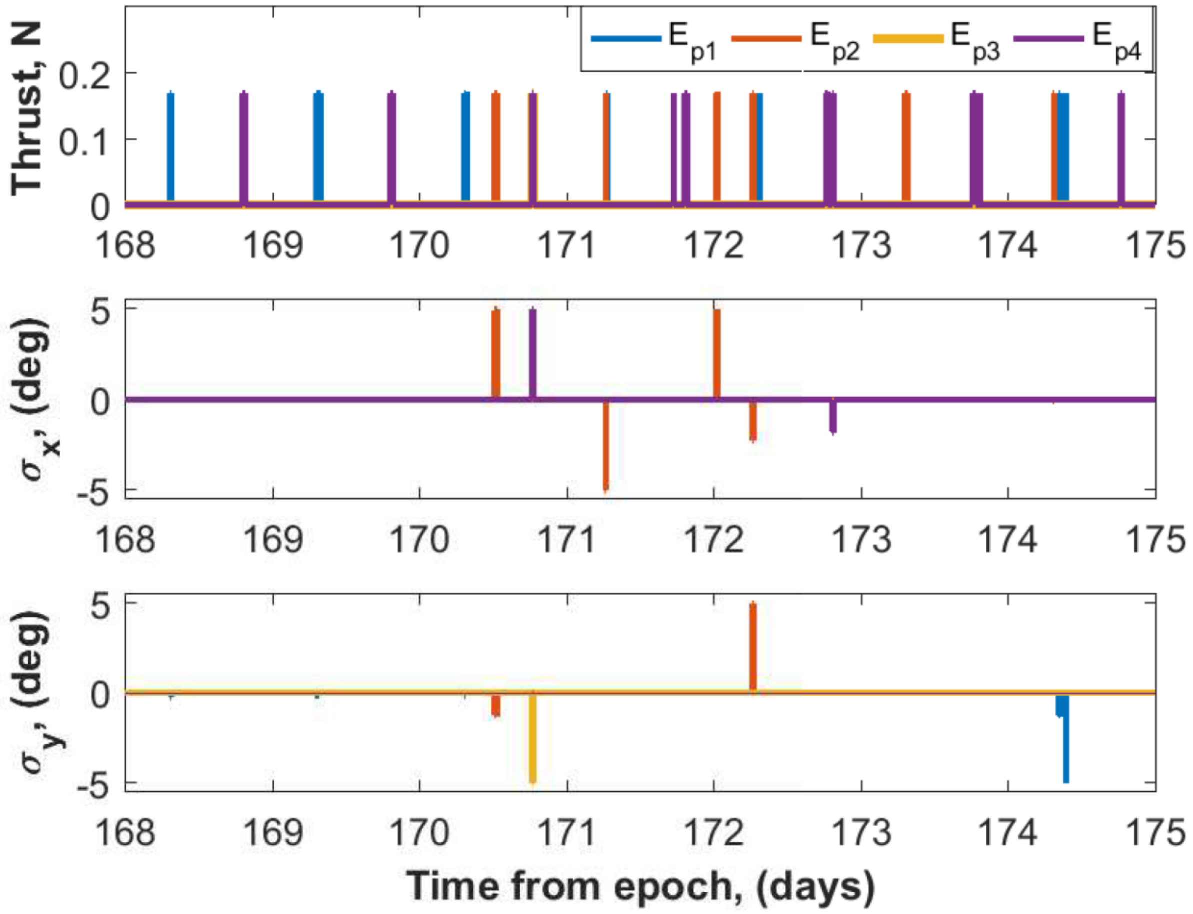


LULEÅ UNIVERSITY OF TECHNOLOGY

- Exemplary one week maneuver plan



a) Leader satellite maneuver plan

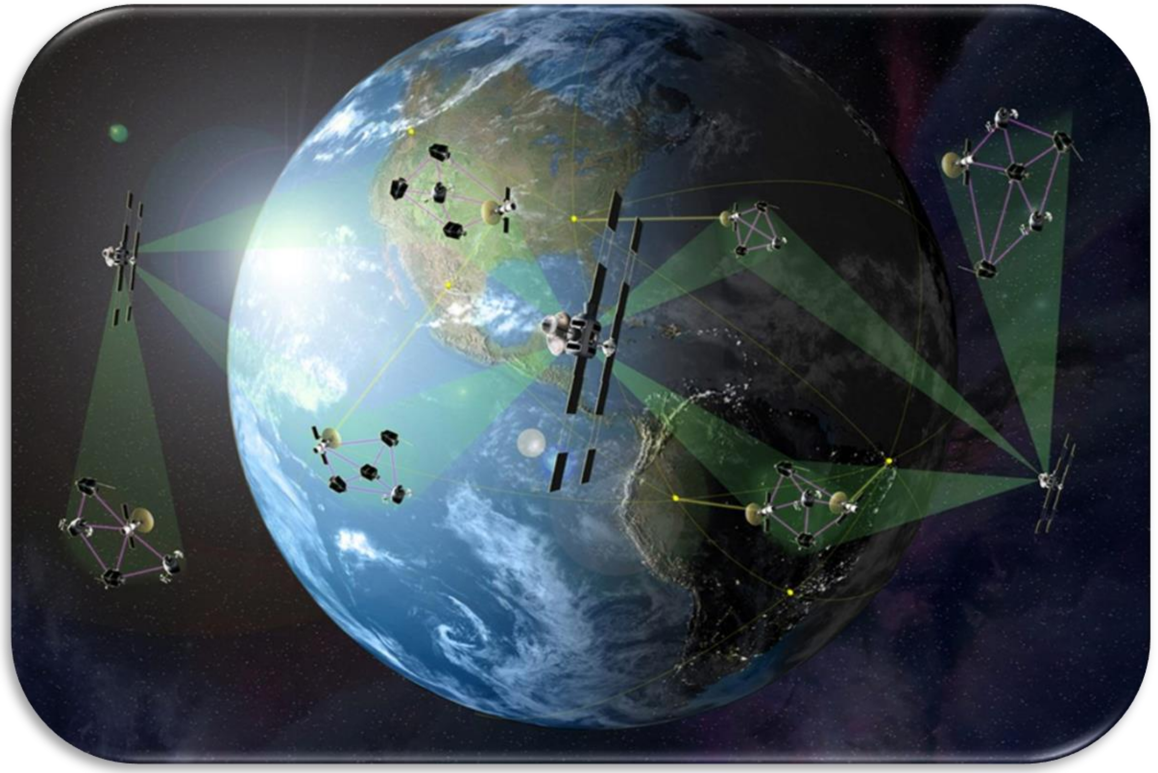


b) Follower satellite maneuver plan

- Fuel consumption
  - The leader satellite consumed about $85.9\ m/s$ of delta-v
  - On an average $74.5\ m/s$ of delta-v is consumed by each follower satellite

LULEÅ UNIVERSITY OF TECHNOLOGY

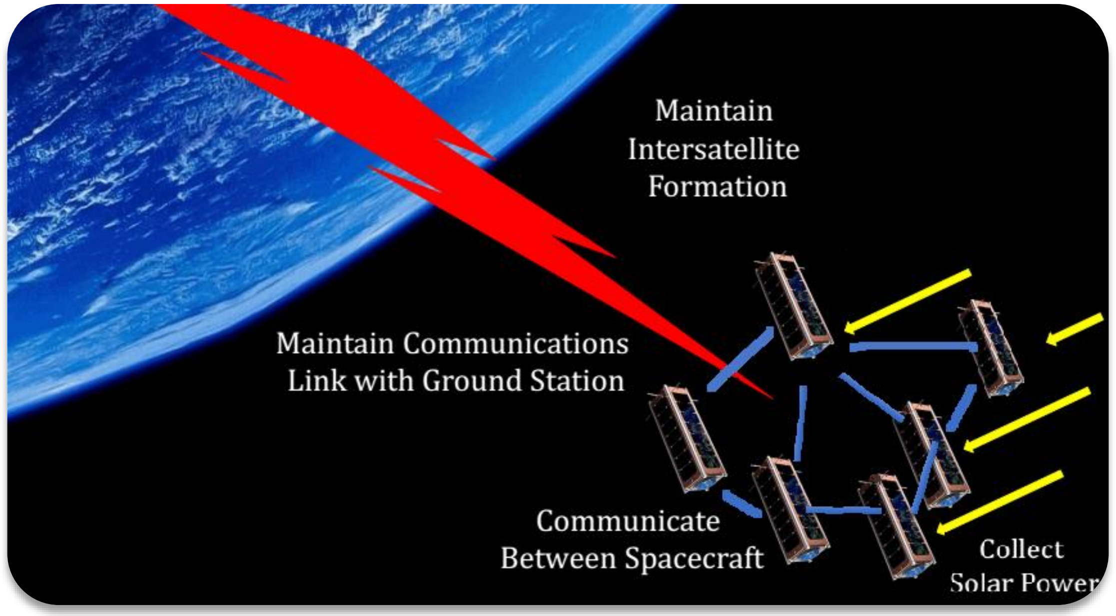
Multi-spacecraft Formation



Credits: DARPA

Research Direction

- Design a *multi-spacecraft formation architecture*
  - *Maintain inter-spacecraft formation*
  - *Fault tolerant capability*
  - *Maintain communication*



Bandyopadhyay et al.

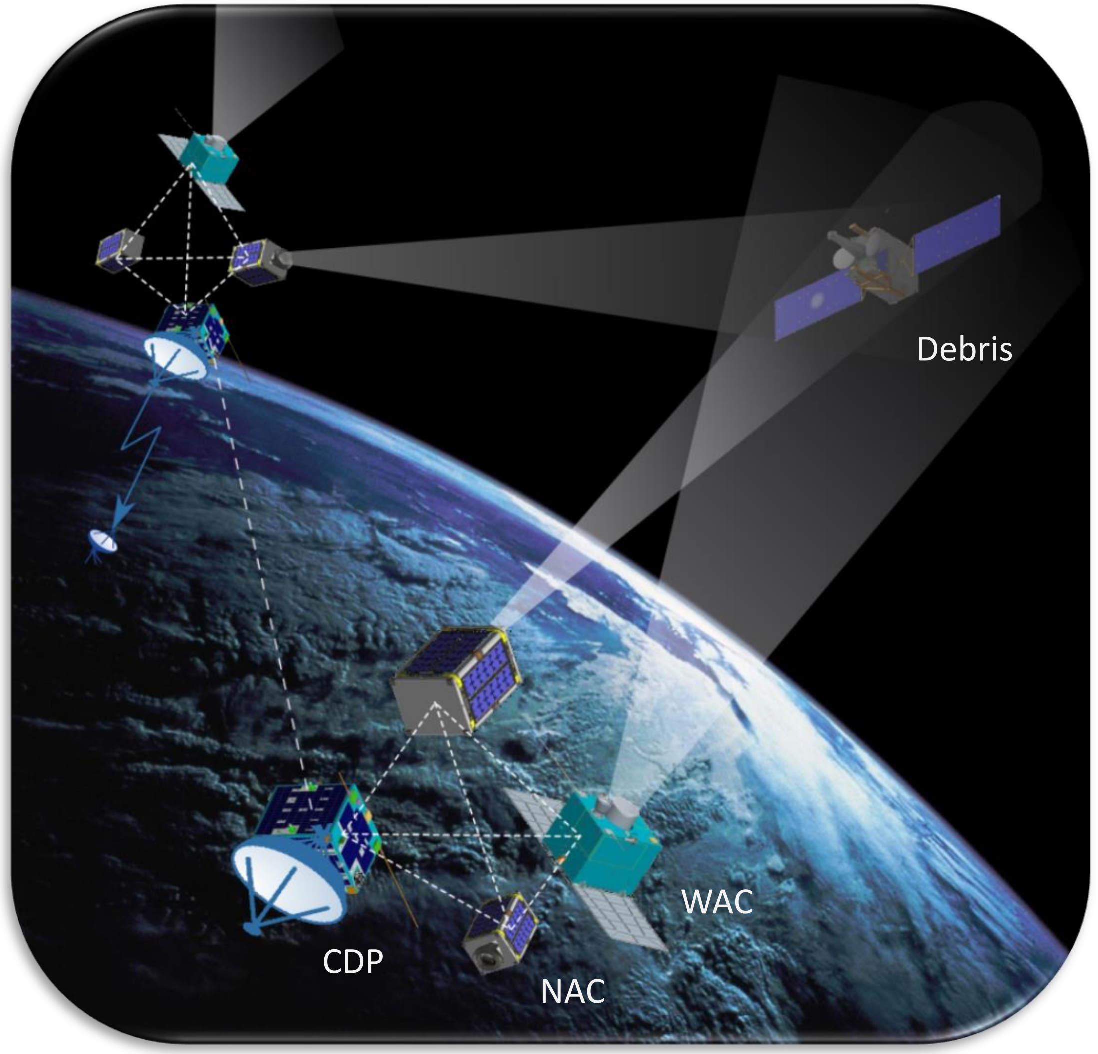
- Formation performance enhancement: *concurrent individual and social learning*
- Formation Reconfigurability: *Dynamic team formation*

Image Ref: Bandyopadhyay, Saptarshi, et al. "A review of impending small satellite formation flying missions." *53rd AIAA Aerospace Sciences Meeting*. 2015.

LULEÅ UNIVERSITY OF TECHNOLOGY

Work in Progress

- *Host-Agent-Avatar (HAA):* A modular architecture for distributed systems
  - Host: Mobile or stationary processors
  - Agent: Control system software modules
  - Avatar: Physical hardware (satellite platform)
- Design a debris surveillance system using HAA architecture
- Constellation mission consisting of fractionated spacecraft
  - Wide-angle camera (WAC)
  - Narrow-angle camera (NAC)
  - Communication and data processing (CDP)



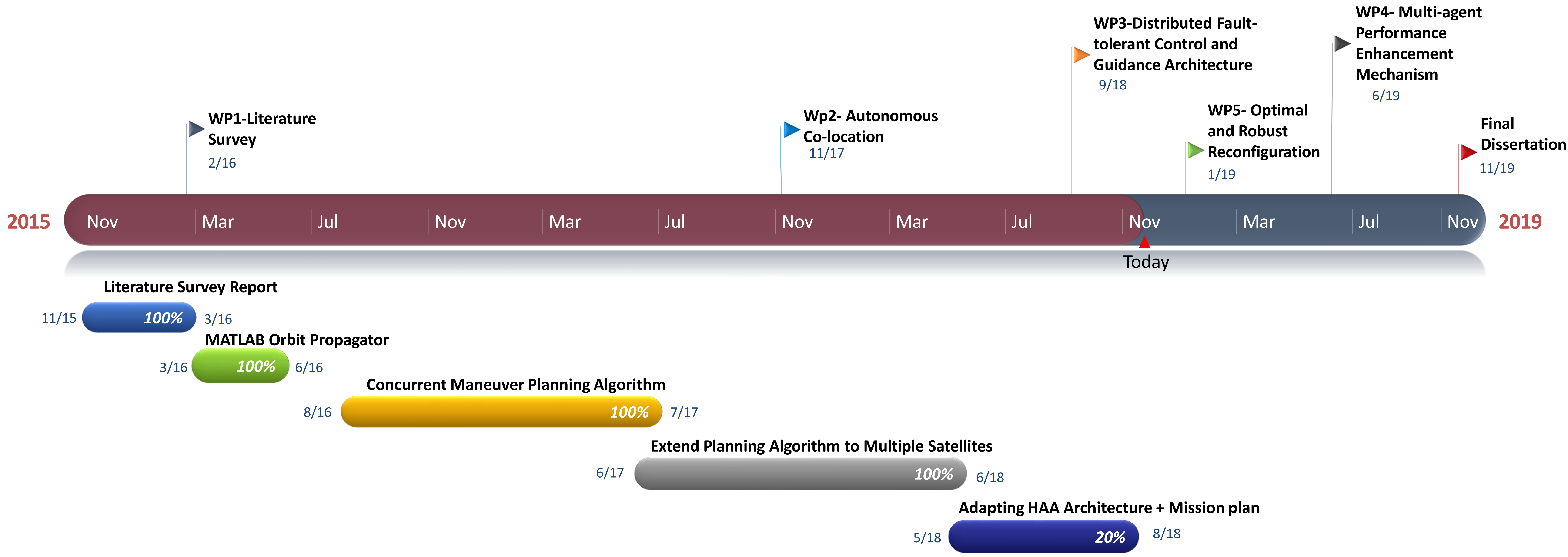
Space Surveillance Mission using fractionated spacecraft

Publications

- Conferences Publications:
  - S. Satpute, M. R. Emami, “*Concurrent maneuver planning for geostationary satellites*”, IEEE Aerospace Conference, 2018.
  - S. Satpute, M. R. Emami, “*Optimal maneuver planning for the co-location of geostationary satellites*”, Conference on Dynamics and Control of Space Systems, 2018.

- Journal Publications:
  - S. Satpute, M. R. Emami, “Concurrent station keeping and momentum management of geostationary satellites”, *The Journal of the Astronautical Sciences*, 2018 (Under review)
  - S. Satpute, M. R. Emami, “Concurrent co-location maneuver planning for geostationary satellites”, *Acta Astronautica, 2018.*

Timeline



LULEÅ UNIVERSITY OF TECHNOLOGY

Thank You