Critical Orbit Control Issues for Fractionated Spacecraft

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Agenda

- **Issues**
  - What are the important issues related to orbit control?
- **Experience**
  - What experience do we have in these areas?
- **Examples**
  - Passive collision avoidance with "safe formations"
  - The effects of navigation uncertainty

"Engineers like to solve problems.

If there are no problems handily available,
they will create their own problems."

– Scott Adams

Motivation

- This fractionated paradigm is motivated by the ideals of:
  - Flexibility
  - Robustness
  - Economy

- While the paradigm itself is a solution to many problems, it also brings new challenges.

- Success depends on several technologies:
  - Distribution of power and actuation
  - Docking and resource transfer systems
  - Relative navigation
  - **Orbit control**

Orbit Control Issues

Now that we've broken it into all of these pieces…
How do we control the orbit?

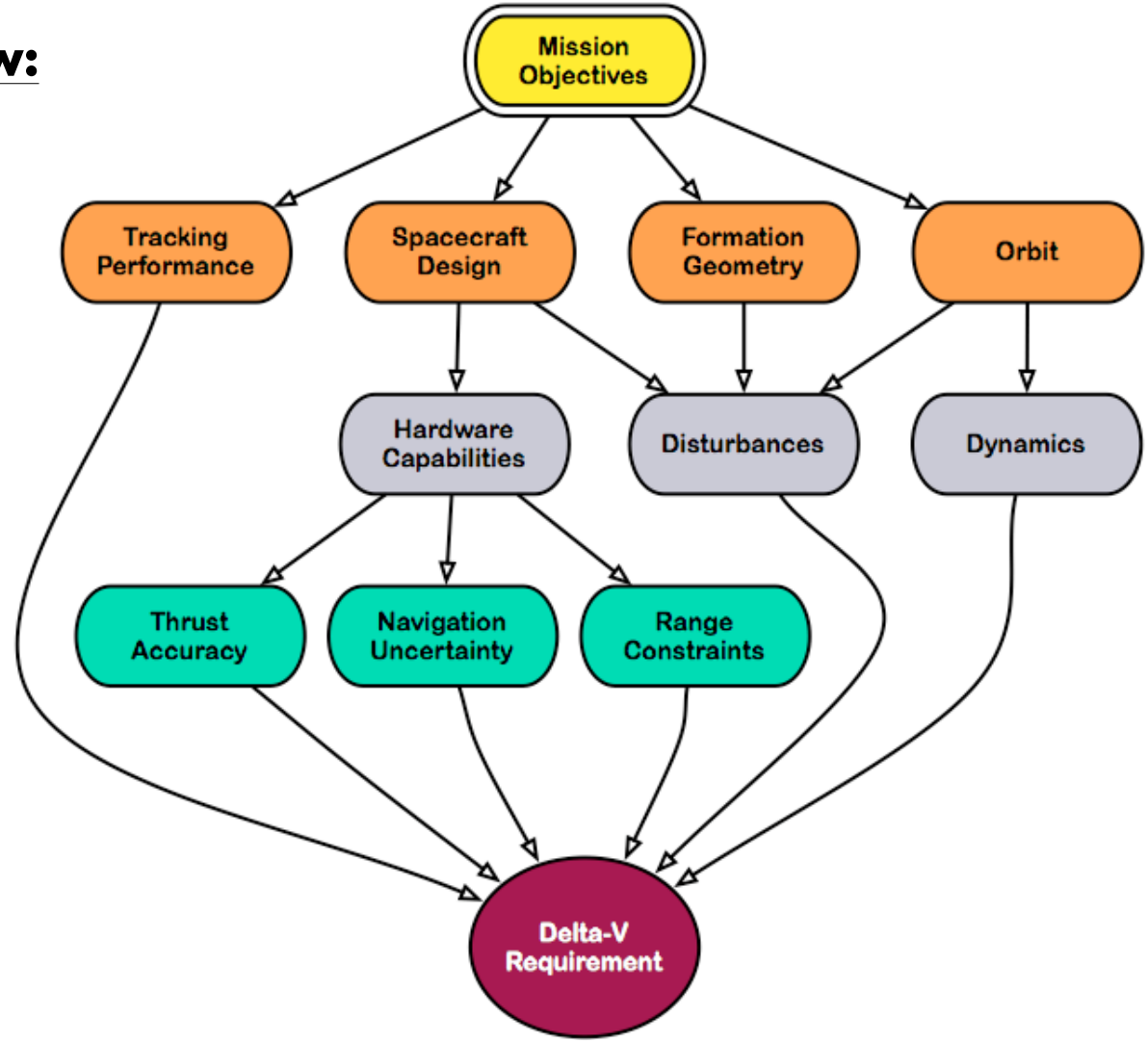
- We must consider ***ALL*** aspects of orbit control:
  - Collision Avoidance
  - Relative orbit control
    - Formation Flying
    - Cluster-Maintenance
  - Absolute station-keeping
    - About 55 m/s annual delta-v for GEO
    - Fewer, larger maneuvers
    - How to do this with a distributed system?

Delta-V Requirement?

Orbit Control Issues

Requirements Flow:

- Relative Orbit Control
  - Formation Flying
  - Cluster-Maintenance



Orbit Control Issues

Requirements Flow:

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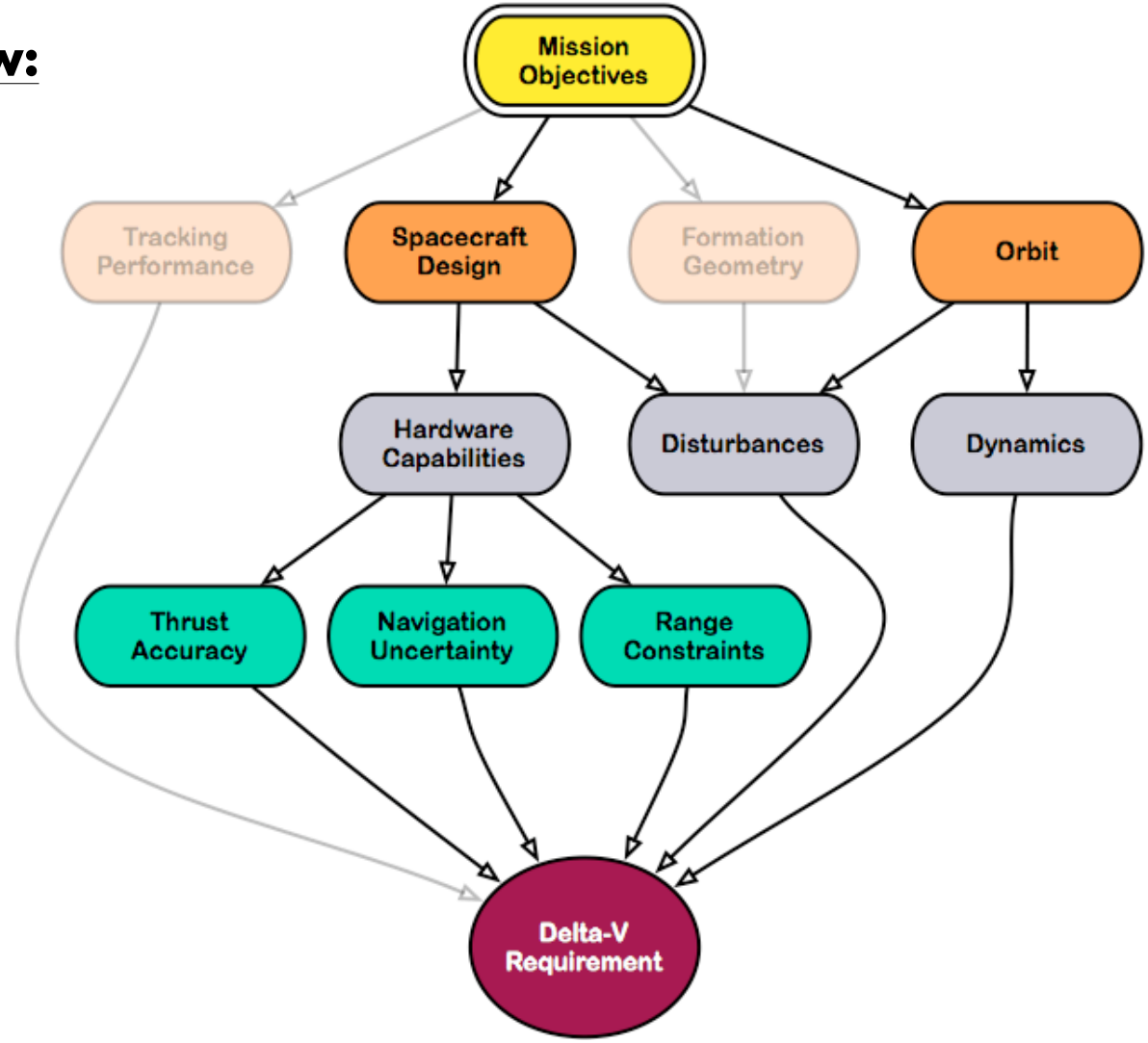
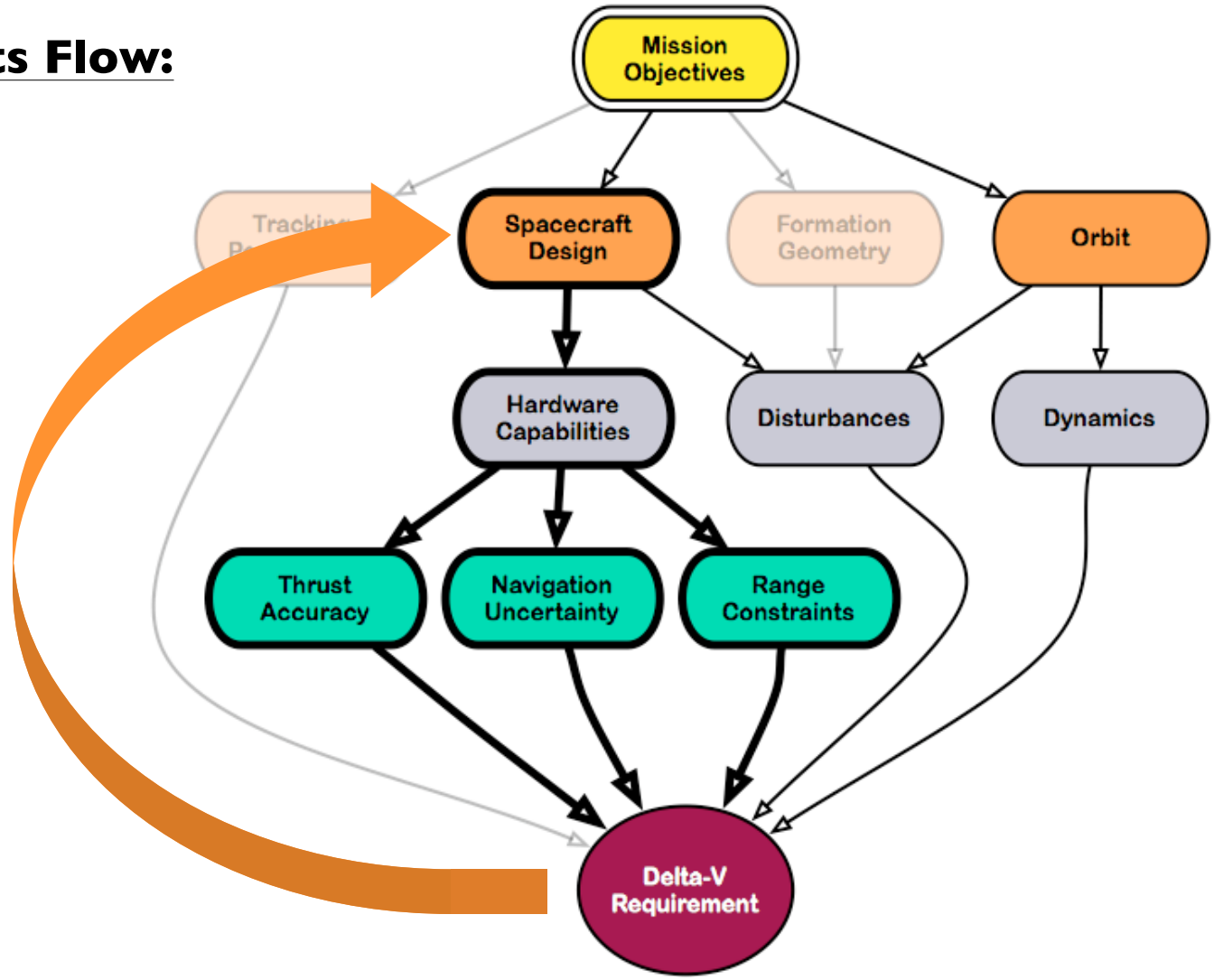


Orbit Control Issues

Requirements Flow:

Must Close the Design Loop to Ensure Feasibility



Orbit Control Issues

Important Questions:

- What is the propulsion capability at each node?
  - Fully distributed vs. Partially distributed with a fuel tug
- What are the tracking requirements for the mission?
  - Precise formation flying vs. Loose cluster control
- What are the range constraints?
  - Range limits imposed by communication systems
- What are the primary differential disturbances?
  - Earth oblateness, atmospheric drag, solar pressure
- What is the relative navigation uncertainty?

Orbit Control Issues

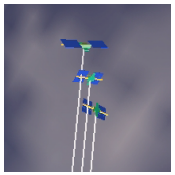
Some Specifics:

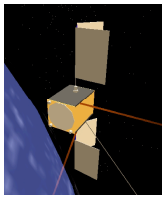
- Even loosely controlled clusters must combat secular drift
  - Differential disturbances, Earth oblateness (J2), Navigation error
- Heterogeneous spacecraft bring differential disturbances
  - Atmospheric drag (LEO)
  - Solar pressure
  - Geometry and Attitude
- Effects of Earth oblateness (J2) depend on the orbit
  - Creates secular drift, linear with time
  - Some effects can be neutralized with choice of relative orbit
- Navigation error
  - Leads to an error in semi-major axis
  - Energy differential → Secular drift

Experience

1999

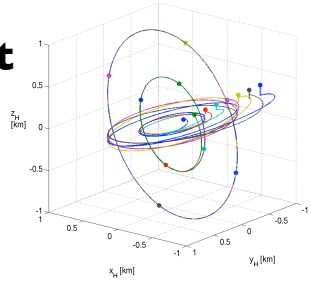
- **TeamAgent Formation Flying**
  - Phase 1-2 SBIR with AFRL Kirtland, TechSat 21



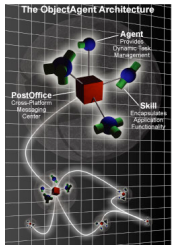


- **Autonomous Rendezvous and Docking**
  - Phase 1-2 SBIR with AFRL Kirtland

- **Autonomous Control of Formation Flying Spacecraft**
  - 3 Year CETDP with MIT, Cornell



- **Integrated Multi-Range Rendezvous**
  - Phase 1 SBIR with NASA Marshall

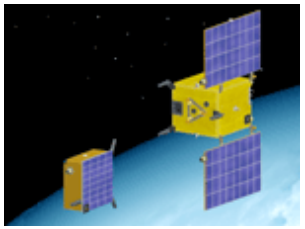


- **Defensive Counter Space - Escort Satellites**
  - Phase 2 SBIR with AFRL Kirtland

- **Decentralized Formation Flying Control System**
  - Phase 1-2 SBIR with NASA Goddard

Present

- **PRISMA**
  - CRADA with Swedish Space Corporation, Launch 2008



Experience

- We focus on **practical implementation** of formation flying technology:
  - How to achieve autonomy with efficiency and robustness?
  - How to scale effectively to large clusters?
  - How to deal with disturbances and hardware constraints?
  - How to develop a fault management plan for the cluster?

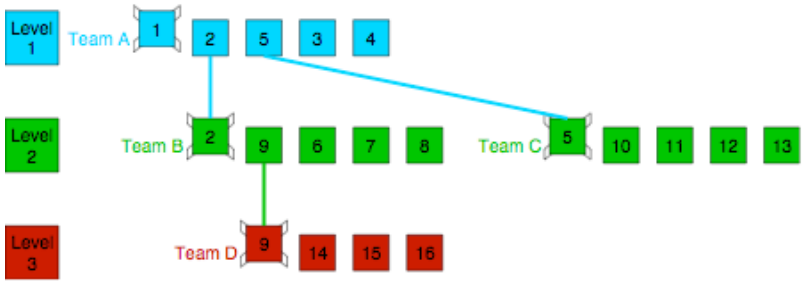
- **Capabilities:**
  - Real-time fuel optimal maneuver planning
  - Model Predictive Control
  - Decentralized Guidance and Control Methods
  - Scalable Architectures
  - Autonomous Cluster Management
  - Collision monitoring using set membership theory
  - Safe guidance methods for collision avoidance (PRISMA)

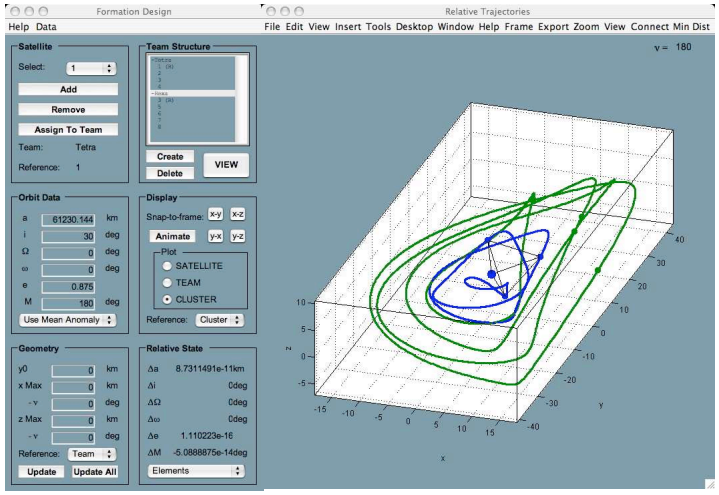
DFF

- Decentralized Formation Flying
  - Phase 1-2 SBIR
  - NASA Goddard

- Scope and Objectives:
  - Guidance and Control
  - Scalable to large systems
  - Extensible to different orbit regimes and spacecraft designs
  - Autonomous Initialization
  - Autonomous Reconfiguration

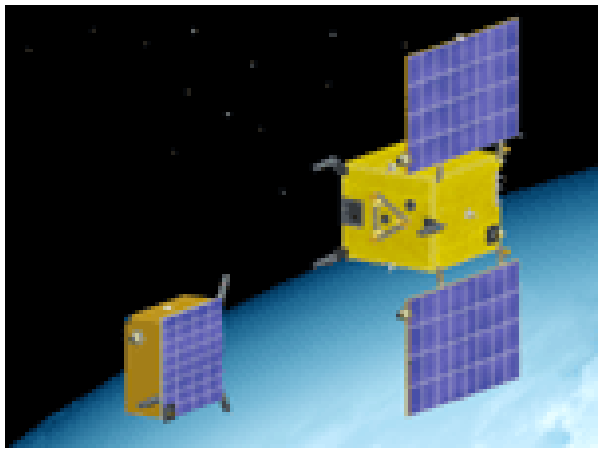
- Fractionation:
  - Hierarchical team framework
  - MANTA middleware

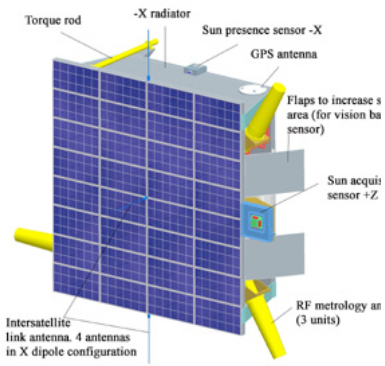


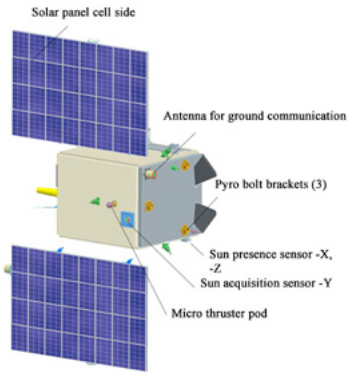


PRISMA

- PRISMA Rendezvous Robots
  - CRADA
  - Swedish Space Corporation (SSC)
  - 2 Spacecraft in LEO
  - Launch 2008
  - GNC Demonstrations:
    - Formation Flying
    - Rendezvous
    - Proximity Operations



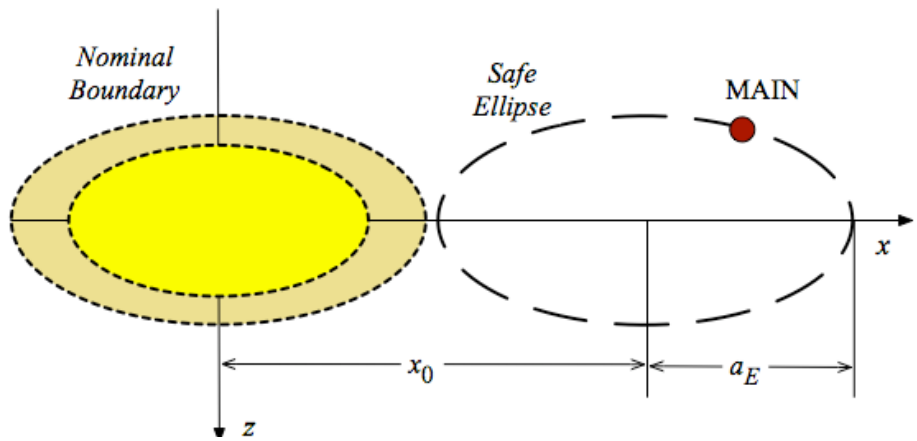


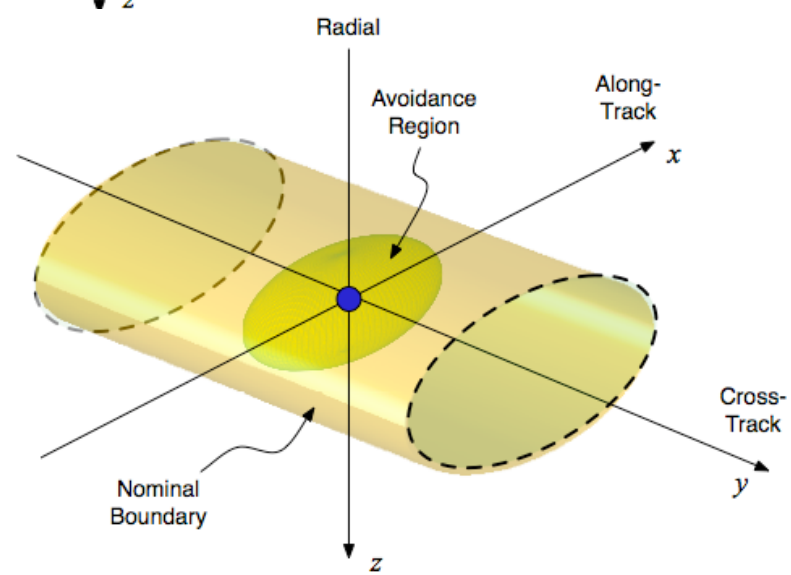


- PSS Developing Algorithms for:
  - Safe Orbit Guidance
  - Collision Monitoring

Safe Orbit Guidance

- Passive collision avoidance
  - Minimum level of effort for relative orbit control
- 2 Guidance Modes
  - Separation
  - Nominal
- Avoidance Region
  - 2x1x1 Ellipsoid

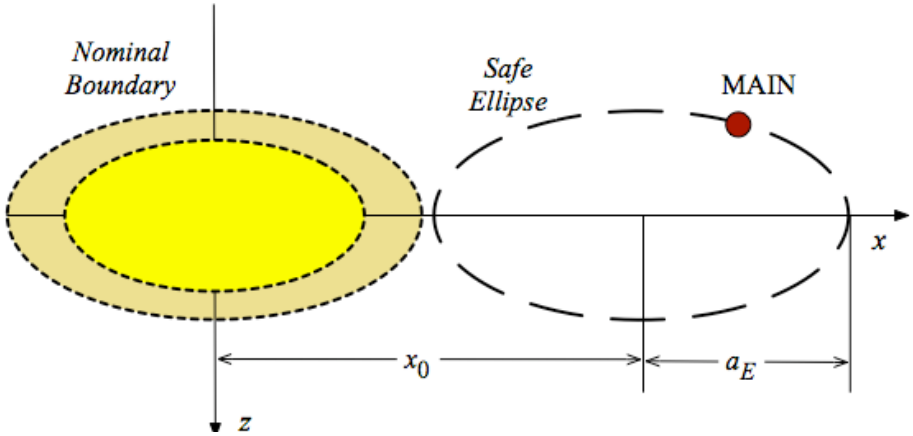


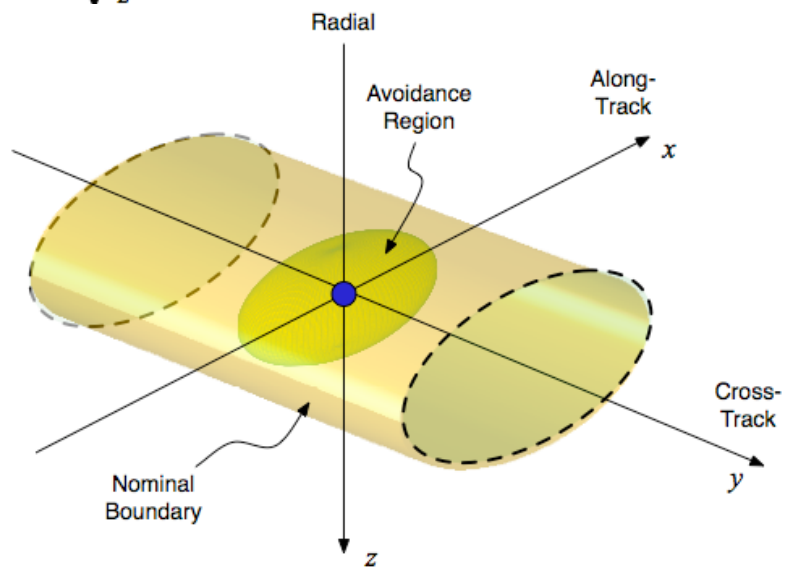


Safe Orbit Guidance

Objectives

- Separation Guidance
  - Single burn
  - Exit region by time T
  - Monotonic separation
  - Passively safe - never reenter region
- Nominal Guidance
  - Achieve and maintain safe ellipse
  - Fuel efficient



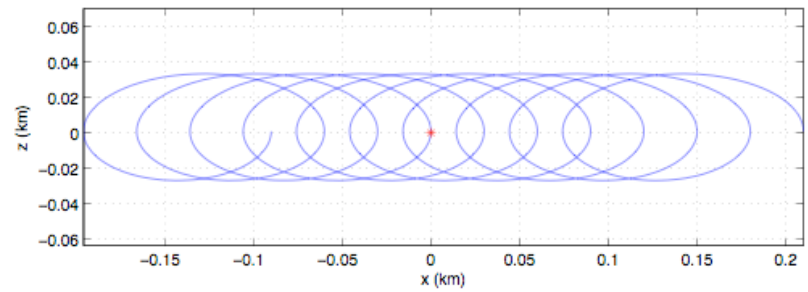


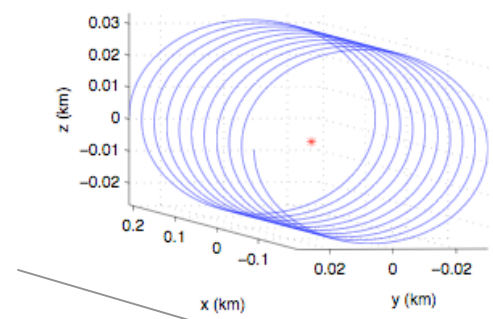
Safe Orbit Guidance

- Safe Ellipse:
  - T-Periodic, or passively stable trajectory
  - Lies outside a "nominal boundary"
  - Coordinated in-plane and cross-track motion
  - Prevents collisions while allowing along-track drift

- Fractionated Missions?
  - Can be applied to large clusters, but increases the maximum range
  - A challenge is to combine safe orbit designs with mission objectives

Orbit-Plane



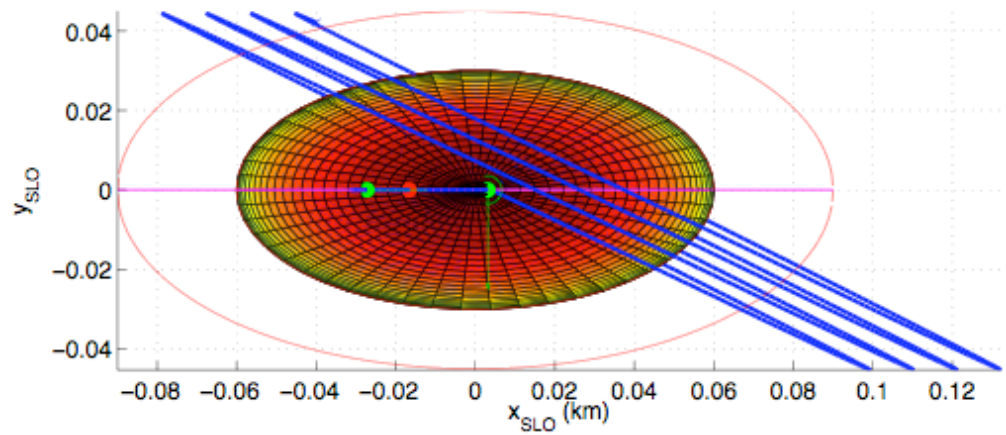


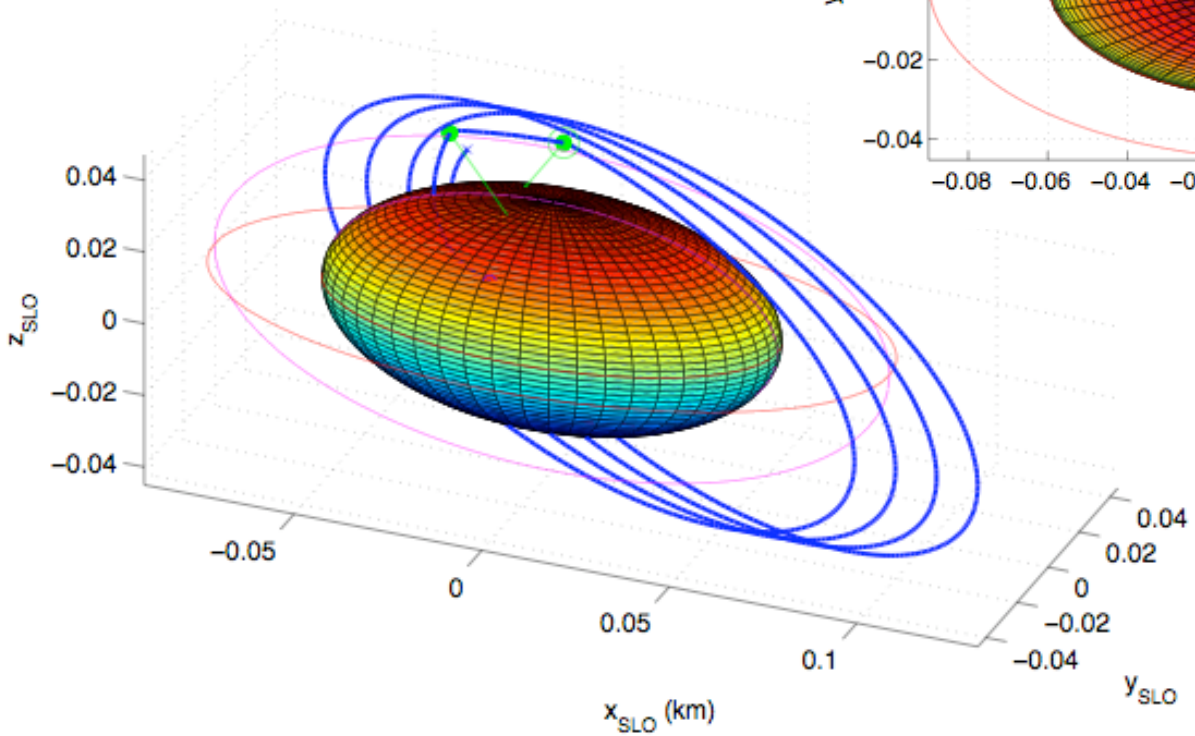
Along-Track

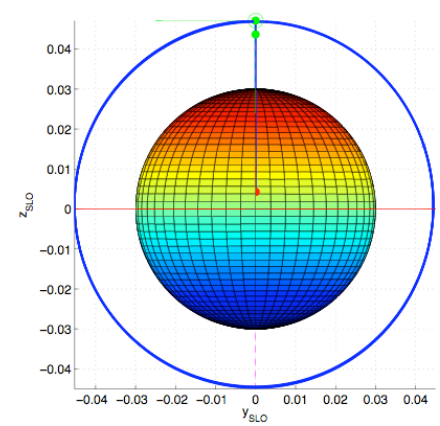
Safe Orbit Guidance

Drifting Safe Ellipse

Drift due to Navigation Error







Safe Orbit Guidance

Deformation

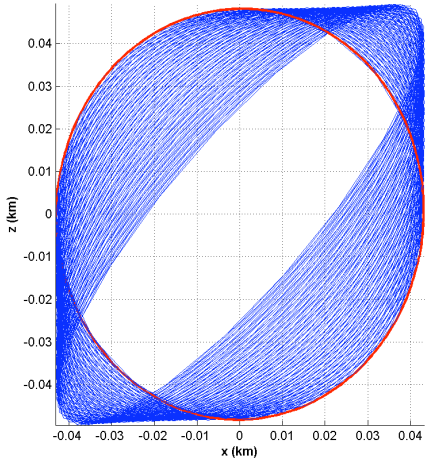
Due to J2

42 Day Period

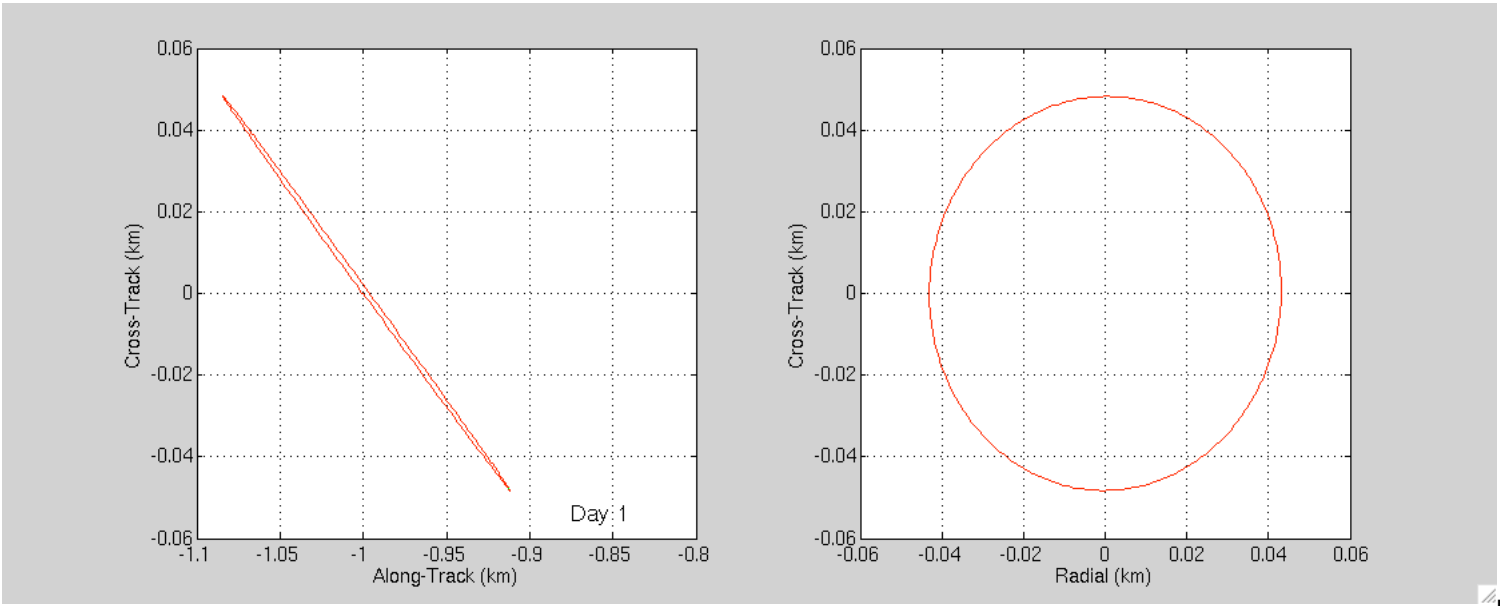
LEO

- Along-Track Drift
- Radial Growth
- In-plane / Cross-track Phase Shift

1 Week Trace:



3 Week Animation:



Navigation Error

- Common to all missions, all orbits
- Significant impact on performance and safety
  - Annual Delta-v
  - Collision Probability
- How does it impact cluster-maintenance?
  - Monte Carlo Analysis
- Model predictive control
  - Maneuver planned when position error exceeds deadband
  - Parameters:
    - Deadband
    - Maneuver duration

Navigation Error

- Parameters of the Monte Carlo Simulation
  - No disturbances, Zero Eccentricity
  - Each case is simulated for 2 weeks
  - Random noise
  - Results are **averaged** from 150 runs

- Altitudes
  - LEO
  - GEO

- Deadband
  - 25 m
  - 50 m
  - 100 m

- Noise Levels
  - Position: 1.0 to 10 cm
  - Velocity: 0.5 to 5 mm/s

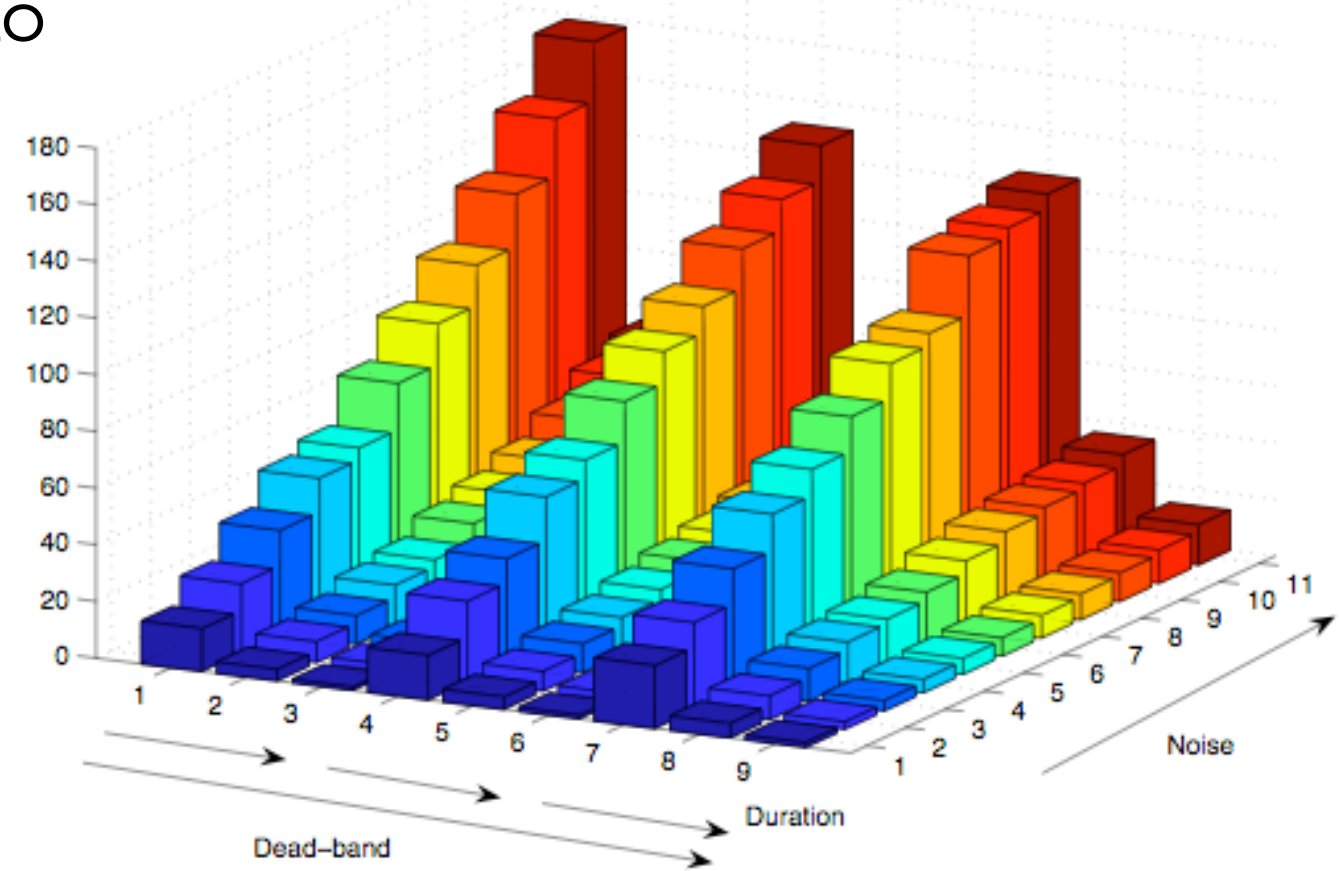
(CDGPS Level)

- Maneuver Duration
  - 30 min
  - 60 min
  - 120 min

Navigation Error

Annual Delta-V (m/s)

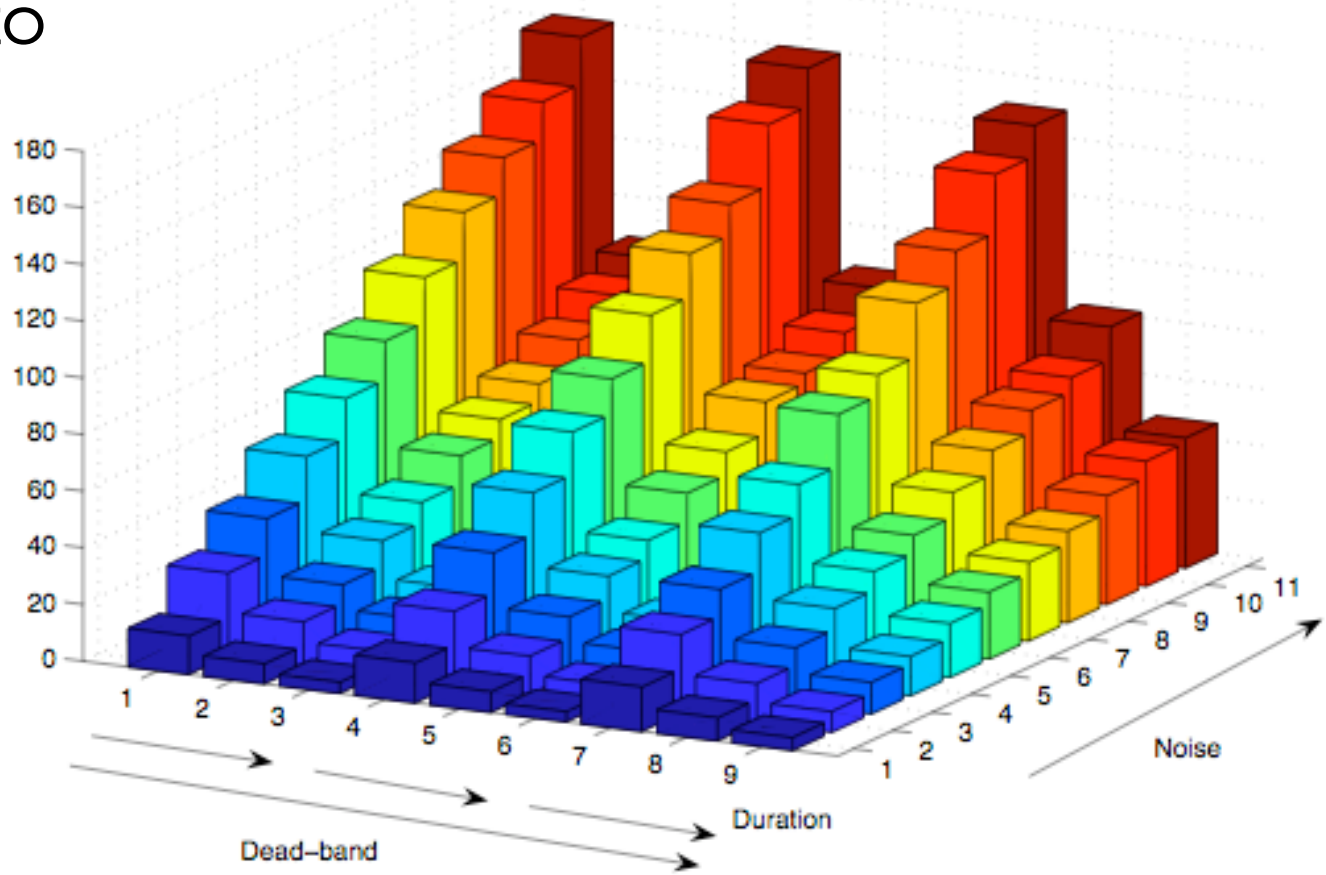
LEO



Navigation Error

Annual Delta-V (m/s)

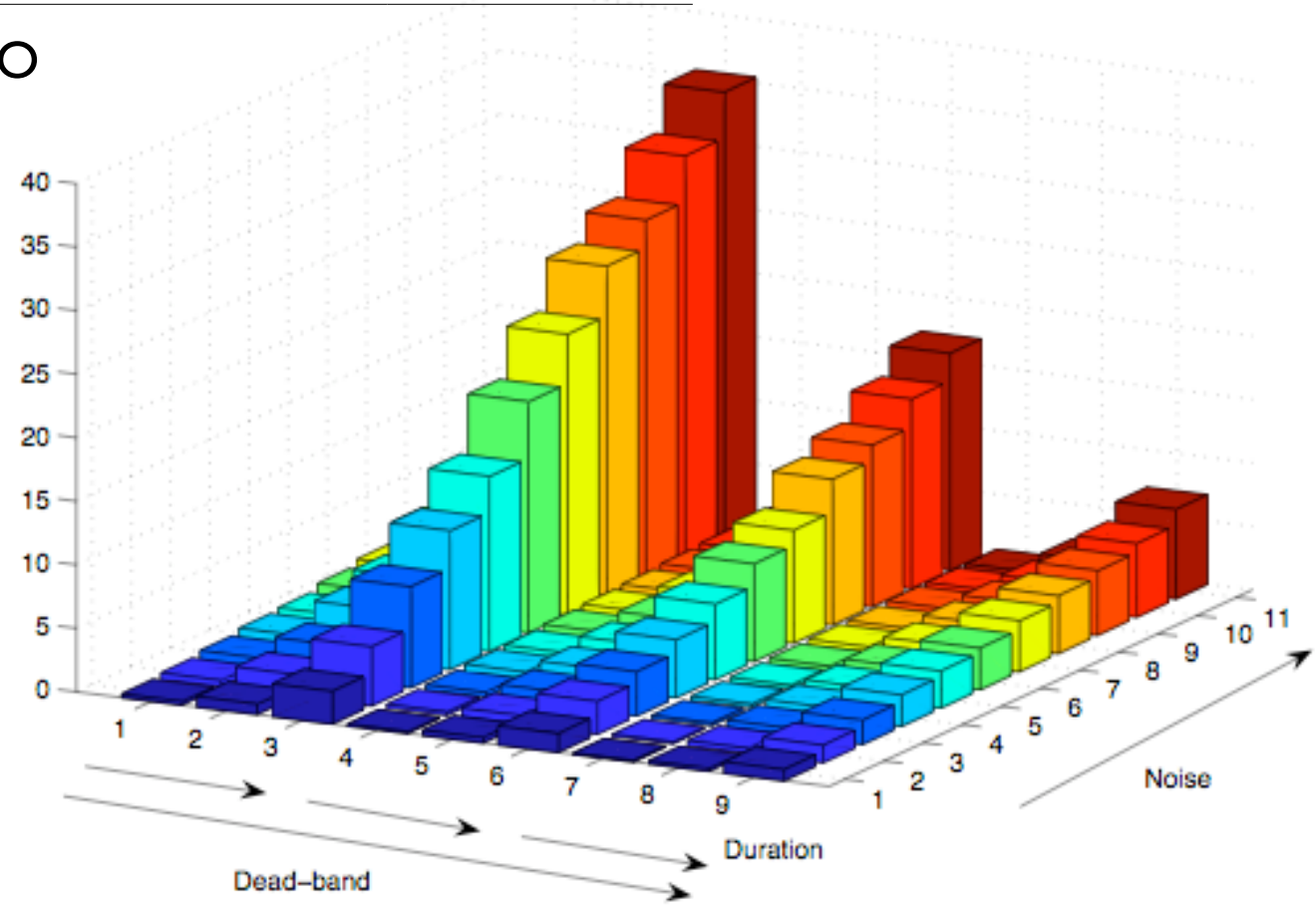
GEO



Navigation Error

% Time Outside Deadband

LEO



Navigation Error

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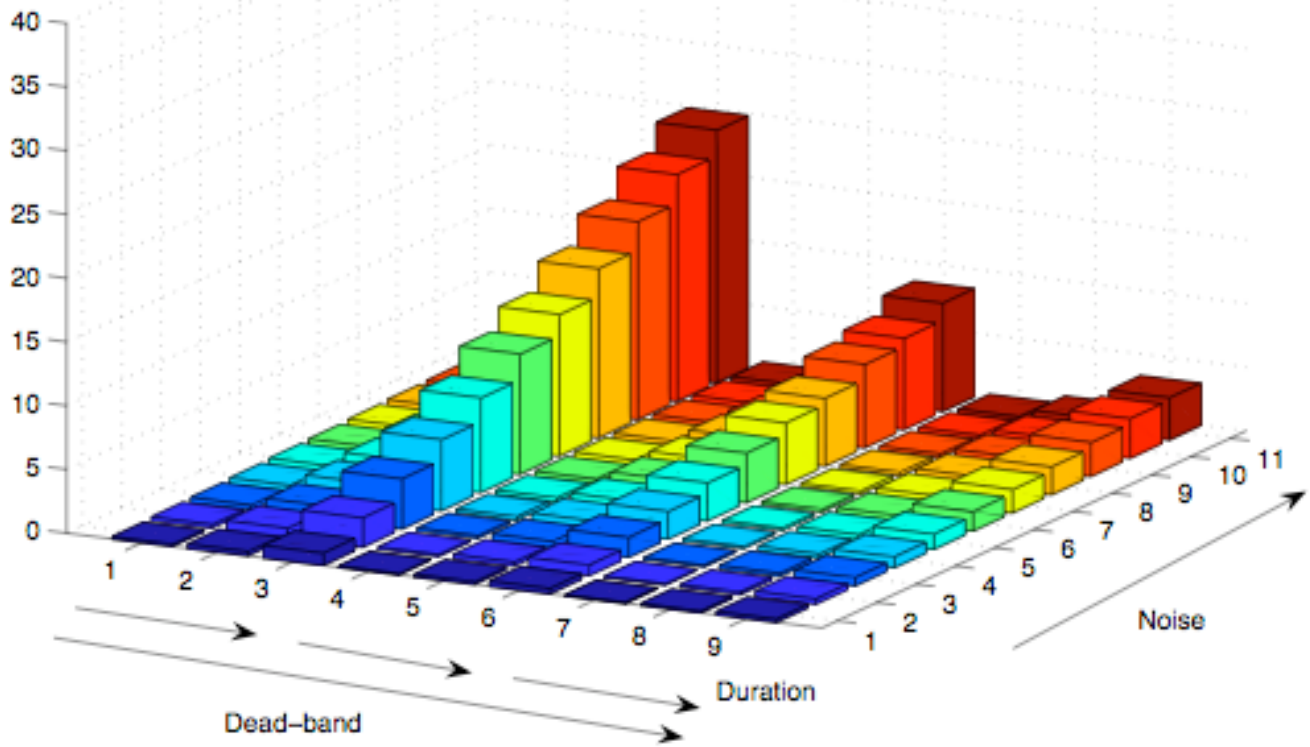
GEO



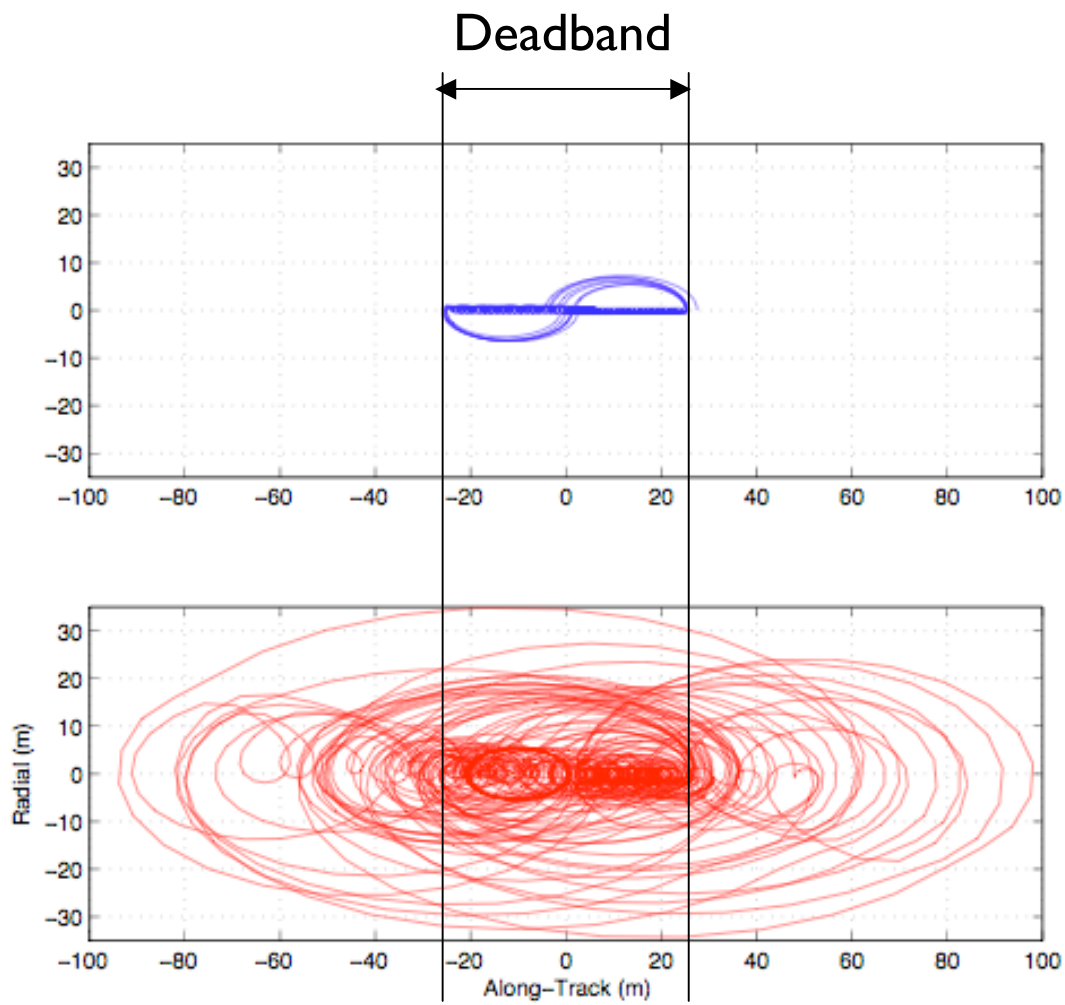
Navigation Error

Trajectory

LEO

Low Noise

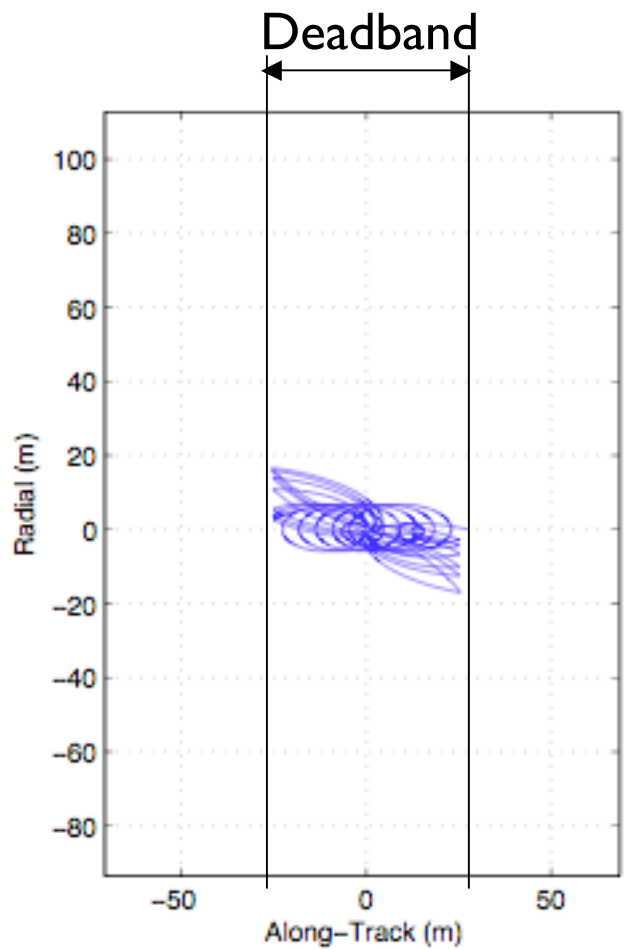
High Noise



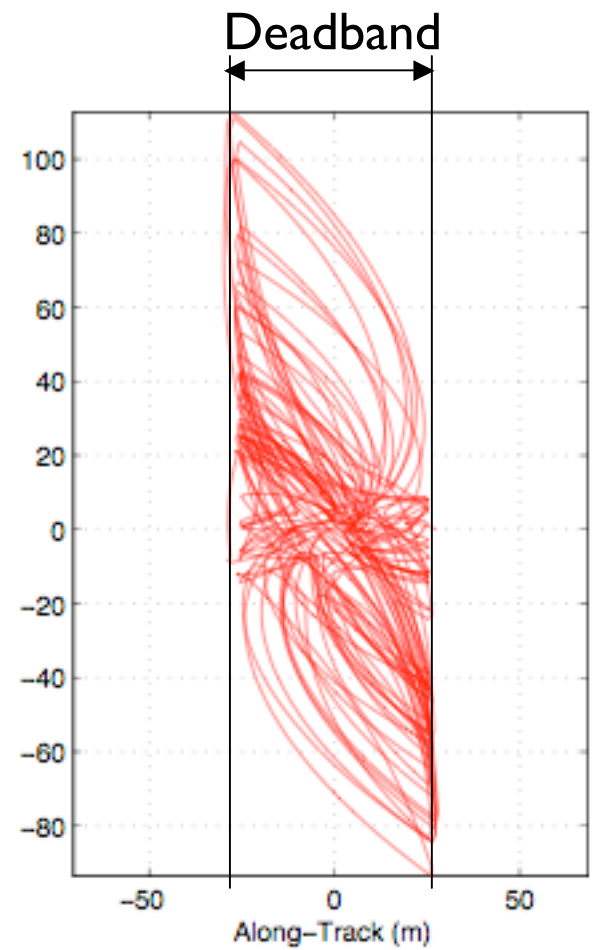
Navigation Error

Trajectory

GEO



Low Noise



High Noise

Concluding Remarks

- Orbit Control for Fractionated Spacecraft
  - Relative Station-Keeping
  - Absolute Station-Keeping
  - Collision Avoidance

- Important questions:
  - How to perform large-scale station-keeping maneuvers with whole cluster?
  - How to best distribute propulsive capabilities to cluster elements?

- Propulsion Requirements
  - Derived from Mission Req's and Spacecraft Design
  - Even "loose" clusters will require moderate delta-v capability
  - Are these requirements feasible for fractionated missions?

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