

LEOP (Launch and Early Operational Phase)

Flight Dynamics and Satellite Operations

04/11/2025

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LEOP (Launch and Early Operational Phase)

Flight Dynamics and Satellite Operations

Summary

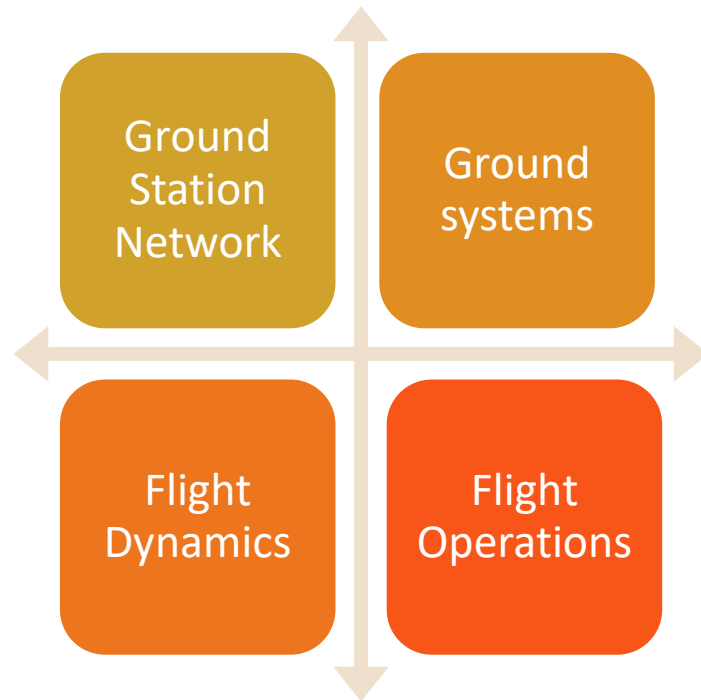
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Roma – 04/10/2025



Entities involved during a LEOP

- **Ground Station Network** – Provides global telemetry, tracking, and command (TT&C) coverage.
- **Ground System** – Integrates mission control infrastructure and software (e.g., EASE Mission Software).
- **Flight Operations** – Manages platform activation, subsystem checkout, and transition from launch separation to nominal orbit operations.
- **Flight Dynamics** – Guidance and Navigation





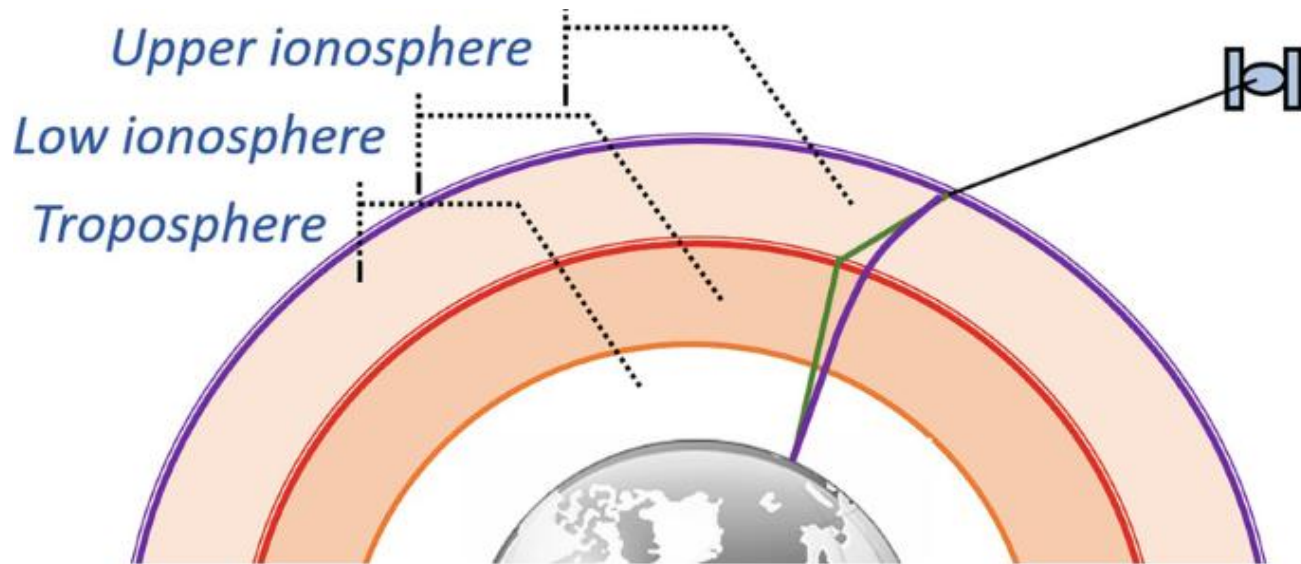
Ground Station Network

Ground stations form the backbone of LEOP operations, enabling continuous spacecraft monitoring, control, and orbit determination.

- **Telemetry, Tracking & Command (TT&C):** Provide real-time communication links with the spacecraft to uplink commands and downlink telemetry during all LEOP phases.
- **Measurement Generation:** Stations acquire and deliver tracking measurements.

Measurements from GSN:

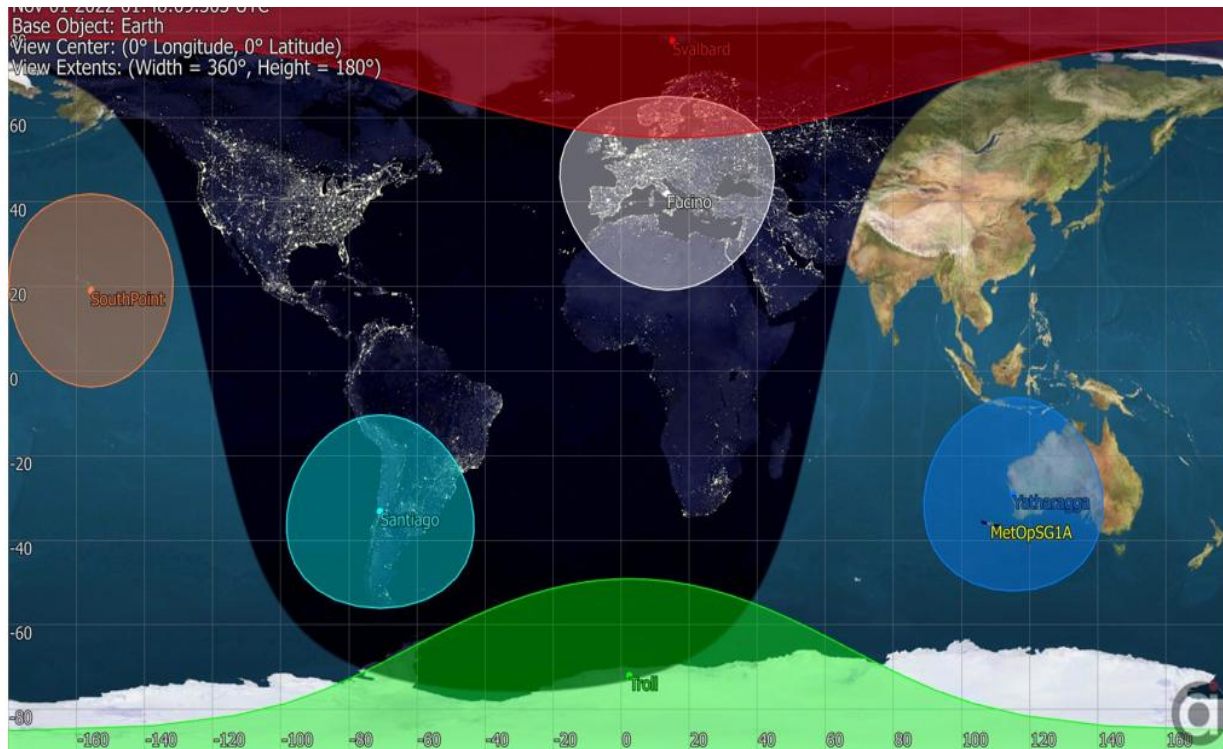
- Angular Measurements
- Range
- Range Rate / Doppler
- Optical Measurements





Ground Station Network: Design Criteria

- **Coverage:** A network of geographically distributed stations ensures visibility across multiple orbital passes and minimizes communication gaps – Mission dependent design e.g. SSO and Moonlight Constellations
- **Redundancy and Reliability:** Overlapping coverage and backup stations guarantee robust communication and operational continuity during critical mission events.





Flight Operations

Leap preparation

- Numerous teams and systems work in parallel - including platform engineers, flight dynamics, ground systems, and mission control.
- **Flight Operation Procedure (FOP):**
 - A predefined sequence of steps and telecommands executed to perform a specific onboard activity (e.g., subsystem activation, configuration change, or maneuver).
 - Designed to ensure repeatability, safety, and full traceability of all commands sent to the spacecraft.
- Continuous coordination and validation are essential to guarantee flawless execution and real-time responsiveness during critical events.



5 years



40 engineers



~600 flight procedures



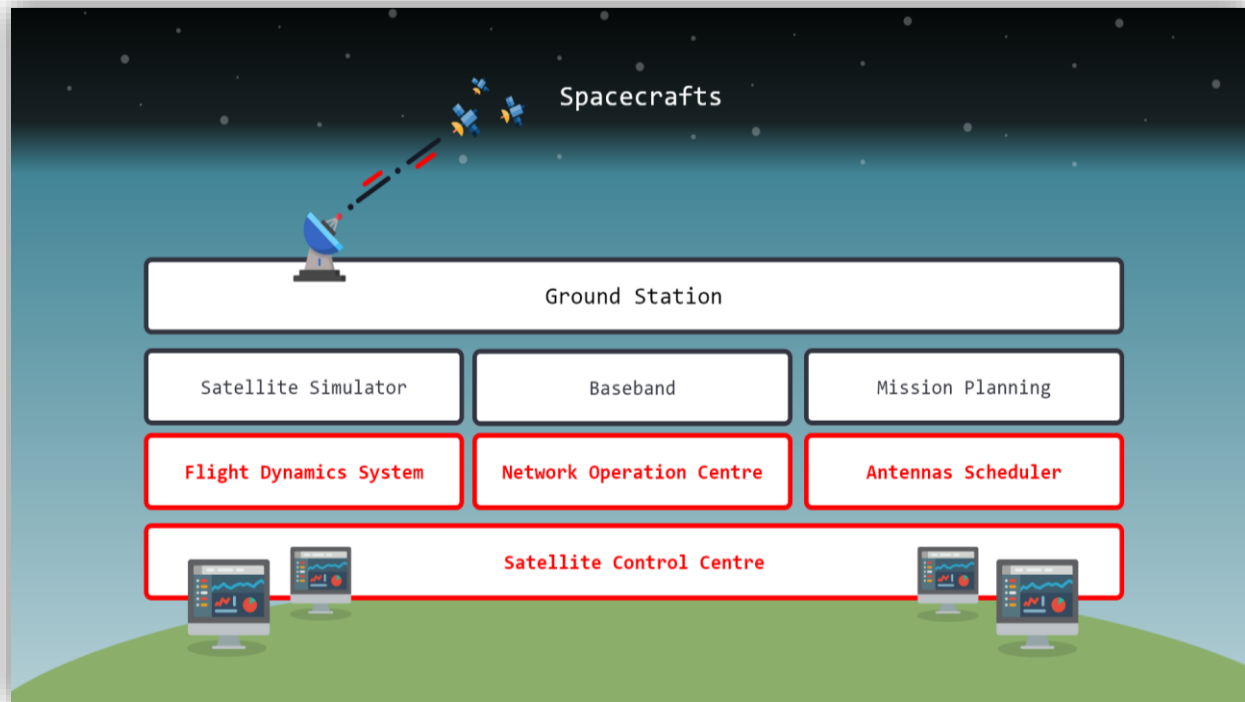
hundreds of simulations



Ground Systems: ease-mission

The EASE Mission System provides the integrated ground infrastructure for LEOP, enabling command execution, telemetry processing, procedure automation, and real-time coordination between spacecraft operations, flight dynamics, and ground stations.

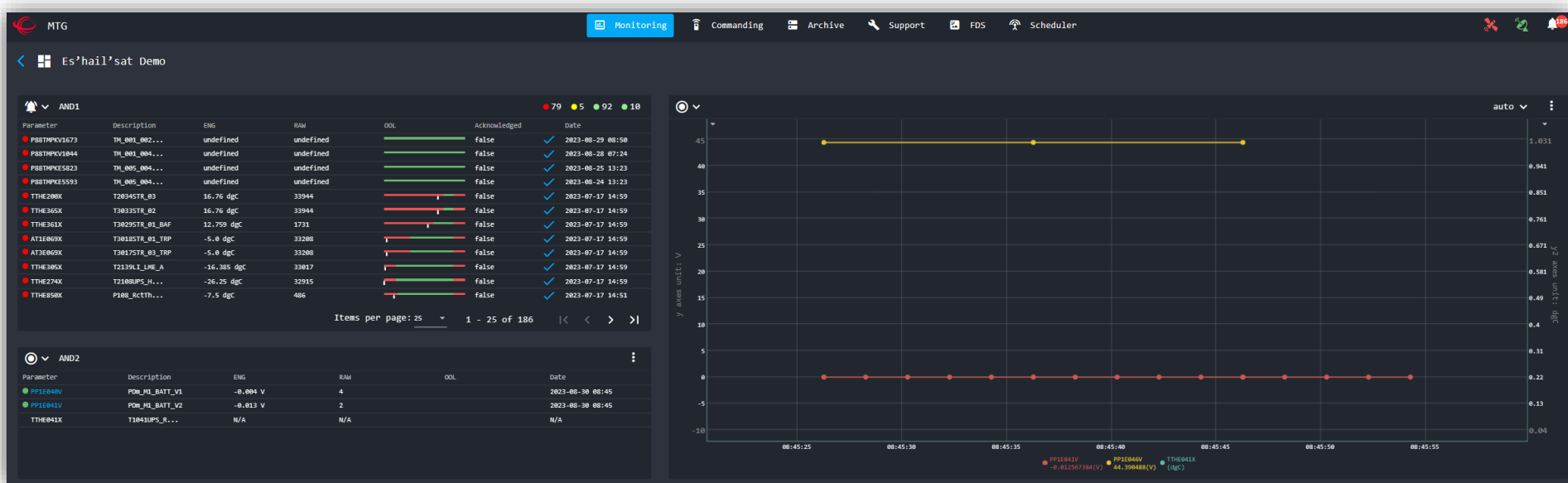
- Satellite Control Center (SCC)
- Flight Dynamics System (FDS)
- Network Operation Center (NOC)
- Antenna Scheduler (SCHED)





Ground Systems:

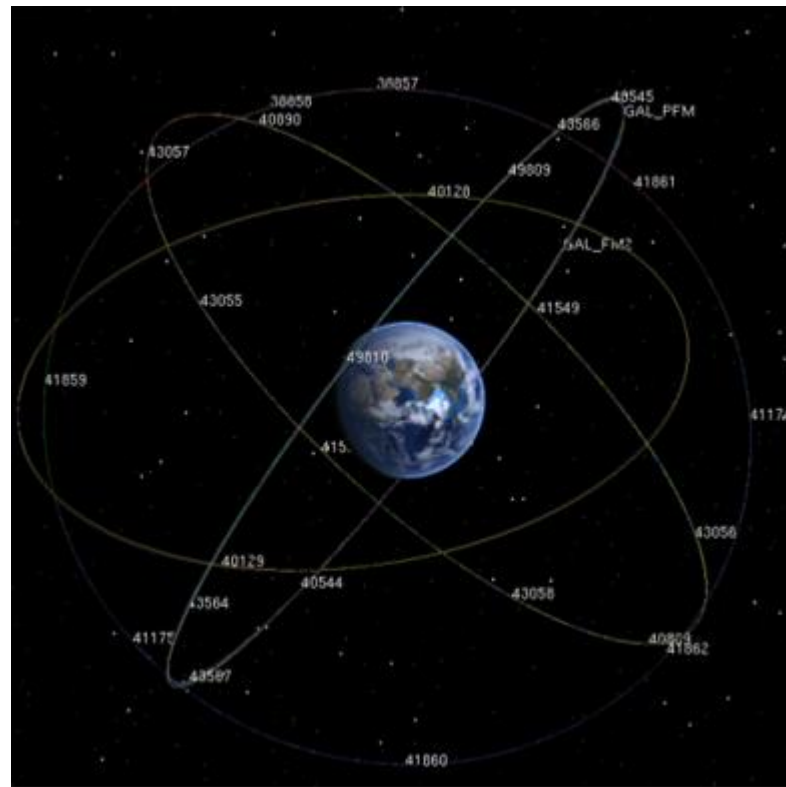
Ease mission visualization suite



Flight Dynamics

Navigation

- **Classical Tools:** Batch Least Squares and Extended Kalman Filter (EKF).
- In FDS operations, most orbit determination tasks are performed **off-line**, making a real-time Kalman filter **unnecessary**.
- Measurement availability can be **limited**, and many missions still operate **without GNSS** support.
- Orbit determination often relies on **range and angular measurements** from ground stations.
- **Interesting Note:** Spaceborne GNSS receivers track signals from satellites on the **opposite side of the Earth**, since Galileo antennas are optimized for **Earth service coverage**.





Flight Dynamics

Guidance Optimization Problem Statement

$$J = \Phi(\mathbf{x}(t_f), t_f) + \int_{t_0}^{t_f} l(t, \mathbf{x}(t), \mathbf{u}(t)) dt$$

subjected to

$$\frac{d\mathbf{x}}{dt} = \mathbf{f}(t, \mathbf{x}(t), \mathbf{u}(t))$$

$$\mathbf{x}(t_0) = \mathbf{x}_0$$

$$\Psi(t_f, \mathbf{x}(t_f)) = 0$$

$$\mathbf{x}_l \leq \mathbf{x}(t) \leq \mathbf{x}_u$$

$$\mathbf{u}_l \leq \mathbf{u}(t) \leq \mathbf{u}_u$$

$$\mathbf{g}(\mathbf{x}(t), \mathbf{u}(t), t) \leq 0$$

Flight Dynamics

Guidance Optimization Approaches

Indirect Methods (Pontryagin's Maximum Principle)

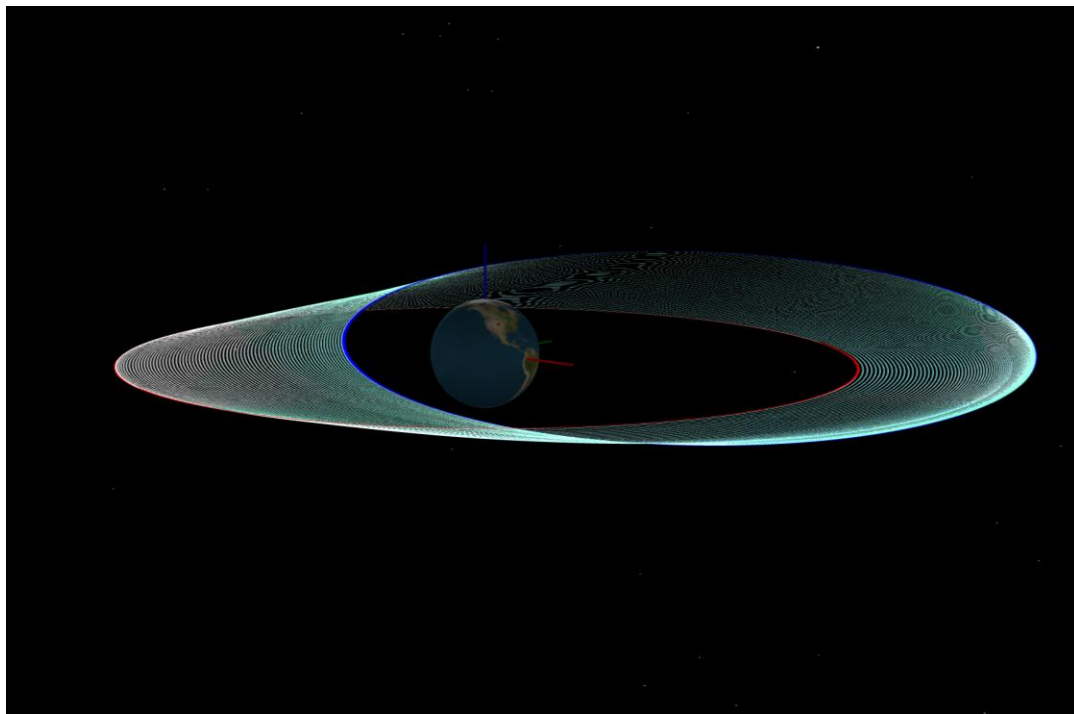
Derive necessary optimality conditions from analytical formulations of the Hamiltonian system.

Require solving **boundary-value problems** with numeric approaches.

Offer excellent accuracy and optimality since it the optimality condition is already included in the formulation of the problem but are sensitive to initial guesses and problem conditioning.

$$H(\mathbf{x}(t), \mathbf{u}(t), \lambda(t), t) = l(\mathbf{x}(t), \mathbf{u}(t), t) + \lambda^T \mathbf{f}(\mathbf{x}(t), \mathbf{u}(t), t)$$

$$\mathbf{u}^*(t) = \arg \min_{\mathbf{u} \in \mathcal{U}} [H(\mathbf{x}^*(t), \mathbf{u}^*(t), \lambda^*(t), t)]$$



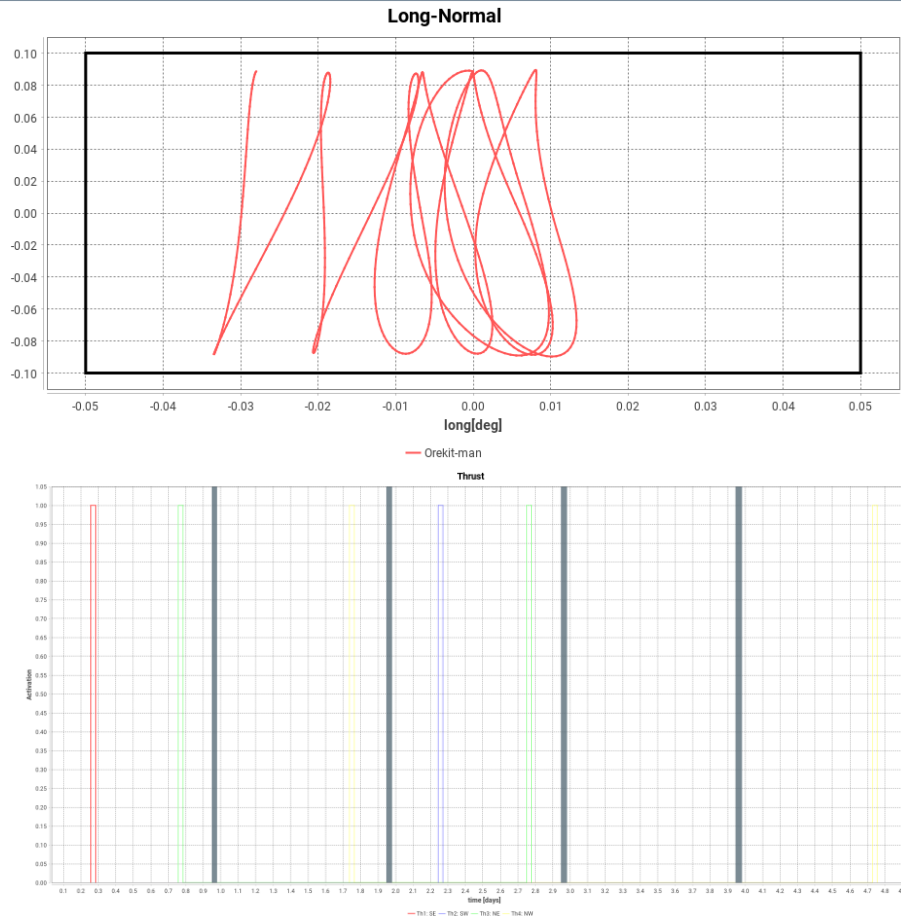


Flight Dynamics

Guidance Optimization Approaches

Direct Methods (e.g., Sequential Quadratic Programming - SQP, Mixed-Integer Programming - MIP, Multiple and Single Shooting Algorithm)

Discretize the control and/or state variables, converting the optimal control problem into a Nonlinear Programming (NLP) problem. More robust to initial conditions and constraints, widely used in operational FDS implementations. Typically, easier to integrate with real mission constraints and software frameworks.





Flight Dynamics

Guidance Optimization Approaches

Hamilton-Jacobi-Bellman & Dynamic Programming

Dynamic Programming (DP) solves optimal control problems by applying the *Principle of Optimality* and computing the optimal cost-to-go function backward in time.

Leads to the **Hamilton-Jacobi-Bellman (HJB) partial differential equation**, which gives a *necessary and sufficient* condition for optimality.

Guarantees the **global optimum**, even for nonlinear and non-convex problems.

Practical limitation: suffers from the “**curse of dimensionality**” – computational cost grows exponentially with state dimension, restricting use to low-dimensional systems.

- Bruce A. Conway - Optimal Nonlinear Control Using Hamilton–Jacobi–Bellman Viscosity Solutions on Unstructured Grids



Flight Dynamics

Guidance - Present and Future

- New autonomous guidance techniques are being developed to run directly on-board small spacecraft, reducing reliance on ground control.
- As launch and spacecraft costs decrease, the **ground segment** is becoming a major share of mission cost - especially for **deep-space missions**, where networks like NASA's DSN are already operating at full capacity and cannot easily support new missions.
- This creates a scalability challenge: adding more satellites is now easier than adding more ground infrastructure.
- In **LEO missions**, a new market segment has emerged: **Ground-Station-as-a-Service (GSaaS)** providers (e.g., Leaf Space in Italy) offer flexible, shared access to ground stations, enabling affordable connectivity for small satellite operators.
- **Robust Optimal Control:** ensuring robustness means maximizing the probability that mission constraints are satisfied. This requires shifting from deterministic optimization to a **probabilistic cost and constraint formulation**.
 - Massimiliano Valise - *Trajectory Optimization Under Uncertainties*
 - Hasnaa Zidani - *Pontryagin's Principle for Some Probabilistic Control Problems*
 - DART Group - Politecnico di Milano



Flight Dynamics

Collision Avoidance - Strategies During LEOP

Collision avoidance activities are a key part of LEOP operations, ensuring spacecraft safety during orbit-raising and early mission phases. The strategy depends strongly on the propulsion type and thrusting profile used for orbit transfer.

Conjunction Monitoring & Risk Assessment:

- Continuous screening of Conjunction Data Messages (CDMs) from surveillance networks (e.g., Space-Track, EUSST).
- Computation of collision probability (P_c) using propagated covariance and conjunction geometry.

Electric Orbit Transfer (EOR):

- Characterized by continuous low-thrust operations lasting weeks or months.
- In case of conjunction risk, avoidance is often achieved simply by temporarily switching off the thrust or adjusting the thrust timing.
- The long and flexible thrust arcs provide natural opportunities to desynchronize from the threatening object without dedicated maneuvers.



Flight Dynamics

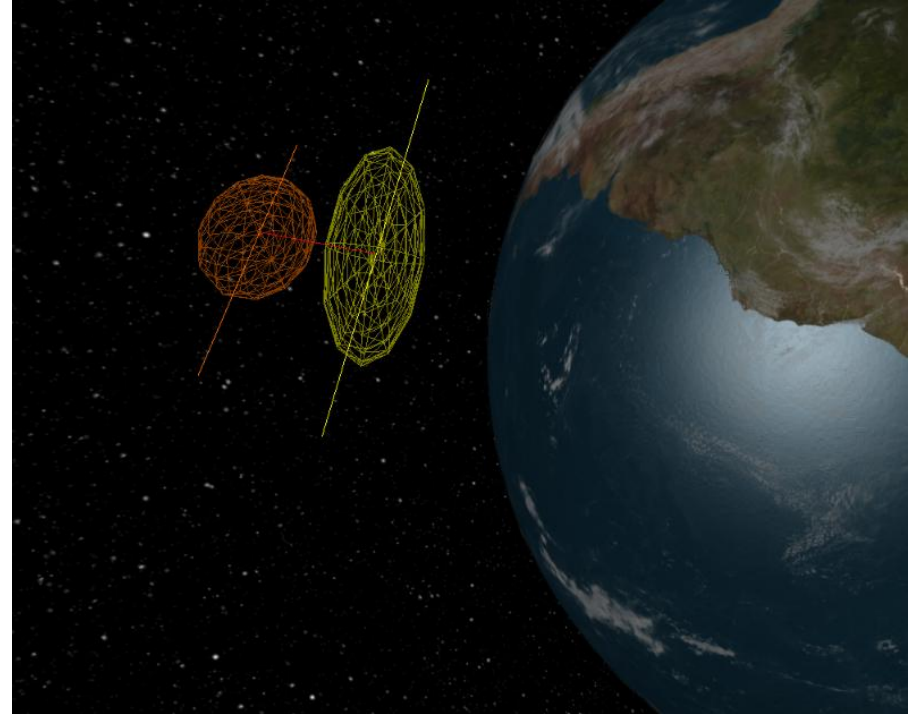
Collision Avoidance - Strategies During LEOP

Chemical LEOP:

- Involves short, high-thrust burns with well-defined time windows.
- Since maneuvers are limited in time, collision avoidance typically requires a dedicated Collision Avoidance Maneuver (CAM).
- CAMs are typically designed using analytical approaches linearizing the problem at the TCA, an example could be the OCCAM technique.

Operational Considerations:

- CAM planning must account for **ground station coverage**, **attitude constraints**, and mission timeline synchronization.
- Decision-making relies on fast FDS analysis, cross-team coordination, and validation through simulation tools.





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