Developing the Reconfigurable Earth Observation Satellite Scheduling Problem

Brycen D. Pearl[1], Joseph M. Miller[2], Hang Woon Lee[3]

[1]Ph.D. Student, [2]Undergraduate Student, [3]Assistant Professor

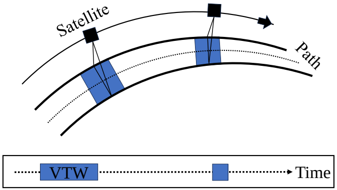
Space Systems Operations Research Laboratory
Department of Mechanical, Materials and Aerospace Engineering
West Virginia University

OPS-02: Operations Innovations
AIAA SciTech Forum: Orlando, FL
January 6-10, 2025

Contents

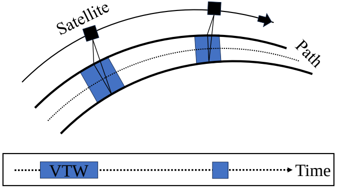
Motivation — Figures from [5]

- The Earth Observation Satellite Scheduling Problem (EOSSP) [1, 2, 3]
  - Optimization problem for scheduling tasks of Earth-observing satellites
  - Maximize observation rewards
  - Requires the visible time window (VTW)
- The standard EOSSP assumes **nadir-directional** satellites

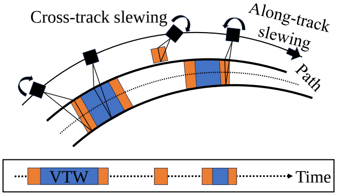


Motivation — Figures from [5]

- The Earth Observation Satellite Scheduling Problem (EOSSP) [1, 2, 3]
  - Optimization problem for scheduling tasks of Earth-observing satellites
  - Maximize observation rewards
  - Requires the visible time window (VTW)
- The standard EOSSP assumes **nadir-directional** satellites



- The Agile EOSSP (AEOSSP), current state-of-the-art
  - Addition of **satellite agility**, the ability to perform attitude control [4]
  - Optimize observation rewards
  - Extends the VTW of targets
- **Provides higher performance than standard EOSSP**



Current Cutting-Edge and Preliminary Research

Constellation Reconfigurability, satellites are able to perform orbital maneuvers, reforming into a more optimal constellation formation [6], is the current cutting-edge.

Current Cutting-Edge and Preliminary Research

Constellation Reconfigurability, satellites are able to perform orbital maneuvers, reforming into a more optimal constellation formation [6], is the current cutting-edge.

Multistage Constellation Reconfiguration Problem (MCRP) [7]

- Maximize observation rewards
- Subject to target VTWs, time-dependent rewards, and an orbital maneuver budget
- Mixed Integer Linear Programming (MILP)

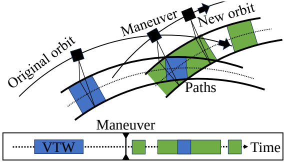


Figure from [5]

Current Cutting-Edge and Preliminary Research

Constellation Reconfigurability, satellites are able to perform orbital maneuvers, reforming into a more optimal constellation formation [6], is the current cutting-edge.

Multistage Constellation Reconfiguration Problem (MCRP) [7]

- Maximize observation rewards
- Subject to target VTWs, time-dependent rewards, and an orbital maneuver budget
- Mixed Integer Linear Programming (MILP)

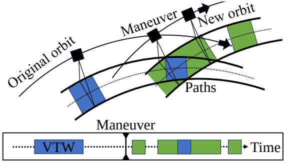


Figure from [5]

Refs. [8, 5]

- Constellation reconfigurability outperformed agility in 95 of 100 cases, average of $35.93\,\%$ over agility
- Constellation reconfigurability had an average increase of $324.92\,\%$ over the baseline
- Serves as a proof of concept that reconfigurability is promising in EO

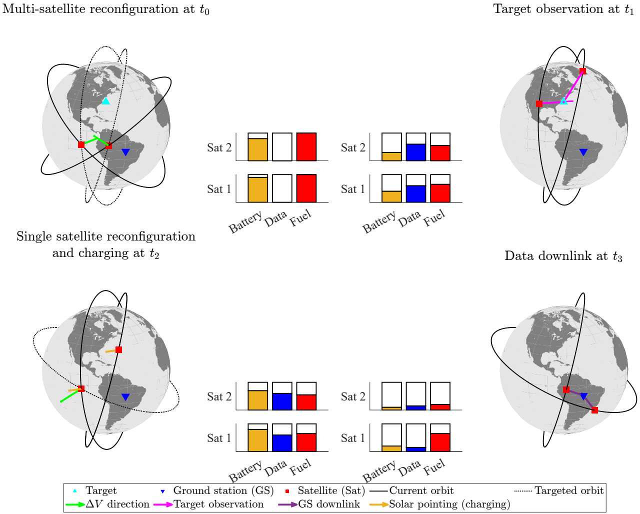
Main Objectives

- Implement constellation reconfigurability to the EOSSP
- Control constellation reconfigurability in a similar manner to the MCRP
- Employ MILP techniques to achieve implementation, flexibility, and provably optimal solutions through the use of commercial solvers

Main Objectives

- Implement constellation reconfigurability to the EOSSP
- Control constellation reconfigurability in a similar manner to the MCRP
- Employ MILP techniques to achieve implementation, flexibility, and provably optimal solutions through the use of commercial solvers
- Overcome the current state-of-the-art limitations [1, 2, 3, 4, 9, 10, 11, 12] to provide a **major advancement** in the results of a scheduling algorithm
- Benchmark against a baseline EOSSP in two formats of experimentation
  1. Random instances
  2. Case study with Hurricane Rita

Technical Contributions



Contents

Parameters

Sets:

- Set of discrete time steps $\mathcal{T}$ (index t)
- Set of stages $\mathcal{S}$ (index s)
- Set of time steps per stage $\mathcal{T}^s$ (index t)
- Set of satellites $\mathcal{K}$ (index k)
- Set of orbital slot options per satellite and stage $\mathcal{J}^{sk}$ (indices i, j)
- Set of targets $\mathcal{P}$ (index p)
- Set of ground stations $\mathcal{G}$ (index g)

Parameters

Sets:

- Set of discrete time steps $\mathcal{T}$ (index t)
- Set of stages $\mathcal{S}$ (index s)
- Set of time steps per stage $\mathcal{T}^s$ (index t)
- Set of satellites $\mathcal{K}$ (index k)
- Set of orbital slot options per satellite and stage $\mathcal{J}^{sk}$ (indices i, j)
- Set of targets $\mathcal{P}$ (index p)
- Set of ground stations $\mathcal{G}$ (index g)

Other Parameters:

- Target visibility $V_{tjp}^{sk} \in \{0, 1\}$
- Ground station visibility $W_{tjg}^{sk} \in \{0, 1\}$
- Sun visibility $H_{tj}^{sk} \in \{0, 1\}$
- Maximum orbital maneuver budget, $c_{\max}^{k} \geq 0$
- Cost to transfer satellite k from orbital slot $i \in \mathcal{J}^{s-1,k}$ to orbital slot $j \in \mathcal{J}^{sk}$, $c_{ij}^{sk} \geq 0$
- Maximum data and battery capacity, $D_{\max}^{k} \geq 0$ and $B_{\max}^{k} \geq 0$, respectively
- Data gained through observations, $D_{\text{obs}} \geq 0$, and Data transmitted through downlink, $D_{\text{comm}} \geq 0$
- Battery charged by solar panels, $B_{\text{charge}} \geq 0$
- Battery consumed by observation, data downlink, reconfiguration, and constant telelmetry calculations, $B_{\text{obs}} \geq 0$, $B_{\text{comm}} \geq 0$, $B_{\text{recon}} \geq 0$, and B_{time}, respectively

Objective Function, Decision Variables, and Indicator Variables

Decision variables - tasks:

- Reconfiguration path - (1a)
- Observation of targets - (1b)
- Downlink of data to ground stations - (1c)
- Solar charging - (1d)

Indicator variables - trackers:

- Data storage capacity - (2a)
- Battery storage capacity - (2b)

Objective function

$$\text{maximize} \quad Z_{\mathrm{R}} = \sum_{k \in \mathcal{K}} \sum_{g \in \mathcal{G}} \sum_{s \in \mathcal{S} \setminus \{0\}} \sum_{t \in \mathcal{T}^s} D_{\text{comm}} q_{tg}^{sk}$$

Decision variables

$$x_{ij}^{sk} \in \{0,1\}, \quad \forall s \in \mathcal{S} \setminus \{0\}, \forall k \in \mathcal{K}, \forall i \in \mathcal{J}^{s-1,k}, \forall j \in \mathcal{J}^{sk} \tag{1a}$$

$$y_{tp}^{sk} \in \{0,1\}, \quad \forall s \in \mathcal{S} \setminus \{0\}, \forall t \in \mathcal{T}^s, \forall p \in \mathcal{P}, \forall k \in \mathcal{K} \tag{1b}$$

$$q_{tg}^{sk} \in \{0,1\}, \quad \forall s \in \mathcal{S} \setminus \{0\}, \forall t \in \mathcal{T}^s, \forall g \in \mathcal{G}, \forall k \in \mathcal{K} \tag{1c}$$

$$h_{t}^{sk} \in \{0,1\}, \quad \forall s \in \mathcal{S} \setminus \{0\}, \forall t \in \mathcal{T}^s, \forall k \in \mathcal{K} \tag{1d}$$

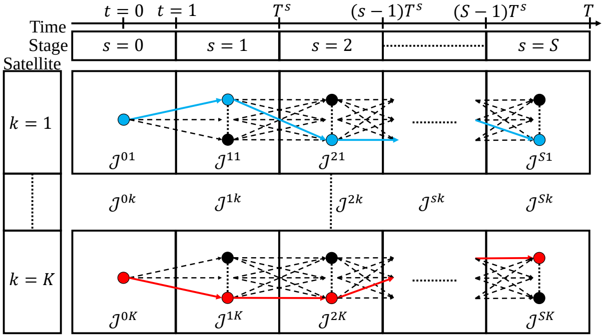
Indicator variables

$$d_{t}^{sk} \in [0, D_{\max}^{k}], \quad \forall s \in \mathcal{S} \setminus \{0\}, \forall t \in \mathcal{T}^s, \forall k \in \mathcal{K} \tag{2a}$$

$$b_{t}^{sk} \in [0, B_{\max}^{k}], \quad \forall s \in \mathcal{S} \setminus \{0\}, \forall t \in \mathcal{T}^s, \forall k \in \mathcal{K} \tag{2b}$$

Reconfiguration Path Continuity Constraints

Transfer from one initial condition to one orbital slot (3a), transfer from one orbital slot to another only if satellite transferred there previously (3b), transfers cannot exceed budget (3c)



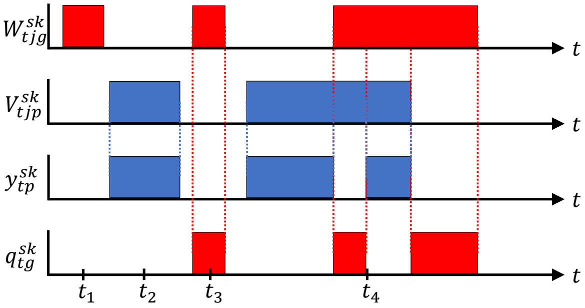
$$\sum_{j\in\mathcal{J}^{1k}} x_{ij}^{1k} = 1, \quad \forall k \in \mathcal{K}, \forall i \in \mathcal{J}^{0k} \tag{3a}$$

$$\sum_{j\in\mathcal{J}^{s+1,k}} x_{ij}^{s+1,k} - \sum_{j'\in\mathcal{J}^{s-1,k}} x_{j'i}^{sk} = 0, \quad \forall s \in \mathcal{S} \setminus \{0, S\}, \forall k \in \mathcal{K}, \forall i \in \mathcal{J}^{sk} \tag{3b}$$

$$\sum_{s\in\mathcal{S}\setminus\{0\}} \sum_{i\in\mathcal{J}^{s-1,k}} \sum_{j\in\mathcal{J}^{sk}} c_{ij}^{sk} x_{ij}^{sk} \le c_{\max}^{k}, \quad \forall k \in \mathcal{K} \tag{3c}$$

Visible Time Window Constraints

Visibility of target (4a), visibility of ground stations (4b), visibility of the Sun (4c), task overlap exclusion (4d)



$$\sum_{i \in \mathcal{J}^{s-1,k}} \sum_{j \in \mathcal{J}^{sk}} V_{tjp}^{sk} x_{ij}^{sk} \geq y_{tp}^{sk}, \quad \forall s \in \mathcal{S} \setminus \{0\}, \forall t \in \mathcal{T}^s, \forall p \in \mathcal{P}, \forall k \in \mathcal{K} \tag{4a}$$

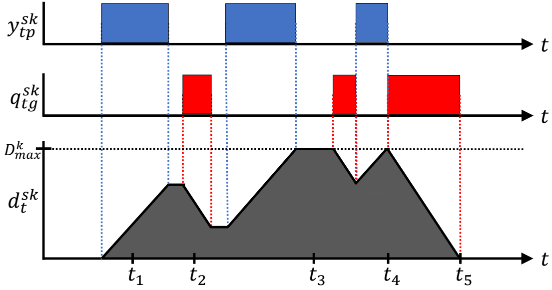
$$\sum_{i \in \mathcal{J}^{s-1,k}} \sum_{j \in \mathcal{J}^{sk}} W_{tjg}^{sk} x_{ij}^{sk} \geq q_{tg}^{sk}, \quad \forall s \in \mathcal{S} \setminus \{0\}, \forall t \in \mathcal{T}^s, \forall g \in \mathcal{G}, \forall k \in \mathcal{K} \tag{4b}$$

$$\sum_{i \in \mathcal{J}^{s-1,k}} \sum_{j \in \mathcal{J}^{sk}} H_{tj}^{sk} x_{ij}^{sk} \geq h_{t}^{sk}, \quad \forall s \in \mathcal{S} \setminus \{0\}, \forall t \in \mathcal{T}^s, \forall k \in \mathcal{K} \tag{4c}$$

$$\sum_{p \in \mathcal{P}} y_{tp}^{sk} + \sum_{g \in \mathcal{G}} q_{tg}^{sk} \leq 1, \quad \forall s \in \mathcal{S} \setminus \{0\}, \forall t \in \mathcal{T}^s, \forall k \in \mathcal{K} \tag{4d}$$

Onboard Data Storage Constraints

Tracking in stages (5a), tracking between stages (5b), must not exceed maximum (5c), must not exceed minimum (5d)



$$d_{t+1}^{sk} = d_t^{sk} + \sum_{p \in \mathcal{P}} D_{\text{obs}} y_{tp}^{sk} - \sum_{g \in \mathcal{G}} D_{\text{comm}} q_{tg}^{sk}, \quad \forall s \in \mathcal{S} \setminus \{0\}, \forall t \in \mathcal{T}^s \setminus \{T^s\}, \forall k \in \mathcal{K} \tag{5a}$$

$$d_1^{s+1,k} = d_{T^s}^{sk} + \sum_{p \in \mathcal{P}} D_{\text{obs}} y_{T^s p}^{sk} - \sum_{g \in \mathcal{G}} D_{\text{comm}} q_{T^s g}^{sk}, \quad \forall s \in \mathcal{S} \setminus \{0, S\}, \forall k \in \mathcal{K} \tag{5b}$$

$$d_t^{sk} + \sum_{p \in \mathcal{P}} D_{\text{obs}} y_{tp}^{sk} \leq D_{\max}^k, \quad \forall s \in \mathcal{S} \setminus \{0\}, \forall t \in \mathcal{T}^s, \forall k \in \mathcal{K} \tag{5c}$$

$$d_t^{sk} - \sum_{g \in \mathcal{G}} D_{\text{comm}} q_{tg}^{sk} \geq 0, \quad \forall s \in \mathcal{S} \setminus \{0\}, \forall t \in \mathcal{T}^s, \forall k \in \mathcal{K} \tag{5d}$$

Onboard Battery Constraints

Tracking in stage (6a), tracking between stages (6b), tracking at stage one (6c)

$$b_{t+1}^{sk} = b_t^{sk} + B_{\text{charge}} h_t^{sk} - \sum_{p \in \mathcal{P}} B_{\text{obs}} y_{tp}^{sk} - \sum_{g \in \mathcal{G}} B_{\text{comm}} q_{tg}^{sk} - B_{\text{time}}, \quad \forall s \in \mathcal{S} \setminus \{0\}, \forall t \in \mathcal{T}^s \setminus \{T^s\}, \forall k \in \mathcal{K} \tag{6a}$$

$$b_1^{s+1,k} = b_{T^s}^{sk} + B_{\text{charge}} h_{T^s}^{sk} - \sum_{p \in \mathcal{P}} B_{\text{obs}} y_{T^s p}^{sk} - \sum_{g \in \mathcal{G}} B_{\text{comm}} q_{T^s g}^{sk} - \sum_{i \in \mathcal{J}^{sk}} \sum_{j \in \mathcal{J}^{s+1,k}} B_{\text{recon}} x_{ij}^{s+1,k} - B_{\text{time}}, \quad \forall s \in \mathcal{S} \setminus \{0, S\}, \forall k \in \mathcal{K} \tag{6b}$$

$$b_1^{1k} = B_{\max}^k - \sum_{i \in \mathcal{J}^{0k}} \sum_{j \in \mathcal{J}^{1k}} B_{\text{recon}} x_{ij}^{1k}, \quad \forall k \in \mathcal{K} \tag{6c}$$

Must not exceed maximum (7a), must not exceed minimum in stage (7b), between stages (7c), at stage one (7d)

$$b_t^{sk} + B_{\text{charge}} h_t^{sk} \leq B_{\max}^k, \quad \forall s \in \mathcal{S} \setminus \{0\}, \forall t \in \mathcal{T}^s, \forall k \in \mathcal{K} \tag{7a}$$

$$b_t^{sk} - \sum_{p \in \mathcal{P}} B_{\text{obs}} y_{tp}^{sk} - \sum_{g \in \mathcal{G}} B_{\text{comm}} q_{tg}^{sk} - B_{\text{time}} \geq 0, \quad \forall s \in \mathcal{S} \setminus \{0\}, \forall t \in \mathcal{T}^s \setminus \{T^s\}, \forall k \in \mathcal{K} \tag{7b}$$

$$b_{T^s}^{sk} - \sum_{p \in \mathcal{P}} B_{\text{obs}} y_{T^s p}^{sk} - \sum_{g \in \mathcal{G}} B_{\text{comm}} q_{T^s g}^{sk} - \sum_{i \in \mathcal{J}^{sk}} \sum_{j \in \mathcal{J}^{s+1,k}} B_{\text{recon}} x_{ij}^{s+1,k} - B_{\text{time}} \geq 0, \quad \forall s \in \mathcal{S} \setminus \{0, S\}, \forall k \in \mathcal{K} \tag{7c}$$

$$B_{\max}^k - \sum_{i \in \mathcal{J}^{0k}} \sum_{j \in \mathcal{J}^{1k}} B_{\text{recon}} x_{ij}^{1k} \geq 0, \quad \forall k \in \mathcal{K} \tag{7d}$$

Full REOSSP Formulation

$$
\begin{aligned}
\max \quad & Z_{\mathrm{R}} = \sum_{k \in \mathcal{K}} \sum_{g \in \mathcal{G}} \sum_{s \in \mathcal{S} \setminus \{0\}} \sum_{t \in \mathcal{T}^s} D_{\mathrm{comm}} q_{tg}^{sk} \\
\text{s.t.} \quad & \sum_{j \in \mathcal{J}^{1k}} x_{ij}^{1k} = 1, && \forall k \in \mathcal{K}, \forall i \in \mathcal{J}^{0k} \\
& \sum_{j \in \mathcal{J}^{s+1,k}} x_{ij}^{s+1,k} - \sum_{j' \in \mathcal{J}^{s-1,k}} x_{j'i}^{sk} = 0, && \forall s \in \mathcal{S} \setminus \{0, S\}, \forall k \in \mathcal{K}, \forall i \in \mathcal{J}^{sk} \\
& \sum_{s \in \mathcal{S} \setminus \{0\}} \sum_{i \in \mathcal{J}^{s-1,k}} \sum_{j \in \mathcal{J}^{sk}} c_{ij}^{sk} x_{ij}^{sk} \leq c_{\max}^{k}, && \forall k \in \mathcal{K} \\
& \sum_{i \in \mathcal{J}^{s-1,k}} \sum_{j \in \mathcal{J}^{sk}} V_{tjp}^{sk} x_{ij}^{sk} \geq y_{tp}^{sk}, && \forall s \in \mathcal{S} \setminus \{0\}, \forall t \in \mathcal{T}^s, \forall p \in \mathcal{P}, \forall k \in \mathcal{K} \\
& \sum_{i \in \mathcal{J}^{s-1,k}} \sum_{j \in \mathcal{J}^{sk}} W_{tjg}^{sk} x_{ij}^{sk} \geq q_{tg}^{sk}, && \forall s \in \mathcal{S} \setminus \{0\}, \forall t \in \mathcal{T}^s, \forall g \in \mathcal{G}, \forall k \in \mathcal{K} \\
& \sum_{i \in \mathcal{J}^{s-1,k}} \sum_{j \in \mathcal{J}^{sk}} H_{tj}^{sk} x_{ij}^{sk} \geq h_{t}^{sk}, && \forall s \in \mathcal{S} \setminus \{0\}, \forall t \in \mathcal{T}^s, \forall k \in \mathcal{K} \\
& \sum_{p \in \mathcal{P}} y_{tp}^{sk} + \sum_{g \in \mathcal{G}} q_{tg}^{sk} \leq 1, && \forall s \in \mathcal{S} \setminus \{0\}, \forall t \in \mathcal{T}^s, \forall k \in \mathcal{K} \\
& d_{t+1}^{sk} = d_{t}^{sk} + \sum_{p \in \mathcal{P}} D_{\mathrm{obs}} y_{tp}^{sk} - \sum_{g \in \mathcal{G}} D_{\mathrm{comm}} q_{tg}^{sk}, && \forall s \in \mathcal{S} \setminus \{0\}, \forall t \in \mathcal{T}^s \setminus \{T^s\}, \forall k \in \mathcal{K} \\
& d_{1}^{s+1,k} = d_{T^s}^{sk} + \sum_{p \in \mathcal{P}} D_{\mathrm{obs}} y_{T^s p}^{sk} - \sum_{g \in \mathcal{G}} D_{\mathrm{comm}} q_{T^s g}^{sk}, && \forall s \in \mathcal{S} \setminus \{0, S\}, \forall k \in \mathcal{K} \\
& d_{t}^{sk} + \sum_{p \in \mathcal{P}} D_{\mathrm{obs}} y_{tp}^{sk} \leq D_{\max}^{k}, && \forall s \in \mathcal{S} \setminus \{0\}, \forall t \in \mathcal{T}^s, \forall k \in \mathcal{K} \\
& d_{t}^{sk} - \sum_{g \in \mathcal{G}} D_{\mathrm{comm}} q_{tg}^{sk} \geq 0, && \forall s \in \mathcal{S} \setminus \{0\}, \forall t \in \mathcal{T}^s, \forall k \in \mathcal{K}
\end{aligned}
$$

$$
\begin{aligned}
& b_{t+1}^{sk} = b_{t}^{sk} + B_{\mathrm{charge}} h_{t}^{sk} - \sum_{p \in \mathcal{P}} B_{\mathrm{obs}} y_{tp}^{sk} - \sum_{g \in \mathcal{G}} B_{\mathrm{comm}} q_{tg}^{sk} - B_{\mathrm{time}}, && \forall s \in \mathcal{S} \setminus \{0\}, \forall t \in \mathcal{T}^s \setminus \{T^s\}, \forall k \in \mathcal{K} \\
& b_{1}^{s+1,k} = b_{T^s}^{sk} + B_{\mathrm{charge}} h_{T^s}^{sk} - \sum_{p \in \mathcal{P}} B_{\mathrm{obs}} y_{T^s p}^{sk} - \sum_{g \in \mathcal{G}} B_{\mathrm{comm}} q_{T^s g}^{sk} - \\
& \qquad \sum_{i \in \mathcal{J}^{sk}} \sum_{j \in \mathcal{J}^{s+1,k}} B_{\mathrm{recon}} x_{ij}^{s+1,k} - B_{\mathrm{time}}, && \forall s \in \mathcal{S} \setminus \{0, S\}, \forall k \in \mathcal{K} \\
& b_{1}^{1k} = b_{\max}^{k} - \sum_{i \in \mathcal{J}^{0k}} \sum_{j \in \mathcal{J}^{1k}} B_{\mathrm{recon}} x_{ij}^{1k}, && \forall k \in \mathcal{K} \\
& b_{t}^{sk} + B_{\mathrm{charge}} h_{t}^{sk} \leq B_{\max}^{k}, && \forall s \in \mathcal{S} \setminus \{0\}, \forall t \in \mathcal{T}^s, \forall k \in \mathcal{K} \\
& b_{t}^{sk} - \sum_{p \in \mathcal{P}} B_{\mathrm{obs}} y_{tp}^{sk} - \sum_{g \in \mathcal{G}} B_{\mathrm{comm}} q_{tg}^{sk} - B_{\mathrm{time}} \geq 0, && \forall s \in \mathcal{S} \setminus \{0\}, \forall t \in \mathcal{T}^s \setminus \{T^s\}, \forall k \in \mathcal{K} \\
& b_{T^s}^{sk} - \sum_{p \in \mathcal{P}} B_{\mathrm{obs}} y_{T^s p}^{sk} - \sum_{g \in \mathcal{G}} B_{\mathrm{comm}} q_{T^s g}^{sk} - \\
& \qquad \sum_{i \in \mathcal{J}^{sk}} \sum_{j \in \mathcal{J}^{s+1,k}} B_{\mathrm{recon}} x_{ij}^{s+1,k} - B_{\mathrm{time}} \geq 0, && \forall s \in \mathcal{S} \setminus \{0, S\}, \forall k \in \mathcal{K} \\
& B_{\max}^{k} - \sum_{i \in \mathcal{J}^{0k}} \sum_{j \in \mathcal{J}^{1k}} B_{\mathrm{recon}} x_{ij}^{1k} \geq 0, && \forall k \in \mathcal{K} \\
& x_{ij}^{sk} \in \{0, 1\}, && \forall s \in \mathcal{S} \setminus \{0\}, \forall k \in \mathcal{K}, \forall i \in \mathcal{J}^{s-1,k}, \forall j \in \mathcal{J}^{sk} \\
& y_{tp}^{sk} \in \{0, 1\}, && \forall s \in \mathcal{S} \setminus \{0\}, \forall t \in \mathcal{T}^s, \forall p \in \mathcal{P}, \forall k \in \mathcal{K} \\
& q_{tg}^{sk} \in \{0, 1\}, && \forall s \in \mathcal{S} \setminus \{0\}, \forall t \in \mathcal{T}^s, \forall g \in \mathcal{G}, \forall k \in \mathcal{K} \\
& h_{t}^{sk} \in \{0, 1\}, && \forall s \in \mathcal{S} \setminus \{0\}, \forall t \in \mathcal{T}^s, \forall k \in \mathcal{K} \\
& d_{t}^{sk} \in [0, D_{\max}^{k}], && \forall s \in \mathcal{S} \setminus \{0\}, \forall t \in \mathcal{T}^s, \forall k \in \mathcal{K} \\
& b_{t}^{sk} \in [0, B_{\max}^{k}], && \forall s \in \mathcal{S} \setminus \{0\}, \forall t \in \mathcal{T}^s, \forall k \in \mathcal{K}
\end{aligned}
$$

Contents

Random Instance Setup

54 instances with randomized parameters

- Time horizon of 10 days
- MATLAB [13] used in conjunction with YALMIP [14] to program simulations
- Gurobi Optimizer (version 11.0.2) used to solve each scheduling problem

Fixed parameters:

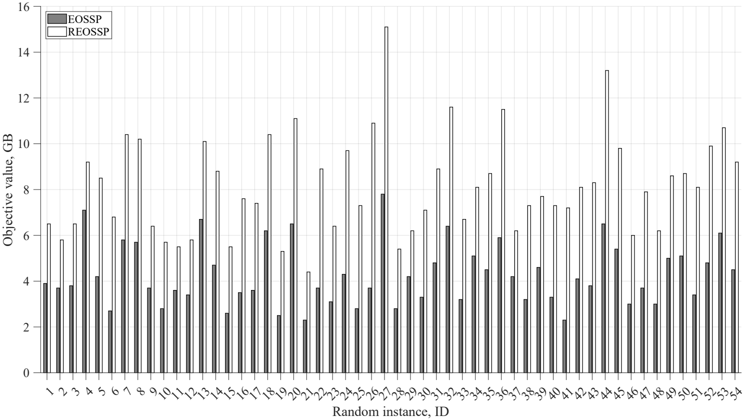
- Conical observation field of view of 45 deg
- Conical communication field of view of 120 deg
- Binary masking of targets on interval T/P

Randomized parameters:

- Targets (5 or 10)
  - Latitude between 80 deg South and 80 deg North
  - Longitude between 180 deg West and 180 deg East
- Stages (4, 5, or 6)
- Satellites (4, 5, or 6) in circular orbits
  - Altitude between 600 km and 1200 km
  - Inclination between 40 deg and 80 deg
  - RAAN between 0 deg and 360 deg
  - Argument of latitude between 0 deg and 360 deg
- Transfer orbital slots (20, 40, or 60)
- G.s. (2), random locations on land

Random Instances

Results with $750\,\text{m/s}$ fuel budget, $102.5\,\text{MB}$ observation, and $100\,\text{MB}$ downlink:



	Improvement, %
Avg.	**96.59**
SD	**34.67**
Max.	**213.04**
Min.	**29.58**

Case Study - Hurricane Rita

In 2005, Hurricane Rita struck the southern United States at Category Five, causing $18.5 billion in damage and 120 deaths [15]. From the first to the final occurrence of tropical storm status (39 to 73 mph [16]), Rita lasted 6.5 days.

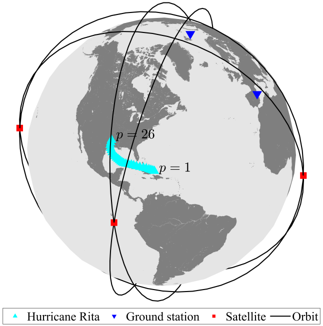


Figure 1: Case study parameters [17, 18].

Results

Changed Parameters:

- Set g.s. in Boecillo, Spain, and Svalbard, Sweden
- Additional plane change orbital slots
- Trajectory optimization

EOSSP, GB	REOSSP, GB	Improvement, %
1.10	2.90	**163.64**

Contents

Conclusions

Key takeaways

1. REOSSP outperforms EOSSP in every case, including real-world data
2. EOSSP and REOSSP consider target visibility, data and battery storage tracking, data downlink, and solar charging
3. REOSSP obtains provably optimal results through the use of MILP and commercial solvers
4. REOSSP implements a cutting-edge concept of operation (constellation reconfigurability) to provide a major breakthrough in scheduling technology

Conclusions

Key takeaways

1. REOSSP outperforms EOSSP in every case, including real-world data
2. EOSSP and REOSSP consider target visibility, data and battery storage tracking, data downlink, and solar charging
3. REOSSP obtains provably optimal results through the use of MILP and commercial solvers
4. REOSSP implements a cutting-edge concept of operation (constellation reconfigurability) to provide a major breakthrough in scheduling technology

Future Work:

- Additional case studies
  - Wildfires (longer time horizon, less dynamic)
  - Flooding caused by Tsunamis (mid-length time horizon, less dynamic)
- Additional solution algorithms
  - Rolling Horizon Policy (category of Model Predictive Control) with a set stage lookahead

Acknowledgments

Brycen Pearl thanks the **Dr. Gerald A. Soffen Memorial Fund** for their partial financial support in attending the 2025 AIAA SciTech Forum and Exposition.

References

[1] Duncan Eddy and Mykel J. Kochenderfer. "A Maximum Independent Set Method for Scheduling Earth-Observing Satellite Constellations". *Journal of Spacecraft and Rockets* 58.5 (2021), pp. 1416–1429. DOI: 10.2514/1.A34931.

[2] Lili Ren, Xin Ning, and Jiayin Li. "Hierarchical Reinforcement-Learning for Real-Time Scheduling of Agile Satellites". *IEEE Access* 8 (2020), pp. 220523–220532. DOI: 10.1109/ACCESS.2020.3040748.

[3] Pei Wang, Gerhard Reinelt, Peng Gao, and Yuejin Tan. "A model, a heuristic and a decision support system to solve the scheduling problem of an earth observing satellite constellation". *Computers & Industrial Engineering* 61.2 (2011). Combinatorial Optimization in Industrial Engineering, pp. 322–335. DOI: https://doi.org/10.1016/j.cie.2011.02.015.

[4] Michel Lemaitre, Gerard Verfaillie, Frank Jouhaud, Jean-Michel Lachiver, and Nicolas Bataille. "Selecting and scheduling observations of agile satellites". *Aerospace Science and Technology* 6.5 (2002), pp. 367–381. DOI: 10.1016/S1270-9638(02)01173-2.

[5] Brycen D Pearl, Logan P Gold, and Hang Woon Lee. "Benchmarking Agility and Reconfigurability in Satellite Systems for Tropical Cyclone Monitoring". *Journal of Spacecraft and Rockets* (2025). (article in advance). DOI: 10.2514/1.A36177.

[6] Olivier L. de Weck, Uriel Scialom, and Afreen Siddiqi. "Optimal reconfiguration of satellite constellations with the auction algorithm". *Acta Astronautica* 62.2 (2008), pp. 112–130. DOI: 10.1016/j.actaastro.2007.02.008.

[7] Hang Woon Lee, David O. Williams Rogers, Brycen D. Pearl, Hao Chen, and Koki Ho. "Deterministic Multistage Constellation Reconfiguration Using Integer Programming and Sequential Decision-Making Methods". *Journal of Spacecraft and Rockets* (2024). (article in advance). DOI: 10.2514/1.A35990.

[8] Brycen Pearl, Logan Gold, and Hang Woon Lee. "Comparing the Effectiveness of Agility and Reconfigurability in Earth Observation Satellite Systems for Disaster Response". *AAS/AIAA Astrodynamics Specialist Conference*. Aug. 2023.

[9] Abhijit Chatterjee and Ratnasingham Tharmarasa. "Reward Factor-Based Multiple Agile Satellites Scheduling With Energy and Memory Constraints". *IEEE Transactions on Aerospace and Electronic Systems* 58.4 (2022), pp. 3090–3103. DOI: 10.1109/TAES.2022.3146115.

[10] Xinwei Wang, Guohua Wu, Lining Xing, and Witold Pedrycz. "Agile Earth Observation Satellite Scheduling Over 20 Years: Formulations, Methods, and Future Directions". *IEEE Systems Journal* 15.3 (2021), pp. 3881–3892. DOI: 10.1109/JSYST.2020.2997050.

[11] Yixin Huang, Zhongcheng Mu, Shufan Wu, Benjie Cui, and Yuxiao Duan. "Revising the Observation Satellite Scheduling Problem Based on Deep Reinforcement Learning". *Remote Sensing* 13.12 (2021). DOI: 10.3390/rs13122377.

[12] Yaxin Chen, Miaozhong Xu, Xin Shen, Guo Zhang, Zezhong Lu, and Junfei Xu. "A Multi-Objective Modeling Method of Multi-Satellite Imaging Task Planning for Large Regional Mapping". *Remote Sensing* 12.3 (2020). DOI: 10.3390/rs12030344.

[13] MATLAB. *24.1.0.2603908 (R2024a) Update 3*. Natick, Massachusetts: The MathWorks Inc., May 2024.

[14] J. Löfberg. "YALMIP : A Toolbox for Modeling and Optimization in MATLAB". *In Proceedings of the CACSD Conference*. Taipei, Taiwan, 2004, pp. 284–289.

[15] National Hurricane Center. *Costliest U.S. tropical cyclones tables updated*. https://www.nhc.noaa.gov/news/UpdatedCostliest.pdf. last accessed November 06, 2024. Jan. 2018.

[16] NOAA US Department of Commerce. *Tropical definitions*. https://www.weather.gov/mob/tropical_definitions. last accessed November 06, 2024. May 2022.

[17] Weather Underground. *Hurricane Archive*. https://www.wunderground.com/hurricane/archive. last accessed November 06, 2024. 2024.

[18] Sreeja Nag, Jacqueline LeMoigne, David W. Miller, and Olivier de Weck. "A framework for orbital performance evaluation in Distributed Space Missions for Earth Observation". *2015 IEEE Aerospace Conference* (Mar. 2015). DOI: 10.1109/aero.2015.7119227.

[19] eoPortal. *DMC-3 (disaster monitoring constellation-3)*. https://www.eoportal.org/satellite-missions/dmc-3. last accessed November 06, 2024. May 2012.

[20] Brandon Maccherone and Shannell Frazier. *Moderate Resolution Imaging Spectroradiometer*. https://modis.gsfc.nasa.gov/about/specifications.php. last accessed November 06, 2024. 2015.

[21] D.A. Vallado. "Fundamentals of Astrodynamics and Applications". Space technology library. Microcosm Press, 2013. Chap. 6, pp. 317–421.

Contents

Full EOSSP Formulation

$$
\begin{aligned}
\max \quad & Z_{\mathrm{E}} = \sum_{k\in\mathcal{K}}\sum_{g\in\mathcal{G}}\sum_{t\in\mathcal{T}} D_{\mathrm{comm}} q_{tg}^{k} \\
\text{s.t.} \quad & V_{tp}^{k} \geq y_{tp}^{k}, && \forall t\in\mathcal{T}, \forall p\in\mathcal{P}, \forall k\in\mathcal{K} \\
& W_{tg}^{k} \geq q_{tg}^{k}, && \forall t\in\mathcal{T}, \forall g\in\mathcal{G}, \forall k\in\mathcal{K} \\
& H_{t}^{k} \geq h_{t}^{k}, && \forall t\in\mathcal{T}, \forall k\in\mathcal{K} \\
& \sum_{p\in\mathcal{P}} y_{tp}^{k} + \sum_{g\in\mathcal{G}} q_{tg}^{k} \leq 1, && \forall t\in\mathcal{T}, \forall k\in\mathcal{K} \\
& d_{t+1}^{k} = d_{t}^{k} + \sum_{p\in\mathcal{P}} D_{\mathrm{obs}} y_{tp}^{k} - \sum_{g\in\mathcal{G}} D_{\mathrm{comm}} q_{tg}^{k}, && \forall t\in\mathcal{T}\setminus\{T\}, \forall k\in\mathcal{K} \\
& d_{t}^{k} + \sum_{p\in\mathcal{P}} D_{\mathrm{obs}} y_{tp}^{k} \leq D_{\max}^{k}, && \forall t\in\mathcal{T}, \forall k\in\mathcal{K} \\
& d_{t}^{k} - \sum_{g\in\mathcal{G}} D_{\mathrm{comm}} q_{tg}^{k} \geq 0, && \forall t\in\mathcal{T}, \forall k\in\mathcal{K}
\end{aligned}
$$

$$
\begin{aligned}
& b_{t+1}^{k} = b_{t}^{k} + B_{\mathrm{charge}} h_{t}^{k} - \sum_{p\in\mathcal{P}} B_{\mathrm{obs}} y_{tp}^{k} - \sum_{g\in\mathcal{G}} B_{\mathrm{comm}} q_{tg}^{k} - B_{\mathrm{time}}, && \forall t\in\mathcal{T}\setminus\{T\}, \forall k\in\mathcal{K} \\
& b_{t}^{k} + B_{\mathrm{charge}} h_{t}^{k} \leq B_{\max}^{k}, && \forall t\in\mathcal{T}, \forall k\in\mathcal{K} \\
& b_{t}^{k} - \sum_{p\in\mathcal{P}} B_{\mathrm{obs}} y_{tp}^{k} - \sum_{g\in\mathcal{G}} B_{\mathrm{comm}} q_{tg}^{k} - B_{\mathrm{time}} \geq 0, && \forall t\in\mathcal{T}, \forall k\in\mathcal{K} \\
& y_{tp}^{k} \in \{0,1\}, && \forall t\in\mathcal{T}, \forall p\in\mathcal{P}, \forall k\in\mathcal{K} \\
& q_{tg}^{k} \in \{0,1\}, && \forall t\in\mathcal{T}, \forall g\in\mathcal{G}, \forall k\in\mathcal{K} \\
& h_{t}^{k} \in \{0,1\}, && \forall t\in\mathcal{T}, \forall k\in\mathcal{K} \\
& d_{t}^{k} \in [0, D_{\max}^{k}], && \forall t\in\mathcal{T}, \forall k\in\mathcal{K} \\
& b_{t}^{k} \in [0, B_{\max}^{k}], && \forall t\in\mathcal{T}, \forall k\in\mathcal{K}
\end{aligned}
$$

Experiment Parameters

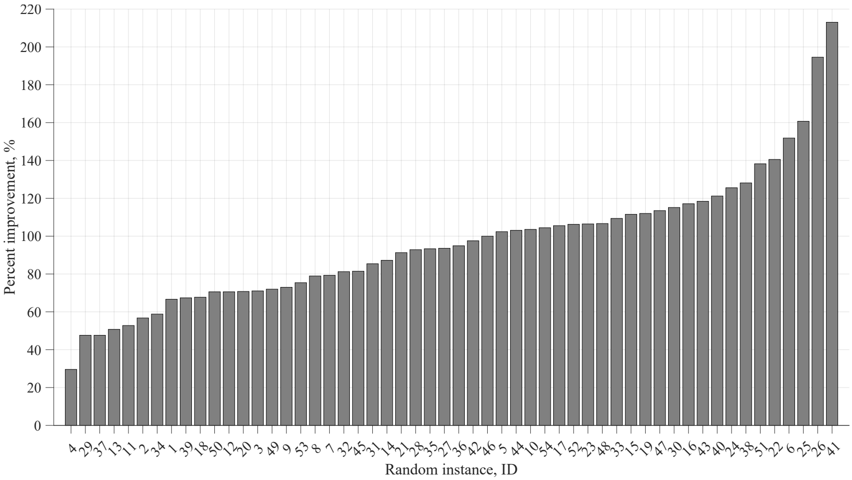
Hardware:

- $D^k_{\max} = 128\,\text{GB}, \forall k \in \mathcal{K}$ [19]
- $D_{\text{obs}} = 102.5\,\text{MB}$ [20]
- $D_{\text{comm}} = 100\,\text{MB}$ [19]
- $B^k_{\max} = 1647\,\text{kJ}, \forall k \in \mathcal{K}$ [19]
- $B_{\text{obs}} = 16.26\,\text{kJ}$ [20]
- $B_{\text{comm}} = 1.2\,\text{kJ}$ [19]
- $B_{\text{recon}} = 0.5\,\text{kJ}$ [19]
- $B_{\text{charge}} = 41.48\,\text{kJ}$ [19]
- $B_{\text{time}} = 2\,\text{kJ}$ [19]

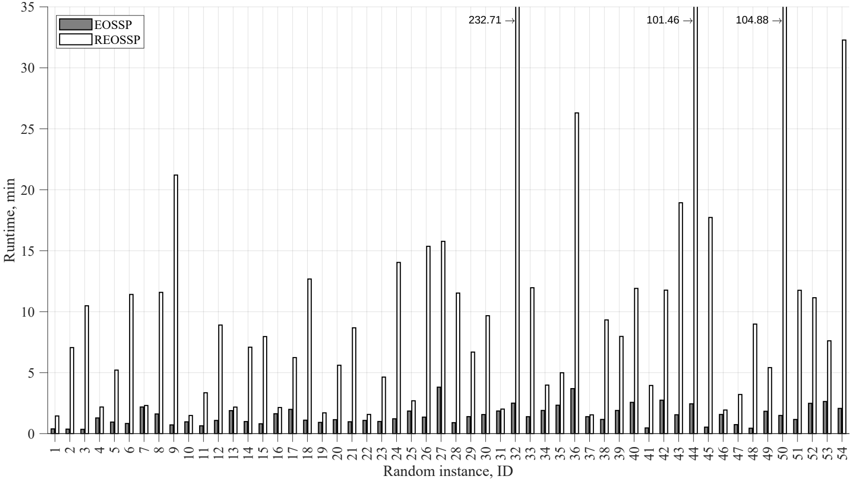
Propagation:

- Visibility matrices V and W are generated using the `access` function from the Aerospace Toolbox [13]
- Visibility matrix H is generated using the `eclipse` function from the Aerospace Toolbox [13]
- Orbital maneuver cost matrix c^{sk}_{ij} generated using algorithms from Ref. [21]
- Propagation via SGP4 (Simplified General Perturbation 4) model

Random Instance Percent Improvement



Random Instance Runtime



Case Study Parameter Changes

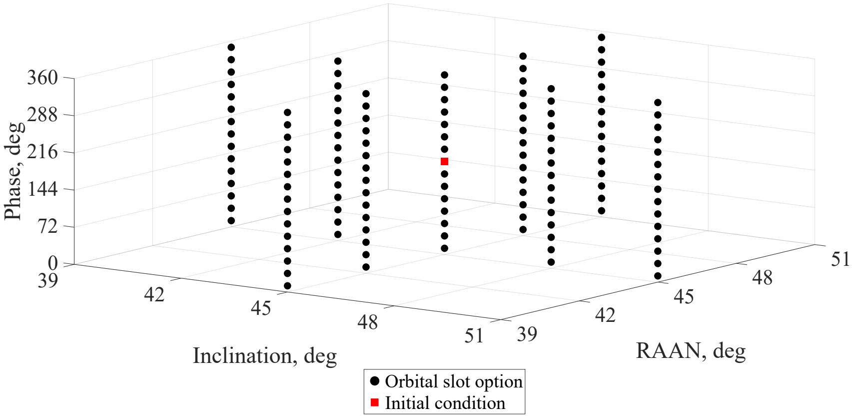
Visibility masking:

$$V_{tp}^{k} = \begin{cases} 1, & \text{if target } p \in \mathcal{P} \text{ is visible to satellite } k \in \mathcal{K} \text{ at time } t \in \mathcal{T}, \\ & \quad \text{and } t \in [1 + (p-1)(T/P), p(T/P)] \\ 0, & \text{otherwise} \end{cases}$$

$$V_{t'jp}^{sk} = \begin{cases} 1, & \text{if, during stage } s \in \mathcal{S} \setminus \{0\}, \text{ target } p \in \mathcal{P} \\ & \quad \text{is visible at time } t' \in \mathcal{T}^s \\ & \quad \text{to satellite } k \in \mathcal{K} \text{ in orbital slot } j \in \mathcal{J}^{sk}, \\ & \quad \text{and } t \in [1 + (p-1)(T/P), p(T/P)] \\ 0, & \text{otherwise} \end{cases}$$

$t' \in \mathcal{T}^s$ if $t \in [1 + (s-1)T^s, sT^s]$

Orbital Slot Distribution (Case Study)



N-impulse Trajectory Optimization

Equations

$$\min \quad \sum_{n=1}^{N} V_n \tag{8a}$$

$$\text{s.t.} \quad \sum_{n=1}^{N} V_n \leq c_{\max} \tag{8b}$$

$$\sqrt{V_{xn}^2 + V_{yn}^2 + V_{zn}^2} = 1, \quad \forall n \in \{1, 2, \ldots, N\} \tag{8c}$$

$$||\boldsymbol{R}_n|| \geq R_{\min}, \quad \forall n \in \{1, 2, \ldots, N\} \tag{8d}$$

$$V_{xn},\ V_{yn},\ V_{zn} \in [-1, 1], \quad \forall n \in \{1, 2, \ldots, N\} \tag{8e}$$

$$V_n \in [0, c_{\max}], \quad \forall n \in \{1, 2, \ldots, N\} \tag{8f}$$

$$\tau \in [\tau_{\min}, \tau_{\max}] \tag{8g}$$

Constraints

- Minimize total impulse cost (8a)
- Total impulse cost under the budget (8b)
- Magnitude of directional components is one (8c)
- Trajectory obeys minimum altitude (8d)
- Directional components in any direction (8e)
- Each impulse is between zero and the budget (8f)
- Time between $\tau_{\min}$ and $\tau_{\max}$ (8g)