Time-expanded Space Logistics Network Modeling and Optimization for On-Orbit Servicing, Assembly, and Manufacturing (OSAM)

SSDL presentation

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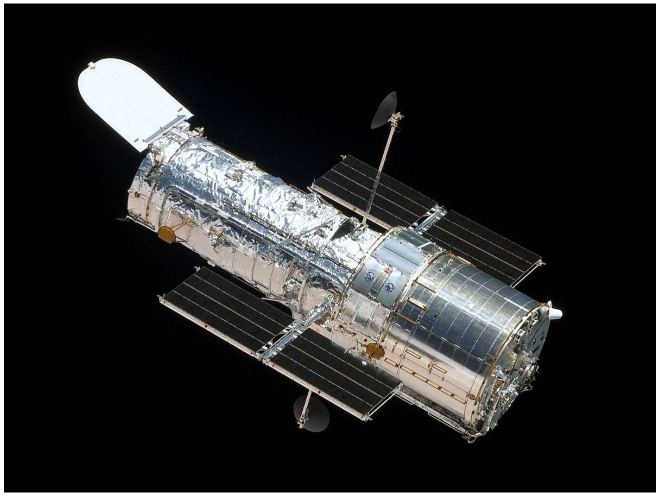
Agenda

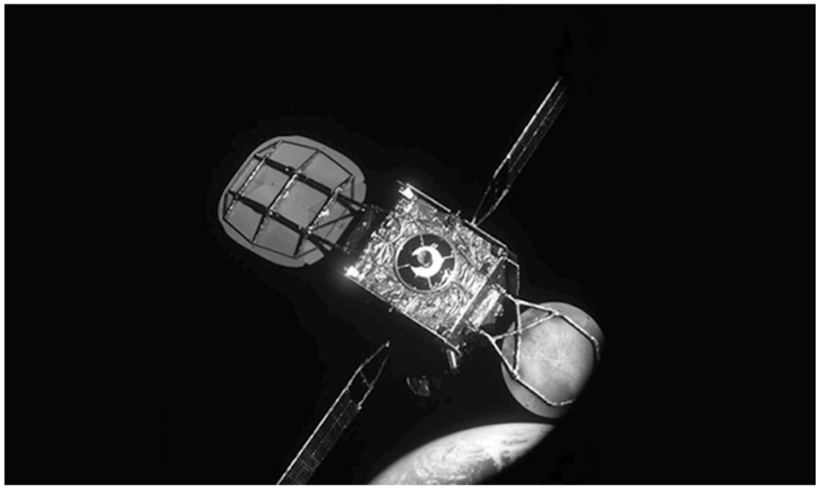
1. Project's vision
The need for robotic On-orbit Servicing (OOS)

Hubble Space Telescope



- Deployed in 1990
- Low altitude: 540km
- First satellite designed to be serviced
- 5 visits by space shuttle and astronauts

GEO satellites: Intelsat 901
→ near term market for OOS



- Modern-day life relies on GEO sats
- Sophisticated and costly spacecraft
- High altitude: 35,786km
- Traditionally not designed to be serviced (this is going to change thanks to spacecraft modularization)
- GEO = harsh environment for astronauts
- Space shuttle no longer in service

1. Project's vision
On-Orbit Servicing State-of-the-Art

On-Orbit Servicing state of the art has mainly focused on:

- Development of space robotics and manufacturing technologies
- Multi-transfer trajectory design to service a finite sequence of satellites
- High-level cost benefit analysis

OOS operators will soon need a system-level logistics modeling tool to concurrently optimize:

- ➢ Operations scheduling of large scale, long-lasting OOS infrastructures
  - ○ *When to assign service needs? To what servicer?*
- ➢ Logistics mission planning for fuel/parts/materials
  - ○ *How frequently to resupply the orbital depots?*
- ➢ OOS infrastructure design
  - ○ *How large the depots? How many servicers?*

2. OSAM Logistics Software
Our response to the upcoming industry need

Modeling inputs
- Customer fleet
- Service needs
- OSAM architecture

User-defined trajectory plug-ins

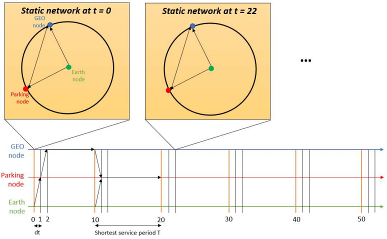
…

High-thrust trajectory

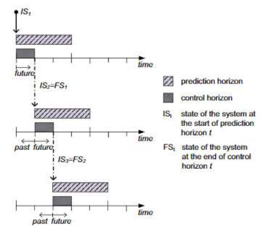
Low-thrust trajectory

Multi-orbit OSAM logistics planning software

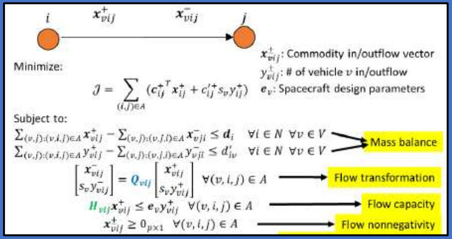
- Time-expanded network



- Rolling horizon procedure



- Space logistics formulation



$x^{\pm}_{vij}$: Commodity in/outflow vector

$y^{\pm}_{vij}$: # of vehicle v in/outflow

e_v: Spacecraft design parameters

Minimize:

$$\mathcal{J} = \sum_{(i,j)\in A} \left({c^+_{ij}}^T x^+_{ij} + c'^+_{ij} s_v y^+_{ij} \right)$$

Subject to:

$$\sum_{(v,j):(v,i,j)\in A} x^+_{vij} - \sum_{(v,j):(v,j,i)\in A} x^-_{vji} \le d_i \quad \forall i \in N \ \forall v \in V$$

$$\sum_{(v,j):(v,i,j)\in A} y^+_{vij} - \sum_{(v,j):(v,j,i)\in A} y^-_{vji} \le d'_{iv} \quad \forall i \in N \ \forall v \in V$$

Mass balance

$$\begin{bmatrix} x^-_{vij} \\ s_v y^-_{vij} \end{bmatrix} = Q_{vij} \begin{bmatrix} x^+_{vij} \\ s_v y^+_{vij} \end{bmatrix} \quad \forall (v,i,j) \in A$$

Flow transformation

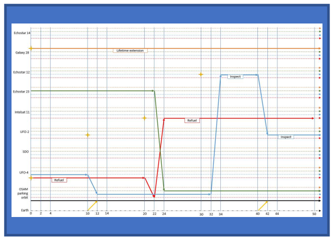
$$H_{vij} x^+_{vij} \le e_v y^+_{vij} \quad \forall (v,i,j) \in A$$

Flow capacity

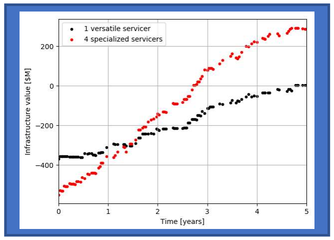
$$x^+_{vij} \ge 0_{p\times 1} \quad \forall (v,i,j) \in A$$

Flow nonnegativity

Use case #1
Short-term OSAM operations scheduling

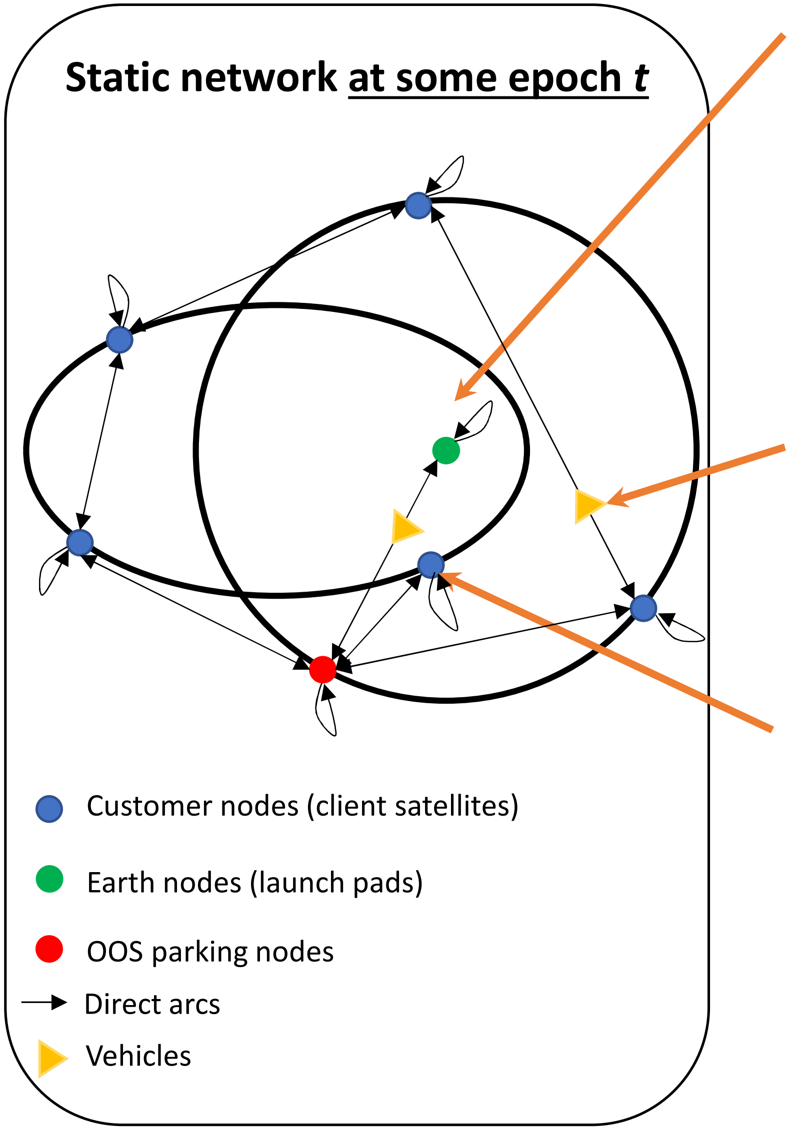


Use case #2
Long-term OSAM strategic planning



3. Static Network

Overview



Commodity flows (variables)

- *Bi-propellant*: continuous
- *Mono-propellant*: continuous
- *EP propellant*: continuous
- *Spares*: continuous
- *Servicer tools*: integer
- *Vehicle*: integer

Vehicles

- *Servicers*: free flying in space (high-thrust, low-thrust, multimodal)
- *Orbital depots*: stationed at OOS parking node(s)
- *Launch vehicles*: from Earth to parking node

Service needs:

- *Refueling*: deterministic
- *Station keeping*: deterministic
- *Inspection*: deterministic
- *Retirement*: random
- *Repositioning*: random
- *Repair*: random
- *Mechanism deployment*: random

3. Static Network

Customer satellites and service needs

Deterministic needs	Inspection	Refueling	Station keeping
Description	Servicer performs proximity maneuver near the satellite without docking to inspect its condition	Servicer rendezvouses and docks to the satellite to top up its tank with additional propellant	Servicer rendezvouses and docks to the satellite to perform station-keeping maneuvers in place of the satellite

Random needs	Repositioning	Retirement	Repair	Mechanism Deployment
Description	Servicer changes the GEO orbital slots of the customer satellite	The servicer transports the defunct satellite to a graveyard orbit 300km above GEO	Servicer docks to satellite and replaces defective parts with spares	Servicer docks to satellite and unlock stuck appendages

Inputs common to all service needs

- Service fee [$]
- Delay penalty cost [$/day]
- ‘No-service’ penalty cost [$]
    - *e.g*, if the OSAM operator is not committing to a contract
- Service duration
- Service window (illustrated in slide 27)

Inputs specific to deterministic needs

- Time of 1st service need occurrence
- Time interval between occurrences

Input specific to random needs

- Mean time interval between occurrences
    - Needs generated from Poisson probability distribution

Additional service specific parameters

- Refueling: amount of propellant needed to refuel the satellite
- Repair: amount of spares needed to repair the satellite
- Repositioning: angular position of the desired new orbital slot of the satellite

3. Static Network

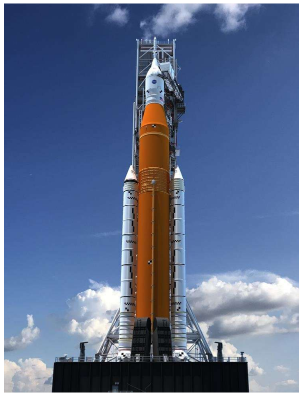
OSAM architectural elements

Servicers

- ❖ Tools: type and number
- ❖ Orbital transfer: trajectory, Isp, propellant capacity, dry mass…
- ❖ Costs: manufacturing and operations
- ❖ Payload capacity for each type of commodity

Orbital depots

- ❖ Dry mass
- ❖ Costs: manufacturing and operations
- ❖ Payload capacity for each type of commodity
- ❖ Own propellant consumption for station keeping maneuvers



Launch vehicles

- ❖ Launch frequency (assumed deterministic)
- ❖ Mass-specific launch price tag
- ❖ Payload capacity to launch commodities in GTO or GEO
- ❖ 'Flight flexibility' parameter: *is the launcher allowed to resupply a servicer anywhere in space or just at the depot location?*

3. Static Network

OSAM architectural elements

Servicers' tools

- Tools are used by the servicers to provide services (*e.g.*, robotic arm, refueling apparatus)
- Tools are swappable or not, depending on the desired design for the servicer
- The software user freely defines:
  - Tool mass
  - Tool cost
  - Service-tool mapping

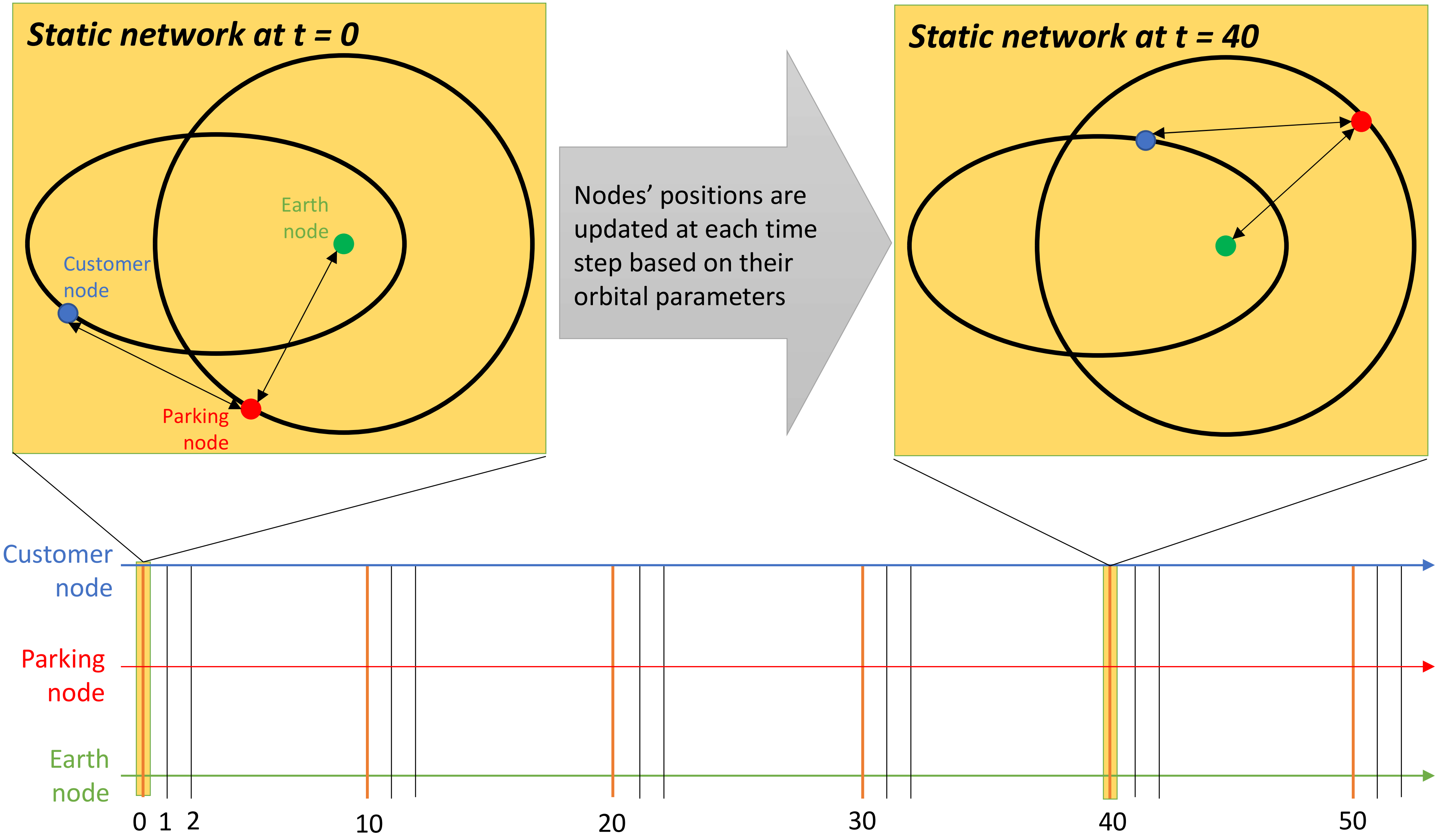
Canadarm is the archetype of in-space robotic arm.

Example of service-tool mapping as software input

Tool	Inspection	Refueling	Station keeping	Retirement	Repositionin g	Repair	Mechanism deployment
T1: Refueling apparatus	0	1	0	0	0	0	0
T2: Observation sensors	1	0	0	0	0	0	0
T3: Dexterous robotic arm	0	0	0	0	0	1	1
T4: Coupling mechanism	0	0	1	1	1	0	0

4. Dynamic network

Static network time expansion



Static network at t = 0

Nodes’ positions are updated at each time step based on their orbital parameters

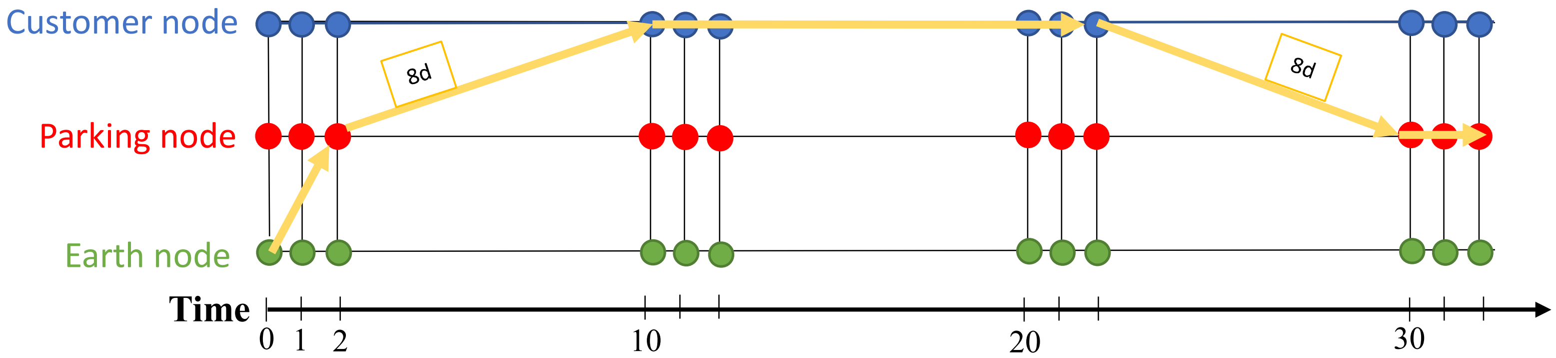
Static network at t = 40

4. Dynamic network

Transportation arcs

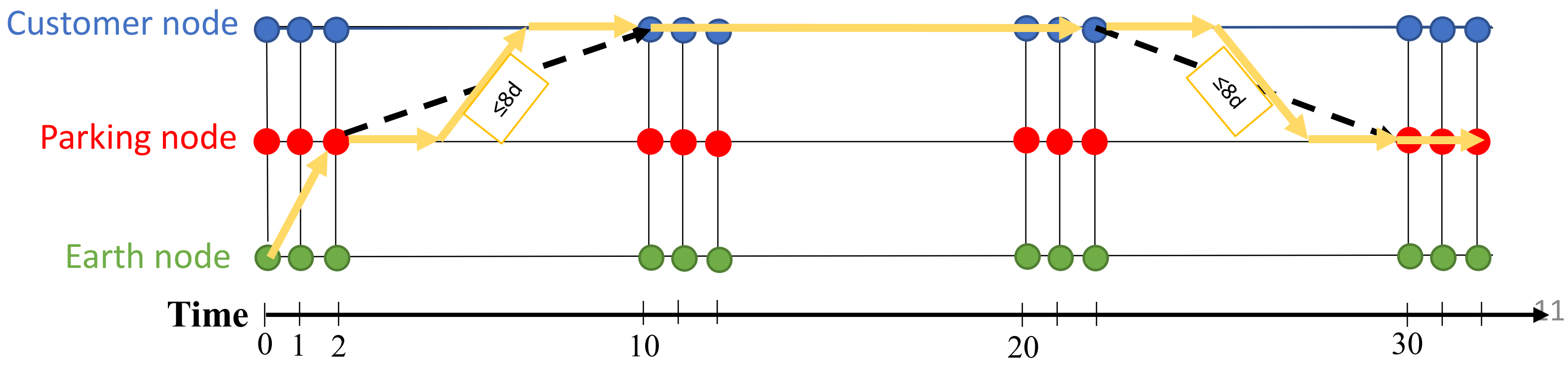
Until January 2021

The length of a transportation arc is the actual duration of the orbital maneuver



After January 2021

The length of a transportation arc is the time window within which the orbital maneuver must start and end



4. Dynamic network

Servicers and orbital trajectories

High-thrust, low-thrust,… or both?

Framework allows OSAM operators to model and simulate servicers with all kinds of propulsive technologies and user-defined trajectories (as plug-ins to the software).

High-thrust trajectory model

Inputs:

- Orbital parameters of the departure and arrival nodes at t_0 (start of the time window)
- Length of the time window (*ie.,* $t_f - t_0$)

Outputs:

- Terminal deltaVs Δv_1 and Δv_2

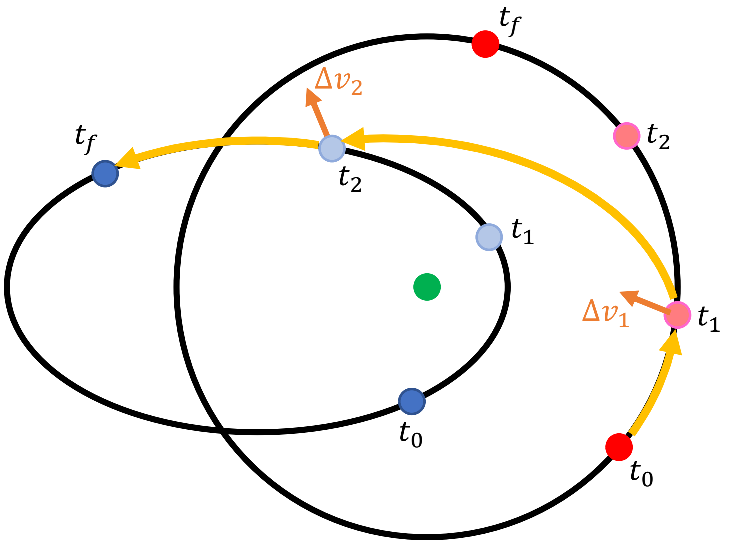
Low-thrust trajectory model

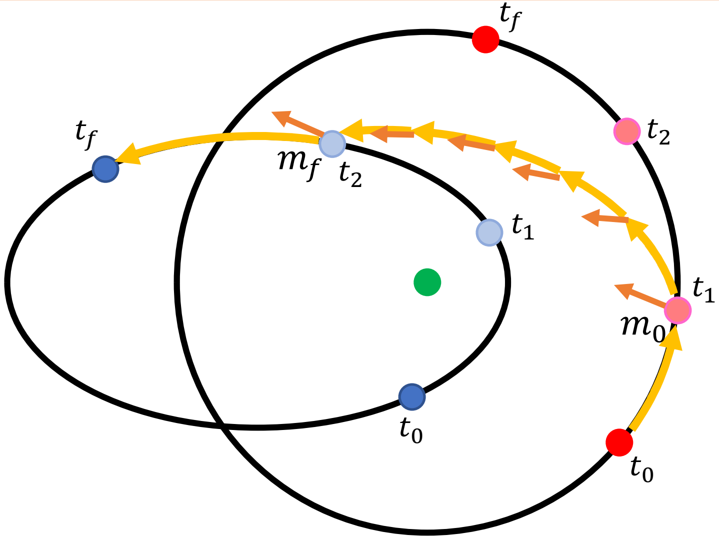
Inputs:

- Orbital parameters of the departure and arrival nodes at t_0 (start of the time window)
- Length of the time window (*ie,* $t_f - t_0$)
- Initial spacecraft mass m_0

Outputs:

- Final mass m_f (propellant consumed = $m_0 - m_f$)





5. Rolling Horizon Procedure

The Rolling Horizon approach:

- *Application*: make decisions in a **dynamic stochastic** environment
- *Underlying idea*: make most immediate decisions, *i.e.*, during a time period called *control horizon* (CH), based on a forecast (deterministic or stochastic) of relevant information over a longer time interval called *planning horizon* (PH)

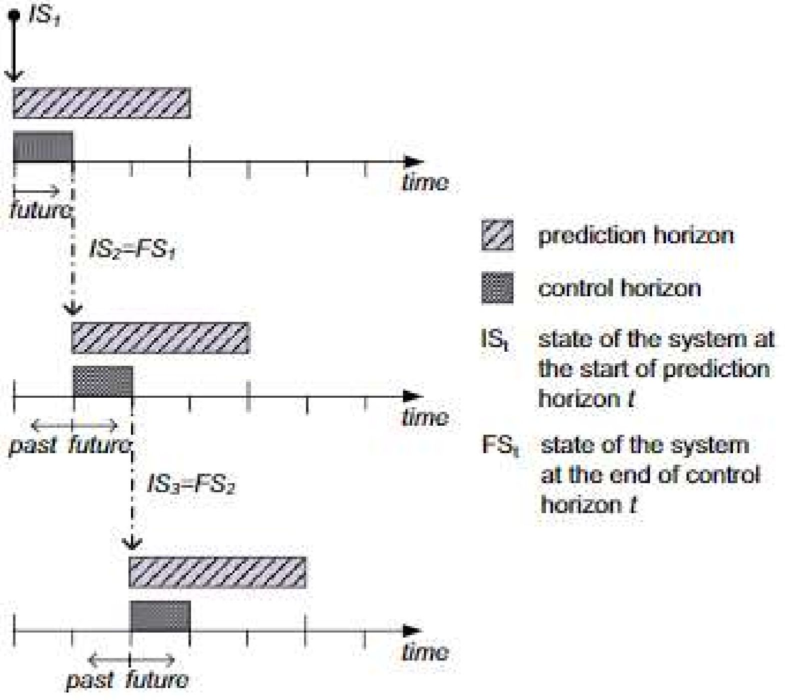


Illustration of the rolling horizon procedure. The prediction horizon is the planning horizon.
Credit: Silvente et al., "A Rolling Horizon Optimization Framework for the Simultaneous Energy Supply and Demand Planning in Microgrids" [1]

Modification of traditional rolling horizon approach for application to on-orbit servicing operations:

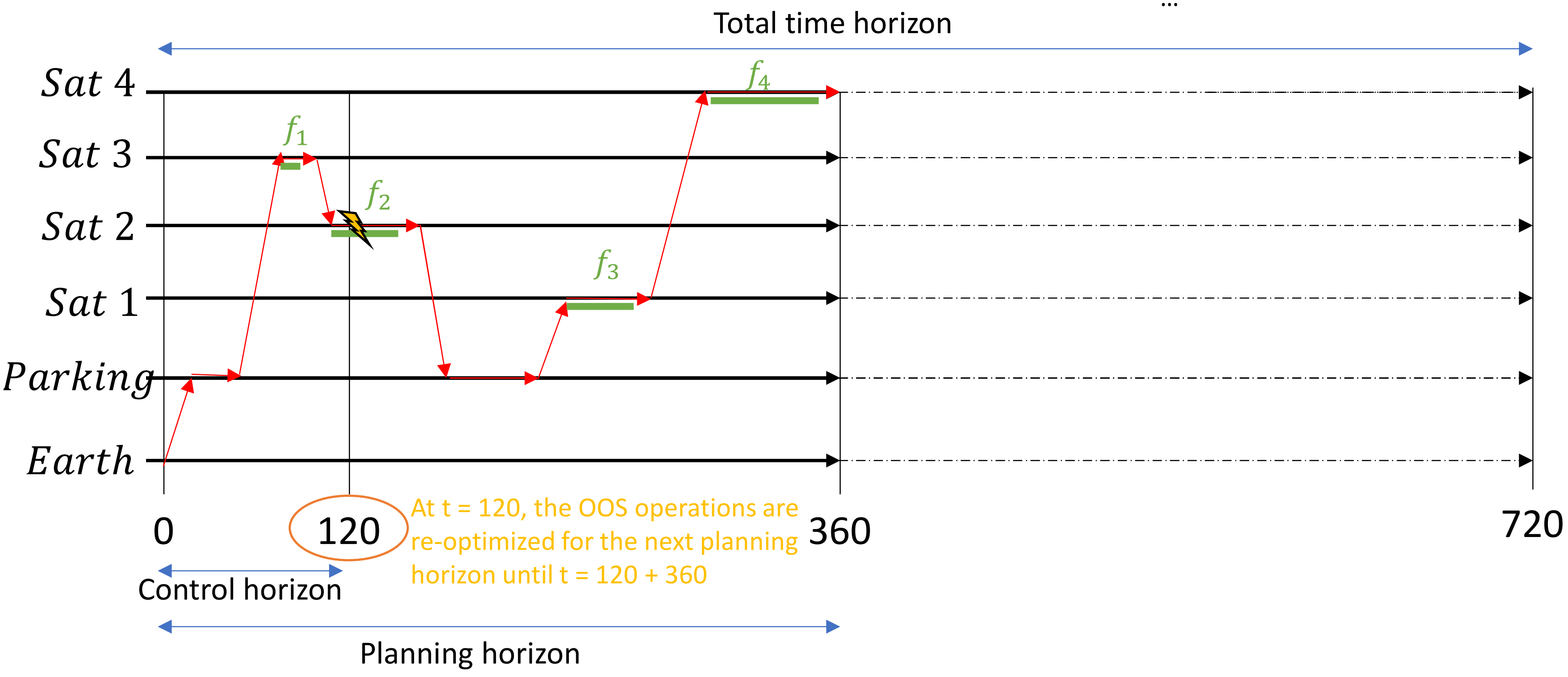
- Only deterministic service needs are forecasted over the planning horizon
- A new planning horizon is defined whenever a random service need arises (*i.e.,* not necessarily on a regular basis)

5. Rolling Horizon Procedure

Plan/optimize OOS operations over planning horizon [0,360] based on service needs recorded before time step t = 360.

Service timeline

f1: [50, deterministic, G3,…]
f2: [110, deterministic, G2,…]
f3: [220, deterministic, G1,…]
f4: [300, deterministic, G4,…]
…



At t = 120, the OOS operations are re-optimized for the next planning horizon until t = 120 + 360

→ Servicers' route(s)

⚡ Servicers' routes cutoff to be propagated to next PH

🟩 Deterministic service provided (e.g., refuel)

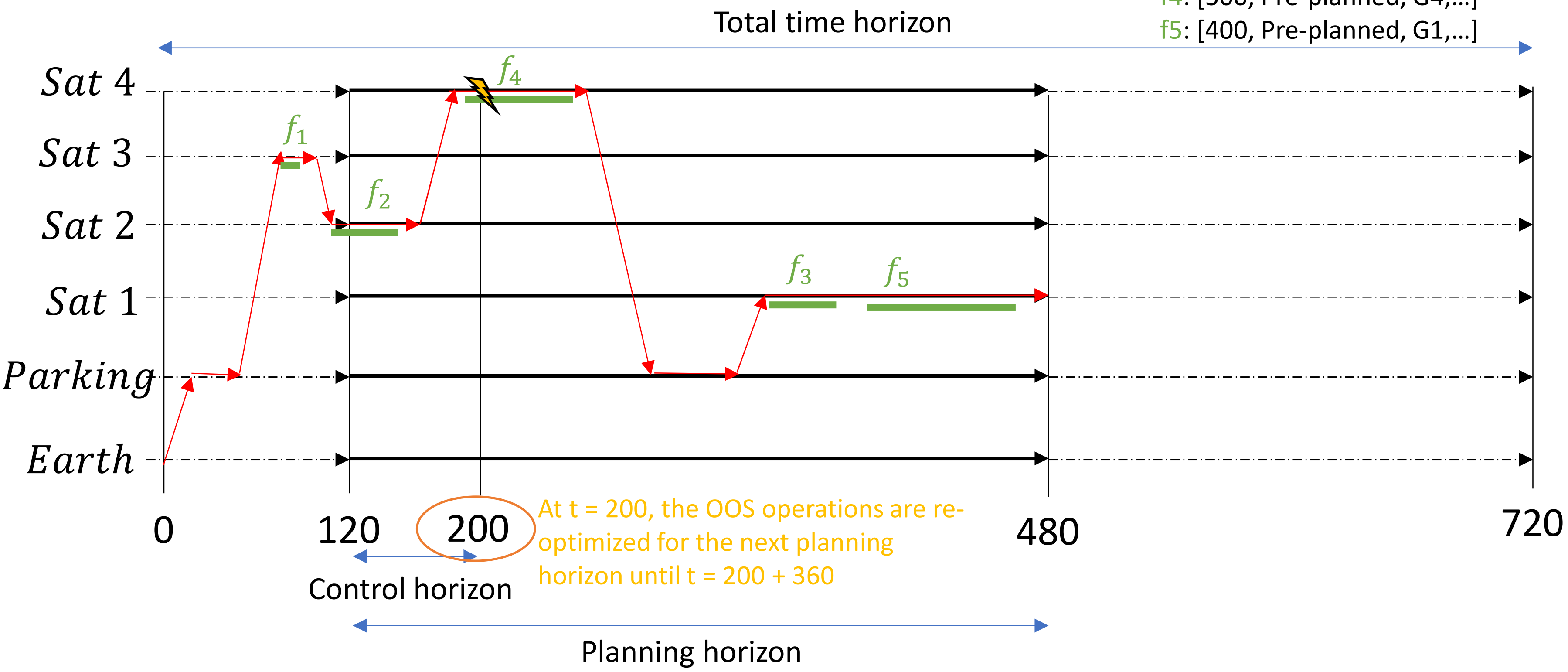
🟦 Random service provided (e.g., repair)

5. Rolling Horizon Procedure

Plan/optimize OOS operations over planning horizon [120,480] based on service needs recorded between time steps t = 120 and t = 480.

Service timeline

f1: [50, Pre-planned, G3,…]
f2: [110, Pre-planned, G2,…]
r1: [200, Random, G3,…]
f3: [220, Pre-planned, G1,…]
f4: [300, Pre-planned, G4,…]
f5: [400, Pre-planned, G1,…]



At t = 200, the OOS operations are re-optimized for the next planning horizon until t = 200 + 360

→ Servicers' route(s)

Servicers' routes cutoff to be propagated to next PH

🟩 Deterministic service provided (e.g., refuel)

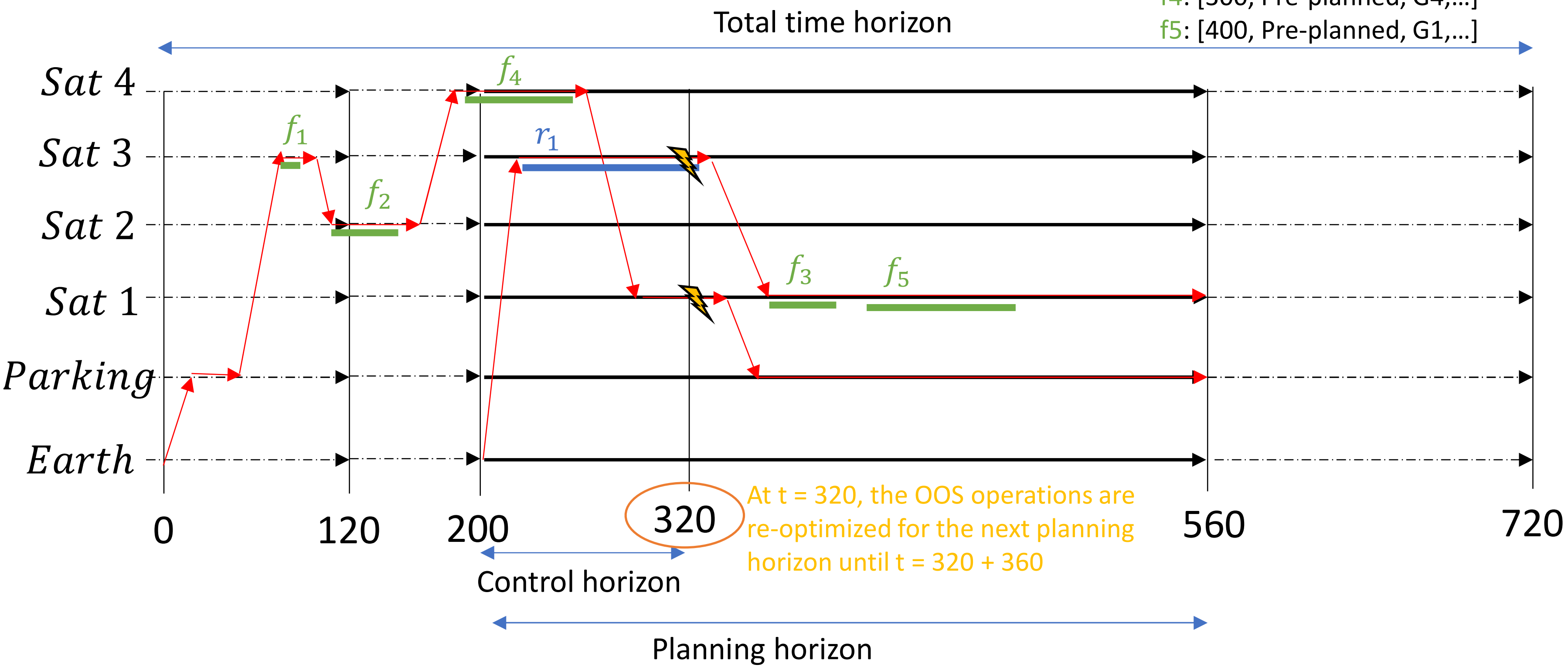
🟦 Random service provided (e.g., repair)

5. Rolling Horizon Procedure

Plan/optimize OOS operations over planning horizon [200,560] based on service needs recorded between time steps t = 200 and t = 560.

Service timeline

f1: [50, Pre-planned, G3,…]
f2: [110, Pre-planned, G2,…]
r1: [200, Random, G3,…]
f3: [220, Pre-planned, G1,…]
f4: [300, Pre-planned, G4,…]
f5: [400, Pre-planned, G1,…]



At t = 320, the OOS operations are re-optimized for the next planning horizon until t = 320 + 360

Servicers' route(s)

Servicers' routes cutoff to be propagated to next PH

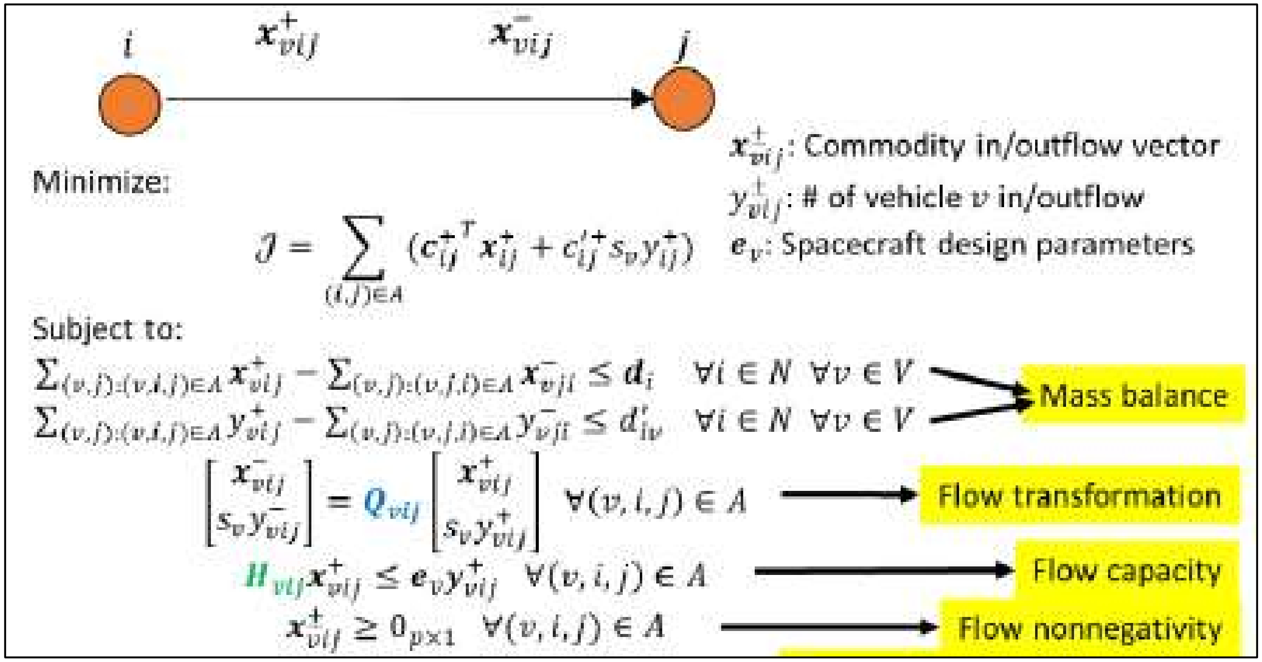
🟩 Deterministic service provided (e.g., refuel)

🟦 Random service provided (e.g., repair)

6. OSAM logistics formulation

Project novelties

- Model the OSAM logistics problem as a *Dynamic Generalized Multi-Commodity Network Flow* (DGMCNF) problem
- Extend the classical DGMCNF problem formulation with variables and constraints specific to OSAM logistics due to the service provision (*cf* next slide)



$x^{\pm}_{vij}$: Commodity in/outflow vector
$y^{\pm}_{vij}$: # of vehicle v in/outflow
e_v: Spacecraft design parameters

Minimize:

$$\mathcal{J} = \sum_{(i,j)\in A} \left({c^{+}_{ij}}^{T} x^{+}_{ij} + {c'}^{+}_{ij} s_v y^{+}_{ij} \right)$$

Subject to:

$$\sum_{(v,j):(v,i,j)\in A} x^{+}_{vij} - \sum_{(v,j):(v,j,i)\in A} x^{-}_{vji} \le d_i \quad \forall i \in N \;\; \forall v \in V$$

$$\sum_{(v,j):(v,i,j)\in A} y^{+}_{vij} - \sum_{(v,j):(v,j,i)\in A} y^{-}_{vji} \le d'_{iv} \quad \forall i \in N \;\; \forall v \in V$$

$$\begin{bmatrix} x^{-}_{vij} \\ s_v y^{-}_{vij} \end{bmatrix} = Q_{vij} \begin{bmatrix} x^{+}_{vij} \\ s_v y^{+}_{vij} \end{bmatrix} \quad \forall (v,i,j) \in A$$

$$H_{vij} x^{+}_{vij} \le e_v y^{+}_{vij} \quad \forall (v,i,j) \in A$$

$$x^{+}_{vij} \ge 0_{p\times 1} \quad \forall (v,i,j) \in A$$

A DGMCNF problem is modeled and solved as a Mixed-Integer Linear Program (MILP). More detailed about the traditional space logistics formulations can be found in [2].

6. OSAM logistics formulation

DGMCNF formulation extension motivations

- Traditional space logistics formulation cannot hold a given vehicle at a given node for some time
- This is essential to force a servicer at a customer satellite's location where a service has to be provided for some duration

Two additional sets of binary variables are defined that leverage the structure of the time-expanded network:

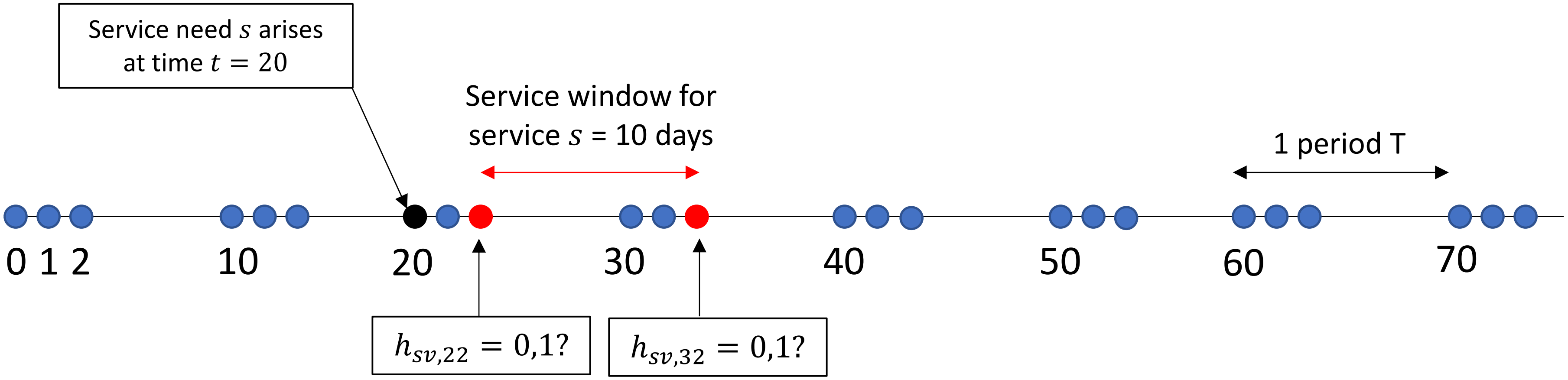
- *Service assignment variables* $h_{sv\tau}$
  - $h_{sv\tau}$ = 1 if a servicer v must **start providing** service s at time step τ
  - $h_{sv\tau}$ is defined only at those time steps τ defined within the service window associated with service s (*cf* next slide)

- *Servicers' logistical variables* b_{svt}
  - b_{svt} = 1 if a servicer v must **be providing** service s at time step t
  - b_{svt} is defined at every time step of the time-expanded network

6. OSAM logistics formulation

The concept of *service window*

- The service window of a service *s* is the interval of time within which a servicer must **start providing** service *s*, provided that the optimizer actually decides to provide it
- Introduced to give more flexibility to the optimizer in the assignment of services to servicers



- ❖ The $h_{sv\tau}$ variables are only defined within the service window associated with service s.
- ❖ The $h_{sv\tau}$ variables are defined only once per period T (red dots)
- ❖ Set of time steps when service s may be started: $\mathcal{W}_s = \{22, 32\}$
- ❖ The blue dots immediately preceding the red dots are for transportation between nodes

6. OSAM logistics formulation

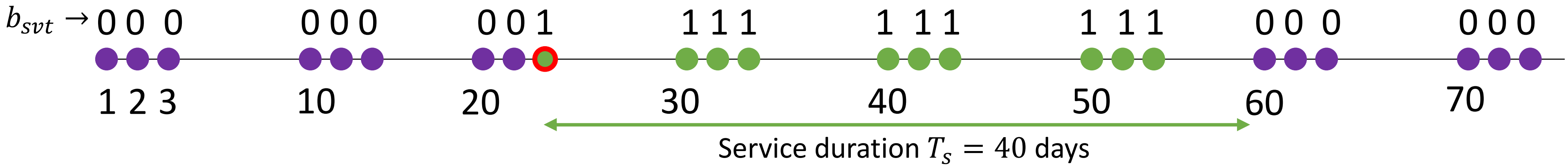
Relationship between $h_{sv\tau}$ and b_{svt} variables: $b_{svt} = \sum_{\tau \in \mathcal{W}_s} h_{sv\tau}\beta_{s\tau t}$
where $\beta_{s\tau t}$ is a binary parameter defined by the software before the optimization

For example in slide 24 we had $\mathcal{W}_s = \{22, 32\}$, so at any time step *t:* $b_{svt} = h_{sv,22}\beta_{s,22,t} + h_{sv,32}\beta_{s,32,t}$

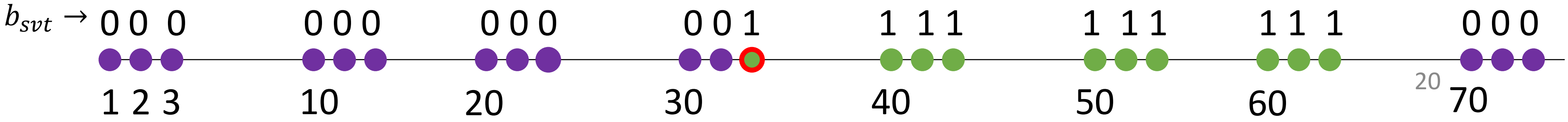
$\beta_{s,22,t}$ and $\beta_{s,32,t}$ are assigned to the time steps of the time-expanded network to specify when a servicer must **be providing** service *s* at time step *t* if the service starts at t = 22 or t = 32 respectively.

time	0	1	2	10	11	12	20	21	22	30	31	32	40	41	42	50	51	52	60	61	62	70	71	72
$\boldsymbol{\beta_{s,22,t}}$	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0
$\boldsymbol{\beta_{s,32,t}}$	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0

- ❖ For example, if $h_{sv,22} = 1$ and $h_{sv,32} = 0$, the service is started at t = 22:



- ❖ But if $h_{sv,22} = 0$ and $h_{sv,32} = 1$, the service is started at t = 32:



6. OSAM logistics formulation

Once the $h_{sv\tau}$ and b_{svt} variables are well defined, we can define the logistics constraints and objective functions associated with the provision of services.

Constraints

(1) Service *s* may be scheduled at most once:

$$\sum_{v\in\mathcal{V}_s}\sum_{\tau\in\mathcal{W}_s} h_{sv\tau} \leq 1 \qquad s \in \mathcal{S}'$$

(2) At most one service is provided to a customer satellite per time step:

$$\sum_{v\in\mathcal{V}_s}\left\{\sum_{s\in\mathcal{S}_i'} b_{svt}\right\} \leq 1 \qquad i \in \mathcal{N}_c, t \in \mathcal{T}$$

(3) Provide a service *s* with the right tools:

$$x_{viitk}^{+} \geq \sum_{s\in\mathcal{S}_{\mathrm{i}}'} \gamma_{sk} b_{svt} \qquad v \in \mathcal{V}_s, i \in \mathcal{N}_c, t \in \mathcal{T}, k \in \mathcal{K}_{tools}$$

γ_{sk} is the mapping between tools and service types (*cf* slide 16)

6. OSAM logistics formulation

The software optimizes the OSAM logistics planning so as to maximize the profits (*i.e.,* revenues – costs) generated over the planning horizon.

Objective functions

(1) Launch cost J_l
(2) Purchase, development and manufacturing costs J_{pdm}
(3) Penalty fees for delayed services J_{delay} (using $h_{sv\tau}$ and b_{svt} variables)
(4) Penalty fees for not providing a service J_{ns} (using $h_{sv\tau}$ and b_{svt} variables)
(5) Operation costs of the depots and servicers J_{ops}
(6) Revenues generated from the provision of services J_r (using $h_{sv\tau}$ and b_{svt} variables)

Maximize the profits: $J = J_r - J_l - J_{pdm} - J_{delay} - J_{ns} - J_{ops}$

7. Case studies

Overview

2 case studies

Case study #1

GOAL: demonstrate the **operational scheduling of 4 specialized high-thrust servicer** over a single planning horizon with GEO satellites at different inclinations

SOFTWARE VALUE: allow OSAM operators to make the best decision regarding what propulsion technology a servicer should use for a given orbital transfer

Case study #2

GOAL: demonstrate ***long-term strategic planning*** of 2 different OSAM architectures with GEO satellites at different inclinations

SOFTWARE VALUE: support technology portfolio management and roadmapping given some market forecast

7. Case studies

Assumptions

Customer fleet assumptions – deterministic service needs

	Inspection	Refueling	Station keeping
Revenues [$M]	10 [5]	15 [5]	20
Delay penalty fee [$/day]	5000 [5]	100000 [5]	100000 [5]
Service duration [days]	10 [5]	30 [5]	180 [7]
Service window [days]	30	30	30
Frequency of occurrence [days]	6310 [6]	2100 [6]	2100 [6]

Customer fleet assumptions – random service needs

	Repositioning	Retirement	Repair	Mechanism Deployment
Revenues [$M]	10 [5]	10 [5]	30	25 [5]
Delay penalty fee [$/day]	100000 [5]	0 [5]	100000 [5]	100000 [5]
Service duration [days]	30 [5]	30 [5]	30 [5]	30 [5]
Service window [days]	30	30	30	30
Mean frequency of occurrence [days]	2520 [6]	2520 [6]	9020 [6]	21050 [6]

Tools and mapping to services

Tool	Inspection	Refueling	Station keeping	Retirement	Repositioning	Repair	Mechanism deployment
T1: Refueling apparatus	0	1	0	0	0	0	0
T2: Observation sensors	1	0	0	0	0	0	0
T3: Dexterous robotic arm	0	0	0	0	0	1	1
T4: Coupling mechanism	0	0	1	1	1	0	0

7. Case studies

Assumptions

Servicers' models (baseline)

	High-thrust versatile	High-thrust specialized
Tools	T1,T2,T3,T4	T1 or T2 or T3 or T4
Dry mass [kg]	3,000	2,000
BP capacity [kg]	1,000	1,000
MP capacity [kg]	200	200 (if equipped for refueling)
Manufacturing cost [$]	$75M	$50M
Propellant type	Bipropellant (BP)	Bipropellant (BP)
Propellant Isp [s]	316	316
Flight durations [days]	2, 4, 10, 14	2, 4, 10, 14

7. Case studies

Assumptions

Depot

- Assumed pre-deployed at an OSAM parking node located on a non-inclined circular GEO orbit
- Propellant consumption rate for station keeping: 0.14kg/day [10]
- Manufacturing cost: $200M
- Operating cost: $13,000/day

Launch vehicle (Falcon 9)

- 1 launch vehicle every 30 days
- Max payload capacity: 8,300 kg
- Launch price tag: $11,300/kg

Commodities' costs

- Spares: $1,000/kg
- Mono-propellant for depot and customer satellites: $230/kg
- Bi-propellant for the high-thrust and multimodal servicers: $180/kg

Tools

- Each tool costs $100,000 and weighs 100kg

7. Case studies

Use case 1: operational scheduling of high-thrust servicers

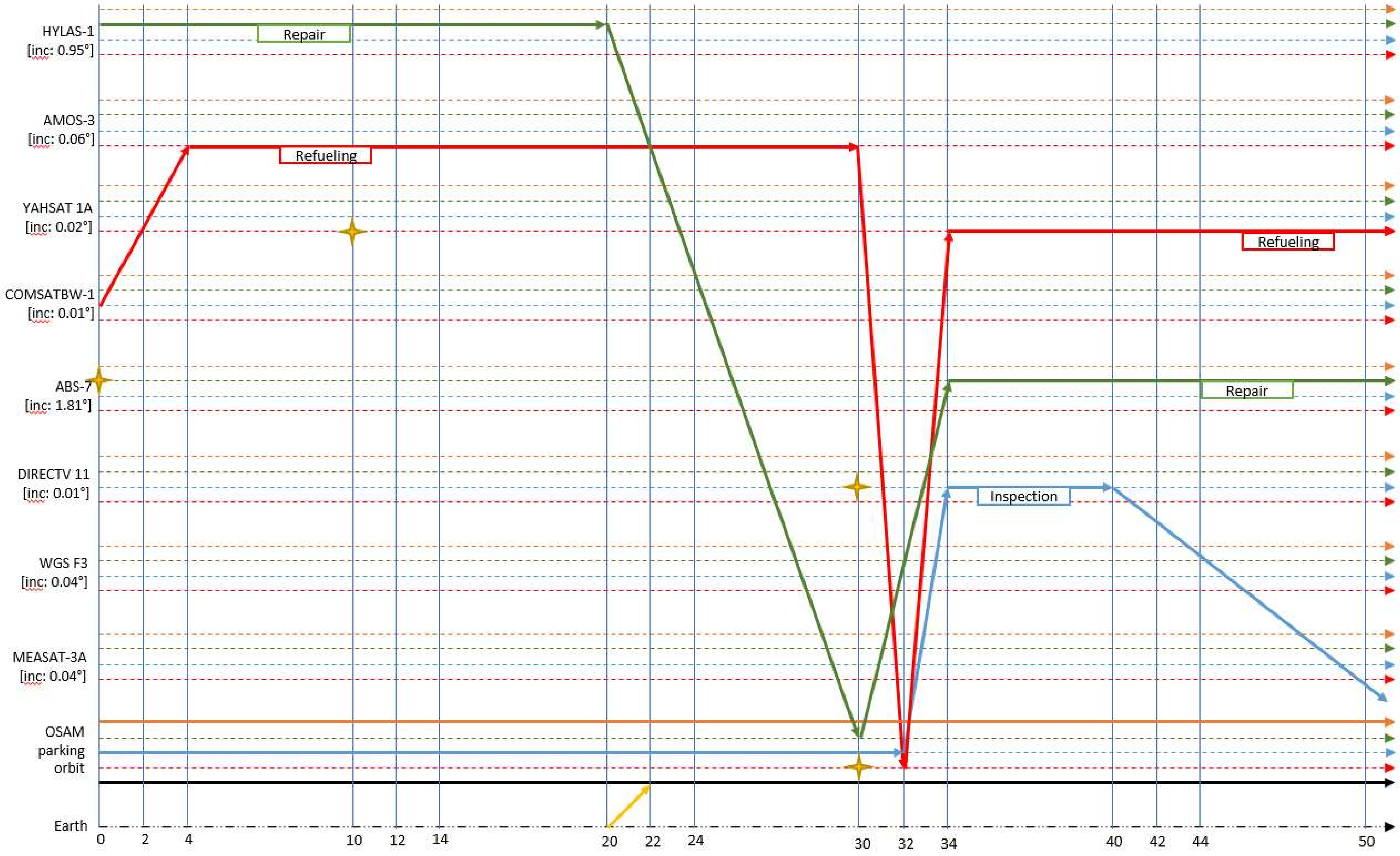
Objective and motivation

- demonstrate the tool capability in planning the operations of 4 specialized high-thrust servicers with several time-of-flight options and with GEO satellites on different orbits

Servicers	4 high-thrust, specialized servicers
Depot	1 depot pre-deployed on a non-inclined GEO orbit
Number of planning horizon optimizations	1
Planning horizon	100 days
Customer fleet	228 GEO satellites distributed along orbits at different inclinations
Flight flexibility	Launch vehicle can't resupply servicers near customer satellites
Servicers' operations	- When not providing a service, servicers must go back to their storage location (same as depot's location); - Servicers can't be staged near a customer satellite to avoid interference with the satellite's operations

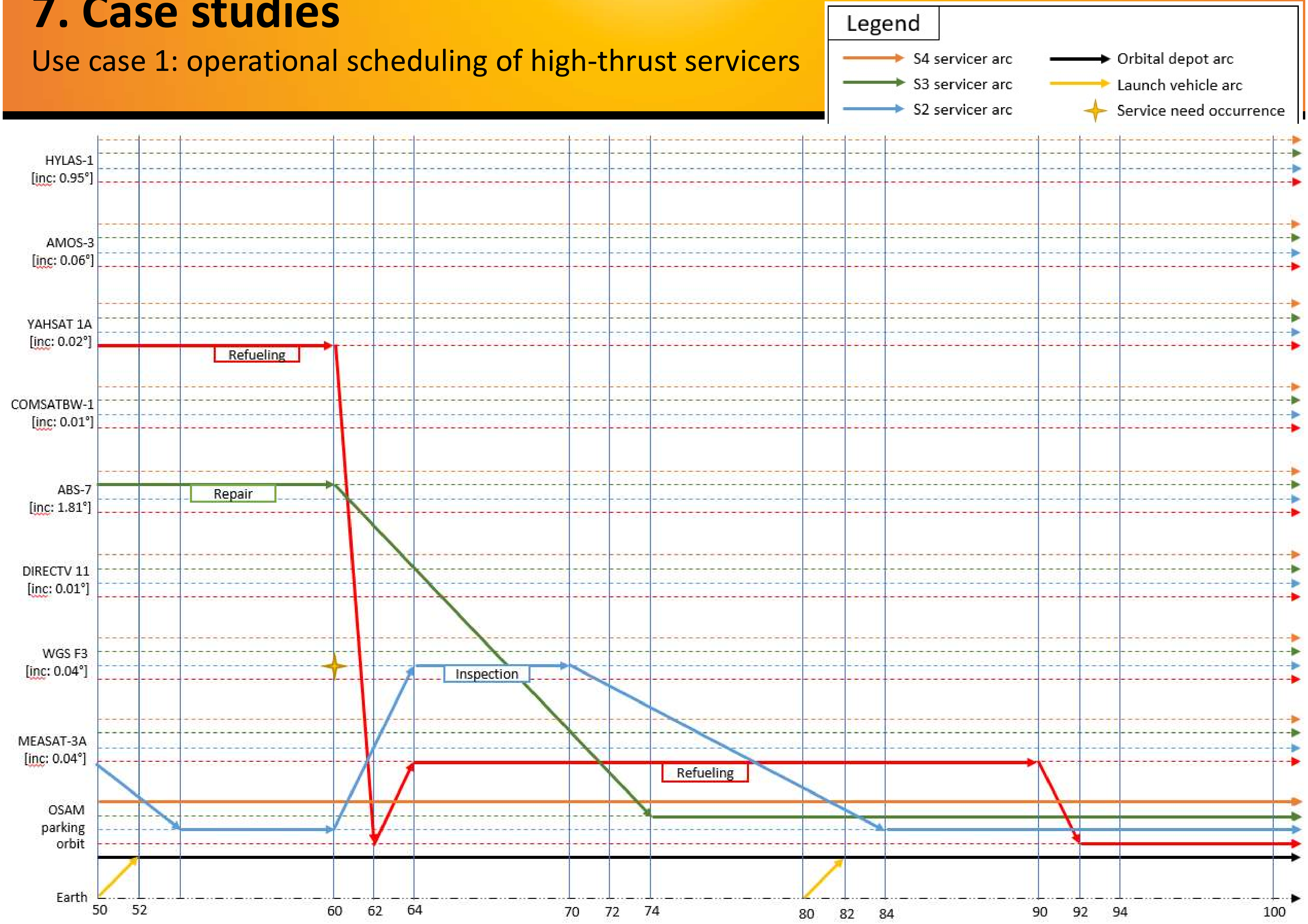
7. Case studies

Use case 1: operational scheduling of high-thrust servicers



7. Case studies

Use case 1: operational scheduling of high-thrust servicers



7. Case studies

Use case 2: long-term strategic planning

Objective and motivation

- ❖ Compare the performance of different OSAM architectures:
  - How long is the payback period?
  - How well do they react to different market conditions, *e.g.*, as the customer base increases?
- ❖ Useful for decision makers and investors to trade OSAM architecture alternatives with respect to initial investment and profitability
  - For example, an architecture may require a low initial investment but may be slow to pay it back; another architecture may require a larger initial investment but may better leverage future market forecast

Experiment: *run software for*

- ➢ 2 different architectures (monolithic VS distributed),
- ➢ 4 levels of service demand (customer base = 30, 71, 142 satellites)

Analysis

Trade architecture options (Distributed VS Monolithic)

Metrics to compare architectures

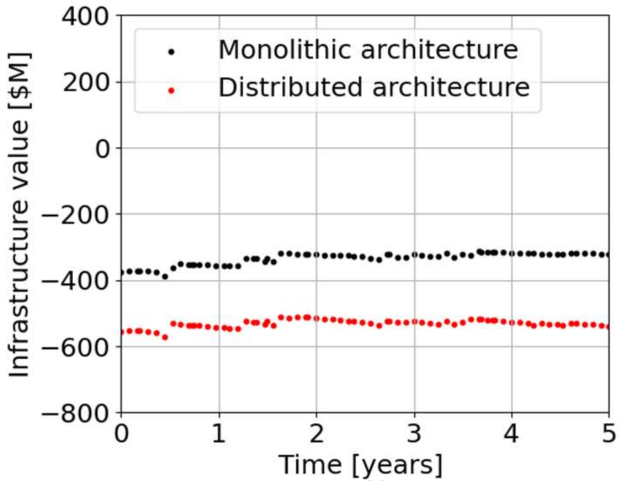
- Profits = revenues – costs
- Value = profits – initial investment

7. Case studies

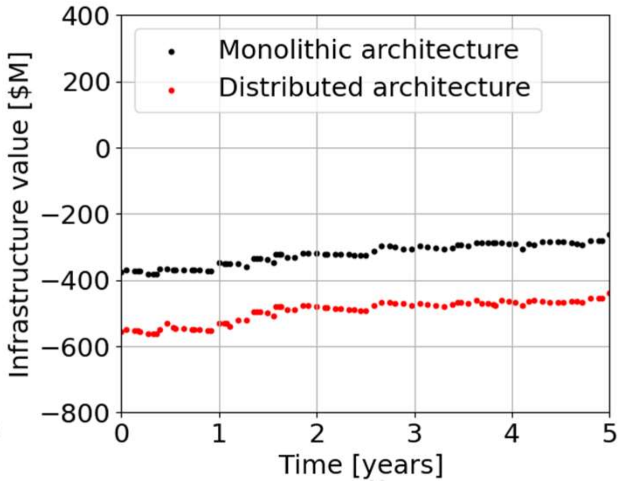
Use case 2: long-term strategic planning

Trading architectural options within the generalized multi-orbit OSAM framework

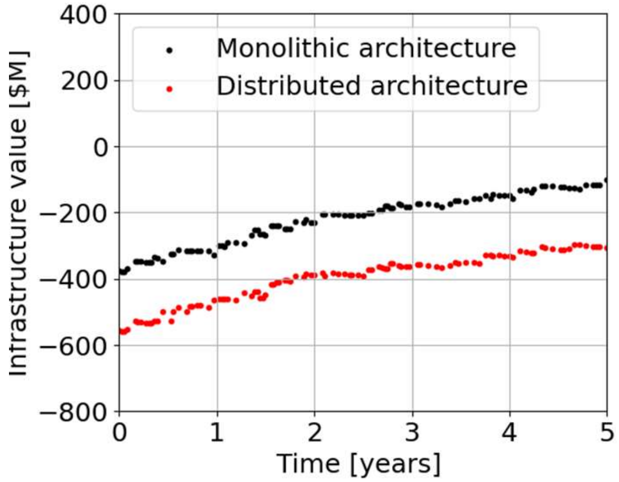
30 satellites



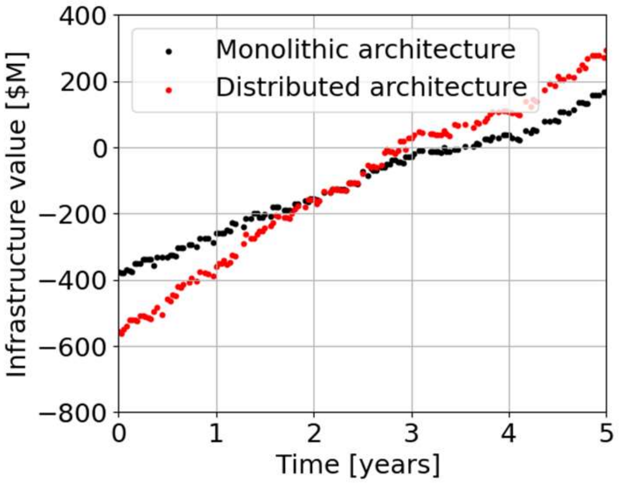
57 satellites



114 satellites



228 satellites



The rate of profitability (slope of the curves) of the distributed architecture increases faster as the market grows (*i.e.*, as the number of customer satellites increases)

<u>30-sat, 57-sat, 114-sat markets</u>: distributed and monolithic architectures can't pay back their initial investments within 5 years of operations

<u>228-sat market</u>:

- Distributed architecture becomes more valuable than monolithic after 2.8 yrs of operations
- Distributed and monolithic architectures become valuable after 2.9 yrs and 3.6 yrs of operations resp.

8. Concluding remarks

- Current software gives users a flexible way to model and simulate any kind of servicer:
  - ➢ Different propulsion technologies
    - ▪ To evaluate low-thrust vs high-thrust at the system level
  - ➢ Different times of flight
    - ▪ To perform tradeoff between time of flight and fuel consumption of servicers
  - ➢ Different trajectory options
    - ▪ To evaluate different operational strategies

- Current version of the software generalizes previous versions to the multi-orbit case
  - ➢ OSAM market analyses can be extended to fleet of customer satellites distributed along orbits of various shapes and sizes

- Current software may be used for at least two OSAM applications:
  - ➢ Short-term operational scheduling
  - ➢ Long-term strategic planning

- Next steps:
  - ➢ Low-thrust simulations long to run: use neural networks and/or Gaussian Processes to build surrogate models that can quickly be evaluated during the simulations
  - ➢ Deliverables:
    - ➢ Simulation framework dedicated to long-term strategic planning (for new entrants)
    - ➢ Simulation framework dedicated to short-term operational scheduling (for existing actors)

8. Summary of Publications So Far

Publications:

- K. Ho, H. Wang, P. DeTrempe, T. Sarton du Jonchay, and K. Tomita, “Semi-Analytical Model for Design and Analysis of On-Orbit Servicing Architecture,” *AIAA Journal of Spacecraft and Rockets*, Vol. 57, No. 6, pp. 1129-1138, 2020.
- T. Sarton du Jonchay, H. Chen, O. Gunasekara, and K. Ho "Framework for Modeling and Optimization of On-Orbit Servicing Operations under Demand Uncertainties," *AIAA Journal of Spacecraft and Rockets* (Published).
- T. Sarton du Jonchay, H. Chen, M. Isaji, and K. Ho "Modeling and Optimization of On-Orbit Servicing Operations with High- and Low-Thrust Propulsion Systems," *AIAA Journal of Spacecraft and Rockets* (Published).
- T. Sarton du Jonchay, Y. Shimane, M. Isaji, H. Chen, and K. Ho “On-Orbit Servicing Framework Generalized to the Multi-Orbit Case,” *2021 AAS/AIAA Astrodynamics Specialist Conference* (Conference paper)

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