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Deterministic and Probabilistic Decision Models for GSaaS-based Satellite Communication Resource Management

14th International Workshop on Planning & Scheduling for Space (IWPSS 2025)

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Toulouse - April 28th 2025 -

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Earth Observation mission

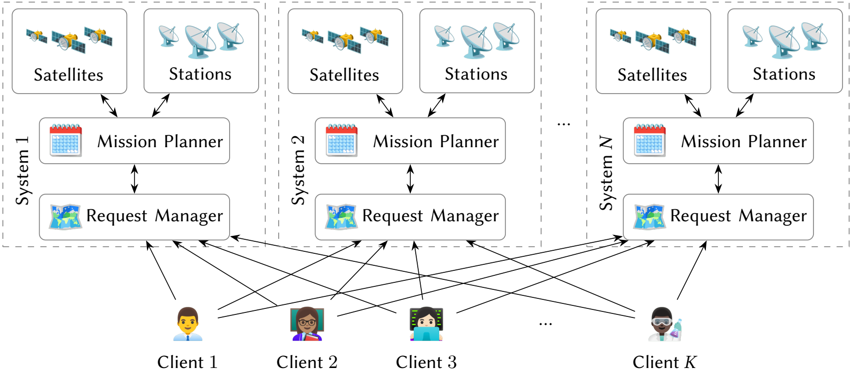

Figure: Conventional architecture

GSaaS

Third-party communication stations adopting the Ground Station as a Service (GSaaS) model [1], such as KSAT (https://www.ksat.no/ground-network-services/) and AWS (https://aws.amazon.com/ground-station/)

GSaaS

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Project objective

By using collaboration between missions and the GSaaS'es, increase the available data transfer per day and observations quality.

DOMINO-E European project

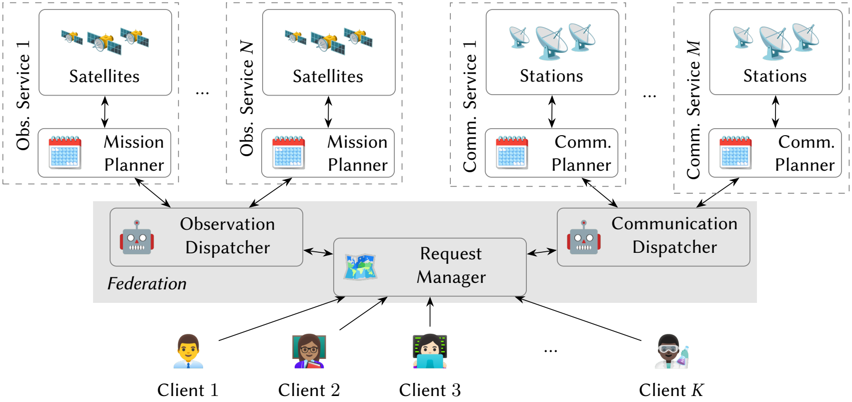

Figure: Multi mission federation [2]

Communication contact

Possible communication for satellite i when entering the visibility mask of a station:

- $s_{i,l}$ its site on ground and
- $[\underline{u}_{i,l}, \overline{u}_{i,l}]$ its time window, of duration $d_{i,l}$.

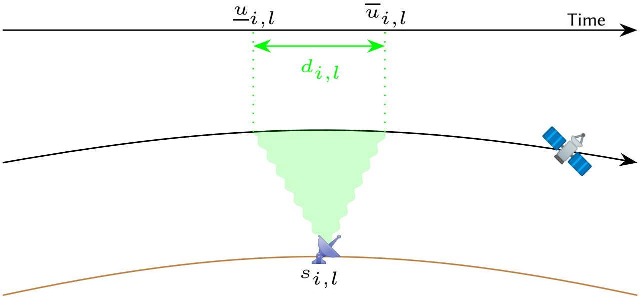

Figure: Communication contact

Communication need

Global Need

- a communication duration $D_{i,k}$,
- a time window $[\underline{t}_{i,k}, \overline{t}_{i,k}]$,
- a radio communication band: S or X, and
- a site list $\mathcal{S}_{i,k}$.

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Localized need

- an observation area,
- maximum delay

Fulfilment

Quantity of effective communication time allocated to a need k during a contact:

- needs on different band do not interfere with each other
- global need fulfilment by contact is $d_{i,k,l} = d_{i,l}$
- localized need fulfilment $d_{i,k,l}$ depends on the overlap with the specialized constraint

Fulfilment

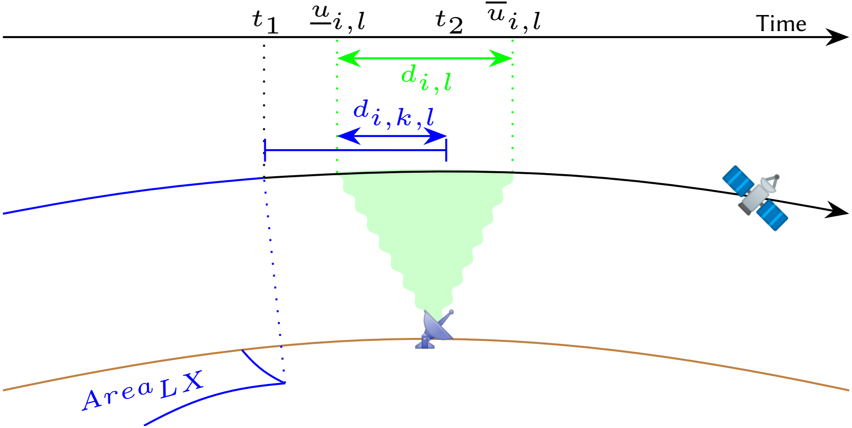


Figure: Contact with Localized need

Allocation

Boolean $x_{i,l}$ for contact l of satellite i.
Find an assignement to x for each contact which respects the constraints.

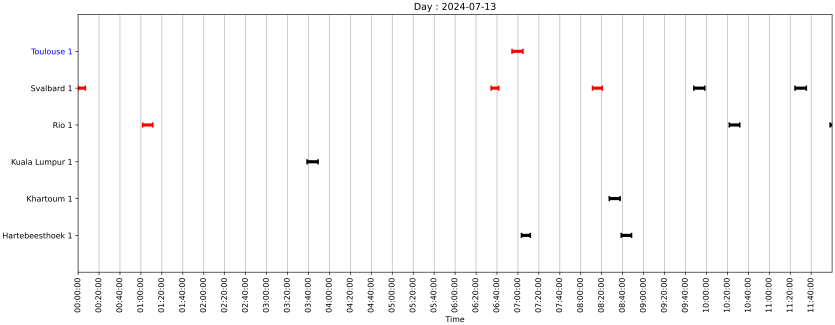


Figure: Allocation example

Objective: Jamming (Secure)

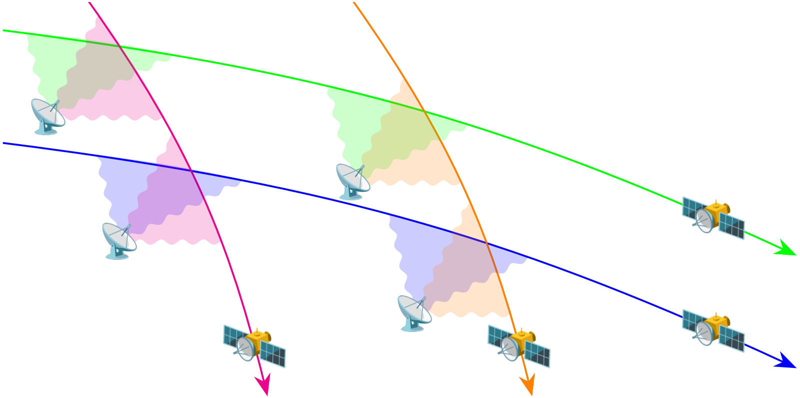


Figure: Communication jamming

Objective: Cost (Mini)

- Pay per Use (PU): cost per minute c_s^t
- Pay per Pass (PP): fixed cost for the contact c_s^0
- Pay per Pass with Commitment (PPC): fixed cost c_s^0 for contacts after a threshold Y_s

$$C = \sum_{s \in PU} \sum_{\substack{l=1 \\ |s=cm(i,l)}}^{L_i} c_s^t d_{i,l} x_{i,l} + \sum_{s \in PP} \sum_{\substack{l=1 \\ |s=cm(i,l)}}^{L_i} c_s^0 x_{i,l} + \sum_{s \in PPC} c_s^0 \max(0, \sum_{i=1}^{N} \sum_{\substack{l=1 \\ |s=cm(i,l)}}^{L_i} x_{i,l} - Y_s)$$

Jamming linearization

Jamming

$$J = \sum_{i=1}^{N-1} \sum_{l=1}^{L_i} \sum_{j=i+1}^{N} \sum_{m=1}^{L_j} b_{i,l,j,m} x_{i,l} x_{j,m}$$

Jamming linearization

Jamming

$$J = \sum_{i=1}^{N-1} \sum_{l=1}^{L_i} \sum_{j=i+1}^{N} \sum_{m=1}^{L_j} b_{i,l,j,m} x_{i,l} x_{j,m}$$

Linearized product

$$J = \sum_{i=1}^{N-1} \sum_{l=1}^{L_i} \sum_{j=i+1}^{N} \sum_{\substack{m=1 \\ / b_{i,l,j,m}>0}}^{L_j} b_{i,l,j,m} y_{i,l,j,m}$$

$$y_{i,l,j,m} \leq x_{i,l}$$

$$y_{i,l,j,m} \leq x_{j,m}$$

$$y_{i,l,j,m} \geq x_{i,l} + x_{j,m} - 1$$

$$\forall i \in \{1, \ldots, N-1\}, \forall l \in \{1, \ldots, L_i\}, \forall j \in \{i+1, \ldots N\}, \forall m \in \{1, \ldots, L_j\} : b_{i,l,j,m} > 0$$

Cost model with commitment linearization

Pay per Pass with commitment

$$\sum_{s \in PPC} c_s^0 \max(0, \sum_{i=1}^{N} \sum_{\substack{l=1 \\ |s=cm(i,l)}}^{L_i} x_{i,l} - Y_s)$$

Cost model with commitment linearization

Pay per Pass with commitment

$$\sum_{s \in PPC} c_s^0 \max(0, \sum_{i=1}^{N} \sum_{\substack{l=1 \\ |s=cm(i,l)}}^{L_i} x_{i,l} - Y_s)$$

Linearized commitment

$$\sum_{s \in PPC} c_s^0 c_s$$

$$\forall s \in PPC \ f_s + c_s = \sum_{i=1}^{N} \sum_{\substack{l=1 \\ |s=cm(i,l)}}^{L_i} x_{i,l}$$

$$\forall s \in PPC \ f_s \leq Y_s$$

Simulation

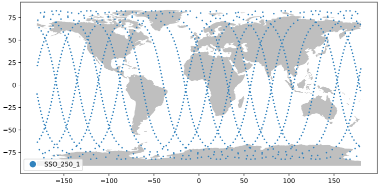
Data:

- satellite constellations,
- constellation and satellite needs requirements,
- GSaaS localizations and bands,
- GSaaS cost models

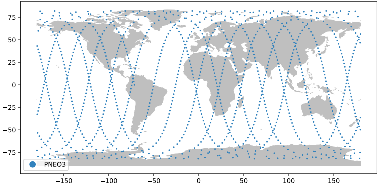
Objective: every day, find a communication plan for the federation for the next 10 days, during 60 days

Satellites

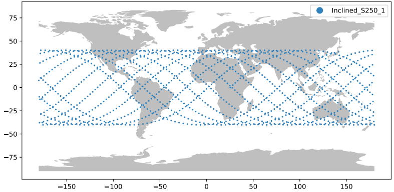
SSO_250_1



PNE03



Inclined_S250_1



- **SSO**: 4 S250 satellites on the same SSO orbit in quadrant phases
- **Inclined**: 2 pairs of S250 in phase opposition
- **PNEO**: 2 S950 satellites on the same SSO orbit in phase opposition

Day 1 satellite communication requirements

constellation/satellite	band	duration (min)
PNEO_S950	S	5
PNEO_S950	X	50
SSO_S250	S	5
SSO_S250	X	70
SSO_S250_1	X	60
Inclined_S250	S	5
Inclined_S250	X	50
Inclined_S250_1	X	50

Table: Initial routine needs per period

Need evolution

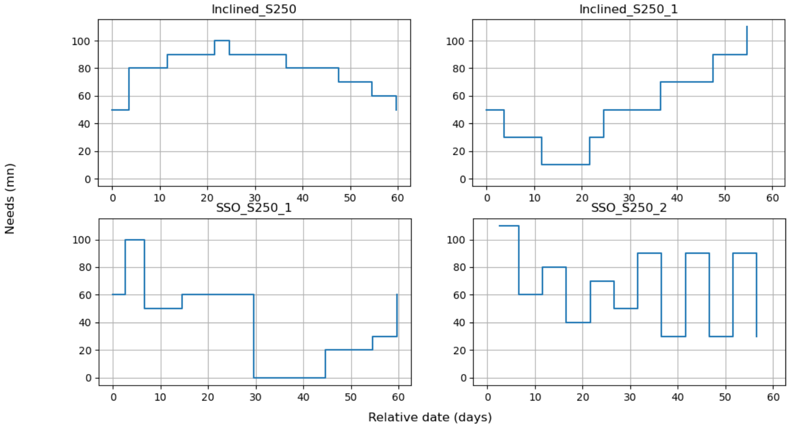


Figure: Evolution of needs in X band

Stations

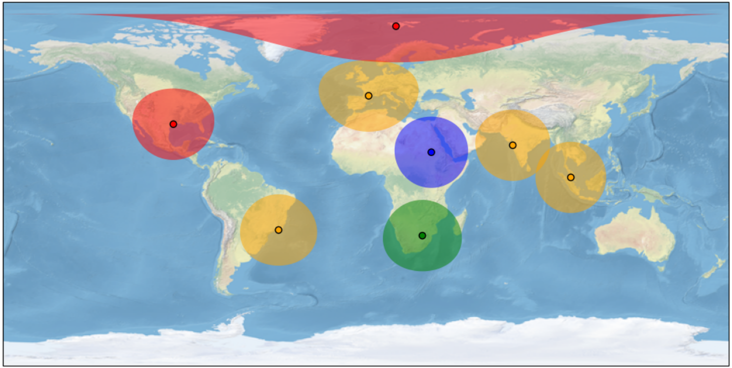


Figure: Stations and their respective visibility circles at 500km altitude: violet is Owned, green is Preferred, yellow is normal, red is Expensive.

Uncertain Service provider policies

	Tier 1			Tier 2			Tier 3		
Station	Type	Cost	$p(\cdot)$	Type	Cost	$p(\cdot)$	Type	Cost	$p(\cdot)$
Owned	PP	0	98%	-	-	-	-	-	-
Preferred	PPC w. 6	50	100%	PU	40	60%	-	-	-
Normal	PP	200	99%	PP	180	80%	PU	250	50%
Expensive	PU	400	100%	-	-	-	-	-	-

Table: Different levels of service for each provider

Fulfilment adaptation

$$\boxed{\sum_{l \in \{1,\dots,L_i\} / k \in \mathcal{Z}_{i,l}} d_{i,k,l} x_{i,l} \geq D_{i,k}}$$

Fulfilment adaptation

Probabilistic need satisfaction

$$P\left(\sum_{l\in\{1,\dots,L_i\}/k\in\mathcal{Z}_{i,l}} d_{i,k,l} z_{i,l} \geq D_{i,k}\right) \geq P_{\text{target}}$$

Fulfilment adaptation

Probabilistic need satisfaction

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Constraint to stimulate overbooking

$$\mathbb{E}(d_{i,k,l} z_{i,l}) - Q_{\text{target}} * \sigma(d_{i,k,l} z_{i,l}) \geq D_{i,k}$$

Fulfilment adaptation

Probabilistic need satisfaction

$$P\left(\sum_{l\in\{1,\ldots,L_i\}/k\in\mathcal{Z}_{i,l}} d_{i,k,l} z_{i,l} \geq D_{i,k}\right) \geq P_{\text{target}}$$

Constraint to stimulate overbooking

$$\sum_{l\in\{1,\ldots,L_i\}/k\in\mathcal{Z}_{i,l}} d_{i,k,l} p_{i,l} x_{i,l} - Q_{\text{target}} * \left(\sum_{l\in\{1,\ldots,L_i\}/k\in\mathcal{Z}_{i,l}} d_{i,k,l}^2 p_{i,l} x_{i,l} (1 - p_{i,l})\right)^{\frac{1}{2}} \geq D_{i,k}$$

Linear approximation

$$\sum_{l \in \{1,\dots,L_i\}/k \in \mathcal{Z}_{i,l}} d_{i,k,l} p_{i,l} x_{i,l} - Q_{\text{target}} * \left(\sum_{l \in \{1,\dots,L_i\}/k \in \mathcal{Z}_{i,l}} d_{i,k,l}^2 p_{i,l} x_{i,l} (1 - p_{i,l}) \right)^{\frac{1}{2}} \geq D_{i,k}$$

Linear approximation

$$\sum_{l\in\{1,\dots,L_i\}/k\in\mathcal{Z}_{i,l}} d_{i,k,l}p_{i,l}x_{i,l} - Q_{\text{target}} * \Big(\sum_{l\in\{1,\dots,L_i\}/k\in\mathcal{Z}_{i,l}} d^2_{i,k,l}p_{i,l}x_{i,l}(1-p_{i,l})\Big)^{\frac{1}{2}} \geq D_{i,k}$$

McCormick envelope

$$\sum_{\substack{l\in\{1,\dots,L_i\}\\/k\in\mathcal{Z}_{i,l}}} d_{i,k,l}p_{i,l}x_{i,l} - Q_{\text{target}}\Delta_{i,k} \geq D_{i,k}$$

$$0 \leq \Delta_{i,k} \leq \overline{\Delta}_{i,k}$$

$$\overline{\Delta}_{i,k} = \Big(\sum_{l\in\{1,\dots,L_i\}/k\in\mathcal{Z}_{i,l}} d^2_{i,k,l}p_{i,l}(1-p_{i,l})\Big)^{\frac{1}{2}}$$

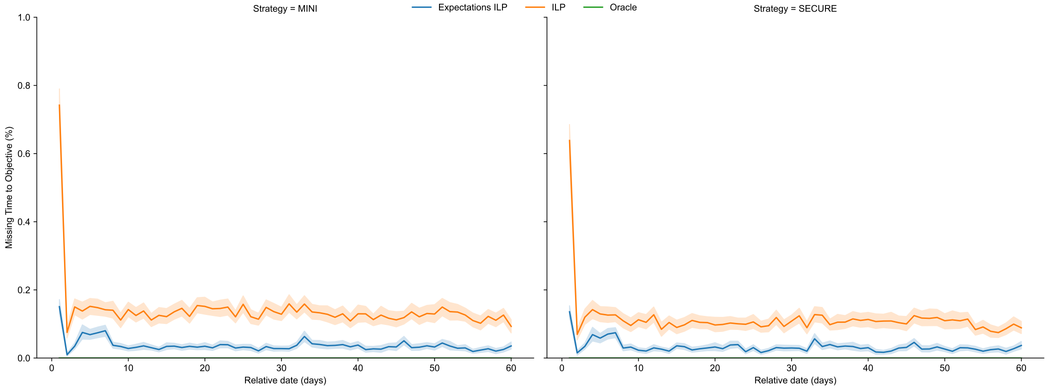
$$\beta_{i,k} = \sum_{\substack{l\in\{1,\dots,L_i\}\\/k\in\mathcal{Z}_{i,l}}} d^2_{i,k,l}p_{i,l}x_{i,l}(1-p_{i,l})$$

$$\beta_{i,k} \geq 0$$

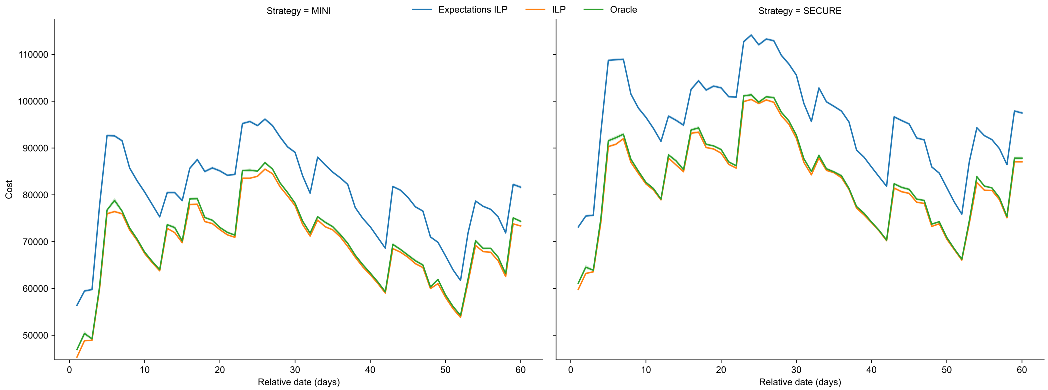
$$\beta_{i,k} \geq 2\Delta_{i,k}\overline{\Delta}_{i,k} - \overline{\Delta}_{i,k}\overline{\Delta}_{i,k}$$

$$\beta_{i,k} \leq \Delta_{i,k}\overline{\Delta}_{i,k}$$

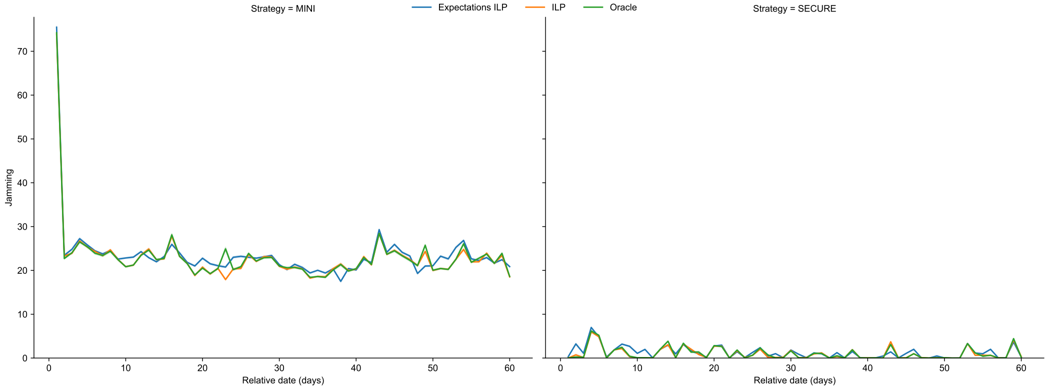
Missing Time for needs comparison for the 60 days scenario



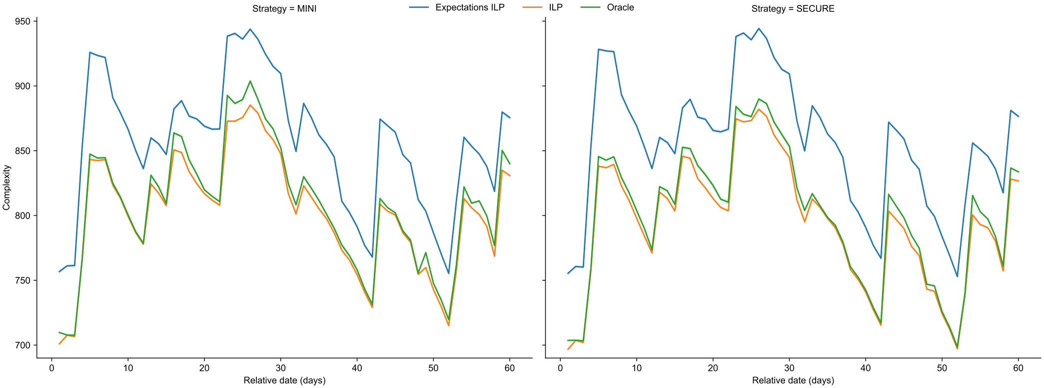
Cost comparison for the 60 days scenario



Jamming comparison for the 60 days scenario



Number of booked contact comparison for the 60 days scenario



Conclusion and perspectives

Summary

- formalization of communication needs and available cost models for the federation
- deterministic MILO formulation
- probabilistic approch MILO formulation using probability of acceptance

Perspectives

- Deeper modelisation of the uncertainty
- Correlation with the estimated charge of the station w.r.t near satellites

Thank you for your attention !

Any questions ?

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References

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