The impact of precise inter-satellite ranges on relative precise orbit determination in a smart formation flying or constellation of CubeSats

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Outline

- Background
- Problem statement
- Proposed solution
- Results
- Summary and conclusion

CubeSats

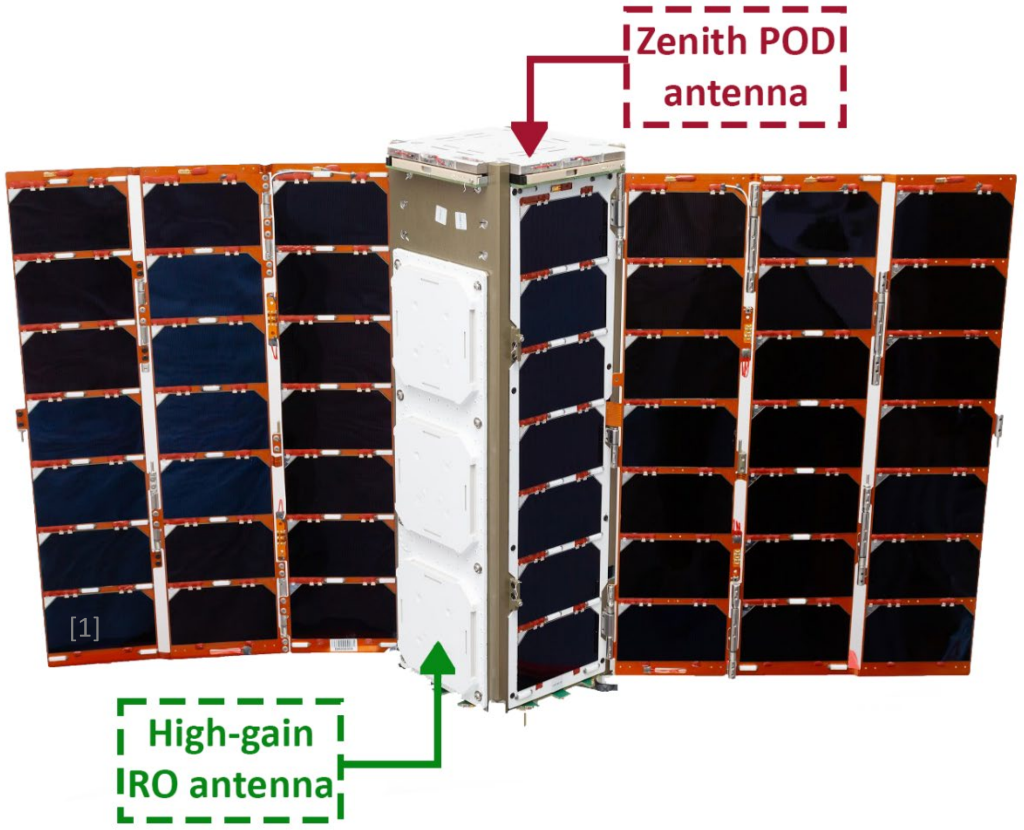
CubeSat's general specifications:

- Small (1U: 10 × 10 × 10 cm), can be multiple of units
- Low-cost (20K ~ 200K USD)
- Low-power (5-20 Watts)

Increasing the applicability?
☑ Launching them in a formation flying or constellation

CubeSats applicability:

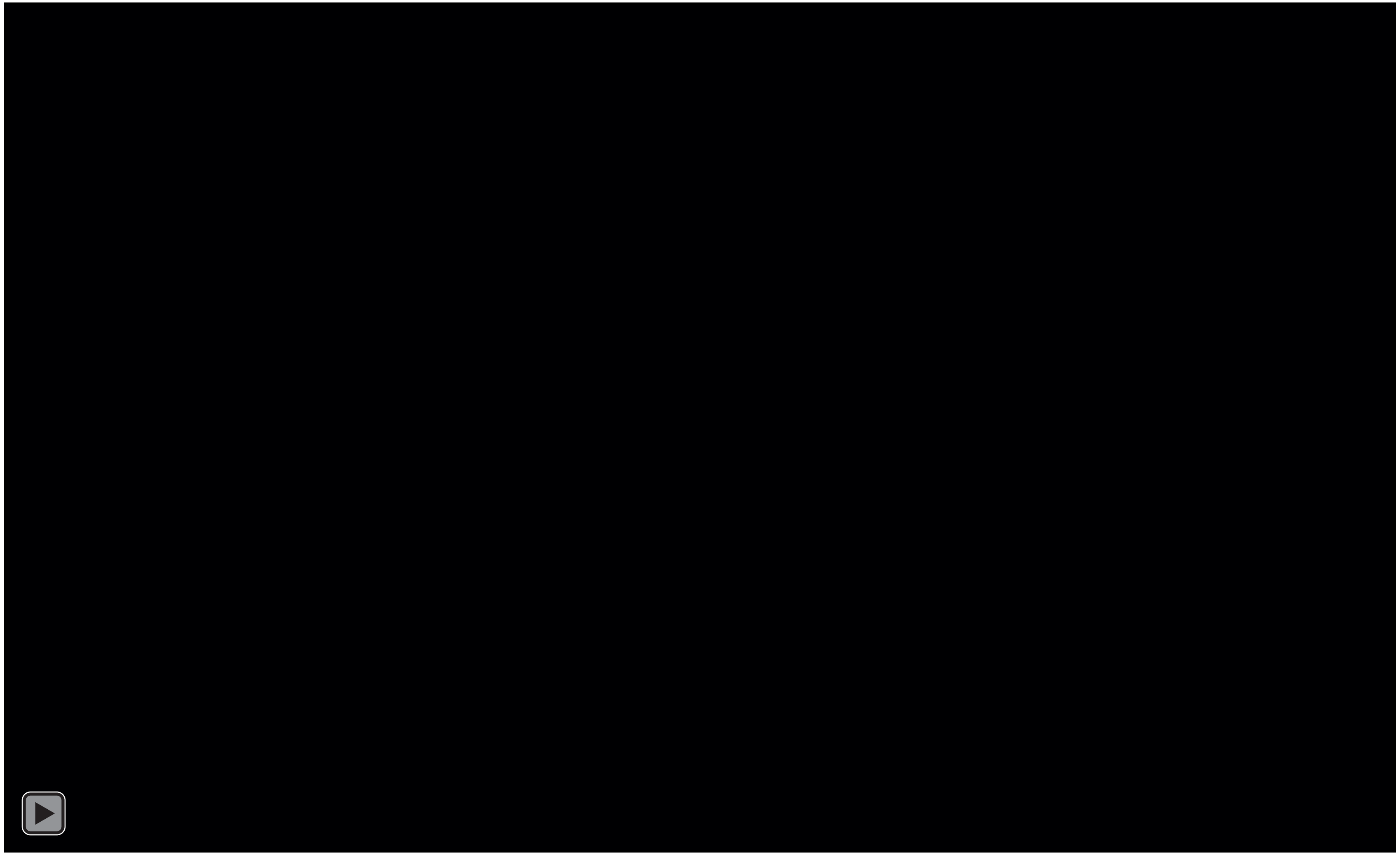
- Space exploration ☑
- Earth science missions☑
- Communication ☑



Example: Spire Global Constellation:

- **>145 3U-CubeSats;**
- **Used for GNSS Radio Occultation**

Precise Orbit Determination (POD) of CubeSats



Augmenting PNT applications?!

POD of CubeSat is essential for different applications!

CubeSat's POD in post-mission has been developed and reached acceptable accuracy [2][3].

The availability of precise corrections for GNSS orbits and clocks in space through , e.g., AU-SBAS and QZSS is a big step in real-time POD [4].

The required accuracy of the real-time POD for most applications are (theoretically) achievable with CubeSats!

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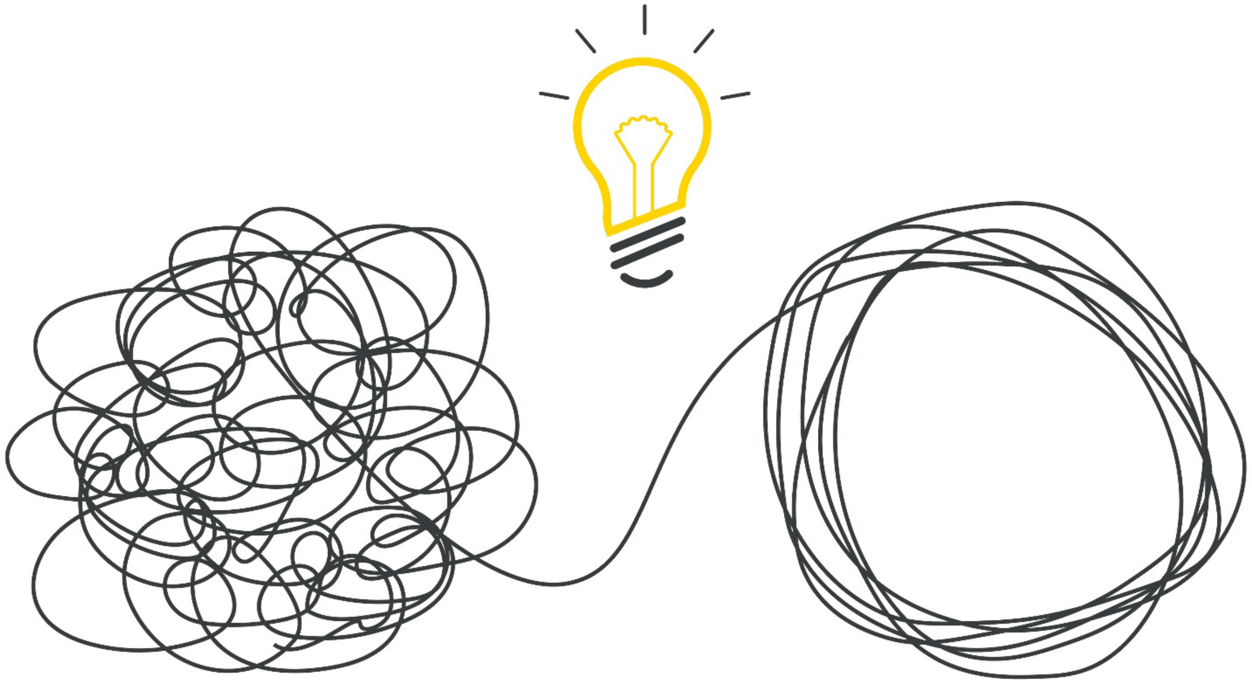


Problem

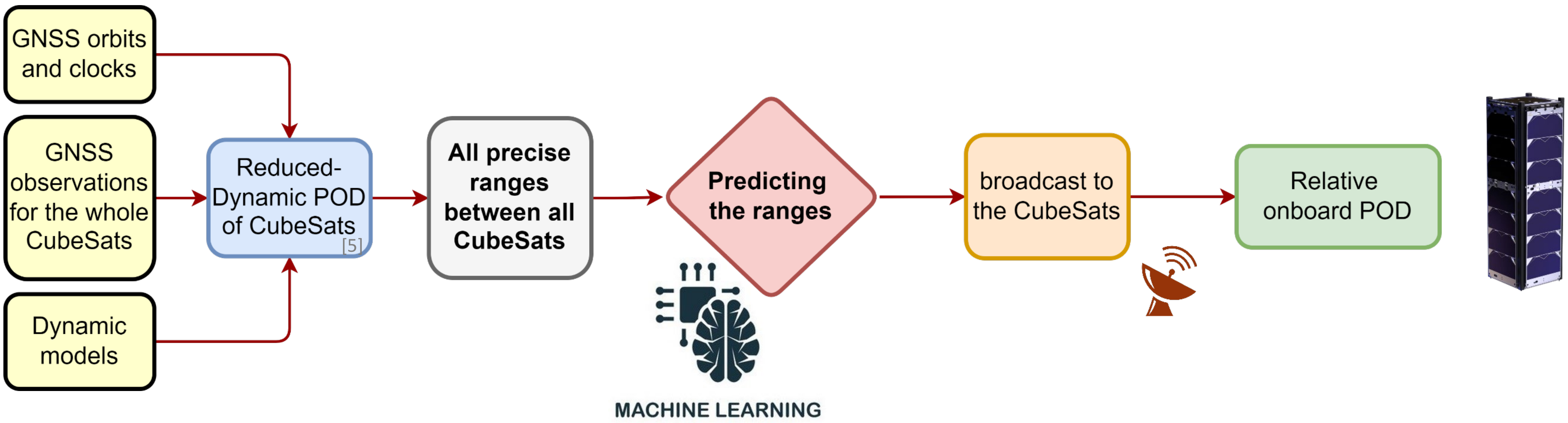
In reality, Real-Time POD for CubeSats is still an issue due to:

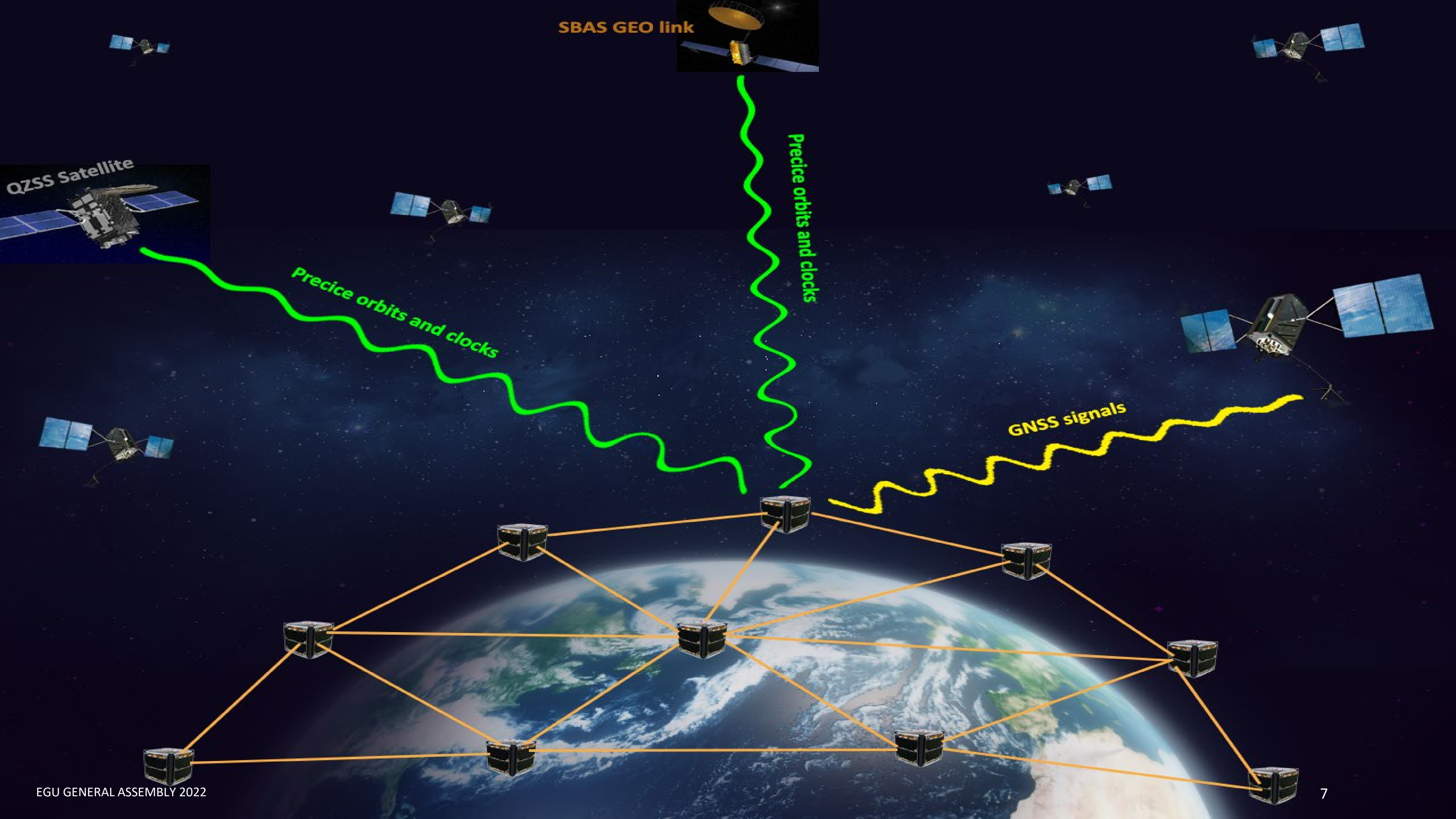
- Limited power and CPU,
- Low-cost onboard receiver and patch antenna,
- Unstable oscillators, etc.

Proposed solution

Augmenting the relative POD with the precise inter-satellite ranges

- Meet the power and computational expectations
- Reduced the impact of the receiver-dependant errors
- Remove the CubeSats clock errors
- Strengthen the model




SBAS GEO link
QZSS Satellite
Precice orbits and clocks
Precice orbits and clocks
GNSS signals

Reduced-Dynamic POD processing models and parameters

Item	Description
Dynamic models	Gravity field: EGM 2008
	Tidal corrections: Updated FES2004
	Relativity: IERS 2010
	Planets ephemeris: JPL DE405
Observation model	Dual-frequency GPS Ionosphere-Free (1 Hz)
	A-priori code and phase standard deviation 0.1 m, 1 mm
	CubeSat and GNSS attitude information: applied [6-8]
	PCO and PCV for GNSS satellites: igs14.atx
	PCO and PCV for CubeSats: applied [9]
	GNSS orbits and clocks: CODE final products
Stochastic accelerations	Velocity changes (pulses) at certain epochs Piecewise constant accelerations

Model and solution for the augmented relative POD

$$\Delta P_{r_{12}}^{s_{12}} = \rho_{r_{12}}^{s_{12}} + e_{r_{12}}^{s_{12}}$$
$$\Delta \Phi_{r_1 r_2}^{s_1 s_2} = \rho_{r_{12}}^{s_{12}} + \lambda\, n_{r_{12}}^{s_{12}} + \epsilon_{r_{12}}^{s_{12}}$$

$$\boldsymbol{A} = \begin{bmatrix} -LOS_{r12}^{S_{12}} & 0 & 0 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ -LOS_{r12}^{S_{1u}} & 0 & 0 & \cdots & 0 & 0 \\ -LOS_{r12}^{S_{12}} & 1 & 0 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ -LOS_{r12}^{S_{1u}} & 1 & 0 & \cdots & 1 & 0 \\ \boxed{\dfrac{b}{PR}} & 0 & 0 & \cdots & 0 & 0 \end{bmatrix}$$

Implementing the Precise Ranges (PR)

u: # of common-in-view GPS satellites

For current study, the ionosphere delays are removed using ionospheric-free linear combination

$$\boldsymbol{X} = \left(b_x, b_y, b_z, n_{r_{12}}^{S_{ref,1}}, n_{r_{12}}^{S_{ref,2}}, \dots, n_{r_{12}}^{S_{ref,u}}\right)^{\mathrm{T}}$$

baseline components (b_x, b_y, b_z); Double-differenced ambiguities ($n_{r_{12}}^{S_{ref,1}}, \dots, n_{r_{12}}^{S_{ref,u}}$)

Solving using Least-Squares filtering

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Testing properties

CubeSats: 9 CubeSats from the Spire Global Constellation:

COSPAR	CubeSat's ID
2019-018G	*ID099*
2019-018H	*ID100*
2019-018J	*ID101*
2019-018K	*ID102*
2019-038S	*ID103*
2019-038L	*ID104*
2019-038Z	*ID106*
2019-038T	*ID107*
2020-061AX	*ID122*

Date:

- 5 Jan 2021

Software to process RD-POD part:

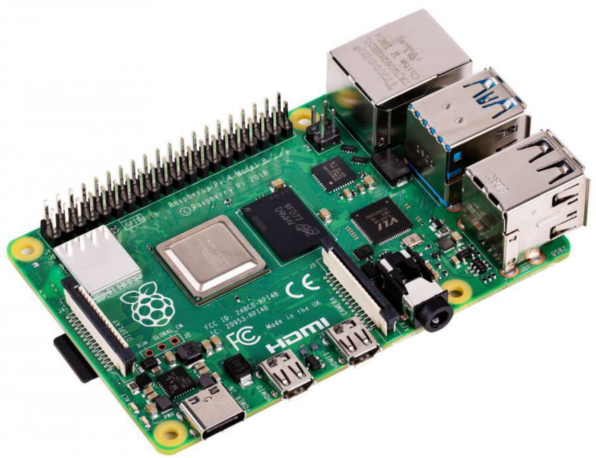
- Bernese v 5.2 (modified to add the SNR weighting function for CubeSats POD [3])

Software to process relative POD part

- leoPod Software (developed by GNSS-SPAN, Curtin University, Australia)

CPU to simulate onboard processing:

- Raspberry Pi 4



Results 1

- Comparing the estimated coordinates of the deputy CubeSat with its reference orbits that are generated in the ground station from RD-POD:

Orbital Parameters	RMSE (m)								
	ID099	ID100	ID101	ID102	ID103	ID104	ID106	ID107	ID122
X	0.47	0.48	0.61	0.45	0.38	0.56	0.51	0.49	0.57
Y	0.49	0.43	0.55	0.56	0.38	0.54	0.52	0.40	0.56
Z	0.52	0.56	0.52	0.55	0.45	0.59	0.48	0.56	0.53

b < 1000 km

→ Several centimetres accuracy

b > 2000 km

→ ~1 meter accuracy

b > 7000 km

→ No common-in-view satellites

Results 2

- Comparing the results of two scenarios for CubeSat ID122: applying and not applying the precise ranges in the model:

Orbital parameters	Mean values of the improvement (m)
X	0.33
Y	0.28
Z	0.16

- Applying the inter-satellite ranges improved the performance of the least-squares filtering and decreased the convergence time.

Essential for CubeSat's processors

Processing time for each epoch is less than 1 s

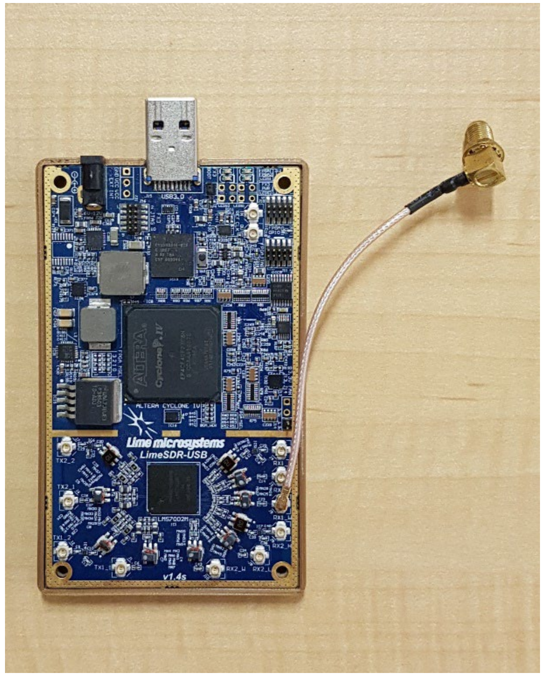
Specifications	Tested CPU	CubeSat's CPU
Processor	Quad-core ARM Cortex (A72)	Dual-core ARM Cortex
RAM	8G DDR4	8 GB DDR3
Power consumption	3.8-5.5 W	1.6 to 2.85 W

Note: leoPod software is developed for research, and not for testing the computational speed, so the processing time can be less for real-world missions

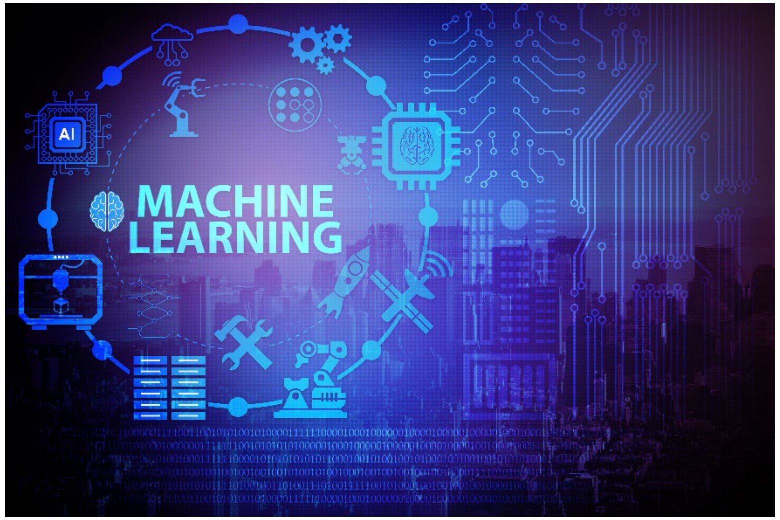
Requirements for the proposed solution

Observations of the chief CubeSat → Software-defined radio (SDR) [10]
- Receiving signals
- Transmitting signals,
- Aiding to process

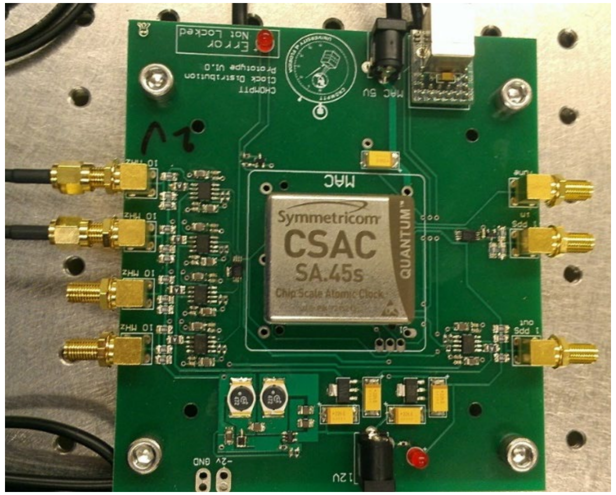
→



Predicted ranges →



Better oscillators → Chip-scale atomic clocks [11] →



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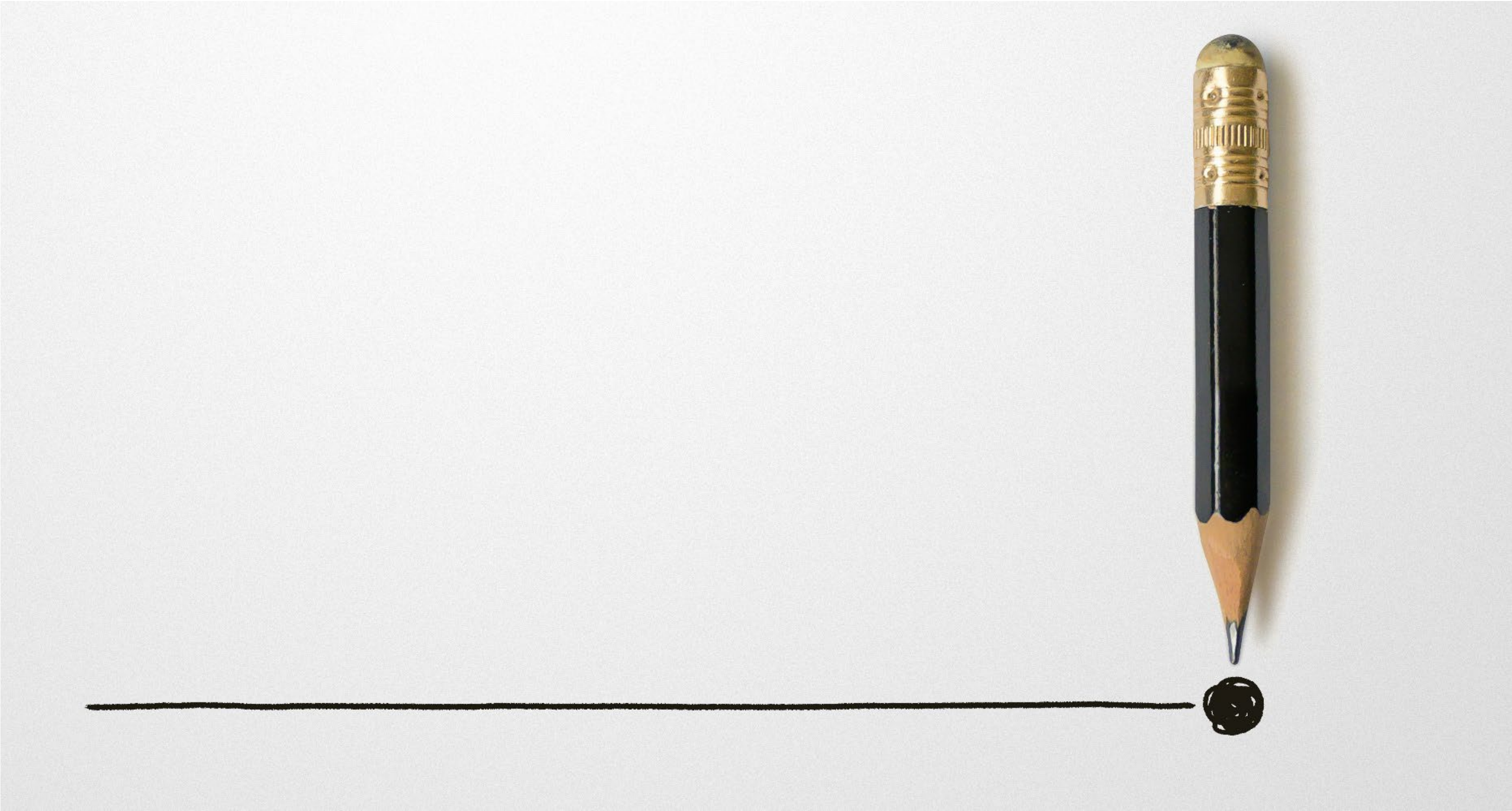

Summary and Conclusion

- Real-Time POD is an essential for augmenting PNT applications using the formation flying or constellation of CubeSats
- There are some limitations for CubeSats for real-Time POD including power and CPU, low-cost receivers and antenna, unstable oscillators, etc.
- The proposed solution is to augment relative POD using the precise inter-satellite ranges,
- Mimicking the onboard situation, several cm accuracy for baselines less than 1000 km and dm accuracy for longer baselines is achievable
- Prediction using Machine Learning algorithms, inter-CubeSat communication using SDRs, and better oscillators are required to implement the proposed solution in a smart constellation,
- More investigations are performed to reach the higher accuracy required for PNT applications.

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More Questions? Let's discuss:

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