Mothercraft-CubeSat Radio Measurement for Phobos Survey

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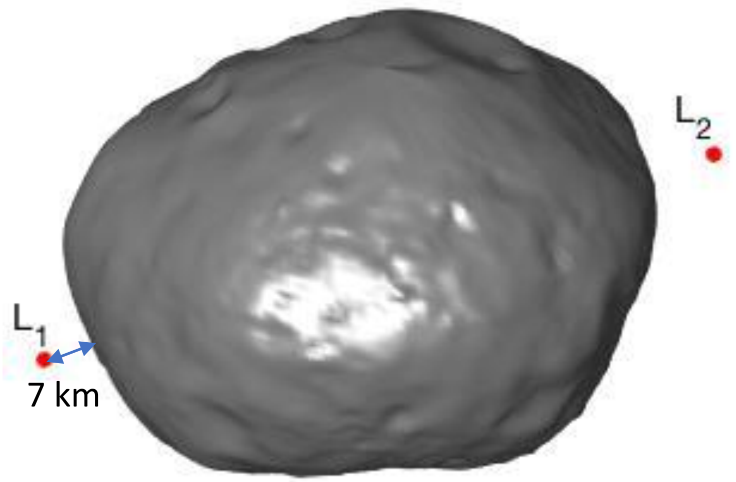
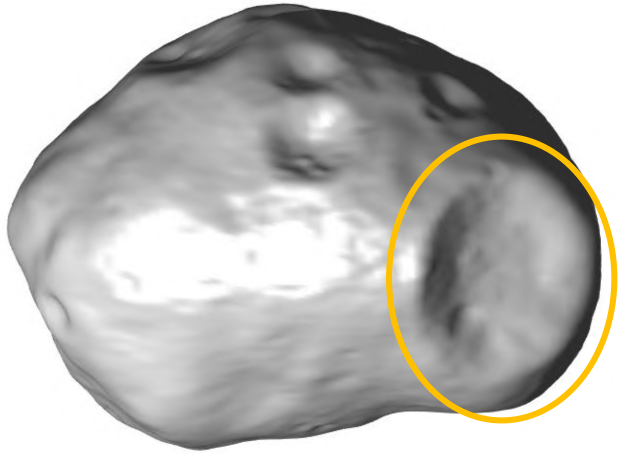
Background: Phobos exploration (1)

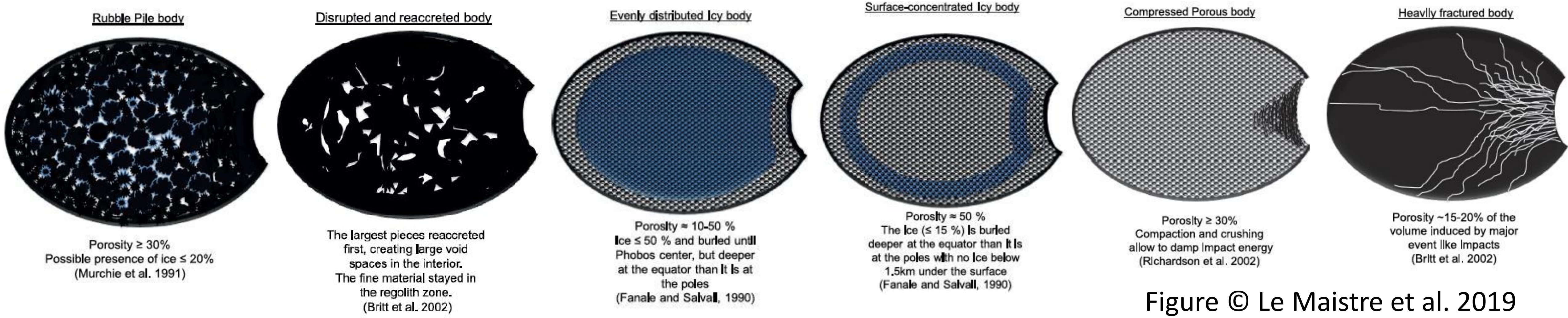
- Many mission proposals
  - MMX, Phootprint, MERLIN, etc.
- Unclear origin of Martian moons
  - captured, formed from Mars ejecta?
- If captured, resemble C-type asteroids
  - Could play a role in transporting water to the rocky planet zone in the early solar system
- Challenging orbing around Phobos
  - Orbits cannot be approximated by Keplerian motions
  - Stability domain of QSO/DRO around Phobos constrained by 1:3 resonance



Background: Phobos exploration (2)

- Determining Phobos physical parameters (e.g. C20, C22, libration amplitude) can
  - De-risk proximity operations (e.g. approaching, landing, descent, etc)
  - Determine its interior structure (homogeneous? monolithic or rubble pile)





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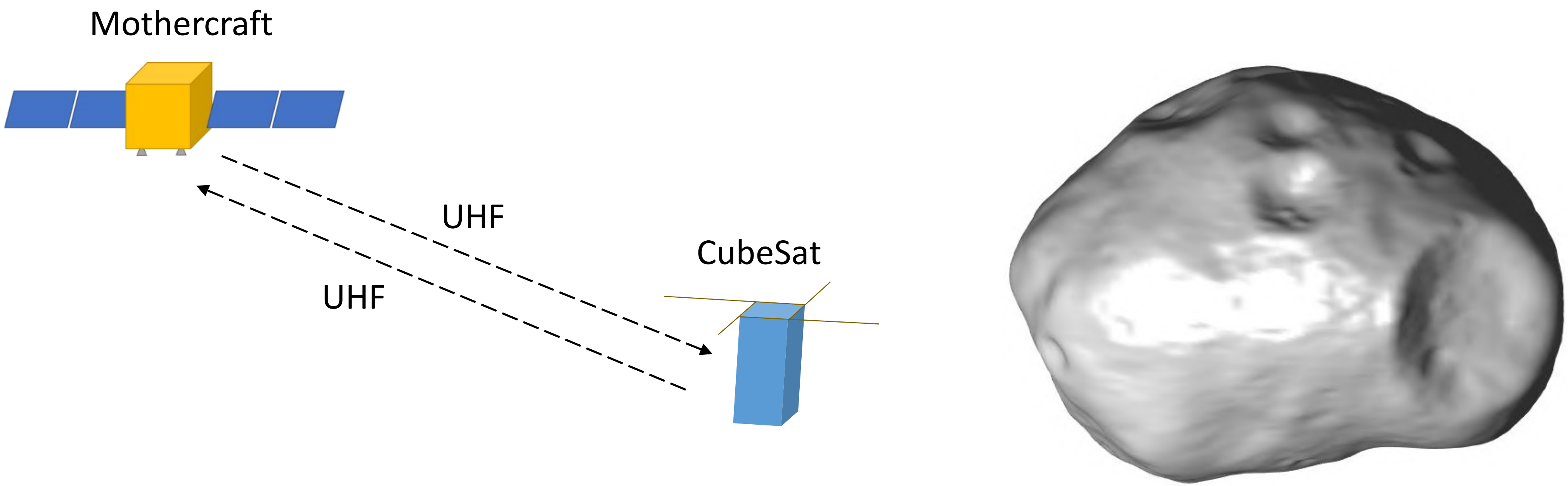
Mission plan and objective

Approach: Mothercraft-CubeSat radio science measurement

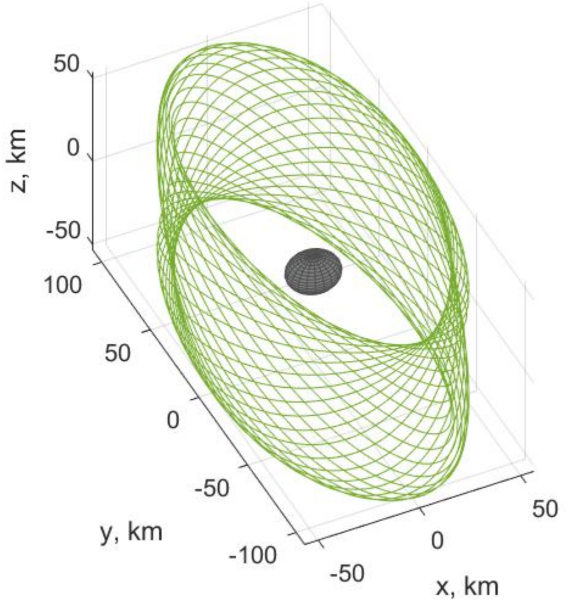


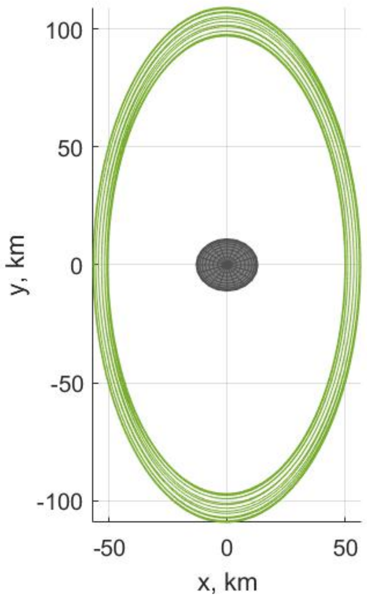
Mothercraft's orbit: far from Phobos, i.e. safe from impact or escape
CubeSat's orbit: close to Phobos, i.e. sensitive to Phobos physical characteristics

Previous work (1): computation of 2D and 3D quasi-satellite orbits (QSO)

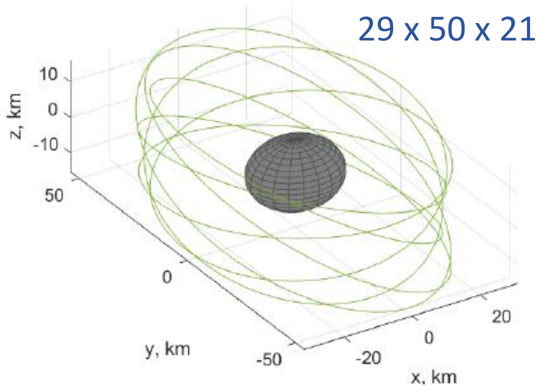
Resonant families of 3D QSO computed using continuation and bifurcation methods

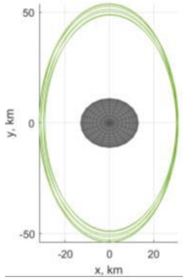
50 x 109 x 53 km 29:30 QSO (Phobos-centered rotating frame)



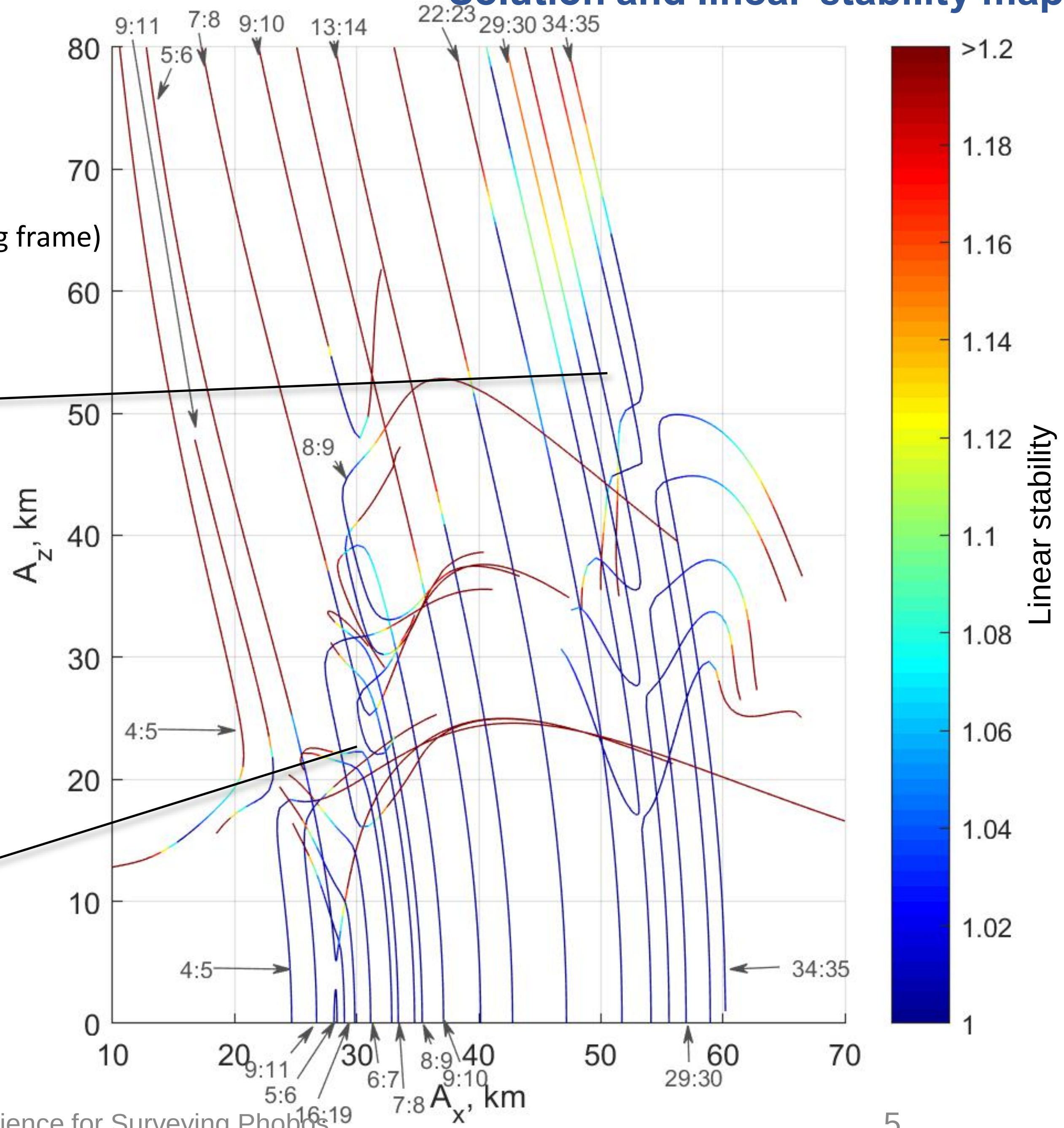


29 x 50 x 21 km 6:7 QSO



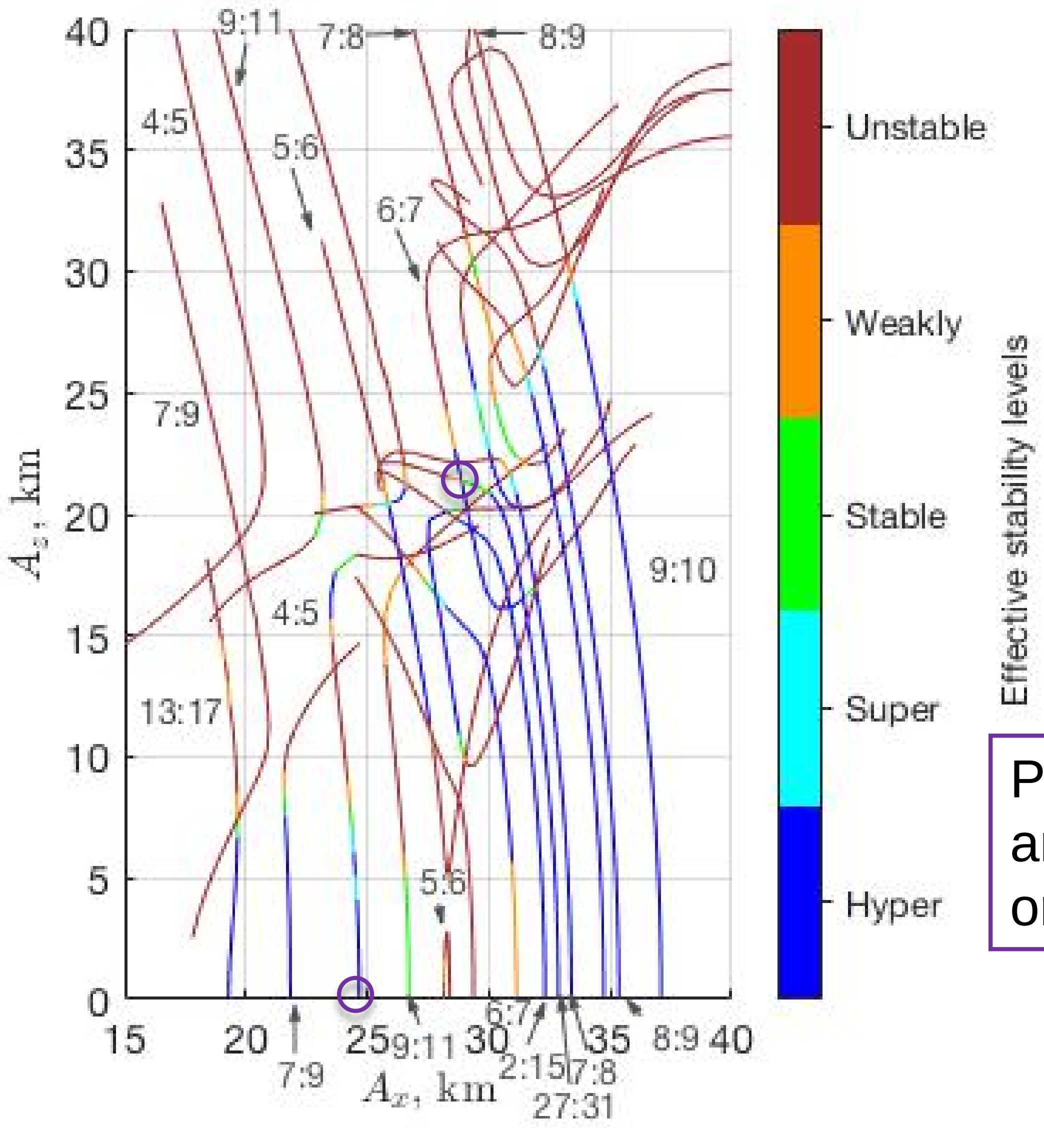


Solution and linear-stability map



Previous work (2): Effective stability

- ✓ Hyper-stable orbit stay bounded around the baseline orbit for > 7 days regardless of the injection epoch



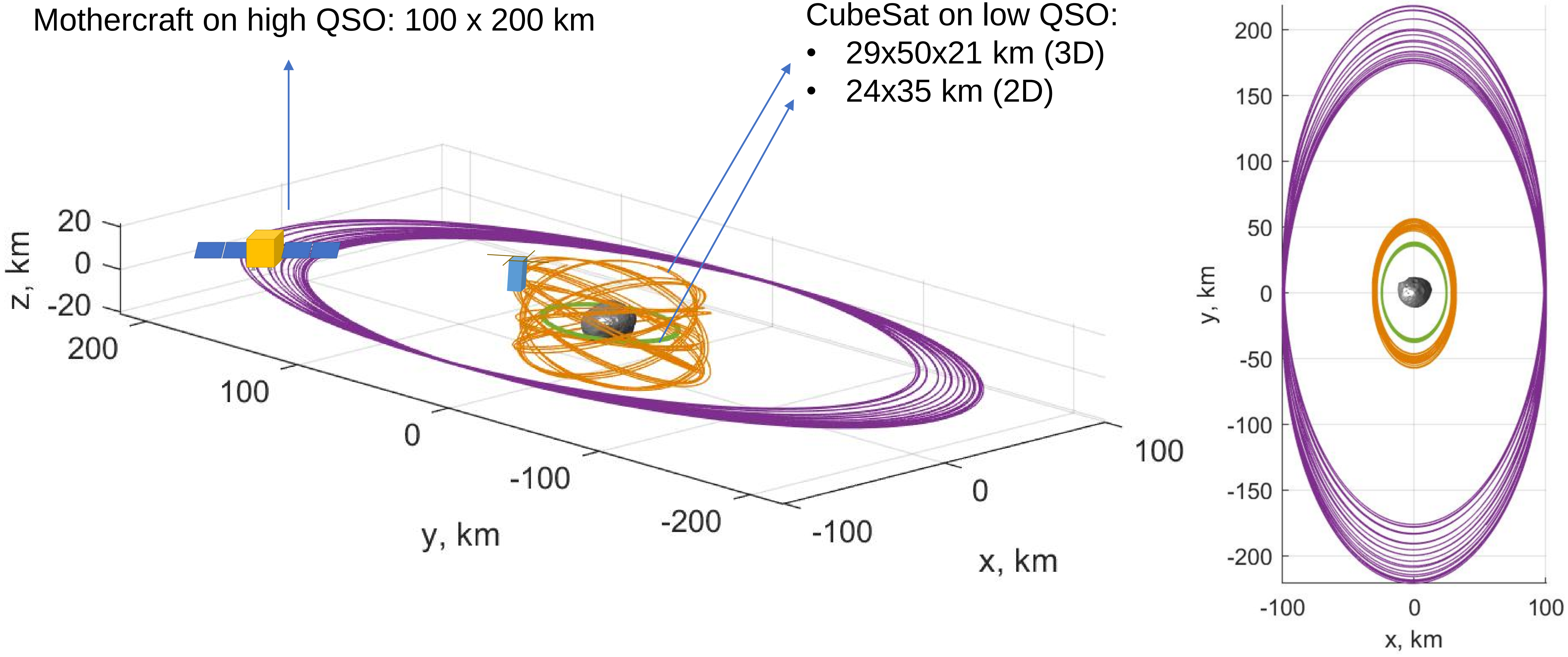
Pick stable low-altitude and high-inclination orbits for CubeSat orbits

Science orbits

Mothercraft on high QSO: 100 x 200 km

CubeSat on low QSO:

- 29x50x21 km (3D)
- 24x35 km (2D)



QSO transfer costs

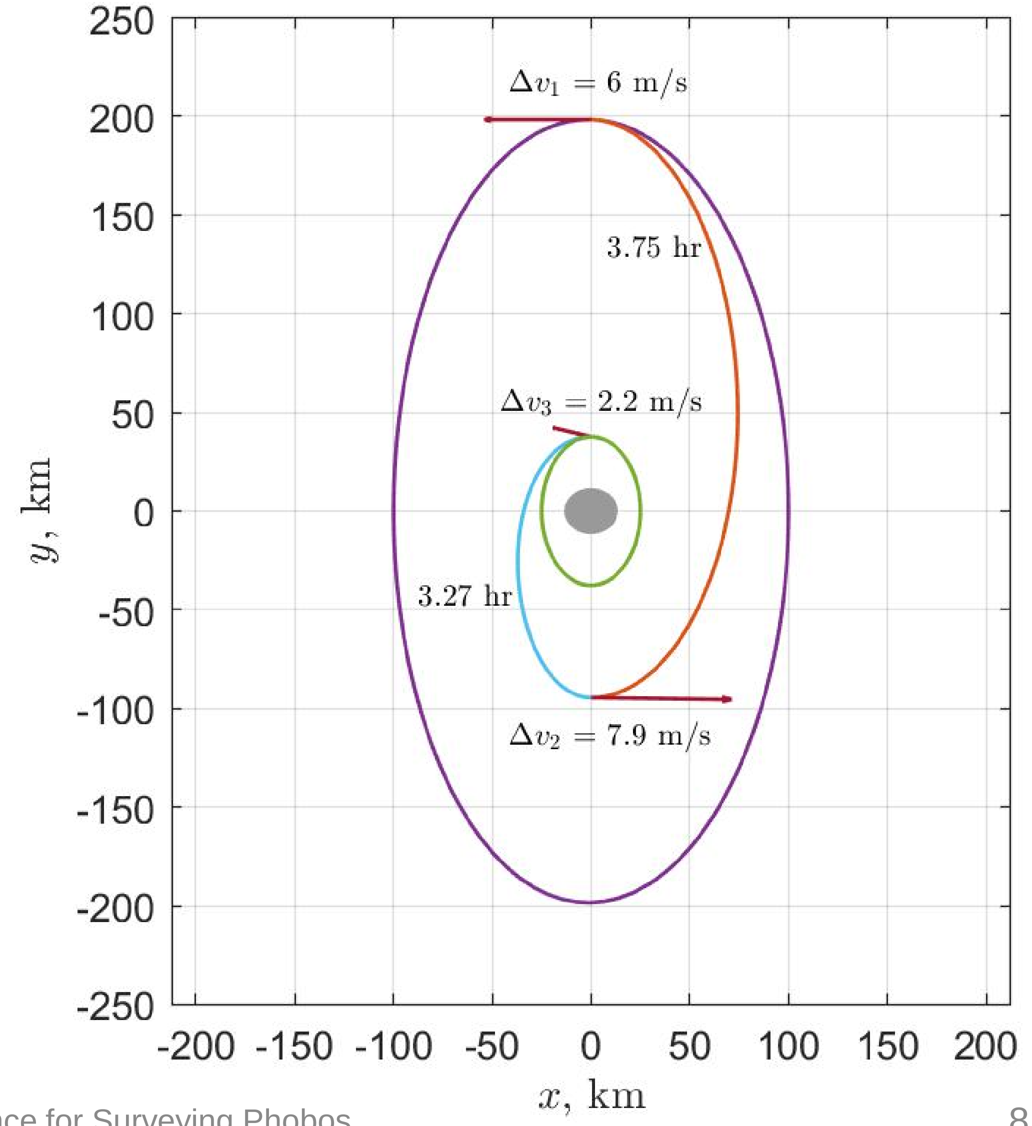
- ✓ Transfer from 100-km 2D QSO to 24-km 2D QSO costs a Δv ~ 16 m/s

- ✓ Transfer from 100-km 2D QSO to 30-km 3D QSO costs a Δv ~ 20 m/s

- ✓ Number of transfer revolutions and time of flight variable for better OD and insertion success rate

  (H. Ikeda, S. Mitani, Y. Mimasu, G. Ono, K. Nigo, and Y. Kwakatsu, "Orbital Operations Strategy in the Vicinity of Phobos," International Symposium on Space Flight Dynamics, Matsuyama, Japan, 2017)

High to Low 2D QSO Transfer (example in CR3BP)



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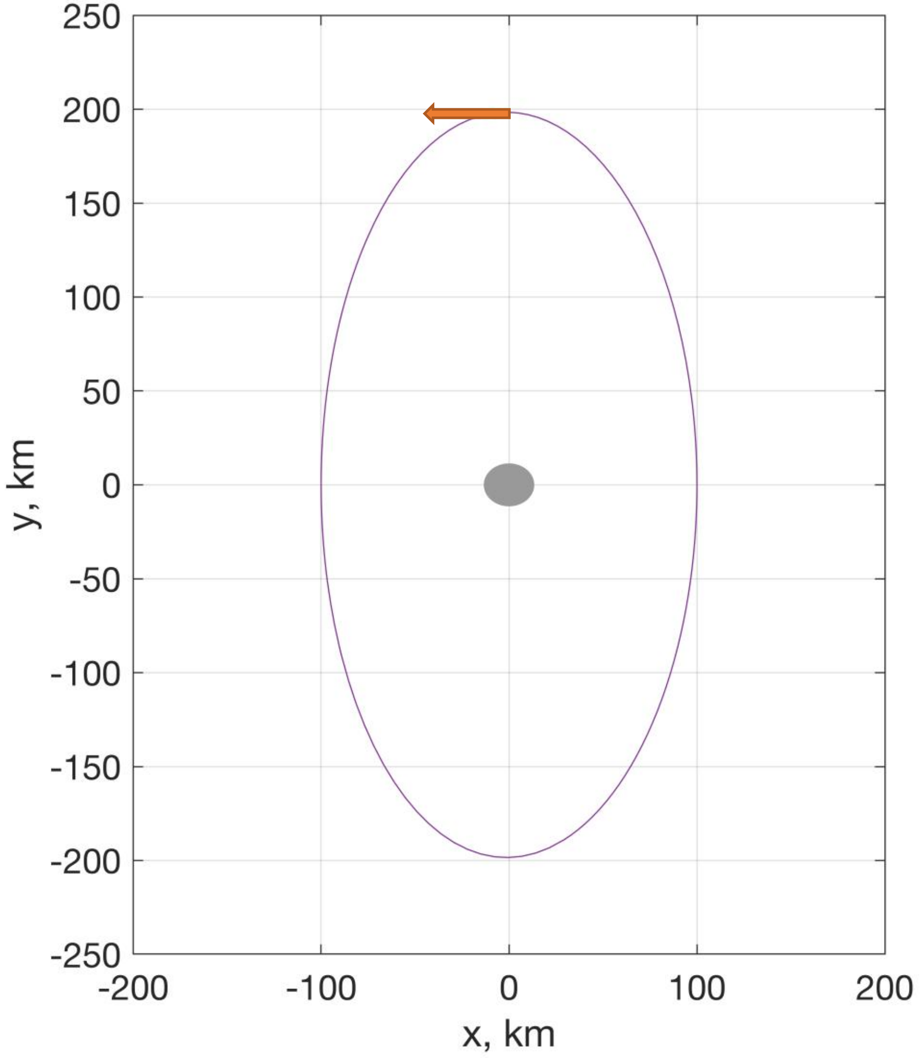
Multi-revolution Transfer (example in CR3BP)



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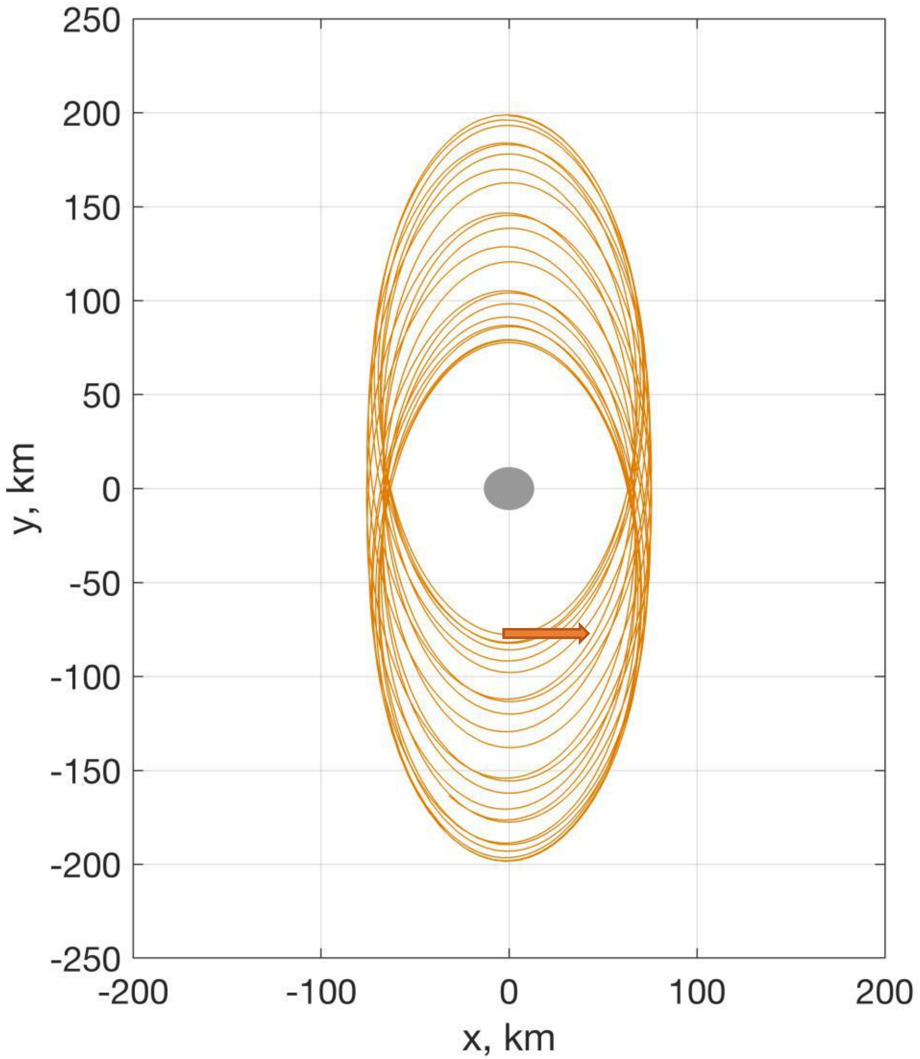

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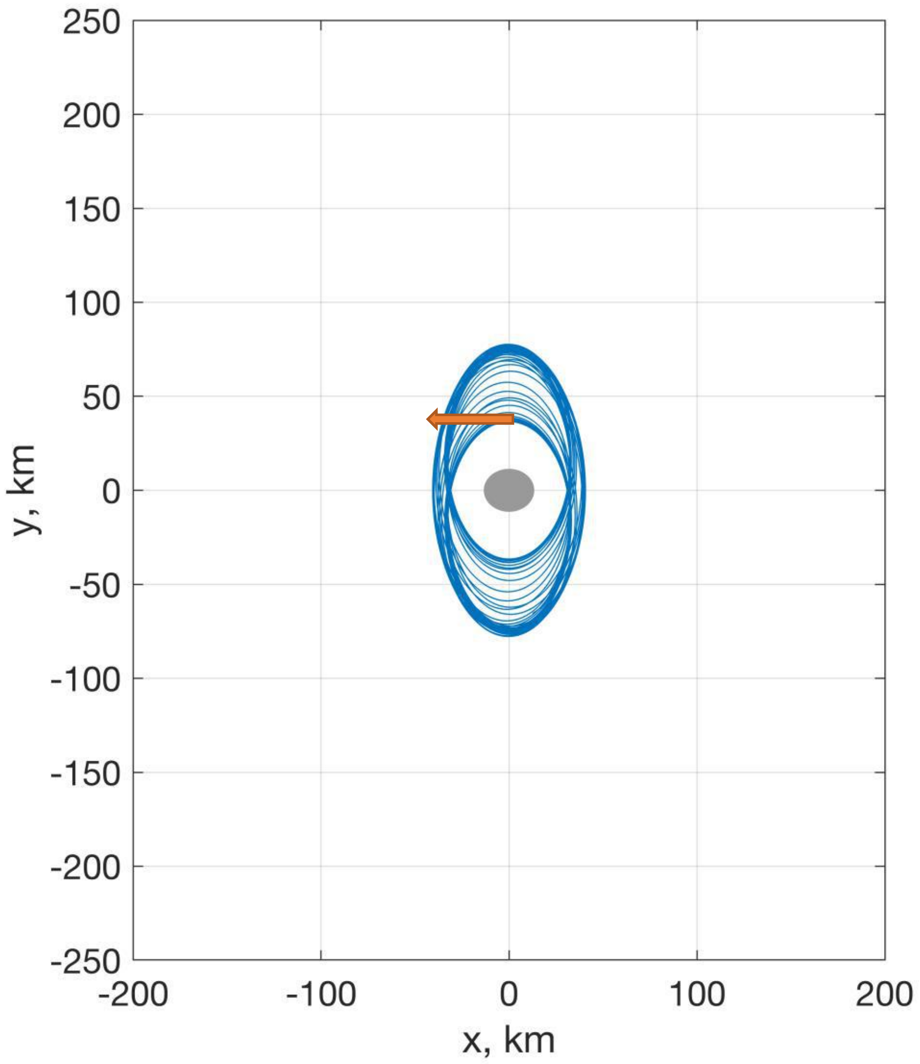

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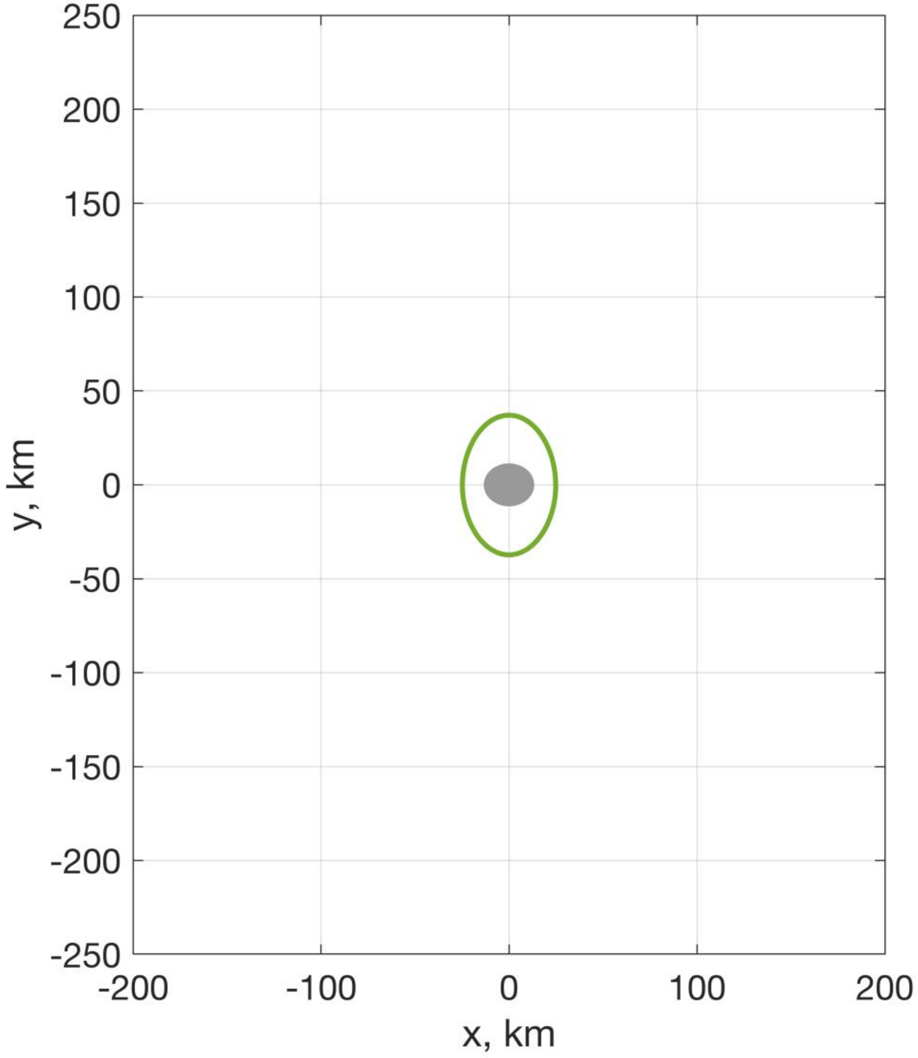
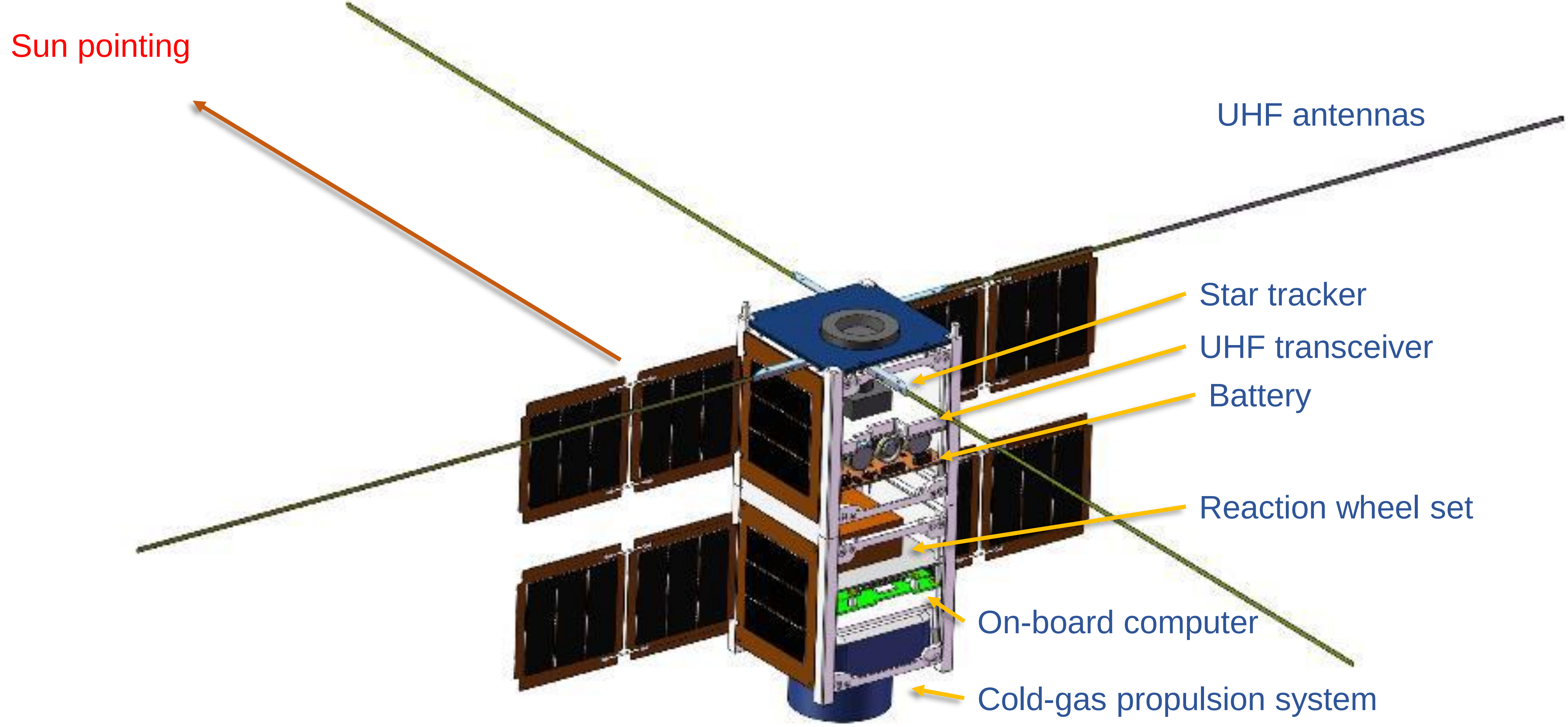


CubeSat specifications

Subsystem	Components	Mass, g	Size, mm^3	Power, W	Remark
Structure	1 **2U** frame	390	100 x 100 x 227		
	Shielding and deployable panels	530			
Thermal	Coating and heaters	50			
Power	> 10 Solar panels	440	82.6 x 98 x 2.2 (each)	12.24	51% of that @ 1 AU
	1 battery	258	93.4 x 87.4 x 23	38.5h	GOMSpace NanoPower BP4
ADCS	1 Reaction wheel set	220	25 x 50 x 55	-0.8	
	Sun sensors		27.4 x 14 x 5.9 (each)	-0.33	
	1 MEMS IMU	20	20 x 20 x 15	-0.6	
	1 Star tracker	170	50 x 50 x 47	-1.5	
Communication	1 UHF transceiver	95	89 x 95 x 11	-4	EnduroSat UHF transceiver II
	1 UHF antenna set	85	98 x 98 x 5.5	-1	EnduroSat UHF antenna
C&DH	1 OBC	100	96 x 90 x 12.4	-0.4	
Propulsion	1 Cold gas jet	676	89 x 89 x 86	-0.25	VACCO End-Mounted Standard MiPS (0.25U)
Margin		301		-0.9	10%
Total		**3308**		**2.4**	

✓ Δv budget 29.8 m/s

CubeSat configuration



Doppler measurement (1/2)

Link budgets

Item	Symbol	Unit	Value	Remark
Frequency	f	MHz	435	UHF
Carrier wavelength	λ_L	m	0.689178064	
Transmitter output power	P	Watts	1	EnduroSat UHF transceiver II
Transmitter output power	P	dBW	-3	
Transmitter output power	P	dBm	27	
Transmit antenna gain	Gt	dBi	0	EnduroSat UHF antenna
Effective isotropic radiated power	EIRP	dbW	-3	
Propagation path length	S	km	250	
Space loss	Ls	dB	-133.1785853	
Atmospheric and rain attenuation	La	dB	0	
Receive antenna gain	Gr	dBi	0	
Received power	C	dB	-136.1785853	
System noise temperature	Ts	K	135	
Carrier to noise density ratio	C/N0	dB	71.118077	
Carrier to noise density ratio	**C/N0**	**Hz**	**12936229.2**	

Doppler measurement (2/2)

Two-way doppler link (USO on Mothercraft)

Item	Symbol	Unit	Value	Remark
Clock stability / time system noise	$\sigma f/f_{time}$		5.00E-13	USO
Code loop noise bandwidth	Bn	hz	20	
Prediction integration time	T	s	5	
FLL tracking noise	$\sigma f/f_{FLL}$		1.87E-13	
Range-rate uncertainty	$\boldsymbol{\sigma v_r}$	**mm/s**	**8.00E-02**	

Dynamics stress error taken into account

Assumptions for simulation

- Observation variables
  - Range-rate uncertainty set 0.1 mm/s; Measurement taken every 10 s
  - Occultation of Phobos considered
- Period 2026-4-1 12:00 to 2026-4-8 12:00 UTC
  - During eclipse-free season
  - Suitable for the mission launched in 2024
- Ballistic flight for 7 days
- Estimated variables
  - Initial orbital states of mothercraft and CubeSat
  - Phobos gravity C_{nm} and S_{nm} coefficients, and libration amplitude θ
- Dynamical model
  - Ephemerides and gravity of the Sun, Mars, and Phobos considered
    - Gravity field of Mars up to 10 x 10 deg, and Phobos 4 x 4 deg.
  - Orientation angles of Phobos computed analytically
  - State transition matrix w.r.t. estimated variables integrated along the orbit.

- Derive range-rate derivatives w.r.t. C_{nm} and S_{nm} and θ. Covariance study to obtain estimation accuracy.

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Orientation model of Phobos

Equations of rotational angles of Phobos:
(Rambaux et al. 2012)

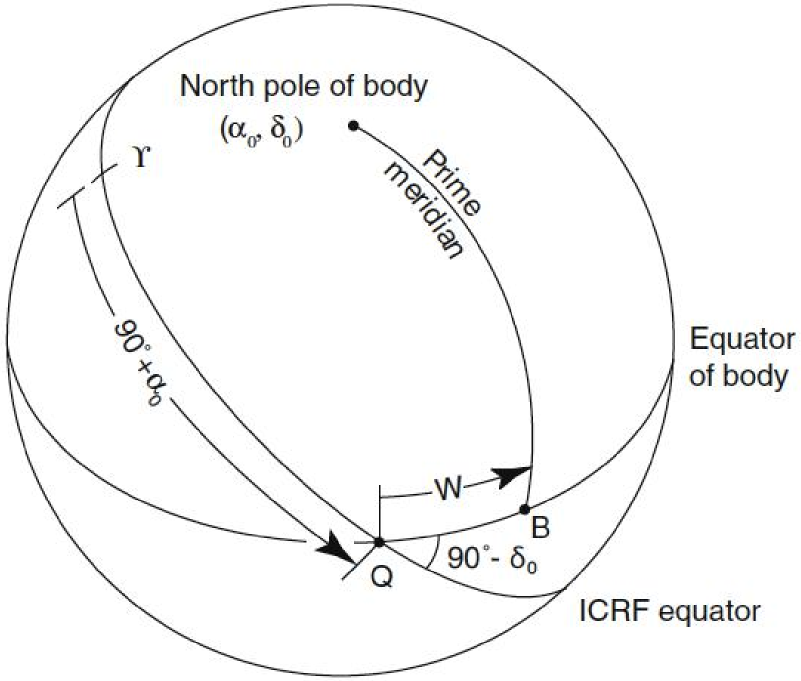


Figure © Report of the IAU Working Group

$$\alpha = 317.652 + 1.789 \sin(\mu_1 d + 169.521)$$

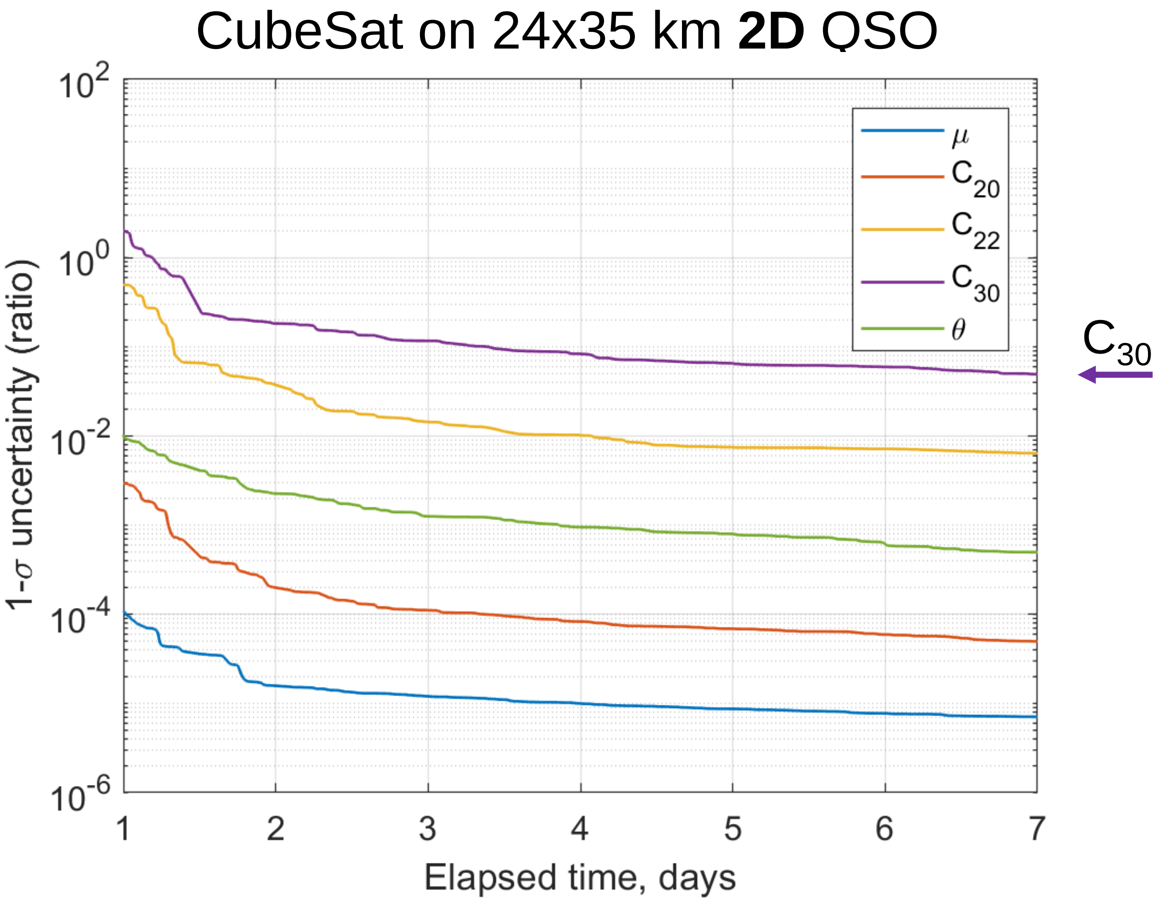
$$\delta = 52.875 - 1.078 \cos(\mu_1 d + 169.272)$$

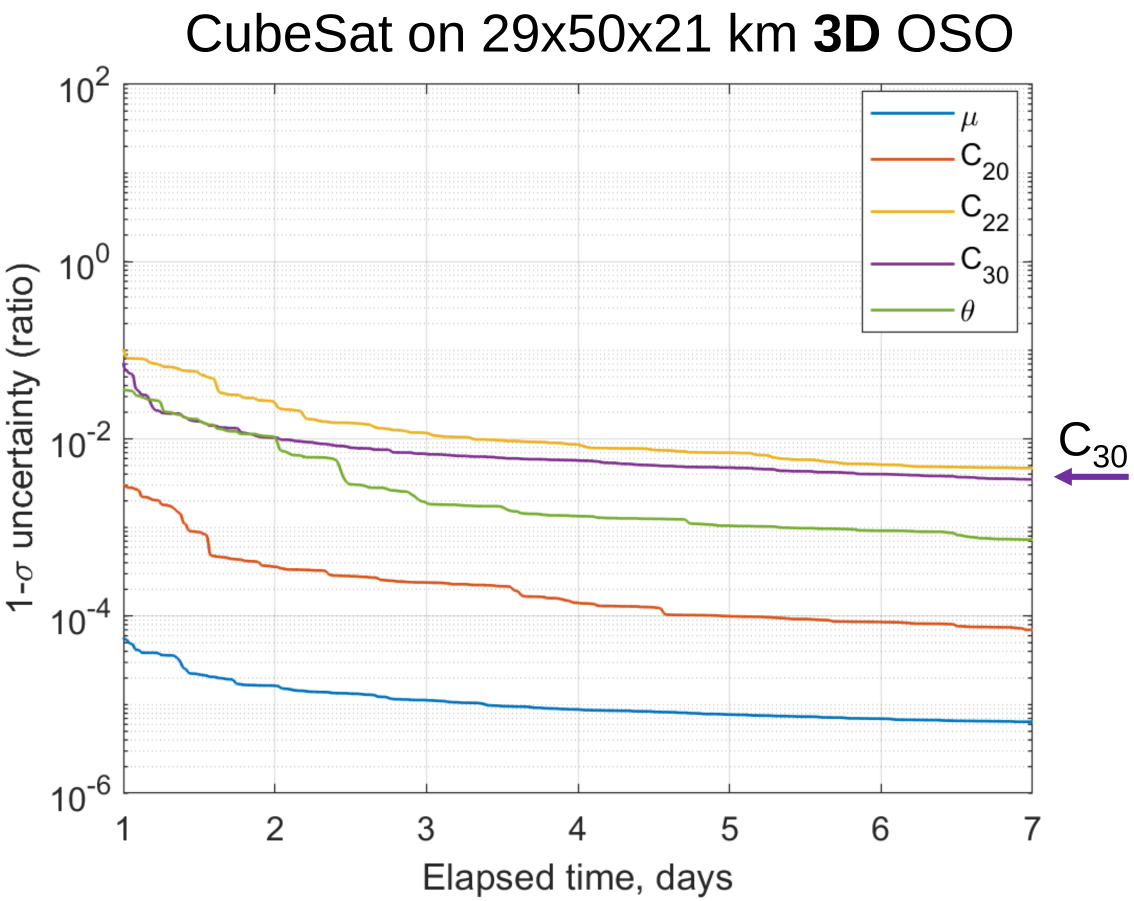
$$W = 34.781 + \mu_3 d + 1.27\,10^{-3} t^2$$
$$- 1.427 \sin(\mu_1 d + 169.488)$$
$$- \boxed{1.100} \sin(\mu_2 d + 189.271)$$

Baseline libration amplitude, θ

$$\mu_1 = -0.436 \text{deg/days} = -2\pi / 826.21 \text{days}^{-1}$$
$$\mu_2 = 1128.41 \text{deg/days}$$
$$\mu_3 = 1128.85 \text{deg/days}$$

Covariance analysis result

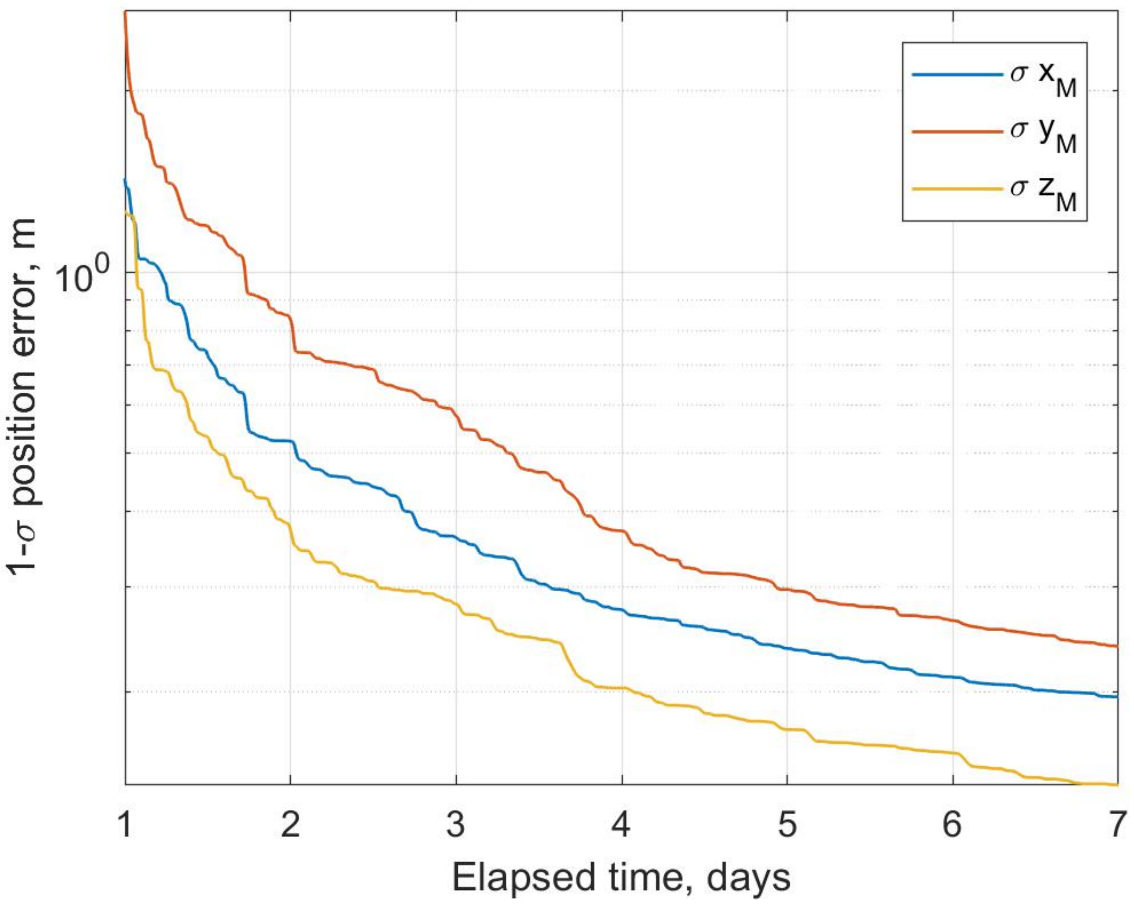




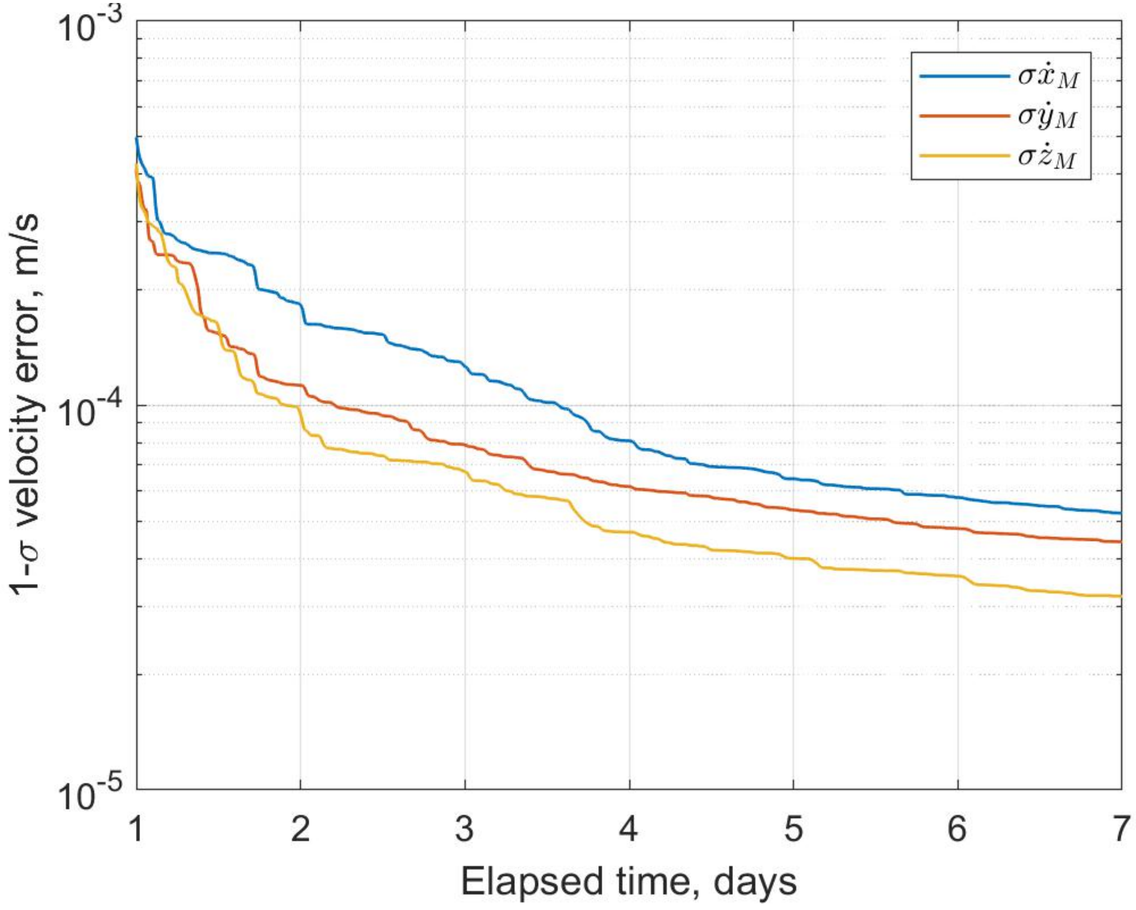
- 3D orbit is more time-efficient for recovering C_{22} C_{30}, θ and in the first 4 days.
- 3D orbit is advantageous for the estimation of zonal coefficients
- C_{20} resolution reduced to 0.07‰, C_{22} 5‰, and libration amplitude θ 0.7‰ (i.e. 0.0008 deg.)

Covariance study result (2)

Orbit determination for the mothercraft



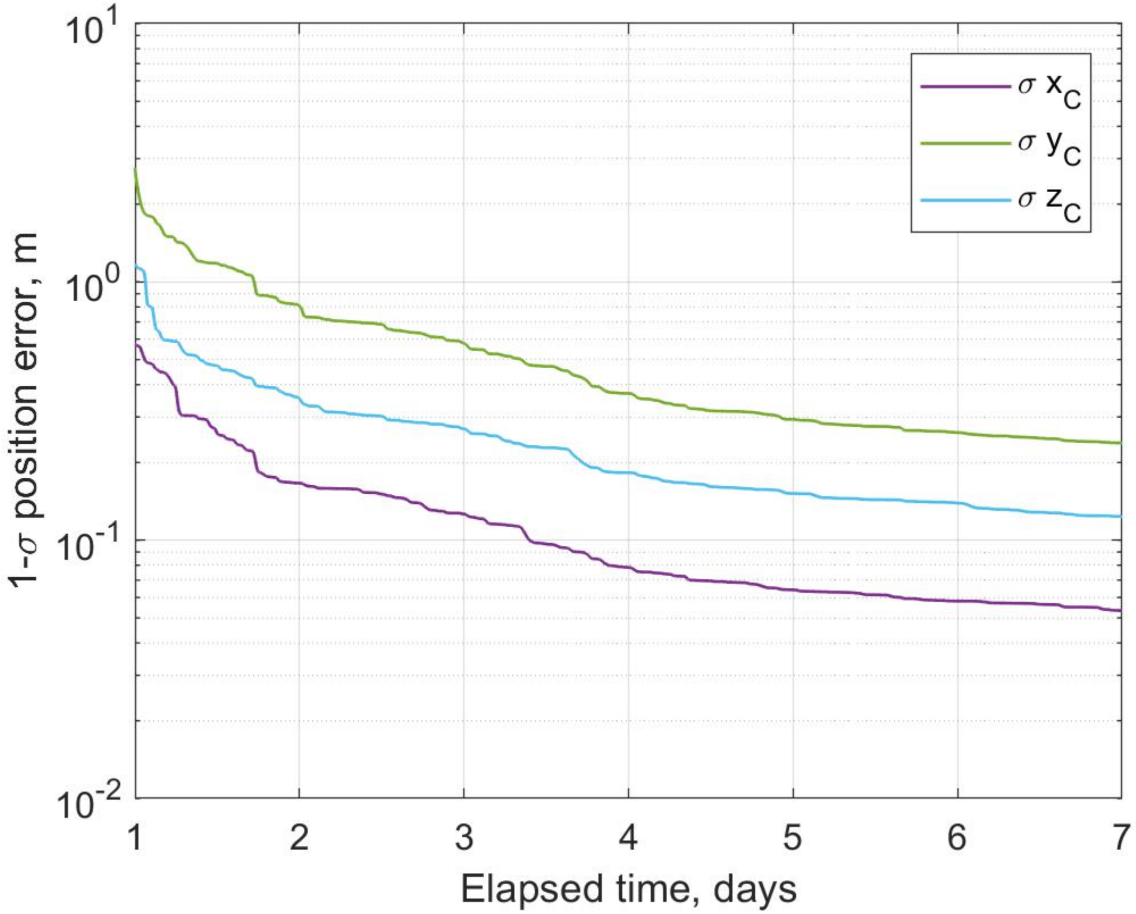
RSS position accuracy ~ 0.34 m



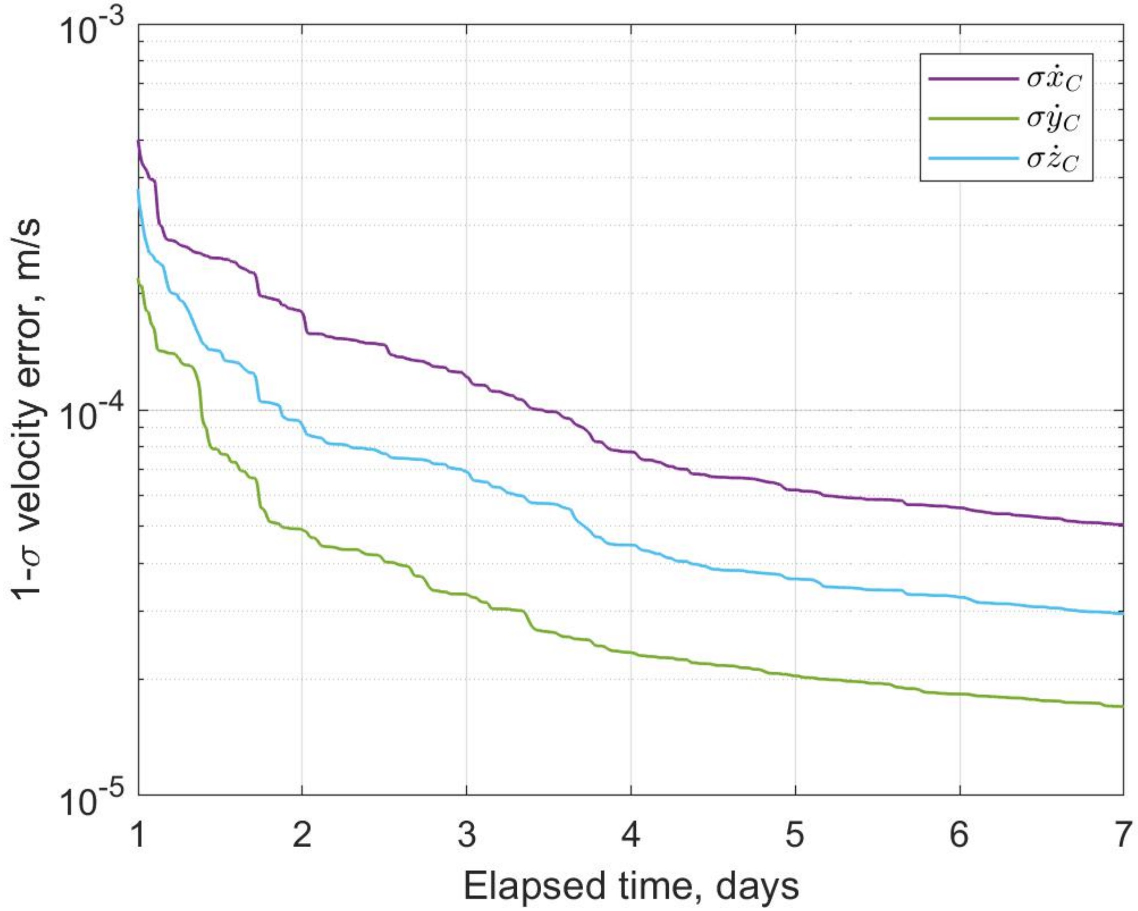
RSS velocity accuracy ~ 0.08 mm/s

Covariance study result (4)

Orbit determination for the CubeSat

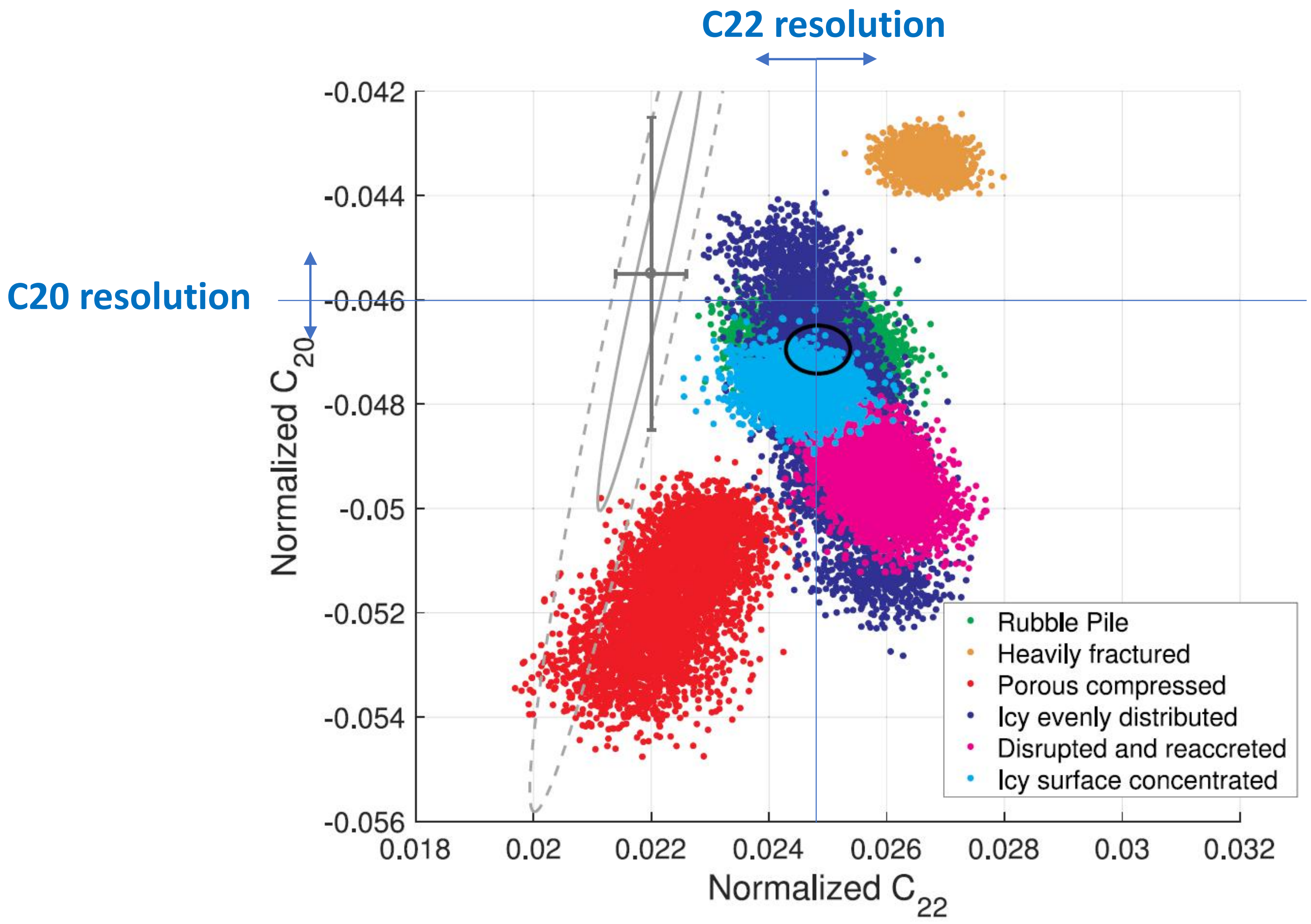


RSS position accuracy ~ 0.27 m



RSS velocity accuracy ~ 0.06 mm/s

Identify interior structure (1)

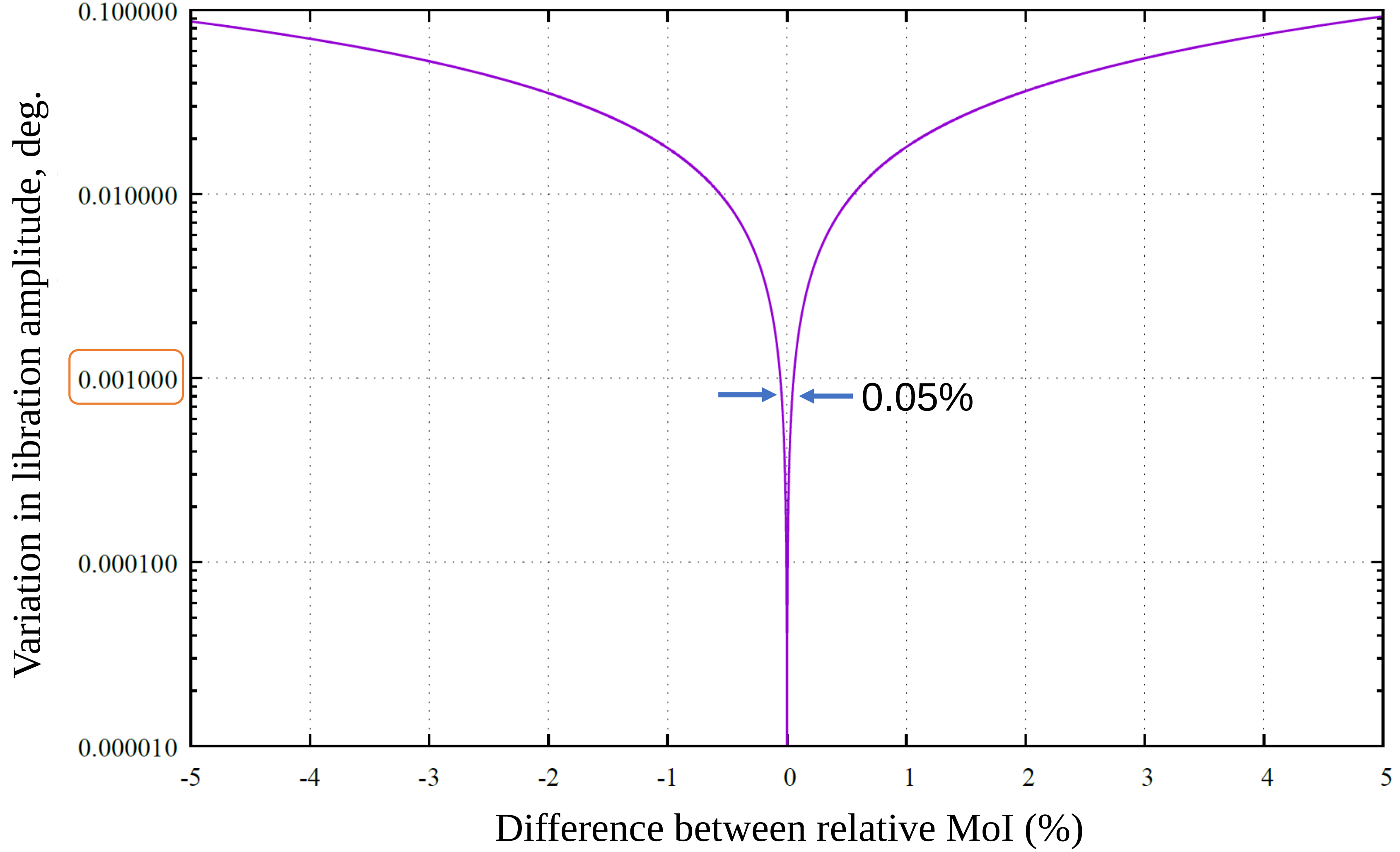


Can at least tell heavily-fractured and porous-compressed from other types.

Figure © Le Maistre et al. 2019

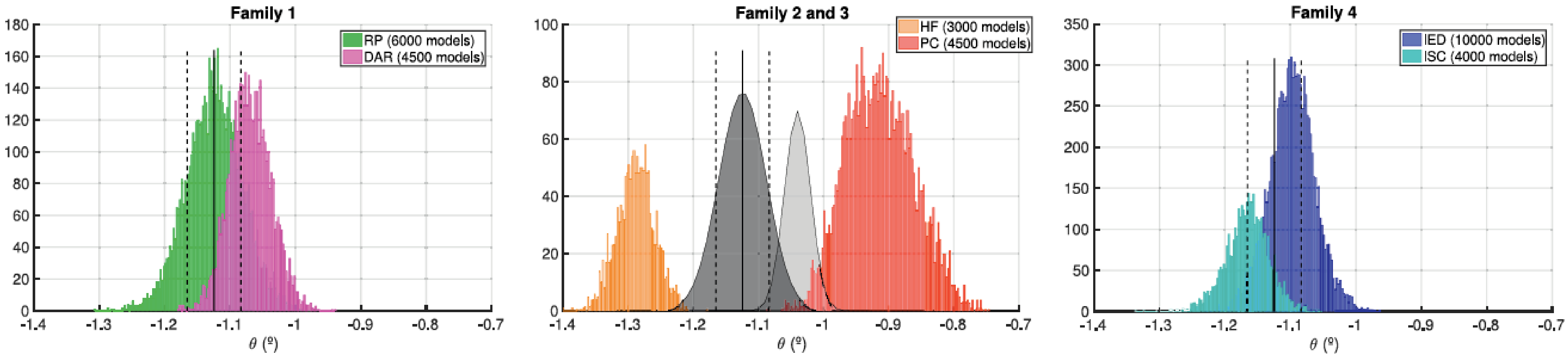
Identify interior structure (2)

With resolution of θ = 0.0008 deg.
macro-porosity difference > 0.5‰ detectable



Identify interior structure (3)

With moment of inertia constrained by the θ resolution of 0.0008 deg, the type of interior structure can be effectively identified.



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Summary

- The mothercraft-CubeSat radio science survey of Phobos carried out on low (< 30-km) and high (100-km) QSO
  - Transfer Δv cost (20 m/s) affordable to a 2U-CubeSat
  - Range-rate measurement accuracy (0.08 mm/s)
- Estimation of zonal coefficients (i.e. C_{n0}) better with the 3D orbit.
- After 7 days, C_{20} resolution reduced to 0.07‰, C_{22} 5‰, and libration amplitude 0.7‰ (i.e. 0.0008 deg.)
  - Resolution of macro-porosity 0.5‰.
  - Can effectively determine the interior structure, at least tell whether heavily-fractured, porous-compressed, or not.
- Inter-sat doppler measurement can also support orbit determination
  - Position accuracy ~0.34 m, velocity accuracy ~ 0.08 mm/s