次世代小天体サンプルリターン(NGSR)ミッション内部構造探査レーダの検討状況
Radar system for sounding of the comet internal structures in Next Generation Small-Body Sample Return (NGSR) Mission

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要旨
次世代小天体サンプルリターンミッション（Next Generation small-body Sample Returnl; NGSR）での彗星核内部構造探査に向けて，バイスタティックレーダの検討が進められている．NGSRは、彗星核（289P/Blanpainを想定）の地下１ｍから、太陽系初期から変化を受けていない物質の採取を主目的とするミッションで、サンプルリターン・その場分析に加えて、レーダ・地震計による内部構造探査の実施も検討されている。レーダによる内部探査では、彗星核が衝突破壊・再集積を経てきたrubble pileか、ダストやペブルが静かに集積して形成されたpebble pileかを識別し、形成プロセスの解明に貢献することが求められている。
1. バイスタティックレーダは，巡行機(DS-OTV)に搭載されるレーダと，着陸機(Lander)に搭載されるレーダ中継機から構成される．巡行機と着陸機（周回運用も予定）の間の交差した複数の伝搬経路で伝搬時間の計測データを取得し，トモグラフィ解析を行うことで，彗星核内部の電波伝搬速度（さらにはバルク誘電率・バルク密度）の空間分布を推定する．
2. バイスタティックレーダの運用周波数は、直径300mの彗星核を透過させるため、中心周波数160MHz, 帯域幅40MHz，送信ピーク電力は0.1Wとする．これに合わせて，送受信アンテナは 700x200 mmのボウタイアンテナとし，特性検証を進めている．レーダ内部探査のための観測運用では、DS-OTVは彗星核から10km、Landerは500mの位置を周回させて、7日間（送信間隔1秒）の計測を行うことによって，全球走査データ1セットが得られる。1セットのデータのサイズは24Mbyte程度と見積もられる。

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1. Next Generation small-body Sample Return (NGSR) mission

- Sample return mission from inactive comet (**289P/Blanpain**). The target is cometary material from below a depth of 1 m, which are not modified since solar system formation.
- Discussed in **NGSR-WG** for **proposal** to **JAXA/ISAS middle-class mission**

Observations

- **Sample return**
- **In-situ analysis** of the volatile materials
- Imaging internal structures by **radar** and **seismometer**

Purpose of NGSR Radar

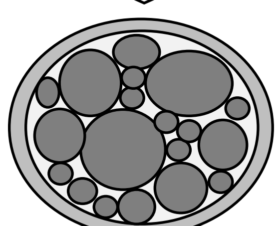
- **Imaging** of the **internal structures** of the comet
- Check of the presence of **several-m rocks** and **voids** in the comet ("**Rubble pile or Pebble pile**")
- Estimation of **bulk permittivity** of subsurface materials for derivation of **bulk density** distribution in the comet nucleus

Catastrophic disruption

⇩

Re-accretion

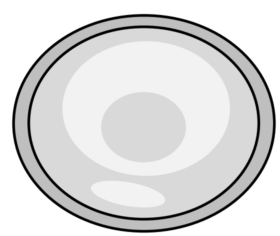
⇩



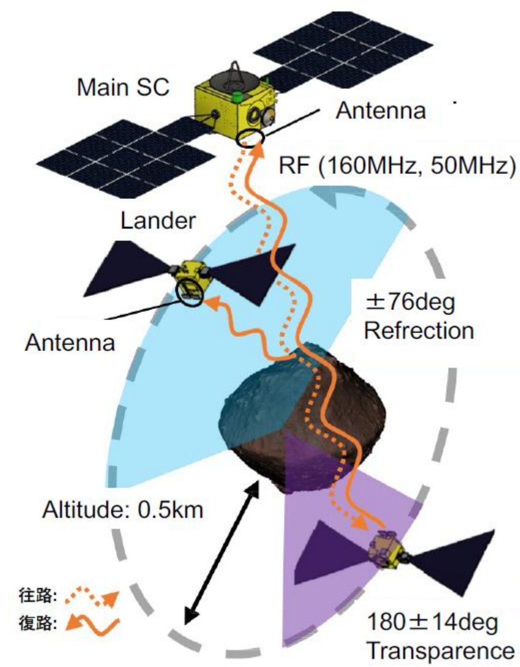
Rubble pile

Gentle gravitational collapse of pebbles

⇩



Pebble pile



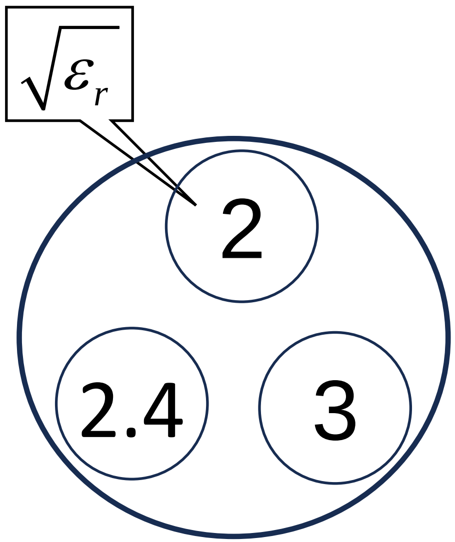
2. Advantages of Bistatic radar

Selection of the radar type

Radar type	Permittivity ε_r	Example
Monostatic radar with single orbiter	Impossible to determine (Assumed in most case)	Apollo17/ALSE MEX/MARSIS MRO/SHARAD SELENE/LRS Hera/JuRa
Bistatic radar with orbiter & fixed lander	Possible to determine →One-dimensional ε_r distribution	Rosetta/CONSERT
Bistatic radar with two orbiters (OTV&Lander. The both can be operated as orbiters)	Possible to determine →Two-dimensional ε_r image	NGSR/Bistatic-radar

Bistatic radar with a lander & orbiter (as Rosetta/CONSERT) vs. Two orbiters (NGSR)

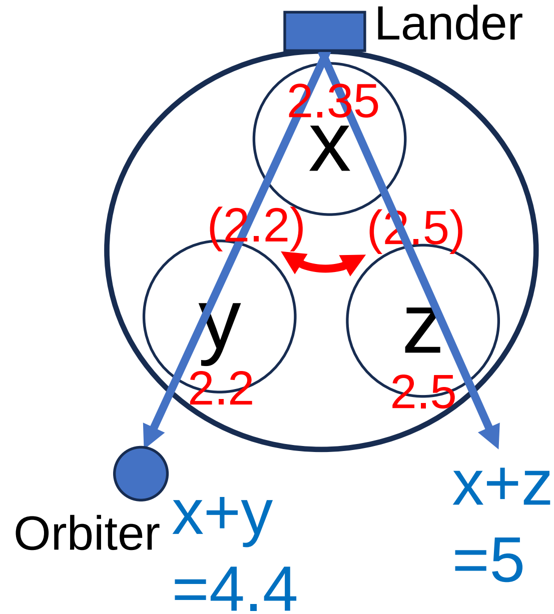
Explanation with simplified model:



Assumed delays in this simplified example

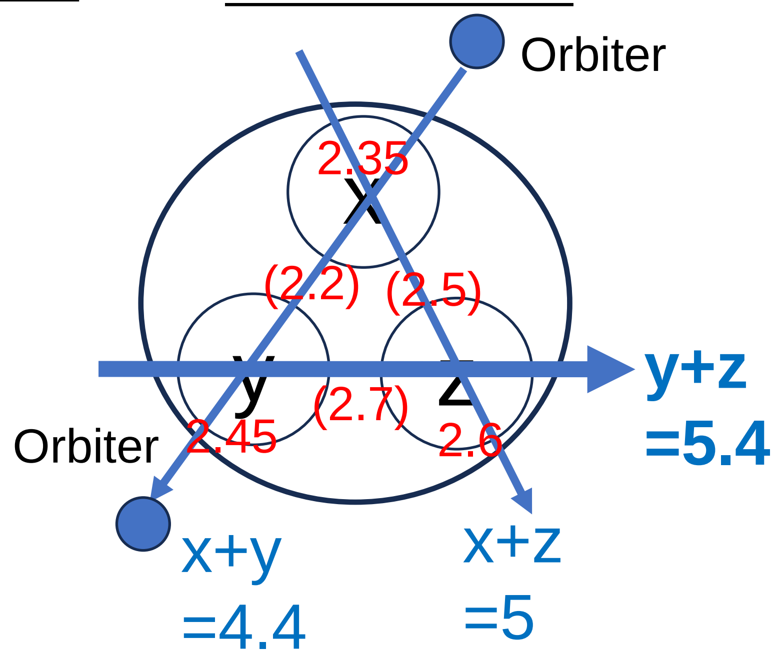
$$\tau = \frac{L}{c/\sqrt{\varepsilon_r}} \propto \sqrt{\varepsilon_r}$$

Orbiter & fixed lander



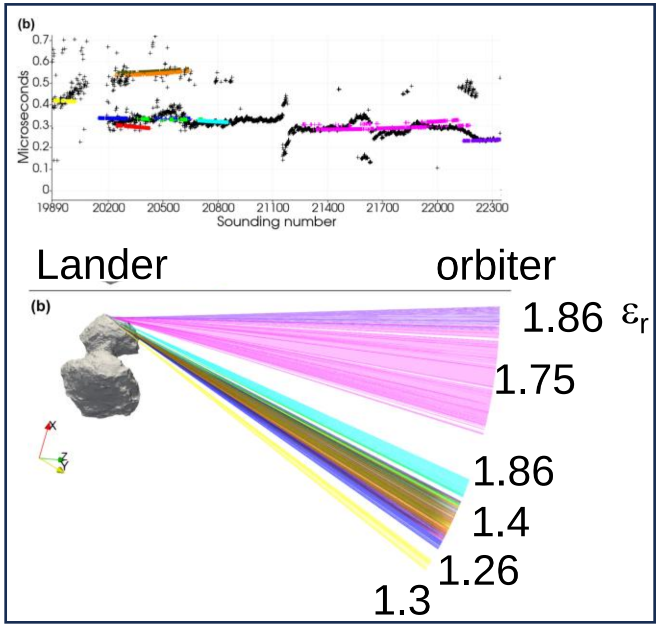
One dimensional
< ε_r> distribution
(=Kirchhoff migration)

Two orbiters



Two dimensional <ε_r> image and also ε_r from three equations with three unknown variables (=Tomography)

Rosetta/CONSERT
A Pioneering observation of the comet with bistatic radar



[Kofman et al., 2020]

Bulk permittivity
Surface (14-25m): 1.7-1.95
Deep (25-150m): 1.2-1.32
[Kofman et al., 2020]

Porosity: 65-85%
Assumed composition:
Ice (H_2O,CO_2,CO),Dust, and Voids
→Agree with gentle gravitational collapse of a pebble cloud [Blum et al. 2017]
[Herique et al., 2019]

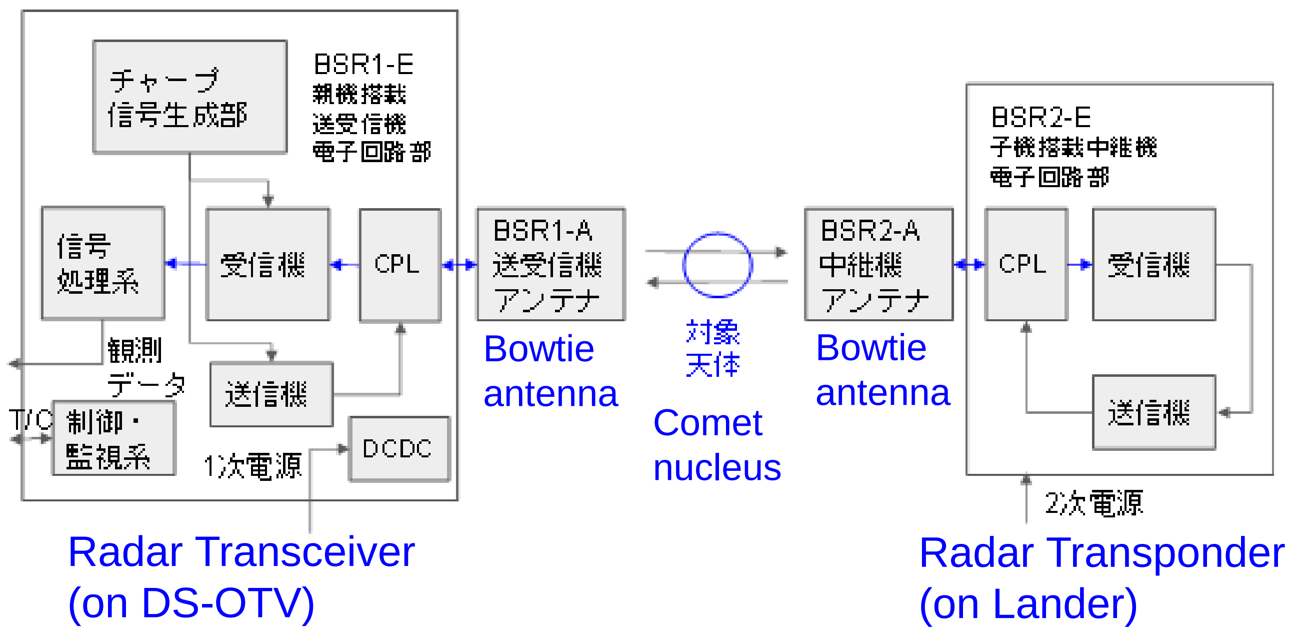
Learned from Rosetta:
- Using Radar and Transponder
- Center frequency: 90MHz (Rosetta), 160MHz (NGSR)

Advantage of NGSR:
- Using dual orbiter for 2D imaging
- Bandwidth: 8MHz (Rosetta), 40MHz (NGSR) for better resolution

3. Specifications of the NGSR Bistatic radar

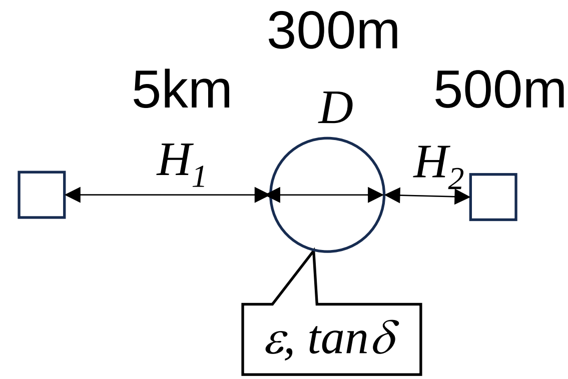
Item	Value
Operation frequency (Range resolution)	140-200MHz (2.5m, in vacuum)
TX peak power	<1W (TBD)
Detection depth	>300m (TBD)
Data rate	500byte /shot 24Mbyte/7days

	Electronics	Bowtie antenna
Unit number	1 (Transceiver, DS-OTV) 1 (Transponder, Lander)	1 (DS-OTV) 1 (Lander)
Mass	2.0 kg (DS-OTV) 0.7kg (Lander)	(0.2+0.2) kg
Size	160x210x120mm (DS-OTV) 160x210x60mm (Lander)	700x200x50mm
Power consumption	14.6W (DS-OTV) 0.7W (Lander)	TBD (deployment)



Block diagram of NGSR Bistatic-radar

Estimation of echo power



The echo power can be estimated by

$$P_{RX} = \frac{\lambda^2 G_A}{4\pi} \frac{P_{TX} G_A}{4\pi\left(H_1 + D + H_2\right)^2} (1-r)^2 \boxed{10^{-\alpha R/10}}$$

The equation is written as

$$10\log_{10} P_{TX} \qquad \text{20dBm}$$

$$+10\log_{10}\left(\frac{\lambda^2 (1-r)^2}{(4\pi)^2 \left(H_1 + D + H_2\right)^2}\right) \qquad \text{–92dB}$$

$$+20\log_{10} G_A \qquad \text{+6dB}$$

$$\boxed{-\alpha D} \qquad \text{–12dB}$$

$$= 10\log_{10} P_{RX} > 10\log_{10} N_{RX} \qquad \text{–78dBm > –90dBm}$$

If radar pulse with a power of 0.1 W is transmitted, the echo can be observed with an SNR of >10 dB.

G_A (Antenna gain): 3dB

N_{RX} (Noise level): -90dBm

ε (bulk permittivity): ~2

$$r = \left(\frac{\sqrt{\varepsilon} - 1}{\sqrt{\varepsilon} + 1}\right)^2 = \left(\frac{\sqrt{2} - 1}{\sqrt{2} + 1}\right)^2 = 0.03$$

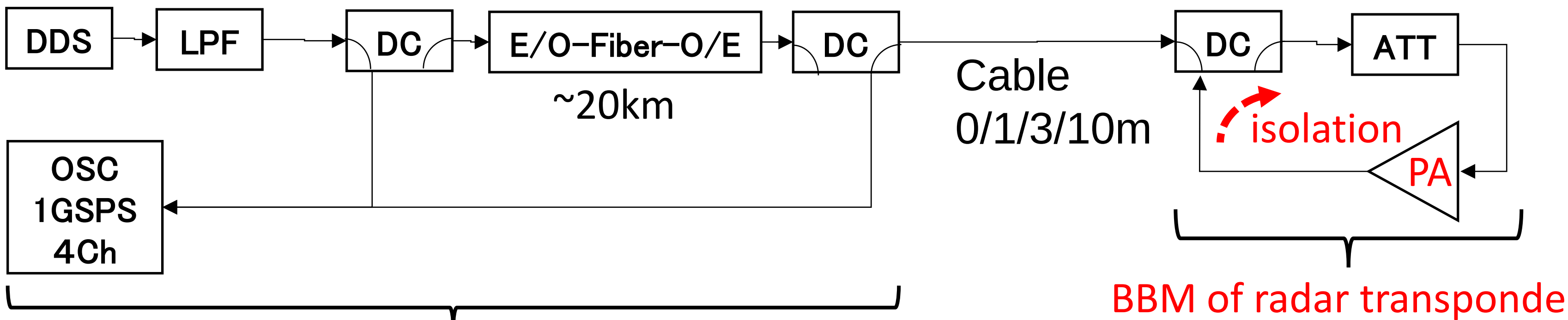
$$\boxed{\begin{aligned} \alpha &= -0.091 f\,[MHz]\sqrt{\varepsilon}\tan\delta \quad \text{[Chyba et al. 1998]} \\ &= -0.091 \times 160 \times \sqrt{2} \times 2 \times 10^{-3} = 0.041\text{dB/m} \end{aligned}}$$

$$\tan\delta = \begin{cases} 5\times10^{-4} & (\text{Ice\&silicates}) \\ \boxed{2\times10^{-3} \quad (\text{Ice\&chondrite})} \\ 2\times10^{-2} & (\text{Metalic chondrite}) \end{cases}$$

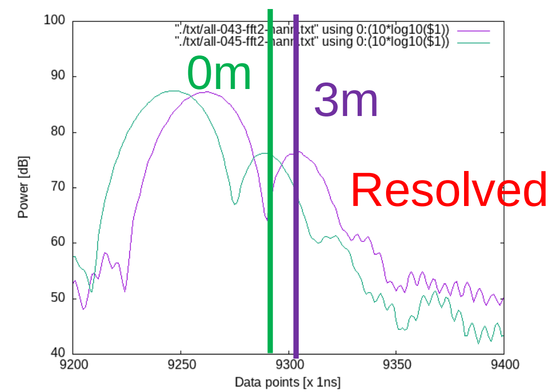
$\mathrm{Im}\varepsilon_r/\mathrm{Re}\varepsilon_r$

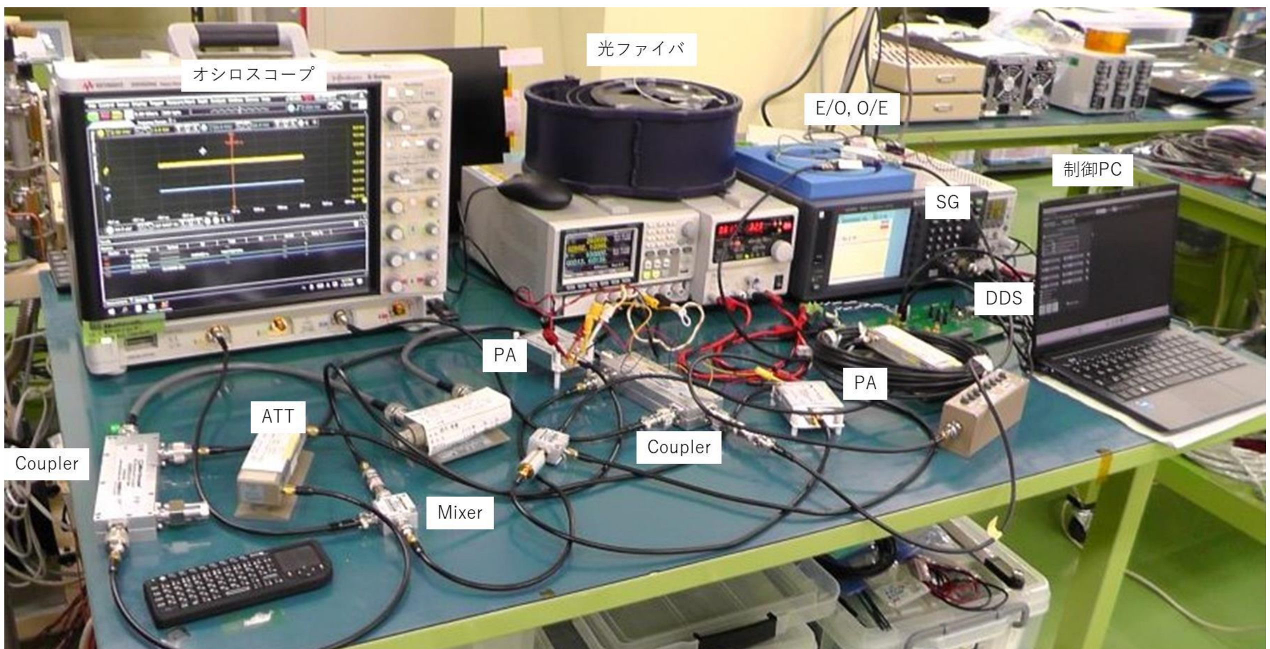
[Kofman et al., 1998]

BBM of radar transponder with evaluation tools



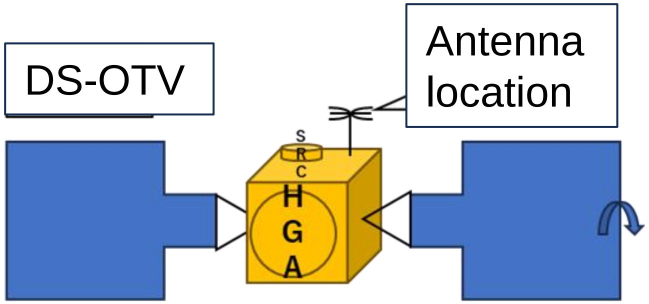
Evaluation tool
(for simulating radar transceiver)

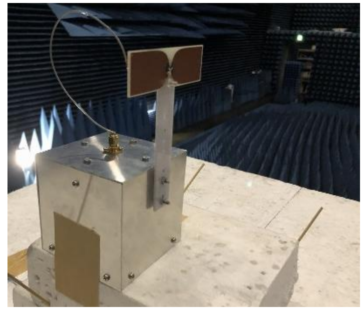


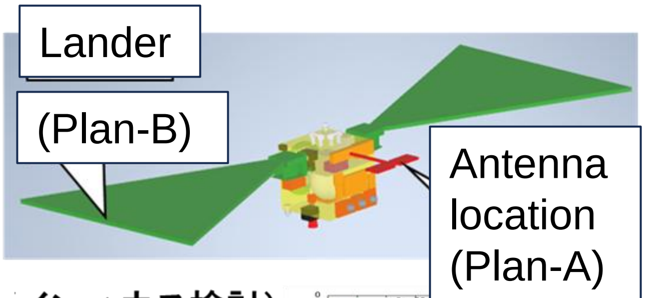


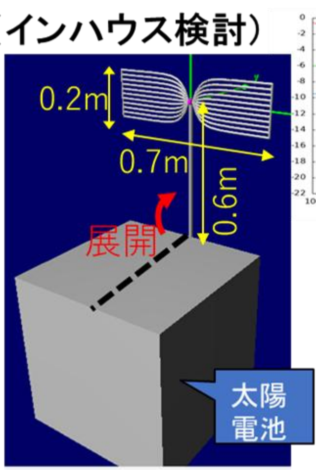
In order to avoid the power amplifier (PA) oscillation in the radar transponder, the PA gain should be less than the isolation of directional coupler.

Antenna

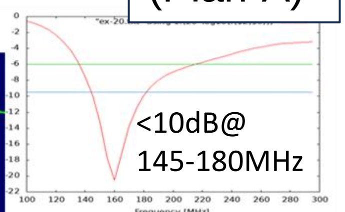




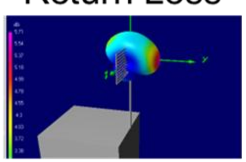




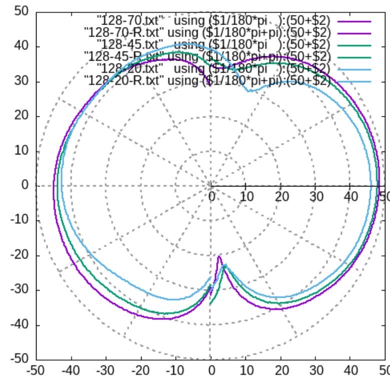
Numerical analysis



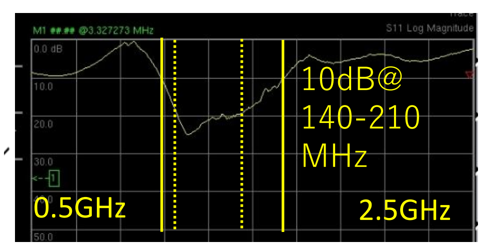
Return Loss



Radiation pattern

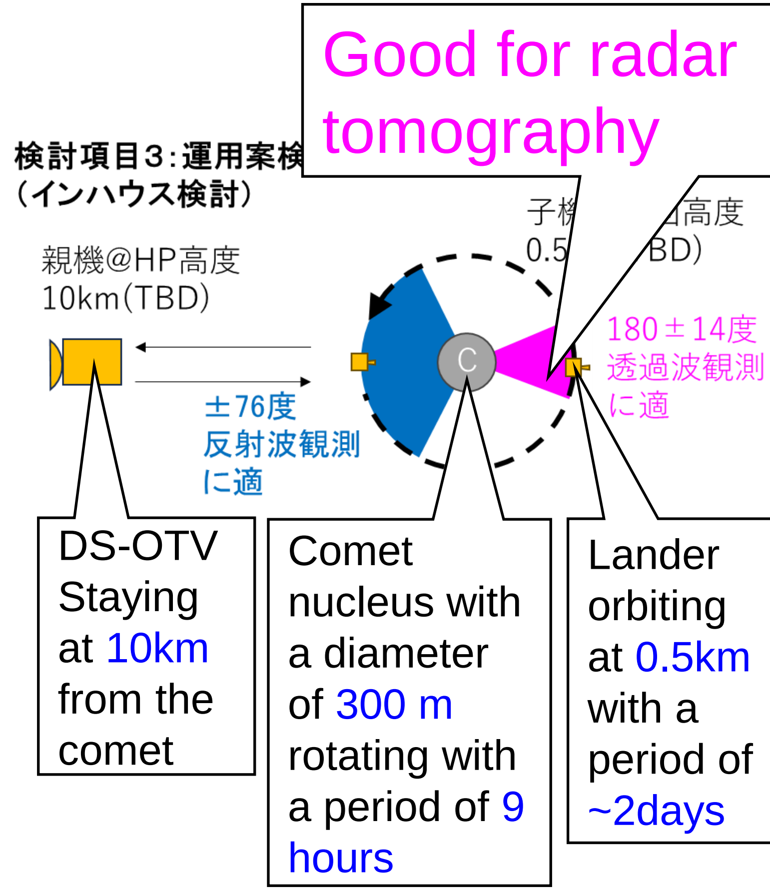


Radiation pattern measured with 1/8 scale model



Return Loss measured with 1/8 scale model

Operation plan



In 7-days operation, we can scan the comet and obtain enough data for tomographic analysis. The data amount is estimated to be 24 Mbyte/7day.

5. Tomographic analysis

$$\mathbf{y} = A\mathbf{x}$$

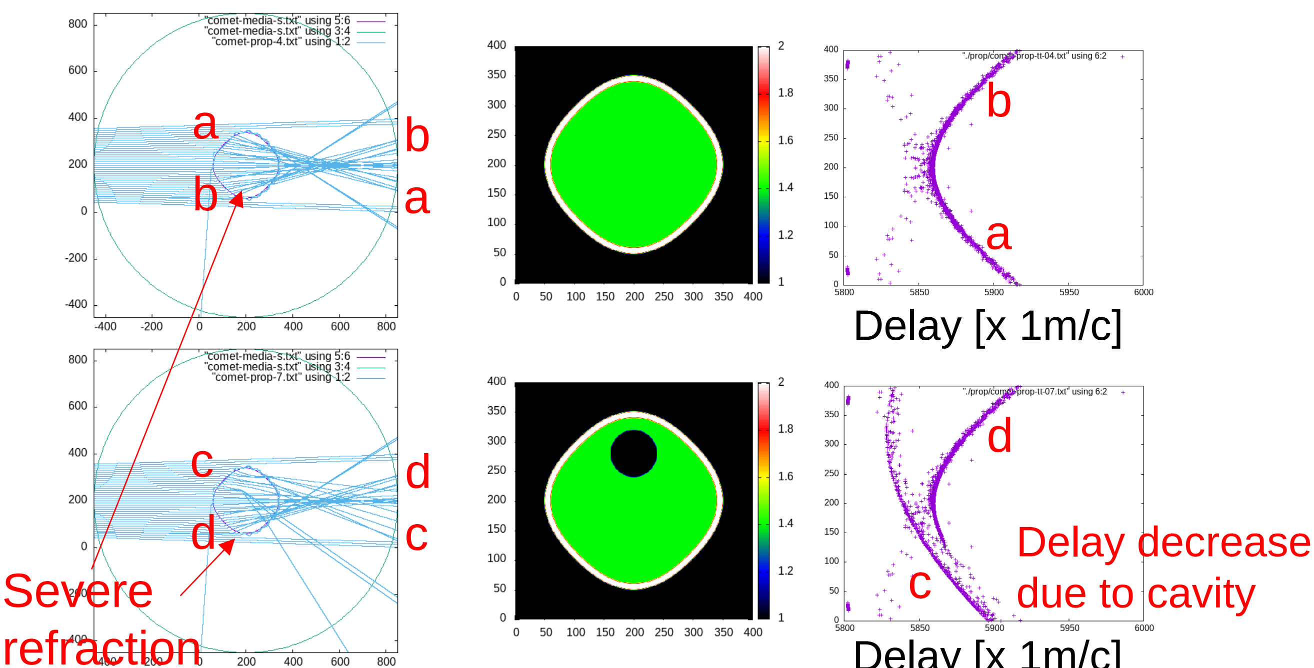
y: Measured **propagation time** (known)
A: **Propagation distance** in each pixel (*known*)
x: **Slowness** in each pixel (unknown)

x can be **numerically** obtained by **SIRT method** （Simultaneous Reconstruction Technique; Gilbert, 1972）：

$$x_j^{(k+1)} = x_j^{(k)} + \frac{1}{\sum_i A_{ij}} \sum_i \frac{\left(y_i - \sum_m A_{im} x_m^{(k)} \right) A_{ij}}{\sum_m A_{im}}$$

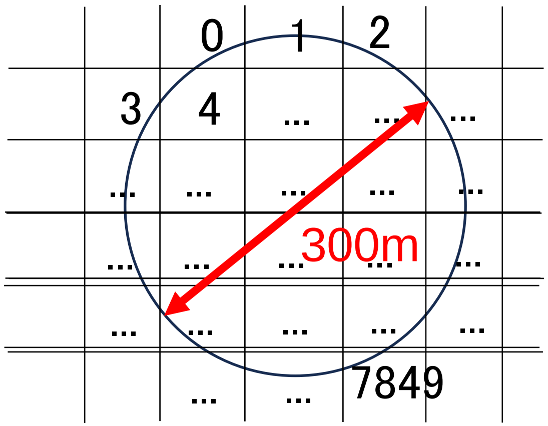
Due to **severe refraction**,
A have to be obtained by **ray tracing**:

$$\frac{d\mathbf{X}}{dt} = \frac{\partial \omega}{\partial \mathbf{k}} \qquad \frac{d\mathbf{k}}{dt} = -\frac{\partial \omega}{\partial \mathbf{X}}$$



Dry run and practice with synthetic data would be needed. (Ongoing)

How much data should be obtained?



Number of pixel with a size of 3×3m: ~8000

<Assumptions>

- Main orbiter: Fixed
- Orbital period of Sub orbiter: ~2 days
- Rotation period of the comet: ~9 hours
- Interval of pulse transmission: 1s
- (Operated during $166<\Phi<180^\circ$)

→Number of propagation time data in 1 day: ~7000

In tomographic analysis,

$$\mathbf{y} = A\mathbf{x}$$

y: Propagation time data (known)

A: Given by propagation distance (known)

x: Slowness in each pixel (unknown) $\boxed{1/v = \sqrt{\varepsilon}/c}$

This inverse problem can be solved using $A = U\Lambda V^T$ as

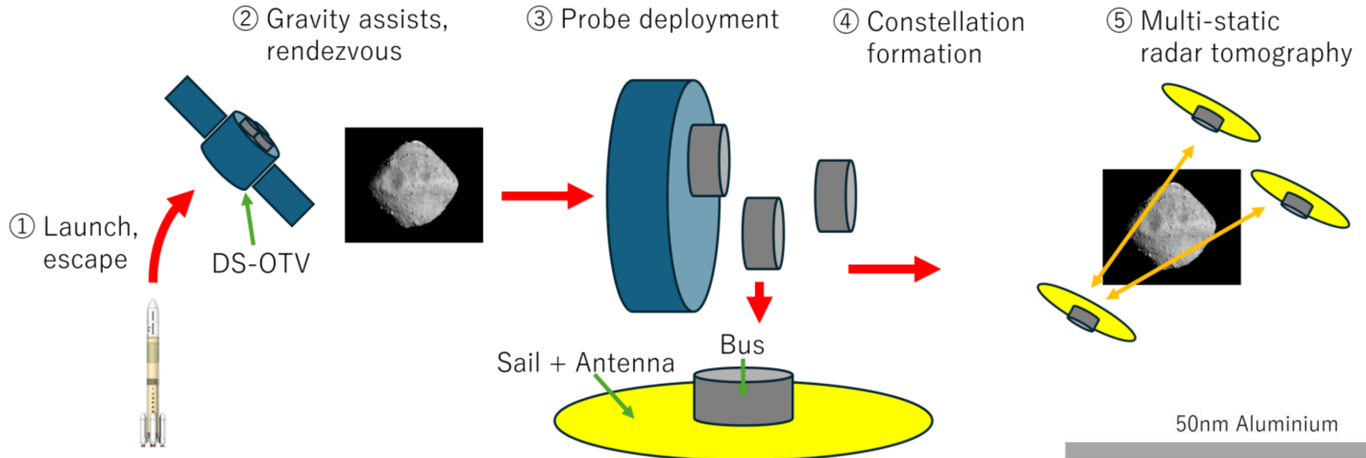
$$\mathbf{x} = \left(A^T A\right)^{-1} A^T \mathbf{y} = \left(V\Lambda^T \Lambda V^T\right)^{-1} A^T \mathbf{y}$$

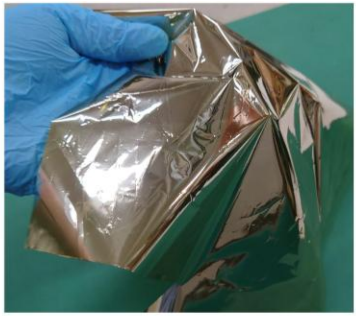
In order to solve without numerical instability, the condition number (ratio of the max. & min. eigen vales, $\lambda_{max}/\lambda_{min}$) should be enough small.

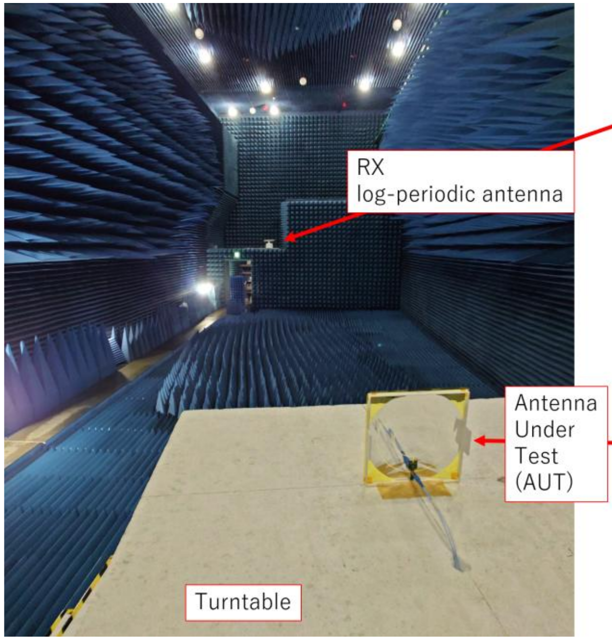
→ Required data number: **~48,000** (~6x8000).

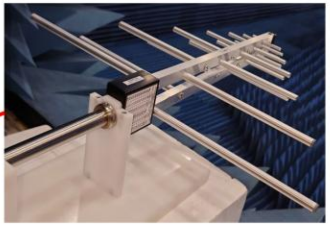
→ The dataset can be obtained in **7 days** with a radar pulse transmission at an interval of **1s.** Storage amount: **24 Mbyte** (500byte for 1 echo profile).

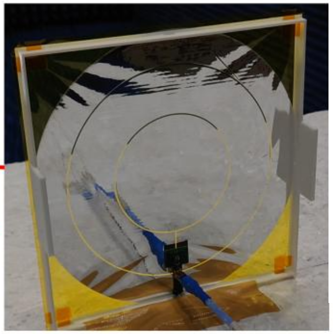
Radar tomography with micro solar sail probes separated from DS-OTV

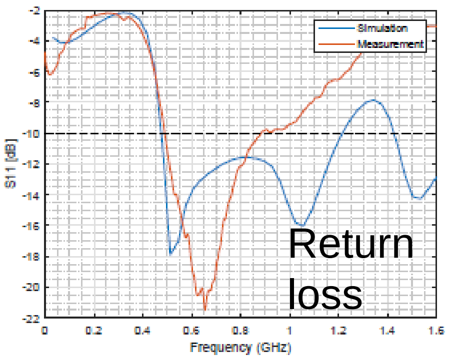


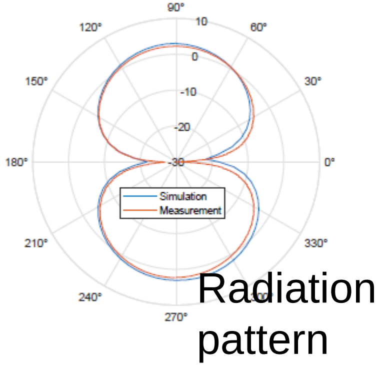












[Sugihara et al., 2024]

6. Summary

An **ambitious comet observation plan** with **bistatic radar** has been investigated for **Next Generation small-body Sample Return (NGSR)** mission.

1. The bistatic radar consists of a **radar transceiver** installed on **DS-OTV (Deep Space Orbital Transfer Vehicle)** and a **radar transponder** installed on **Lander** operated as sub-orbiter. Using dataset of the propagation time for multiple penetrating paths **from DS-OTV, to comet, and to Lander,** distribution of the **bulk permittivity (**ε) can be derived by **tomographic analyses**.
2. The operation frequency range and transmission peak power for **NGSR Radar** has been determined as **140-200MHz**, and **0.1W**, respectively. Antenna design (with a size of **700x200 mm**) and operation plan (**7days**, generating data with an amount of **24Mbyte**) were also investigated.

Acknowledgment: This study is supported by JAXA/ISAS grant for **strategic development research** for **NGSR Working Group**. We also appreciate **Meisei Electric Co. Ltd**. for supporting conceptual design of the bistatic radar.

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