SMALL BODY RADAR INVERSE SCATTERING IN MONOSTATIC AND BISTATIC GEOMETRIES

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Introduction: Understanding the interior structure and composition of solar system small bodies is crucial for addressing decadal science priorities and for informing planetary defense mitigation strategies. Low-frequency radar (HF/VHF bands) is the best method for remotely probing and imaging small body interiors. To date, only Rosetta-CONSERT has made limited bistatic transmission measurements of comet 67P/C-G, [1], and ESA's Hera mission will carry the cubesat Juventas and VHF radar JuRa to image the interior of asteroid Didymos B, [2].

There are three general types of radar imaging methods for small body interiors: 1) tomographic synthetic aperture radar (SAR) which form images of backscatter using traditional focusing techniques [3], 2) inversions of average dielectric properties using kinematic properties of waves (e.g., speed and time delay), like Rosetta-CONSERT [4], or 3) full-wave nonlinear inverse scattering algorithms that create volumetric images of the interior dielectric via optimization and have the potential for sub-wavelength resolution, [5,6], sometimes called full-wave tomography. The choice of imaging method together with the radar acquisition geometry (monostatic vs bistatic) and transmit bandwidth drive image performance, instrument design, mission architecture and ultimately science return.

In this work, we study monostatic and bistatic radar acquisition geometries and their effects on the performance of inverse scattering algorithms in 2D. We test the algorithms on a low-contrast dielectric small body interior model. We use a frequency-domain source-independent forward scattering model that allows us to cleanly test monostatic vs bistatic imaging geometries.

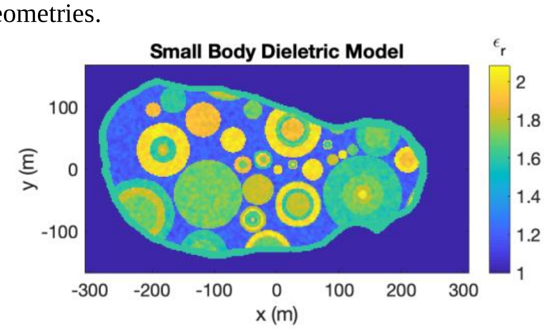

Figure 1: 2D small body dielectric model.

Small Body Dielectric Model: The small body dielectric model we use is a 2D slice of the model used in [7], shown in Figure 1. It is the size and shape of asteroid Itokawa with maximum real part of the dielectric constant of about 2, which is consistent with comet material. It is composed of an aggregate of layered disks, voids, random dielectric variation, a regolith layer, and is discretized at 2 meters.

Forward Scattering Model: We use the Method of Moments (MoM) as the forward scattering simulator which is accelerated with the Characteristic Basis Function Method (CBFM) [8,9]. The MoM is a frequency-domain, source-independent scattering solution of the total field volume integral equation given a dielectric object. The interior total field is then used to predict the measured scattered field for arbitrary source/receiver combinations. The CBFM compresses the MoM matrix using a domain decomposition technique enabling electrically large problems to be solved with less computation. Figure 2 shows the domain decomposition as applied to the small body dielectric model and imaging domain.

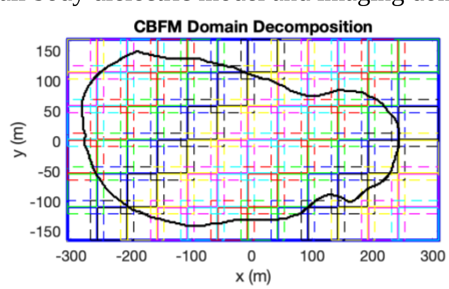

Figure 2: Characteristic Basis Function Method (CBFM) domain decomposition used to accelerate the forward scattering solution.

Inverse Scattering Algorithm: The Distorted Born Iterative Method (DBIM), [10], is used to invert the dielectric interior from simulated scattered fields. At each iteration, the DBIM solves for the change in the object dielectric relative to the previous object estimate using a guess of the interior total field. The dielectric change is solved via conjugate gradient optimization of an L2 cost function with Gaussian priors and Tikhonov-like regularization that minimizes the difference between scattered field measurements and predictions, [6]. The new object is then used to update the interior total field with the MoM-CBFM, and the process repeats. To accelerate convergence, iterations start from a homogenous object with the body shape and dielectric constant of 1.6.

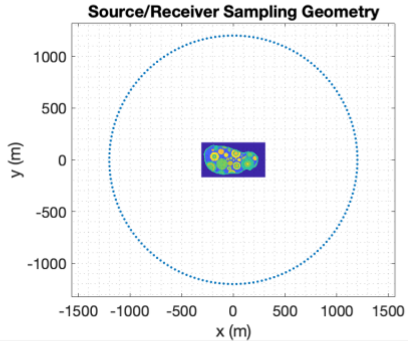

Figure 3: Source and receive positions around the object. Bistatic simulations use half as many points shown here. The angular step satisfies Doppler sampling requirements.

Results: Scattered fields are simulated for four acquisition geometries: 1) full monostatic reflection (all possible reflection measurements), 2) transmission only, 3) transmission and reflection, and 4) full bistatic (all possible combinations of source/receiver data are collected). The sampling points around the object are shown in Figure 3. Bistatic data are sampled with half as many points, but all source/receiver combinations are used. Our focus is on understanding the source geometries, so simulations are noise-free and assume perfect knowledge of the source positions.

Figure 4 shows inversion results for the four acquisition geometries using monochromatic waves at 5 MHz (the body diameter is ~10 wavelengths). Fewer than 20 DBIM iterations are needed for convergence in all cases. Only the full bistatic geometry recovers the object correctly with a single frequency, where dielectric features less than the smallest wavelength in the object (60 m/sqrt(2) = 42 m) are resolved. Figure 5 shows the monostatic and bistatic cases when 11 discrete frequencies from 4 to 6 MHz are used in the inversion. Here, the monostatic geometry is capable of reconstructing the object under ideal settings albeit with some artifacts relative to the bistatic case.

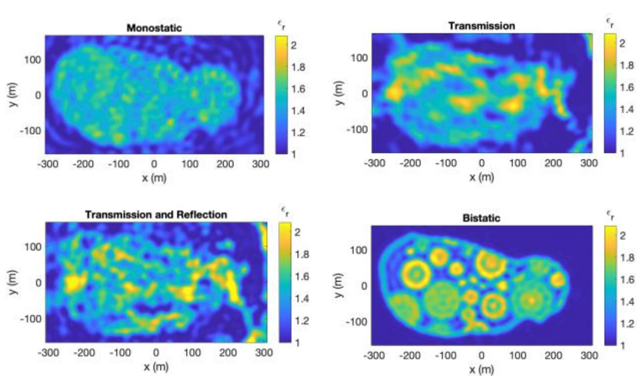

Figure 4: Monochromatic (5 MHz) inverse scattering reconstructions of the object in Figure 1 under four different sampling geometries.

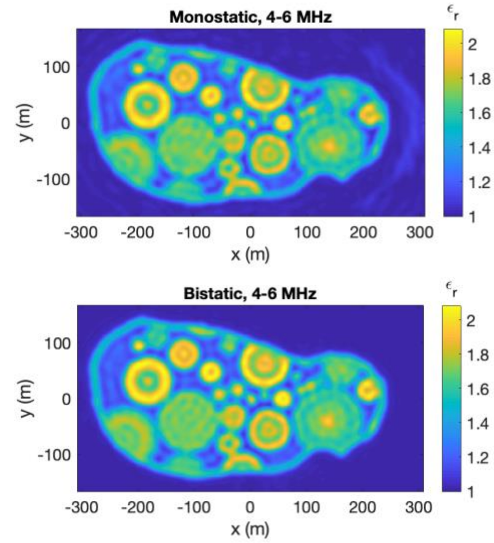

Figure 5: Monostatic and bistatic reconstructions using 11 discrete frequencies from 4-6 MHz. The monostatic geometry is capable of reconstructing the object with some artifacts using ideal data.

Conclusions: We have demonstrated a radar inverse scattering algorithm for reconstructing the interior dielectric profile of low-contrast solar system small bodies. The use of the MoM-CBFM forward solver together with DBIM inversion allows easy testing of different acquisition geometries and probing bandwidths which is needed to inform future radar instrument design and mission architectures (e.g., a bistatic radar mission to Apophis or other small body).

Future work includes developing more realistic interior models, extending the inversion algorithm to 3D vector waves, and studying the effects of partial bistatic converge to assess the optimal combination of radar bandwidth and coverage. In addition, we will study the effects of realistic orbits, thermal noise, and sensor position errors, which are expected to stress and degrade the image reconstructions.

Acknowledgments: This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

References: [1] Kofman, W. et al. (2007) *SSR 128*(1-4), 413–432. [2] Michel, P. et al. (2018) *COSP 42*, B1– 1. [3] Arumugam, D. D., et al. (2018). *IEEE APS*, 1795–1796). [4] Herique, A., et al (2016) *MNRAS 462*, S516–S532. [5] Sava, P., and Asphaug, E. (2018b) *ASR 61*(8), 2198–2213. [6] Haynes, M., et al. (2012). *IEEE TAP 60*(4), 1854–1867. [7] Sava, P. et al. (2018) *LPI*, (2083), 1996. [8] Mittra, R. and Du, K. (2008) *JPIER* 6, 307-336. [9] Fenni, I. et al. (2014) *IEEE TAP* 62.8 (2014): 4282-4291. [10] Chew, W. C. and Wang, Y.-M. (1990) *IEEE TMI* 9.2, 218-225.