3D MONOSTATIC WAVEFIELD TOMOGRAPHY OF COMET INTERIORS. P. Sava[1], E. Asphaug[2], M. Haynes[3], [1]Center for Wave Phenomena, Colorado School of Mines, Golden, CO 80401, psava@mines.edu, [2]Lunar and Planetary Laboratory, University of Arizona, Tucson AZ 85721, asphaug@lpl.arizona.edu, [3]Jet Propulsion Laboratory, California Institute of Technology, Pasadena CA 91109, Mark.S.Haynes@jpl.nasa.gov.

Introduction: Fundamental answers about small planetary bodies origin and evolution hinge on our ability to image in detail their interior structure in 3D and at high resolution [2]. The interior structure is not easily accessible without redundant data, e.g., radar reflections observed from multiple viewpoints, as in medical tomography. The ideal targets for such investigation are Jupiter Family Comet (JFC) nuclei smaller than 20km, for three reasons: (1) Large, undisturbed comets are profoundly important objects scientifically and are vital to the scientific understanding of the Solar System [1]. (2) The Rosetta mission discovered that cometary nuclei are radar-transparent to depths of kilometers, and are therefore especially well-suited to global 3D imaging. (3) The JFCs have been scattered inwards fairly recently by the giant planets, many of them on Earth-approaching orbits inside Jupiter with periods of around 5-6 years, which makes them the most accessible targets for low-cost science exploration of the outer solar system.

Imaging: Due to its remote sensing character, and because electromagnetic waves penetrate deep in icy structures, radar imaging is best suited to cometary nuclei. Radar imaging can be performed using techniques adapted from global and exploration seismology. We consider full wavefield methods that enable high quality imaging of small body interiors by exploiting both the phase (traveltime) and the amplitude of the reflected electromagnetic waves. Two types of imaging techniques can be applied to radar reflection data: (a) *wavefield migration*, designed to position interfaces between different material properties in the comet interior, and (b) *wavefield tomography*, designed to evaluate the radar wave propagation speed throughout the interior of the comet. Tomography is best suited to characterize the nuclei structure and absolute dielectric properties.

Acquisition: We assume a monostatic system (a single antenna acting as transmitter Tx and receiver Rx) operated in two bands centered at 5 and 15 MHz, with 1.25 and 3.75MHz standard deviation, respectively, from a spacecraft in slow polar orbit around a spinning comet nucleus. Seen from the perspective of the comet nucleus, the S/C describes increasingly dense trajectories that illuminate its interior from all directions, similarly to a 3D tomograph (Figure 1) [6]. Using a combination of lower and higher frequencies, this radar system enables imaging using techniques from the full wavefield inversion family [7], adapted to the specific comet nucleus shape and orbital acquisition geometry.

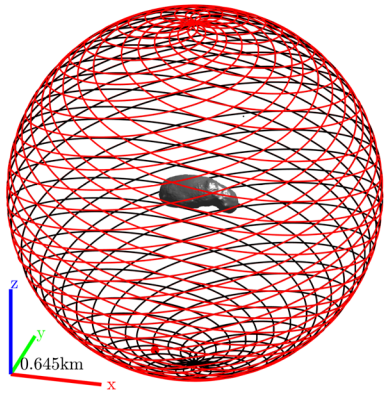

Figure 1: Nucleus-centered acquisition geometry for 30 days from a S/C with a radius of 1.3km and a period of 52.9hrs around a target with a rotation period of 12.1hrs.

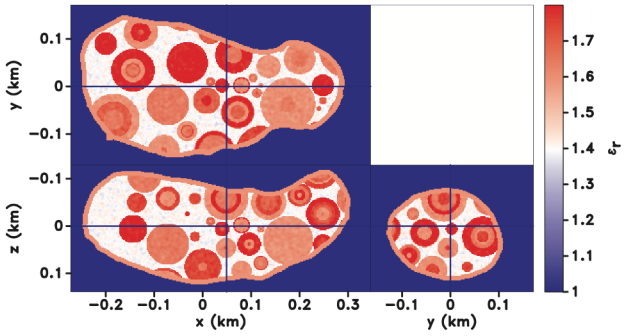

Figure 2: Synthetic comet model consisting of an accumulation of inhomogeneous rounded cometesimals.

Tomography: We develop wavefield tomography under the exploding reflector model [3], which exploits the fact that waves propagation paths from Tx to reflectors and from reflectors to Rx are identical. This assumption reduces the computational cost by enabling processing of all acquired data at once, while still describing wave propagation in complex media with spatial velocity variation and reflectors of arbitrary shapes and orientations. The key idea underlying our tomography is that we know a-priori and with high precision the exterior shape of the comet nucleus, and thus we can impose the condition that the radar data backpropagated through the nucleus interior images its back-side at the correct known location. The existence of the back-side reflection is the mechanism that enables the monostatic imaging geometry to sample the low spatial frequencies of the object, and thus reconstruct the mean and large-scale velocities.

Our wavefield tomography belongs to the full waveform inversion (FWI) family, common in terrestrial seismology [4,7]. Thus, the method inherits key FWI requirements, i.e. that the observed and predicted wavefields match within a fraction of a cycle. One way to avoid cycle skipping is to lower the frequency band when predicting data with poorly-known models, and to raise the frequency when the model is better known [5]. This multiscale technique allows imaging of large-contrast models with starting from unknown initial models.

Example: We illustrate our technique with a layer pile comet nucleus [8] model consisting of inhomogeneous rounded cometesimals (Figure 2). The model has a homogeneous evolved surface of relative permittivity $\epsilon_r = 1.6$. The interior is populated with spherical cometesimals with random radii that follow a Rayleigh distribution. The cometesimals have up to 5 homogenous layers with random radii and random ϵ_r between 1.6 and 2, and the interior fill has relative permittivity of 1.2 and is overlaid with zero mean Gaussian random perturbations with standard deviation of 0.03. The shape model is borrowed from asteroid 25143 Itokawa.

We assume 90 days of orbital acquisition, which provide enough coverage of the nucleus from all directions. The first tomography scale uses the range compressed wavelet depicted in Figure 3, which avoids cycle skipping for propagation along the longest dimension of the model. The tomography, depicted in the bottom panel of Figure 3, shows a low-resolution version of model with hints of the high-permittivity regions, but no structural detail. The second tomography scale starts with the model obtained at the first scale and uses the range compressed wavelet depicted in Figure 4. The inverted model captures most model features at nearly the resolution of the original model from Figure 2. Our technique enables even certain sub-wavelength features inside the cometesimals to be imaged accurately.

Conclusions: (1) Under the exploding reflector model assumptions, and with frequency hopping, the 3D interior structure of a comet nucleus can be inferred using realistic radar orbital sampling. (2) Interior nucleus imaging can be accomplished progressively as data are being acquired through successive orbits. (3) Exploiting the known exterior shape of the nucleus enables sub-wavelength tomographic resolution comparable with the resolution of bi-static radar systems

References: [1] A'Hearn M. F. et al. (1995) *Icarus, 118,* 223–270. [2] Asphaug E. (2010) *AAS/DPS* Abstract #49.32. [3] Claerbout J. (1985) *Blackwell*. [4] Nolet G. (2008) *Cambridge*. [5] Operto S. et al. (2004) *Geoph. Prosp. 52*, 625-651. [6] Safaeinili A et al. (2002) *Meteor. & Planet. Sci., 37*, 1953-1963. [7] Tarantola, A. (1997) *Elsevier*. [8] Weidenschiling S. (1997), *Icarus, 127*, 290-306.

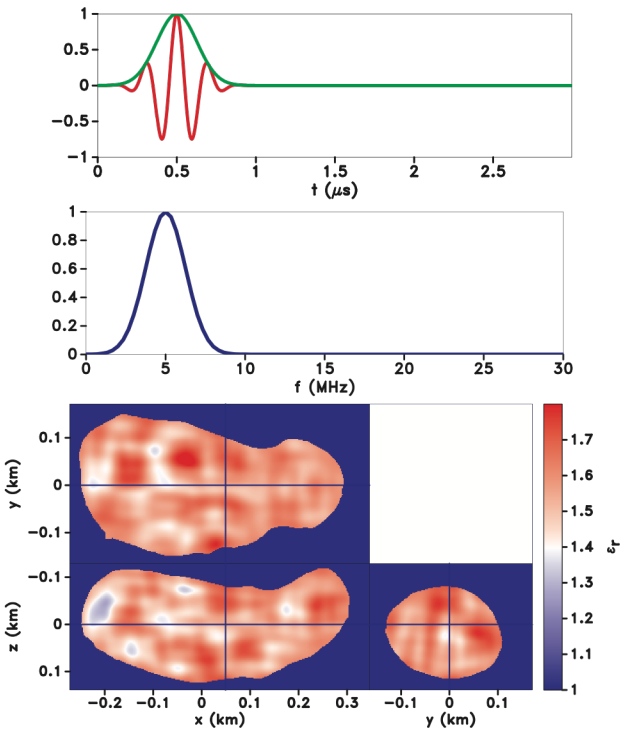

Figure 3: 5MHz tomography: compressed radar pulse wavelet & spectrum, and wavefield tomogram obtained from a homogeneous starting model.

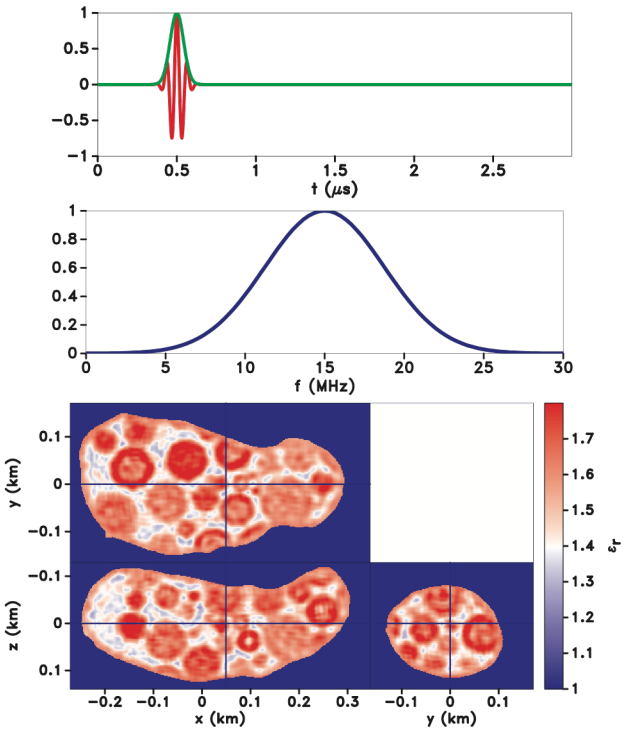

Figure 4: 15 MHz tomography: compressed radar pulse wavelet & spectrum, and wavefield tomogram obtained starting from the 5MHz final tomogram (Figure 3).