RADAR IMAGING THE INTERIORS OF SMALL BODIES: INITIAL MIGRATION STUDIES.

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Introduction. The origin and evolution of small bodies, particularly their collisional histories, may be elucidated by wavefield imaging of their interiors. Several mission and instrument concepts have been developed [e.g.,1] and the CONSERT radio-transmission experiment is flying on Rosetta [2]. However, there has been no systematic investigation of the capabilities of these methods to resolve interior structures. Here we report progress on a definition study using radar migration (imaging internal surfaces) and tomography (imaging internal volumes), in which we adapt the analytical methods of terrestrial exploration seismology. To date, we have found that the strong velocity contrasts likely between solid rock, regolith, and vacuum will require full migration tomography to properly image asteroid interiors. Furthermore, deployment of a subsatellite radar receiver will greatly improve imaging of both asteroids and comets.

Asteroid Model. We chose the shape of asteroid 433 Eros for the external geometry, but scaled it to just 1 x 0.3 x 0.3 km to simulate a near-earth asteroid (e.g., 1999 RQ36). We used a simple algorithm [3] to generate asteroid internal structures comprised of closely packed spheres of specified maximum overlap. We assumed that the asteroid is comprised of two materials, “rock” (0.11 m/ns) and “regolith” (0.22 m/ns). It is possible that asteroids are essentially rock and void. We chose an initial (largest) fragment radius of 100 m, 10% maximum fragment overlap, and 300 fragments. After a number of trials, we selected a model that was 50% rock in 3D and has a mean density 2 g/cm^3. Our initial 2D analyses use a central slice (**Fig. 1**). We imposed a small-scale scattering loss of 40 dB/km (1/e attenuation length ~200 m); actual values in fractured rocks could be higher [4].

Radar Geometry. We adopted 20 MHz for the radar center frequency, akin to SHARAD. We considered two mission geometries for imaging the model asteroid. In the first, a single spacecraft transmits and receives radar energy from a circular orbit at semimajor axis 2.5 km. This has an orbital period of 3 days. In 2D any further mapping is redundant, but a spinning 3D object would require many orbits to image. A co-located source and receiver is known in exploration seismology as “zero-offset.” A “multi-offset” variety of source-receiver separations is desirable to improve imaging quality. Therefore we considered a second option where receivers are available ±60° from the transmitter. A more realistic geometry presently under test explicitly models a subsatellite, perhaps comparable to those used by Apollo 15-16, at semimajor axis 1.9 km. With a 2-day period for the subsatellite, the two spacecraft move through 360° of relative offset in 6 days. This scenario will also be treated in the future for spin and 3D geometry.

Wavefield Imaging. Migration is the reconstruction of internal reflecting boundaries using wavefields. It requires prior knowledge of the velocity. Tomography uses travel times to reconstruct velocities, but smooths boundaries. This initial study uses migration only: tomography and joint migration tomography will be assessed later. We migrated simulated zero-offset data using the simple exploding-reflector model [5]. For simulated multi-offset data, cross-correlation of the source and received wavefields reveals the internal boundaries [5,6]. Conventional seismic codes modified for attenuative electromagnetic waves are used for all migrations shown here.

Results. Zero-offset imaging (**Figs. 2-3**) reconstructs much of the structure within the first attenuation skin depth. However, differences appear depending on the velocity assumed. If the rock velocity is chosen, only those interfaces in which the wave initially passed through rock are accurately resolved and positioned. The converse is true if the regolith velocity is chosen. Large electromagnetic-velocity contrasts may be a unique feature of asteroids compared to comets, much larger than acoustic contrasts in medical ultrasound or even in exploration seismology. Therefore we can anticipate using full migration tomography to accurately image asteroid interiors.

Multi-offset data using even a single transmitter yields a better migrated image on the part of the target facing the transmitter point (**Figs. 4-5**). When the transmitter is moved through 360° of longitude, the improvement is clear (**Fig. 6**). Interfaces near the center are evident, in spite of the attenuation.

Future work will include more realistic orbital geometries, 3D imaging, target rotation, seismic imaging of asteroids, and radar imaging of comets. This work was supported by NASA PIDDP.

References. [1] Asphaug E. et al. (2010) *LPSC XVI*, #2670. [2] Kofman, W. et al. (2007) *Space Sci. Rev., 128*, 413. [3] Tanga, P. et al. (1989) *Icarus, 141,* 65. [4] Grimm, R. et al. (2006) *JGR,* doi:10.1029/2005 JE002619. [5] Claerbout, J. (1985) *Imaging the Earth’s interior*, Blackwell. [6] Berkhout, A. (1982) *Imaging of acoustic energy by wave field extrapolation*, Elsevier.

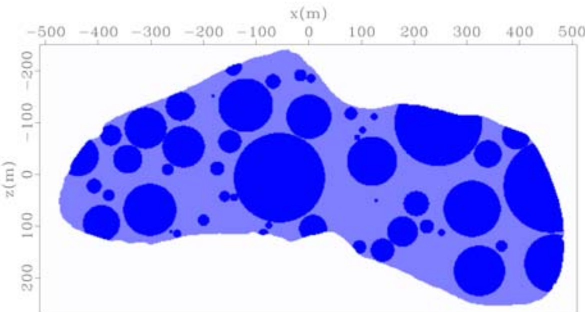

Figure 1. Asteroid model used to test imaging reconstruction. Dark = rock, light = regolith. This is a 2D slice of a 3D model.

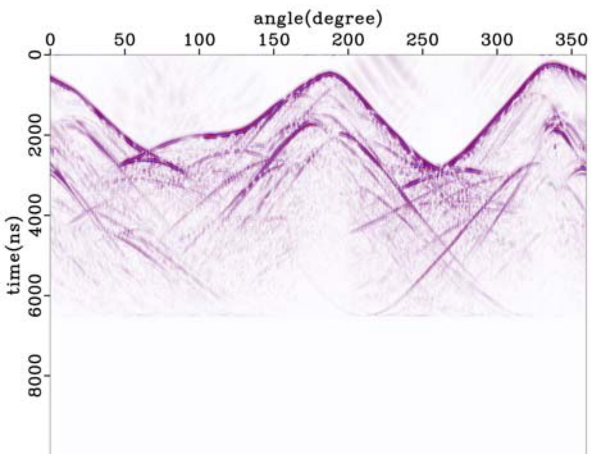

Figure 2. Radargram produced using co-located source and receiver ("zero offset" = single orbiting spacecraft).

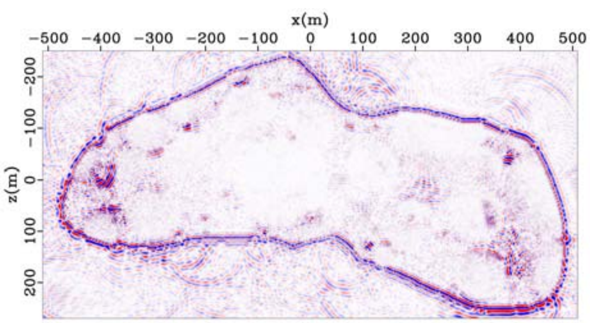

Figure 3. Image produced by migration of zero-offset data. Artifacts outside the asteroid can be neglected, but interior imaging is limited by geometry and attenuation.

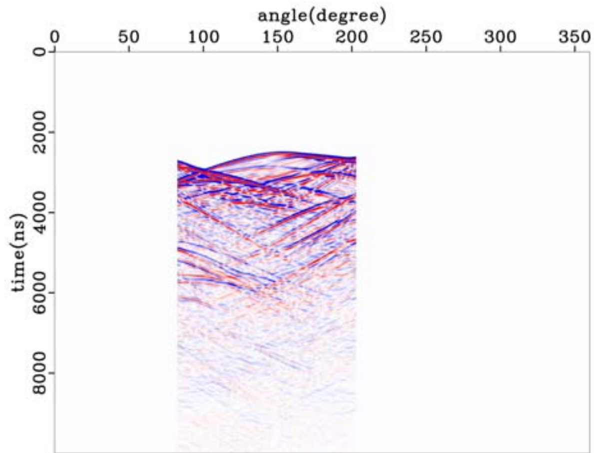

Figure 4. Radargram for one source at longitude 150° with "multi-offset" receivers distributed ±60°. In reality, a second subsatellite receiver would be at a different semimajor axis, and the varying orbital periods would produce a variety of offsets.

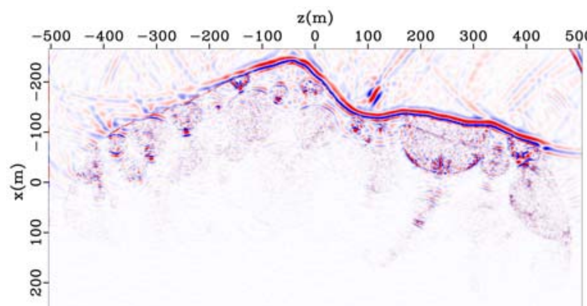

Figure 5. Image reconstruction by migration of data in Fig. 4.

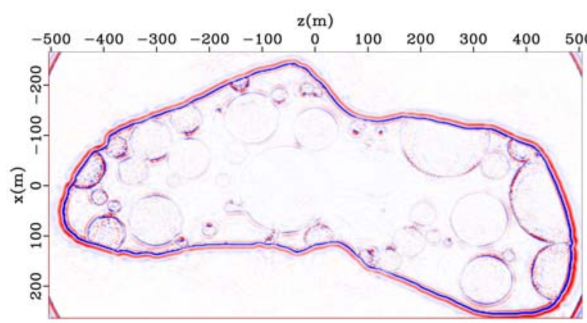

Figure 6. Image reconstruction by migration of multi-offset data with sources through 360° of longitude. Individual fragments are well-resolved, even to near the asteroid's center.