3D RADAR IMAGING OF COMET INTERIORS BY WAVEFIELD MIGRATION AND TOMOGRAPHY

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Introduction: Wavefield imaging comprises a body of techniques used in medicine, nondestructive testing, and seismic exploration to reconstruct the inaccessible interior structure of a target. *Migration* [1] is the reconstruction of 3D internal reflecting boundaries, and it requires prior knowledge of the velocity distribution. *Tomography* [2] uses separate receivers or reflections from the known exterior contour of the imaged object to evaluate the 3D propagation velocity. Joint (iterative) migration and tomography are required for accurate radar imaging inside objects with strong velocity heterogeneity likely present in asteroids [3,4], but migration assuming uniform or smooth velocity has proven sufficient for the martian polar caps [5]. Here we explore application of wavefield imaging methods to radar sounding of comets, using a realistic acquisition geometry, the actual shape of 67P/Churyumov-Gerasimenko [6], and an assumed internal structure. We compute *point spread functions*, analogous to optical imaging, for migration and tomography in order to characterize their resolution under realistic acquisition assumptions. Because large quantities of data are treated simultaneously by these methods, we find that 3D migration resolution at 15 MHz of a few tens of meters and 3D tomography resolution at 5 MHz on the order of 100m can be achieved. This analysis shows that 3D wavefield imaging can be applied directly to large comets, e.g. Tempel 2 [7].

Resolution analysis: Both migration and tomography can be described as linear processes: **Lm**=**d**. We can associate with any linear operator **L** a resolution measure through the so-called resolution matrix consisting of point spread functions estimated for any point in the model. For example, **L** can be the wavefield modeling operator (**m** represents the migrated image and **d** represents the observed radargrams), or the wavefield tomography operator (**m** represents a velocity model perturbation, and **d** represents the observed wavefield perturbations.

The point spread functions of both problems depends on all elements comprising the *imaging system*: (1) the source wavelet defined by predefined peak frequency and bandwidth; (2) the comet exterior shape obtained using observations using the navigation cameras, (3) the image point location inside the comet; (4) the velocity inside the comet; (5) the acquisition geometry. All factors are important in characterizing the point spread function of the imaging system; some factors are given (e.g. the wavelength and the acquisition geometry), others can be known through observations during the mission (i.e. the exterior shape), but others are unknown (i.e. the velocity) and remain to be determined through tomography.

Here we seek to evaluate the PSFs for an object with the complexity of comet 67P/CG (Fig 1), and a plausible polar acquisition geometry [8] (Fig 2). The acquisition tracks are represented in a coordinate system fixed relative to the comet, and take into consideration both the orbiter and the comet movement.

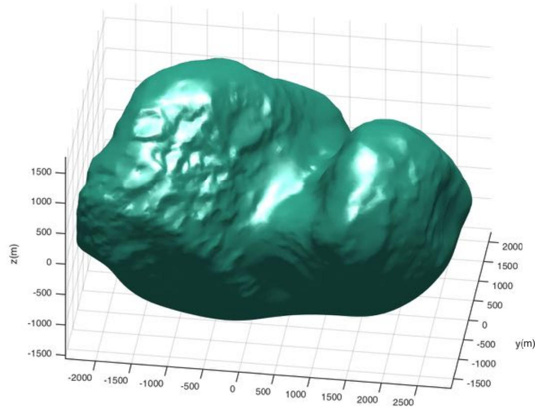

Figure 1: Shape model of comet 67P/CG.

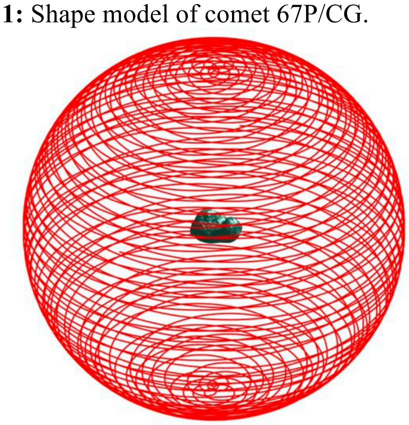

Figure 2: Orbital coverage in comet-fixed coordinates after 90 days of continuous radar sounding. The orbiter moves on a sphere of 20km radius.

Figures 3 and 4 show the ideal PSFs at a representative location inside the comet for wavefield migration (15 MHz with 10 MHz bandwidth) and tomography (5 MHz with 1 MHz bandwidth), respectively. These PSFs assume perfect (dense, uniform) coverage surrounding the comet. In contrast, Figures 5 and 6 show

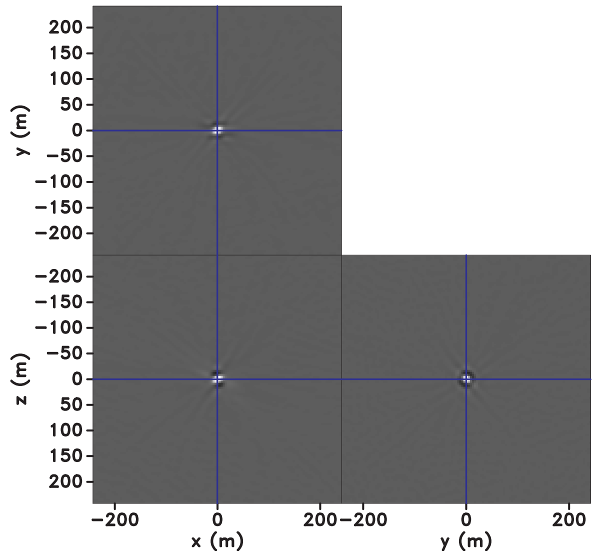

Figure 3: *Migration PSF* for ideal (dense, uniform) radar acquisition at 15 MHz peak frequency.

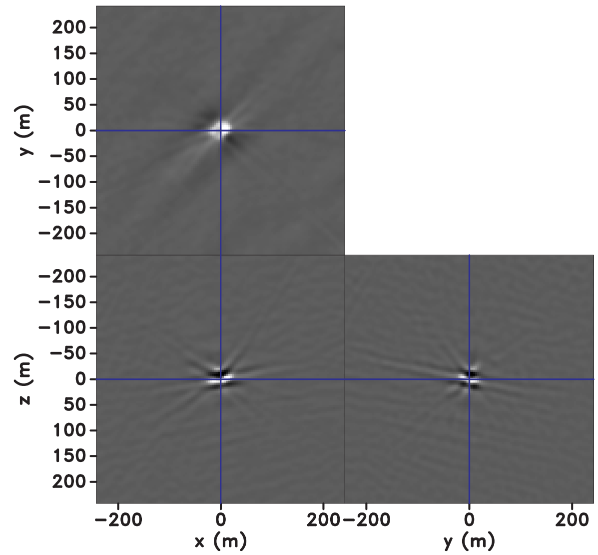

Figure 5: *Migration PSF* for the realistic radar acquisition geometry shown in Figure 2.

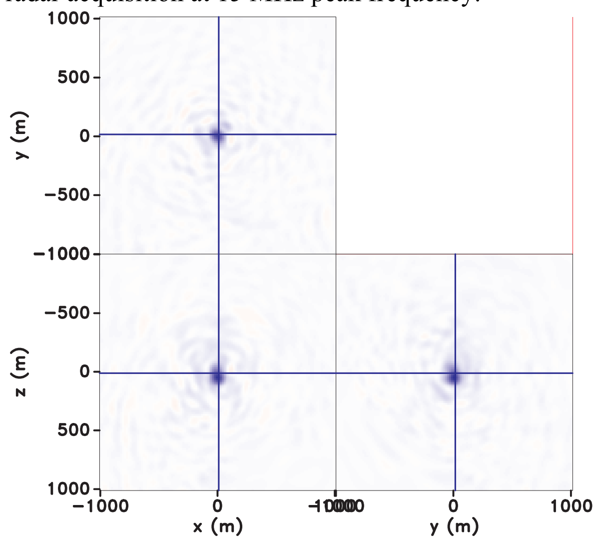

Figure 4: *Tomography PSF* for ideal (dense, uniform) radar acquisition at 5 MHz peak frequency.

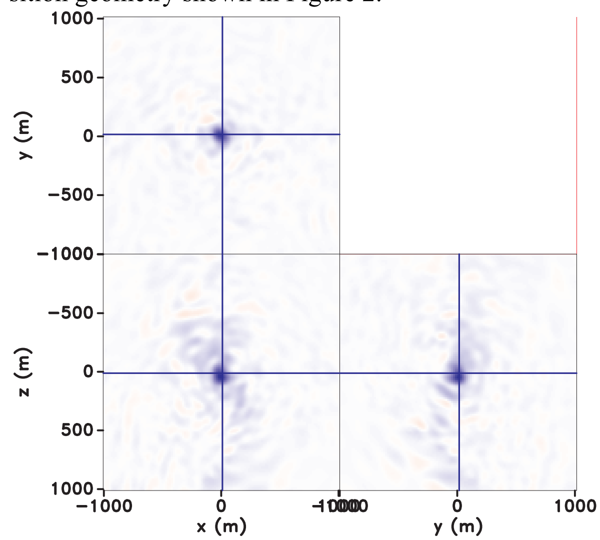

Figure 6: *Tomography PSF* for the realistic radar acquisition geometry shown in Figure 2.

the PSFs for the realistic acquisition geometry depicted in Fig 2. Both migration and tomography need to be done in 3D to account for the illumination complexity of an object like 67P/CG. Moreover, the irregular track coverage depicted in Fig. 2 provides sufficient sampling of the wavefield to produce PSFs comparable with what can be achieved using ideal coverage around the comet.

Migration and tomography are methods developed primarily for seismic imaging. The seismic-radar analogy does have one operational difference, in that spacecraft radar data are commonly undersampled to remove the carrier (e.g., 15 MHz) but preserve the signal bandwidth (e.g., 10 MHz), thus reducing the transmitted data volume. The returned data are therefore an envelope of the original full waveform. Nonetheless, the Shannon-Nyquist theorem assures that the full waveform can be reconstructed.

References. [1] Claerbout, J. (1985) *Imaging the Earth's interior,* Blackwell. [2] Tarantola, A. (1987), *Inverse Problem Theory: methods for data fitting and model parameter estimation*, Elsevier. [3] Sava et al. (2014) *ASR*, doi: 10.1016/j.asr.2014.10.021. [4] Grimm et al. (2015) *ASR*, in press. [5] Putzig N. et al. (2014) LPSC VL, #2624. [6] sci.esa.int/rosetta/ 54728-shape-model-of-comet-67p. [7] Asphaug et al. (2014), *DPS* 46, #209.07. [8] Kofman and Safaeinili (2004), *Mitigation of hazardous comets and asteroids*, Cambridge.