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

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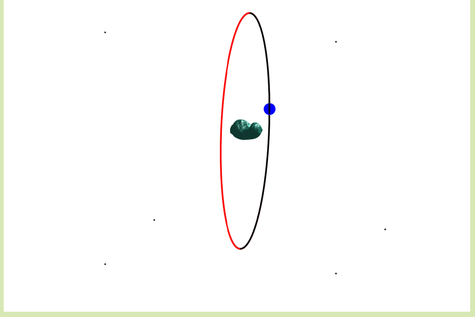
Summary

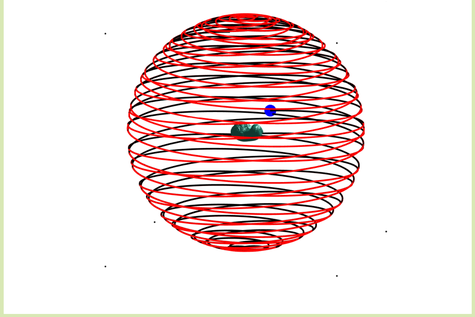
Wavefield imaging comprises a body of techniques used in medicine, nondestructive testing, and seismic exploration to reconstruct the inaccessible interior structure of a target. *Migration* [1] is the reconstruction of 3D internal reflecting boundaries, and it requires prior knowledge of the velocity 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. that 3D wavefield imaging can be applied directly to large comets, e.g. Tempel 2 [7]. 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.

Acquisition

Orbiter trajectory in **space coordinates**

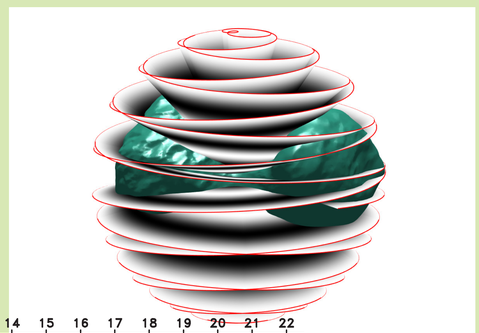


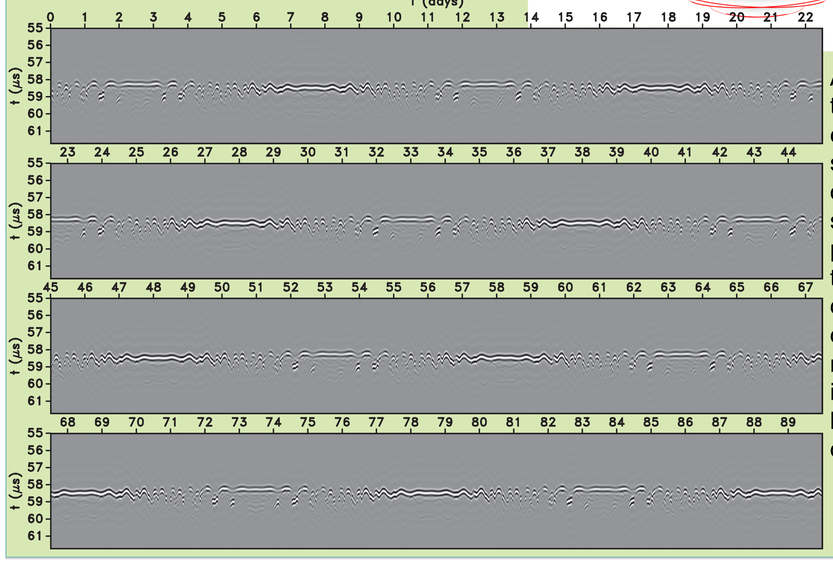
Orbiter trajectory in **comet coordinates**



Track-based processing (equivalent to 2D imaging) cannot account for the complexity of the "helical" trajectories around an object with the geometrical complexity similar to that of 67P/CG.

2D processing incorrectly assumes that all reflections occur in the track plane, and thus it cannot locate all reflected energy at a single point in 3D space.

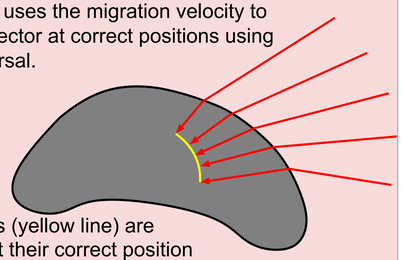




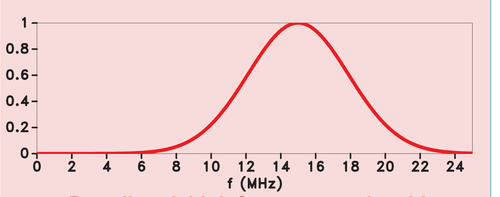
All the data in this simulation correspond to a single point diffractor in the subsurface; 2D processing treat all these data as a distributed reflector, instead of a localized point diffractor.

Migration

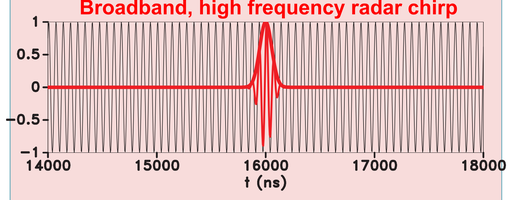
Migration (surface imaging): identify reflectors /interfaces in the comet interior. It uses the migration velocity to place reflector at correct positions using time reversal.

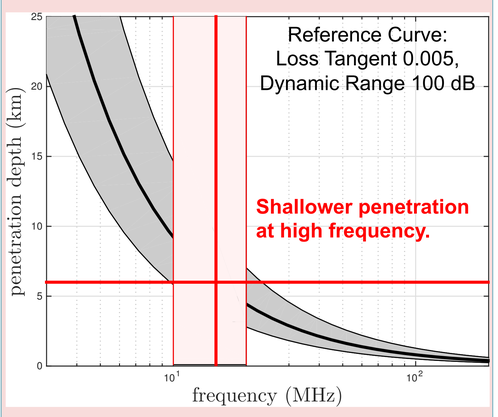


Reflectors (yellow line) are imaged at their correct position by time reversal in known velocity.



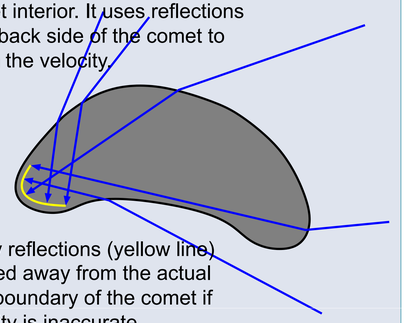
Broadband, high frequency radar chirp



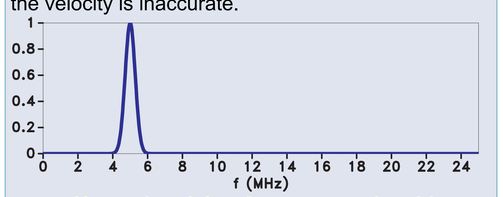


Tomography

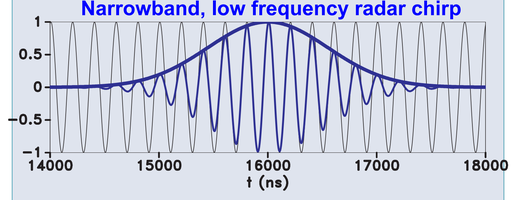
Tomography (volume imaging): characterizes propagation velocity in the comet interior. It uses reflections from the back side of the comet to constrain the velocity.

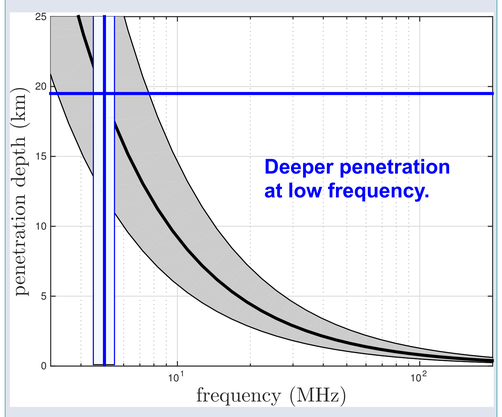


Boundary reflections (yellow line) are imaged away from the actual (known) boundary of the comet if the velocity is inaccurate.



Narrowband, low frequency radar chirp

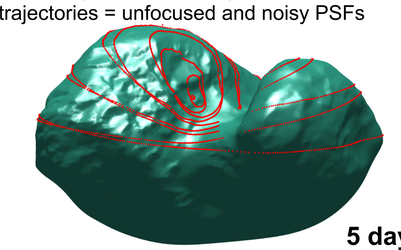




Resolution

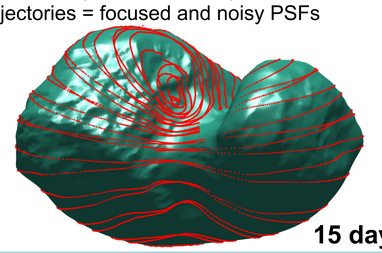
- Both migration and tomography can be described as linear processes: **Lm=d**
- We can associate with any linear operator **L** a resolution measure through the so-called resolution matrix consisting of **point spread functions** estimated for any point in the model.
  1. **L** can be the **wavefield modeling** operator (**m** represents the migrated image and **d** represents the observed radargrams),
  2. **L** can be 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.
- Our goal is to evaluate the PSFs for an object with the complexity of comet 67P/CG, and a plausible polar acquisition geometry [8]. 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.

Short acquisition time = sparse and uneven trajectories = unfocused and noisy PSFs



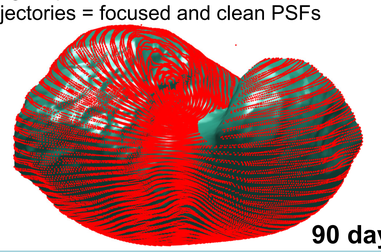
5 days

Medium acquisition time = sparse but even trajectories = focused and noisy PSFs

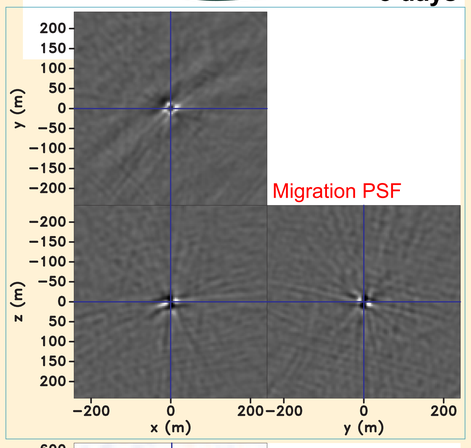


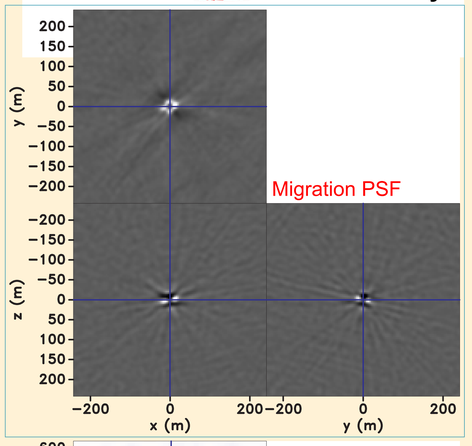
15 days

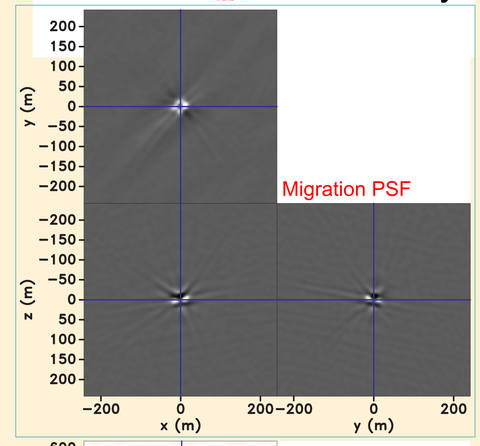
Long acquisition time = dense but even trajectories = focused and clean PSFs

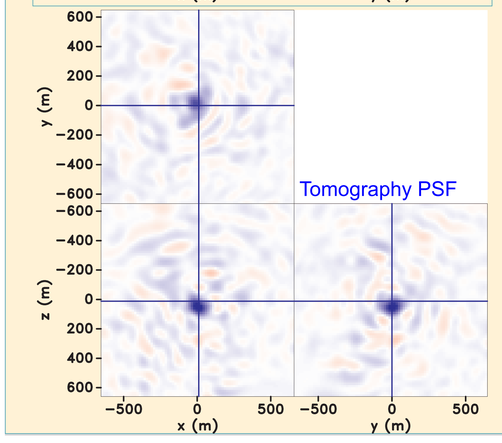


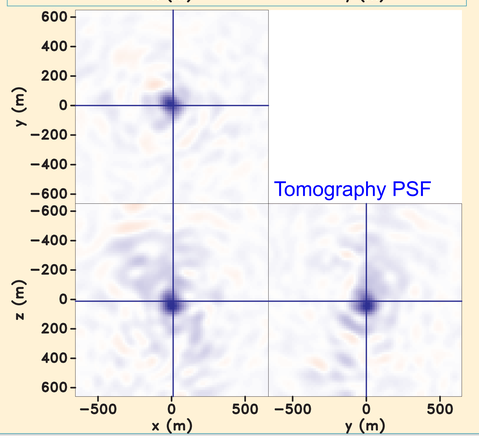
90 days

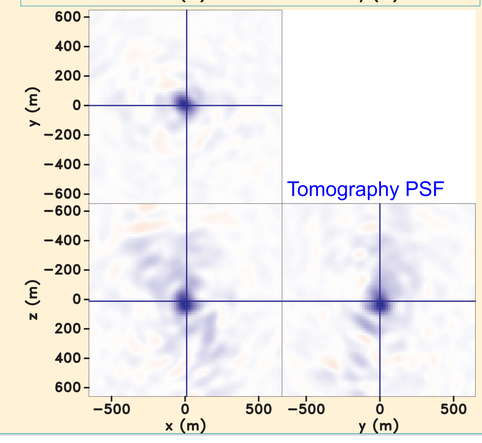












References

[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), *Radio Reflection Imaging of Asteroid and Comet Interiors I: Acquisition and Imaging Theory*, ASR.
[4] Grimm et al. (2015), *Radio Reflection Imaging of Asteroid and Comet Interiors II: Results and Recommendations*, ASR.
[5] Putzig N. et al. (2014), New views of Planum Boreum in a 3-D volume of Sharad data, LPSC VL, #2624.
[6] sci.esa.int/rosetta/ 54728-shape-model-of-comet-67p.
[7] Asphaug et al. (2014), *The Comet Radar Explorer Mission*, *DPS* 46, #209.07.
[8] Kofman and Safaeinili (2004), *Mitigation of hazardous comets and asteroids*, Cambridge.