Comet/Asteroid Radio Reflection Tomography (RRT)

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Proposed as an instrument on "The Deep Interior Mission"† to the NASA Office of Space Science Discovery Program

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Deep Interior Mission

Science Significance:

Information about the interior of asteroids and comets gives clues about the early stages of the solar system and how these objects evolved.

Social Significance:

-A key component in the long term risk mitigation strategy of asteroid impacts.
-Potential for mining (e.g. valuable minerals, water, etc)

Instruments on The Deep Interior

- Radio ReflectionTomography instrument
  - Multi-frequency radar
  - Provides 3-D volumetric imaging capability
- Multi-spectral Wide Field Camera Imaging system
  - Provides stereo imaging capability for surface topographic imaging
  - Image sequence (movie) capability to capture dynamic events
  - Exterior shape information through ground data processing
- Active science
  - Disturbing the surface of the object through grenade deployment

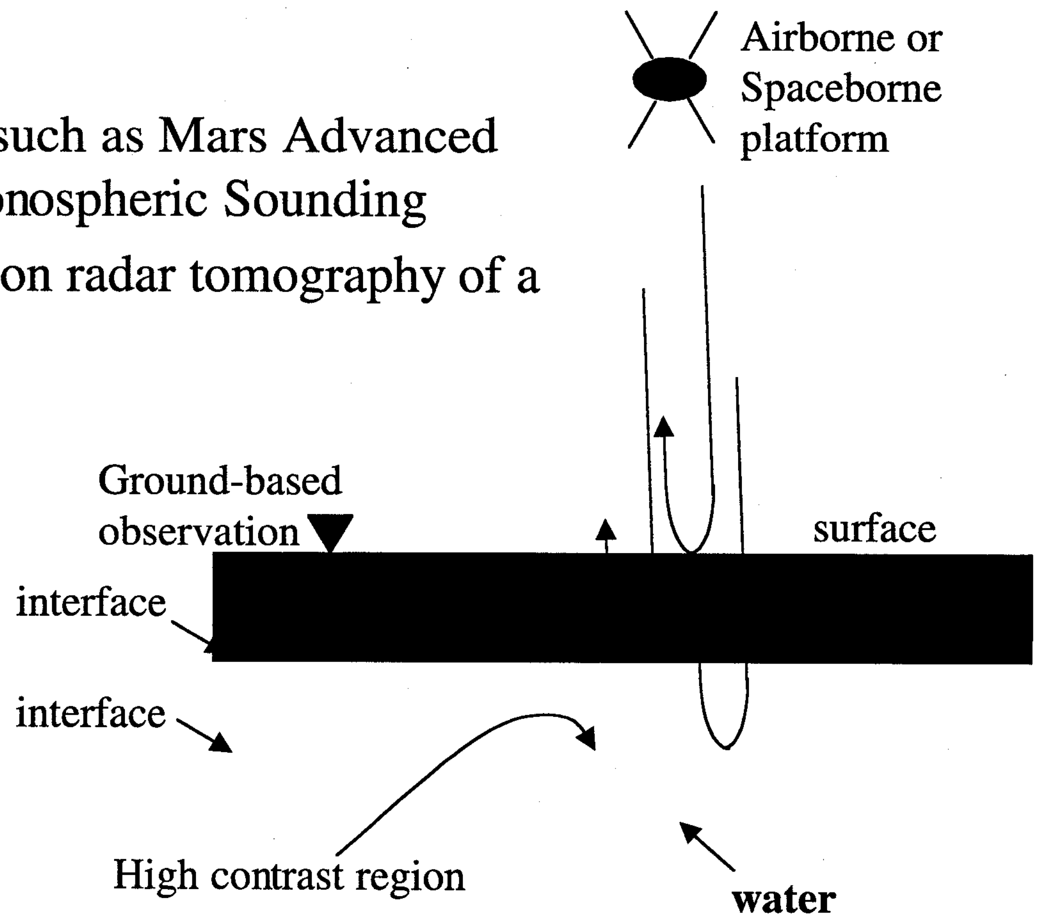
There is significant operational synergy among the instruments. The RRT will rely on the imaging system for spacecraft positioning in the body-fixed coordinate system and determination of the external shape of the object. Radar will in turn assist in ranging and timing determination related to explosive deployment

Why Radio Reflection Tomography?

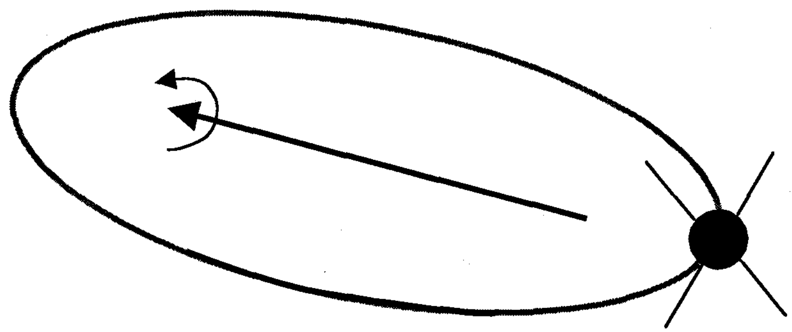
- Radio waves in the HF/VHF range are well suited for the study of the interior of comets and asteroids.
- HF/VHF radio waves have been used extensively in radar sounding of ice and ground penetrating radar applications.
- The relatively small dimension of asteroids and comets provides the opportunity to use radio waves to image the interior of the object through coherent and/or incoherent tomographic techniques.
- The volumetric image would show the dielectric distribution and/or discontinuities inside the object which would correspond to different materials and/or presence of cracks or voids.

Radar Sounding Heritage

- Ground-based radar sounders used in mining and inspection industry.
- Airborne ice-sounding
- Spaceborne radar sounders such as Mars Advanced Radar for Subsurface and Ionospheric Sounding
- CONSERT: First transmission radar tomography of a comet



Radio Reflection Tomography

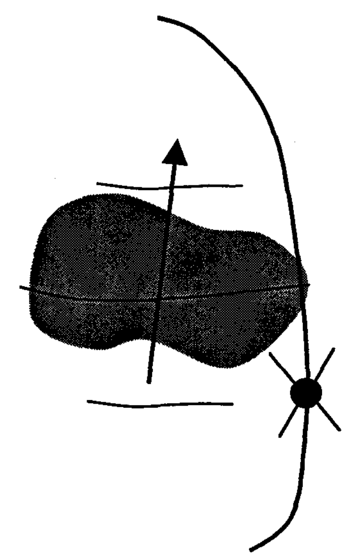


Technical Issues

- Data collection
  - In order to obtain a high quality image of the interior of the object it is necessary to view the object from all possible directions.
  - Finite bandwidth radio echoes collected on a surface around the object provide a 3-D data sets which can result in the 3-D volumetric image of the dielectric contrast inside the object

Ground Tracks on the Asteroid Due to Asteroid/Orbiter Rotation

Object period = 4 hrs
Orbiter period = 64 hrs



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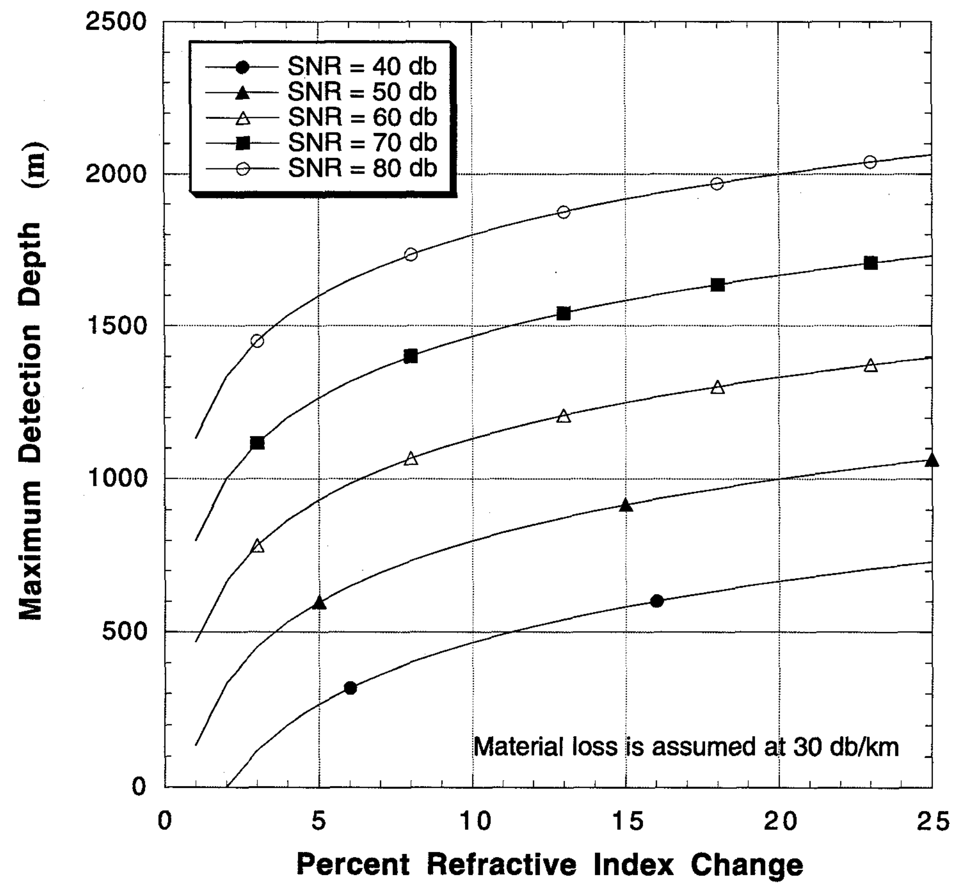
- Signal strength
  - Adequate transmission power
  - Target material property/attenuation
  - Dielectric contrast within the object

Maximum Depth of Detection vs. Refractive Index Contrast

This figure shows the maximum depth at which an interface of given contrast can be detection. This depth is shown for a family of curves corresponding to different signal SNR conditions. The signal SNR corresponds to the surface signal SNR.



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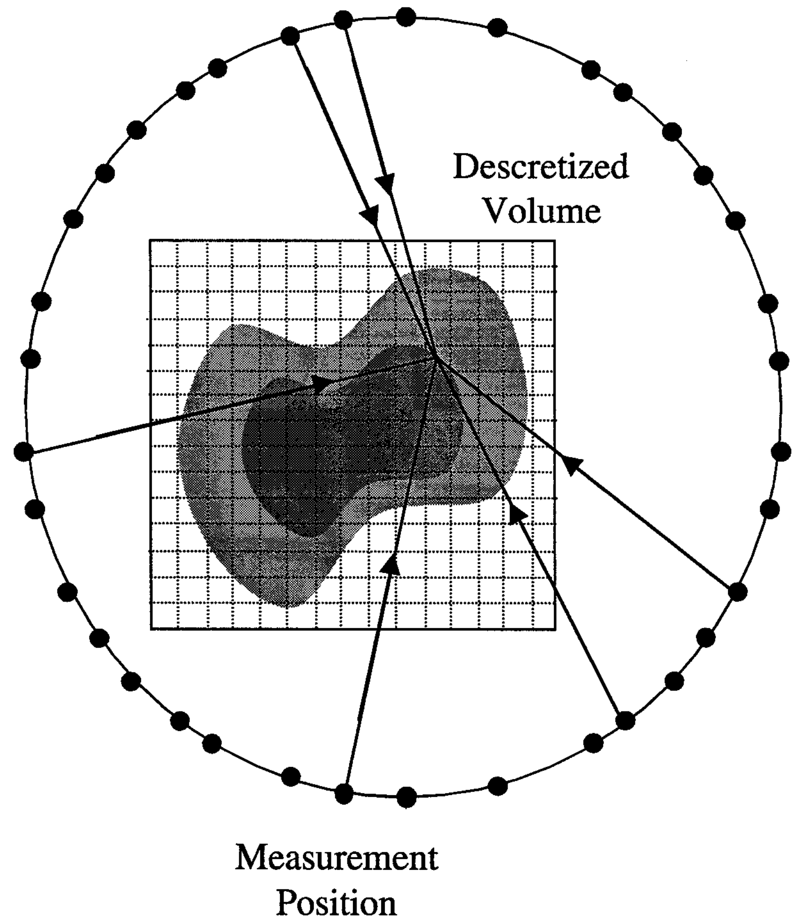
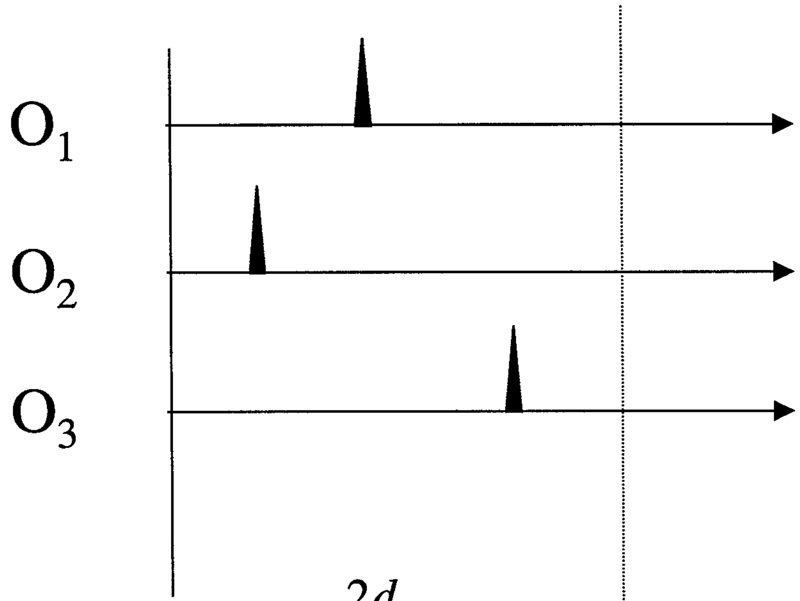
Tomographic Inversion

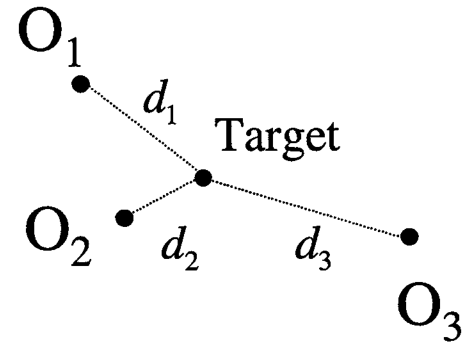
The inversion will use the back-propagation technique to reconstruct the interior of the object. This approach leverages the knowledge of the object's exterior shape which is derived, independently, using a stereo optical approach. The volumetric imaging will be carried out on the ground.



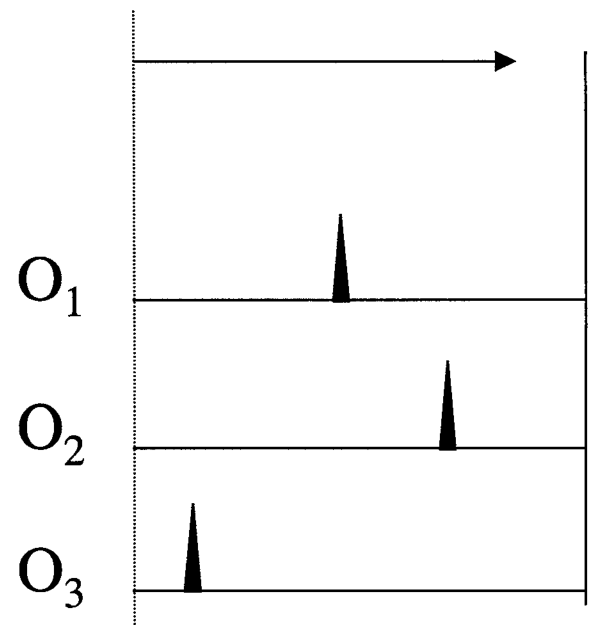
Reflection Tomography Inversion Principle



$$t_i = \frac{2d_i}{c} \quad \text{or} \quad t_i = \frac{d_i}{(c/2)}$$

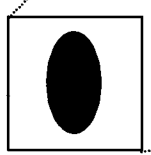


Reverse the time and back-propagate at half the speed of light! This is the basic idea, but in the actual case, the final solution is obtain through an iterative inversion process where object dielectric property is changed until the best match with radio reflection data is obtained. The inversion includes the calculation of forward radio wave interaction with the asteroid calculated based on the available numerical techniques.



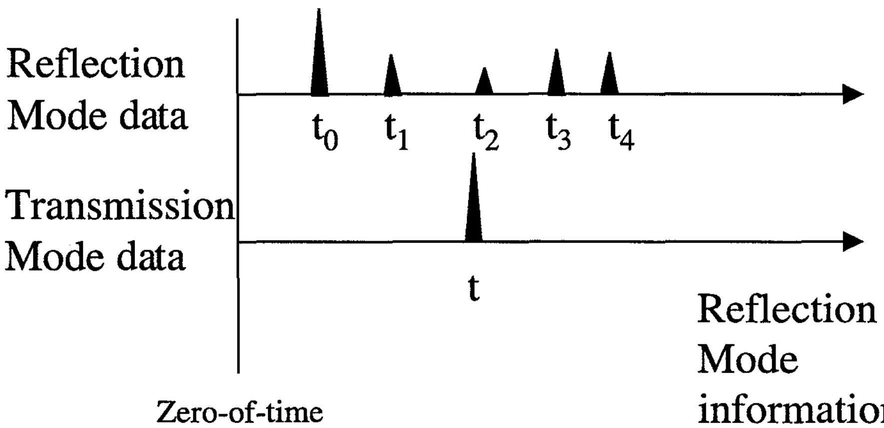
2-D Tomographic Inversion Demonstration

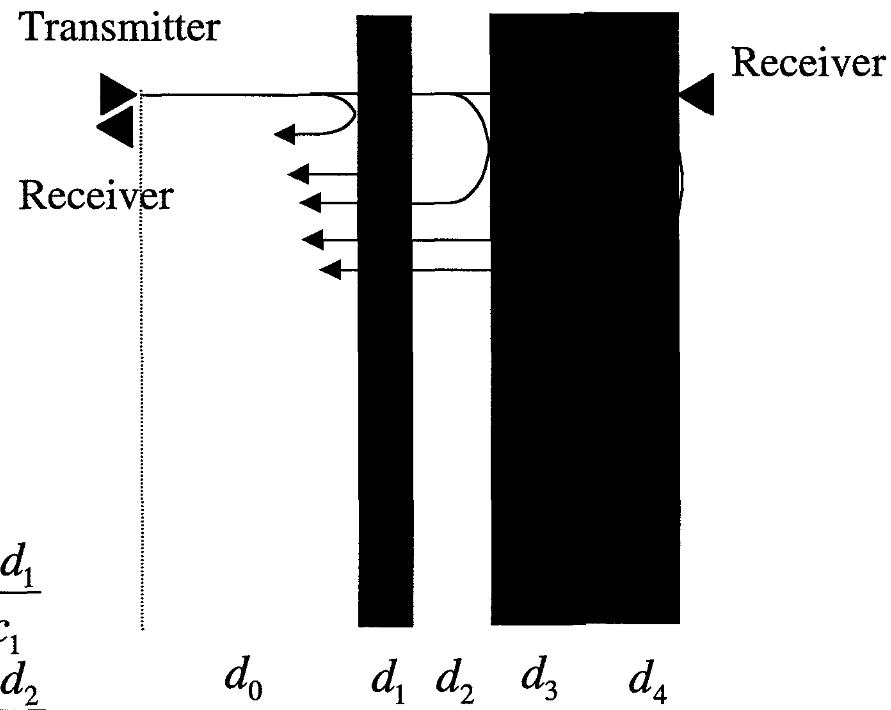
The radar data is acquired at 360 points on a 180 degree arc at a 10 km orbit. The radar frequency is 5 MHz with a 1 MHz bandwidth. This example assumes the knowledge of object's dielectric constant and does not include any material attenuation or ray-bending due to refractive index change.



The tomographic reconstruction is achieved by back-propagating the radar signal onto a 5 km by 5 km area with a 25 m pixel resolution. This demonstrates the principle of reflection tomography inversion. In a 3-D inversion, the radar signal from measurements on a surface around the object are back-propagated to form the volumetric image of the discontinuities within the object.

Reflection *vs.* Transmission





The transmission and reflection radio tomography provide different but complementary type of information about the object as simply demonstrated in the schematics.

Reflection Mode information

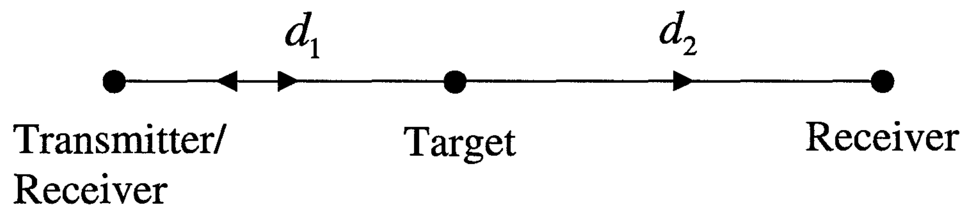
$$\begin{cases} t_0 = \dfrac{2d_0}{c_0} \\ t_1 = t_0 + \dfrac{2d_1}{c_1} \\ t_2 = t_1 + \dfrac{2d_2}{c_2} \\ t_3 = t_2 + \dfrac{2d_3}{c_3} \\ t_4 = t_3 + \dfrac{2d_4}{c_4} \end{cases}$$

Transmission mode information

$$t = \frac{d_0}{c} + \frac{d_1}{c} + \frac{d_2}{c} + \frac{d_3}{c} + \frac{d_4}{c}$$

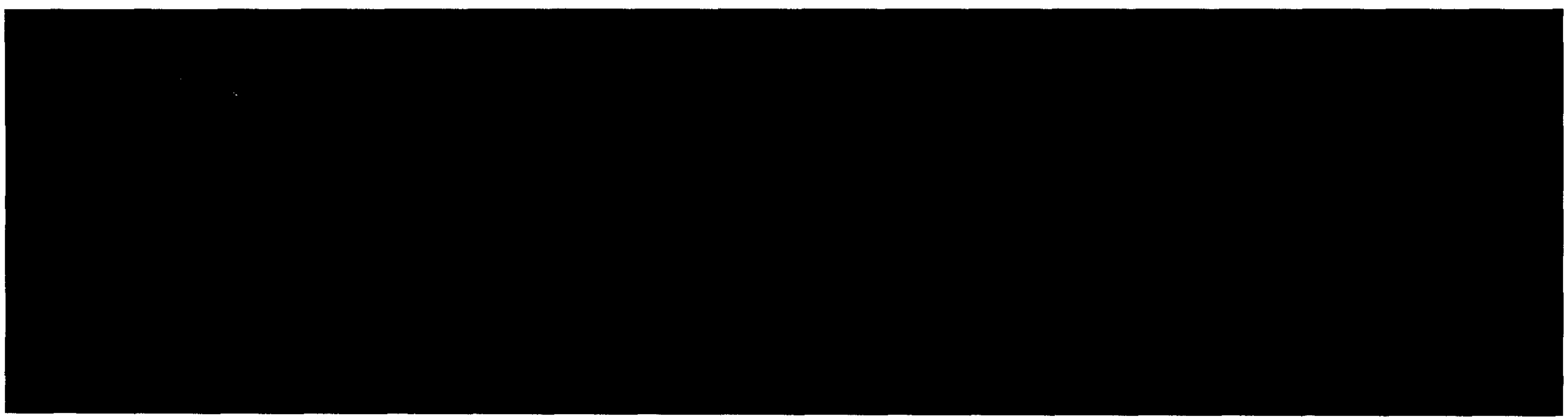
The Issue of The Resolution

For a fixed bandwidth system, the reflection tomography offers much better resolution. This can be demonstrated by the following example:



Transmission measurement: $t = \frac{d_1 + d_2}{c}$

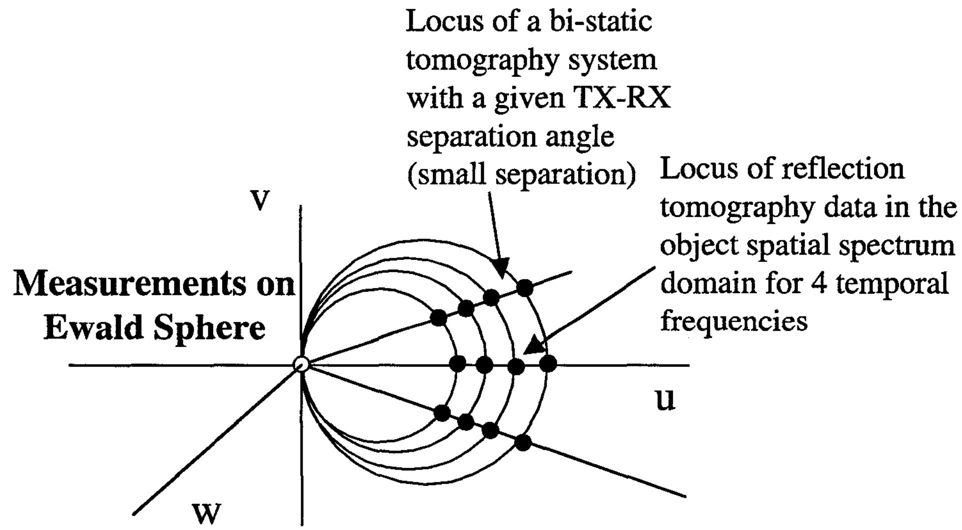
Reflection measurement: $t = \frac{2d_1}{c}$

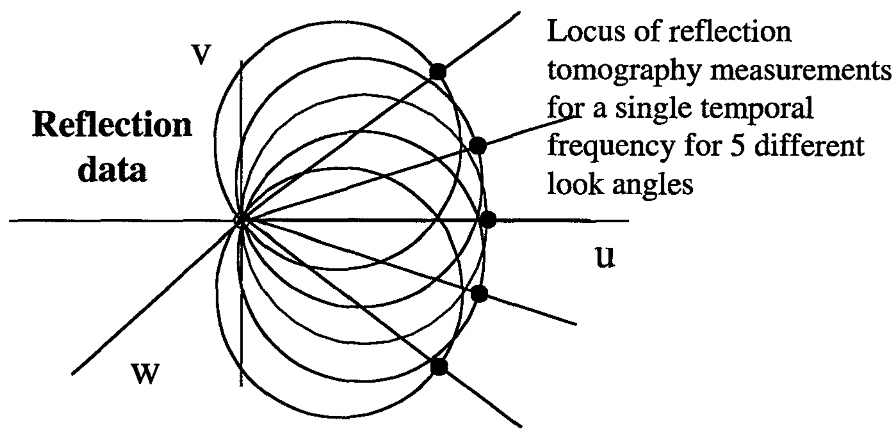


Reflection/Transmission Tomography

The reflection/transmission tomography data provide information about the object on the *Ewald Sphere.* In order to achieve a complete reconstruction of the object, a 3-D sample of the object in its spatial spectral domain (u,v,w) is required. For example, such a coverage can be obtained by acquiring radio data in the reflection mode with wide-band radio system and viewing the object from all possible angles. In practice such a complete coverage is not possible due to limited temporal bandwidth and limited angular access to the object. However, even with an incomplete coverage, internal structure of the object can be imaged.

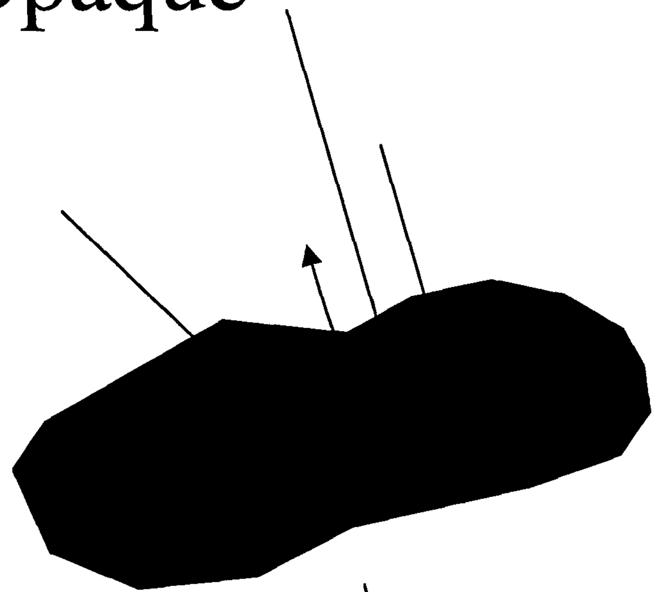
Using a system with finite temporal bandwidth, it is desirable to have both the reflection and transmission data. This will provide a complete spatial spectral coverage even in the presence of finite temporal bandwidth.





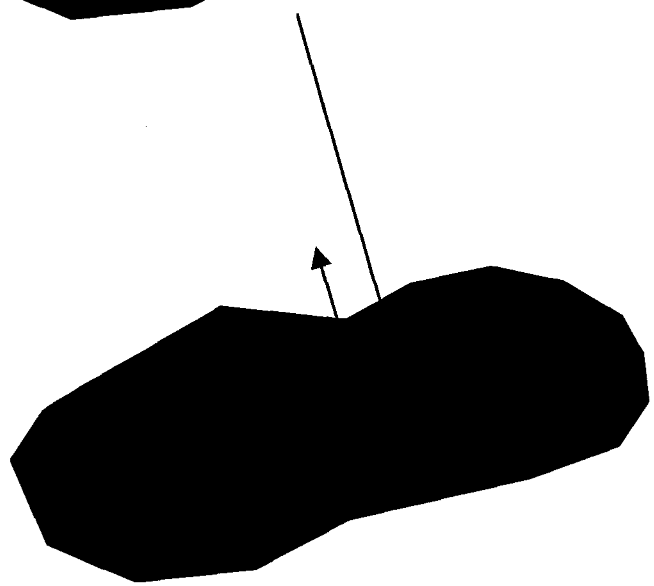
Transparent *vs.* Opaque

The case of the transparent object:



Reflection signal can be observed from front-surface internal layering and the back-surface. **Transmission** signal is also available.

The case of the opaque object:



Reflection signal can be observed from the front-surface internal layering but NOT the back-surface. **Transmission** signal may NOT be available which would mean no signal at all for analysis.