National Aeronautics and Space Administration

FY24 R&TD Innovative Spontaneous Concepts (ISC)

Mapping the Planetary Boundary Layer by Use of Synthetic Aperture Radar

Principal Investigator: George Hajj (335); **Co-Investigators:** Chi Ao (335)

Objectives: Our goal is to improve the spatial and temporal characterization of temperature and water vapor within the lower troposphere, particularly in the Planetary Boundary Layer (PBL). We present a novel method for generating 3D temperature and water vapor maps in the PBL using bi-static Interferometric SAR (InSAR) principles. Fig. 1a illustrates the InSAR concept, referred to below as Cross-Track Imaging (CTI). In CTI, a satellite in low Earth orbit (LEO-1) transmits two signals (~20 and 22 GHz) in the cross-track direction toward the Earth's limb. These signals are received by two antennas on LEO-2, flying roughly parallel to LEO-1 but on the opposite side of the Earth's limb. With sufficiently accurate prior knowledge of surface height, range and phase measurements can be converted into integrated atmospheric delays, while differences in the received power of the two signals yield integrated water vapor density. Tomographic inversion of path-integrated observations can be applied to generate a 3D map of temperature and water vapor in the vicinity of plane between the two orbits. Fig. 1b depicts a similar concept, but the signals are transmitted and received in the satellites' along-track directions. We refer to this geometry as Along-Track Imaging (ATI).

Background: The PBL interacts directly with the Earth's surface, influencing temperature, moisture, and pollutant dispersion. Sensing the PBL is crucial for improving weather and air quality forecasts. Due to its shallowness (~2 km), conventional remote sensing instruments like microwave and infrared sounders lack the vertical resolution needed to characterize the PBL. Other methods under investigation include hyperspectral infrared and microwave sensors, differential absorption lidar (DIAL), differential absorption radar (DAR), and crosslink radio occultation (XO). While each has specific strengths and limitations, the novel approaches discussed here provide all-weather, global solutions with high horizontal and vertical spatial resolution.

Approach and Results: Delay and Doppler measurements of the reflected signals are used to determine the point of reflection for each raypath. The differential phase delay between the two antennas on LEO2 is used to measure the integrated total atmospheric delay along the ray paths (assuming the surface height is known). Differential absorption between the 20 and 22 GHz signals is used to measure the integrated water vapor delay along the ray paths. These measurements are inverted by use of tomography to obtain 3D images of temperature and water vapor profiles in the PBL in a swath on both sides of the plane connecting LEO1 and LEO2.

The measurements are taken from bi-static low-elevation angles (low θ_1 and θ_2 in Fig. 3). These low angles increase sensitivity to atmospheric delays while reducing sensitivity to surface height uncertainties. To understand the impact of the field of view on tomographic reconstruction, consider the geometry in Fig. 3 and the analysis in Fig. 4. For a 10° antenna beamwidth (Fig. 3a), the surface area observed spans an alpha$_1$ range of 7.25-12.75° (~600 km on the surface), with theta$_1$ and theta$_2$ values of 9.5-23° (Fig. 3b). A wider 20° beamwidth (Fig. 3c) expands the alpha1 range to 4.75-15.25° (~1000 km on the surface), with theta$_1$ and theta$_2$ ranging from 6-35° (Fig. 3d). This broader range of intersecting angles improves tomographic reconstruction.

Significance/Benefits to JPL and NASA: Sensing the PBL is a top priority for NASA's Earth Science Division (ESD) over the next decade. Achieving global PBL measurements with the resolution necessary to meet pressing scientific and societal demands, however, presents a formidable technological challenge. To address this, NASA has committed significant resources, including the establishment of the Decadal Survey Incubation (DSI) program, to explore innovative methods capable of meeting the stringent PBL measurement requirements outlined in the 2017-2027 Decadal Survey. The research conducted in the coming years will be crucial in shaping future NASA's PBL mission. The work presented here represents a critical first step toward evaluating the feasibility of a novel approach—one fundamentally different from existing methods such as DIAL, DAR, and XO outlined above. This new technique has the potential to extend the proven utility of InSAR technology by generating detailed 3D maps of the PBL. By investing in the research and development of this technique, JPL positions itself to lead and compete for the next generation of Earth science missions.

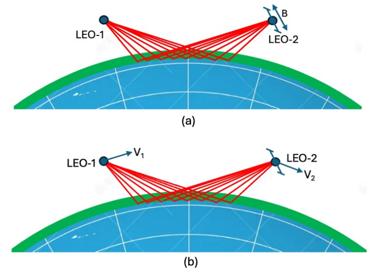
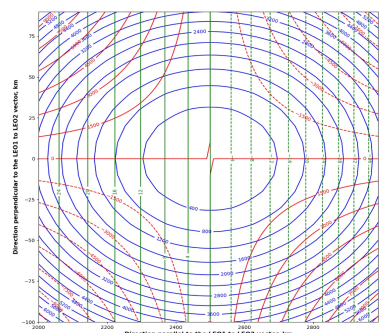
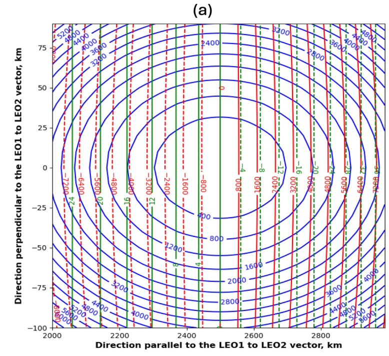


Fig. 1: (a) A pictorial of the Cross-Track Imaging (CTI) InSAR concept showing two satellites flying in parallel (i.e., velocity perpendicular to the page). LEO-1 transmit two signals (~20 and 22 GHz) in the cross track direction while LEO-2 receives the signal from two antennas separated by a baseline B. (b) A pictorial of the Aross-Track Imaging (ATI) where the transmitted/received signals are in the same orbital plane (i.e., velocity parallel to the page).



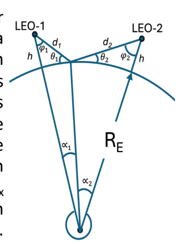
(a)



(b)

Fig. 2: (a) Contours of equi-range (blue), equi-Doppler (red), and equi-phase (green) for the geometry in Fig. 1a. Units are meters, meters/second, and cycles, respectively. A flat reflecting surface is assumed. LEO-1 is at (0, 0, 410 km), while LEO-2 is at (5000 km, 0, 410 km), with the first and second coordinates along horizontal and vertical axes. (b) Similar to (a) but for the geometry in Fig. 1b.

Fig. 3: Defining angles for the geometry of Fig 1a and 1b for a reflection point on the Earth's surface. The two satellites are at altitude *h*. The distances from the satellites to any reflection point are d_1 and d_2. α_{max} is chosen such that when θ_1=90 (i.e., α_1=0), θ_2=0. For *h*=500km, α_{max} = 22°.



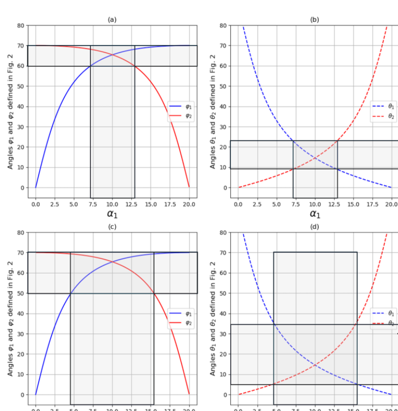


Fig. 4: Variation of angles defined in Fig. 3 as a function of α_1 for LEO satellites at a 410 km altitude. These figures allow for an analysis of the transmit and receive antenna beamwidth's impact on the tomographic reconstructions as explained in the report.

National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

www.nasa.gov

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PI/Task Mgr. Contact Information: George Hajj
George.a.hajj@jpl.nasa.gov