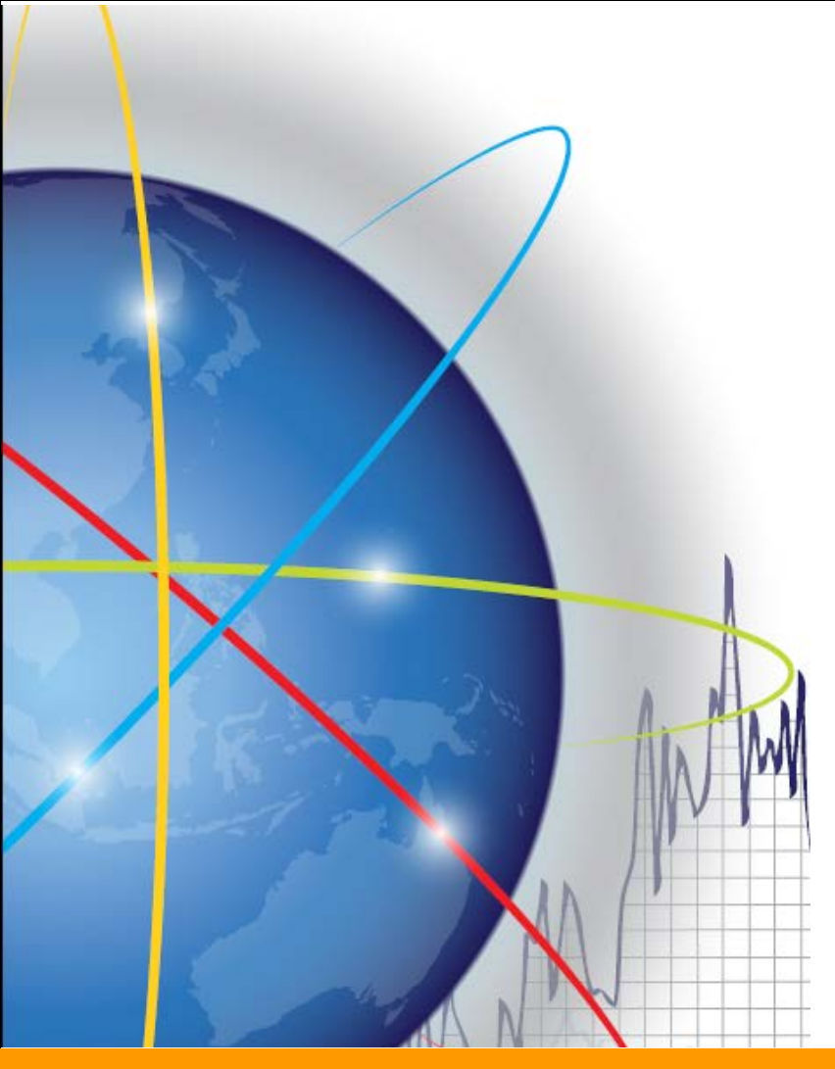

3-D ray tracing of GPS radio occultation paths

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Introduction and Background

GPS Radio Occultation (RO) is an emerging and robust, space-based, Earth observation technique with the potential for atmospheric profiling and meteorological applications. GPS RO uses GPS receivers onboard Low Earth Orbit (LEO) satellites to measure the radio signals transmitted from GPS satellites. The technique enables the atmospheric profiles of parameters such as temperature, pressure and water vapour to be obtained via atmospheric retrieval processes.

The RO technique was developed for sounding planetary atmospheres and has aided NASA's planetary exploration programs to Venus, Mars and the outer planets. In recent times the technique has been applied to determine the structure of the Earth's neutral atmosphere and the ionosphere.

The ionosphere and atmosphere can affect the paths of the L-band electromagnetic signals transmitted from GPS satellites. Figure 1 shows an artist's impression of the bending of ray paths due to electron density gradients in the ionosphere and the refractivity in the lower atmosphere caused by the wet and dry molecules and the permanent dipole moment of the water vapour molecule. It should be noted that the bending of the ray paths in this figure is exaggerated. Improving ionospheric RO retrievals remains a major challenge for the overall GPS RO technique. The traditional retrieval methods assume local spherical symmetry of the ionosphere, which fails to take into consideration significant temporal variations in ionospheric horizontal and vertical electron density gradients.

This research is aimed at GPS RO and in particular ionospheric and atmospheric effects on GPS signals. In particular, results are displayed to show the refractivity of the Earth's ionosphere and atmosphere at different times and locations. Through this research we have developed a 3-dimensional numerical ray tracing technique which utilises geometrical optics principles to trace GPS L-band ray paths using the most advanced ionospheric and atmospheric models available.

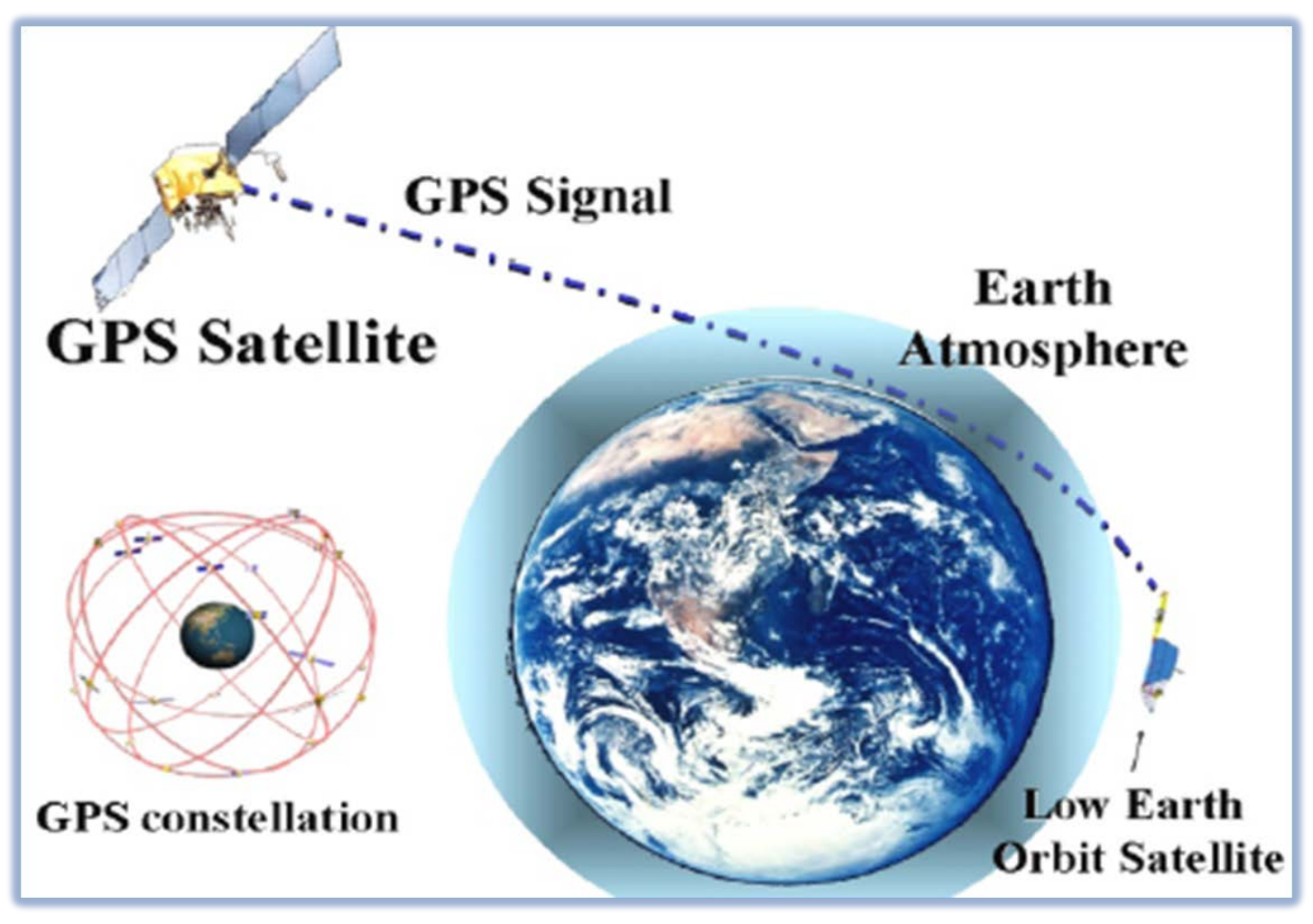


Figure 1a. Space-borne GPS RO geometry

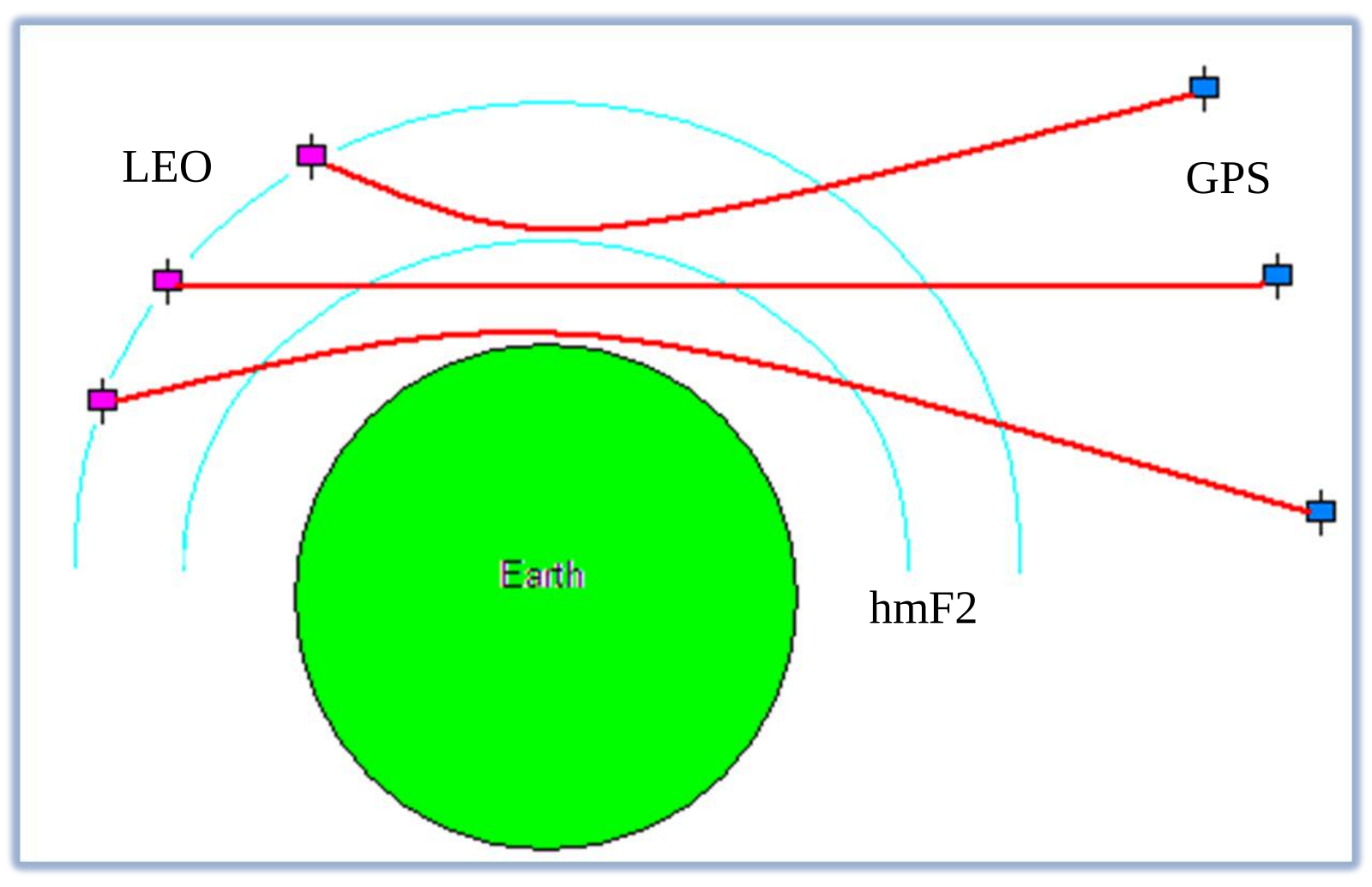


Figure 1b. L-band frequency ray paths from GPS to LEO satellites (artist impression not to scale)

Methodology and Numerical Ray Tracing

Ray tracing techniques are commonly used for calculating the path of an electromagnetic signal in a medium specified by a position-dependent refractive index. Ray tracing techniques offer important tools for High Frequency (HF) communications and radar systems; such as Over The Horizon Radars (OTHR) and more recently GPS tomography and GPS RO.

In this study numerical 3-D ray tracing is used to trace L-band frequency paths using the most advanced ionospheric model, namely the International Reference Ionosphere (IRI2007). The 3-D ray tracing technique traces a ray tube and includes the incident effects caused by the Earth's magnetic field. The numerical ray tube technique requires eighteen differential equations representing the position and direction of the principle ray path as well as the two linearly independent variational ray paths. These eighteen differential equations are integrated simultaneously at each point along the propagated ray path. This ray tracing technique not only traces the propagated signal but also enables the calculation of signal strength and has homing-in capability.

Ionosphere

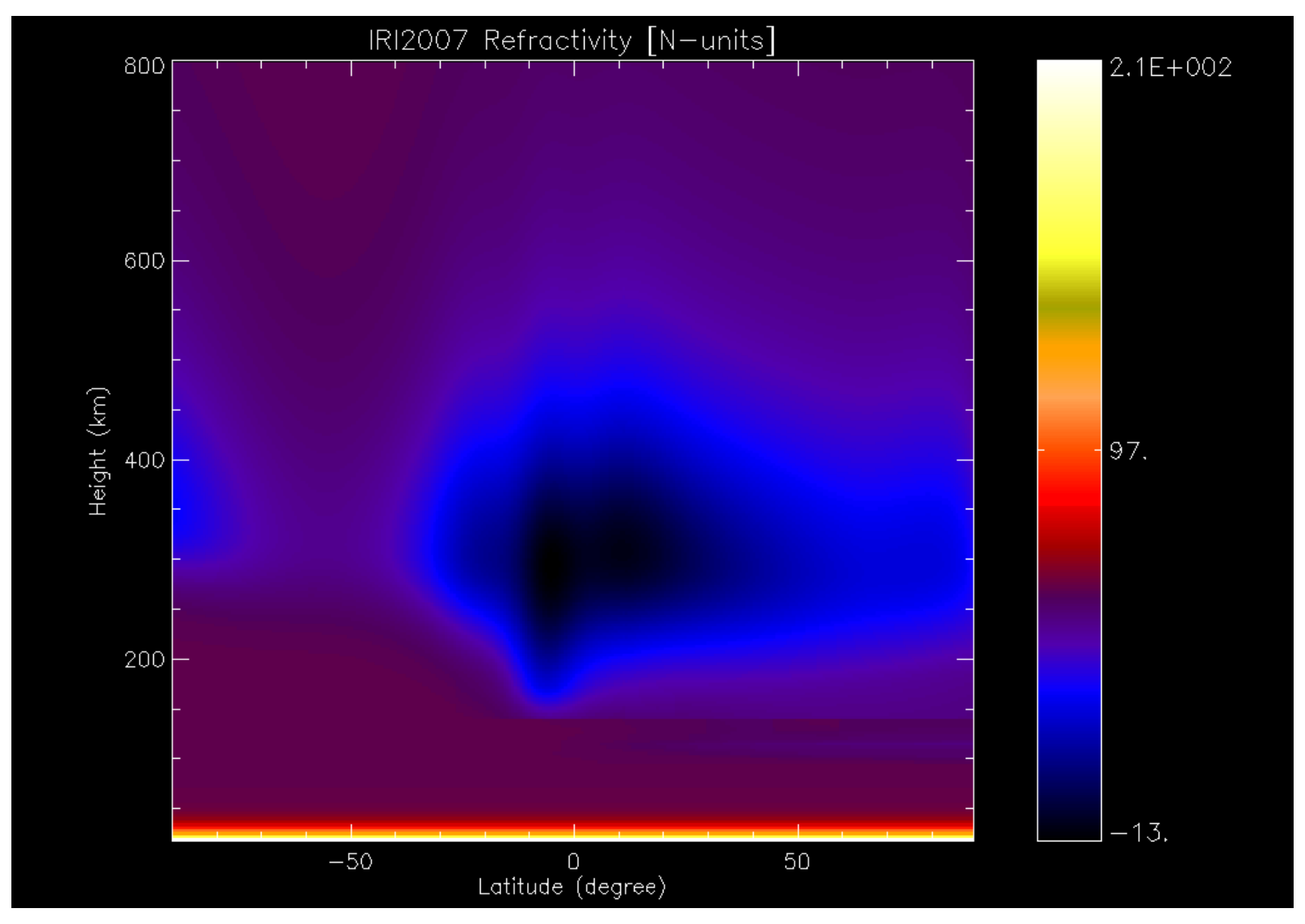
The ionosphere is the region of the Earth's upper atmosphere located at altitudes between 60 and 1500 km. Normally considered as the transition zone between our atmosphere and outer space its primary source of ionisation is incident ultra violet solar radiation. The ionosphere is highly dynamic and the study of "space weather" or "space climate" refers to the ionosphere's important connection to the Earth's atmosphere and its dynamic nature. The ionosphere thickens, changes its density, and supports a wide range of travelling disturbances, generated by the flux of incident ionising radiation from the sun and varies diurnally and seasonally. Some of the major features of the ionosphere are the ionospheric electron density layers, equatorial anomaly, troughs of ionization and a range of travelling ionospheric disturbances.

The phase refractive index in the ionosphere is given by the Appleton-Lassen equation:

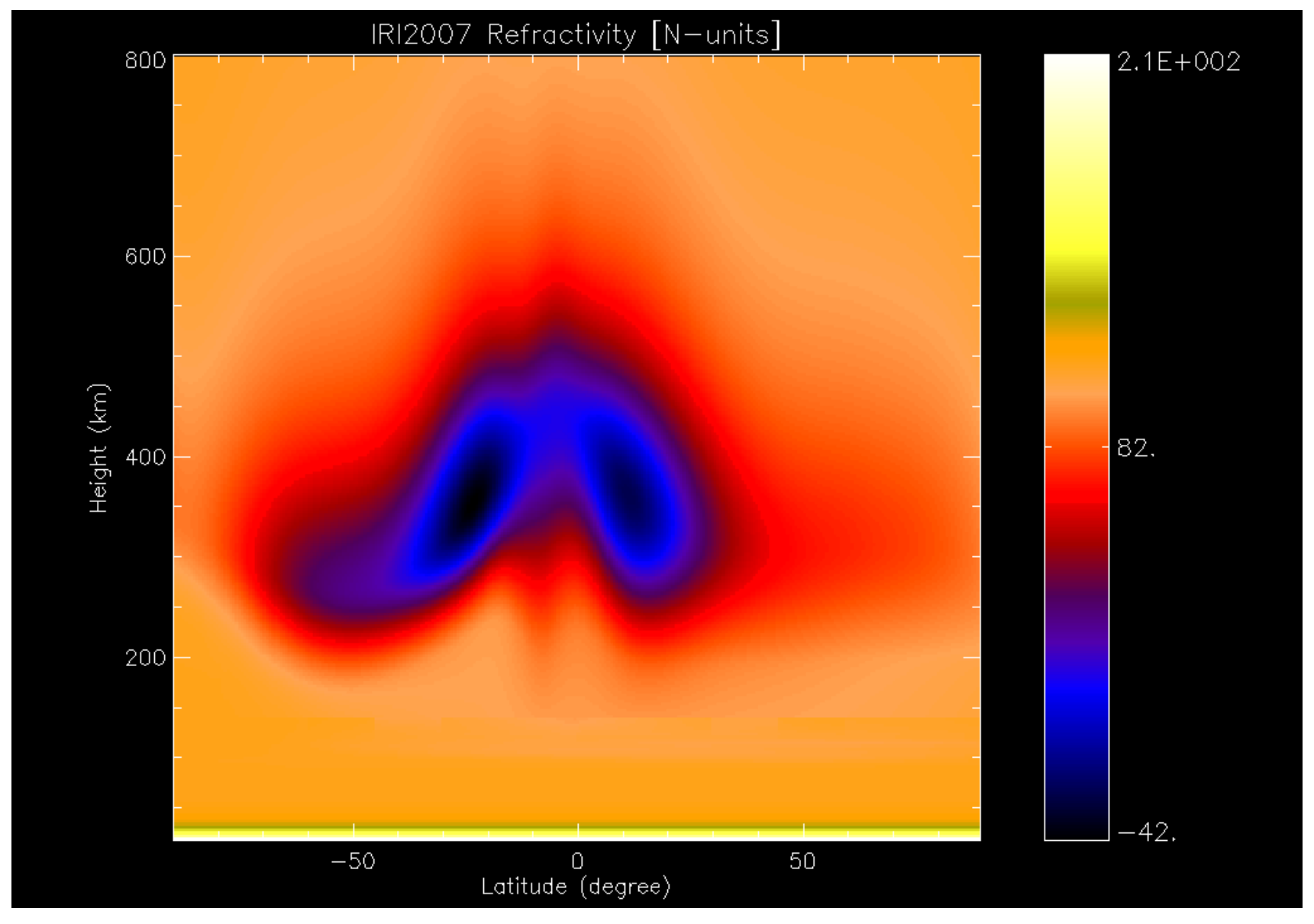
$$n^2 = 1 - \frac{X}{1 - iZ - \frac{\frac{1}{2}Y^2\sin^2\theta}{1-X-iZ} \pm \frac{1}{1-X-iZ}\left(\frac{1}{4}Y^4\sin^4\theta + Y^2\cos^2\theta\,(1-X-iZ)^2\right)^{1/2}}$$

Ionosphere and Lower Atmosphere

Figures 2 and 3 highlight the respective refractivity at 0600LT and 1200LT as a function of height and latitude, for a given the longitude of 225ºE. These results were obtained using the IRI2007 and the MSISE90 models during day 267, 2010.
Figure 4 shows the negative refractivity in the ionosphere and the near zero refractivity from heights of 40 km to 90 km. The refractivity at the Earth's surface is approximately 300 N-units and decreases almost exponentially with a scale height ~7.5 km.



Figures 2. Refractivity 0600LT



Figures 3. Refractivity 1200 LT

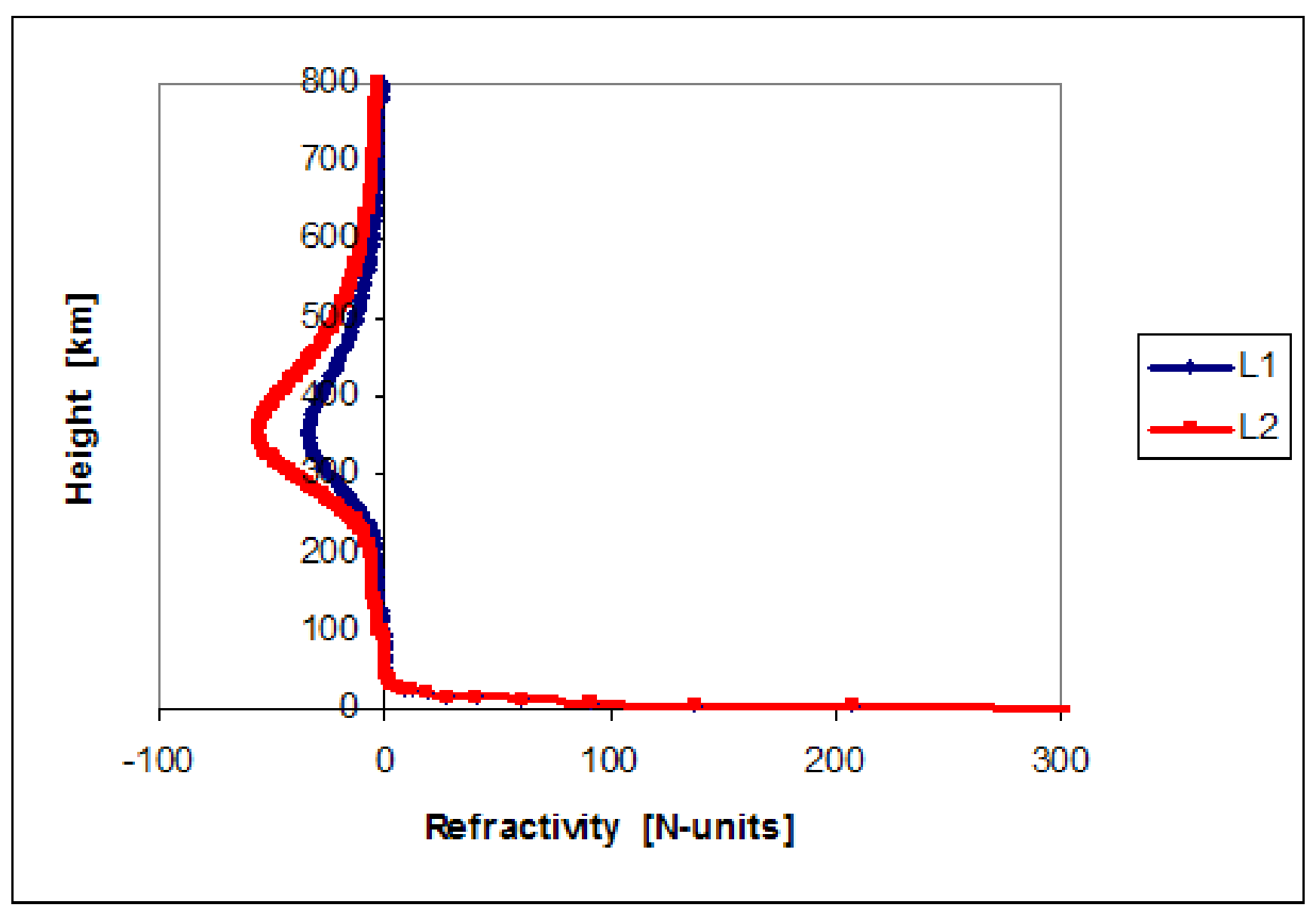


Figure 4. Refractivity Profile for L band GPS frequencies, 15ºS

Ray Tracing Results

- GPS satellite located at height 20,200 km, 50.0º N, 225.28º E.
- Northward propagation.
- Inputs for the IRI2007 model: 2010, day of year = 267 and 1200LT.

Figure 5 compares the perigee height – line of sight differences for the GPS L2 band frequency for the no- magnetic field (L2-NF), extraordinary (L2-X), ordinary (L2-O) and spherically stratified (L2-SS) ray paths.

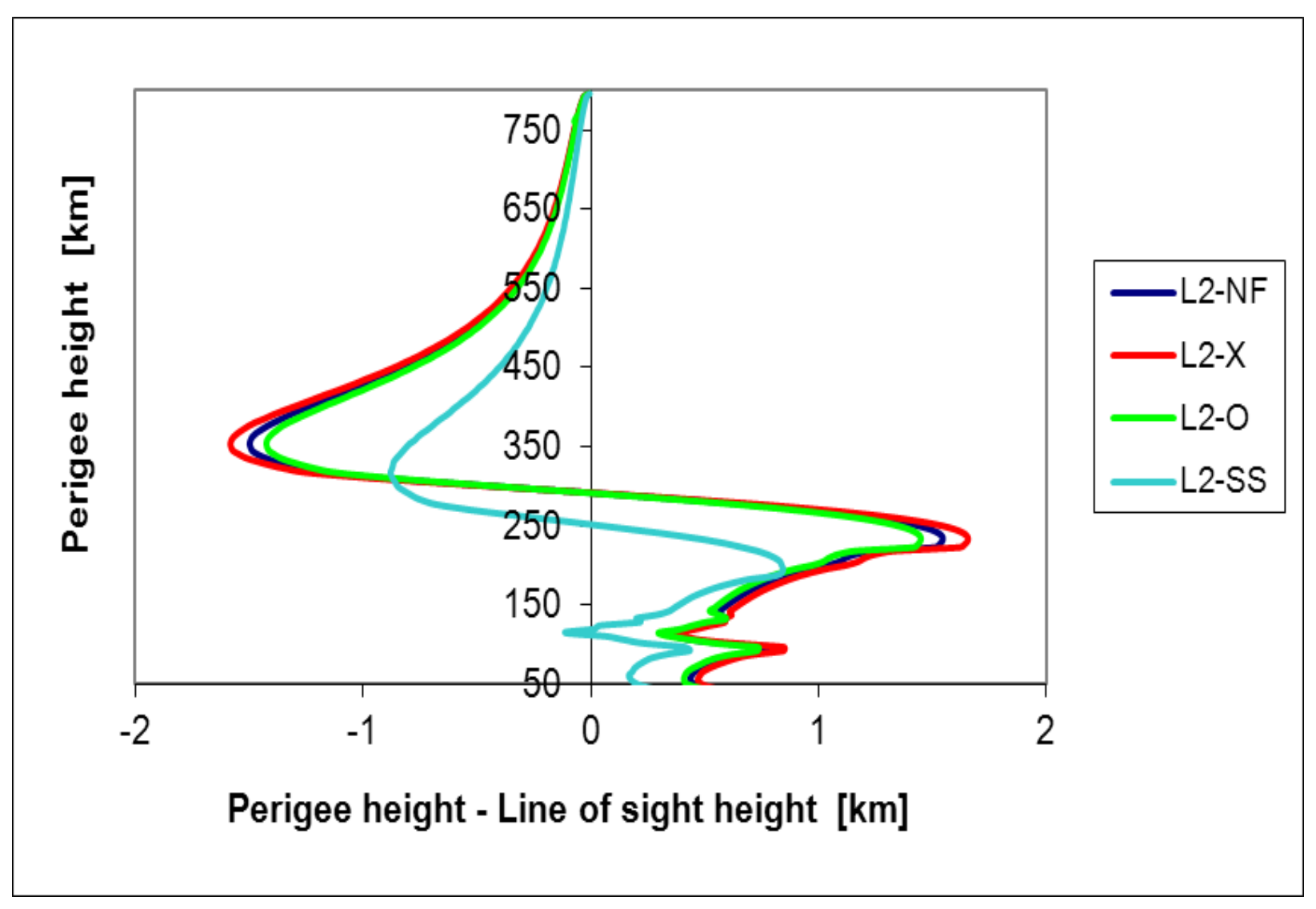


Figure 5a. Perigee height differences

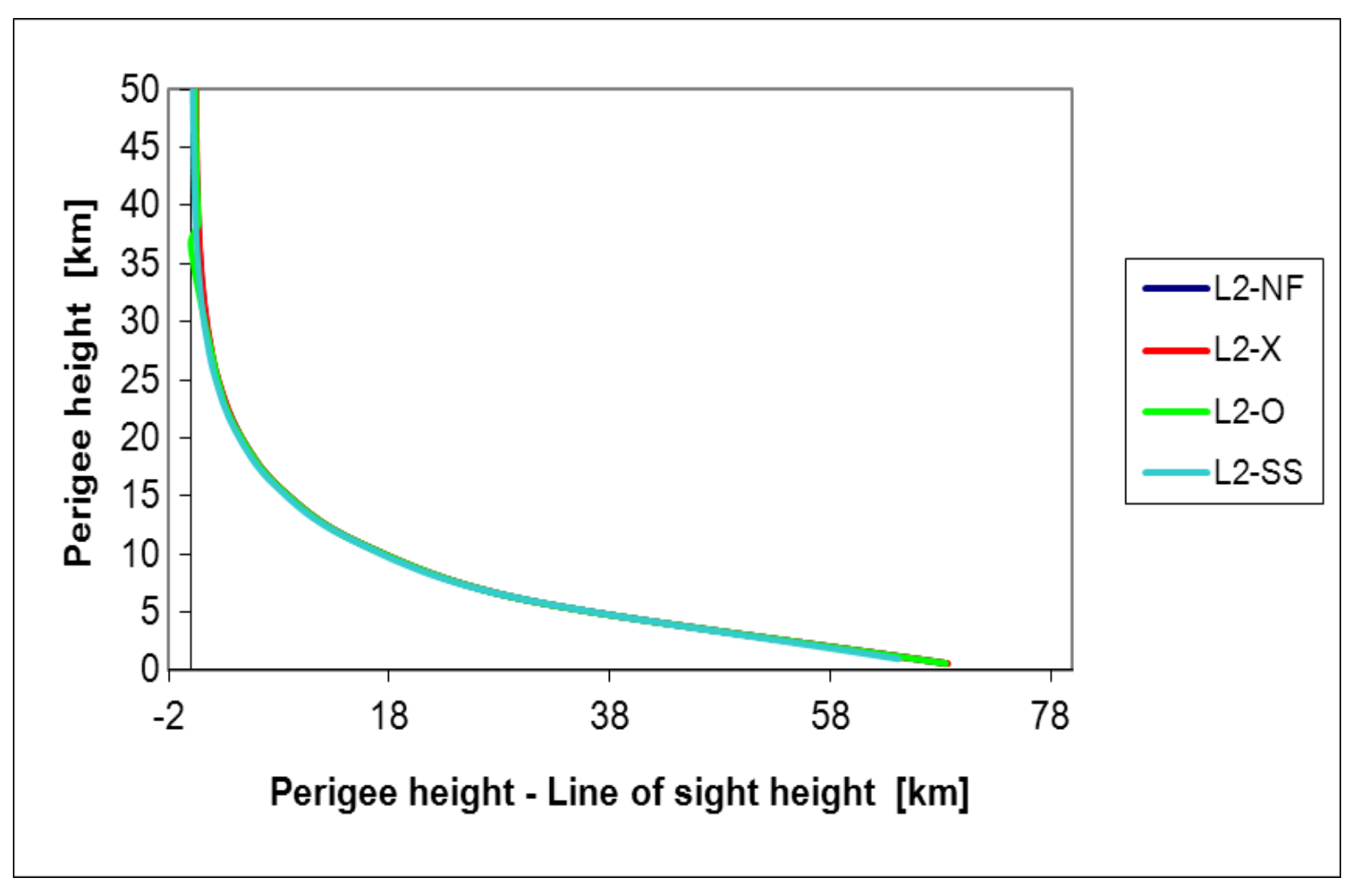


Figure 5b. Perigee height differences

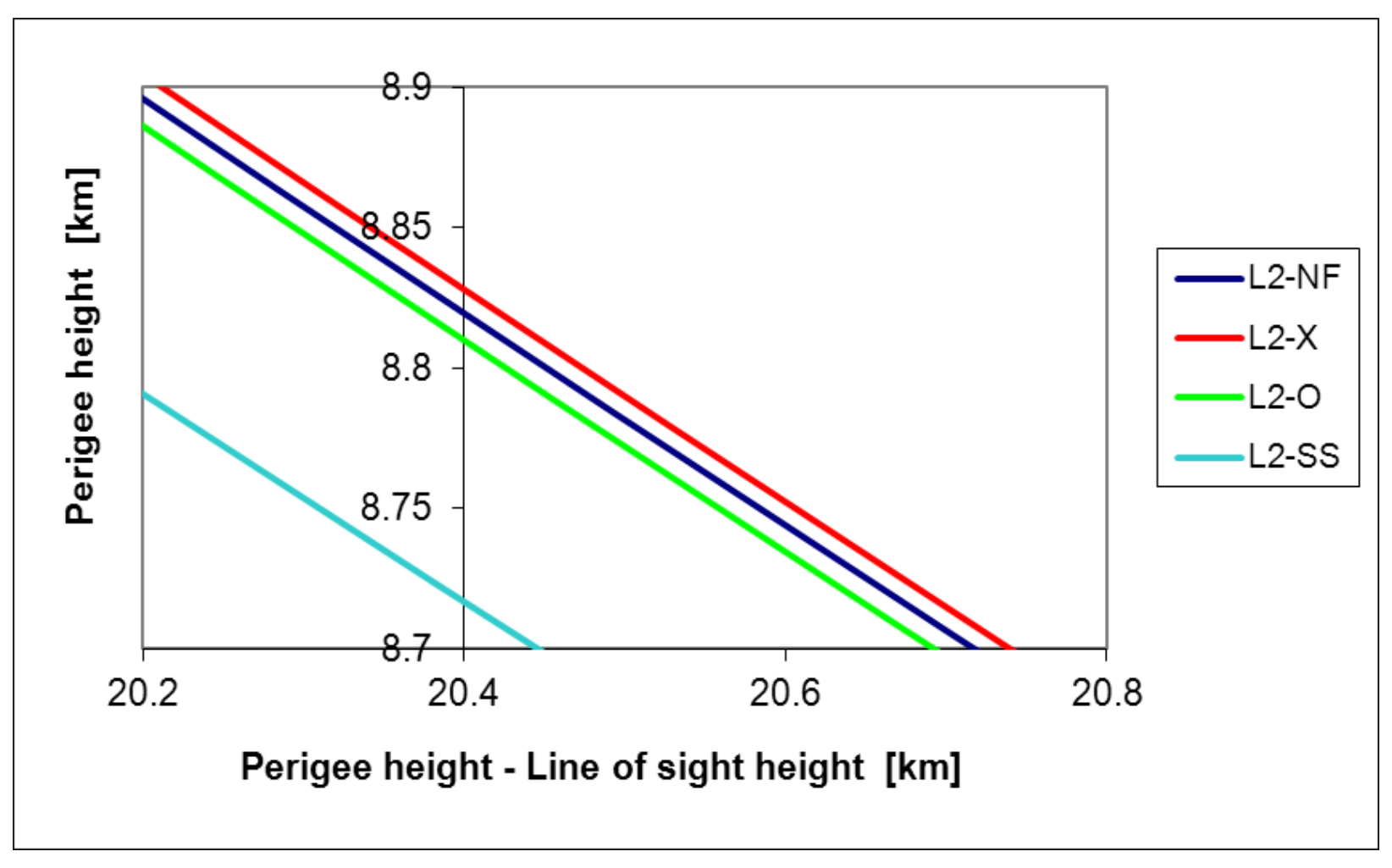


Figure 5c. Perigee height differences

The divergent signal strength is determined from the area of the resultant ray tube at the LEO satellite. The relative values are important as they show at what altitudes the signal is strongest and weakest.

From Figure 6, the divergent power loss remains relatively constant for perigee heights of 800 km down to ~ 30 km. The divergent power loss then begins to increase slightly down to a height of ~ 15 km and then decreases sharply for ray paths grazing the Earths surface. Note: Antenna patterns and absorption have been ignored.

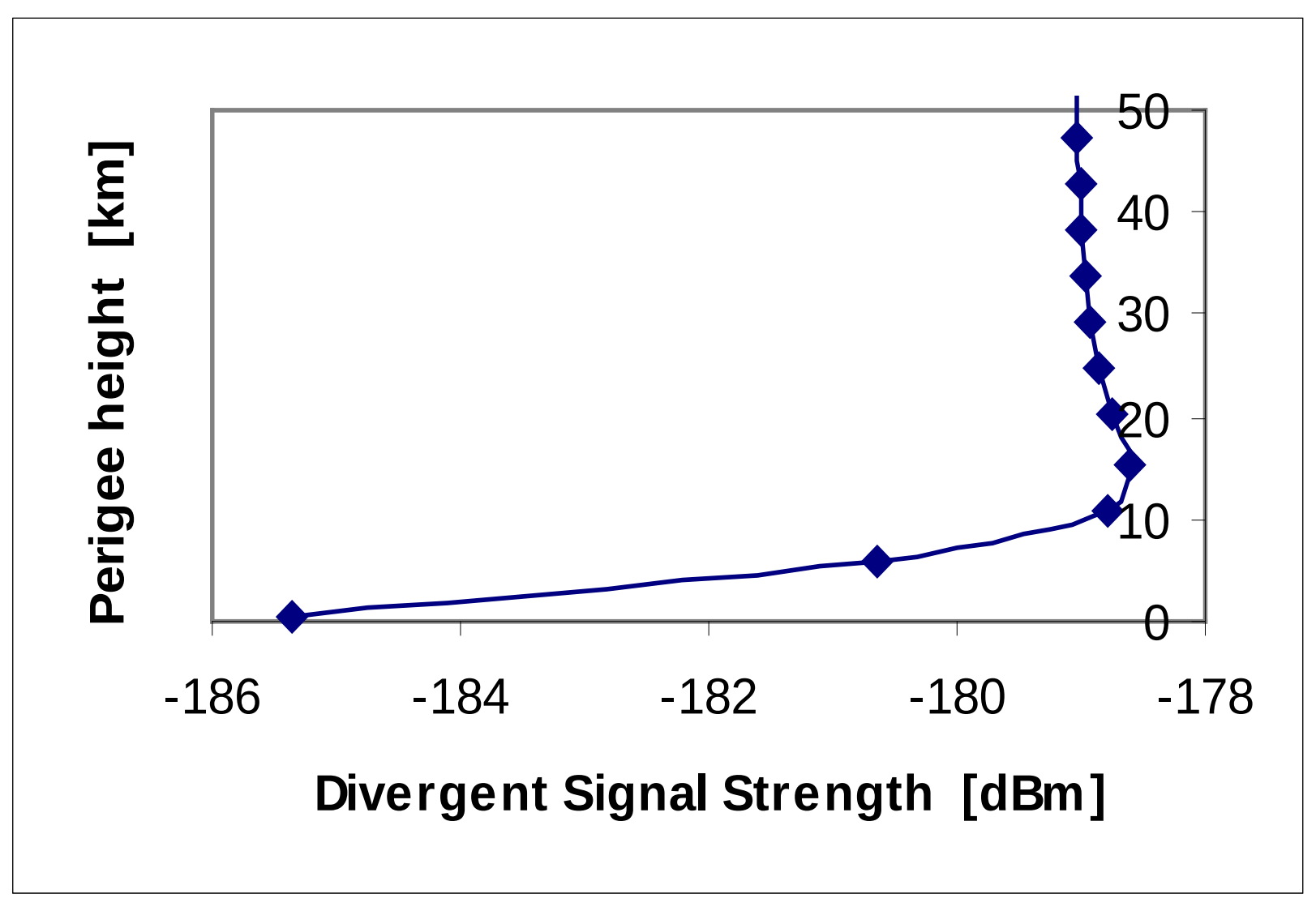


Figure 6. Perigee height versus Divergent power loss

Summary

Simulated numerical ray paths in the troposphere showed significant bending where the synthesised GPS RO ray paths were more than 60 km above the GPS-LEO line of sight. Refractive bending of the RO ray path above hmF2 causes the ray path to dip closer to the Earth, below the line of sight linking the GPS satellite to the LEO satellite. The magnetic field effects are also important and show that the signal has two modes the extraordinary and the ordinary mode and that the signal paths can differ by up to 10 metres in the lower atmosphere.

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