[Draft: Short invited article for Eos on Fall 1 995 AGU Session G-05]

G eoscience from GPS/MET

On April 3, 1995, a Pegasus rocket launched MicroLab 1, a small research satellite, into a low circular orbit at an altitude of 750 km and an inclination of 70 deg. In addition to its primary scientific payload, Micro] ,ab 1 carried the GPS/Meteorology (GPS/MET) flight instrument, which is a TurboRogue GPS receiver that had been adapted for space operations. This receiver was commanded to power up on April 16; within 35 minutes with no further assistance from the ground the receiver began tracking in parallel the navigation signals from up to 8 Global Positioning System (GPS) satellites. The received dual-band (at 1226 MHz (L]) and 1575 MHz (1.2)) carrier phase measurements from the tracked satellites are sent to ground in non-real time where they are merged with a set of concurrent measurements made by a global network of continuously tracking GPS ground receivers. These data streams from flight and ground are combined in a differential GPS mode (to eliminate clock errors in the flight and ground equipment) and processed by orbit determination programs to provide ephemerides of decimeter accuracy for all satellites in the GPS constellation and for MicroLab 1. The orbit perturbations resulting from errors in the nominal mode] of the geopotential can be sensed in the GPS observations made aboard MicroLab 1 and used to improve that model, particularly the spectral components with wavelengths longer than about 700 km, and those in resonance for this orbit.

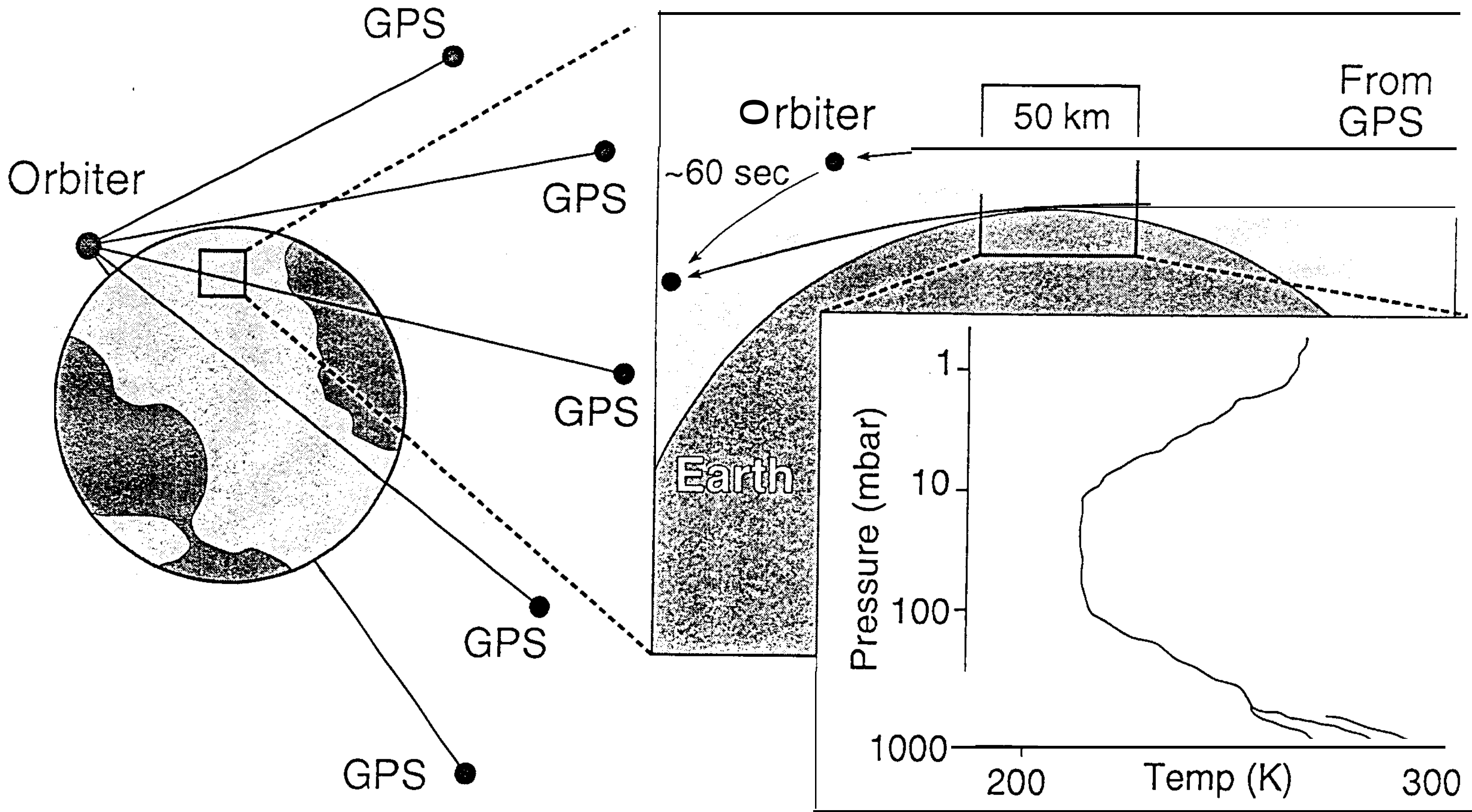
The GPS/MET experiment has dramatically demonstrated an innovative and powerful limb-sounding approach for monitoring the terrestrial ionosphere and atmosphere by the technique of GPS radio occultation. As a GPS satellite is observed from a low Earth orbiter (1 ,EO) to set behind the Earth's limb (see figure), the occulted signals are bent and delayed by the intervening medium. GPS/MET can in principle observe daily up to 250 setting occultations distributed nearly uniformly around the globe (in fact, it observes less because of operational limitations, about 1 SO on a good day). A linear combination of the dual-band carrier phase 'measurements, which can be sampled at rates up to 50 Hz, provide a very accurate measure of the change in total electron content (TEC) along the ray path from the GPS satellite to the LEO. The vacuum-equivalent phase measurement has a precision (for MicroLab 1) of around 1 mm at a 1 sec averaging interval. As the point of tangency to the Earth's limb descends, the ray path from the occulted GPS satellite is increasingly retarded and bent by refractive gradients in the Earth's atmosphere. At cutoff by the Earth's limb the total delay observed on the LEO exceeds 1 km; hence, occultation by the Earth induces a signature in the observed carrier phase data over a period of about 1 minute that has an enormous dynamic range.

If one makes the assumption that the refractive index in the Earth's atmosphere is essentially invariant along an equipotential surface and one defines the strati graphy of that surface, then one can use ray tracing techniques to obtain a direct relationship between the observed rate of change (Doppler) of the excess atmospheric phase delay and the total refractive bending angle induced by the atmosphere. Ionospheric effects can be removed almost perfectly by an appropriate linear combination of the total bending on the L1 and L2 carriers. The time series of determined bending angles can be inverted to obtain a vertical profile of refractivity for each occultation. When the assumption of local spherical symmetry is applied, a simpler Abel Transform technique, which has its roots in seismology, can be used to directly invert the Doppler time series into a vertical refractivity profile. The linear relationship between the density of dry air and its refractivity allows one to convert to a density profile for those regimes where significant water vapor is known to be absent, i.e., for altitudes above the -250 K isotherm. The assumption of hydrostatic equilibrium and use of the gas law enable one to recover pressure and temperature profiles throughout this regime. Theoretical accuracies of the recovered temperature profiles are better than 1 K for altitudes in the 6-30 km range and better than 0.5 K at the tropopause. The along-track (horizontal) resolution is 200-300 km, which is typical for a limb sounder. The vertical resolution is diffraction-limited by the vertical diameter of the first Fresnel zone, which is about 1.5 km at the top of the atmosphere, decreasing because of defocusing to an average of about 0.5 km at the Earth's limb. Fresnel deconvolution techniques may be used in the future to sharpen these limits in vertical resolution.

in the lower troposphere typically below an altitude of 6-8 km, water vapor, which has a refractivity per mole at GPS microwave frequencies of about 17 times that of dry air, limits the accuracy of the recovered temperature and pressure profiles except in very cold geographical regions. Tracking GPS satellites through the lower troposphere is difficult for GPS/MET because of the propensity for sharp vertical gradients in refractivity at these low altitudes clue to water vapor, which is further confounded by increased defocusing at lower altitudes due to the larger density gradient of dry air. Roughly 10% of the recovered profiles have reached the surface of the Earth and these successes tend to be correlated with higher latitude ray tangency points where more benign signal conditions are likely to prevail That percentage should improve significantly with improved phase tracking software soon to be installed in the GPS/MET flight receiver, and it should further improve on future missions where antennas with much higher gain will be used. For temperate and tropical regions, the challenge remains of using the radio occultation technique (combined with atmospheric models to account for the dry air contribution to refractivity) to recover water vapor profiles. Nevertheless, advocates of the technique are confident that future technical improvements will yield this prize. Knowledge of water vapor distributions around the globe, because of water vapor's capability for enormous thermal energy transport, would make an important contribution to weather forecasting. A constellation of 20 LEOs making GPS radio occultation measurements could provide 5,000-10,000 daily profiles around the globe.

The session will feature comparisons of GPS/MET-derived temperature profiles principally with radiosonde profiles and with atmospheric analyses based on global models developed by the European Centre for Medium-range Weather Forecasts (ECMWF) and data bases from the National Meteorological Center (NMC). These comparisons for altitudes above 6-8 km (i.e., for temperatures below 250 K) and below about 30 km mainly show biases of less than 0.5 K for mid-latitudes and higher, and about 1 K for tropical latitudes. In isolated geographical regions - for example, in certain southern oceanic regions where atmospheric analyses are poorly constrained due to lack of radiosonde measurements - the agreement degrades to about 2 K. GPS occultation determinations of geopotential heights of constant pressure surfaces offers a promising new method to detect secular trends in global climate by tracking, for example, the global topography of the tropopause. Occultations in the tropical regions consistently show evidence of wave-like structures in the lower stratosphere that arc probably Rossby gravity waves. The effect of departures from the assumption of invariance of refractivity along geopotential surfaces (due to internal gravity waves, for example) is discussed. The session also will address the advantages and challenges of deploying a space array of LEOs devoted to GPS radio occultation. The potential of monitoring the ionosphere from a constellation of LEOs using tomographic techniques is discussed. Collectively, the session makes the case that GPS radio occultation offers major contributions to global change and weather prediction programs, and, in conjunction with ground networks, to imaging the global ionosphere with high resolution in space and time.

William G. Melbourne
Jet propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109
(8 18) 354-5071
e-mail: William.G.Melbourne @jpl.nasa.gov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