Assessing the effect of gravity anomalies on GPS/RO-derived temperatures: First results from the GRACE mission

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Abstract

This paper introduces a novel technique to identify the response of the Earth's vertical temperature profile to gravity anomalies. The approach is to combine measurements from active sounding techniques and global gravity field models. The Global Positioning System radio occultations (GPS/RO) are active limb sounding measurements that provide information about the Earth's thermal structure between 3 km and 50 km altitude. These measurements are retrieved at GPS/RO processing centers using the Earth's normal gravity field and thus, they are inherently biased by the Earth's gravity anomalies. Significant progress is possible with a joint retrieval combining the RO refractivity measurements with global gravity field models from the Gravity Recovery and Climate Experiment (GRACE) mission using the ideal gas law, in an atmosphere in hydrostatic equilibrium. Comparing the retrieved temperature profiles with those derived using the Earth's normal gravity field, we observe negative systematic temperature biases between 0.1 K and 0.5 K, in all cases studied.

Introduction

The GPS/RO is an active remote sensing technique probing the Earth's atmosphere since 1995 [*Ware et al.,* 1996]. The principal observable during a RO event is the rate of change in the propagation delay of transmitted dual-frequency (f_1=1.57542 GHz; f_2=1.22760 GHz) GPS signals as function of occultation time, as they traverse the Earth's atmosphere (cf., Fig. 1), between a GPS and a LEO satellite located on opposite sides of the Earth's limb [*Vergados and Pagiatakis,* 2009].

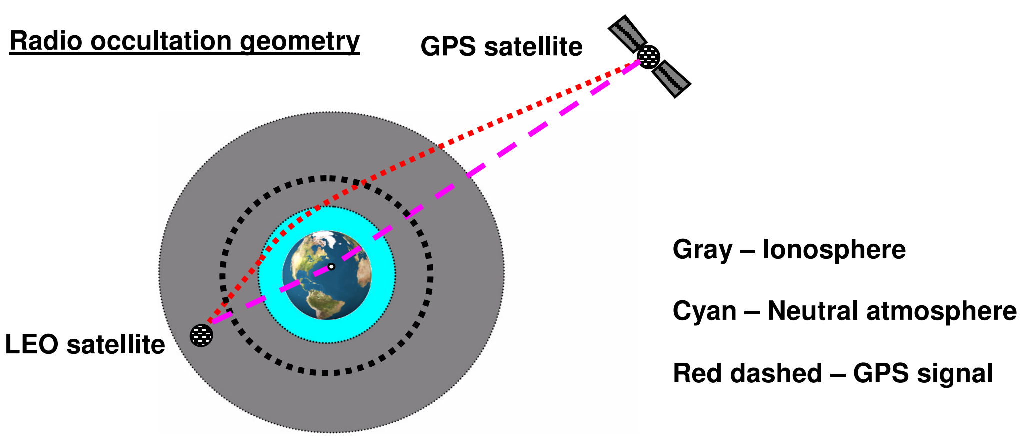

Figure 1: Schematic of a GPS-LEO radio occultation technique.

A GPS/RO profile of propagation delay is converted to an atmospheric refractivity profile using geometrical optics approximations, in which the GPS signal paths are treated as rays that curve in accordance to Snell's law. In turn, the atmospheric refractivity (N in N-units) is related to the total atmospheric pressure (P in mbar), temperature (T in K) and the water vapour pressure (e in mbar) through [e.g., *Hajj et al.,* 2002]:

$$N(z) = 77.6\frac{P(z)}{T(z)} + 3.73\times10^5\,\frac{e(z)}{T(z)^2}\,. \tag{1}$$

The first term in the right-hand-side (RHS) of Eq. (1) describes the Earth's dry atmospheric refractivity related to the ability of neutral atmospheric atoms and molecules to become polarized by GPS signals. The second term in the RHS of Eq. (1) describes the wet refractivity component, which is associated with the absorption of GPS signals by water vapour molecules. In regions where the water vapour pressure is negligible (above about 5 km), the second term in the RHS of Eq. (1) is neglected and the dry atmospheric temperature is estimated directly from the refractivity profiles. Assuming that the air is an ideal gas and in hydrostatic equilibrium, the total atmospheric pressure is [*Clapeyron,* 1834]:

$$P(z) = P(ztop) + \int_{ztop}^{z} \rho(z')g(z')dz', \tag{2}$$

where $g(z')$ (m/s^2) denotes the Earth's gravity field as function of altitude. In Eq. (2), the pressure at the top of the atmosphere is defined either by climatological models or by satellite observations. To-date, all GPS/RO processing centers and Numerical Weather Prediction (NWP) models, either assume the Earth's gravity field constant as function of altitude, or they calculate by it using the World Geodetic System 1984 Normal Gravity Formula [*National Imagery and Mapping Agency,* 2000]:

$$g(z) = 9.7803267714 \frac{1 + 0.00193185138639 \sin^2 \phi}{\sqrt{1 - 0.00669437999013 \sin^2 \phi}} - 3.086 \times 10^{-6} z \tag{3}$$

where ϕ is the latitude and z the height above the mean sea level (MSL) (in km). Therefore, the atmospheric pressure and temperature estimated from Eqs. (1) and (2) will be negatively biased due to the Earth's gravity anomalies.

General methodology and procedure

To assess the impact of the Earth's gravity anomalies on the vertical structure of the Earth's temperature profiles derived from RO experiments, we propose an inter-disciplinary approach that combines multi-instrument satellite data products. We identify the geographic locations of maximum positive (e.g., Northern Atlantic Ocean, San Andreas Fault and Indonesian Peninsula) and negative (e.g., Hudson Bay and North Indian Ocean) gravity anomalies. We download GRACE monthly mean estimations of the spherical harmonic coefficients for the Earth's gravitational potential from the University of Texas Center for Space Research (UTCSR) to calculate the necessary gravity anomalies.

We select RO events that occurred over the geographic locations with the maximum positive and negative gravity anomalies for the years 2008, 2009 and 2010. We calculate the Earth's gravity anomalies as function of altitude at the geographic locations specified above using the GEOPOT97 software provided by the National Geodetic Survey (NGS). The altitude grid for the calculations is provided by the RO measurements. Adding the vertical profiles of gravity anomalies to the normal gravity field, we calculate the total gravity field and we retrieve improved temperature profiles.

To examine the systematic biases introduced to the temperature profiles by the gravity anomalies, we compare the improved temperature profiles with the ones obtained using the normal gravity field (cf., Eq. (3)). The proposed analysis provides unique information on measurement biases and variances of atmospheric temperature profiles due to the Earth's gravity anomalies.

Results and discussion

The vertical distribution of the Earth's gravity anomalies in 2008, 2009 and 2010 for the months of January through December for selected geographic locations specified in the methodology section, as well as their mean annual variability have been retrieved. In all cases, the gravity anomalies decrease linearly with height and range between 19.58 mgal at the surface and 19.17 mgal at 60 km altitude above the mean sea level (MSL).

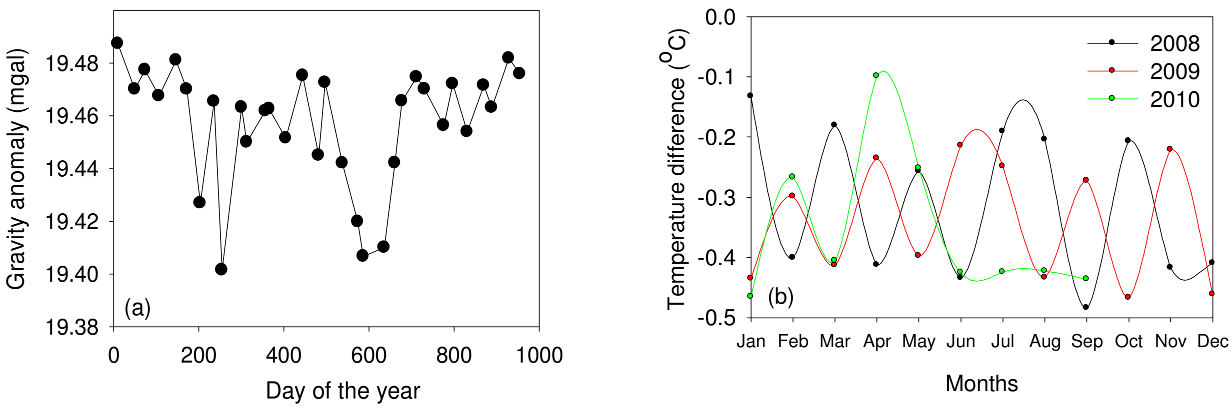

Figure 2: (a) Annual variability of the Earth's monthly mean gravity anomalies and (b) annual variability of mean temperature differences between the temperature profiles retrieved using the improved gravity field and those using the normal gravity field from January 2009 (day 0) to September 2010 (day 955).

Figure 2*a* shows how the monthly mean of the Earth's gravity anomalies vary from January 2008 (day 0) to September 2010 (day 955). The monthly mean gravity anomalies are computed by taking the mean of the vertical profile of the Earth's gravity anomaly and thus, correspond to an altitude of ~30 km above MSL. The seasonal variation of the mean gravity anomalies exhibits an oscillatory behaviour with two minima occurring in mid-July (day 253) with a value of ~19.403 mgal and in mid-August 2009 (day 585) with a value of ~19.407 mgal. From August 2009, the mean gravity anomalies start to increase obtaining a maximum value of ~19.482 mgal in September 2010. Unlike in the previous years, in 2010 we do not observe a decrease in the mean gravity anomalies around the summer season.

Figure *2b* presents the difference statistics between temperature profiles derived using GRACE gravitational field models and the Earth's normal gravity field for the years 2008, 2009 and 2010 for the months of January through December for selected geographic locations specified in the methodology section, as well as their mean annual variability. Our results show mean temperature differences between -0.5 K at the surface and -0.1 K at about 50 km altitude, respectively, in all cases. The seasonal variability of the temperature differences follows a sinusoidal relationship that oscillates between -0.5 K and -0.1 K, respectively, following the trend of the monthly mean gravity anomalies (cf., Fig. 2*a*). The amplitude of oscillation of the monthly mean temperature differences slowly increases from January through December, obtaining its maximum value between June and September coinciding with the sudden decrease of the Earth's gravity anomalies presented in Fig. 2*a*.

Conclusions

To-date, general circulation models, Mumerical Weather Prediction centres and atmospheric dynamic models do not use the global gravity field models provided by space missions (e.g., GRACE). Thus, the precision and accuracy of atmospheric parameters is inherently biased due to the Earth's gravity anomalies. The significance of this research lies on the fact that we are the first to present the complementary nature of RO measurements and global gravity field models. Our results reveal that the seasonal variability of the Earth's gravity anomalies follows a wave-like behaviour, which manifests itself as a sinusoidal effect on the Earth's temperature profiles. A mean gravity anomaly of about 19.5 mgal introduces a mean temperature bias of -0.5 K. The effect of gravity anomalies on the Earth's thermal structure appear to be more profound between June and September, where the temperature differences presented in Fig. 2*b* show increasing oscillation amplitude.

References

Bos, A. G. (2005), Kinematics of the southwestern U.S. deformation zone inferred from GPS motion data, *J. Geophys. Res.*, **110**, B08405

Clapeyron, E. (1834), Mémoire sur la puissance de la chaleur, *J. de l' École Polytechnique,* **14,** pp. 150 190

Hajj, G. A., E. R. Kursinski, L. J. Romans, W. I. Bertiger, and S. S. Leroy (2002), A technical description of atmospheric sounding by GPS occultation, *J. Atmos. Sol. Terr. Phys.,* **64**(4), pp. 451–469, doi:10.1016/S1364-6826(01)00114-6

National Imagery and Mapping Agency (2002), Department of Defence World Geodetic System 1984, Nima TR8350.2, Third Edition, January 2002

Vergados, P. and S. D. Pagiatakis (2009), Preliminary results on the sensitivity of atmospheric bending angles retrieved from COSMIC radio occultations to Doppler frequency shift and satellite velocity variations**,** *Can. J. of Earth Sci.,* **46**(8), pp. 597–610

Ware, R., M. Exner, D. Feng, M. Gorbunov, K. Hardy, B. Herman, Y. Kuo, T. Meehan, W. Melbourne, C. Rocken, W. Schreiner, S. Sokolovskiy, F. Solheim, X. Zou, R. Anthes, S. Businger, and K. Trenberth (1996), GPS Sounding of the Atmosphere from Low Earth Orbit: Preliminary Results, *Bull. Am. Meteorol. Soc.,* **77**, pp. 19–40