Atmospheric Research 212 (2018) 33–42

Contents lists available at ScienceDirect

Atmospheric Research

journal homepage: www.elsevier.com/locate/atmosres

Satellite laser ranging as a tool for the recovery of tropospheric gradients

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ARTICLE INFO

Keywords:
Horizontal gradients
Tropospheric delay
Numerical weather models
SLR
GNSS
Satellite geodesy

ABSTRACT

Space geodetic techniques, such as Global Navigation Satellite Systems (GNSS) and Very Long Baseline Interferometry (VLBI) have been extensively used for the recovery of the tropospheric parameters. Both techniques employ microwave observations, for which the troposphere is a non-dispersive medium and which are very sensitive to the water vapor content. Satellite laser ranging (SLR) is the only space geodetic technique used for the definition of the terrestrial reference frames which employs optical – laser observations. The SLR sensitivity to the hydrostatic part of the troposphere delay is similar to that of microwave observations, whereas the sensitivity of laser observations to non-hydrostatic part of the delay is about two orders of magnitude smaller than in the case of microwave observations. Troposphere is a dispersive medium for optical wavelengths, which means that the SLR tropospheric delay depends on the laser wavelength. This paper presents the sensitivity and capability of the SLR observations for the recovery of azimuthal asymmetry over the SLR stations, which can be described as horizontal gradients of the troposphere delay. For the first time, the horizontal gradients are estimated, together with other parameters typically estimated from the SLR observations to spherical LAGEOS satellites, i.e., station coordinates, earth rotation parameters, and satellite orbits. Most of the SLR stations are co-located with GNSS receivers, thus, a cross-correlation between both techniques is possible. We compare our SLR horizontal gradients to GNSS results and to the horizontal gradients derived from the numerical weather models (NWM). Due to a small number of the SLR observations, SLR is not capable of reconstructing short-period phenomena occurring in the atmosphere. However, the long-term analysis allows for the recovery of the atmosphere asymmetry using SLR. As a result, the mean offsets of the SLR-derived horizontal gradients agree to the level of 47%, 74%, 54% with GNSS, hydrostatic delay, and total delay from NWM, respectively. SLR can be thus employed as a tool for the recovery of the atmospheric parameters with a major sensitivity to the hydrostatic part of the delay.

1. Introduction

The Satellite Laser Ranging (SLR) observations significantly contribute to the determination of precise satellite orbits, to the realization of the origin of the reference frame, the global scale, the gravitational standard parameter GM, and low-degree spherical harmonics of the Earth's gravity field, especially the oblateness term (Chen and Herring, 1997; Chen and Wilson, 2008; Sośnica et al., 2015; Biancale et al., 1991; Bloßfeld et al., 2015). SLR became an exceptional contributor to space geodesy in particularly after the launch of the first two SLR-designed geodetic satellites, i.e., Starlette in 1975 and the LAserGEOdynamics Satellite (LAGEOS) in 1976 (Smith and Turcotte, 1993). The SLR contribution to science is essential due to providing range measurements to geodetic satellites of a high accuracy at a level of a few millimeters. The observational techniques of space geodesy, such as Global Navigation Satellite Systems (GNSS) and Very Long Baseline Interferometry (VLBI), have been extensively used for the recovery of the tropospheric parameters (e.g., Böhm and Schuh, 2004; Hobiger et al., 2008; Thaller, 2008; Teke et al., 2015). In particular GNSS is used for the recovery of the water vapor content, GNSS 4-dimensional tomography of the atmosphere or supporting the numerical weather predictions models NWM (Böhm et al., 2009; Rohm et al., 2014; Wilgan et al., 2015; Douša et al., 2016). Using spaceborne GNSS radio occultation data, collected, e.g., by the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) mission, significantly improves the predictions of the typhoons affecting in particular the tropical areas (Kursinski et al., 1997; Cucurull et al., 2007; Bonafoni and Biondi, 2016; Fonseca et al., 2018).

GNSS and VLBI techniques employ microwave observations, for which the troposphere is a non-dispersive medium. Currently, the SLR technique has a very long history of observations to geodetic satellites collected by a global network of stations, which have a potential to

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https://doi.org/10.1016/j.atmosres.2018.04.028
Received 19 December 2017; Received in revised form 27 April 2018; Accepted 27 April 2018

recover information about the state of the atmosphere above those stations.

The estimation of the horizontal gradients is widely applied in GNSS processing (Li et al., 2015, Rohm et al., 2014, Masoumi et al., 2016). In VLBI due to the low number of observations per session the horizontal gradients are replaced by gradients based on numerical models (Landskron and Böhm, 2018). Currently, the troposphere delay model in SLR includes only the zenith delay mapped onto particular elevation angle, whereas the horizontal gradients describing the tropospheric asymmetry above the station are neglected.

This paper discusses the sensitivity and the capability of the SLR observations for the recovery of atmospheric asymmetry over the SLR stations which can be described as horizontal gradients of the troposphere delay. The observations from over 40 co-located stations with GNSS receivers were reprocessed. As a result, we retrieved the horizontal gradients from the optical observations and further the mean values of the data time series were compared with the horizontal gradients especially with the hydrostatic part derived from the project Global Geodetic Observing System (GGOS) Atmosphere. The structure of this paper is organized as follows. Section 2 describes the models that are currently recommended for the troposphere delay modeling in SLR solutions and also contains the proposal of the model extension with considering horizontal gradients. Section 3 shows horizontal and elevation-dependent systematic errors included in SLR observation residuals when neglecting the estimation of the horizontal gradients. Section 3 provides also the results from the estimation of tropospheric gradients using SLR data and a comparison with GNSS results and the numerical weather models using 14 years of processed data. Section 4 discusses and summarizes the results from the paper, which fulfill the recommendation concerning using gradients in SLR solutions.

2. Methodology

2.1. Troposphere modeling in the SLR solutions − the current status

The optical signal propagating from a laser station to a satellite and tracing back to the station is subject to the delay due to the presence of the atmosphere. The atmospheric propagation delay experienced by a laser signal in the zenith direction may be defined as (e.g., Petit and Luzum, 2011):

$$d_{atm}^{z} = 10^{-6}\int_{r_s}^{r_a} N dz = \int_{r_s}^{r_a} (n-1) dz, \tag{1}$$

or, if one splits the zenith delay into the hydrostatic ($d_h{}^z$) and non-hydrostatic ($d_{nh}{}^z$) components, the delay reads as:

$$d_{atm}^{z} = d_h^z + d_{nh}^z = 10^{-6}\int_{r_s}^{r_a} N_h dz + 10^{-6}\int_{r_s}^{r_a} N_{nh} dz \tag{2}$$

where $N = (n - 1) \times 10^6$ is the (total) group refractivity of the moist air, n is the (total) refractive index of the moist air, N_h and N_{nh} are the hydrostatic and the non-hydrostatic components of the refractivity, r_s is the geocentric radius of the laser station, r_a is the geocentric radius of the top of the neutral atmosphere, and $d_{atm}{}^z$ and dz. have unit lengths.

The formerly recommended delay model derived by Marini and Murray (1973), contains the zenith path delay and implicitly, the mapping function for the projection of the zenith delay to the given elevation angle. The currently recommended refraction model, developed by Mendes and Pavlis (2004) consists of formulae for the hydrostatic and non-hydrostatic zenith delay components and a common mapping function FCULa (Function commonly used in Laser Ranging). Mendes and Pavlis (2004) derived a closed-form expression for the computation of the zenith delay for the hydrostatic component:

$$d_h^z = 0.002416579\frac{f_h(\lambda)}{f_s(\phi, H)}P_s \tag{3}$$

where $d_h{}^z$ denotes the zenith hydrostatic delay and P_s denotes the surface barometric pressure. The term $f_s(\phi, H)$ is a function of the delay w.r.t. the geodetic latitude of the station ϕ and the geodetic height H, whereas the term $f_h(\lambda)$ is the dispersion equation for the hydrostatic component depending on the wavelength of the laser observation and the content of carbon dioxide.

The hydrostatic delay in zenith depends thus mostly on the pressure and amounts to 1.59 m, 2.05 m, and 2.39 m for the barometric pressure of 700, 900, and 1050 hPa, respectively (assuming station height of 100 m at the latitude 40° and the laser wavelength 532 nm). The hydrostatic delay is thus comparable to that of the GNSS and VLBI delays (e.g., Böhm et al., 2009).

For the non-hydrostatic component, the delay can be expressed by:

$$d_{nh}^z = 10^{-4}(5.316 f_{nh}(\lambda) - 3.759 f_h(\lambda))\frac{e_s}{f_s(\phi, H)} \tag{4}$$

where $d_{nh}{}^z$ is the zenith non-hydrostatic delay in meters, e_s is the surface water vapor pressure, and f_{nh} is the dispersion formula for the non-hydrostatic component. For the humidity of 100% the non-hydrostatic delay equals to 0.8 mm, 1.8 mm, and 10.0 mm for the temperature 0°, 10°, and 40 °C, respectively. This means that the SLR observations are almost two orders of magnitude less sensitive to the wet part of the troposphere delay than the microwave GNSS and VLBI observations. Therefore, the meteorological records at the SLR stations are typically sufficient to estimate the delay of a sufficient quality, at least in the zenith direction.

Mendes and Pavlis (2004) concluded that these zenith delay models have overall RMS errors for the total zenith delay below 1 mm across the whole frequency of spectrum for more than 90% stations from the comparison assessments of the zenith models with respect to the ray tracing for the most used wavelengths in the SLR solutions. The comparison for the frequency of 532 nm, which is used by the majority of the SLR stations, shows that the Mendes and Pavlis (2004) troposphere delay model introduces a bias of 0.1 mm with the standard deviation of 0.6 mm in the zenith.

The currently recommended mapping function does not distinguish the hydrostatic and non-hydrostatic delays. The same function is applied to the total atmospheric refraction using the function for the hydrostatic part, namely:

$$d_{atm} = d_{atm}^z \cdot m(e) \tag{5}$$

where $d_{atm}{}^z$ is the total zenith propagation delay and $m(e)$ is the mapping function. Mendes et al. (2002) derived a formula, named FCULa, based on a truncated form of the continued fraction in terms of 1/sin (e).

Marini (1972), normalized to unity at the zenith:

$$m(e) = \frac{1 + \frac{a_1}{1 + \frac{a_2}{1 + a_3}}}{\sin e + \frac{a_1}{\sin e + \frac{a_2}{\sin e + a_3}}} \tag{6}$$

The same formula is used for the radio and microwave techniques, but with different parameters a_n. The model described by eq. (5) is currently recommended by the International Earth Rotation and Reference Systems Service (IERS) 2010 Conventions (Petit and Luzum, 2011) and is used in the SLR operational products by all International Laser Ranging Service (ILRS) Analysis Centers (Pearlman et al., 2002).

Hulley and Pavlis (2007) developed a technique for the computation of the total atmospheric delay for the SLR observations by the three-dimensional atmospheric ray tracing with meteorological fields from the atmospheric infrared sounder, which takes into account the asymmetry of the tropospheric delay over the SLR stations. This technique has been verified using two years of the SLR data from LAGEOS 1 and 2 for ten SLR stations. The method developed by Hulley and Pavlis (2007) requires a numerical integration along the path of a laser pulse starting at the surface and passing through the atmosphere to the geodetic satellites such as LAGEOS. For this purpose NWM of high spatial and