GEOCENTRE MOTION: TERMINOLOGY AND MEASUREMENT ASPECTS

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***Abstract**: Changes in eustatic sea level and ice mass are determined with respect to the geocentre, which has become an important geodetic parameter in the context of increasing interest in global climate change. The geocentre represents the origin of terrestrial reference frames (TRFs) and is most commonly defined as the centre of mass of the Earth system (CM), including the solid Earth, oceans, continental ground water, the atmosphere, and the cryosphere. Alternative definitions of the origin of a TRF and, implicitly, approximations of the Earth's centre of mass are the centre of mass of the solid Earth (CE), the centre of surface figure (CF) and the centre of network (CN). Geocentre motion is the temporal variation of the vector offset between the origins of two TRFs and can be observed using space geodetic techniques or predicted by geophysical models. This paper reviews the terminology around geocentre motion and the approaches used to estimate it.*

***Keywords:** geocentre motion, reference frame, centre of mass, mass redistribution*

1. Introduction

Terrestrial reference systems (TRSs) are fundamental to geodesy in particular and to geosciences in general because they provide the framework for modelling the gravity field of the Earth, navigation, positioning, as well as for the separation and interpretation of global scale geophysical phenomena. Modern TRSs are four-dimensional by nature, each being defined by an origin, a scale, and a conventionally chosen orientation together with its time evolution. The origin of a geocentric TRS (GTRS) is assumed to coincide with (or be close to) the centre of mass of the Earth system (CM), including the solid Earth and its fluid envelope (FE), i.e. the hydrosphere (oceans and continental ground water), the atmosphere, and the cryosphere. A terrestrial reference frame (TRF) represents the realisation of a TRS through a set of physical points fixed to Earth's crust and with precisely determined coordinates and velocities at a reference epoch (Petit and Luzum, 2010).

The International Terrestrial Reference System (ITRS) is the GTRS realised and maintained by the International Earth Rotation and Reference Systems Service (IERS). To date, twelve realisations of the ITRS were published, the most recent of which is denoted as ITRF2008 (Altamimi et al., 2011). The ITRF2008 origin exhibits zero translations and translation rates at epoch 2005.0 relative to CM, determined by the weighted mean of satellite laser ranging (SLR) time series of station positions and modelled as a secular (linear) function of time. While ITRF2008 and ITRF2005 agree well in terms of the translation rates of the frame origins, the large Z-translation rate of 1.8 mm/yr between ITRF2000 and ITRF2005 origins prompted several authors to conclude that the ITRF2000 origin is imprecisely determined (Altamimi et al., 2011; Argus, 2007; Métivier et al., 2010).

Other possible definitions of the origin of a TRF are the centre of mass of the solid Earth (CE), the centre of surface figure (CF), and the centre of network (CN), as illustrated in Fig. 1. Farrell (1972) derived the load Love numbers in the CE frame, which is predominantly used in the geophysics community, but it has the disadvantage of being inaccessible to observation (Blewitt, 2003). The CF frame closely approaches CE (Dong et al., 1997) and is theoretically realised by a uniformly distributed and infinitely dense network of stations and their velocities. However, due to its ideal character, CF is substituted in practice by CN (Wu et al., 2002), a more realistic approximation of Earth's centre of mass considering the sparseness and asymmetric distribution of satellite tracking networks. As argued by Dong et al. (2003), the kinematic model-dependent ITRF origin is just a CN, which resembles CM at secular timescale and CF at seasonal and shorter timescales starting with the ITRF2000 revision and CF at all timescales in previous versions of ITRF. Significant errors are introduced in the inversion for degree-one surface load coefficients and geocentre motion from GPS data when CF is equated with CN (Wu et al., 2002).

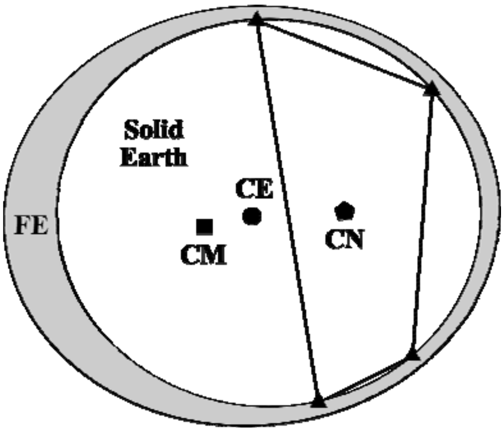

Fig. 1. Illustration of the possible geocentre definitions (adapted from Tregoning and van Dam, 2005)

The definitions of the geocentre and the geocentre motion (or variation) are inconsistent in the literature, especially in early studies on the topic. CM is the most common definition of the geocentre (Chen et al., 1999; Collilieux et al., 2009; Crétaux et al., 2002; Feissel-Vernier et al., 2006; Petit and Luzum, 2010; Watkins and Eanes, 1997; Wu et al., 2002), but CF (Métivier et al., 2010) and CE as a rebound-adjusted geocentre (Argus, 2007) are also used to denote the geocentre. The geocentre motion is generally described as the temporal variation of the vector offset (translation or displacement) between the origins of two TRFs, either CM with respect to CF (Collilieux et al., 2009; Crétaux et al., 2002; Feissel-Vernier et al., 2006; Petit and Luzum, 2010; Swenson et al., 2008; Wu et al., 2002, 2011, 2012) or CF relative to CM (Greff-Lefftz, 2000; Dong et al., 1997, 2003; Klemann and Martinec, 2009; Lavallée et al., 2006; Métivier et al., 2010; Vigue et al., 1992). Some studies neglected the small vector displacement of CE with respect to CF, mostly due to degree-one deformation, thus assuming the geocentre motion CM-CF equivalent to CM-CE (Chen et al., 1999; Watkins and Eanes, 1997). CM-CF and CF-CM are opposite vectors.

In this paper, we briefly review the theory of geocentre motion. Section 2 discusses the geophysical origins of geocentre motion and its geodetic implications. The current methods used for geocentre motion estimation are reviewed in Section 3, while Section 4 provides the conclusions of the paper.

2. Causes and implications

Irrespective of its definition, the geocentre displays variations at several timescales. Tidal diurnal and semi-diurnal variations are accurately modelled and agree well with predictions of ocean tide models (Watkins and Eanes, 1997). Non-tidal seasonal motion, predominantly at annual, but also at semi-annual timescale is due to surface mass redistribution within the Earth's fluid envelope. Crétaux et al. (2002) analysed the non-tidal inter-annual signal, which is also caused by surface mass redistribution but seems to be poorly determined. Mass redistribution within the Earth's interior resulting as a combined effect of geophysical and geodynamic phenomena such as glacial isostatic adjustment (GIA), tectonic plate motions, mantle and long-period climate dynamics determines geocentre motion at secular timescale. Surface and internal mass redistribution also alter Earth's rotation and perturb its gravity field.

Most studies on geocentre motion focused on the seasonal signal which is more accurately determined than the secular signal mainly due to the inability to directly observe internal mass redistribution. Secular geocentre motion was previously determined only from geophysical models (Greff-Lefftz, 2000; Klemann and Martinec, 2009; Métivier et al., 2010). Theoretically, apart from inherent measurement errors, geodetic solutions of geocentre motion account for the combined effect of all geophysical processes that cause mass to redistribute on and within the Earth. The secular signal equals the difference between geocentre variations derived from space geodetic observations and the seasonal signal induced by surface mass redistribution. Unfortunately, continental ground water mass, which is the largest contributor to the seasonal signal, is still highly uncertain.

An important contributor to secular geocentre motion is GIA. To date, several authors predicted geocentre motion caused by GIA. By using the glaciation history ICE-3G, Greff-Lefftz (2000) found the contribution of GIA to geocentre motion (defined as CF-CM) to vary between 0.2 and 0.5 mm/yr depending on the Earth's viscosity profile. Argus (2007) obtained a velocity between CM and CE induced by GIA lower than 0.1 mm/yr, by considering the Earth model VM2 and the glaciation history ICE-5G. The dependence on the Earth model and the glaciation history is also emphasised by Klemann and Martinec (2009), who predicted a present day GIA-induced geocentre motion (CF–CM) between 0.1 and 1 mm/yr. The vector is pointing towards east of Hudson Bay and its magnitude and direction are equally influenced by the adopted lower mantle viscosity and glaciation history. Variations in the upper mantle viscosity and the lithospheric thickness have minimum impact on the geocentre motion. The secular displacement of the geocentre due to present day global ice melting and sea level rise was estimated to range between 0.3 and 0.8 mm/yr, which can be added to the GIA-induced geocentre velocity to give a secular geocentre velocity of roughly 1 mm/yr (Métivier et al., 2010).

By conservation of linear momentum, the physical principle that governs geocentre motion, CM is static in inertial space when no net external forces are acting on the Earth system. Accordingly, CM is the most appropriate frame for modelling satellite dynamics and SLR observations. Circular satellite orbits are centred at CM, while in the case of an elliptical orbit CM is one of the two foci. Global navigation satellite systems (GNSSs) satellite orbits are nearly circular.

Global mean sea level and ice mass changes are determined with respect to the geocentre. Geocentre modelling errors propagate into estimates of sea level and ice mass changes. Thus a submillimeter level of accuracy of the geocentre translation and translation rate is required to avoid misinterpretation of global scale geophysical processes. Furthermore, high accuracy geocentre motion estimates can be used to place constraints on models involving global mass redistribution (Dong et al., 1997).

3. Geocentre motion estimation

Geocentre motion can either be predicted by geophysical models or observed using space geodetic techniques. Atmospheric surface pressure, ocean bottom pressure (OBP) as output of ocean models, and continental water mass (soil moisture and snow depth) are commonly used to estimate the annual and semi-annual components of the geocentre motion (Chen et al., 1999; Crétaux et al., 2002; Dong et al., 1997; Feissel-Vernier et al., 2006; Moore and Wang, 2003). Estimates from atmospheric loading models are generally in good agreement with each other. However, large differences are recorded between predictions from OBP and particularly from continental water mass, which is difficult to quantify compared to the other two main contributors (Dong et al., 1997).

Historically, the following three methods have been used to estimate geocentre motions from geodetic observations: (1) the dynamic approach, (2) the network shift approach, also known as the geometric approach, and (3) the degree-one deformation approach. The proportionality between the coordinates of Earth’s centre of mass and the degree-one coefficients of the spherical harmonic expansion of Earth’s gravitational potential (Hofmann-Wellenhof and Moritz, 2006) constitutes the basis of the dynamic approach. The network shift approach models the three components of the geocentre motion as translation parameters in a seven-parameter similarity transformation utilised to align two TRF. Geocentre motion is inferred from degree-one mass load coefficients using the degree-one deformation approach. Lavallée et al. (2006) merged the network shift approach (equivalent to the dynamic approach under minimal constraints) and the degree-one deformation approach into a unified model used to derive geocentre motion from Global Positioning System (GPS) data. The unified method is demonstrated to perform better than individual approaches when a full weight matrix is used. A larger disagreement between geodetic estimates of geocentre motion can be observed than in the case of predictions from loading models.

The most often employed space geodetic method for observing geocentre motion is SLR (Crétaux et al., 2002; Chen et al., 1999; Feissel-Vernier et al., 2006; Moore and Wang, 2003). Other dynamic techniques such as GPS (Lavallée et al., 2006; Vigue et al., 1992; Wu et al., 2002) and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) (Crétaux et al., 2002; Feissel-Vernier et al., 2006) were also used, the latter having the advantage of the most uniformly distributed tracking network. Despite this, DORIS geocentre motion estimates are the least reliable, particularly for the Z-component (Altamimi et al., 2011). Although the Gravity Recovery and Climate Experiment (GRACE) is inherently insensitive to long-wavelength degree-one deformation terms, Swenson et al. (2008) solved for geocentre motion using a combination of GRACE data and OBP. The degree-one deformation approach can be used to determine geocentre motion using data from the non-satellite technique Very Long Baseline Interferometry (VLBI), as distances between telescopes are modified by elastic loading of the Earth. The Z-component of the geocentre motion is the most poorly determined by any technique due to polar gaps in the satellite constellations and the limited number of tracking stations located at high latitudes.

SLR is acknowledged to be the most reliable space geodetic technique for determining geocentre motion. Nevertheless, an assessment of the ITRF origin accuracy proves difficult due to fact that only SLR observations are used to realise the origin. Translations of the ITRF origin relative to CM, which amount to approximately 1 mm/yr, are only a measure of the internal inconsistency of the ITRF (Wu et al., 2011). Collilieux et al. (2009) militate in favour of a multi-technique data combination and illustrate that SLR and GPS are complementary techniques in terms of geocentre motion estimation.

Care must be taken when comparing SLR geocentre motion results with predictions of geophysical models. As argued by Collilieux et al. (2009), due to the imperfect configuration of the tracking network SLR estimated network translations and geocentre motion are distinct from each other. Their difference is known as the network effect and is dominated at sub-decadal timescales by loading signals. Moreover, the degree-one deformation approach to geocentre motion estimation suffers from the aliasing of loading signals (Wu et al., 2002). Neglected higher-degree load components contained especially in the global annual hydrological cycle alias into the degree-one terms and the method yields inaccurate results.

4. Conclusions

Geocentre motion driven by mass transport at the surface and within the Earth is one of the most challenging research topics debated in geodetic and geophysics communities. Estimates of geocentre motion components can be derived by ground-based tracking of Earth-orbiting satellites or as predictions from geophysical models. A reconciliation of geodetic and geophysical results is possible at some extent, but there are still no secular geocentre motion estimates from geodetic measurements due to the shortness of the available time series. High accuracy geocentre motion estimates are required in climate modelling to avoid misinterpretation of global scale geophysical phenomena and constrain models involving global mass redistribution. Instantaneous geocentre motion is currently insufficiently constrained to be used in geodetic or geophysical applications.

The ITRF could be improved by using a multi-satellite data integration model for geocentre motion estimation, which would balance out the limitations of some satellite geodetic techniques. Adopting a trustworthy model for the Z-component's annual variation in future realisations of the ITRS may also prove beneficial.

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