Global NAVIGATION Satellite System Contribution for Observing the Tectonic Plate Movements: Status and Perspectives

Lect. Oday Yaseen Mohamed Zeki
Instructor
Department of Surveying Engineering
College of Engineering
Baghdad University
E-mail: oday_alhamadani@hotmail.com

ABSTRACT

The long-term monitoring of land movements represents the most successful application of the Global Navigation Satellite System (GNSS), particularly the Global Positioning System. However, the application of long term monitoring of land movements depends on the availability of homogenous and consistent daily position time series of stations over a period of time. Such time series can be produced very efficiently by using Precise Point Positioning and Double Difference techniques based on particular sophisticated GNSS processing softwares. Nonetheless, these rely on the availability of GNSS products which are precise satellite orbit and clock, and Earth orientation parameters. Unfortunately, several changes and modifications have been made periodically on the policy of producing these products which led to degradation in the consistency of these products over time. For the long term monitoring of land movements, it is essential that any such developments and changes can also be used to produce improved products that go back in time, to enable the homogeneous reprocessing of archived observation data. This paper deals with two main themes. Firstly, it demonstrates the significant and imperative role of the GNSS in geological applications by addressing major global and regional studies of the Earth's deformation which represent one of the main and essential applications in satellite geodesy. The role of the continues GPS measurements in this application is highlighted and discussed for modeling global and regional plate motions and modeling Glacial Isostatic Adjustment. Secondly, this paper locates the most important obstacles which stand behind the inability to use the GNSS in applications of long-term monitoring of land movements.

Key words: land movements, GNSS, deformation, glacial isostatic adjustment

اسهامات الانظمه الملاحيه العالميه لمراقبة حركة الصفائح التكتونيه: الحاله والمنظورات

د.م عدي ياسين محمد زكي
قسم هندسة المساحه
كلية الهندسة/جامعة بغداد

الخلاصة

المراقبه طويلة الامد لحركة القشره الارضيه تمثل من اهم وابرز تطبيقات الانظمه الملاحيه العالميه (GNSS) وخصوصاً نظام تعين المواقع العالميه (GPS). حيث شهدنا مؤخرا العديد من البحوث والدراسات في هذا المجال. بيد ان عملية مراقبة حركة القشره الارضيه بأستخدام الانظمه الملاحيه العالميه تعتمد بكل اساسي على توفّر سلسله زمنيه لمواقع ارضيه دقيقه ومتجانسه ومستقره لفترات طويله الامد لمحطات ارضيه منتشره حول العالم. السلسله الزمنيه للمواقع الارضيه يمكن ان تُنتج بشكل فعال عن طريق تقنيات تعيين المواقع الدقيقه والمواقع التفاضليه باستخدام برامج المعالجه الدقيقه لارصادات التوابع الملاحيه. بيد ان هذه العمليه تعتمد كلياً على توفّر معلومات دقيقه لمواقع الاقمار الصناعيه و تصحيح ساعات القياس ومعاملات نمذجة حركة محور دوران الارض. ولكن بسبب التغيرات والتحديثات العديده والمستمره على اساليب حساب هذه المعلومات

أدى ذلك الى انحطاط كبير وملحوظ في مستوى التجانس والاستقراريه في دقة هذه المعلومات والذي اثر بشكل سلبي على اعتماد هذه المعلومات في حساب المواقع الدقيقه للمحطات الارضيه واستخدامها في رصد حركة القشره الارضيه.
هذا البحث يسلط الضوء على موضوعين رئيسيين في موضوع المراقبه طويلة الامد لحركة القشره الارضيه باستخدام ال GNSS. الموضوع الاول يعرض الدور الكبير والفعال لل GNSS في التطبيقات الجيولوجيه عن طريق الاشاره الى اهم الدراسات المنجزه (بمقياس عالمي ومحلي) في موضوع التشوهات الارضيه والتي تعتبر من المواضيع الاساسيه في علم جيوديسيا التوابع الملاحيه. وهذا الموضوع يشمل عرض ومناقشة اهم الدراسات والبحوث المنشوره في استخدامات ارصادات ال GPS المستمره لنمذجة حركة الصفائح التكتونيه و Glacial Isostatic Adjustment . اما الموضوع الثاني فانه يبحث في اهم المعوقات الاساسيه التي تقف وراء عدم امكانيه استخدام قياسات ال GNSS بشكل دقيق في مراقبة حركة القشره الارضيه.

الكلمات الرئيسية: القشره الارضية, التشوه الارضي, النظام الملاحي العالمي.

1. INTRODUCTION

The expression “long-term monitoring of land movements” covers an extensive range of geophysical phenomena studies using GNSS. In general, this is based on the interpretation of time series of the changes in continuous high precision horizontal and vertical positions over a period of time. Because the long-term monitoring of land movements based on GPS data is one of the main objectives of this paper, a considerable amount of literature that has been published on this subject is presented and highlighted in this study.

Owing to the fact that the Earth’s deformation leads to continuous changes in the geometric configuration of geodetic networks, the determination of the Earth’s deformation parameters has become one of the main and essential applications in geodesy. In the past, classical geodetic surveys were used to establish horizontal and vertical positions. Many drawbacks are associated with these techniques, e.g. their high-cost and time-consuming nature due to the effort required. In addition, the monitoring of the Earth’s deformation over vast areas requires precise and simultaneous measurements over long baselines, and classical geodesy does not provide this capability. Furthermore, because the horizontal and vertical positions are calculated from different types of measurements, which are collected at different times and places, this adds a complexity in the analysis of these time series. Consequently, research on the Earth’s deformation, since three decades ago, have tended towards using space geodetic techniques to estimate velocities over certain observation periods, based on: (1) Satellite Laser Ranging (SLR) **Smith et al., 1990**, and **Sengoku, 1998**; (2) Very Long Baseline Interferometry (VLBI) **Robaudo** and **Harrison, 1993**, and **Sato, 1993**; (3) GPS **Dixon et al., 1991, Dixon, 1993, Argus** and **Heflin, 1995, Larson et al., 1997, Segall** and **Davis, 1997, Prawirodirdjo** and **Bock, 2004, Mazzotti et al., 2007, Bouin** and **Wöppelmann, 2010,** and **Hammond et al., 2011**; (4) Doppler Orbitography and Radiopostioning Integrated by Satellite (DORIS) **Cazenave et al., 1992, Soudarin** and **Cazenave, 1993,** and **Soudarin** and **Cazenave, 1995**.

Recently, the use of continuous GPS (CGPS) data has received considerable interest as the essential means of geodetic investigation in comparison with the other space geodetic techniques for many reasons: first of all, GPS hardware and software are readily available and relatively inexpensive in comparison with the other techniques, which necessitate higher budgets; secondly, because some geodetic monitoring work, like earthquakes and volcanoes, require continuous, sub daily, and instantaneous observations, the GPS technique provides this capability due to continuous satellite coverage **Elósegui et al., 1995**; finally, the mobility of field GPS equipment which only requires small surveying teams **Segall** and **Davis, 1997**. In summary, studies of the Earth’s deformation have been widely carried out based on GPS data, especially after the dramatic increase in the number of CGPS instruments installed regionally and globally around the world.

In 1993, CGPS data was firstly used by **Bock et al., 1993** and **Blewitt et al., 1993** for the Southern California Permanent GPS Geodetic Array (PGGA) to estimate the co-seismic displacements resulting from the Ms 7.5 Landers, California earthquake on 28th June 1992. **Bock et al., 1993** used ten weeks of PGGA data to demonstrate the possibility of using GPS data to detect the seismic deformation before, during and after the earthquake. They showed that there was no pre-seismic displacement, remarkably consistent co-seismic displacements at all PGGA stations, and post-seismic displacement at one PGGA station. **Blewitt et al., 1993,** then confirmed the results of **Bock et al., 1993,** through the detection of pre-seismic, co-seismic, and post-seismic displacements with millimeter precision by analyzing IGS data over three months. Consequently, many individuals, institutions, and geodetic agencies have established CGPS stations around the world which are coordinated by the International GNSS service (IGS). The IGS network is being used to routinely monitor the Earth's deformation and many significant achievements have increased the growth in the research into long-term monitoring of land movements with GPS. Since then, with the advent of the production of GPS satellite and receiver clock products as individual products, the methodology of Precise Point Positioning (PPP) has also been enabled in many software packages to provide three-dimensional absolute positions with a high-level of accuracy based on the introduced satellite orbit and clock, and the Earth Rotation Parameters (EOP) products.

In general, both of the methodologies of double-difference relative positioning and PPP can be employed for the long-term monitoring of land movements, but they depend entirely on the availability of consistent and homogeneous precise satellite orbit and clock, and EOP products over certain periods of time. In addition to the space geodetic techniques of SLR, VLBI, GPS, and DORIS, remote sensing technologies like Interferometric Synthetic Aperture Radar (InSAR) and Light Detection and Ranging (LiDAR) techniques (terrestrial, airborne, and satellite) have also taken on a significant role that cannot be ignored in the investigations of Earth’s deformations . See **Chang et al., 2007, Sousa et al., 2010,** and **Wei et al., 2010** for InSAR technique, and **Kayen at al., 2006, Muller** and **Harding, 2007,** and **Jian-Qing** and **Ting-Chen, 2010,** for LiDAR technique.

This study addresses major global and regional studies of the earth’s deformation which represent one of the main and essential applications in geodesy. The role of the CGPS measurements in this application will be highlighted and discussed for modeling global and regional plate motions; and modeling Glacial Isostatic Adjustment.

2. DEFORMATION of the EARTH: A BRIEF INTRODUCTION

The plate tectonic theory divides the Earth's lithosphere into a number of rigid plates (eight major and many minor plates) based on data from paleomagnetics, which is the study of the observations of the Earth’s magnetic field, and seismological studies **DeMets et al., 2010**. Furthermore, both the continental drift and sea-floor spreading hypotheses contributed to the development of the theory of plate tectonic. These tectonic plates continually move relative to one another at one of three kinds of plate boundaries: convergent; collisional; or transform.

In general, geologists and geodesists classify the Earth’s crustal deformations under two terms, global and regional deformations. The global deformations stand for all of the kinds of deformations that occur on very large areas like tectonic motions, whereas, the regional deformations involve smaller areas like plate boundaries. Under this concept, both the deformations of continents and sea-floor movement, which correspondingly result from the continental drift and sea-floor spreading hypotheses, can be presented as global deformations. In general, the tectonic motions which cause global deformations lead to regional deformations which occur along plate boundaries, such as: earthquakes; faults; volcanoes; and oceanic trench formation **Prawirodirdjo** and **Bock, 2004**.

In the past, many global plate models were developed to describe plate motions, see **Larson et al., 1997**. In general, these models were based on data of spreading rates, transform fault azimuths, and earthquake slip vectors, which represent an average over a long-period of time **DeMets et al., 1990**. For more than two decades, many global plate motion models have then been developed to describe the current plate motions (see the UNAVCO website (http://www.unavco.org/unavco.html) which provides the latest models with their associated reference frames).

3. GLOBAL PLATE MOTION MODELS

Global plate motion models have shown great success in the interpretation of large scale plate motions. The global plate motion models are classified into two types, absolute plate motion models and relative plate motion models. These global plate motion models, in general, are realized using different methods, such as No-Net-Rotation (NNR) frame, hotspot data, and space geodetic measurements like VLBI, SLR, DORIS and GPS. However, such space geodetic techniques have also been used in the recent decade to observe the velocities of globally distributed CGPS stations for the estimation of the rotation vectors of rigid plates. The combination between the global plate motion model and any of these methods leads to a geophysical kinematic model that can describe the rigid plates' motion over a period of time (based on the used method) **Larson et al., 1997**.

Absolute plate motion models define the plate motions with respect to the Earth's deep interior (mesosphere). In contrast, relative plate motion models describe the plate motions with respect to an arbitrary fixed tectonic plate. Generally, these models can be formed based on various kinds of data, for instance, geological seismic data and conventional or space geodetic measurements; where space geodetic measurements can be effectively employed to obtain relative velocity estimates to sufficiently high precision over long-base lines.

One of the main initial global plate motion models that represented the basis for developing more recent models was NUVEL-1. This model, which has been widely used, was developed by **DeMets et al., 1990.** It depends on earthquake slip vectors and the average transform fault azimuths and spreading rates for the last 3Myr to predict tectonic plate velocities and provide the absolute angular velocity vectors for thirteen tectonic plates. **DeMets et al., 1994** recalibrated the NUVEL-1 model based on the latest amendments to the geomagnetic reversal time scale at that time. They found that by multiplying the NUVEL-1 angular velocities by a calibration factor (0.9562), results comparable with other rates of motion, especially those estimated based on the space geodetic measurements, were obtained. They pointed out that the motion rates for NUVEL-1A are faster on average by only 2% when compared to space geodetic measurements, whereas they were faster by about 6% with NUVEL-1 model.

The models NUVEL-1 and NUVEL-1A reference the plate motion to a No-Net-Rotation (NNR) frame to create a geophysical kinematic model (NNR NUVEL-1 and NNR NUVEL-1A) that can be used to describe the plate motions at any epoch over millions of years. In the NNR frame, the angular velocities for each plate are calculated with respect to the average of angular velocities for all plates. NNR NUVEL-1A model was widely used in the 1990s, but it has some weaknesses. **Drewes** and **Angermann , 2001** stated that the NNR NUVEL-1A model does not meet the condition of NNR for two reasons. Firstly, it can be used effectively to describe the plate motions over the last 3 Myr but is not valid for the present time, which can yield biased velocity estimates for some plate pairs due to the continuous change in their speed and direction, for example the Nazca-South America plates **Angermann et al., 1999**. Secondly, the NNR NUVEL-1A model cannot be considered as a full global model due to lack of coverage for some zones, like the Mediterranean, the Pacific belt, and Japan. For these two reasons, **Drewes** and **Angermann, 2001** computed two different kinematic models based on space geodetic observations to estimate the angular velocities for globally distributed stations. The first model, was called the ITRF2000 kinematic model, and was based on using 405 ITRF2000 station velocities to estimate the motion of eleven major plates. While for the second kinematic model, which was called Actual Plate Kinematic Model (APKIM), they combined the space geodetic observations from SLR, VLBI, and GPS to compute 279 station velocities and estimate the velocity vectors (Euler vectors) for twelve tectonic plates. Both of these models were constrained to no-net-rotation.

In addition to the NNR NUVEL-1A deficiencies referred to by **Drewes** and **Angermann, 2001**, **Sella et al., 2002** mentioned that the NNR NUVEL-1A may also be biased due to insufficient kinematic data, for example the relative motion of America with respect to the Pacific plate**,** **DeMets** and **Dixon, 1999** and the relative motion of the Caribbean plate with respect to the North and South American plates **Pérez et al., 2001**. Furthermore, **Sella et al., 2002** pointed to the existence of systematic errors in the NNR NUVEL-1A model as a result of depending on sea-floor spreading rates which are calculated from sea-floor magnetic data that do not reflect the full plate rate as a result of tectonic complexities. They developed a new global plate motion model for REcent plate VELocities (REVEL) based on CGPS data over the period January 1993 to December 2000 to estimate the relative velocities for 19 plates and continental blocks with respect to ITRF97 **Sella et al. , 2002.** For this effort, GIPSY OASIS II V.5.0 was used for PPP with non fiducial GPS satellite orbit and clock products from JPL **Zumberge et al., 1997**. Moreover, they assessed the plate rigidity though the use of strict and autonomous estimates for CGPS velocity errors which are propagated to the relative angular velocity estimates.

Prawirodirdjo and **Bock** used a methodology similar to **Sella et al., 2002** to develop a global plate motion model. They analyzed CGPS observations from 106 globally distributed stations over the period from January 1991 to July 2003 to estimate velocities for seventeen major and minor plates. They aligned their solution with IGS00, the IGS realization of ITRF2000 **Altamimi et al., 2002.** Based on a seven-parameter similarity transformation and they applied a no-net-rotation condition. This is due to the fact that the latter (ITRF2000) maintained a no-net-rotation condition through aligning its orientation time estimates to NNR NUVEL-1A **Altamimi et al., 2003**. In addition, the semi-annual and annual effects, as referred to by **Nikolaidis, 2002** which were not considered by **Sella et al., 2002** modeled to improve the precision of the CGPS velocity estimates.

Most recently, **DeMets et al., 2010** presented a new global geological model, called MORVEL, to describe the angular velocities for twenty five tectonic plates. The MORVEL model combines two kinds of data: it depends on sea-floor spreading rates and fault azimuths data to provide the angular velocity estimates for 19 plates surrounded by mid-ocean ridges, including all major plates; and CGPS station velocities and azimuthal data for six smaller plates. In general, the MORVEL model is more useful than NUVEL-1A as it includes many small plates which are not included in NUVEL-1A, especially in Asia and the western Pacific. Thus, the MORVEL model is recommended to be used for studying the Earth's crustal deformation in these areas. Furthermore, **DeMets et al., 2010** stated that significant differences can be observed between

NUVEL-1A angular velocities and MORVEL angular velocities. Generally, they pointed that the historical description of the current plate motion that can be estimated by the MORVEL model is more accurate than when using the NUVEL-1 and NUVEL-1A models. This conclusion was realised based on carrying out least-squares differences between angular velocities estimated from GPS observations and those for the MORVEL, NUVEL-1, and NUVEL-1A models, with the MORVEL angular velocities being nearer to those estimated from CGPS.

Another recent model is GEODVEL 2010 which has been released by **Argus et al., 2010.** This model was determined based on space geodetic observations from SLR, VLBI, GPS, and DORIS data. The relative angular velocities of eleven major tectonic plates were estimated simultaneously assuming that the earth's center is fixed in ITRF.

4. PLATE MOTION STUDIES BASED on GPS DATA

Time series of regionally or globally distributed geodetic network based on observations obtained with GPS have been employed for investigating different-scales of geophysical phenomena. For example, **Dixon et al. 1991** estimated the Pacific-North American plates relative motions based on GPS observations from campaigns carried out in 1985 and 1989 in the Gulf of California. In addition, this relative motion was estimated based on VLBI by **Argus** and **Gordon 1991a.** and in the global plate motion models NUVEL-1 and NUVEL-1A **DeMets et al., 1990, DeMets et al., 1994**. **Argus** and **Gordon 1991b** showed that the Pacific-North American relative plate motion based on VLBI is faster than the relative motion predicted by NUVEL-1. Afterward, **Dixon, 1993** estimated the Cocos-Caribbean plates relative motion using GIPSY software based on the GPS observations from central and south America campaigns carried out in 1988 and 1991 for the Cocos-San Andres baseline and Cocos-Liberia baseline (Cocos Island on the Cocos plate and San Andres Island and Liberia on the Caribbean plate).

Since July 1992, when the nominal 24-GPS satellite constellation was completely realised, many geodynamics investigations have been carried out based on GPS observations. Some of the applications of such data were demonstrated initially by **Blewitt, 1993** who studied the development stages of the GPS user hardware from the early 1970s to the early 1990s. Furthermore, **Blewitt 1993** highlighted methods of assessment of GPS precision and accuracy which focused on repeatability of the coordinate estimates, comparison with other coordinate estimates from different space geodetic techniques, like VLBI and SLR, and the use of statistical analysis. Additionally, **Blewitt, 1993** detailed the precision, technique and network scale and density required for each geophysical application, (see **Table 1**) **Blewitt, 1993**.

Argus and **Heflin 1995** used the CGPS data for 43 globally distributed stations over four years to estimate fifteen relative angular velocities between six major plates, and the relative motion between the plate boundaries at ten sites in plate boundary zones. They showed that the relative angular velocities between six major plates based on GPS data differ slightly from the corresponding relative angular velocities predicted from NUVEL-1A, which is based on average plate motion over the last 3 Myr. Furthermore, they concluded that the Pacific-Eurasian and Pacific-North American relative motions are faster than the corresponding relative motions predicted by NUVEL-1A. Thus, they supported the **Argus** and **Gordon, 1991b** inference that based on VLBI that the Pacific-North American relative motion has sped up over the past 3Myr.

The first effort to estimate the Antarctica plate motion based on space geodetic data was carried out by **Larson** and **Freymueller, 1995**. Three years of CGPS observations were used in this effort to estimate the angular velocities for seven IGS sites on the Australian, Pacific and Antarctica plates. They showed an agreement between their solution and the angular velocity predicted from the NNR NUVEL-1A kinematic model. **Larson et al., 1997** carried out a similar effort to that of **Argus** and **Heflin, 1995** but with more sites, more tectonic plates, and a longer time series. They estimated velocities for 38 globally distributed sites, based on analyzing one day per week of the CGPS observations collected over the period of time, from January 1991 to March 1996. They used the estimated station velocities to compute eight absolute angular velocities for eight tectonic plates and twenty eight relative angular velocities, and found an agreement within 95% confidence between the absolute angular velocities based on GPS with those predicted from NNR NUVEL-1A, except for the Pacific plate. In addition, an agreement was found between the relative angular velocity based on GPS for each plate pair with the corresponding one predicted from NUVEL-1A, except for some of those associated with the Pacific plate. To prevent aliasing systematic errors in the estimated station velocities which increases the complexity of the tectonic interpretations, **Larson et al., 1997** emphasized the necessity of analysing time series which are built on consistent, homogenous and precise data over the entire period of time. Consequently, they used the same models and strategies for this effort, see **table 2**, **Larson et al., 1997.**

Segall and **Davis 1997** surveyed the capability of employing the GPS technique for geophysical investigations to observe a wide range of different geophysical phenomena e.g. seismology, hydrology, volcanology, tectonic plate motion and Earth's crustal deformation at plate boundaries, and deformation related to Glacial Isostatic Adjustment (GIA), Earth rotation, and Earth mass distribution.

Regarding the combination between GPS and other geodetic techniques, in the early 1990s, the geophysical applications of radar interferometry gained massive attention. **Massonnet** and **Feigl, 1998** reviewed the geophysical applications that were published before 1998 and stated that the majority of the publications dealt with the geophysical monitoring of natural risks caused by earthquake, volcanoes, and glaciers. In addition, they presented some case studies of monitoring natural risk and environmental alterations related to landslides, subsidence, and agriculture

In recent years, space geodetic techniques have been employed in conjunction with the Interferometric Synthetic Aperture Radar (InSAR) technique (terrestrial, airborne, and satellite InSAR), to become a reliable means for monitoring the Earth's deformations. Airborne and satellite InSAR imagery can be used effectively to generate maps of deformation or digital elevation models based on two or more SAR images which cover the area of interest. Typically, this technique can be used to observe rapid centimetre-level changes in deformation for thousands of points in a relatively small area, while the GPS technique gives long-term stability and better temporal coverage , **Wei et al., 2010**. **Zerbini et al., 2007** stated that the main point from the combination between space geodesy techniques and InSAR technique is to complement the weaknesses of each technique through the strengths of the other technique.

5. GLACIAL ISOSTATIC ADJUSTMENT STUDIES

Over hundreds of thousands of years, a cycle of alternating glacial and interglacial conditions has happened as a result of the Earth's climate change with a periodicity of the order of 105 years. In the duration of a glacial period, the ice sheets grow at higher altitudes, due to low temperatures that lead to removal of water from the ocean basins and relative sea-level (RSL) falls. On the contrary, during the period of interglacial conditions, several of these ice sheets are melted, which leads to a return of water to the ocean basins and additional changes in the RSL because of the Earth's crustal deformation under the load of ice and water and the change in the gravitational potential of the Earth–ocean-ice system **Lambeck, 2004**. This periodic movement of water over the Earth's surface acts like a load upon the Earth's lithosphere. Consequently, the Earth's crust is deformed in response to the action of these forces. Earth's deformations caused by the change in ice-mass loading, are known as Glacial Isotactic Adjustment (GIA) or post-glacial rebound. GIA is defined, conventionally, as the global response of the solid Earth to the ice-mass redistribution that occurred during cycles of glaciation and deglaciation **Whitehouse, 2009**. The speed of this response is variable based on the viscosity of the mantle.

Many geophysical studies have been carried out on GIA to realize how this process can be modelled and understand the horizontal and vertical crustal deformations, and the changes in sea-level and the volume of the ice sheets, during the last glacial cycle **Peltier, 1998**. Furthermore, GIA involves changes in pole motion and Earth rotation **Mitrovica et al., 2001**.

For more than three decades, many studies have been achieved successfully for numerical modelling of GIA, especially in North America, Europe, and Australia. These numerical models have shown great success in representing GIA, especially after the introduction of additional constraints which have been made on GIA models, such as: absolute gravity (AG) measurements **Larson** and van **Dam, 2000,** and **Lambert et al., 2001**; geological sea-level records **Lambeck, 2004**; tide gauge records **Teferle, 2003**; and space geodetic measurements **Blewitt, 1993**. The latter playing a major role in providing a precise description to the structural features of the Earth's interior.

One of the initial projects established in support of this purpose was the BIFROST project (Baseline Inferences for Fenno-Scandinavia Rebound Observations, Sea-level, and Tectonics). This project was initiated in 1993 to detect the Earth's crustal deformations in Fenno-Scandinavia due to GIA. This project combines networks of CGPS receivers in Sweden and Finland. **Johansson et al. 2002** compared horizontal and vertical crustal deformations based on the BIFROST CGPS results over the period from 1993 to 2000, to predictions calculated from a high-resolution Fenno-Scandinavia deglaciation model proposed by **Lambeck et al., 1998**. They obtained an agreement in the order of 1 mm/yr between the maximum observed uplift rate and maximum predicted uplift rate, which is approximately 10 mm/yr.

Since 2002, such accurate GIA models (global and local scales) have become increasingly required by the Gravity Recovery and Climate Experiment (GRACE) satellites mission. GRACE data have been used to investigate exchange between the ice sheets and ocean basins' water, but this application requires accurate GIA models to detect signals of the horizontal mass distribution. Unfortunately, GIA models are uncertain, owing to a lack of sufficient constrains for the past glacial changes, and a lack of available measurements of surface velocities in the Polar regions. For these reasons, space geodetic measurements can be used to improve constraints on global and local GIA models, especially local GIA models which are formed based on specific ice distribution and lithosphere depths that can be estimated effectively using accurate CGPS measurements. **Johansson et al., 2002** pointed to the urgent need for a dense and robust CGPS network for obtaining accurate horizontal and vertical velocity estimates in order to observe the Earth's deformations.

Some studies have also been carried out on the greenland ice sheet. **Wahr et al., 2001, Dietrich et al., 2005** and **Wahr et al., 2001** studied vertical crustal motion of the Greenland ice sheet, using vertical velocities based on CGPS measurements taken at stations Kellyville and Kulusuk. For this effort, GIPSY OASIS II V.5.0 was used for PPP **Zumberge et al., 1997,** with GPS satellite orbit and clock products generated by the JPL AC based on analysing more than 40 globally distributed stations. These studies compared the vertical velocity estimates based on CGPS measurements with the corresponding estimates from absolute gravity observations and showed that these vertical velocity estimates are associated with the ongoing viscolelastic response of the Earth to changes in Greenland's ice mass. Later, **Khan et al.,** 2008 expanded the study carried out by **Wahr et al. 2001,** by taking account of seven more years of CGPS measurements at Kellyville and Kulusuk and including three additional CGPS stations

(Qaqortoq, Scoresbysund, Thule). The daily coordinates for these sites were again calculated based on GIPSY OASIS II's PPP strategy **Zumberge et al., 1997**. They found the vertical velocity estimates for Kellyville and Kulusuk differed from the estimates of **Wahr et al., 2001** and gave the reasons of using a different reference frame realisation and different models. In the meantime, **Dietrich et al., 2005** studied vertical crustal deformation in the west of Greenland by analyzing GPS measurements which were taken over a period from 1995 to 2002 at 10 locally distributed GPS stations in the area of interest; BSW5.0 software with double-difference strategy was used for this effort. They strongly emphasized the necessity of using consistent and homogeneous time series of GPS satellite orbit and EOP products to generate equivalently homogeneous station coordinate time series; a homogeneity that can only be reached when applying unique standards (models and reference frame) over the whole of the period of interest. Consequently, **Dietrich et al., 2005** stated that using the IGS products during the period under consideration would result in inhomogeneous results due to using different standards, so, they used the GPS satellite orbit products and EOPs from a first reprocessing of the global GPS network **Rothacher et al., 2004**.

In addition, many studies have been carried out to investigate the isostatic rebound to resolve the vagueness concerned with Antarctic deglaciation and enhance the uncertainties associated with velocity changes and lithosphere thickness. **Velicogna and Wahr 2002** showed that when adding CGPS measurements, vertical velocity estimates taken near or around the ice accumulation centers have noticeable effect on the improvement of the ice mass balance estimations and the postglacial rebound generated based on a combination of space-based observations of the gravity and altimetric height.

Raymond et al., 2004 analyzed the CGPS measurements taken over the period between November 1996 and January 2001 at two CGPS stations located in the Northern Transantarctic Mountains to study the three-dimensional velocity estimates in this area. For this study, they used GIPSY OASIS II V.5.0 and the PPP strategy. **Zumberge et al., 1997** stated that the uplift that they estimated was caused by GIA, and that the uplift estimated based on the CGPS measurements differed from predictions based on the global models of late Pleistocene deglaciation ICE-3G .**Tushingham and Peltier, 1991**, ICE-4G ,**Peltier, 1994**, and **Dietrich et al., 2004** analysed CGPS measurements from more than 20 stations distributed in Antarctica between 1995 and 1998 using BSW4.2 software to provide a regional densification solution for the ITRF2000. As they focused on the deformation of the Antarctic Peninsula, the estimated GPS stations velocities showed that the relative motion between the east and west of Antarctic does not exceed 2 mm/yr in the horizontal, with maximum uplift rates of about 10 mm/yr in the Northern Antarctic Peninsula. They also stated that even if the deformation signals are relatively small in the horizontal components, the GPS observations still provide constraints for GIA models.

Ohzono et al., 2006 analyzed CGPS measurements taken from 9 IGS stations distributed around Antarctica between 1998 and 2003. They used precise satellite orbit and clock, and EOP products provided by JPL to carry out a PPP processing strategy in GIPSY/OASIS II **Zumberge et al., 1997**. Their PPP horizontal components, which were referred to ITRF2000 and presented as coordinate time series, showed that the Antarctic plate motion can be explained as a rigid plate motion. While their vertical velocity estimates from most of processed sites appeared to be an effect of GIA. Furthermore, they concluded that none of the current GIA models could effectively reproduce their results for vertical crustal movement.

More recently, the level of uncertainty in the surface displacement (3-dimention) for the current local GIA models for Greenland and Antarctica ice sheets have been demonstrated by **King et**

al., 2010 who stated that improving GIA modeling necessitates massive effort due to the very short time period of the CGPS measurements.
In summary, with the advent of modern space geodetic techniques (SLR, VLBI, GPS, and DORIS), GIA has become observable along with other geodynamic signals which come from the changes in the Earth's global gravity field, variation in the Earth's rotation rates, and the geocentre motion **Chao et al., 2000**.

6. SUITABILITY OF GNSS FOR MONITORING OF THE EARTH'S DEFORMATION

One of the most significant current discussions in the crustal deformations studies is the application of GNSS to long-term monitoring of land movements. In general, this application is based completely on producing daily time series of the changes in positions of stations over a period of time. In recent years, the methodologies of double-difference relative (DD) or precise point positioning (PPP) have been used to investigate horizontal and vertical land movements at the millimeter level, and this has been referred to in the review of literature mentioned in this paper. However, these methodologies depend entirely on the availability of satellite orbit and clock, and Earth orientation parameter (EOP) products that are precise, homogeneous and consistent over such a period of time. Consequently, any lack in the accuracy, homogeneity, and consistency of these products will be an obstacle to employ GNSS for monitoring the land movements.
The International GNSS Service (IGS) represents the main source of post-mission, precise satellite orbit and clock, and EOP products. Since its beginning in June 1992, the IGS has provided high quality observation data and an uninterrupted series of its products as the standard for GNSS in support of Earth science research, multidisciplinary applications, and education. **Table 1** summarizes the GPS satellite products currently available through the IGS (http://igscb.jpl.nasa.gov/components/prods.html).

The IGS is continually trying to improve their products and gain a higher-level of accuracy by implementation of the latest and most sophisticated approaches for modeling the atmospheric delay. For example. in November 2006, significant improvements were made through the adoption of absolute antenna phase center models for both satellite and receiver antennas and the use of mapping functions based on numerical weather models, such as the Global Mapping Function (GMF) for the modeling of tropospheric delay. Furthermore, there have been periodic changes of International Terrestrial Reference Frame (ITRF), and the subsequent realization of the IGS reference frame. **Figure 1** shows the changes in the used reference frame for the generation of the IGS final products; on 2nd December 2001 it was changed from IGS97 to IGS00, on 11th January 2004 it was changed from IGS00 to IGb00, and finally, on 5th November 2006, it was changed from IGb00 to IGS05 **Teferle et al., 2007**.

However, such changes in the realization of the ITRF together with the significant enhancement of different models and processing strategies considered individually by the IGS Analysis Centers (ACs) have contributed to inhomogeneous and inconsistent products over time. Nevertheless, such improvements only really benefit short term applications, such as GNSS meteorology and future monitoring schemes. Furthermore, the continuous development and improvement of the processing software employed by the IGS ACs and the changes in the realization of the reference frame have also played a significant role in the refinement and improvement of IGS products. Moreover, due to the growing quantity and quality of GNSS observations and the improvement in the processing strategies which have been witnessed during the last decade, further effects had to be considered which were unthought-of in the past. Accordingly, several studies have pointed out that the accuracy of coordinate estimates can be adversely affected due to the insufficient modeling of the tropospheric delay, not taking into account higher-order ionosphere corrections, and applying different loading processes for both the GNSS product generation and coordinate estimation.

As a consequence, the IGS products are constantly evolving over time. For long-term monitoring, the ideal would be for such developments to be used to produce improved products not only for the future but that go back in time. This then enables the re-analysis of older observation data that has been continuously recorded and archived to obtain improved estimates of, for example, land movements. **Zumberge at al., 1997** mentioned the disadvantage of constraining different reference frames in the analysis of data from a global network to generate satellite products. Moreover, they pointed out the future necessity of reprocessing the global data to overcome the discontinuity problems. Therefore, a strong emphasis has been placed on the importance of re-analysing the GNSS archived observation data to generate accurate, consistent, and homogenous precise satellite orbit and clock, and EOP products over a long period of time.

The IGS made its first effort (repro1) to reprocess all the GPS observation data which were recorded and archived during the period between 1994.00 and 2007.99 as one of its core objectives to produce a fully accurate, consistent, and homogenous set of precise satellite orbit and clock, and EOP products **Ray, 2011**. IGS repro1 campaign was finalized in April 2010 **Gendt** and **Ferland, 2010**. **Alhamdani 2012** carried out an evaluation of the individual IGS repro1 ACs’ products as well as the IGS repro1 combined products. Two techniques were considered in this evaluation to investigate the consistency and the homogeneity of the re-processed GPS satellite orbit, clock and EOP products. In the first technique, the IGS repro1 orbit and available clock products were assessed individually over ten years (1998.0 to 2007), whereas in the second technique, PPP was considered to assess IGS ACs' products over the same period. One of the more significant findings to emerge from **Alhamadani, 2012** study is that an obvious improvement in the orbit products over ten years. Moreover, there is high level of consistency between some IGS ACs. However, **Alhamdani, 2102** pointed out that there is a clear problem and significant deviations in some IGS ACs due to wrong constraints in their solutions affecting the frame in which the orbit products were estimated. Additionally, the most interesting finding of **Alhamadni, 2012,** study was that the repro1 products are suitable only for double difference relative positioning technique and not for precise point positioning (PPP) technique due to some weaknesses in the satellite clock products.

7. CONCLUSIONS

The long-term monitoring of different parameters of the Earth system, such as the land movement which is of particular interest in this study, can be carried out through the geophysical interpretations of coordinate time series derived from Global Navigation Satellite Systems. However, in the past, such geophysical interpretations could not be trusted owing to the fact that such time series were inconsistent and inhomogeneous, due to periodic changes in processing strategies, modeling of the atmospheric delays, parameterization, and the definition of the geodetic datum. As a result, many of the studies previously carried out have emphasized the necessity to reprocess all the continuous GPS observation data and produce a fully consistent set of products using the latest processing strategies, modeling techniques of the atmospheric delays, and parameterization.

This paper drew an attention to some of the recent regional and global monitoring studies based on CGPS measurements. Here, it was interesting to note that in most of the regional investigations of the Earth's deformation studies were carried out based on the double-difference processing strategy to obtain a high level of precision for three-dimensional relative velocity estimates between stations, whereas the absolute horizontal and vertical velocity estimates for global networks have been produced very efficiently using PPP processing strategy.

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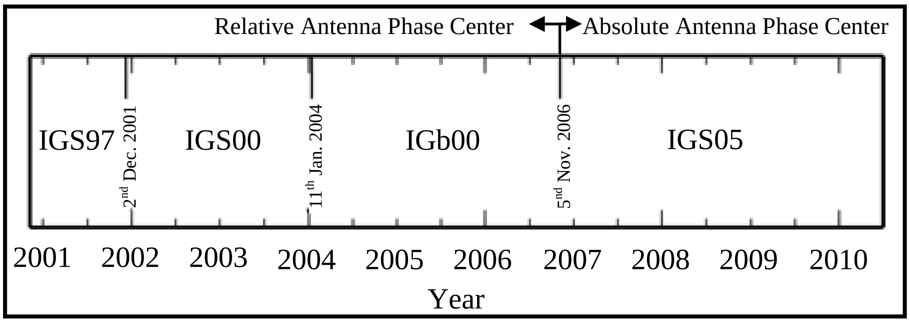

Figure 1. Changes in the used reference frame for the IGS final products generation.

Table1. Accuracy and latency of IGS GPS satellite products.

<table>
<tr><th colspan="3">IGS product types</th><th>Sample Interval</th><th>Accuracy</th><th>Latency</th><th>Update</th></tr>
<tr><td colspan="2" rowspan="2">Final combination</td><td>Orbits</td><td>15 min</td><td>~2.5 cm</td><td rowspan="2">12-18 days</td><td rowspan="2">Weekly/ Every Thursday</td></tr>
<tr><td>Clocks</td><td>30 sec</td><td>~ 75 ps*</td></tr>
<tr><td colspan="2" rowspan="2">Rapid combination</td><td>Orbits</td><td>15 min</td><td>~2.5 cm</td><td rowspan="2">17-41 hours</td><td rowspan="2">Daily/at 17 UTC daily</td></tr>
<tr><td>Clocks</td><td>5 min</td><td>~75 ps*</td></tr>
<tr><td rowspan="4">Ultra-rapid combination</td><td rowspan="2">Observed half</td><td>Orbits</td><td>15 min</td><td>~3 cm</td><td rowspan="2">3-9 hours</td><td rowspan="4">4 times per day at 03, 09, 15, 21 UTC</td></tr>
<tr><td>Clocks</td><td>15 min</td><td>~150 ps*</td></tr>
<tr><td rowspan="2">Predicted half</td><td>Orbits</td><td>15 min</td><td>~5 cm</td><td rowspan="2">Real time</td></tr>
<tr><td>Clocks</td><td>15 min</td><td>~3 ns*</td></tr>
<tr><td colspan="7">* Root Mean Square (RMS).</td></tr>
</table>