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## THE INFLUENCE OF OCEAN TIDES TO DETERMINE THE EARTH'S ORIENTATION PARAMETERS

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### RESUME

The paper deals with the themes of the Earth's orientation and rotation. The parameters of the Earth's orientation can be determined by several methods. The emphasis in this paper is the influence of ocean tides to determine the parameters of the Earth's orientation with one of the space-geodetic techniques, called Very long baseline interferometry (VLBI). After determining the parameters, the results obtained using the VLBI were compared between reference system VieVS and Vrf2008, as well as influence of ocean tides and without its impact.

When processing the data, the obtained results were compared using different reference systems and various that influence their changes were analyzed. The used data belong to different series of programs that are continuously observed. The results are the product of software VieVS with data from a continuing series CONT14.

Key words: *Earth's orientation parameters, rotation, ocean tides, VLBI, geodetic reference systems*

### INTRODUCTION

The influence of ocean tides to determine the Earth's orientation parameters (EOP) is important for the Earth's rotation. Ocean tides are long-term waves that move through the ocean in response to the forces of the Moon and the Sun. Tides come from the ocean and move to the coast where they show in the normal rise and fall of sea surface [1]. Very long baseline interferometry is space geodetic technique which is able to independently determine all parameters of the Earth's orientation: two components of polar motion, two components of precession-nutation and proper rotation (measured as Universal Time UT1, or its negatively taken first time derivative, length-of-day).

Precession-nutation is dominantly caused by torques exerted by the Moon, Sun and planets on the rotating flattened Earth. In addition to torques exerted by the Moon, Sun, and planets, changes of the EOP are known to be caused also by excitations by the atmosphere and oceans [2]. Very long baseline interferometry technique was used to determine EOP which were compared between two different reference frames and different impacts. Results were obtained with Vienna VLBI software.

## THE EARTH'S ORIENTATION PARAMETERS

The Earth's orientation parameters describe the irregularities of the Earth's rotation. The Earth's rotation is not even. Any motion in/on the Earth causes a slowdown or speedup of the rotation, or a change of rotation axis [3].

They are the parameters which provide the rotation of the International Terrestrial Reference Frame (ITRF) to the International Celestial Reference Frame (ICRF) as a function of time [4]. These parameters are referred to the Celestial Ephemeris Pole (CEP), which is close to the rotation pole. Its motion in space is the precession-nutation motion. Practically its motion is equivalent to that of the geographic pole (ITRF pole) for periods greater than 2 days [5]. The Earth's orientation parameters are:

- Universal time (UT1) is the time of the Earth clock, which performs one revolution in about 24h. It is practically proportional to the sidereal time. The excess revolution time is called length of day (LOD).
- The polar motion (X,Y) are the coordinates of the Celestial Ephemeris Pole (CEP) relative to the IRP, the IERS Reference Pole.
- Celestial pole offsets ( $d\psi, d\epsilon$ ) or ( $dX, dY$ ) are described in the IAU Precession and Nutation models. The observed differences with respect to the conventional celestial pole position defined by the models are monitored and reported by the IERS [6].

### Determination of the Earth's orientation parameters

Observations from a number of different techniques can be used to determine Earth orientation parameters such as the Earth's polar motion and the length of day. More than 40 years modern techniques of determining the parameters of the Earth's orientation are in use. Modern techniques are more accurate than techniques used before, which were based on optical astrometry. Techniques for determination of Earth orientation parameters are [7]:

- Very long baseline interferometry (VLBI).
- Laser measuring distance to satellites and the moon (SLR, LLR).
- Global positioning system (GPS).
- Doppler orbitography with radio positioning integrated on satellite (DORIS).

The Earth orientation parameters obtained through periodic VLBI observations also connect the Celestial reference frame (CRF) to the Terrestrial reference frame (TRF). Very long baseline interferometry-based EOP products are updated daily as new VLBI data become available and can be used individually or combined with EOP results from other techniques [8].

Very Long Baseline Interferometry observations for geodesy have been conducted since late seventies. These observations can be used to establish and define an astrometric quasi-inertial CRF, positions and velocities of radio antennas that define a VLBI-based TRF and the EOP that link the CRF and the TRF [9].

## THE EARTH'S ORIENTATION PARAMETERS

Very long baseline interferometry is the only technique capable of measuring all components of the Earth's orientation accurately and simultaneously. Currently, VLBI determinations of earth-rotation variations, and of the coordinates of terrestrial sites and celestial objects are made routinely and regularly with estimated accuracies of about  $\pm 0.2$  arc seconds or better [10].

Namely, VLBI is a geometric method for determining the distance and orientation of very long baseline, measuring the difference in arrival time of the wave fronts on two VLBI radio antenna on the end of a long base [11], (Figure 1).

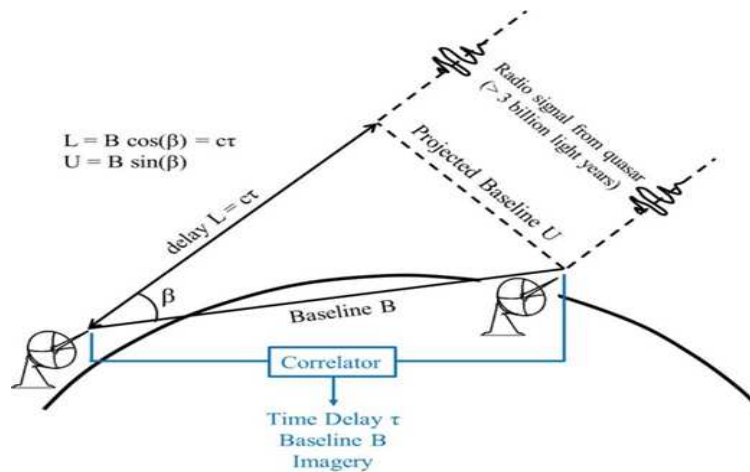


Figure 1. Very Long Baseline Interferometry (VLBI)

Geodetic observing sessions run for 24 hours and observe a number of different radio sources distributed across the sky. Very long baseline interferometry is a technique being used to determine the reference frames for stars and the Earth and to predict the variable orientation of the Earth in three-dimensional space. Knowing the celestial and terrestrial reference frames is important in order to maintain the accuracy of the GPS.

#### Principle of VLBI

The principle of VLBI is a geometric technique which measures the time difference in the arrival of a radio wavefront emitted by a distant astronomical radio source between at least two Earth-based radio telescopes [12]. Knowing the time difference ( $\tau$ ), and the angular separation ( $\beta$ ) between the viewpoint and the baseline between the antennas of the telescopes, the distance between the telescopes can be determined. Because the time difference measurements are precise to a few picoseconds, VLBI determines the relative positions of the cooperating radio telescopes to a few millimeters and the positions of the radio source to a few milliarcseconds [13]. Usually the VLBI-data are acquired over a 24 hour period on about 30 quasars in about 300 different directions. Since the radio telescopes are fixed on the rotating Earth, VLBI tracks instantaneously the orientation of the Earth in an inertial reference frame provided by the very distant quasars [14].

#### OCEAN TIDES AND THE EARTH'S ROTATION

Certain factors affects relative change of the Earth's rotation relative to the Earth or inertial space:

- Gravitational attraction of Moon, Sun and planets.
- Uneven distribution of mass within the Earth.
- Other causes of different origin.

Fluctuations in the Earth's rotation can be measured and explain with the following phenomena:

- The elasticity of the Earth's crust.
- Flattening of the Earth.
- The structure and characteristics of the border areas of tread.
- Atmospheric changes in weather and climate.

The gravitational forces between the Earth and the Moon cause different effects. The most obvious such forces are the tides. Gravitational pulls between the earth, moon and sun dictate the tides. The moon, however, influences tides the most. The Moon's gravitational attraction is stronger on the side of the Earth nearest to the Moon and weaker on the opposite side. Since the Earth, and particularly the oceans, is not perfectly rigid it is stretched out along the line toward the Moon. The effect is much stronger in the ocean water than in the solid crust so the water bulges are higher. And because the Earth rotates much faster than the Moon moves in its orbit, the bulges move around the Earth about

once a day giving two high tides per day. Tides are caused by rotation- the twice daily rise and fall of sea level. Tides are the result of the gravity of the Moon and the gravity of the Sun. Sometimes the Sun and the Moon are lined up with the Earth, but most of the time they are not. Tides are highest when the Earth, Sun and Moon are in a straight line.

#### Ocean tides

Sea level rises and falls twice a day as the Earth rotates. Combination of gravitational pull of the Sun and Moon determine the tidal range. The gravitational force of the Moon is about 2.2 times greater than that of the Sun, at the surface of Earth. The tide-producing action of the Moon arises from the variations in its gravitational field over the surface of Earth as compared with its strength at Earth's centre (Figure 2).

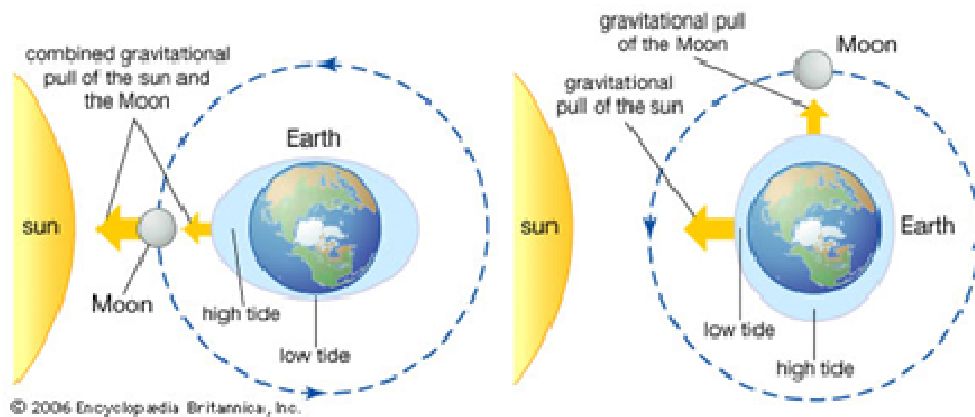


Figure 2. Gravitational pull of the Moon and Sun

The effect is that the water tends to accumulate on the parts of Earth's surface directly toward and directly opposite the Moon and to be depleted elsewhere. The regions of accumulation move over the surface as the position of the Moon varies relative to Earth, mainly because of Earth's rotation but also because of the Moon's orbital motion around the Earth. There are approximately two high and two low tides per day at any given place, but they occur at times that change from day to day; the average interval between consecutive high tides is 12 hours 25 minutes.

The effect of the Sun is similar and additive to that of the Moon. Consequently, the tides of largest range or amplitude (spring tides) occur at new moon, when the Moon and the Sun are in the same direction, and at full moon, when they are in opposite directions; the tides of smallest range (neap tides) occur at intermediate phases of the Moon [15]. Tides are most easily observed along seacoasts, where the amplitudes are exaggerated. When tidal motions run into the shallow waters of the continental shelf, their rate of advance is reduced, energy accumulates in a smaller volume, and the rise and fall is amplified. The details of tidal motions in coastal waters, particularly in channels, gulfs, and estuaries, depend on the details of coastal geometry and water depth variation.

Tidal amplitudes, the contrast between spring and neap tides, and the variation of times of high and low tide all vary widely from place to place. For that reasons, purely theoretical calculation of the times and heights of tides at a particular station is quite impossible. Nevertheless, tides are successfully predicted on the basis of accumulated observations of the tides at the place concerned. The analysis of the observations relies on the fact that any tidal pattern (in time) is a superposition of variations associated with periodicities in the motions of the Moon and the Sun relative to the Earth.

The periods involved are the same everywhere, ranging from about 12 hours to a year or more, but the relative sizes of their contributions are highly variable. Observations over a sufficient time make it possible to calculate which contributions are significant at a particular location and, thus, to forecast tidal times and heights. It is common that 40 components may be significant for practical calculations at one location [16].

## EXPERIMENT

The aim of the experiment was the influence of ocean tides to determine the parameters of the Earth's orientation. The results are processed in VieVS software, and were compared between vievstrf and vtrf 2008 reference systems [16]. The applied methods were determining of EOP on a daily basis, at every hour and using global solution. Determined parameters were: polar motion, universal time and celestial pole offsets. Analyzed data were compared with the impact of the ocean tides and without ocean tides. Tides come from the ocean and move to the coast where they show in the normal rise and fall of sea surface. Used data, series CONT14 belong to very successful continuous VLBI campaigns [17], (Figure 3). Period of observation lasted 15 days in 2014 [16].

Name	Code	Observatory name and location
BADARY	Bd	Badary Radio Astronomical Observatory, Russia
FORTLEZA	Ft	Space Radio Observatory of the Northeast (ROEN), Fortaleza, Brazil
HART15M	Ht	Hartebeesthoek Radio Astronomy Observatory, South Africa
HOBART12	Hb	Mt. Pleasant Radio Astronomy Observatory, Hobart, TAS, Australia
HOBART26	Ho	Mt. Pleasant Radio Astronomy Observatory, Hobart, TAS, Australia
KATH12M	Ke	Katherine Observatory, Katherine, NT, Australia
KOKEE	Kk	Kokee Park Geophysical Observatory, Kauai, HI, USA
MATERA	Ma	Centro di Geodesia Spaziale G. Colombo, Matera, Italy
NYALE S20	Ny	Niy Alesund Geodetic Observatory, Spitsbergen, Norway
ONSALA60	On	Onsala Space Observatory, Sweden
TSUKUB32	Ts	Tsukuba VLBI Station, Japan
WARK12M	Ww	Warkworth VLBI Station, New Zealand
WESTFORD	Wf	Westford Antenna, Haystack Observatory, MA, USA
WETTZELL	Wz	Fundamentalstation Wettzell, Germany
YARRA12M	Ya	Yarragadee Observatory, Yarragadee, WA, Australia
YEBES40M	Ys	Astronomical Center at Yebes, Spain
ZELENCHK	Zc	Radioastronomical Observatory Zelenchukskaya, Russia

Figure 3. Stations used in campaign CONT14

The network consists of seventeen stations in sixteen cities throughout the world (ten in the northern hemisphere and seven in the southern hemisphere), observational mode depends on the ability of cells, media resources, e-transfer capacity, and correlated resources.

## RESULTS AND DISCUSSION

An important aspect of analysis and interpretation of the influence of ocean tides to determine the earth's orientation parameters is visibility results. Therefore, it was done in this paper too. The first phase of the experiment was determining EOP on a daily basis, comparing results between VieVSTrf and Vtrf2008, under the influence of ocean tides and without the influence of ocean tides. The second phase of the experiment was determining EOP each hour, comparing results between VieVSTrf and Vtrf2008, under the influence of ocean tides and without the influence of ocean tides. And the third phase of the experiment was determining EOP using global solution, comparing results between VieVSTrf and Vtrf2008, under the influence of ocean tides and without the influence of ocean tides.

Next section will show the determination of the following parameters: polar motion, universal time and movement of celestial pole. In this part of the experiment is set out analysis of the results obtained by determining EOP using global solution in reference frames VieVSTrf and Vtrf2008 under the influence of ocean tides and without the influence of ocean tides.

Assessment of parameters of the Earth's orientation using global solution obtained by using the reference frame VieVSTrf

a) X POLE

In assessing X POLE, are shown the results with and without the influence of ocean tides (Figure 4). The left figure shows in a darker color solution without ocean tides and a lighter color shows solution with the ocean tides, while the right figure shows the difference between the two solutions which is minimal and it is around 0.05  $\mu$ as, which corresponds to 0.15 cm on the Earth.

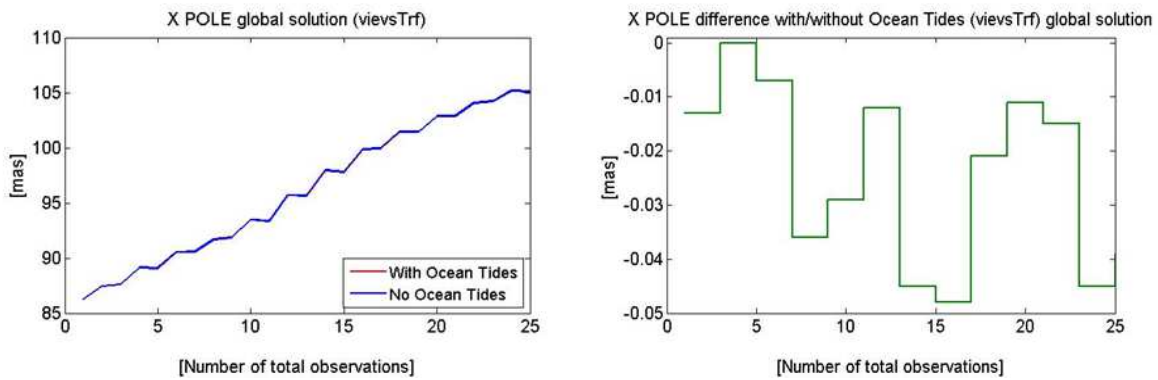


Figure 4. Assessment X POLE with global solution using VieVSTrf reference frame, including and excluding ocean tides

b) Y POLE

In assessing Y POLE, are shown the results with and without the influence of ocean tides (Figure 5). The left figure shows in a darker color solution without ocean tides and a lighter color shows solution with the ocean tides, while the right figure shows the difference between the two solutions which is minimal and it is around 0.10  $\mu$ as, which corresponds to 0.30 cm on the Earth.

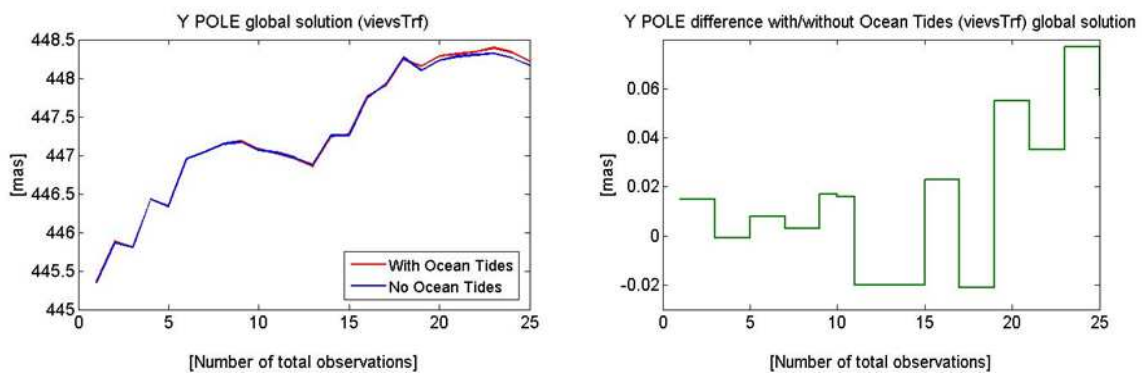


Figure 5. Assessment Y POLE with global solution using VieVSTrf reference frame, including and excluding ocean tides

c) dut1

In assessing dut1, are shown the results with and without the influence of ocean tides (Figure 6). The left figure shows in a darker color solution without ocean tides and a lighter color shows solution with the ocean tides, while the right figure shows the difference between the two solutions which is minimal and it is around 0.12  $\mu$ as.

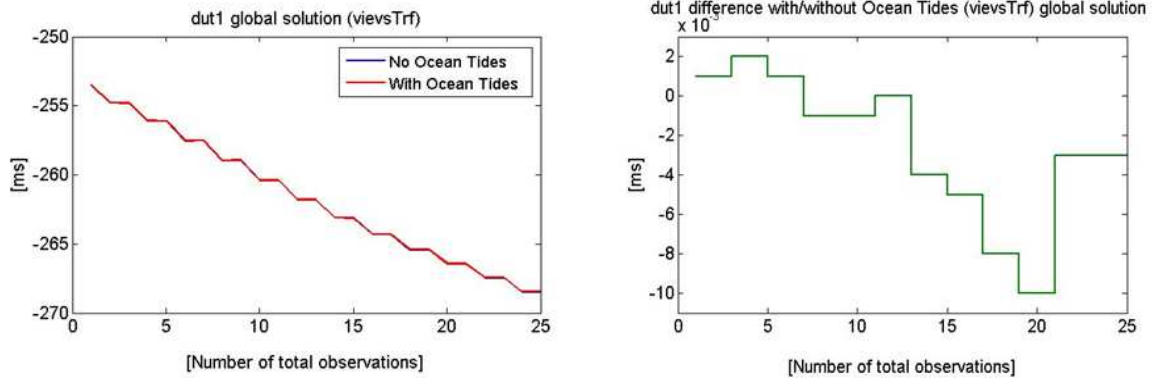


Figure 6. Assessment dut1 with global solution using VieVSTrf reference frame, including and excluding ocean tides

d) nut dX

In assessing nut dX are shown the results with and without the influence of ocean tides (fig.7). The left figure shows in a darker color solution without ocean tides and a lighter color shows solution with the ocean tides, while the right figure shows the difference between the two solutions which is minimal and it is around 0.25  $\mu$ s, which corresponds to 0.75 cm on the Earth.

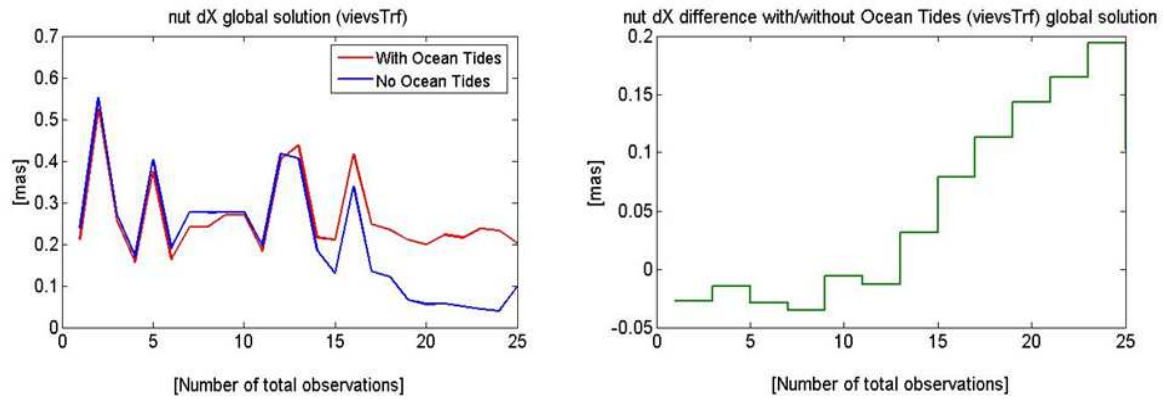


Figure 7. Assessment nut dX with global solution using VieVSTrf reference frame, including and excluding ocean tides

e) nut dY

In assessing nut dX are shown the results with and without the influence of ocean tides (Figure 8). The left figure shows in a darker color solution without ocean tides and a lighter color shows solution with the ocean tides, while the right figure shows the difference between the two solutions which is minimal and it is around 0.20  $\mu$ s, which corresponds to 0.60 cm on the Earth.

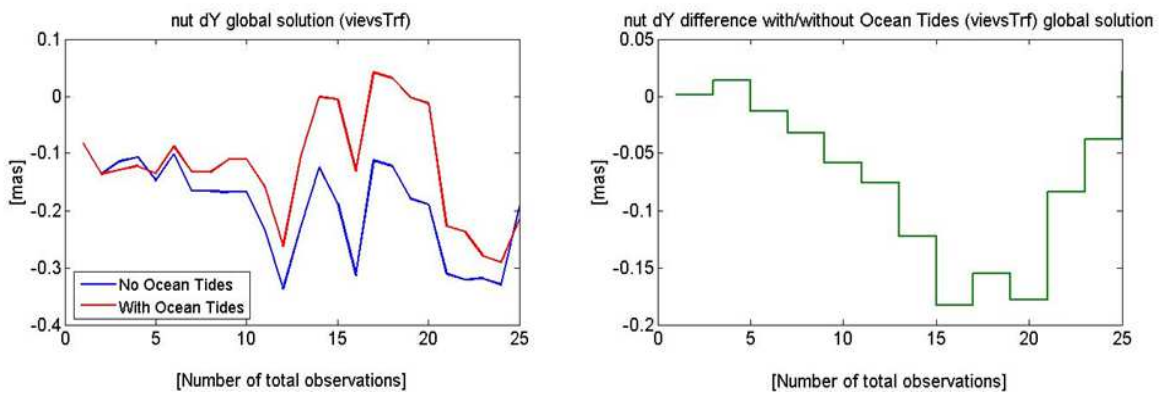


Figure 8. Assessment nut dY with global solution using VieVSTrf reference frame, including and excluding ocean tides



Assessment of parameters of the Earth's orientation using global solution obtained by using the reference frame Vtrf2008

a) X POLE

In assessing X POLE, are shown the results with and without the influence of ocean tides (Figure 9). The left figure shows in a darker color solution without ocean tides and a lighter color shows solution with the ocean tides, while the right figure shows the difference between the two solutions which is minimal and it is around 0.15  $\mu\text{s}$ , which corresponds to 0.45 cm on the Earth.

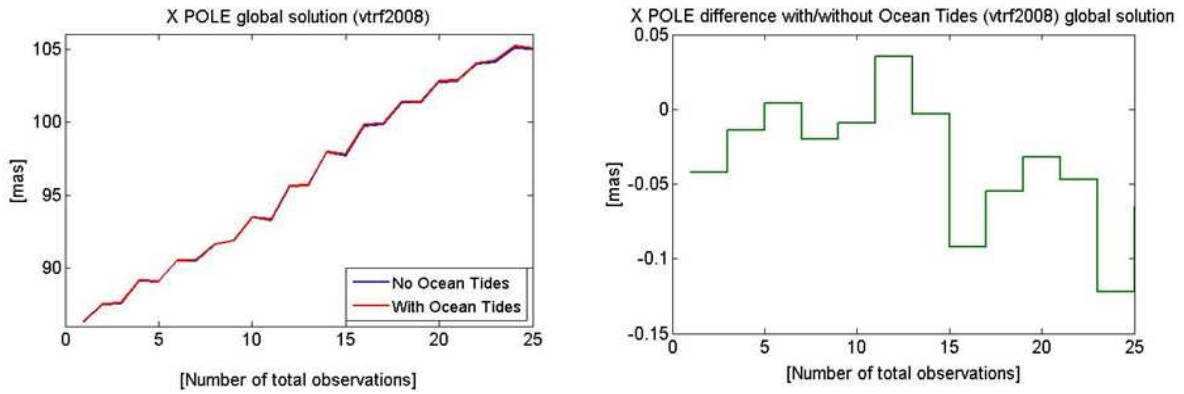


Figure 9. Assessment X POLE with global solution using Vtrf2008 reference frame, including and excluding ocean tides

b) Y POLE

In assessing Y POLE, are shown the results with and without the influence of ocean tides (Figure 10). The left figure shows in a darker color solution without ocean tides and a lighter color shows solution with the ocean tides, while the right figure shows the difference between the two solutions which is minimal and it is around 0.10  $\mu\text{s}$ , which corresponds to 0.30 cm on the Earth.

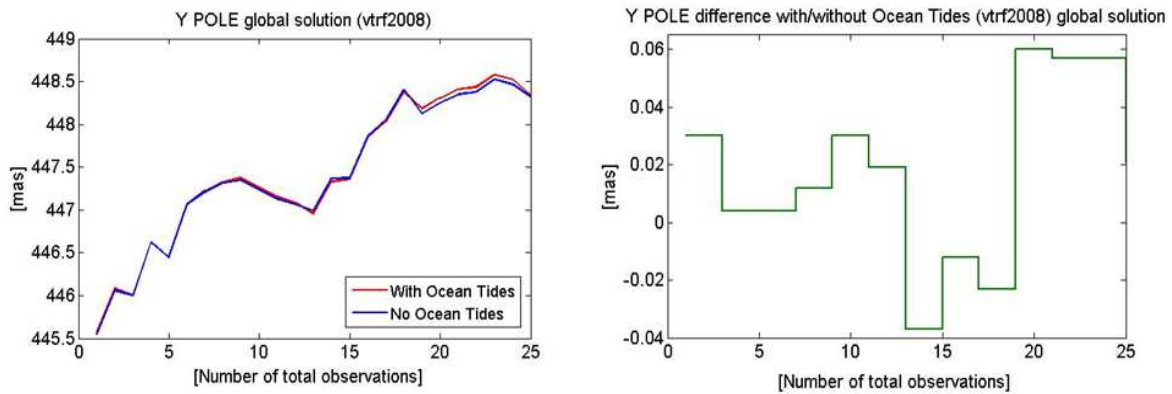


Figure 10. Assessment Y POLE with global solution using Vtrf2008 reference frame, including and excluding ocean tides

c) dut1

In assessing dut1, are shown the results with and without the influence of ocean tides (Figure 11). The left figure shows in a darker color solution without ocean tides and a lighter color shows solution with the ocean tides, while the right figure shows the difference between the two solutions which is minimal and it is around 0.007  $\mu\text{s}$ .



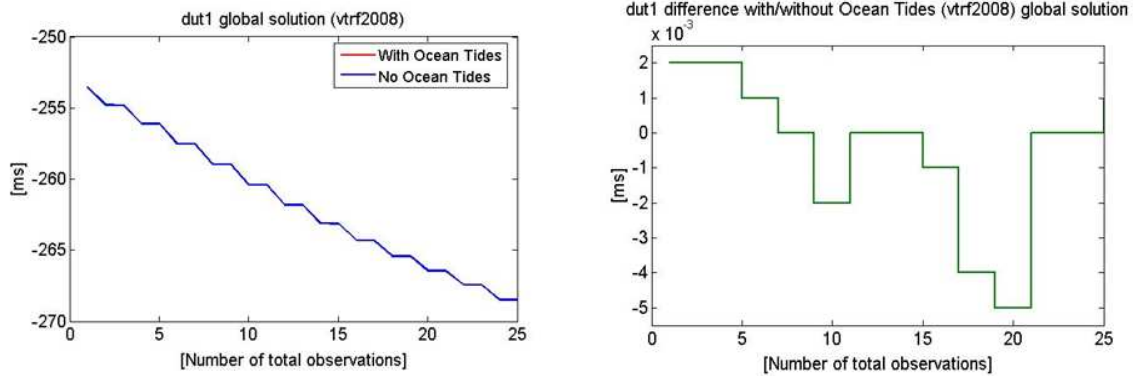


Figure 11. Assessment dut1 with global solution using Vtrf2008 reference frame, including and excluding ocean tides

d) nut dX

In assessing nut dX are shown the results with and without the influence of ocean tides (Figure 12). The left figure shows in a darker color solution without ocean tides and a lighter color shows solution with the ocean tides, while the right figure shows the difference between the two solutions which is minimal and it is around 0.25  $\mu$ as, which corresponds to 0.75 cm on the Earth.

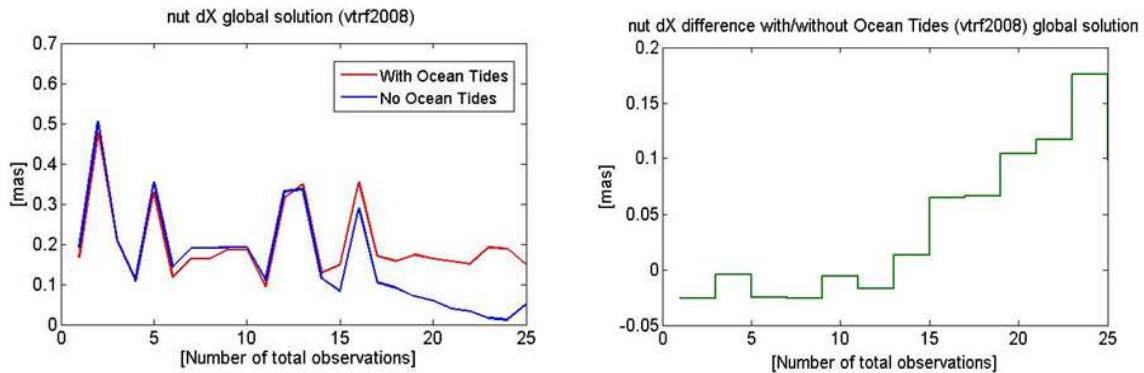


Figure 12. Assessment nut dX with global solution using Vtrf2008 reference frame, including and excluding ocean tides

e) nut dY

In assessing nut dY are shown the results with and without the influence of ocean tides (Figure 13). The left figure shows in a darker color solution without ocean tides and a lighter color shows solution with the ocean tides, while the right figure shows the difference between the two solutions which is minimal and it is around 0.25  $\mu$ as, which corresponds to 0.75 cm on on Earth.

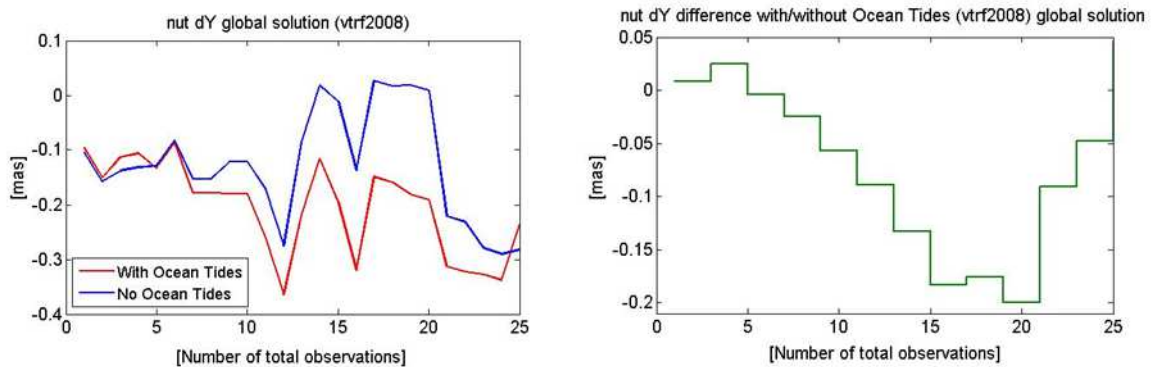


Figure 13. Assessment nut dY with global solution using Vtrf2008 reference frame, including and excluding ocean tides

Table 1 shows the Root Mean Square (RMS) values of all parameters of the Earth's orientation through the numerical representation of the effect of different reference frames and ocean tides.

Table 1. RMS values of the parameters monitored on a daily basis

RMS	vievsTrf OT	vievsTrf nOT	vtrf2008 OT	vtrf2008 nOT
X pole	97,511	97,531	97,504	97,533
Y pole	447,381	447,361	447,524	447,502
dut 1	262,655	262,653	262,666	262,665
nut dX	0,273	0,242	0,215	0,193
nut dY	0,212	0,166	0,222	0,178

## CONCLUSION

Research has shown the influence of ocean tides on EOP using very long baseline interferometry and results from this research must be corrected. Data processing and comparison between two reference frames showed that VieVSTrf provides better results than Vtrf2008. Results with reference frames were expected because VieCSTrf is based on Vtrf2008 which is updated last time in 2008. In experiment beside global solution, compared results from other methods showed that the difference when tides are included and when they are not included are:

- For X pole: 0.05  $\mu\text{s}$  to 0.17  $\mu\text{s}$  which represents the difference on the Earth from about 0.15 cm to 0.51 cm.
- For Y pole: 0.09  $\mu\text{s}$  to 0.10  $\mu\text{s}$  which represents the difference on the Earth from 0.27 cm to 0.30 cm.
- For dut1: 0.007  $\mu\text{s}$  to 0.11  $\mu\text{s}$  on the Earth represents a difference of 0.021 cm to 0.33 cm.
- For the nut dX: 0.25  $\mu\text{s}$  which corresponds to 0.75 cm on the Earth.
- For the nut dY: 0.20  $\mu\text{s}$  to 0.25  $\mu\text{s}$  equivalent of 0.60 cm 0.75 cm on the Earth.

The results can be used for further research and compared with the results obtained by using other space geodetic techniques. The suggested technique is GPS because of the similarity with the VLBI technique in terms of secured results: precession, nutation, polar motion, network coverage and moving tectonic plates.

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