Geodynamic Research at the Department of Planetary Geodesy, SRC PAS

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Review article

GEODYNAMIC RESEARCH AT THE DEPARTMENT OF PLANETARY GEODESY, SRC PAS

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Abstract

The Department of Planetary Geodesy of the Space Research Centre PAS has been conducting research on a broad spectrum of problems within a field of global dynamics of the Earth. In this report we describe the investigations on selected subjects concerning polar motion (modeling and geophysical interpretation of the Chandler wobble, hydrological excitation of seasonal signals, search for optimal prediction methods), tectonic activity in the region of the Książ Geodynamic Laboratory of the SRC, and finally the new joint Polish-Italian project GalAc analyzing feasibility and usefulness of equipping second-generation Galileo satellites with accelerometers.

Keywords: *Department of Planetary Geodesy, Geodynamic Research*

1. Introduction (J.B. Zieliński)

The fortunes of the research institutions in Warsaw working on satellite geodesy and geodynamics were always interconnected. The Warsaw University of Technology responsible for the education provided a number of excellent researchers who found its place in the Department of Planetary Geodesy of the Polish Academy of Sciences. On the other hand some scientists from the PAS returned to WUT in order to contribute to the educative mission. We can remember the founder of the

Department of Planetary Geodesy prof. Ludosław Cichowicz with the group of younger colleagues - Tadeusz Chojnicki, Weneda Dobaczewska, Jan K. Łatka, Janusz B. Zieliński – who formed the base of the Geodetic Section of the Institute of Geophysics at the PAS. Later on another important person from WUT – prof. Barbara Kołaczek - joined the group which has been moved to the Space Research Centre, PAS and constituted the present Department.

In the last years the direction of the personal transfer changed – prof. Aleksander Brzeziński became the full professor of WUT and the head of the Chair of Geodesy and Geodetic Astronomy.

During the years many joint projects and publications have been done. The Astro – Geodynamical Observatory in Borowiec of PAS and Geodetic Observatory Józefosław of WUT took part in the world wide observation campaigns and exchanged data as well as experience. In this paper we can present some results from the work of the Dept. of Planetary Geodesy.

2. **Investigation on the Chandler wobble** (A. Brzeziński, J. Nastula)

The research on Earth rotation has been performed at the Department of Planetary Geodesy of the Space Research Centre, PAS in Warsaw since late 1970-ties. A central subject of this research was analysis of the free Chandler wobble which is the largest component of the observed polar motion. Here we describe briefly our investigations on that subject.

The Chandler wobble (CW) is the most important eigenmode in Earth rotation. The corresponding free oscillation of the pole is a quasi circular motion in prograde (counterclockwise) direction with a mean period of 433 days and a mean amplitude of about 170 milliarcseconds (mas). Here mean values were taken over the period from 1900 up to now with available observations of polar motion. In addition, the Chandler resonance has an important influence on the excitation of the seasonal wobbles and contributes to the transfer function of the forced lunisolar nutation. The CW was predicted theoretically in the middle of XVIII century by L. Euler, who derived the resonant period for a rigid Earth to be equal to 305 days. This free wobble was confirmed observationally, though with much longer period, by S. Chandler at the end of XIX century and has been monitored since that time on regular basis. The observed free wobble shown in Figure 1 has variable amplitude but it does not exhibit any permanent decaying trend. It is a proof that there exist a process, or a combination of processes, which excites this free wobble and maintains it against the energy dissipation.

One important task of the research concerning the Chandler wobble is to determine its parameters, the frequency F_c (or, equivalently, the period $T_c = 1/F_c$) and the quality factor Q_c, which are closely related to the shape and physical properties of the Earth. Another task is a search for the excitation mechanism of the free wobble. That includes both the modeling efforts and analysis of the available estimates of the geophysical excitation data.

There were many attempts in the past to explain the excitation mechanism of the Chandler wobble; see (Brzeziński, 2005a, b) and the references therein for review. Certainly, the best observed mechanism was the redistribution of air masses and changes in wind patterns causing variations of atmospheric angular momentum (AAM). However, most of the earlier excitation studies using the available meteorological observations and models indicated that AAM variations provide less than half of the power needed to explain the observed free wobble.

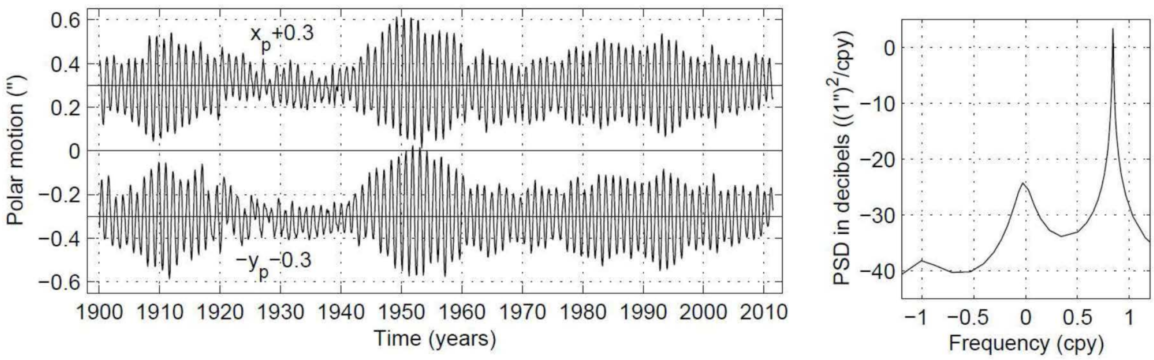


Fig. 1: Polar motion series IERS C01 after removal of the annual retrograde and prograde components and of the linear trend (left), and the corresponding power spectral density (PSD) of the complex series $p = x_p - iy_p$, where *i* denotes the imaginary unit (right). Frequency is expressed in cycles per year (cpy).

One possible candidate for explaining the remaining large gap in the Chandler wobble excitation balance was the non-tidal variation of the ocean angular momentum (OAM). Its significant part expressing the ocean response to the overlying air pressure variations has long being modeled by adding the so-called inverted barometer (IB) correction to the pressure term of AAM. Estimation of the remaining dynamic component of OAM was much more difficult because it required three-dimensional modeling of the global ocean dynamics. Only recently there have been successful attempts to develop the high-quality ocean general circulation models and estimate the corresponding OAM data. Our excitation study (Brzeziński and Nastula, 2002), using the OAM and AAM data from the improved global models could demonstrate that during 1985-1996 the Chandler wobble was mostly driven by the irregular angular momentum transfer from the coupled atmosphere-oceans system to the solid Earth; see Figure 2. The most important excitation mechanisms were the ocean-bottom pressure and atmospheric pressure fluctuations. The next attempt of (Brzeziński et al., 2002) using a 50-year time series of OAM yielded significantly worse results than those of (Brzeziński and Nastula, 2002).

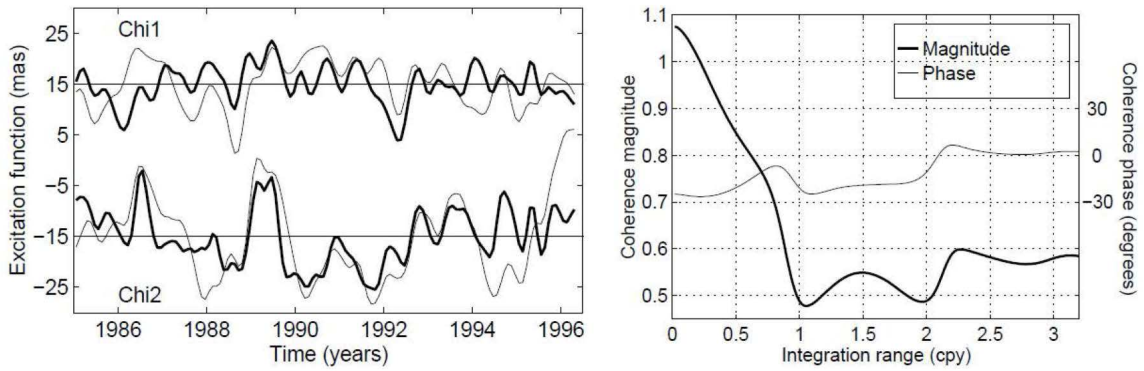


Fig. 2. Comparison of the inferred non-atmospheric excitation of polar motion NAM (thin line) with the oceanic excitation data OAM (thick line) - left. Right panel shows the maximum entropy method estimate of the coherence of NAM and OAM at the Chandler frequency as a function of the cross-power spectrum integration interval (Brzeziński and Nastula, 2002).

The subject of the geophysical excitation of the Chandler wobble was revisited by (Brzeziński et al., 2011) using the same method of analysis but other available estimates of atmospheric and oceanic excitation of polar motion. The authors also tried to assess the role of land hydrology in the CW excitation balance by taking into account the hydrological angular momentum (HAM) estimates. The results generally confirmed earlier conclusions concerning the atmospheric and oceanic excitation. Adding the hydrological excitation was found to increase slightly the Chandler wobble excitation power, while the improvement of coherence depended on the geophysical models under consideration.

Our earlier attempts to estimate the Chandler wobble parameters, the period T_c and the quality factor Q_c, from the observations of polar motion were summarized in (Brzeziński, 2005a, b). We used the maximum entropy method based on the autoregressive (AR) modeling of time series, as well as the maximum likelihood method associated with the autoregressive integrated moving-average (ARIMA) stochastic model. The new investigations by (Brzeziński and Rajner, 2014), (Nastula and Gross,2015) enabled estimation of CW parameters from a simultaneous analysis of the polar motion and geophysical excitation data. (Brzeziński and Rajner, 2014) applied for that purpose the Kalman filter developed for deconvolution of polar motion data. They estimated the CW parameters from different sets of polar motion and geophysical excitation (AAM, OAM, HAM) data and compared them to each other as well as to the earlier results derived by the alternative algorithms. (Nastula and Gross, 2015) derived the CW parameters from the simultaneous use of both space-geodetic polar motion observations and from satellite laser ranging (SLR) and Gravity Recovery and Climate Experiment (GRACE) observations of the degree-2 coefficients of the Earth's time-varying gravitational field. The models of the polar motion excitation functions that they used were derived from general circulation models of the atmosphere and oceans and from hydrologic models. Their preferred estimates of T_c and Q_c were 430.9 ± 0.7 solar days and 127 (56, 255), respectively.

3. Seasonal hydrological signals in polar motion excitation

(J. Nastula, M. Wińska)

Global geophysical excitation functions of polar motion have not fully explained polar motion as determined by geodetic techniques. The impact of continental hydrologic signals from land, water, snow and ice on polar motion excitation (Hydrological Angular Momentum; HAM), is still inadequately estimated and not as well-known as atmospheric and oceanic impacts (Chen and Wilson, 2005), (Seoane et al., 2011), (Nastula et al., 2011), (Jin et al., 2012), (Wińska et al, 2016). A comparison of HAM with hydrological signals in observed geodetic excitation functions is a common method of assessing the influence of land hydrology on the polar motion excitation function. HAM can be estimated either from global models of land hydrosphere or from the harmonic coefficients Cnm and Snm of the Earth's gravity field.

In this study seasonal hydrological~gravimetric HAM is estimated from degree-2, order-1 harmonics of the Earth's gravity field, derived from the Gravity Recovery and Climate Experiment (GRACE), Satellite Laser Ranging (SLR) and GNSS data, together with global models of land hydrosphere (GLDAS, LSDM, NCEP/ NCAR). A hydrological signal in polar motion excitation is estimated as the difference between observed geodetic excitation functions (Geodetic Angular Momentum, GAM) and a sum of Atmospheric Angular Momentum (AAM) and Oceanic Angular Momentum (OAM). Our work attempts to determine the optimum HAM series that is most consistent with the hydrological signal in observed polar motion excitation, using the Least Squares (LS) method.

We compared χ_1 and χ_2 components of hydrological~gravimetric excitation functions of polar motion computed from five GRACE solutions (CNES, CSR, JPL, GFZ and Tongji), three sets of SLR-based data, GNSS-based data and three hydrological models (NCEP/NCAR, GLDAS and LSDM) with geodetic residuals in the seasonal part of spectrum. A visual inspection of the time series shows that gravimetric~hydrological excitation functions differ significantly both in the seasonal and non-seasonal part of the spectrum, and for χ_1 and χ_2 (Fig. 3).

The magnitudes of the correlation coefficients between G-A-O and individual excitation functions and the percent of G-A-O variance explained by variation in the excitation functions show also considerable scatter (Fig. 4). The best agreement between G-A-O and excitation functions can be seen for seasonal GRACE data (Figs. 3, 4).

Next we attempted to determine combinations of individual excitation functions that matched geodetic residuals. To that end, all excitation time series were scaled by coefficients obtained from least squares fitting. The resulting series are a sum of individual scaled time series. Finally, we determined seven models based on the following datasets (Fig. 5):

- MODEL13: NCEP/NCAR, LSDM, GLDAS – Land Hydrosphere models
- MODEL14: NCEP/NCAR, LSDM, GLDAS, CNES, JPL, GFZ, CSR, Tongji – Land Hydrosphere and GRACE data
- MODEL15 GNSS, SLR1, SLR2, SLR3 – GNSS and Laser data
- MODEL16: GNSS, SLR1, SLR2, SLR3, CNES, JPL, GFZ, CSR – GNSS, Laser and GRACE data
- MODEL17: GNSS, SLR1, SLR2, SLR3, CNES, JPL, GFZ, Tongj – GNSS, Laser and GRACE data
- MODEL18: SLR1, SLR2, SLR3, CNES, JPL, GFZ, CSR, Tongji – Laser and GRACE data
- MODEL19: CNES, JPL, GFZ, CSR, Tongji – GRACE data

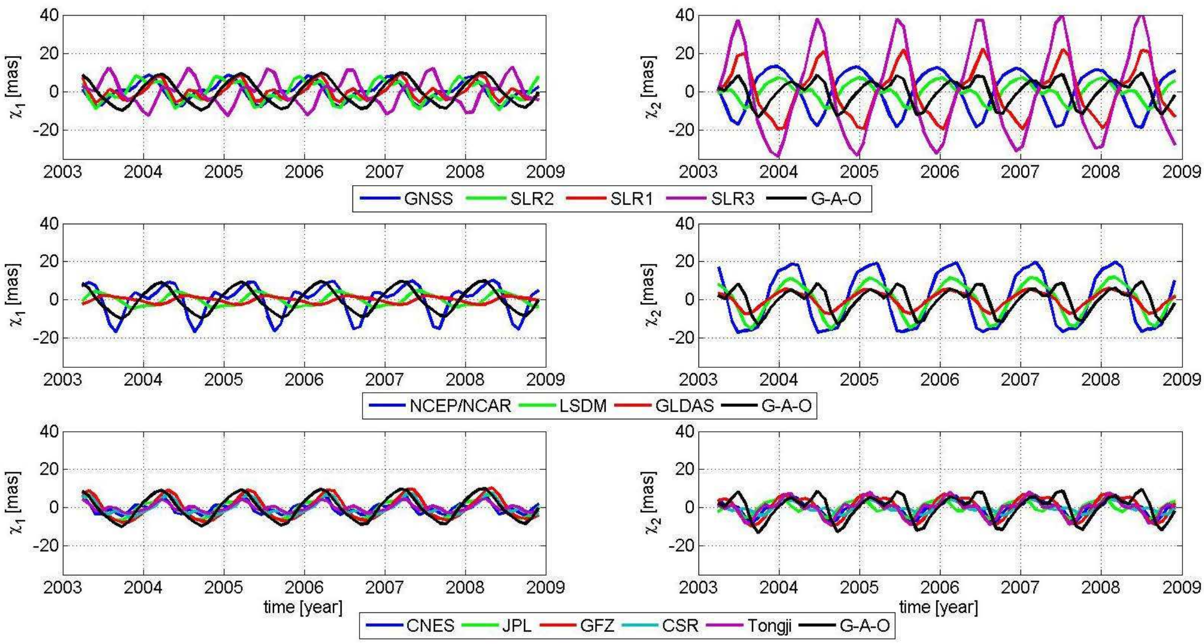
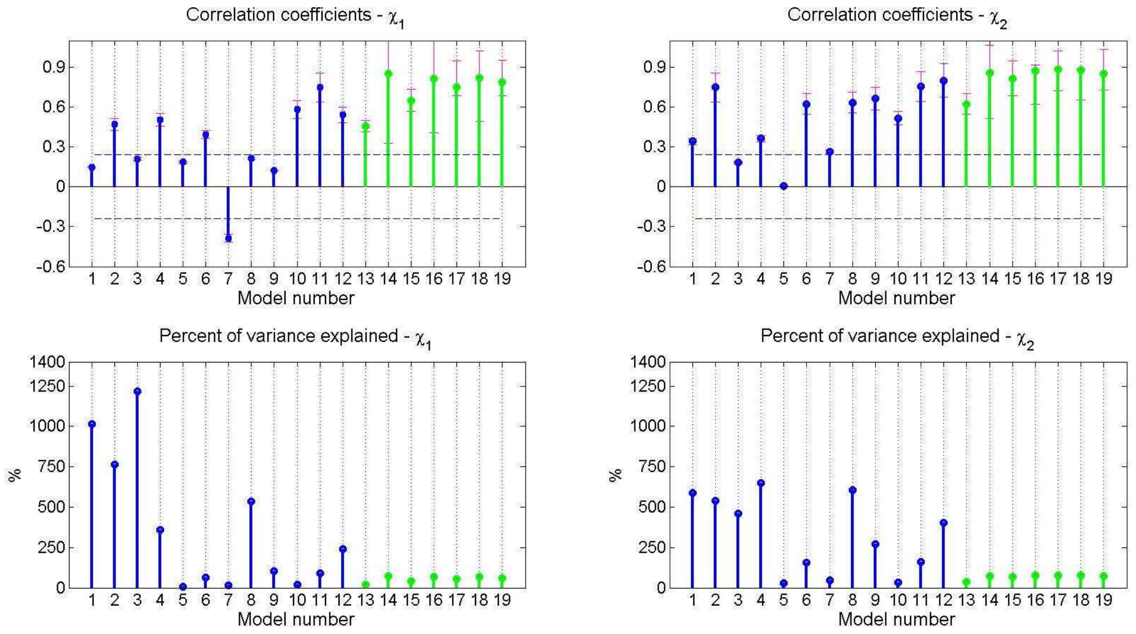


Fig. 3. Comparison of χ_1 and χ_2 components of geodetic residuals G-A-O with hydrological and gravimetric excitation functions. All data were smoothed with a step of 30 days, FWHM=60. The model shows 365.25, 180.0 and 120.0-day oscillations.



1. GNSS 2. SLR2 3. SLR1 4. SLR3 5. NCEP 6. LSDM 7. GLDAS 8. CNES 9. JPL 10. GFZ 11. CSR 12. Tongji 13. MODEL13 14. MODEL14 15. MODEL15 16. MODEL16 17. MODEL17 18. MODEL18. 19. MODEL19

Fig. 4. a) Correlations coefficients between geodetic residuals and different polar motion excitation functions b) Percentage of variance of geodetic residuals explained by polar motion excitation functions. The blue lines shows the results obtained for the individual series, and green lines for their combination. The dotted lines shows a critical value of the correlation coefficient for 70 points.

To compare the combined series with the G-A-O correlation coefficients and variances were determined (Fig. 4). The analysis showed that in general, series determined by LS combinations of individual series were more consistent with G-A-O than individual series (Figs. 4 and 5). This result needs a physical interpretation, specifically a comparison of the magnitude of scale factors for individual functions. Such an analysis may yield a new hydrological~gravimetric model based on the available data.

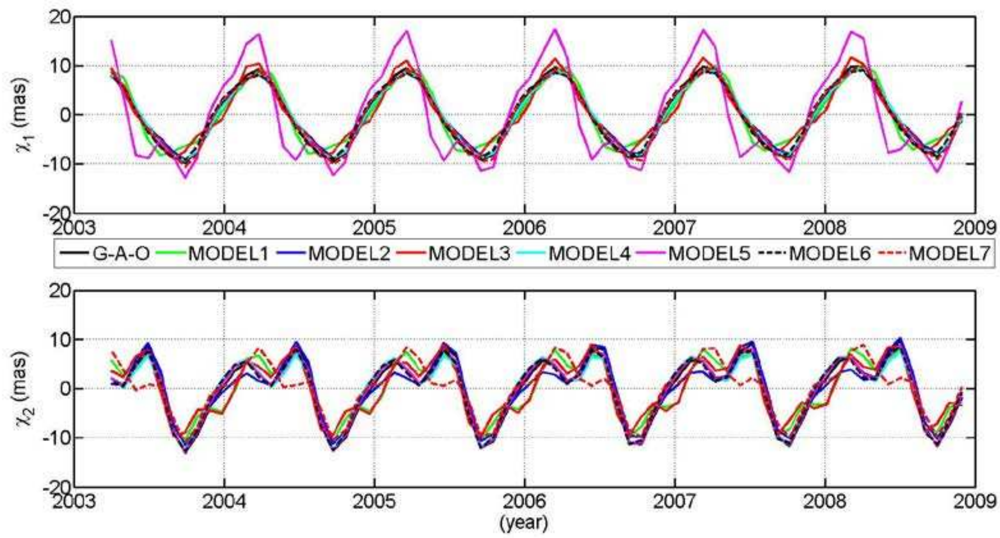


Fig. 5. Comparison of the seasonal components, χ_1 and χ_2, seven combinations of the excitation functions and geodetic residuals.

4. Tectonic activity of Świebodzice Depression and their probably connections in time-domain with strong and deep seismic events in Lubin copper mining region (M. Kaczorowski, Z. Szczerbowski , D. Kasza, R. Zdunek, M. Jóźwik, R. Wronowski)

Recent tectonic activity of Świebodzice Depression is observed since seventies years of the last century. In this time in Ksiaz was constructed Geodynamic Laboratory of Space Research Centre, Polish Academy of Sciences (SRC PAS). Permanent clinometric observations executed since 1975 with use of quartz horizontal pendulums as well as measurements of tiltings and vertical motions executed since 2003 by two long water-tubes tiltmeters provided numerous observations of tectonic activity. Collected observations contain irregularly occurring events (lack of seasonality) of rapid variations of equilibrium position of tiltmeters as well as large variations of water level in long water tubes tiltmeters hydrodynamic systems (Kaczorowski, 2006). The magnitudes of registered tectonic effects by quite different tiltmeters long water tubes as well as horizontal pendulums achieve 10 times of tidal signals magnitudes (Kaczorowski, 2009). The executed investigations allow us to eliminate instrumental and all non-tectonic effects as a possible reason of these phenomena. Additionally, tectonic activity is confirmed by system of secondary faults visible in underground corridors of Ksiaz massive as well as characteristic pictures of deformations of Pełcznica river meander which result from present activity of local faults.

Discussion on the Fore-Sudetic monocline seismicity in the context of tectonic activity of Swiebodzice Depression was initiated in the spring of 2015. This is quite a new problem included into the scientific program of the Geodynamic Laboratory of the SRC PAS in Ksiaz. The area of seismicity of the Fore-Sudetic monocline is at the distance of about 50 km from Swiebodzice Depression orogen and the Ksiaz Laboratory. This small distance suggests that the fields of tectonic pressure appear in the Ksiaz Laboratory and in the Fore-Sudetic monocline in approximation simultaneously. This view inspires us to search for relationship between the recent tectonic activity of Swiebodzice Depression and the seismic events in the monocline. Natural geological and tectonic conditions of the Swiebodzice Depression such as very hard and coherent rocks are very suitable for execution of precise measurements of geodynamic signals. The Geodynamic Laboratory was built in gneiss conglomerate rocks about 300 mln years old.

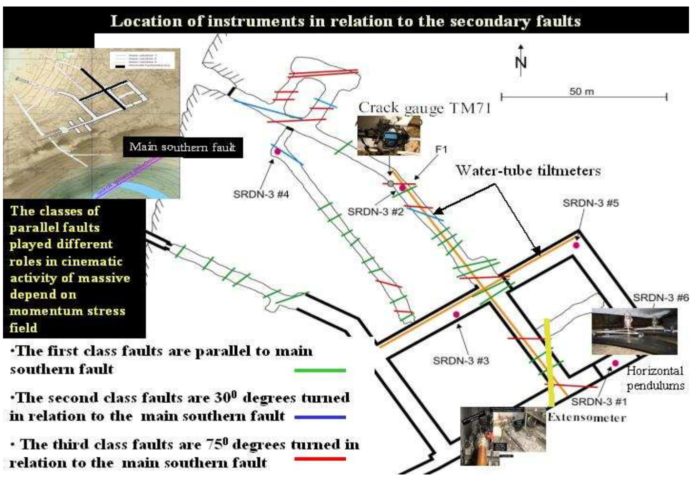


Fig. 6. The system of recognized faults in the Ksiaz massif and distribution of instruments in space of the laboratory applied for measurements of tectonic signals.

The great age of the Swiebodzice Depression massif explains the existence of rich system of faults which makes it possible today for complex deformations and displacements of the Ksiaz massif blocks (Fig. 6) (Kaczorowski and Wojewoda, 2011). This property probably assures compensation of stresses through the contribution of local system of faults which prevents earthquakes in the Swiebodzice Depression Massif. The recent tectonic activity of Swiebodzice Depression is observed since the seventies of the last century. In that time in Ksiaz there was constructed the Geodynamic Laboratory of SRC PAS (Kaczorowski et al., 2015).

Permanent clinometric observations executed since 1975 with the use of quartz horizontal pendulums (HP) as well as measurements of tiltings and vertical motions executed since 2003 with two long water-tube tiltmeters (WT) provided us with numerous observations of the effects of tectonic activity such as tiltings and vertical motions of blocks. The collected observations contain irregularly occurring epoch (lack of seasonality) of increase of tectonic pressure which is visible in the growth of kinematic activity of blocks in the massif. During the epoch of tectonic activity we observed rapid variations of equilibrium position of quartz pendulums as well as large variations of water level in (WT) tiltmeters. The greatest effects of tectonic activity took place in the years 2009 and 2010 when they achieved about 1000 micrometers of vertical displacements (Fig. 7). The magnitude of tectonic effects registered by different tiltmeters (HP and WT) significantly exceed the magnitude of tidal signals. The long-standing measurements allow us to eliminate the non-tectonic effects and to conclude explicitly that the strong signals observed by (HP and WT) tiltmeters are the result of the recent tectonic activity in the Sudetic and neighboring regions. Characteristic pictures of deformations of the Pełcznica river valley which was transformed from cycloide into the broken line additionally confirm the recent activity of numerous faults.

Because the quartz horizontal pendulums are situated on the platforms cut in rocky walls, they are subject to the field of tectonic stresses which produce tiltings of block.

In the other way, the WT tiltmeters are distributed over the large space (hundred meters) and cross over the numerous secondary faults visible in the underground corridors of the Ksiaz laboratory (Fig. 6) (Kasza, et al, 2014.).

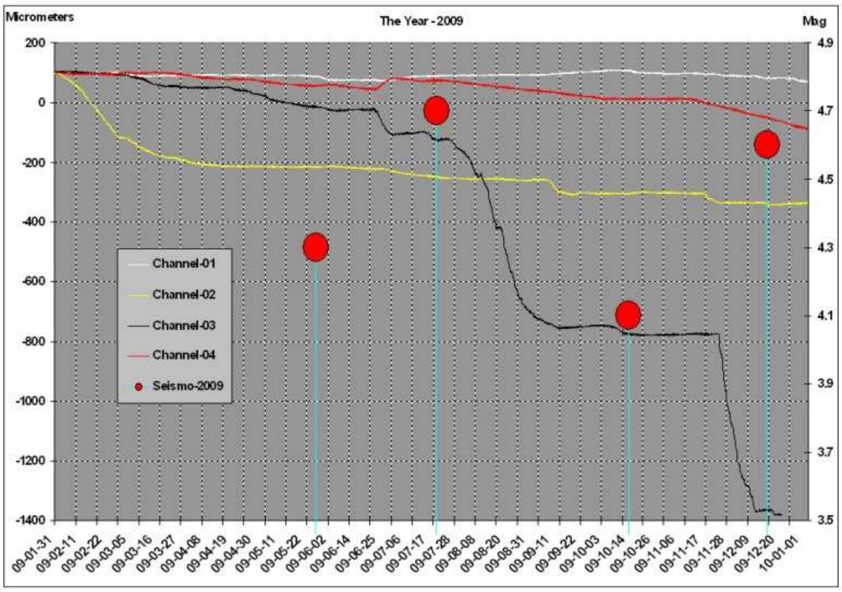


Fig. 7. The plots of water level variations on four channels in 2009 with two rapid and extremely large effects and seismic events from the Fore-Sudetic Monocline

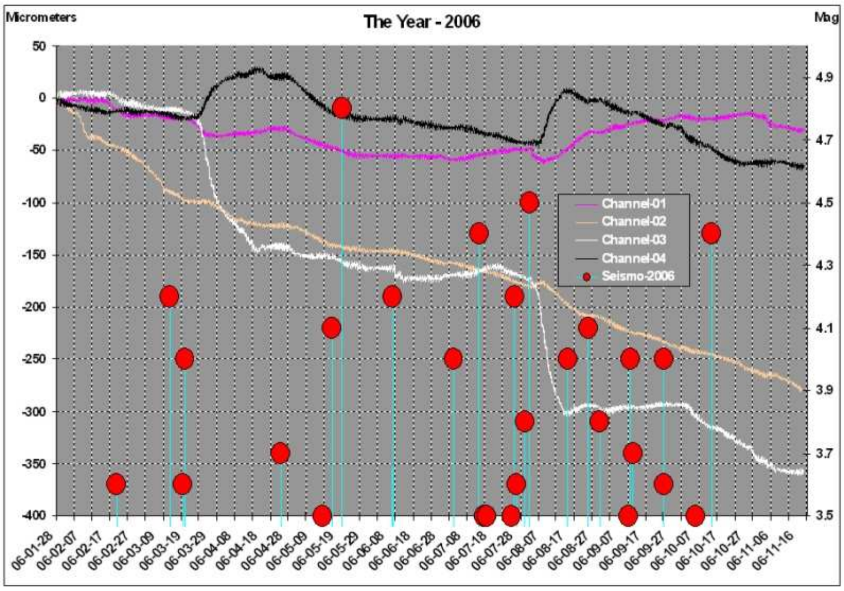


Fig. 8. The plots of water level variations on four channels in 2006 with two rapid and large effects and seismic events from the Fore-Sudetic Monocline

The vertical motions of blocks which are situated under the tubes of WT tiltmeters produced strong water level variations. Therefore the WT are very sensitive gauges monitoring changes of tectonic activity of secondary faults in the massif of Swiebodzice Depression. We consider that the epochs of kinematic activity of Ksiaz massif (complex deformations of blocks) are associated with the increase of tectonic pressure in the Swiebodzice Depression. The epochs of kinematic activity of the massif take place during the compression phase. The original sources of the fields of tectonic pressures are very far from the Sudetic area in the contact zone between Africa plate and European peninsula and in the rift zone of the northern Atlantic. The measurements of numerous permanent GNSS stations in the Central Europe, i.e. in the Czech Massif, the Sudetic and Fore-Sudetic zones, show almost uniform field of velocities vectors (Fig. 10) (Zdunek et al., 2014). Basing on the law of mechanics the resultant tectonic pressure vector is parallel to the resultant velocities vector, in good approximation.

This observation suggests that the field of tectonic stresses is also uniform as the field of velocity vectors. Therefore, the kinematic activity of the Swiebodzice Depression takes place in the sometime as the kinematic activity of adjacent areas, among others of the copper mining region of the Fore-Sudetic Monocline. The seismic events which take place on the faults of the Fore-Sudetic Monocline are separated into two groups.

The anthropogenic origin of low level shocks are kind of response of orogen on the stresses cumulating during the process of mining exploitation. The second class shocks are of higher energy than the first class, and their hypocenters usually lie deeper than 5 km.

The shocks greater than 3 degrees magnitudes seem to be too large and their hypocenters too deep to be explained by compensation processes of post-mining stresses. The strong seismic events in the Fore-Sudetic Monocline indicate rather theirs natural origin associated with tectonic activity of massif. On Fig. 7 and Fig. 8 there are shown the seismic effects from the Lubin copper mining region in combination with the plots of tectonic activity of the Ksiaz massif of the Swiebodzice Depression. The plots were constructed on the basis of WT tiltmeters measurements in the Geodynamic Laboratory of SRC PAS in Ksiaz. On Fig. 7 and 8 it is well visible that the strong seismic events in the Fore Sudetic Monocline occurred during the epochs of low activity of massif of Swiebodzice Depression and never happened during strong activity. We expect that the observations of the epochs of kinematic activity of the Ksiaz massif of Swiebodzice Depression can be used as a method of evaluation of possibilities of earthquake occurrence in the Fore Sudetic Monocline. The observation from Fig. 9 suggests that there is also a correlation between the phase of tidal signal and the seismic events. The seismic events happen in similar phases of the tide.

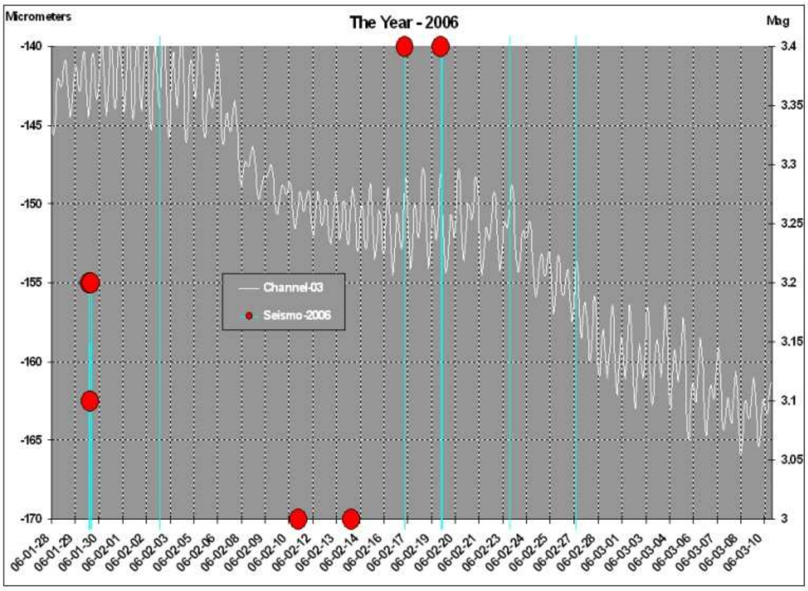


Fig. 9. The observation of the fact that in spring 2006 earthquakes took place in similar phases of tidal signal

The first group of shocks is probably associated with the mining activity only. They are of lower magnitudes than 3 Mg and with shallower depths of hypocenters in comparison with the depths of hypocenters of the second group shocks.

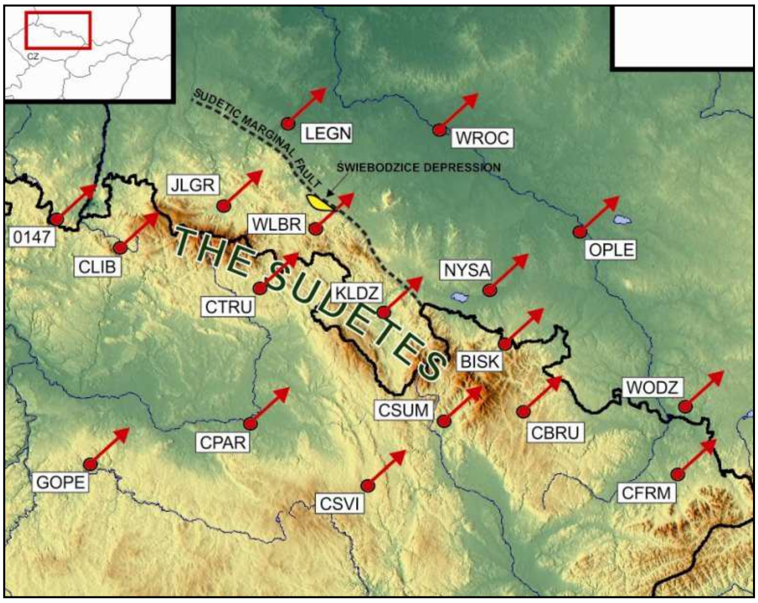


Fig. 10. The mean horizontal vectors of velocities (~3 mm/Year) of GNSS stations

5. Causes of increase of pole coordinates data prediction errors with prediction length (W. Kosek)

Future Earth orientation parameters data are necessary to compute real time transformation between the celestial and terrestrial reference frames. This transformation must be realized by predictions of x, y pole coordinates, UT1-UTC data as well as precession-nutation extrapolation model together with prediction of small dX, dY corrections to this model. This chapter is focused on the pole coordinates data prediction, its accuracy and possible causes of prediction errors which increase with prediction length. The current prediction method of x, y pole coordinates data applied in the IERS is the combination of the least-squares and autoregressive (LS+AR) (Kosek et al., 2012) forecast model which has been also used in this chapter. The following x, y pole coordinates data EOPC04_IAU2000.62 from the IERS since 1962.0 till now with the sampling interval of 1 day were used (IERS 2016).

In order to find what are the causes of increase of prediction errors with prediction length the time series of differences between future x, y pole coordinates data and their LS+AR predictions were computed for starting prediction epochs since 1978 till now and for different prediction lengths from 1 to 420 days in the future (Fig. 11). It can be noticed that the absolute values of these difference increase with the prediction length and the agreement of real future pole coordinates data with their predictions depends mostly on starting prediction epochs and seems to have a seasonal character. The highest differences between x, y pole coordinates data and their predictions were noticed in 1982, in 2006 and at the beginning of 2007 as well as in 2012.

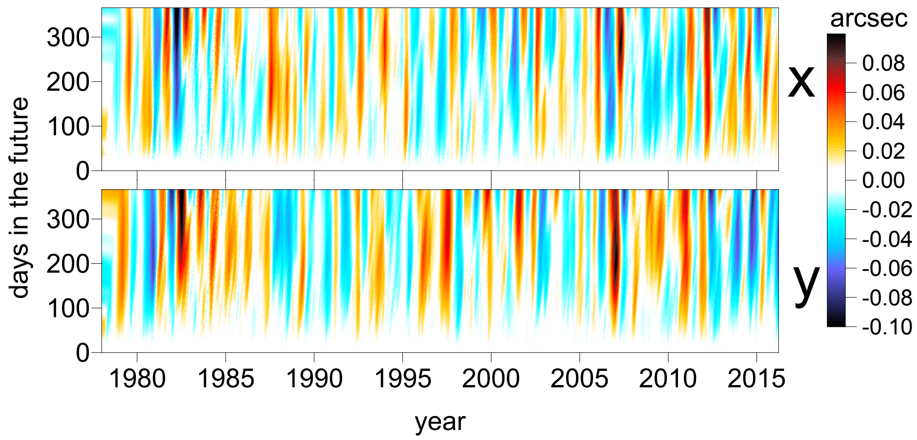


Fig. 11. The differences between x,y pole coordinate data and their predictions from 1 to 420 days in the future computed by the LS+AR prediction.

In order to check if the differences between x, y pole coordinates data and their LS+AR predictions follow the normal distribution some basic statistics such as standard deviation error (SDE), mean absolute error (MAE), skewness (SKE) and kurtostis (KUR) were computed as a function of prediction length (Fig. 12) (Kalarus et al. 2010). The SDE and MAE statistics which represent the mean prediction errors show that the accuracy of y pole coordinate data predictions is better than for x pole coordinate for prediction lengths less than about 140 days. The SKE values, which represent a measure of the asymmetry of the probability distribution, for x pole coordinate are smaller/greater than for y pole coordinate for prediction lengths greater/smaller than about 40 days, respectively. Generally, the SKE values oscillate near zero which suggest that the probability distribution of the difference between pole coordinates data and their LS+AR predictions follow normal distribution. The KUR values, which represent the peakedness of a probability distribution, for x, y pole coordinates prediction differences are almost similar for prediction lengths less than about 240 days and from about 50 to longer prediction lengths they are equal to 3 which suggest that these differences follow normal distribution. For prediction lengths less than about 50 days and smaller the probability distribution becomes more leptokurtic than normal.

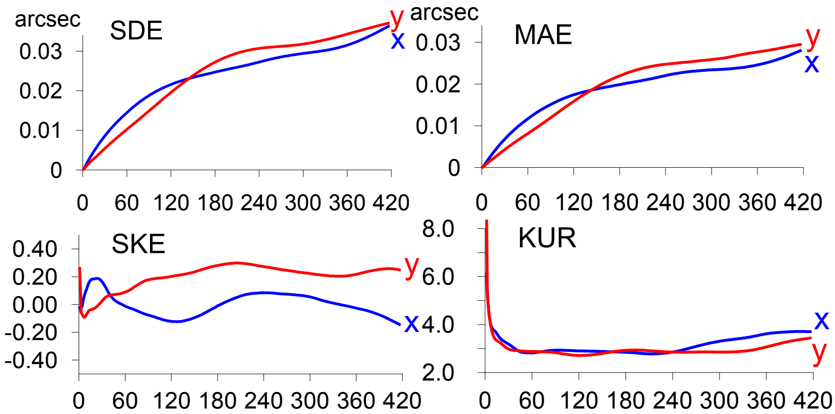


Fig. 12. The SDE, MEA, SKE and KUR statistics of the differences between x, y pole coordinate data (in 1978- now) and their predictions from 1 to 420 days in the future computed by the LS+AR prediction.

To find what irregular oscillations are responsible for increase pole coordinate data prediction errors with prediction length the amplitude spectra of the difference between pole coordinate data and their LS+AR predictions at 1,2 and 4 weeks in the future were computed by the Fourier transform band pass filter (FTBPF) (Fig. 13) (Kosek, 1995). It can be noticed that these time frequency amplitude spectra of these differences for different prediction lengths are very similar and show maxima in the frequency band corresponding to the prograde Chandler and annual oscillations. The highest maxima in these time frequency amplitude spectra correspond to years: 2006, beginning of 2007 and from 2011 to beginning of 2012. These maxima correspond to staring prediction epochs where prediction errors of pole coordinates data attained bigger values (Fig. 11).

Prograde character of these oscillations suggests that they were mismodelled in the LS+AR prediction model. In this LS+AR prediction model the LS model is fit to the last 10 years of pole coordinates data and the autoregressive coefficients are estimated from the last 850 days of the LS extrapolation residuals.

Indeed, in the LS model the amplitudes and phases of Chandler and annual oscillation are treated as constant but their real values change with time in the 10 year time span. Moreover, the autoregressive model in the LS+AR combination is more tuned to higher frequency variations than to frequency variations corresponding to the annual and Chandler frequency band. The autoregressive coefficients in the autoregressive model were estimated by Barrodale and Erickson (1980) algorithm adopted to complex-valued time series by Brzeziński (1994). The mean FTBPF amplitude spectra computed for more narrow frequency bandwidth than time variable FTBPF amplitude spectra of the differences between pole coordinate data and their LS+AR predictions at 2, 4 and 8 weeks in the future show the peaks for residual prograde Chandler and annual oscillations (Fig. 14).

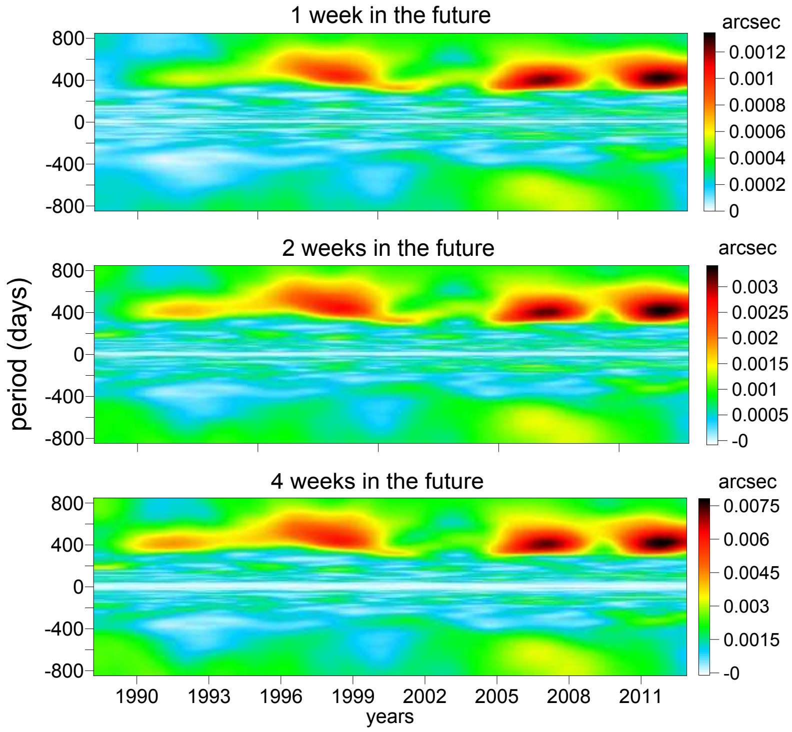


Fig. 13. The time frequency amplitude spectra of the differences between x,y pole coordinates data and their LS+AR predictions computed for prediction lengths of 1, 2 and 4 weeks in the future.

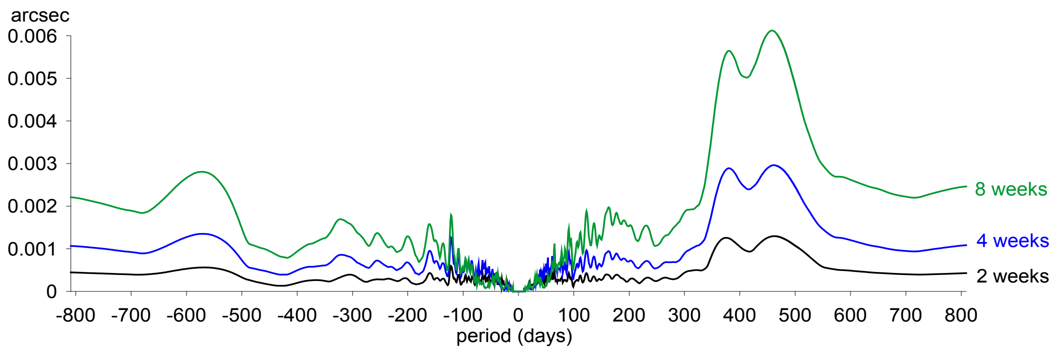


Fig. 14. The mean time frequency amplitude spectra of the differences between x, y pole coordinates data and their LS+AR predictions computed for prediction lengths of 2, 4 and 8 weeks in the future.

The increase of the differences between pole coordinates data and their prediction with the prediction length is caused by mismodelling of the irregular Chandler and annual oscillations in the LS+AR forecast models.

Generally, The skewness and kurtosic values of the differences between pole coordinates data and their LS+AR predictions for prediction lengths greater than about 50 days are close to 0 and 3, respectively which means that they follow normal distribution. For shorter prediction lengths the probability distribution of these predictions differences becomes more leptokurtic than normal.

6. **GalAc** (M. Kalarus)

The Space Research Centre, PAS is a lead partner in GalAc, which is a joint project with the Institute for Space Astrophysics and Planetology in Rome. Its purpose is to analyse the feasibility and usefulness of equipping second-generation Galileo spacecraft with accelerometers, in order to improve the accuracy of the Precise Orbit Determination (POD) and the Galileo Terrestrial Reference Frame (GTRF). The project addresses the objectives of the GNSS Evolution Scientific and Innovative Technology Research AO, related to the study and development of innovative GNSS methodologies and technologies, including algorithms, software and hardware. It is anticipated that the GNSS positioning accuracy will reach the level of millimetres, while ground infrastructures need to be simpler and more cost-effective.

Accelerometer data may be used to directly measure the unmodelled effects of non-gravitational forces and spacecraft acceleration due to onboard activity. As there will probably be no increase in the number of ground stations, such solution may be the answer. Next potential step in this direction is the introduction of the Inter-Satellite Link (ISL), which can significantly enhance the orbital solution.

The ambitious goal of this project is to establish, both theoretically and experimentally, the feasibility of using the know-how acquired in the development of the Italian Spring Accelerometer (ISA), developed with the support of the ASI (*Agenzia Spaziale Italiana*), and adapt it to the Galileo system. This will provide recommendations for further improvements, and the first steps in its implementation.
The Satellite Laser Ranging (SLR) station in Borówiec (Galileo satellites are equipped with retroreflectors) is considered essential to improve and validate the estimation process.

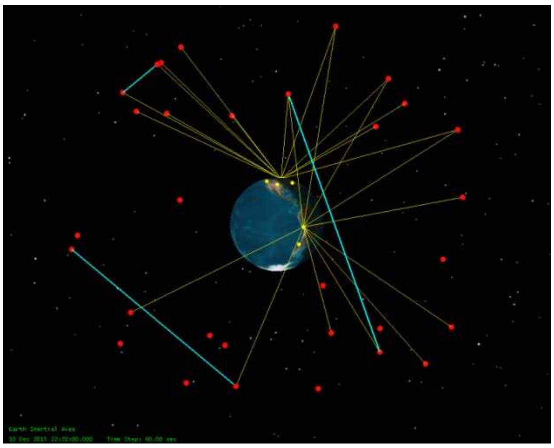


Fig. 15. Potential Inter-Satellite Link configuration

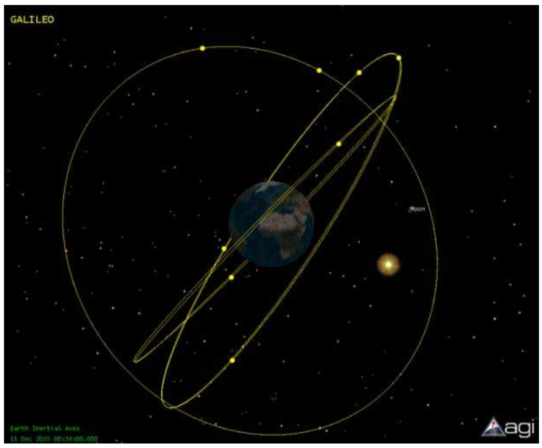


Fig. 16. Galileo constellation on 11 December 2015

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