USE OF GALILEO NEQUICK IONOSPHERIC ESTIMATION FOR SATELLITE OPERATIONAL ORBIT DETERMINATION

Daniel Navarro Reyes[(1)], Rubén Castro Gálvez[(2)], Andrés Ayala Novoa[(3)], Roberto Prieto-Cerdeira[(4)] and Raúl Orús Pérez [(5)]

[(1)]*ESA, ESTEC Keplerlaan 1, Noordwijk an Zee, The Netherlands, +31 71 5658313, Daniel.Navarro-Reyes@esa.int*

[(2)]*CGI, ESTEC Keplerlaan 1, Noordwijk an Zee, The Netherlands, +31 71 5658576, Ruben.Castro@esa.int*

[(3)]*GMV, ESTEC Keplerlaan 1, Noordwijk an Zee, The Netherlands, +31 71 5653683, Andres.Ayala@esa.int*

[(4)]*ESA, ESTEC Keplerlaan 1, Noordwijk an Zee, The Netherlands, +31 71 5658658, Roberto.Prieto.Cerdeira@esa.int*

[(5)]*Vitrociset, ESTEC Keplerlaan 1, Noordwijk an Zee, The Netherlands, +31 71 5658325, Raul.Orus.Perez@esa.int*

Abstract:
Galileo, Europe's own global navigation satellite system, consists of a constellation of 30 spacecraft (24 operational in a Walker 24/3/1 constellation and 2 active spare satellites per plane) in MEO at 23,222 km altitude. Galileo will provide positioning and timing services through L-band signals containing ranging codes and navigation messages with satellite ephemeris, clock corrections and ionospheric corrections. Galileo relies on S-band ranging to perform precise orbit determination for orbit manoeuvres because the L-band service is interrupted during orbit correction activities. In order to minimize the time to re-establish the L-band service, the orbit determination needs to be done as fast and precisely as possible. Currently, measurements in the orbit determination are modelled using the International Reference Ionosphere (IRI). This approach imposes two drawbacks, the dependency on an external supplier and the latency of the solar and ionospheric indices updates. To overcome this, Galileo is considering using NeQuick G, the ionospheric delay correction model provided to Galileo L-band single-frequency users (with near-real time updates), as a model for correcting ionospheric delays in the S-band ranging. This paper shows the results of a study carried out to assess the performance of NeQuick G in a S-band ranging operational set-up.

Keywords: *Galileo, Operational Orbit Determination, NeQuick G, Ionospheric correction*

1. Introduction

Galileo is Europe's own global navigation satellite system, consisting of a constellation of 30 spacecraft (24 operational in a Walker 24/3/1 constellation and 2 active spare satellites per plane) in MEO at 23,222 km altitude. Four satellites have already been launched and positioned in their operational orbit, as part of the in-orbit validation phase, IOV. 22 more satellites have been contracted for the full operational capability, FOC. The next launches are scheduled in the time frame 2014-2015 from the Kourou Space Port in French Guyana using the Soyuz/Fregat and Ariane-5/EPS launch vehicles.

The Galileo system provides precise positioning, velocity and timing information through L-band signals containing ranging codes and navigation message with satellite ephemeris, timing and ionospheric correction information. The availability of Galileo service performance levels is driven by several factors, among them, the low number of station keeping manoeuvres needed during each of the satellite's lifetime thanks to the station keeping strategy implemented in Galileo [1]. During a manoeuvre, the L-band ranging service provided by that particular satellite has to be interrupted as the broadcast ephemerides for the users are not accurate. Service can only be restarted once the post-manoeuvre orbit has been measured. This is to verify that the manoeuvre has performed as expected and that no additional corrective manoeuvres are needed, that is, the semi-major axis is within 5 meters of the target value. In order to minimise the unavailability of service, a fast and precise operational orbit determination has to be done using S-band ranging only.

S-band two-way ranging measurements are taken through the TC/TM S-band link, in spread spectrum modulation, between the ground station and the satellite. These S-band ranging measurements have proven to provide excellent results in terms of stochastic 2-way ranging errors:

- 40 cm standard deviation in one pass
- 1.4 m RMS once station biases are removed, for a 10-day arc.

This performance, together with excellent stability of the station and satellite calibrations, makes the S-band ranging a quite accurate means for operational orbit determination. However, the large amount of satellites in the constellation, and the reduced number of ground stations, makes the ranging data sparse. Having good quality ranging data from the few batches of ranging acquired is the only means to reach the specified orbit determination accuracy in a short time.

As a way of further improving the orbit determination accuracy, additional work is being done to enhance the orbit and ranging modelling. The well-proven models used in Galileo are based on experience from the work done by the European Space Agency in the area of Space Geodesy [2].

Currently, the ionospheric corrections rely on a climatological model such as IRI-2007 [3]. The use of this model presents two disadvantages:

- Updates to this model and changes to the interface are not controlled by Galileo, and require changes to the Galileo infrastructure involving a complex procurement structure.
- The latency of public updates of the dynamic parameters is a few months. In a real-time operational context, only IRI data predicted several months earlier can be used.

The start of regular broadcasting of Galileo messages, even though as part of the current in-orbit validation phase, has opened the opportunity to use the ionospheric model provided for L-band single-frequency users (NeQuick G). This is very attractive for operational purposes:

- First, being a model driven by broadcast parameters from the Galileo navigation message, the control of its interface definition and performance falls within the responsibility of the Galileo system. The Galileo operational orbit determination process can, therefore, have direct access to up-to-date input parameters of NeQuick G to obtain accurate short-term predictions of ionospheric corrections for the S-band range measurements.
- Second, the Galileo system already provides near-real time updates in the broadcast navigation message, which are also distributed internally within the Galileo Control

Centre; this improves the accuracy of the ionospheric corrections. Other satellite operators may also consider using the NeQuick G model together with the broadcast parameters as a way of obtaining ionospheric information.

This paper presents the work performed by the Mission Analysis team at the Galileo Project in collaboration with the Wave Interaction and Propagation section at ESA/ESTEC, in order to characterise the performance of NeQuick G used in an operational orbit determination environment based on S-band ranging.

Real S-band ranging measurements retrieved from the current two Galileo ground stations and the four in-orbit satellites have been processed using both the operational model currently implemented, IRI-2007, and NeQuick G for comparison. Additionally, operational-like orbit determination has been performed for different arc lengths in order to see whether the use of NeQuick G could reduce the arc length needed to achieve the specified accuracy.

The products generated, ranging and orbits were compared to very precise reference orbits obtained as part of the L-band processing done independently by the ESA/ESOC Navigation Office.

2. Objectives

The objectives of the study performed can be summarised as follow:

- Characterise the two-way range residuals for the IRI and NeQuick G models in an operational set-up, i.e. using latest updates available at the time of the ranging measurement acquisition. “A posteriori” IRI data, i.e. latest update based on observation data, is also used for comparison.
- Assess the improvement in the Orbit determination performance (accuracy and execution time) using NeQuick G versus IRI, and the potential shortening of the required data arc length to reach the specified orbit accuracy.
- Finally, assess the improvement in the Orbit prediction.

3. Background information on NeQuick G

Ionospheric electron density and ionospheric effects in general depend on different factors such as time of the day, location, season, solar activity and the interaction between solar activity and the Earth’s magnetic field or level of disturbance of the ionosphere, such as those happening during geomagnetic storms. On a large time-scale, solar activity follows a periodic 11-year cycle. The level of solar activity (and hence the solar cycle) is usually represented by solar indices such as the Sun Spot Number (SSN) or the solar radio flux at 10.7 cm (F10.7). The equatorial anomaly regions, located at around ±15-20 degrees on either side of the magnetic equator, usually present the largest electron density values. Mid-latitude regions’ daytime total electron content values (TEC, integral of electron density along a given transmission path) are usually less than half the value found in the equatorial anomaly region. Polar and auroral regions present moderate TEC values but larger variability than in mid-latitudes due to the characteristics of the geomagnetic field.

NeQuick is a three-dimensional and time-dependent ionospheric electron density model based on an empirical climatological representation of the ionosphere. It predicts monthly mean electron density from analytical profiles, depending on the solar activity-related input values: R12 or F10.7, month, geographic latitude and longitude, height, UT. This model is recommended by the International Telecommunications Union for TEC estimation used for radio wave propagation predictions.

The NeQuick model has been adapted for Galileo single-frequency ionospheric corrections, referred to as NeQuick G, in order to derive real-time predictions based on a single input parameter: the Effective Ionisation Level, Az. This parameter is computed using Eq. 1 together with the Modified Dip Latitude (MODIP) from the true magnetic dip (I) and the geographical latitude (φ), given by Eq. 2:

$$Az = a_{i0} + a_{i1} \times MODIP + a_{2i} \times (MODIP)^2 \tag{1}$$

$$\tan MODIP = \frac{I}{\sqrt{\cos\varphi}} \tag{2}$$

The three polynomial coefficients a_{i0}, a_{i1}, and a_{i2}, are broadcast in the navigation message. They are determined by the Galileo system using L-band measurements of the whole satellite fleet from a worldwide network of L-band receivers.

Slant TEC is obtained integrating numerically the electron density values obtained with NeQuick G along the ray path. For each discrete electron density, the Az computed for the ground station is used. The slant delay is then given in meters by Eq. 3, with TEC in TEC units (1 TECu = 10^{16} electrons per m^2) and frequency in Hz.

$$\Delta s = 40.3 \times 10^{16} \times \frac{TEC}{f^2} \quad (m) \tag{3}$$

For S-band two-way ranging, the ionospheric delay is the sum of the up-link leg delay and down-link leg delay.

The performance of the Galileo Single Frequency ionospheric correction algorithm during several months of the In Orbit Validation phase, in 2013, can be found in [4]. In spite of using only a reduced infrastructure (4 satellites and a partial set of Galileo Sensor Stations), the results already show very good correction accuracies in comparison to other correction models such as GPS Klobuchar model. This is especially the case in equatorial regions where the three dimensional nature of NeQuick is strongly beneficial for proper representation of the ionosphere in comparison to the two dimensional thin layer approximation of other models.

The publication of the NeQuick G model and the Galileo single-frequency correction algorithm is under preparation for public release by the European Commission.

4. SW implementation

The analysis has been performed using the Constellation Mission Analysis Facility (CMAF), an evolution of the existing Galileo Flight Dynamics Facility (FDF), based on ESA/ESOC's NAPEOS [2] and GMV's focusCn [5]. CMAF contains several modules customised for Galileo to calculate launch windows, satellite target state vectors for the launcher, satellite deployment sequences, and to optimise the station keeping and disposal orbits as well as to support the characterisation of the satellite properties relevant to Astrodynamics.

The CMAF modules used for this study are an S-band data pre-processor (PREPRO), an orbit estimator (BAHN), an orbit propagator (PROPAG), and other ancillary orbit tools.

The orbit propagation models used are:

- Adams-Bashford explicit multi-step integration with eight steps, initialised with eight-step Runge-Kutta
- 240 steps per orbit
- Earth Gravity field Grace Model, 12x12
- Solar and Moon Gravity, JPL de405 ephemeris
- Solid and Ocean tides
- Integrator re-start to avoid eclipses discontinuities
- SRP Cannon ball model, constant area and estimated scale factor. (No other empirical accelerations, such as Y-bias, are considered in this study.)

The observation models used are:

- Troposphere delay corrected using Saastamoinen, with meteorological data provided by the ground stations
- Ionosphere model, depending on the scenario analysed: IRI-2007 or NeQuick G
- Centre of mass correction, using ideal satellite yaw steering.
- Solid tide correction
- Ground station range bias, estimated per arc

For this study, the NeQuick G subroutines have been implemented in the orbit estimation module (BAHN) so the correction is applied to the ranging observations during the orbit determination process. The input files have been simplified for the study; instead of the full navigation message, a file is used that contains a summary of the coefficients a_{i0}, a_{i1}, and a_{i2} from each navigation message broadcast.

5. Test data set

The test data set is comprised of:

- Static configuration files (ground station coordinates, S-band frequencies, satellite properties, etc.)
- S-band ranging and meteorological data acquired by the Galileo ground stations
- IRI data (static and dynamic) available at the time-stamp of ranging data
- NeQuick G data available from the Navigation message (real time)

- Reference orbits

Two periods of ten days (ground track repeat cycle) have been chosen:
- 15 May to 25 May, 2013: “bad ionosphere”
- 9 June to 19 June, 2013: “good ionosphere”

5.1. S-band ranging and meteorological data.

The current IOV configuration of the Galileo space segment comprises two TM/TC ground stations (ES21 in Kourou, French Guyana; and ES28 in Kiruna, Sweden) and four satellites.

Official name	Model	Pseudo range number	Slot
GSAT0101	IOV PFM	E11	B5
GSAT0102	IOV FM1	E12	B6
GSAT0103	IOV FM2	E19	C4
GSAT0104	IOV FM3	E20	C5

Table 1: Deployed Galileo satellites, used in the study, and its diverse ID. PRN as per RINEX convention.

Figure 1 shows the geographic location of the IOV ground stations, and the ground track of one of the satellites for illustration purposes. Such a geographic configuration allows for having a contact every orbit revolution from ES28 and some long passes from ES21.

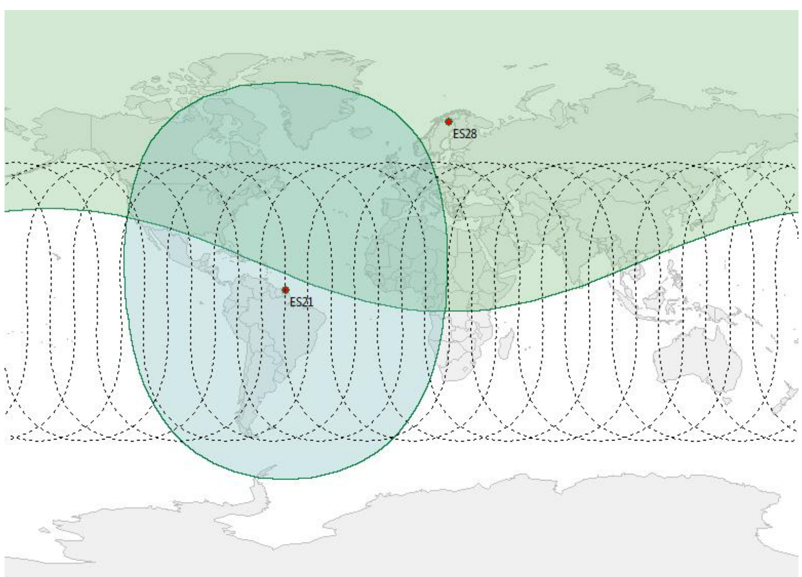

Figure 1. Galileo ground-track (one satellite) for 10 sidereal days, with visibility areas from ES21 and ES28.

Ranging and meteorological data generated by the two ground stations for the four satellites have been extracted from the Galileo Control Centre for those periods. Routine ranging data acquisition is based on passes of about six minutes, with a ranging data rate of 1Hz.

Table 2 shows the number of 2-way ranging measurements retrieved for each satellite, per ground station, of both study periods:

	First period		Second period	
	ES21 (Kourou)	ES28 (Kiruna)	ES21 (Kourou)	ES28 (Kiruna)
GSAT0101	5308	5119	4816	3926
GSAT0102	4928	3926	3721	3878
GSAT0103	5624	6314	3215	4707
GSAT0104	6182	3509	*	*

Table 2: S-band ranging observations retrieved and used for the study.

* In the second period, 3126 observations were acquired by ES21 and 3269 by ES28. However, since the reference orbits for GSAT0104 were not accurate enough for that period, it was decided to discard GSAT0104 for the second study period.

5.2. IRI Data

The latest *ig_rz.dat* file available, as per IRI-2007 definition, at the time of the ranging data acquisition is used. The file was retrieved from:
ftp://nssdcftp.gsfc.nasa.gov/models/ionospheric/iri/iri2007/

For the "a posteriori" IRI model, based on observations, the file was retrieved from an alternative source:
http://irimodel.org/indices/

5.3. NeQuick Galileo Ionospheric Data

As mentioned above, two periods of 10 days were chosen inside the IOV experimentation in 2013:

- The first period (15-25 May, 2013; day of year 135 to 145) corresponds to 10 days where NeQuick G performed worse than its average performance during IOV experimentation. This underperformance is mainly due to the seasonal behaviour of the ionosphere.
- The second period (9 to 19 June, 2013; day of year 160 to 170) corresponds to 10 days where NeQuick G performed better than average during IOV experimentation.

Figure 2 depicts the NeQuick G RMS (for L1) for the whole period, showing how the error decreases when moving away from the equinox.

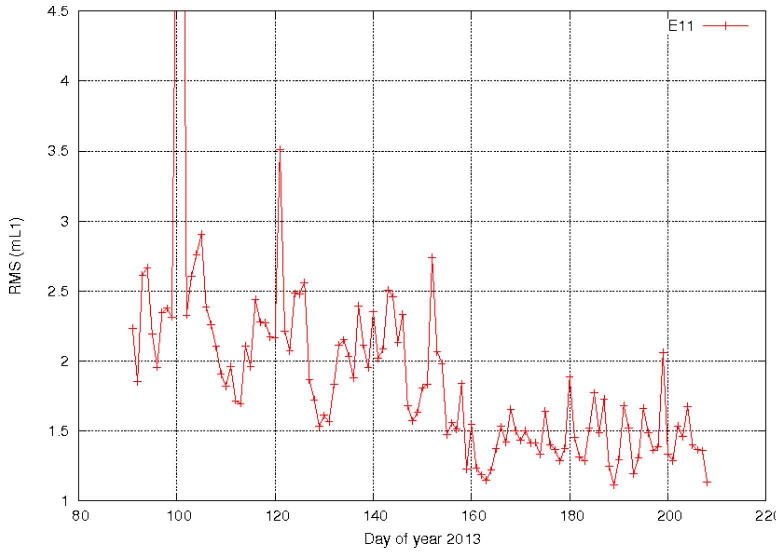

Figure 2. NeQuick G daily RMS residual error for L1 derived from over 100 stations globally distributed [4]**.**

Static data are defined as per the model [6] and are not changed. The dynamic data, i.e. the coefficients a_{i0}, a_{i1}, and a_{i2} for each epoch, were obtained from the broadcast navigation message. Figure 3 shows the a_{i0} value only, in order to illustrate its temporal variation for each of the two study periods.

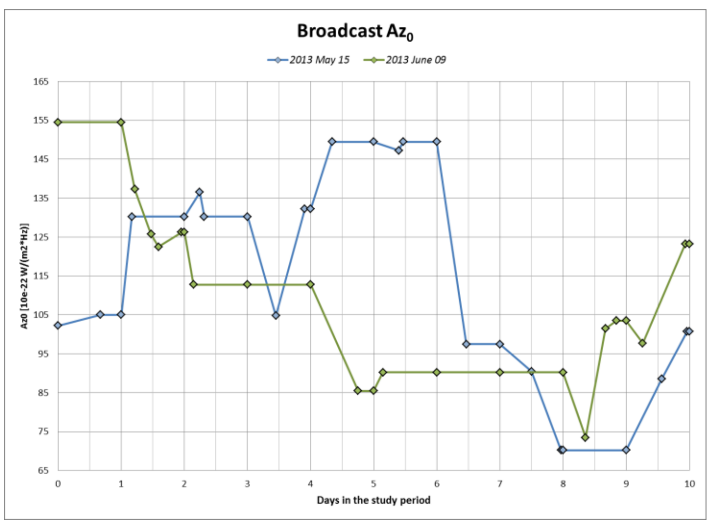

Figure 3. Broadcast a_{i0} values (default used when value not valid) for the two study periods.

5.4 Orbit reference data

The orbit data used as reference were provided by the ESOC Navigation Office. These orbits were determined using L-band measurements from a network of L-band receivers, wider than, and independent from, the operational network used by the Galileo system. The orbit determination is done in arcs of two days in a moving window with one day overlap between solutions. The methodology for orbit determination is different from the one used by Galileo, combining GPS signals to enhance common view (especially since only four Galileo satellites are deployed so far) and satellite laser ranging (SLR) provided by the International Laser Ranging Service (ILRS) network [7]. The latter allows to independently confirm the accuracy of the orbits obtained through L-band processing, since SLR is not affected by clock biases or ionospheric delay.

To assess the accuracy of the reference orbit, a routine internal consistency check is done. Figure 4 shows the 1-way ranging error that a ground station in a worst location would have, for the first period. The error is computed based on the orbit difference in the overlap of two consecutive solutions; the error is the RMS taking into account worst viewing angle for the user (zero elevation). Figure 5 corresponds to the second period. From both figures it seems that the first period RMS is slightly worse than the second period RMS. In any case, worst user location is generally a pessimistic measure of the ranging error because possible correlations on the orbit error components are ignored.

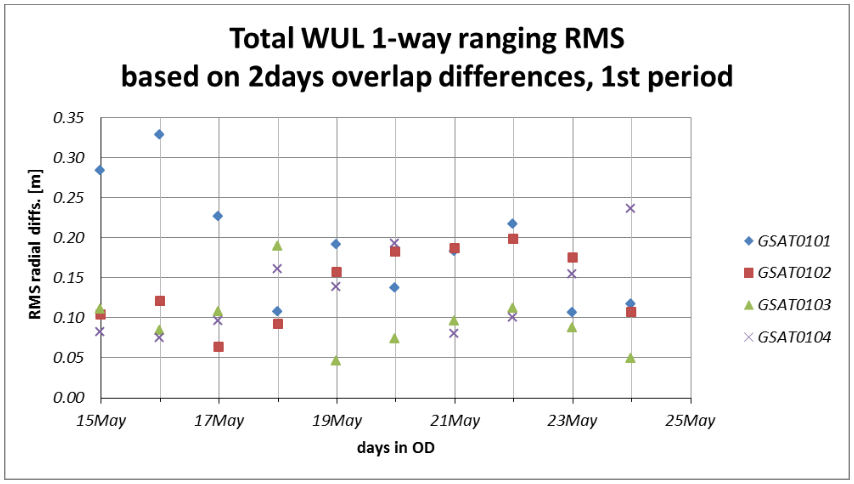

Figure 4. Total Worst-user-location 1-way ranging error, first period.

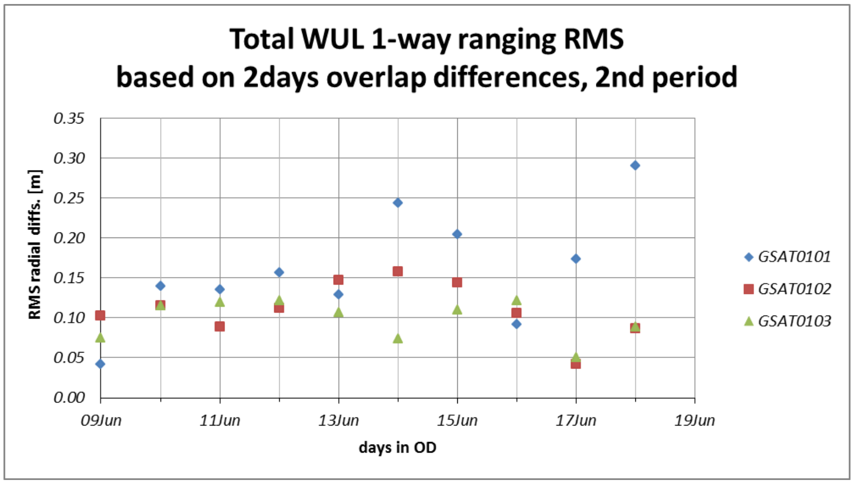

Figure 5. Total Worst-user-location 1-way ranging error, second period.

An alternative way of assessing the ranging error derived from the reference orbit is the SLR residuals. SLR data are sparse and do not add much to the L-band solution. However, the SLR residuals can be used as an independent quality measure of the orbit error in the direction of the slant range. Figure 6 shows the 2-way SLR residual RMS for each of the solutions (day of the year corresponds to the first day of the two-day arc). As suspected, the first period presents higher errors than the second one, especially for GSAT0103 and GSAT0104. Possible causes can be the "bad" ionosphere itself, or the presence of eclipses in GSAT0103 and GSAT0104. Days 135 and 136 are also not too good for GSAT0101. In any case, the 2-way ranging RMS are in the order of 23 cm for first period and 11 cm for the second period, providing confidence that these orbit solutions are suitable as reference orbits for the study.

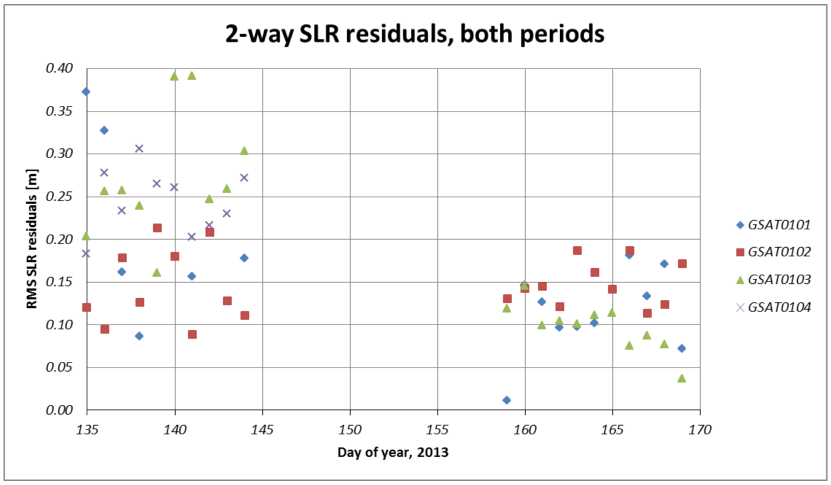

Figure 6. 2-way SLR residuals for both periods.

6. Methodology and results

The first step is to run the S-band ranging through the pre-processing module, (PREPRO). The main objective is to correct the ranging data using the ground station calibrations and to rearrange the data in a so-called NAPEOS tracking data file, containing calibrated ranging and meteorological data.

The correction of the ionospheric delay is done in next steps by the orbit determination module (BAHN) depending on the SW configuration selected. For each of the two models, the data are run through the processes explained hereafter. At the end the outputs (corrected ranging, determined orbit, predicted orbit) are compared to the reference orbit, and the resulting differences are analysed.

6.1. Data pass-through

The processed raging data are fed into the orbit determination module. There, the reference orbits are used as a priori orbits. The orbit determination program is configured as "pass-through". This means that the ranging data are corrected (using the models described in section 4), but no orbit determination is performed. The corrected data are compared to the geometric range calculated from the reference orbit, obtaining ranging residuals which are analysed.

The results of the data pass-through are plotted versus the elevation in order to see if clear correlation with elevation can be detected. Figure 7 shows the residuals in the first studied period for all four satellites as a function of elevation when the operational IRI model is used. A negative bias seems to be present. A correlation of the residuals with elevation cannot be validated.

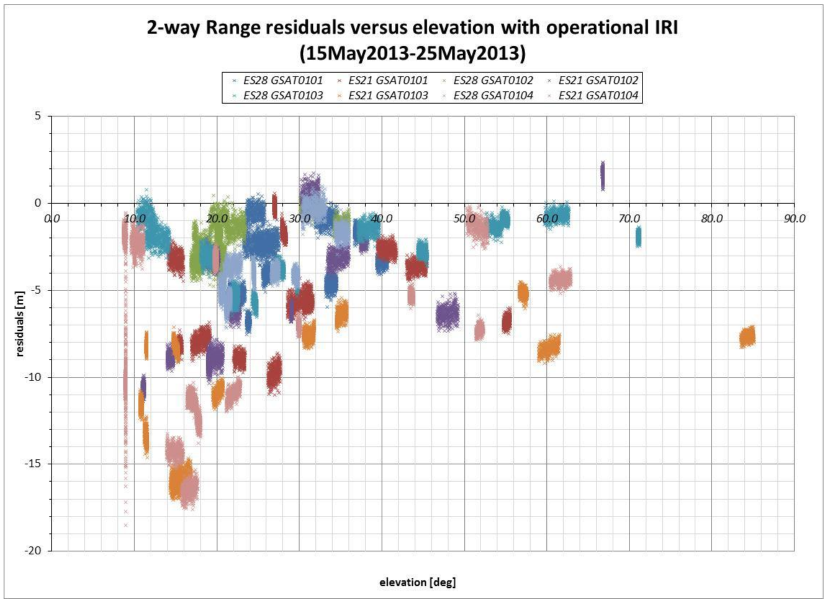

Figure 7. 2-way range residuals versus elevation, Operational IRI, first study period.

Figure 8 shows the residuals for the NeQuick G model during the same period. The figure clearly illustrates that, in this case, the results show no bias. However, the dispersion of residuals around the zero mean seems similar to the previous case. A correlation with elevation is not clear either.

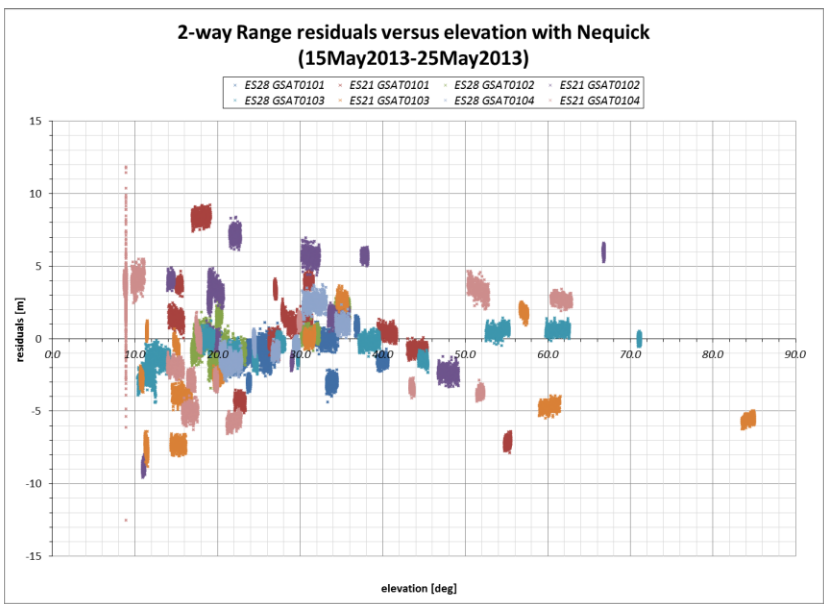

Figure 8. 2-way range residuals versus elevation, NeQuick G, first study period.

From both figures above it is evident that NeQuick G has improved the residuals.

In order to see whether the improvement is due to the model itself or to the fact that IRI was using predicted values, the ranging data has been passed through again with the IRI model but using “a posteriori” data. Figure 9 shows again the residuals versus elevation, this time for the “a posteriori” IRI data: a bias close to zero can be observed and a similar dispersion of residuals as in the case for NeQuick G.

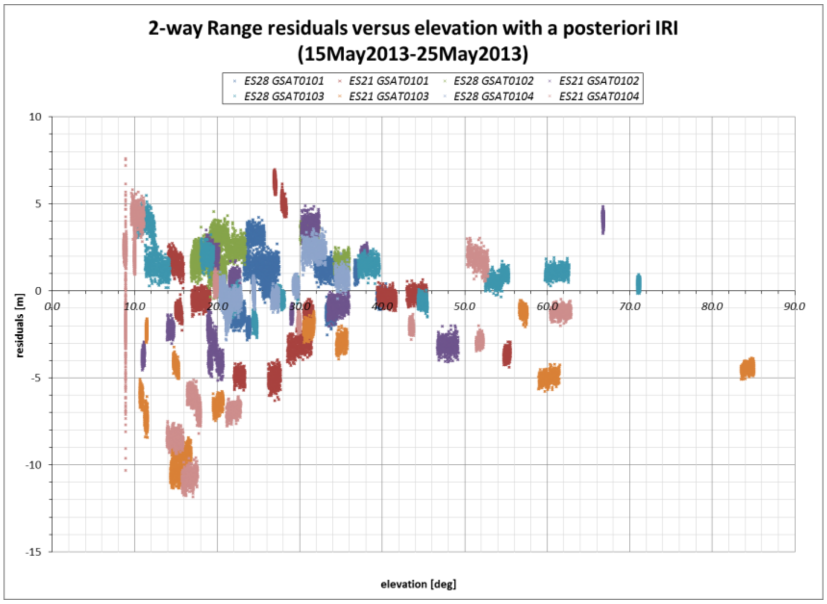

Figure 9. 2-way range residuals versus elevation, “A posteriori” IRI, first study period.

The stochastic behaviour of the ranging data can be seen by how close together the residuals are in each pass. Without considering the non-zero mean of each pass, the dispersion of residuals is very small, about 20 cm standard deviation (basically of the same order as SLR residuals).

In order to better characterise the residuals, histograms and statistic parameters have been generated by each of the cases, period and models.

Figure 10 shows the residuals histograms for the first period, one per station, for the three models. The means of the residuals for NeQuick G and “A posteriori” IRI are closer to zero than for Operational IRI.

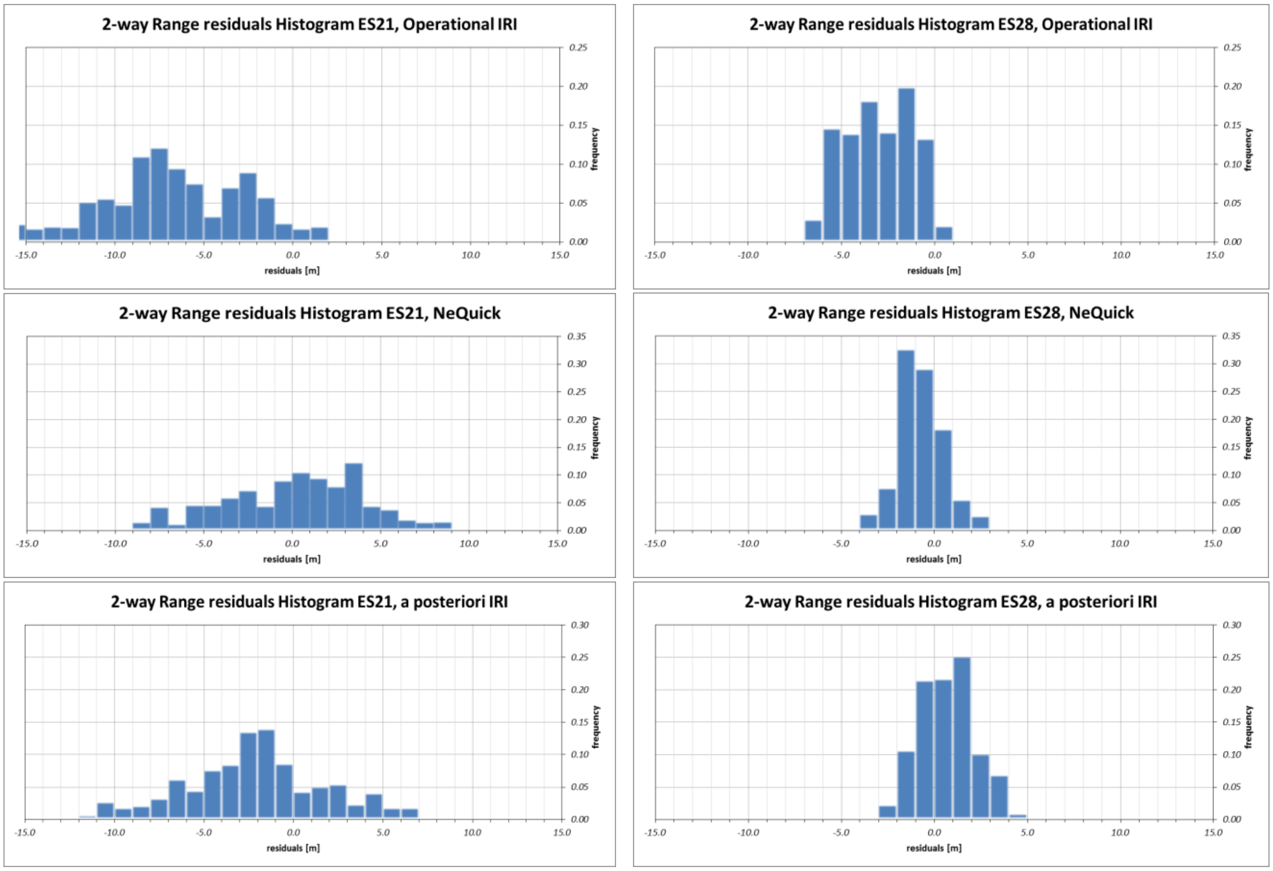

Figure 10. 2-way range residuals histograms, per station and per model, for the first study period.

Table 3 provides the mean and standard deviation for each ground station and model used. A significant improvement of the mean residual for NeQuick G and “a posteriori” IRI is observed, while the dispersion improves only slightly.

	ES21		ES28	
Model	Mean [m]	St. dev. [m]	Mean [m]	St. dev. [m]
Operational IRI	-6.96	4.26	-3.01	1.81
NeQuick G	0.10	4.02	-0.68	1.26
A posteriori IRI	-2.16	3.93	0.71	1.51

Table 3: Residual statistic of pass-through, first study period.

Figure 11 shows the same histograms for the second period. Similar conclusions can be derived. The dispersion for ES21 is smaller (practically half) than for the first period. This could be due to the closer proximity of the first period to the maximum error near day 100 (see section 5.3).

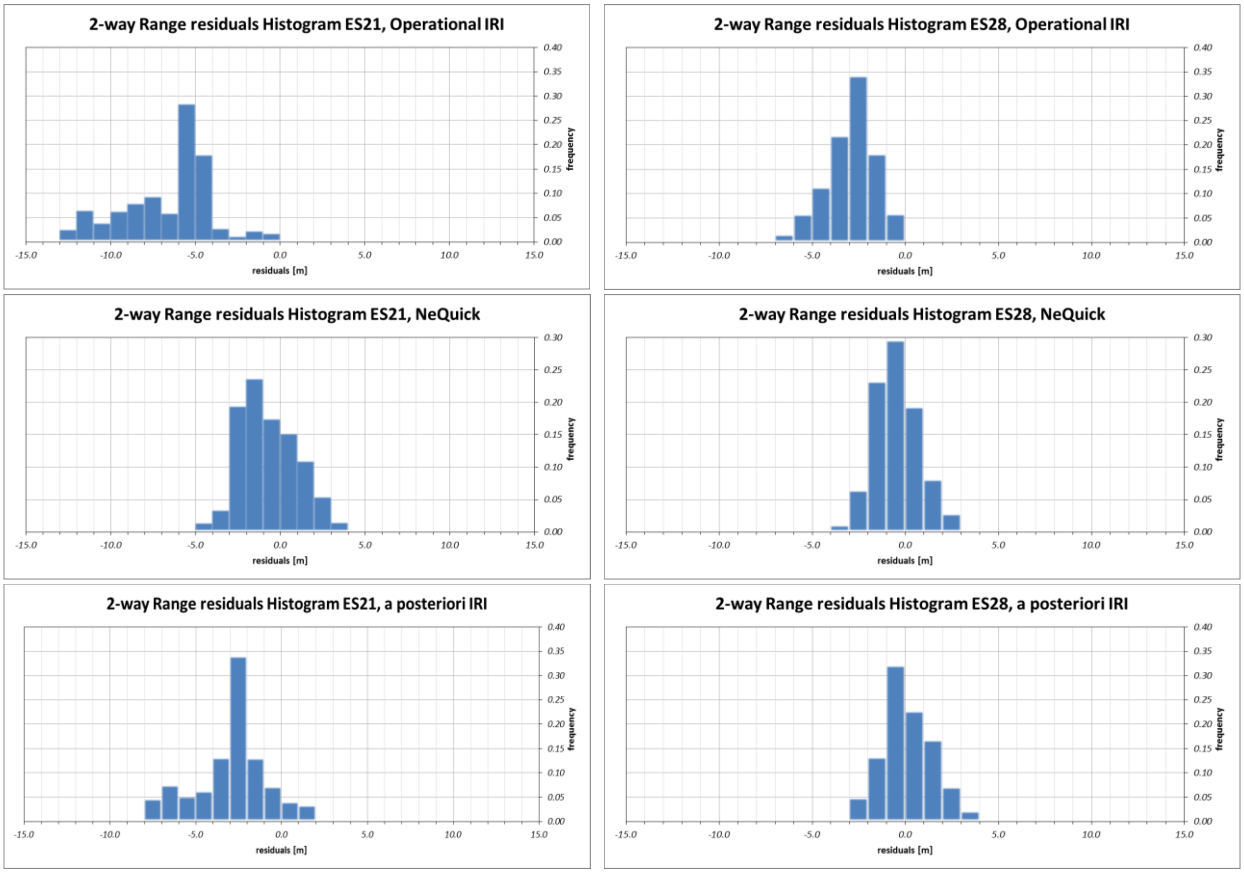

Figure 11: 2-way range residuals histograms, per station and per model, for the second study period.

Table 4 shows the mean and standard deviation confirming what the histograms show.

	ES21		ES28	
Model	Mean [m]	St. dev. [m]	Mean [m]	St. dev. [m]
Operational IRI	-6.43	2.67	-2.60	1.53
NeQuick G	-0.69	1.71	-0.44	1.24
A posteriori IRI	-2.87	2.17	0.17	1.36

Table 4: Residual statistic of pass-through, second study period.

6.2. Orbit Determination

The processed raging data are fed into the orbit determination program. There, the reference orbits are used as a priori orbits. The orbit determination program is configured to use the data within a given time-span. The program is then run for several arc-lengths, generating as output the solved-for orbits for each of the arc lengths used. In each of the cases, the orbit is determined as a six-element state vector plus a SRP scale factor. One ranging bias per ground station (thereafter called station bias) and per arc is also solved for. Those output orbits are compared to the reference orbits and differences are analysed.

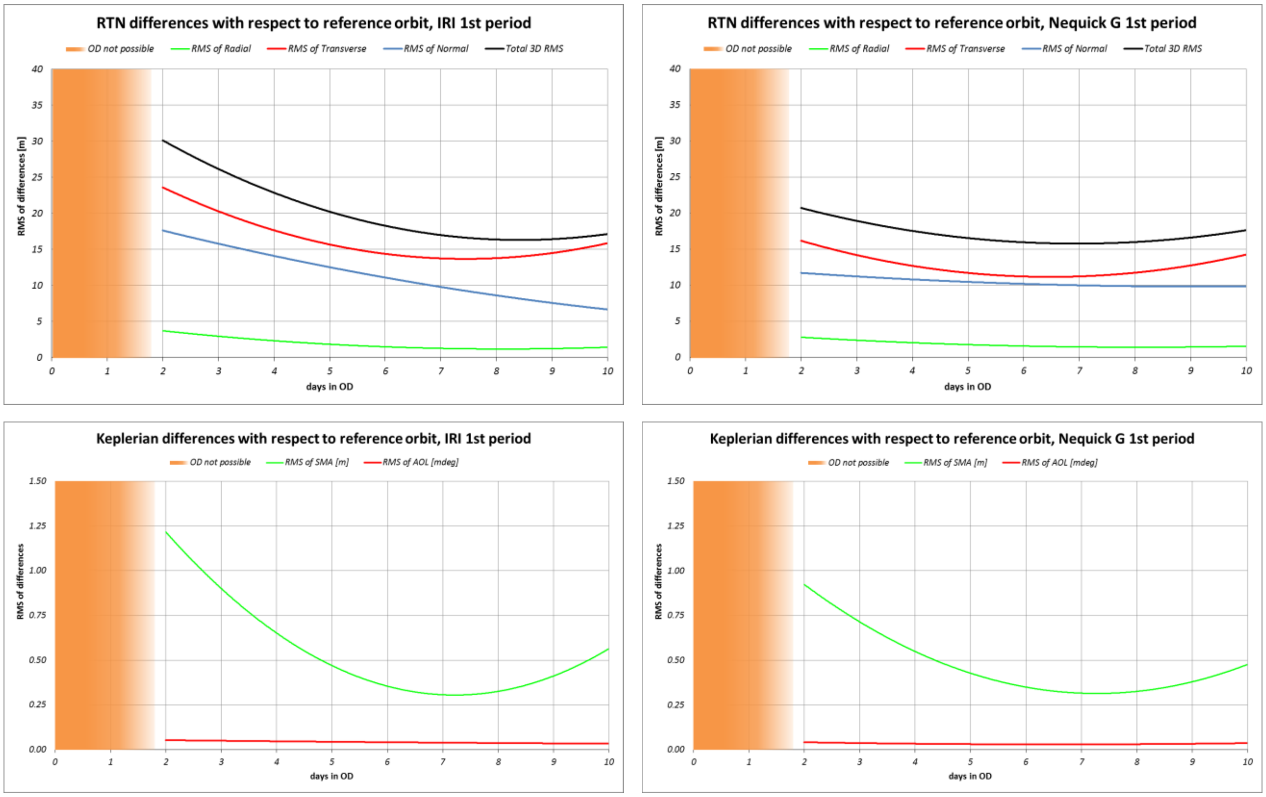

Figure 12: Orbit determination error as a function of arc length, first study period.

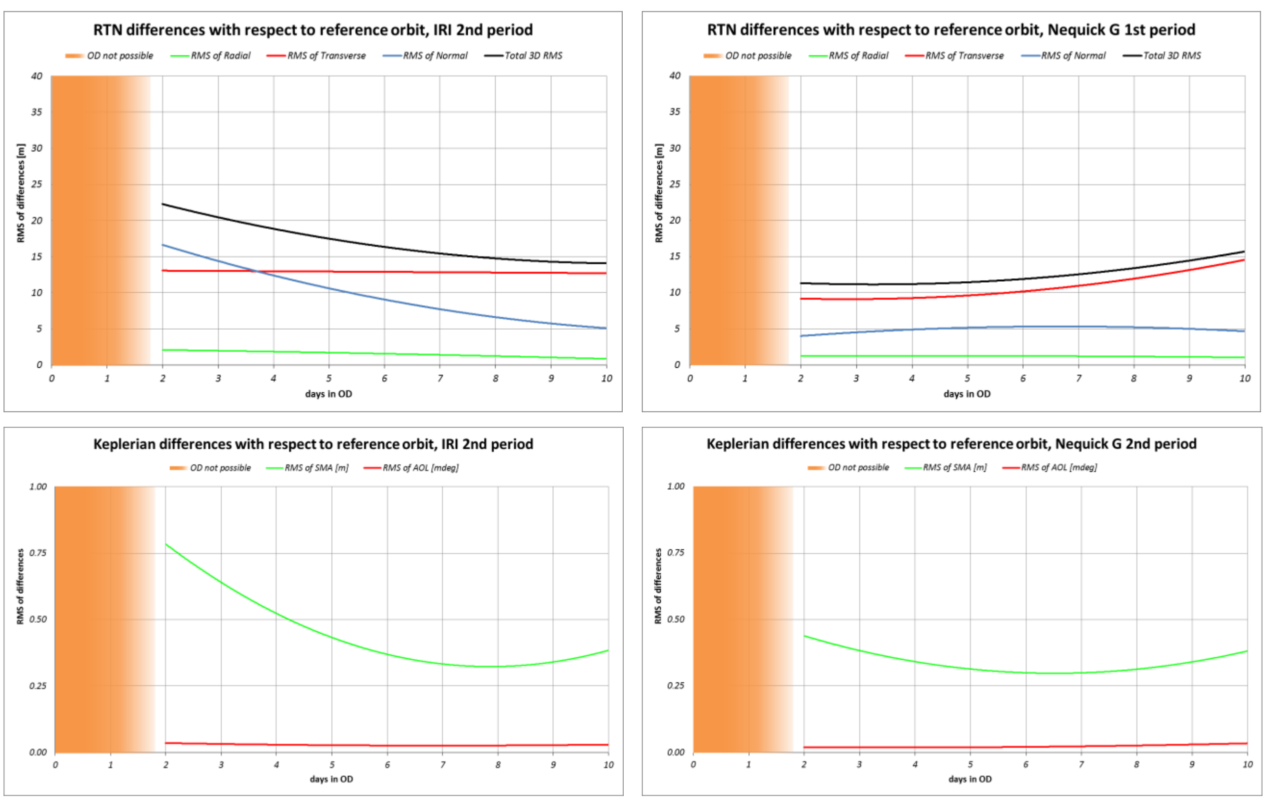

Figure 13: Orbit determination error as a function of arc length, second study period.

Figure 12 and Figure 13 show the orbit determination error (with respect to the reference) as function of the arc length. As expected, the longer arcs provide more accurate determined orbit. But up to a limit: the orbit dynamics model used in the study are quite precise, but do not account for empirical accelerations that are known to affect many satellites (such as the Y-bias). As the arc length grows beyond 8 days the orbit determination error starts to grow.

The use of NeQuick G for the period of analysis in this paper shows a modest improvement on the results but not as much as expected from the residual histograms. This is due to the fact that all the orbit determination cases (for all the models) are solving for station biases. The mean residual observed in the histograms for the operational IRI is actually absorbed by those station biases, so the results are quite similar for both models. The results with NeQuick G do look better for shorter arcs. In those cases, with not many ranging data passes, any improvement to the model have a higher impact on the improvement of the orbit determination.

6.3. Orbit Prediction

With the orbit determined for each of the arc lengths, an orbit prediction of two days is done and compared to the reference orbits. The differences are then analysed.

Similarly to the orbit determination cases, the orbit prediction based on NeQuick G does not show a drastic improvement with respect to the Operational IRI. The major improvement happens in the cases with shorter arc lengths for NeQuick G. Again, the prediction seems more robust than those based on IRI.

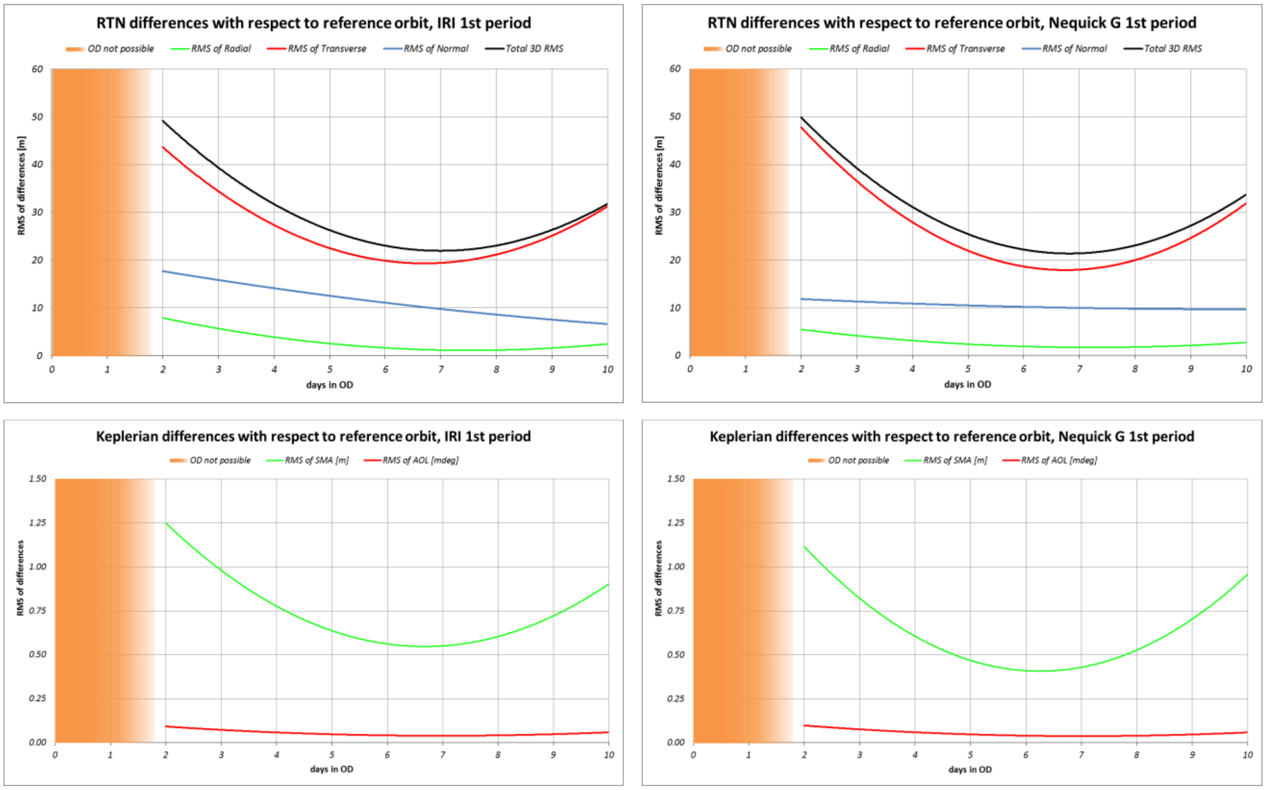

Figure 14: 2-day orbit prediction error as a function of arc length, first study period

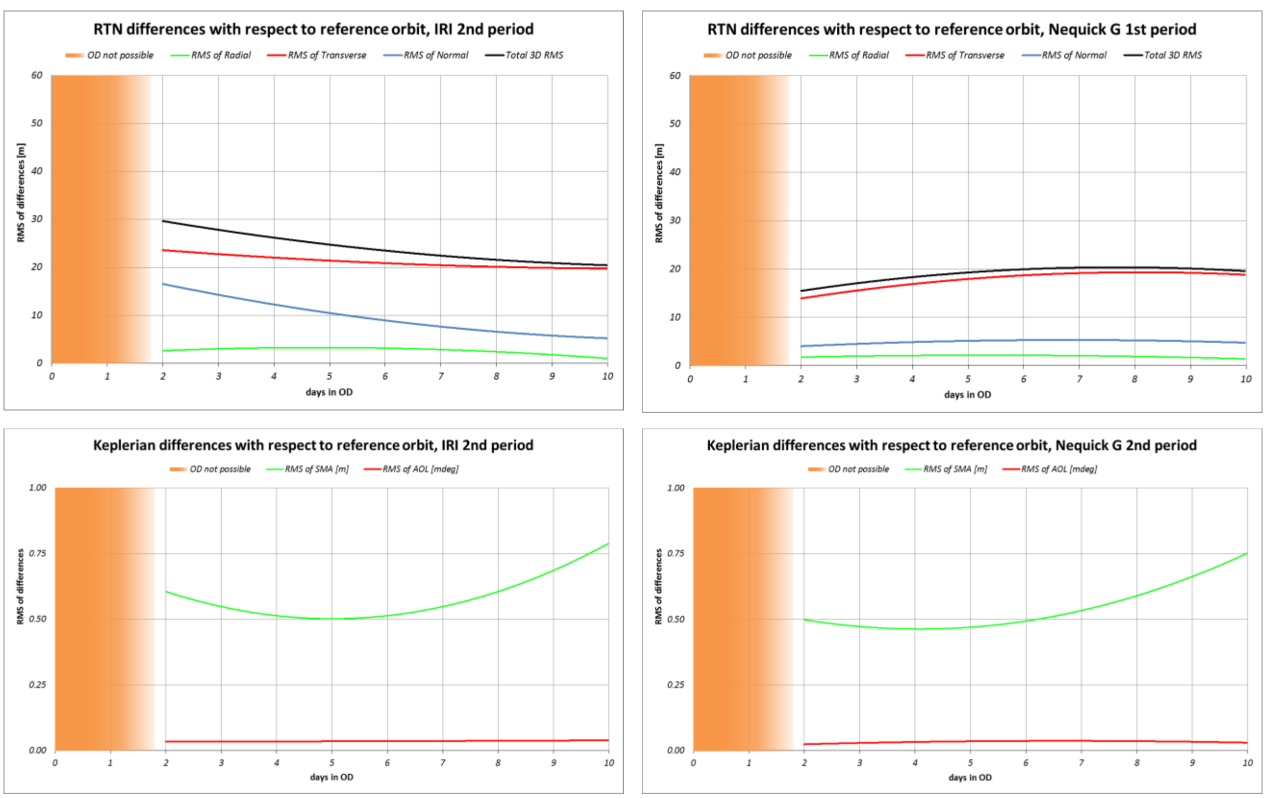

Figure 15: 2-day orbit prediction error as a function of arc length, second study period.

8. CPU run time comparison

During the executions of the test cases it was observed that the orbit determination execution durations based on NeQuick G were about double faster than those based on IRI. Figure 16 shows the execution time with both IRI and NeQuick G, for both study periods. This improvement in execution time will have a higher importance when the full constellation is deployed since the amount of data to process will be seven to eight times larger.

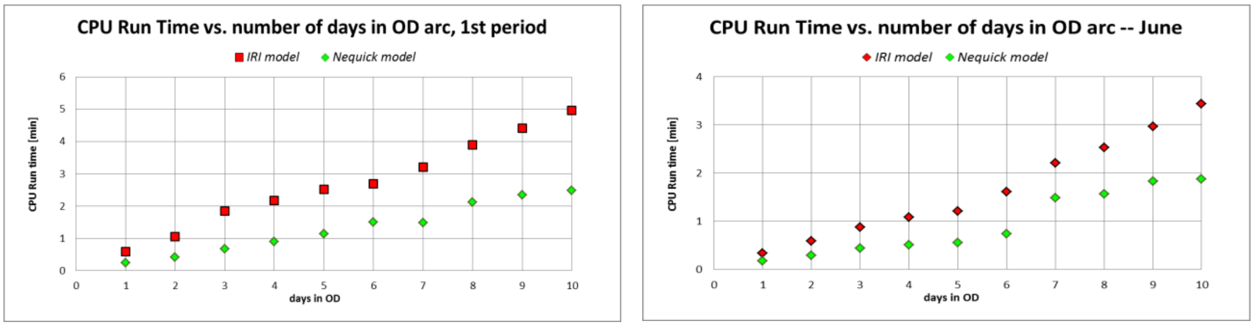

Figure 16: Orbit determination CPU run time for IRI and NeQuick, for both study period.

9. Conclusions

NeQuick G is an attractive model for ionospheric correction of S-band ranging data for operational orbit determination. In the case of Galileo operations, NeQuick data updates are available near real-time in the Galileo Control Centre. For other satellite operators, the data are available on the navigation message broadcast by the satellites.

For Galileo, the NeQuick G model presents some advantages in the operational orbit determination over the current ionospheric model implemented, IRI:

- NeQuick is based on measured up-to-date values of the ionosphere and the data are provided in near-real time.
- The interfaces to the NeQuick G model are under control of Galileo.

From the performance point of view, three advantages have been found:

- NeQuick provides ionospheric corrections that make the residual zero-mean. The dispersion (standard deviation) is also slightly improved. Therefore, for S-band characterisation, the use of NeQuick allows to remove a large amount of the ionospheric delay, and focus on other effects that need better modelling.
- Even though it does not seem that the arc length can be reduced much, from an orbit determination and prediction point of view, NeQuick offers a slight improvement for short arcs.
- The computational load of NeQuick is also lower, around 50% of the CPU time used when using IRI model.

It is important to remark that the NeQuick G broadcast parameters used during the test are based on a reduced Galileo infrastructure (with only 4 IOV satellites), and therefore the performance of NeQuick G on delay estimation when more satellites and sensor stations are deployed, is expected to improve, with some potential for additional performance improvements.

Future prospects include comparisons with the usage of Global Ionospheric Maps in IONEX format that already anticipated promising results.

10. Acknowledgement

The authors would like to acknowledge the support provided by the ESA/ESOC Navigation Office in Darmstadt (Germany) and by the Galileo Control Centre in Oberpfaffenhofen (Germany).

11. References

[1] Navarro-Reyes, D., Notarantonio, A., Taini, G., "Galileo Constellation: Evaluation of Station Keeping Strategies." Proceedings 21th International Symposium on Space Flight Dynamics – 21th ISSFD. Toulouse, France, 2009.

[2] Springer, T., Dilssner, F., Escobar, D., Flohrer, C., Otten, O., Svehla, D., and Zandbergen, R. "NAPEOS: The ESA/ESOC tool for Space Geodesy." Geophysical Research Abstracts, Vol. 13, EGU2011-8287, 2011

[3] D. Bilitza, D., Reinisch, B.W. "International Reference Ionosphere 2007: Improvements and new parameters". Advances in Space Research 42, 599–609, 2008.

[4] Orus-Perez, R., Prieto-Cerdeira, R., Arbesser-Rastburg, B. "The Galileo single-frequency ionospheric correction and positioning observed near the solar cycle 24 maximum", in Proceedings of 4th International Colloquium Scientific & Fundamental Aspects of the Galileo Programme, Prague, December 2013.

[5] Pérez-Cambriles, A., Molina-Cobos, M.A., Pérez-López, F., "focusCn: GMV Solution for Satellite Constellation Operations." Proceedings 3rd ESA Workshop on Astrodynamics Tools and Techniques. ESTEC, Noordwijk, The Netherlands, 2006.

[6] European Commission, "Galileo Open Service SIS ICD", to be published.

[7] Pearlman, M.R., Degnan, J.J., and Bosworth, J.M., "The International Laser Ranging Service", Advances in Space Research, Vol. 30, No. 2, pp. 135-143, July 2002.