Analysis of GPS Signal-in-Space Accuracy using GalTeC

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BIOGRAPHY

Dr. Hua Su
Currently the Senior GNSS Systems Engineer at THALES ATM GmbH, Germany. He obtained his Dr. –Ing. from the University FAF Munich, Germany in 2000. Over the last 20 years he has been responsible for many projects related to development of precise satellite orbit determination, differential GPS positioning, satellite navigation and GPS receiver software. In the period 2001 to 2005, he was responsible for systems engineering for EGNOS System AIV (Assemble, Integration and Validation) project dealing with EGNOS subsystems RIMS A/B/C and TUE performance, system monitoring and performance analysis. Since May 2005 he has being worked for Galileo projects regarding Galileo services performance monitoring and analysis.

Walter Ehret
graduated as an Aeronautical and Space Engineer from the Technical University (TU) of Braunschweig, Germany in 1996. Since 1996 he is involved continuously in research and engineering activities related with Satellite Navigation and its applications. Currently he is active as Senior Systems Engineer at THALES ATM in Stuttgart where he was and is involved in Galileo related programs and studies. His expertise is dedicated particularly to Integrity related aspects of GNSS.

ABSTRACT

Satellite Navigation users utilize the GNSS broadcast ephemeris and clock correction parameters for positioning and navigation. The accuracy and integrity performance of the navigation application are directly affected by GNSS signal-in-space (SIS) errors caused by broadcast orbit and satellite clock errors.

The GPS SIS performance is analysed in this work based on GPS measurements from the IGS (International GNSS Service) network and precise GPS reference orbits generated by GalTeC and IGS. GalTeC is a joint venture between Thales and NavPos Systems supported by the German DLP (German Aerospace Centre). This system allows for the independent monitoring of the associated services related to Global Satellite Navigation Systems GPS, Galileo and potentially GLONASS. The project is in the mid-term phase and one of the first implementations is the GPS SIS analysis capability.

In order to analyse GPS SIS performance, precise GPS reference orbits are determined using GPS measurements from IGS network. GPS broadcast ephemeris are compared with the precise reference ephemeris to calculate the orbit differences as GPS SIS errors in three directions (along, radial and cross tracks) and satellite clock errors. These errors reflect the GPS broadcast SIS performance that impacts on the performance of user positioning and navigation. The GPS broadcast orbit errors and satellite clock errors in the orbit domain are converted to the ranges domain at the directions of the worst user locations (WUL). The range errors to the WUL are defined as Signal-in-Space Reference Errors (SISRE). The SISRE are then compared with URA (User Range Accuracy) to check whether URA over-bounds the SISRE or GPS SIS errors correctly. The actual SISRE over-bounding called SISRA (Signal-in-Space Reference Accuracy) are also computed in order to further compare SIS errors with URA. Analogue analysis (with SISA instead of URA) is planned to be performed by GalTeC once the Galileo system is initially operational.

By analysis of GPS SIS errors it is found that in the most cases URA from the GPS broadcast ephemeris reflect the accuracy of GPS broadcast ephemeris due to orbit and clock errors. But sometimes URA over-bounds the orbit errors only, not orbit and clock errors. URA performance is dependent on the types of satellite clocks, for example, it was found from the data analysis that URA over-bounded the GPS broadcast errors better with rubidium clocks than with caesium clocks. It was also observed that most of the (apparent) satellite clock jumps occurred when GPS broadcast ephemeris was updated. The updating of GPS broadcast ephemeris can be determined by checking IODE and IODC. From data analysis so far URA usually does not reflect these jumps. This would potentially impact the user integrity performance without additional aid from space or ground augmentation systems.

INTRODUCTION

GalTeC (Galileo Technology Centre) is projected as Service Centre offering various GNSS information services and high-end analysis services for different kind of user groups [2]. GalTeC will provide its users with unique capabilities of satellite orbit determination, navigation data processing, performance analysis (PVT), safety of life application analysis regarding RAIM, SBAS and Galileo integrity performance. Also some receiver signal analysis for GPS, GLONASS and Galileo systems will be provided. The GalTeC components are shown in the figure below.

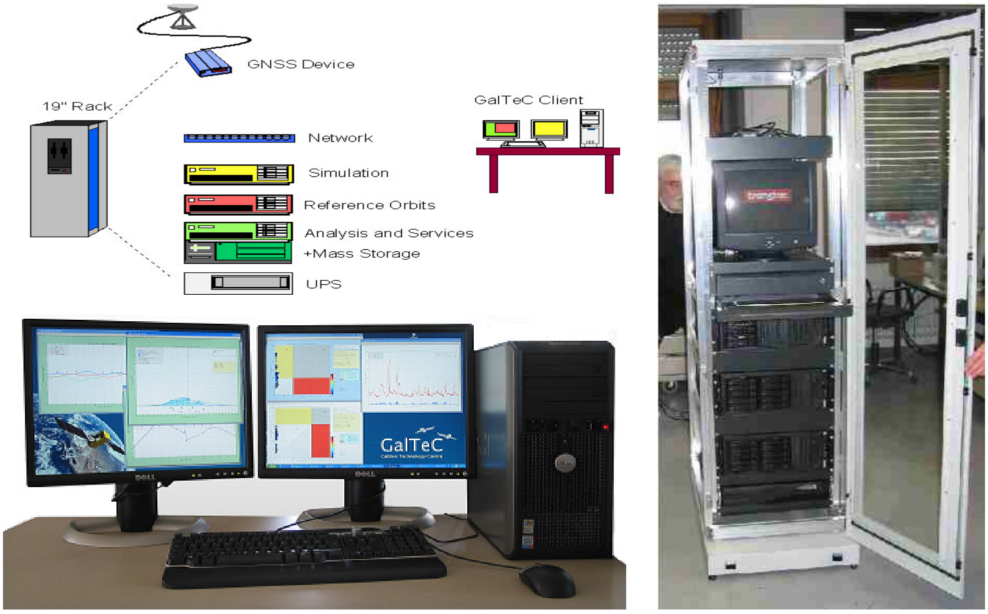

Figure 1: GalTeC Server and Client HW

The hardware is composed of three servers dedicated to different tasks - Reference Satellite Orbit and Clock determination - Simulation and Prediction - Analysis, Reporting and Web Services. The central capability of GalTeC used for the analysis presented is the GNSS Signal-In-Space (SIS) Reference determination and some of its performance analysis capability. This capability is currently implemented for the GPS system and will be further extended to Galileo capability and optionally to GLONASS capability.

APPROACH OF GPS SIGNAL-IN-SPACE ANALYSIS

In order to analyse GPS signal-in-space performance the precise reference GPS satellite orbit will be generated by GalTeC reference orbit determination component based on the raw data from IGS, GSS or user ground monitoring station network. The following figures show one of the examples of GalTeC orbit determination results compared with IGS precise GPS orbit ephemeris in the three space directions: radial, along and cross tracks.

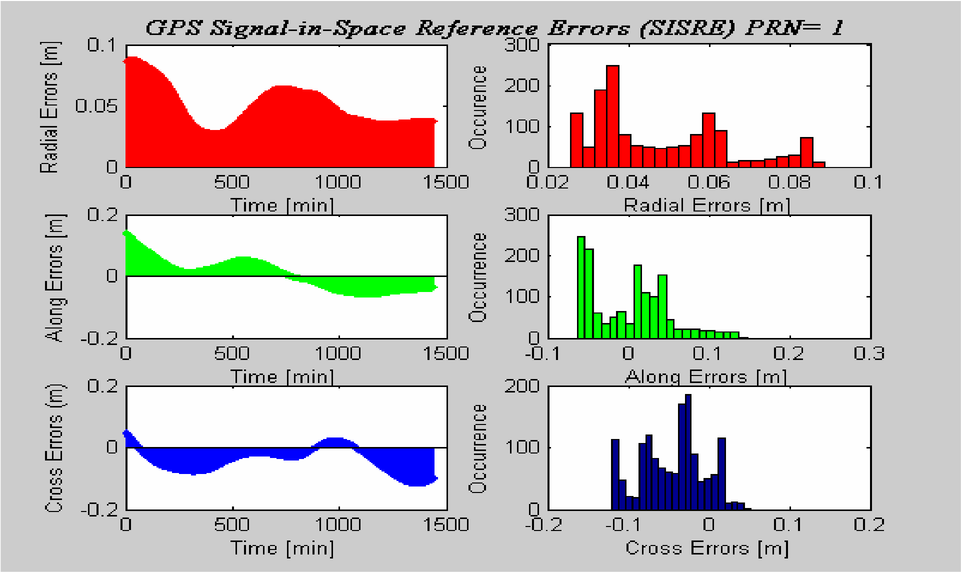

Figure 2: GalTeC Reference Orbit vs. IGS Precise Ephemeris

From the figure above it can be seen that the GalTeC reference orbit determination can achieve about 10 centimetre levels of accuracy compared with IGS precise ephemeris using 24 hour raw data from about 40 – 45 IGS sites.

GPS Signal-in-Space performance can be analysed by comparing GPS broadcast ephemeris with the precise reference orbit. The orbit errors can also be converted into the range errors to the directions of the so-called worst user location (WUL) so that the influence of range measurement errors on user position domain can be further analysed. The analysis results of GPS orbit errors in the along, radial and cross tracks (left frame) as well as the related range errors at the WUL directions (right frame) are shown in the following figure with related histograms.

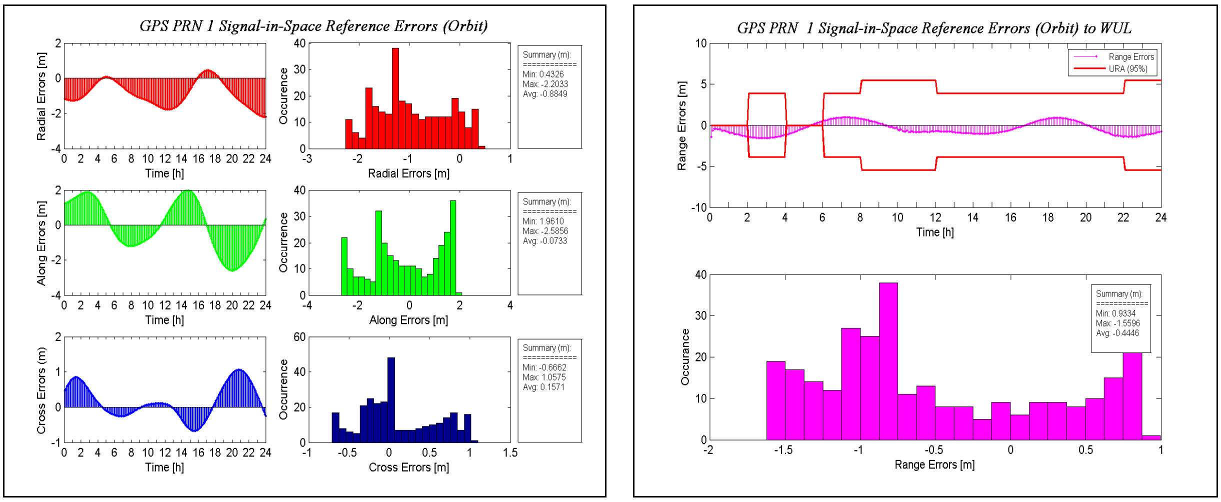

Figure 3: GPS Orbit Errors and Related Over-Bounding URA

In the presented example from 21.1.06 the maximum errors for GPS PRN 1 have been approximately 2.2 m radially, 2.6 m along the track and 1 m across to the track. Projected to worst user location directions the maximum range errors were 1.56 meters. For integrity analysis purpose, GPS broadcast accuracy indicators URA can also be compared with the range errors converted from GPS SIS errors to the WUL to check whether the URAs are really over-bounding the range errors. In the figure above, right frame the URA (in meters) along the timeline is represented by the red line.

In addition to the satellite orbit errors, the satellite clock performance can also be analysed using the GalTeC. The following Figure 4 shows the analysis results of the GPS satellite clock performance.

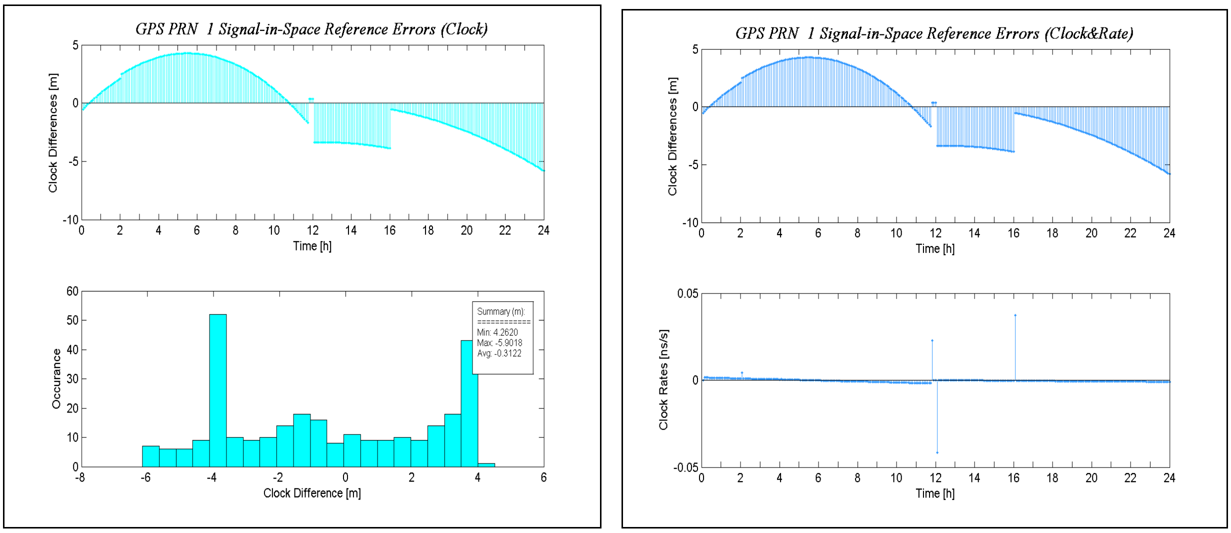

Figure 4: Satellite Clock Analysis

The Figure 5 shows a new developed graphical capability with further developed methodology. The right frame shows the projected range errors plus clock errors (SISRE) to worst user location and confronts it wit the broadcast URA (magenta dotted). The markers represent an Ephemeris change (IODE/IODC change). Here the errors often are out of the URA indicated range. The left figure shows the histogram representation to evaluate the often stated assumption on normal distribution of SIS errors. The related normal curves are generated by simple statistical computations over the samples (standard deviation and mean).

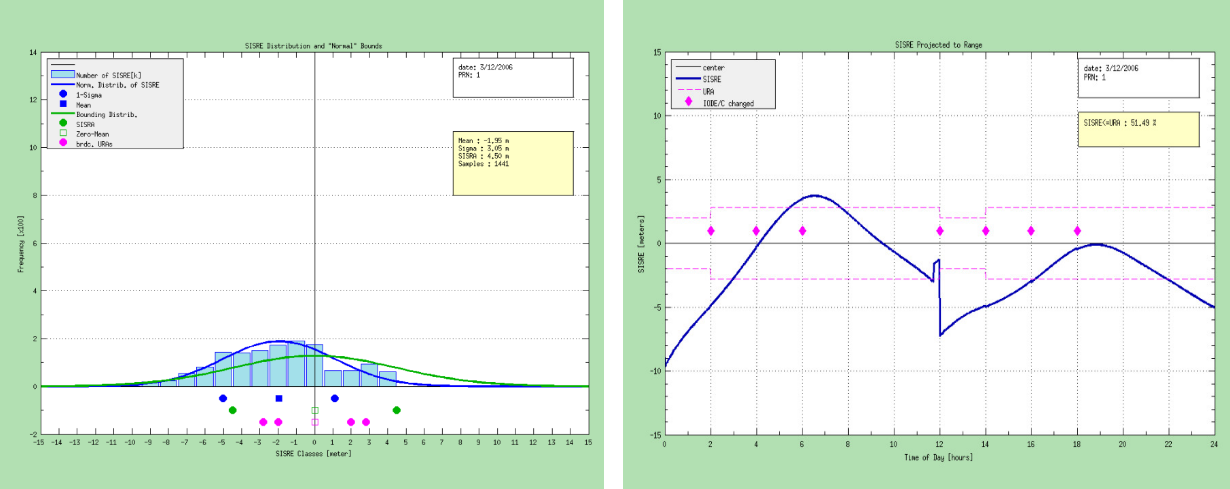

Figure 5: Actual GPS Orbit Errors Over-bounding and URA

The blue curve is the non central standard form bounding the error distribution. As URA represents as later-on SISA in case of Galileo a central distributed bounding another bound has been computed with zero-mean. The sigma (SISRA) value is generated in a first approach such that it bounds approximately more than 68% of samples. The value is graphically shown as green marker. The blue markers are the mean and 1-sigma of the non-central curve. The magenta markers are the URAs broadcast this day (3.12.2006) for the PRN 1. As the green markers are outside the magenta markers an integrity case would appear if one would rely on URA for safety of life application. However the results need to be validated by other means in a later phase of analysis and by more data samples.

GPS SIGNAL-IN-SPACE ANALYSIS

The paper presents the analysis results of GPS signal-in-space performance for the whole month January of 2006. As a comparison, the analysis results for the month of January 2007 are also presented in the lower section (**Figure 21**). The precise GPS orbit produced by GalTeC and IGS precise ephemeris were used as reference orbits. The GPS broadcast ephemeris daily collected by IGS network was used for GPS SIS analysis.

General GPS Signal-in-Space Performance

The following two figures show the maximum GPS SIS errors in the range domain converted from GPS broadcast orbit errors to the so-called worst user location, and the related GPS unhealthy status.

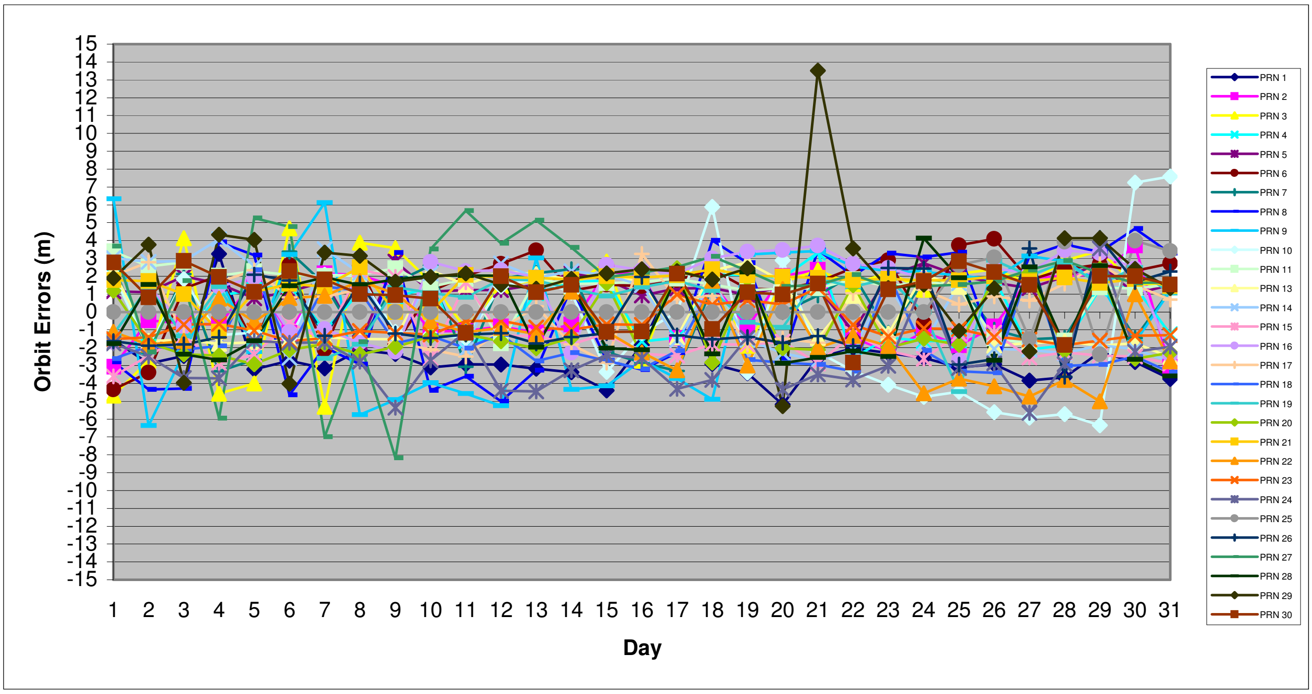

Figure 6: Maximum GPS Satellite Orbit Errors in the Worst User Location (January 2006)

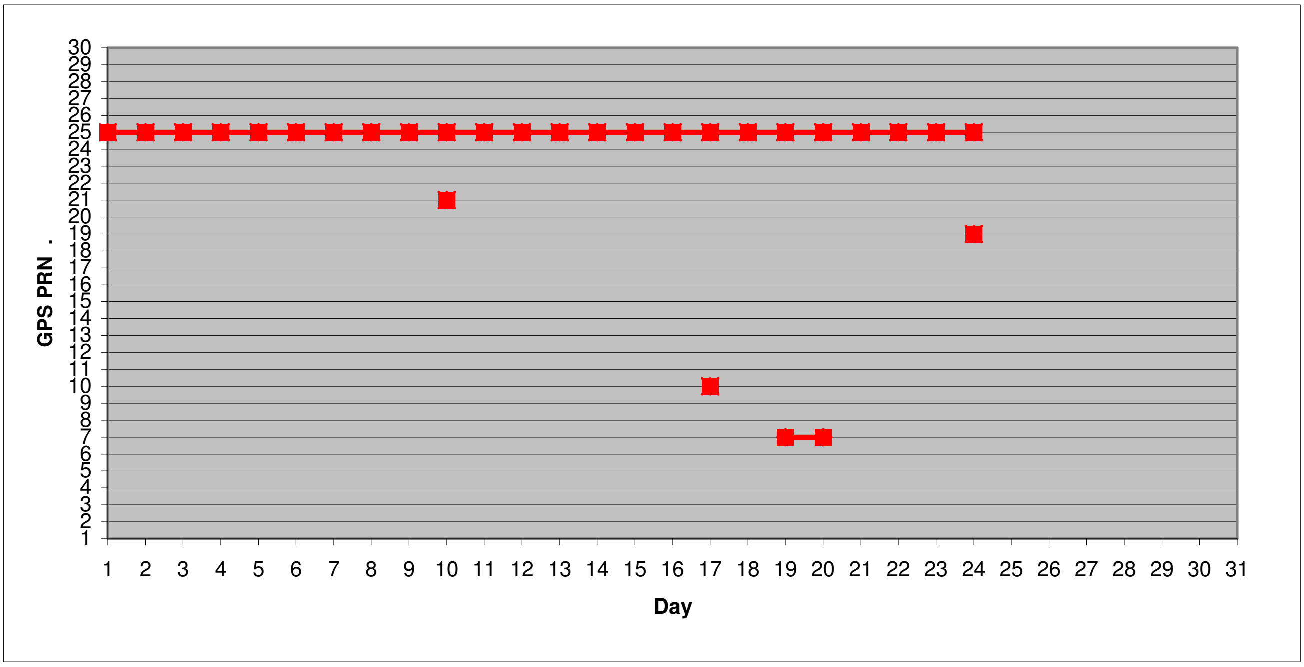

Figure 7: GPS Unhealthy Status on January 2006

From the figures above it can be seen that the general accuracy of the GPS signal-in-space (orbit) for January 2006 was about ± 8 m. GPS PRN 25 had an unhealthy status for about 24 days. PRN 7, 10, 19 and 21 also had an unhealthy status for one or two days. There was no significant impact on the GPS signal availability globally due to the unhealthy status of these satellites (see Figure 9 below for the minimum satellite visibility in the WUL). It was observed that GPS PRN 29 had a large jump (>13 m) in the day 21. Compared with other GPS satellite errors, the jump was significantly large. Checking the PRN 29 satellite clock errors, it was found that the performance of the satellite clock was quite normal. The maximum satellite clock errors converted to range errors were about –1.14 m. Clearly the jump was not related to the satellite clock behaviour. Further checking the satellite orbit errors and the related range errors in the worst user location (Figure 8 below), it was found that the jump was caused by satellite error in the along track direction. The URA broadcast by GPS PRN 29 was not over-bounding the satellite orbit errors. Usually the GPS satellite PRN 29 should have been set to an unhealthy status temporarily in the GPS broadcast ephemeris. Therefore PRN 29 might cause some integrity problems in user positioning if some GPS integrity channels do not detect the jump or the large GPS satellite orbit errors.

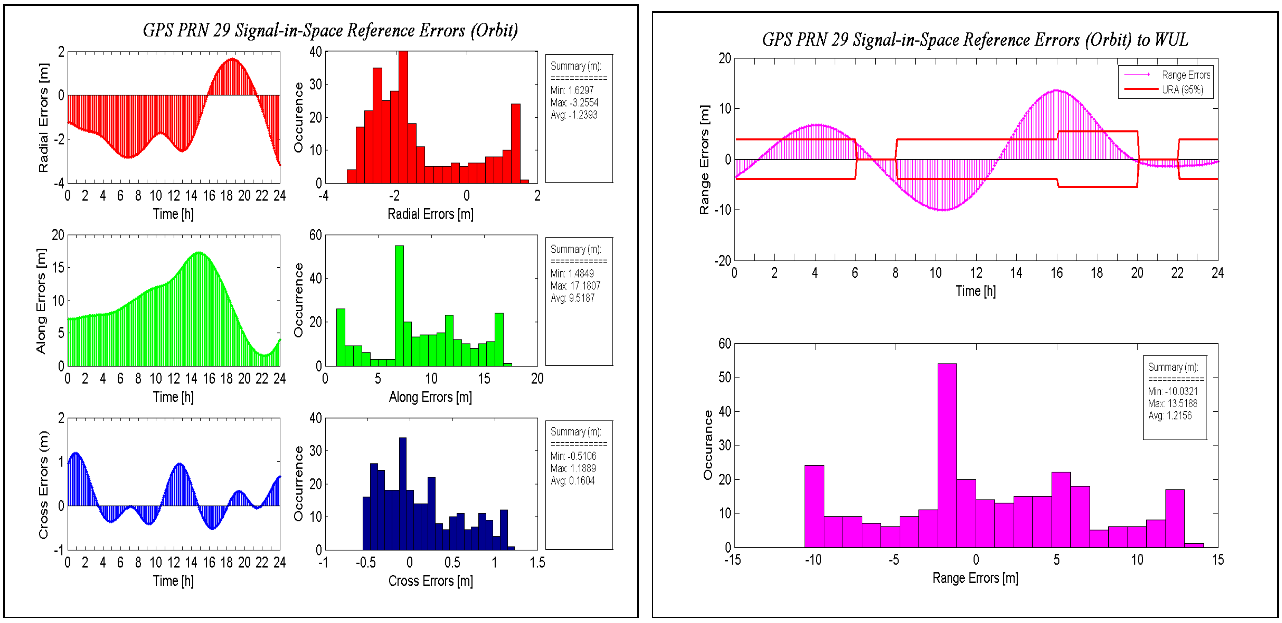

Figure 8: GPS PRN 29 Satellite Orbit Errors on Jan. 21, 2006

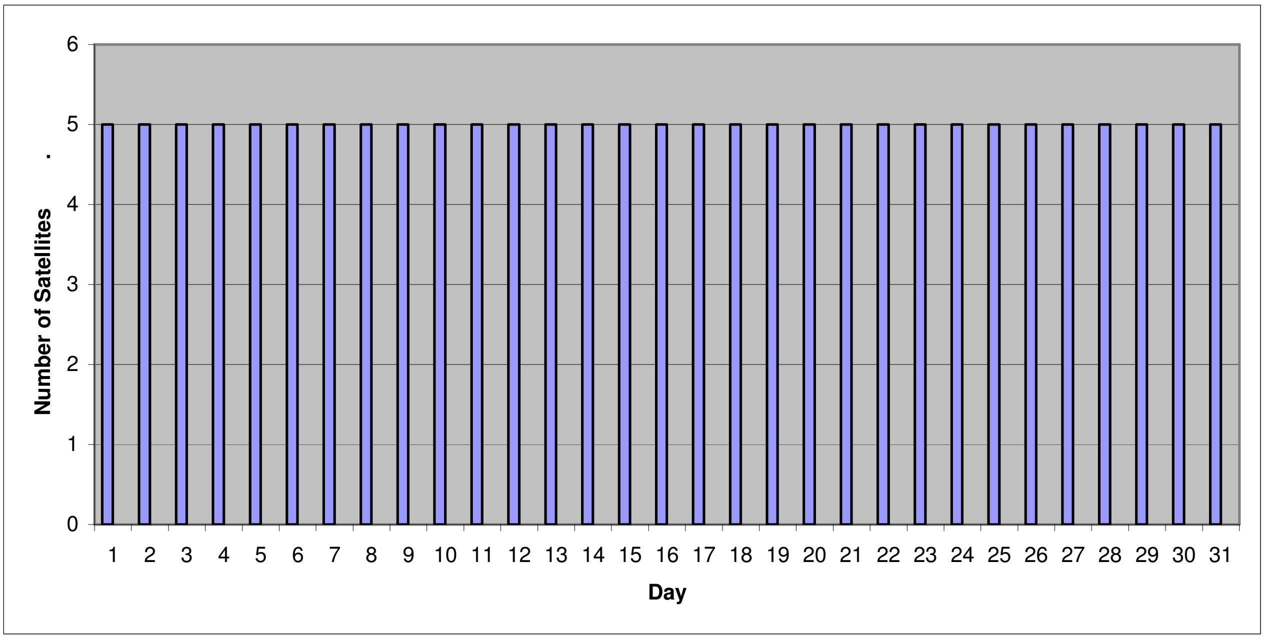

Figure 9: Minimum Number of GPS Satellites Visible from the Worst User Location

GPS Satellite Clock Errors

The following figures show the GPS satellite clock performance. The majority of the clock errors were within ± 7 m. PRN 1 and PRN 25 show some large clock errors. The large clock errors will lead to large residual errors in the user navigation solution. If there is enough redundancy, the related measurements will be deleted by the receiver software.

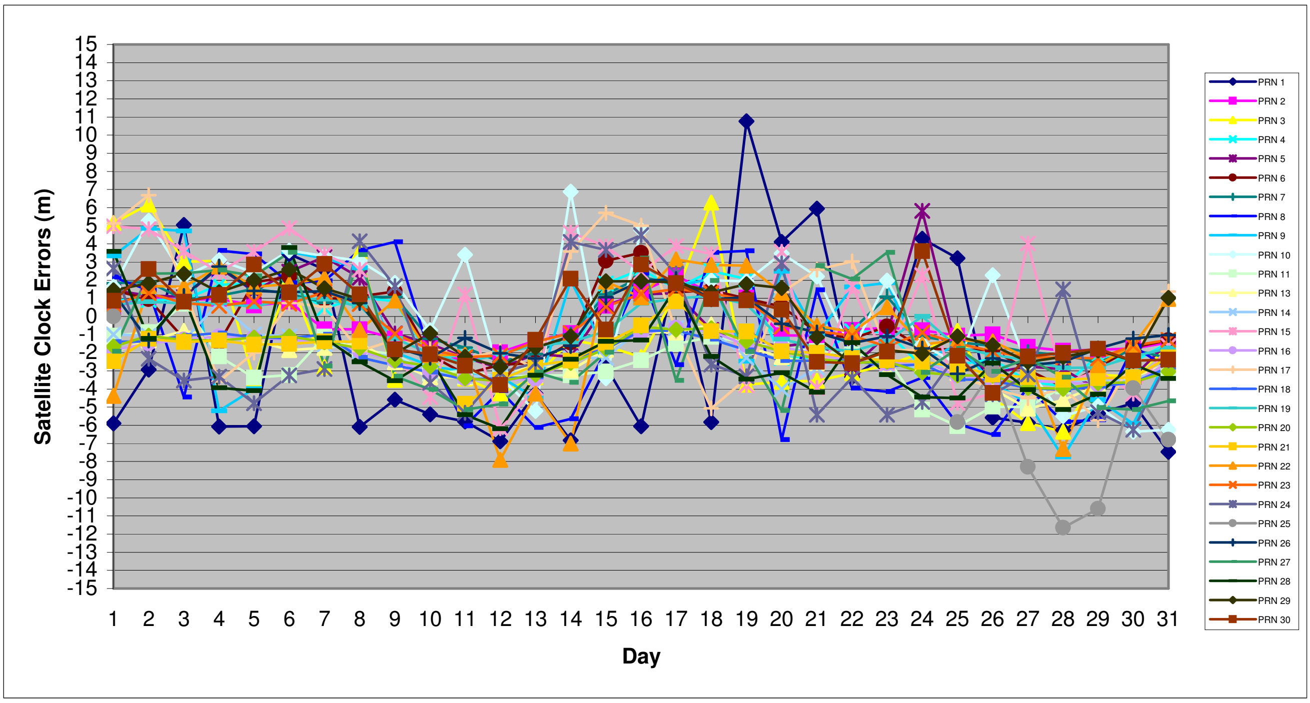

Figure 10: Maximum GPS Satellite Clock Errors (January 2006)

The Orbit Performance of GPS Block IIA and Block IIR Satellites

In order to better understand the GPS SIS performance, the analysis was also performed according to satellite types or satellite ages. Currently there are two generations of GPS satellites in operation: Block IIA and Block IIR/IIR-M. Block IIA satellites were designed to provide a possibility for 180 days of operation without contact from the control segment. The first Block IIA satellite was launched in Nov.11, 1990. Currently there are still 15 Block IIA satellites operational in space. The Block IIR satellites are currently deployed and designed to provide at least 14 days of operation without contact from the control segment and up to 180 days of operation when operating in the autonomous navigation (AUTONAV) mode [1]. The first Block IIR was successfully launched on Jul. 23, 1997. Until now there are 14 Block

IIR satellites available for navigation. The following two figures show the signal-in-space performance of GPS Block IIA and Block IIR satellites.

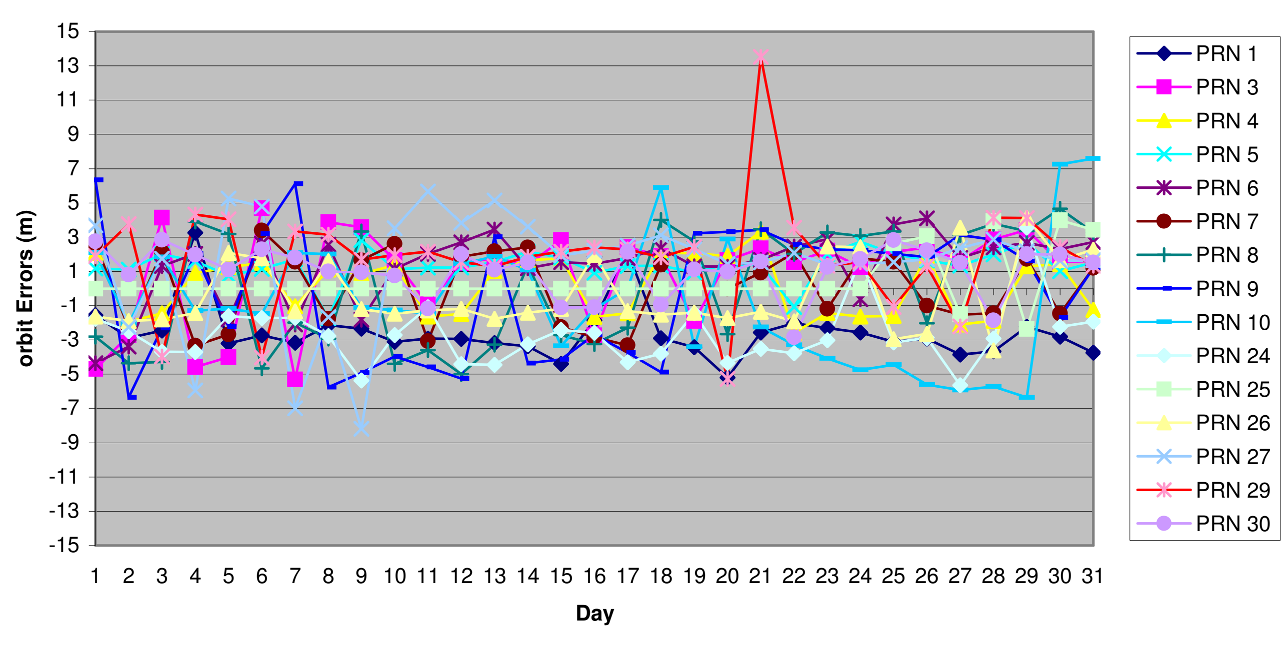

Figure 11: Maximum GPS Satellite (Block IIA) Orbit Errors in the Worst User Location (January 2006)

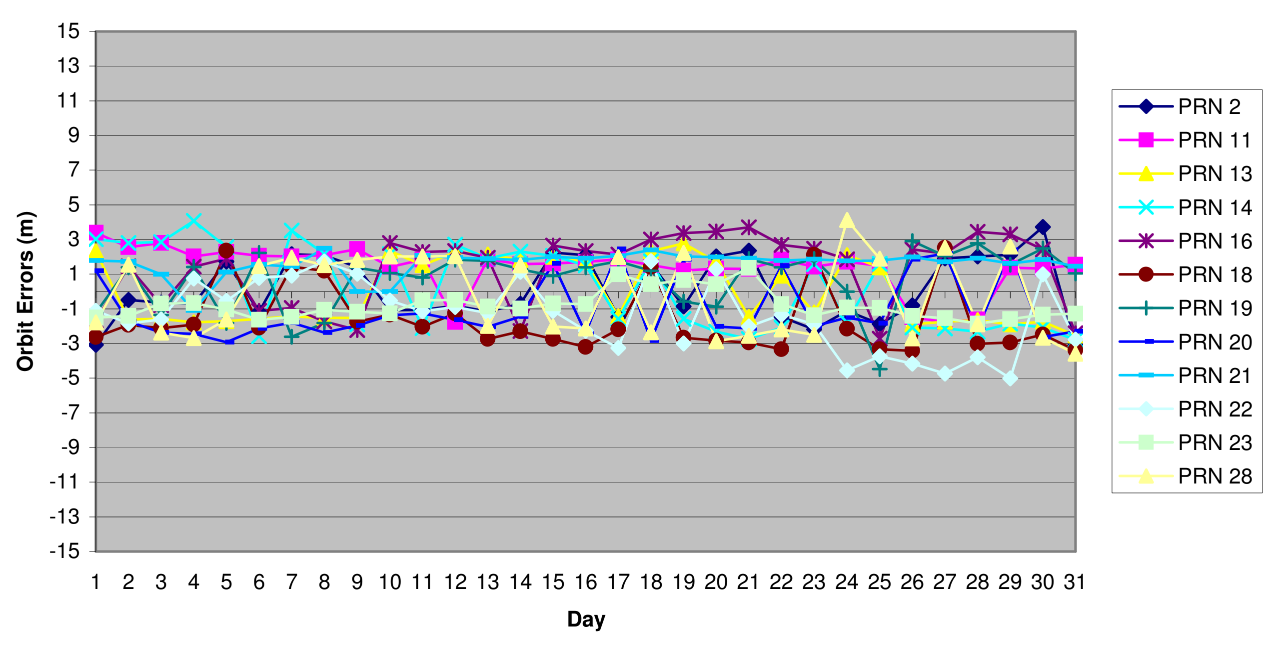

Figure 12: Maximum GPS Satellite (Block IIR) Orbit Errors in the Worst User Location (January 2006)

From the figures it can be seen that the accuracy of Block IIR satellites was about ± 5 m and Block IIA were about ± 8 m. The accuracy of Block IIR satellites was better than Block IIA, but the difference was not so significant.

The Performance of Caesium and Rubidium Clocks

The GPS SIS performance is also dependent on the satellite clock behaviour; therefore it is also related to the satellite clock types. In the operational GPS system each satellite is equipped with two types of atomic clocks, caesium and rubidium clocks. One clock is active and another is a hot backup. All signal transmission is derived from an active highly stable atomic clock. The stability of the satellite clocks plays an important role in the performance of user navigation. For the period of January 2006, GPS PRN 1, 3, 8, 10, 15, 24, 25 and 27 are operational with active caesium clocks. Other GPS satellites are operational with active rubidium clocks. The figures below show the performance of two types of GPS satellite clocks.

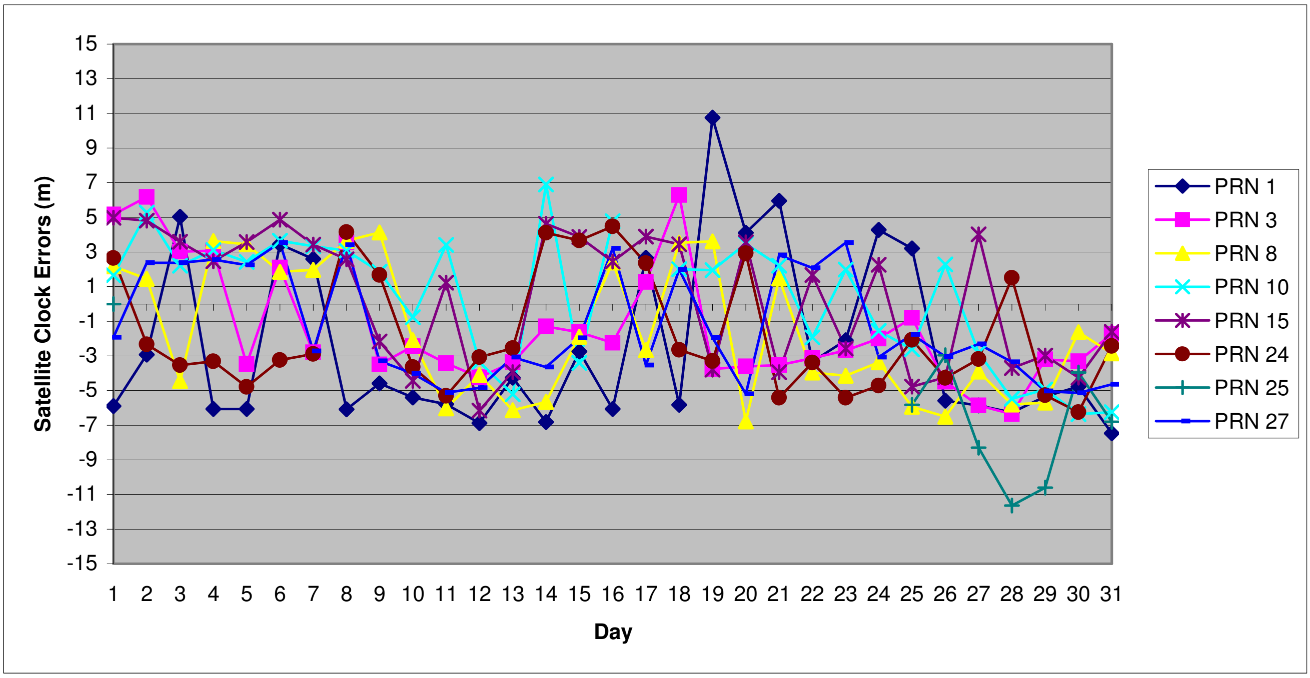

Figure 13: Maximum GPS Satellite Clock (Caesium) Errors (January 2006)

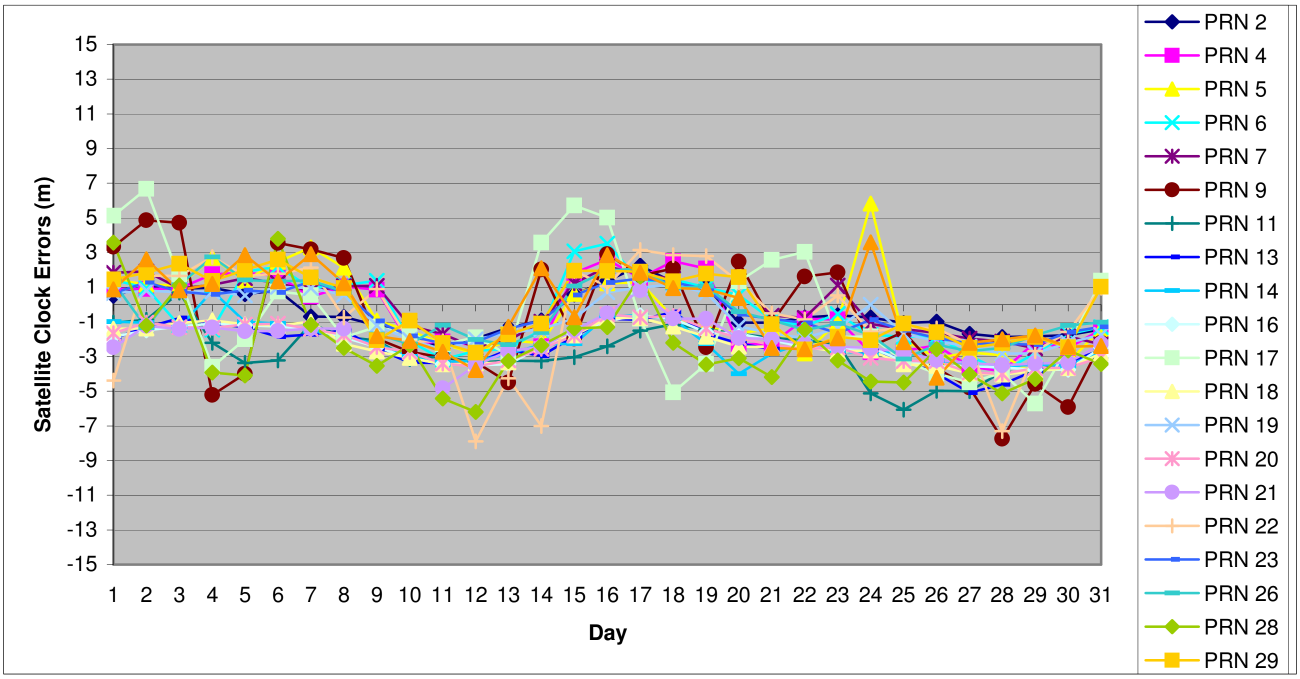

Figure 14: Maximum GPS Satellite Clock (Rubidium) Errors (January 2006)

Clearly, the maximum caesium satellite clock errors were about ± 12 m. The maximum rubidium satellite clock errors were about ± 8 m. The caesium clocks show a larger deviation, but better long term stability. The rubidium clocks show smaller deviation, but show a long term drift. The conclusion is based on one month data analysis. A better conclusion can be achieved when further data analysis for a longer time of period are done. It would be interesting to analyse the change from day-to-day of single satellites as it might be possible to predict the drifts of Rubidium steered GPS satellites for the near period eventually better, however this is a first impression and this is maximized day values. The daily resolution clock (or satellite time) behaviour shows some significant jumps as Figure 4 shows.

URA with GPS Signal-in-Space Performance

In general, the User Range Accuracy (URA) broadcast by GPS ephemeris should be an over-bound of the GPS signal-in-space errors due to GPS ephemeris and satellite clock errors [2], i.e. the GPS signal-in-space errors mapping to the range errors in the worst user location shall be over-bounded by URA as figures shown below.

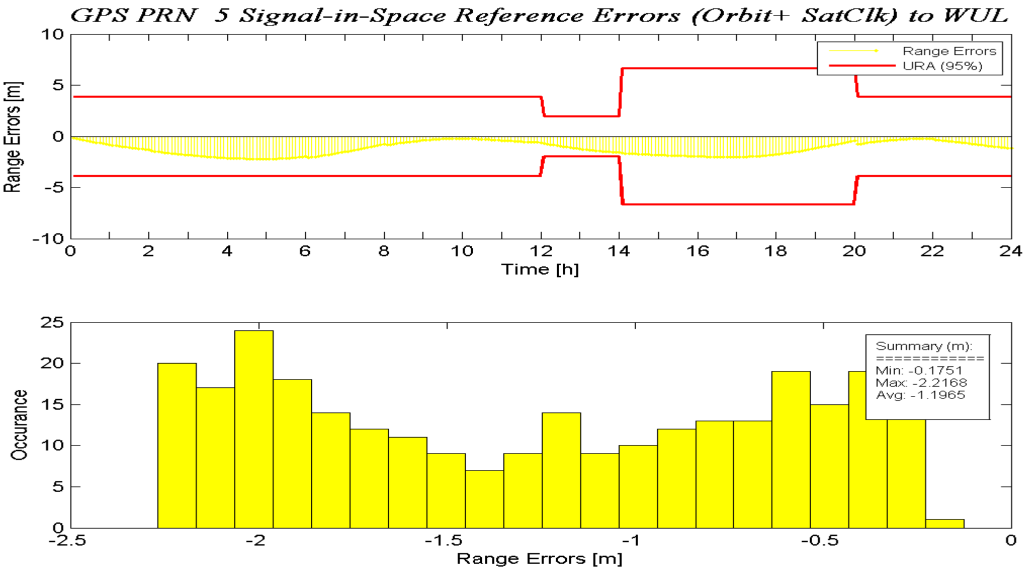

Figure 15: Satellite Orbit Errors Mapping to WUL on Jan. 10, 2006

But according to our analysis of GPS broadcast ephemeris collected on January 2006, the URA predicted by GPS broadcast ephemeris was sometimes not over-bounding the GPS broadcast orbits and satellite clocks errors. The broadcast URA's over-bound the satellite orbit errors only, not clock errors - see some examples in the Figure 16, Figure 17 and Figure 18 below.

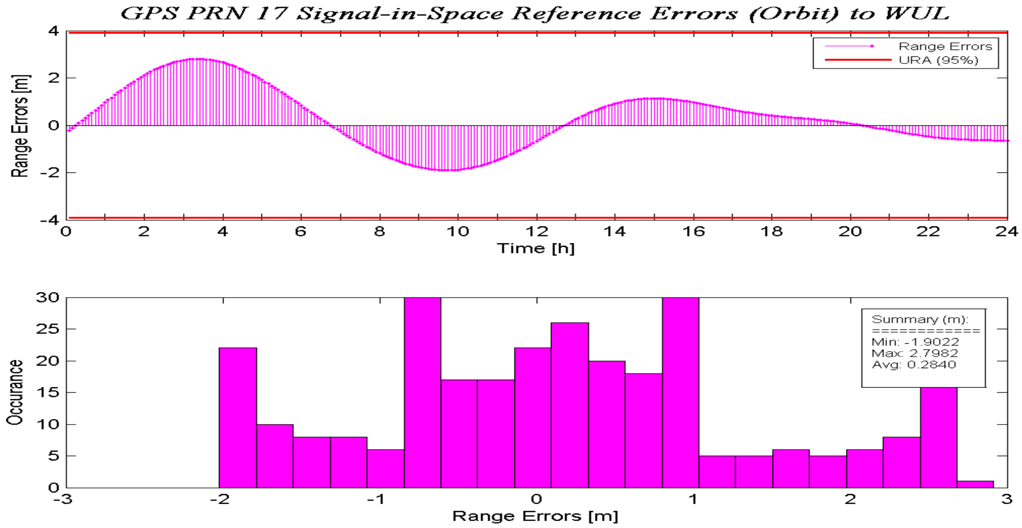

Figure 16: Satellite Orbit Errors Mapping to WUL on Jan. 2, 2006

Figure 16 shows that (worst) user range errors due to orbit errors only lie well between the URA bounds (constant 4 meters all the day). Figure 17 shows the user range errors based on Clock error only, which alone are the first 8 hours of day > 4 meters. Clearly superimposing both range sources in a single SIS error as shown in Figure 18 is outside the URA for almost 1/3 of day. This behaviour is seen during our analysis in some other cases (satellites and days). Further analysis must confirm whether there is a systematic error behind. This will be done by performing the analysis with data of past months in 2007 where GalTeC also continuously recorded EGNOS correction data. The clock errors and orbit errors should be independently determined (Fast Corrections and Slow Corrections).

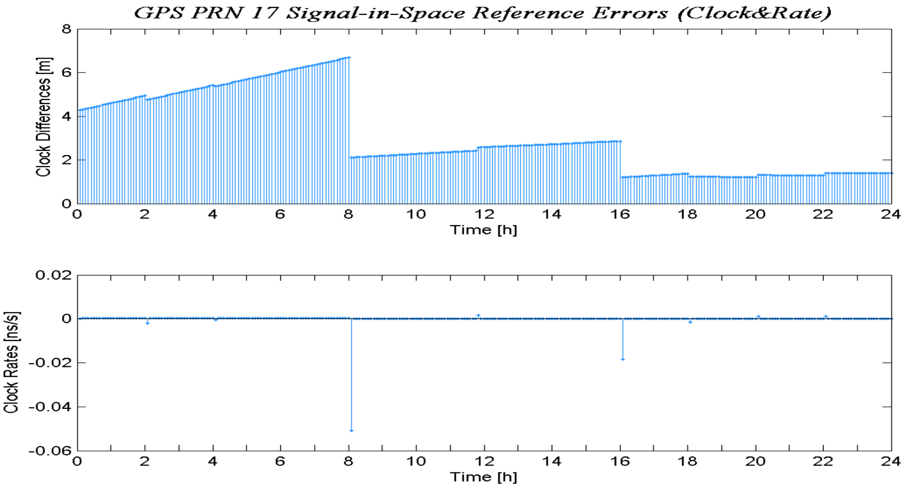

Figure 17: Satellite Clock and Clock Rate on Jan.2, 2006

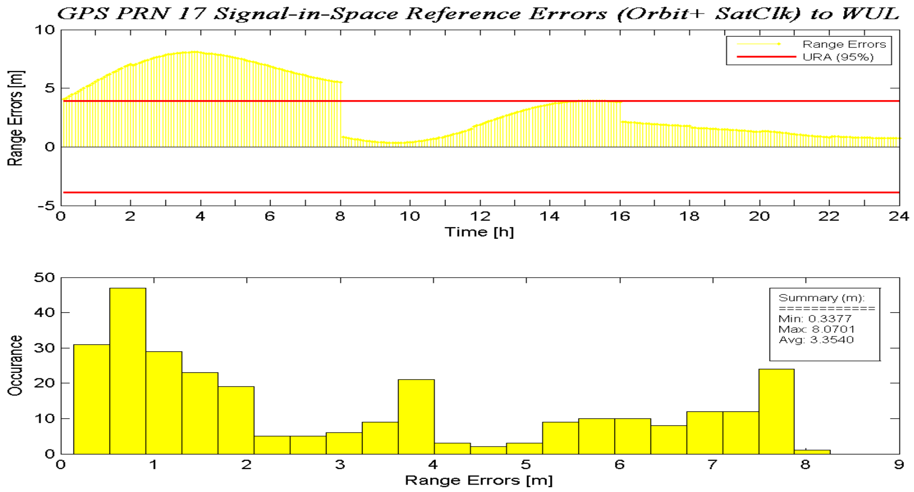

Figure 18: Satellite Signal-in-Space Errors due to Orbits and Clocks on Jan.2,2006

GPS Satellite Clock Jumps

It was found in the data analysis that there were many small satellite clock jumps from GPS broadcast ephemeris, especially when IODC/IODE were changed (about 2-hour periods).

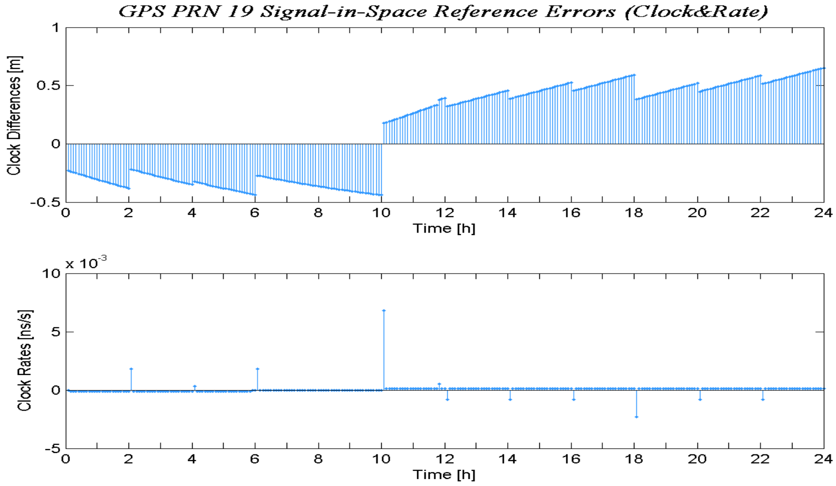

Figure 19: GPS Satellite Clock Jumps (Data on Jan.1, 2006)

Large clock jumps were found when large changes of the IODC/IODE occur, probably due to the fact that GPS satellite ephemeris were uploaded by AUTONAV mode on board. According to GPS ICD-200C[2], cutovers to new data sets will occur only on hour boundaries except for the first data set of a new upload, which may be cut-in at any time during the hour. Therefore, it seemed that the following large clock jump occurred at 10 o'clock in Figure 19 was not caused by the first data set of a new upload.

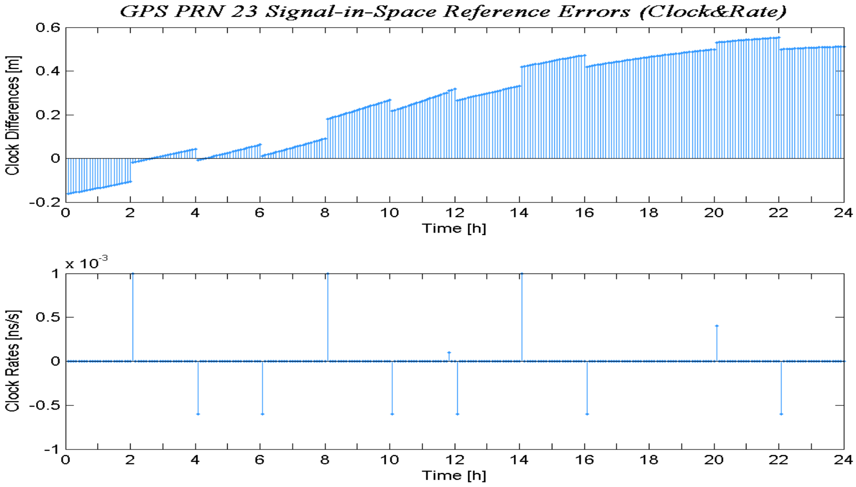

Figure 20: GPS Satellite Clock Jumps (Data on Jan. 15, 2006)

If the satellite clock offsets are stable as in the figure right above, it might not significantly impact on the continuity performance of navigation solution (PVT), but it introduces errors in the navigation position, especially for real time users.

Current Status of GPS Performance

In order to compare the current GPS signal-in-space performance with that from January 2006, the analysis results of GPS signals-in-space performance on January, 2007 are presented here.

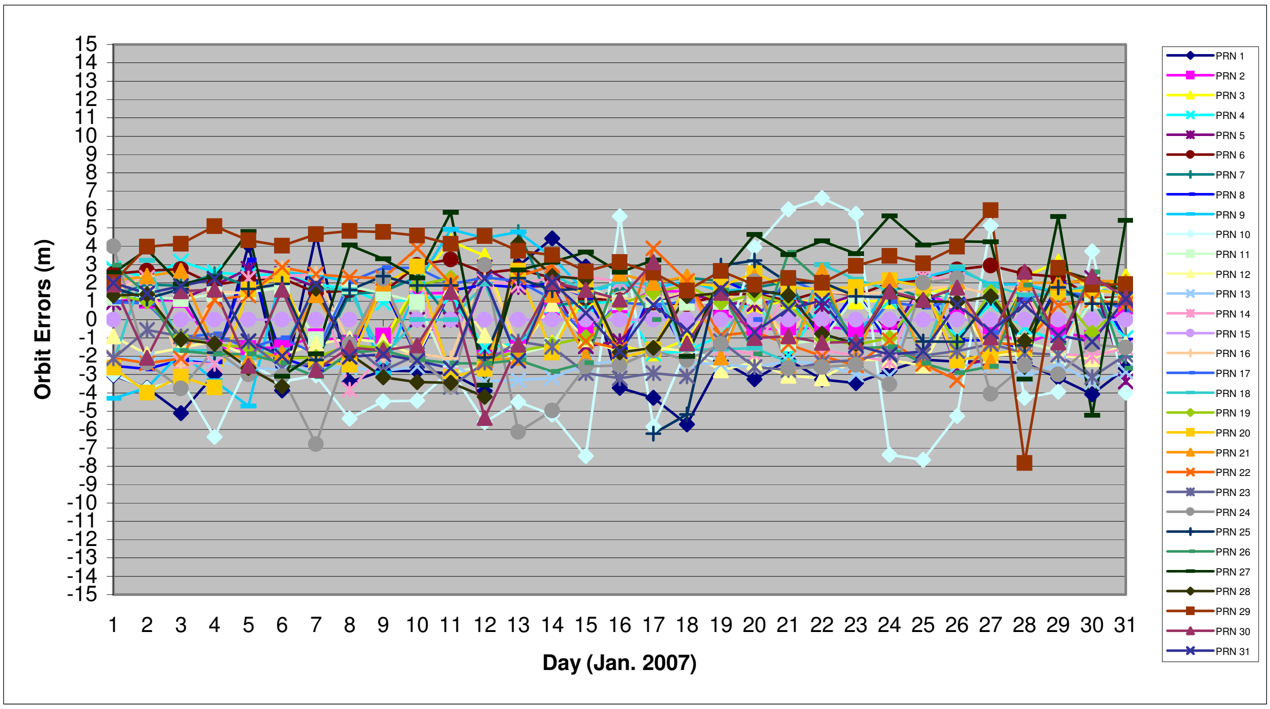

Figure 21: Maximum GPS Satellite Orbit Errors in the Worst User Location

If comparing with the Figure 6 the performance of orbit prediction with GPS ephemeris is comparable with values around 5 meters with some outliers up to 8 meters (also again PRN 29). The next figure is to be compared with Figure 10. Again the clock errors lie in a comparable range of +/- 7 meters.

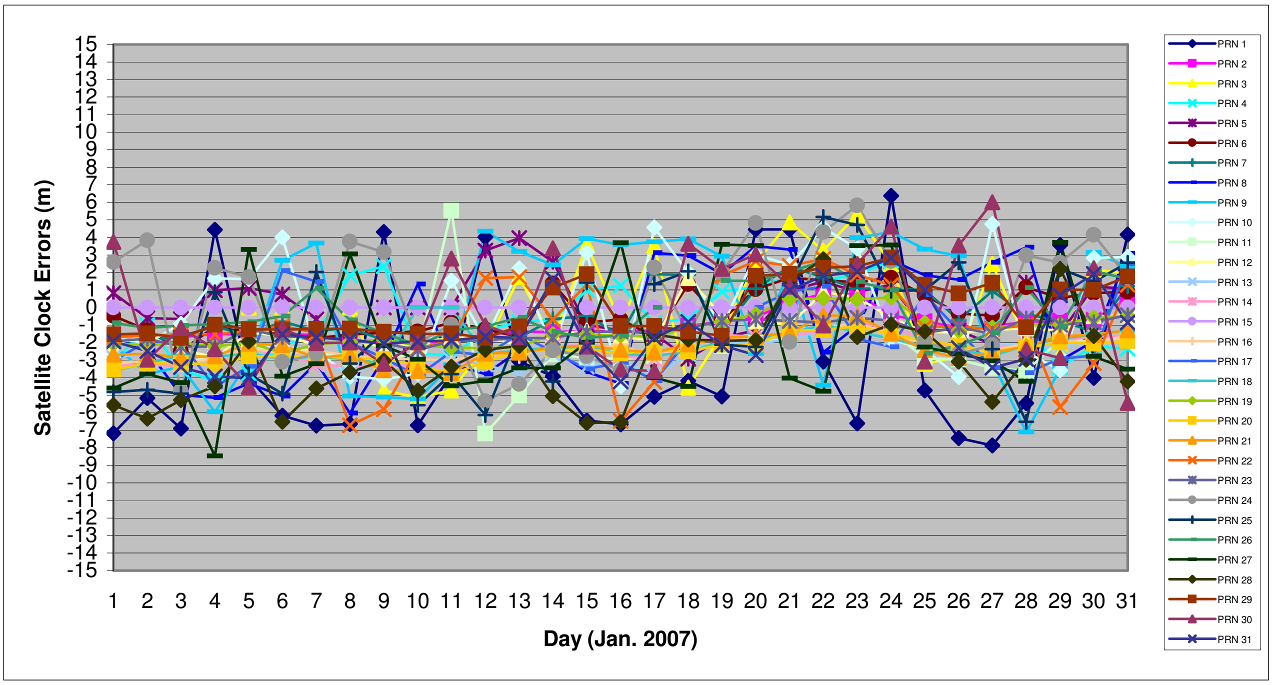

Figure 22: Maximum GPS Satellite Clock Errors

CONCLUSIONS

This paper has shown a first batch of systematic analysis with GalTeC over a longer period of time. The analysis was performed mainly with the Reference Orbit & Clock module and related analysis and graphic modules. GPS orbits and clock errors were observed and compared with the URA which shall describe the same set of errors. The analysis was performed purely in SIS or range domain. The results show that generally the errors which are dedicated to orbits are in the range of 5-7 meters. The range errors due to errors in clocks are slightly higher in the same range. Some outliers do exist both in orbit and clock components and in some cases they are not correctly bound by URA (at least in 95% of samples), however URA in the most cases bounds the pure orbit errors. Further analysis must be performed both - in time domain (more samples) as in-depth (e.g. validation by other sources). GalTeC is still a prototype and a thorough validation campaign will be performed with the end of the project in late 2008. The next step in the GalTeC project will be to automate some of the presented functions and complement the analysis with effects on position domain and integrity domain (Protection Level and MI/HMI counts etc.). Currently GalTeC already continuously records automatically SIS received by a Septentrio EGNOS receiver together with all SBAS computations by the receiver. The next steps are to implement also the Galileo capability with the use of Giove observations as the project ends in 2008. A major development will be the Service capability with standardised graphics and report scheme to summarise the results. Also the prediction capability is a major tool to be further adapted to Galileo Integrity scheme and Galileo architecture to enable service dimensioning consultancy to support future location or navigation based service business cases.

ACKNOWLEDGEMENTS

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The interpretation of results does represent only the author's opinions and in no case a company view.

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