

TIME AND FREQUENCY TRANSFER USING EGNOS SATELLITE SYSTEM

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Abstract

EGNOS (European Geostationary Navigation Overlay Service) is the European satellite navigation system which augments GPS and makes it suitable for safety critical applications. It is one of the Satellite Based Augmentation Systems (SBAS). It uses three geostationary satellites transmitting signals in the GPS L1 frequency channel. These signals are almost identical to the GPS signal and thus can be used for time transfer in the same way.

Since the geostationary satellites move slightly and very slowly towards the user, one can assume that some of the measurement errors (e.g. multipath, atmospheric delay) will also show small and slow variation compared to GPS measurements and better performance of the time and frequency transfer can be expected. We therefore performed an experimental measurement in order to verify that the fluctuations in measured delay of the received signal caused by multipath are really much slower compared with using GPS and the time transfer can be improved by using EGNOS. We applied the same time reference to a pair of GTR50 receivers and performed the time comparison against one of the EGNOS satellites. Antennas with hemispheric directional characteristics were used. The distance between the antennas was 5.5 m.

From the continuous several-day measurement, we observed that the code measurement has markedly lower accuracy compared to the signal from GPS (10 ns standard deviation). This is caused by the narrow bandwidth of the transmitted signal which is only 2.2 MHz in the case of EGNOS. We confirmed that the fluctuations caused by multipath are very slow but with relatively higher amplitude. On the other hand, the results obtained from the carrier phase measurements are promising. The standard deviation from the whole measurement was 12 ps. Together with the white phase noise we observed small diurnal fluctuations in the measured time delay caused by daily variations in temperature of the antennas and antenna cables. We see the main advantage of using the EGNOS for the carrier phase measurements is its permanent availability. We believe it could be used ideally for continuous short-distance comparisons of precise frequency sources.

EGNOS

EGNOS (European Geostationary Navigation Overlay Service) is the first pan-European satellite navigation system. It augments the US GPS satellite navigation system and makes it suitable for safety critical applications such as flying aircraft. Similar satellite systems with coverage of a limited area exist around the world and are designated altogether as SBAS (Satellite Based Augmentation Systems). WAAS (Wide Area Augmentation System) was launched as a first of this type in the U.S. All of these

systems are based on a single specification [1] in order that the user's receivers can be used in each continent. SBAS along with GPS serves to provide user with reliable positioning with accuracy of a few meters in the area of coverage. SBAS is based on the network of ground stations monitoring the GPS signal continuously. Data messages generated from the measurements at these stations are then broadcast via geostationary satellites. The data messages contain information on the correctness of the GPS signal, time corrections and corrections of the positions of GPS satellites as well as data that can be used for accurate correction of ionospheric and tropospheric delays in the covered area.

The EGNOS signal is broadcast in GPS L1 frequency channel (1575.42 MHz) and is GPS alike. It is a pseudo-random ranging signal generated the same way as the C/A code in GPS satellites. Pseudo-random codes with numbers between PRN 120 and PRN 138 are reserved for usage in SBAS. The satellites broadcast data messages besides the ranging signal. The data encoding, rate, format, and content differ from GPS data. The constellation of GPS satellites can be extended by SBAS satellites because the position of the geostationary satellite can be determined from data messages similar to those concerning GPS.

EGNOS is a common project of the European Space Agency, the European Commission, and the European Organization for the Safety of Air Navigation EUROCONTROL. The EGNOS Open Service has been available since October 2009. EGNOS positioning data are freely available in Europe through satellite signals to anyone equipped with an EGNOS-enabled GPS receiver. Specifications of EGNOS are in documents [2] and [3]. Three geostationary satellites are used within EGNOS. The satellite names, position at geostationary orbit and number of broadcast pseudo-random code (PRN) are listed in Table 1.

Table 1. EGNOS satellite names, positions and PRNs.

Satellite	Position	PRN
Inmarsat AOR-E, III F2	15.5°W	120
ESA Artemis	21.5°E	124
Inmarsat IND-W, III F5	25.0°E	126

USING EGNOS FOR TIME TRANSFER

EGNOS satellites broadcast GPS alike pseudo-random ranging signals together with data messages including ephemerides of the geostationary satellites (Message Type 9). When the user is equipped with a receiver capable to measure the delay between the received signal and an external time reference, it is possible to use this signal for comparison of distant time scales by the common view technique. EGNOS makes use of geostationary satellites, unlike GPS, and thus the variations in the relative position between the satellite and the receiver are small and very slow. Several specific properties of the radio channel important for the time transfer can be derived from this fact.

MULTIPATH PROPAGATION

Multipath propagation is caused by signal reflection off objects in the vicinity of the receiver antenna. Multipath is then characterized locally. If the distance between the receivers is small, the overall error of comparison is given by the error from the multipath. Azimuth and elevation of a GPS satellite change dramatically during flyover. Therefore the variations in delay of reflected signals are fast and the measured delay fluctuates because of interference of the direct and reflected signals. For a geostationary

satellite, changes in azimuth and elevation are very slow and the error caused by multipath propagation fluctuates very slowly as well.

IONOSPHERIC AND TROPOSPHERIC DELAYS

The signal from the satellite is delayed up to some tens of nanoseconds while going through the ionosphere and troposphere. These delays nearly cancel out in the common view comparison, but even the residual error is proportional to the ionospheric and tropospheric delays in both sites and their variations still affect the comparison. Both delays depend strongly on satellite elevation. The dependence is extremely high in the case of the tropospheric delay. It varies in the range of 6:1 for satellite elevation between 10° and 90°. The ionospheric delay varies in the range of 3:1 for the same range of elevation. Periodic daily changes in ionospheric delay are typically observed with minimum in early morning hours and maximum after noon.

Azimuth and elevation are nearly constant for a geostationary satellite. The variations in the ionospheric delay are then very slow compared to GPS and diurnal. Possible variations in the tropospheric delay then respect actual weather conditions.

EXPERIMENTAL MEASUREMENTS

The goal of our measurements was to verify that the EGNOS radio channel behaves according to our theoretical presumptions, namely that the fluctuations in measured signal delay caused by multipath propagation are smaller in magnitude and much slower compared to GPS.

We used a pair of GTR51 receivers capable to receive signals from GPS as well as EGNOS. These receivers were provided with UTC(TP) time reference with daily stability of $2 \cdot 10^{-14}$. The receivers were denoted TPX and TPY and their time references UTC(TPX) and UTC(TPY). Novatel GPS-702 antennas were used for reception of signals from GPS and EGNOS satellites. Both antennas were installed on the roof of the building with a distance of 5.5 m in between. The distance is sufficient to consider the effect of multipath propagation in each antenna independent. Antennas were connected to receivers by Belden H155 cables, each approximately 30 m long and both exposed to sunlight.

We focused on the signal from the EGNOS satellite PRN 120 during experimental measurements. We observed that the accuracy of ephemerides flag in data messages is set very low. Therefore we asked the system operator ESSP (European Satellite Services Provider) for explanation. According to response the ranging function in EGNOS is currently not supported.

COMPARISON OF EGNOS TIME WITH UTC(TPX)

First we compared the EGNOS time with UTC(TPX) without correcting the path delay. Measurement results are not affected by broadcast ephemerides in this case. Measurement was done in MJD 55475. The measured time difference is approximately 130 ms which corresponds to the assumed distance between the satellite and antenna, i.e. approximately 39 000 km. We observed linear drift in the measured time difference with a slope of $-0.95 \cdot 10^{-9}$ together with slow diurnal changes caused by imperfect satellite placement in the geostationary orbit. Figure 1 shows the measured time difference UTC(TPX) – EGNOS time with the constant delay and the linear drift removed. The amplitude of daily variations in the time difference is $\pm 60 \mu\text{s}$ which corresponds to $\pm 18 \text{ km}$ in distance.

We performed comparison of EGNOS time with UTC(TPX) in standard way in the next step, i.e. the path delay was compensated based on received ephemerides. Again the time difference measured within three

days showed linear drift with the same slope of $-0.95 \cdot 10^{-9}$. Figure 2 shows residuals after the drift removal. Standard deviation of the residuals is 15 ns.

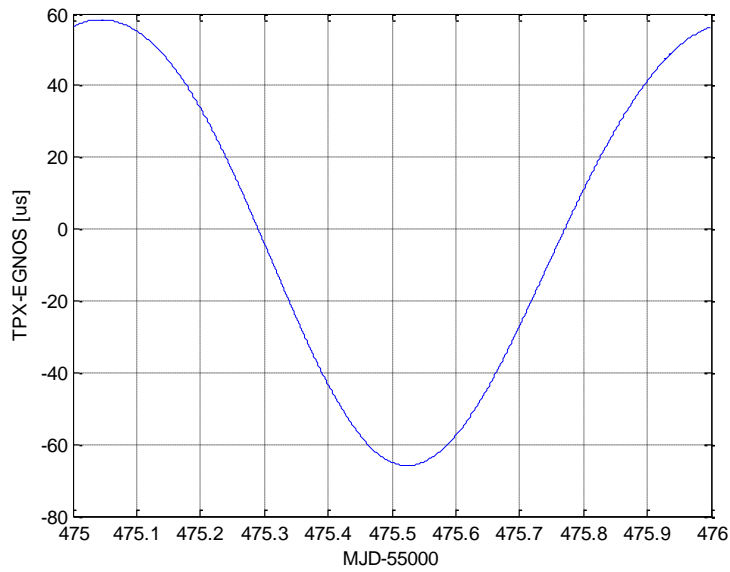


Figure 1. Measured time difference UTC(TPX) – EGNOS time with linear drift and constant delay removed, EGNOS satellite PRN 120.

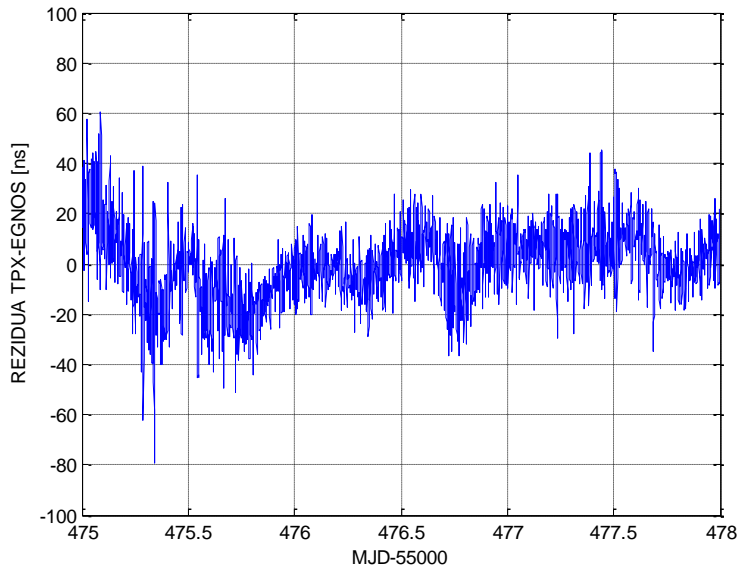


Figure 2. Residuals of measured time difference UTC(TPX) – EGNOS time after removal of linear drift, EGNOS satellite PRN 120, carrier phase measurement, $\sigma = 15$ ns.

The obtained results suggest that the EGNOS signal is currently linked to a stable source of frequency with a high frequency offset. On the other hand, the measured time difference allows EGNOS to be used

for common view comparisons. Residuals after the linear drift removal showed that the accuracy of received ephemerides was in the level of a few meters.

COMPARISON OF UTC(TPX) AND UTC(TPY) USING EGNOS

We evaluated properties of the time difference UTC(TPX) – UTC(TPY) measured between MJD 55475 and MJD 55478. The satellite azimuth and elevation was 216° and 26° respectively throughout the whole measurement. Changes in both azimuth and elevation were below 0.1°. Average carrier-to-noise ratio of 41.1 dBHz was observed.

Figure 3 shows the time difference obtained from code measurements. Here the standard deviation is 9.7 ns. It is obvious that the curve is made by superposition of two processes: slow diurnal changes caused by multipath propagation with standard deviation of approximately 7 ns and fast variations caused by noise with standard deviation of about 6 ns. A noise level of 3 ns would be measured using the GPS signal with the given carrier-to-noise ratio. It appears that fluctuations in the EGNOS signal are higher. This disproportion was later explained. The signal from the EGNOS satellite is similar to the signal from GPS, but the bandwidth of the former is limited to 2.2 MHz while the latter has a bandwidth of 20 MHz [4]. The bandwidth of the EGNOS signal will be extended to 4.0 MHz after switching to Inmarsat IV satellites and the planned signal in the L5 frequency channel will have a bandwidth of 20 MHz [4].

It was confirmed that the fluctuations caused by interference of direct and reflected signals are many times slower compared to typical measurements via GPS satellites. The deterioration is caused by the limited bandwidth of the EGNOS signal.

Figure 4 shows the time difference obtained from carrier phase measurements. The standard deviation is 12 ps. Again the curve is made by superposition of two processes. We assume that slow diurnal fluctuations with an amplitude of 10 ps are caused by daily variations in temperature of antennas and antenna cables. Fast fluctuations with standard deviation of about 10 ps are caused by noise.

SIMULTANEOUS COMPARISON OF UTC(TPX) AND UTC(TPY) USING EGNOS AND GPS

To compare results of time transfer using EGNOS and GPS we performed measurements against EGNOS satellite PRN 120 and against GPS satellite PRN 26 simultaneously. The duration of measurement on MJD between UTC 02:00 and UTC 07:00 was defined by visibility of the GPS satellite. The elevation of the GPS satellite started at 20°, culminated with 87° at UTC 04:30 and decreased down to 17°. The elevation of the EGNOS satellite was 26° during the whole measurement. The carrier-to-noise ratio of the GPS satellite moved in the range between 40 dBHz and 55 dBHz depending on the elevation. The average value of CNR was about 50.3 dBHz. No significant fluctuations in signal strength from the EGNOS satellite were observed; the mean value of CNR was 40.3 dBHz.

Figures 5 and 7 show the time difference plots obtained from code measurements. The standard deviation of the fluctuations is 1.5 ns in case of GPS (Figure 5) and 6.6 ns in case of EGNOS (Figure 7), i.e. approximately four times higher. This is the impact of lower CNR and the above-mentioned narrower bandwidth of the EGNOS signal. The corresponding time stabilities in terms of TDEV for averaging intervals between 1 s and 1000 s are shown in Figure 9. It can be seen that the comparison using EGNOS code measurement is much less stable in the whole range of the averaging interval compared to GPS.

The time differences obtained from carrier phase measurements are plotted in Figures 6 and 8. The standard deviation of fluctuations is 17 ps when using the GPS signal (Figure 6) and 11 ps when using the signal from EGNOS (Figure 8). Slow variations in the time difference measured using GPS correspond to error of the antenna position. The size of this error is approximately 1 cm. Fluctuations caused by

multipath propagation can be clearly seen when the satellite elevation is low. The plot of the time difference measured using EGNOS is fully straightened and has lower standard deviation of fluctuations although the CNR is lower compared to GPS. In addition the signal is available continuously. Time stability in terms of TDEV is again plotted in Figure 10. It can be seen that the comparison via GPS is slightly more stable for averaging intervals below 10 s. This is caused by the higher CNR compared to EGNOS. Comparison via EGNOS is more stable for averaging intervals above 10 s. The white phase modulation noise is predominant in the TDEV plot for averaging intervals between 10 s and 200 s and thus the accuracy of comparison can be further improved by averaging.

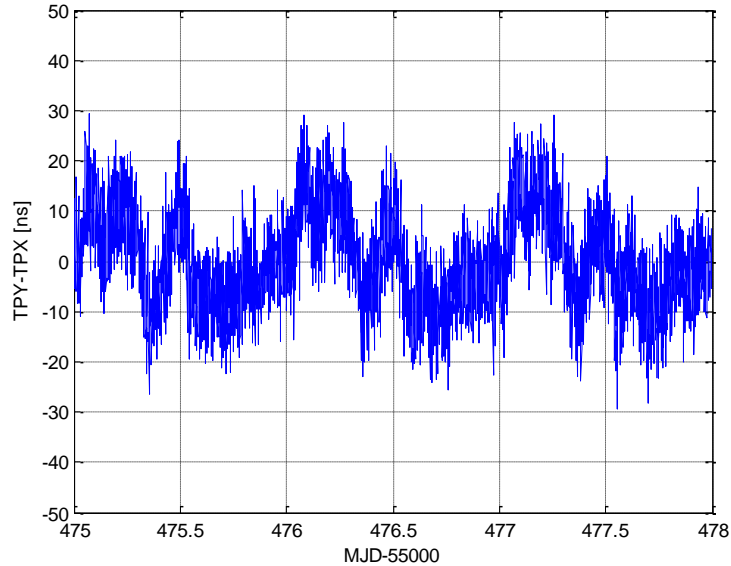


Figure 3. Measured time difference UTC(TPY) – UTC(TPX), EGNOS satellite PRN 120, code measurement, $\sigma = 9.7$ ns.

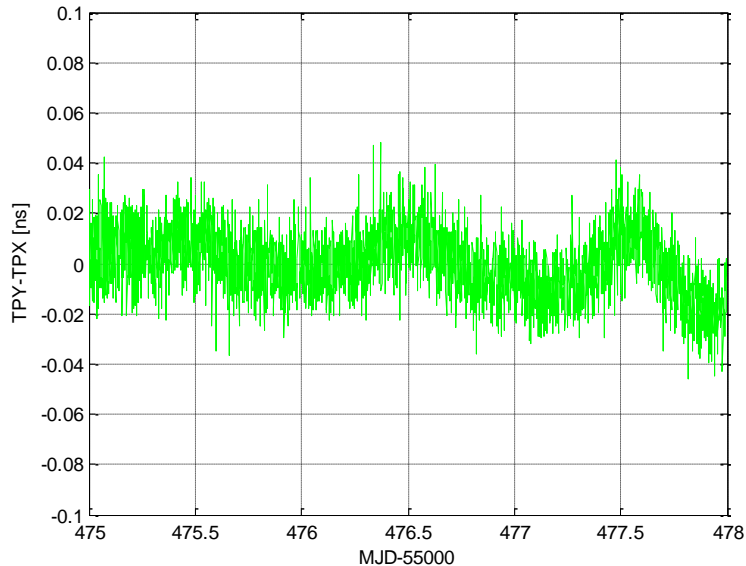


Figure 4. Measured time difference UTC(TPY) – UTC(TPX), EGNOS satellite PRN 120, carrier phase measurement, $\sigma = 12$ ps.

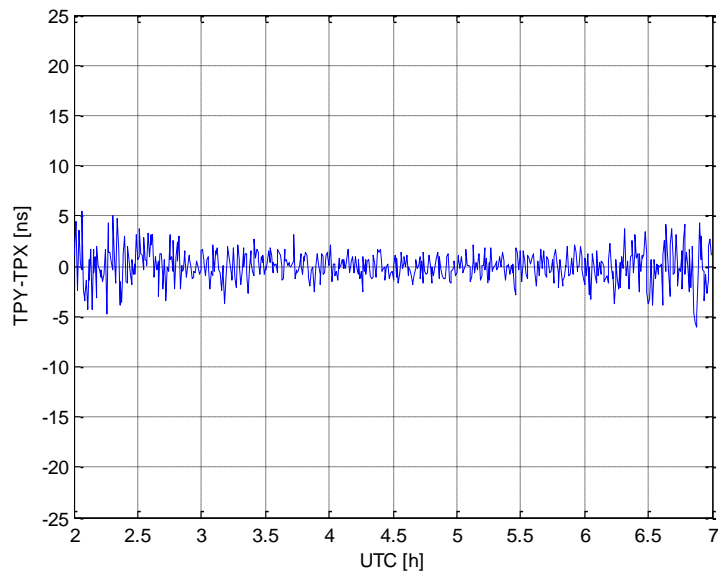


Figure 5. Measured time difference UTC(TPY) – UTC(TPX), GPS satellite PRN 26, MJD 55475, code measurement, $\sigma = 1.5$ ns.

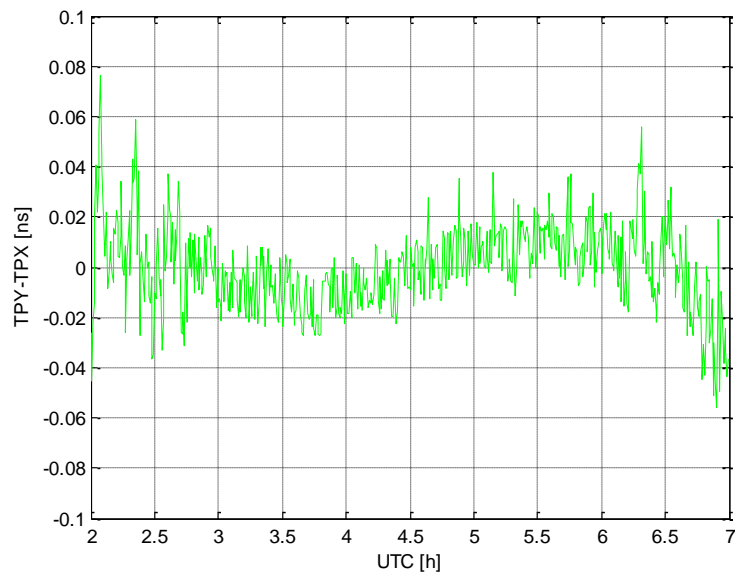


Figure 6. Measured time difference UTC(TPY) – UTC(TPX), GPS satellite PRN 26, MJD 55475, carrier phase measurement, $\sigma = 17$ ps.

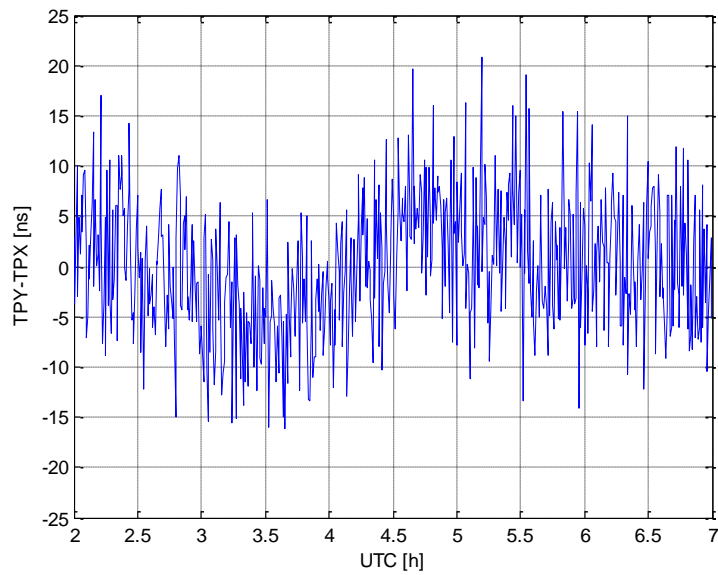


Figure 7. Measured time difference UTC(TPY) – UTC(TPX), EGNOS satellite PRN 120, MJD 55475, code measurement, $\sigma = 6.6$ ns.

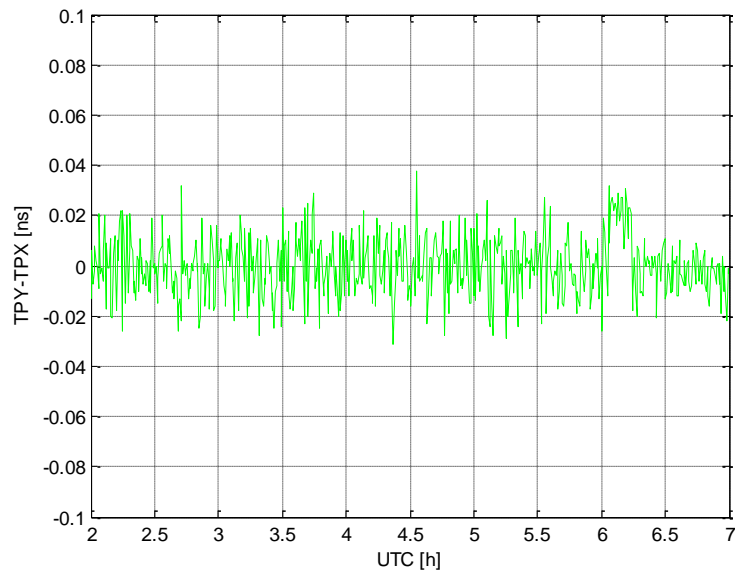


Figure 8. Measured time difference UTC(TPY) – UTC(TPX), EGNOS satellite PRN 120, MJD 55475, carrier phase measurement, $\sigma = 11$ ps.

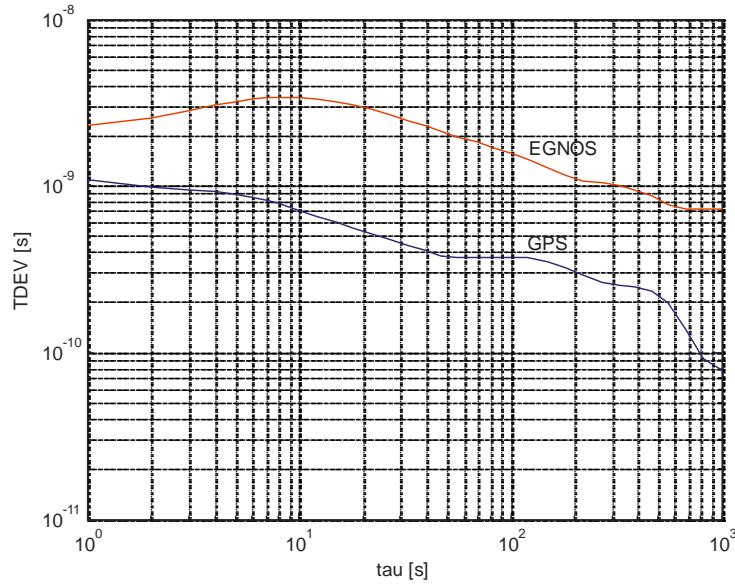


Figure 9. Time stability of comparison, code measurements, MJD 55475.

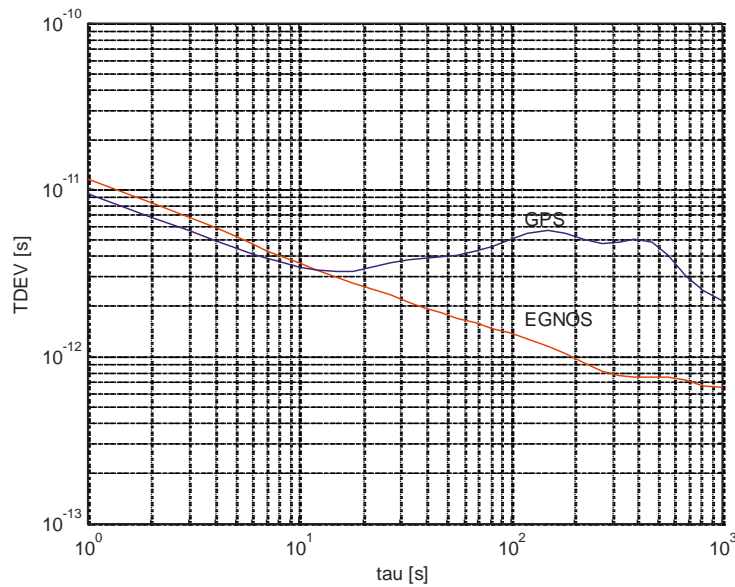


Figure 10. Time stability of comparison, carrier phase measurements, MJD 55475.

CONCLUSION

Experimental measurements were done while the ranging function is not fully supported by the EGNOS operator. It seems that obtained results are not affected by that fact. The accuracy of ephemerides was on the order of a few meters throughout the measurements but a high uncompensated drift in the signal delay with a slope of approximately 10^{-9} was observed. This drift makes no limitation to use EGNOS for the common view comparison of time scales.

The accuracy of code measurements using EGNOS is many times worse compared to GPS. The standard deviation of fluctuations is about 10 ns. This is caused by the narrow bandwidth of the transmitted signal. Improvement can be achieved after EGNOS is switched to Inmarsat IV satellites where the signal bandwidth is doubled. The accuracy is also bad influenced by lower carrier-to-noise ratio, but this can be compensated by using a directional antenna. Results confirmed that fluctuations caused by multipath propagation are very slow in case of EGNOS but still the time stability of comparison based on code measurements is worse compared to GPS.

The carrier phase measurements are promising, on the other hand. The standard deviation of fluctuations within a few days is 12 ps. The main advantage of using EGNOS for carrier phase measurements is that the signal is available continuously and thus it makes EGNOS optimal for continuous short-baseline comparisons of precision frequency sources.

REFERENCES

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