



DYNAMIC POSITIONING CONFERENCE
October 7 - 8, 2008

Sensors II

INS-GNSS Integration Based on MEMS Technology

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Abstract

The quality of GPS and combined GPS/Glonass systems as reference systems for DP operations has been improved through a long and incremental development cycle. Accuracy, availability and integrity have reached a level that was unthinkable some years ago. Even if this development will continue for many years to come, there are some physical limitations and common mode effects that will make barriers to further progress. Sensor hybridization is regarded as a promising approach to address these topics.

Different methods for combining GPS and inertial sensors have been around from the early days of GPS when lack of satellite coverage was the main limiting factor. However, these solutions were never able to be a success as reference systems for DP operations due to factors like cost, limited sensor life time and some operational constraints.

Over the last years there has been a sustained development of new sensor clusters based on MEMS gyros that in combination with novel approaches to sensor hybridization seems to have potential to overcome these limiting factors. This development is especially important considering that ionospheric activity is assumed to increase over the next 5-6 years causing occasional degradation of quality of GPS and Glonass signals.

The paper outlines improvements of applied MEMS gyro technology addressing achievements in hybridization with advanced GPS technology. Initial results from a test program demonstrating some of the potential of such solutions for DP reference systems are included

Introduction

After GPS reached Full Operational Conditions (FOC) in 1995 there have been a series of improvements both to GPS and other Global Navigation Satellite Systems (GNSS). Accuracy is improved by e.g. more accurate clocks and ephemerides, availability is improved by e.g. the ability to use combinations of interoperable GNSS satellite constellations and integrity is improved by e.g. introducing overlay systems like WAAS and EGNOS and by implementing advanced Receiver Autonomous Integrity Monitoring (RAIM) algorithms. All these, and many other, achievements have made GNSS the most important means for Navigation and Location determination on a global basis. Current plans and several new initiatives indicate that this development will continue for decades ahead.

In spite of all these developments and improvements one cannot expect GNSS to solve all problems or be able to meet all kinds of requirements and expectations. There will still be common mode failures since satellites will fly at about the same heights and signals propagate through the same atmospheric layers (ionosphere and troposphere). The frequencies set aside for GNSS are so far more or less in the same bands and signals expected to reach the face of the earth will be incredibly weak. Even if signal modulations will be redefined in the future, GNSS signals can always be jammed either by accident or as a consequence of hostile acts.

The idea of sensor hybridization between inertial sensors and GNSS is far from new. A long range of solutions exist spanning from deep coupling between GNSS and military grade ring laser gyros to low cost solutions for mobile phones and the automotive market.

None of these solutions has so far become very common as solutions for Dynamic Positioning reference systems due to different reasons. The development of emerging Microelectromechanical System (MEMS) based Inertial Motion Unit (IMU) may very well represent a technology disruption that will change this situation.

INS-GNSS Integration

Different INS-GNSS integration schemes are traditionally classified as loosely, tightly or deeply coupled. These concepts may be a little too simplified for a real-life implementation of an optimal solution for a DP reference system. The concept of parallel processing of all available observables should be taken into account as shown in **Figure 1**.

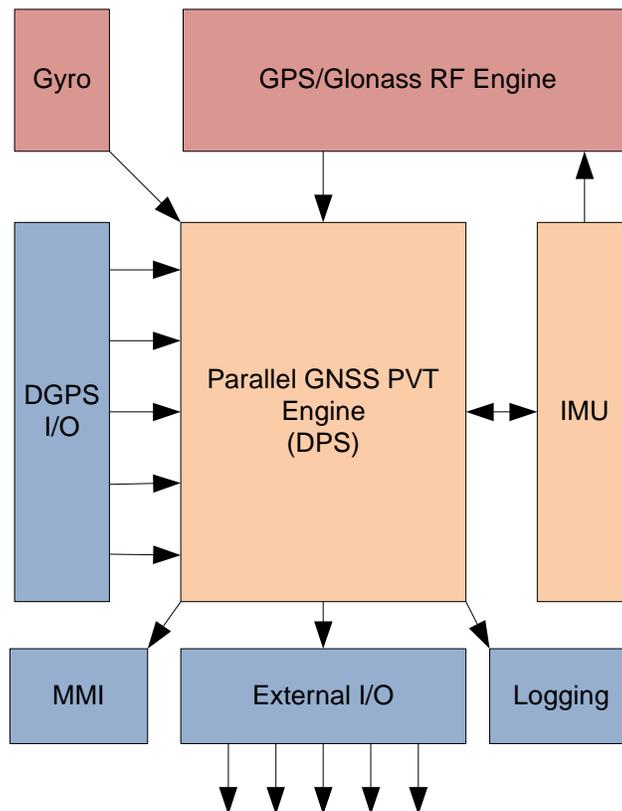


Figure 1 GNSS/IMU integration scheme

As the figure illustrates, it is foreseen that the IMU both needs to be interfaced directly to the GNSS RF engine to be able to support aiding of the tracking loops and to a parallel GNSS PVT including e.g. a Kalman Filter for combination of inertial and GNSS range-domain data. This approach will to the extent possible minimize the possible effect of common mode failures and maintain a sufficient integrity level.

There are quite many considerations to be taken into account with regards to the implementation of such an integration scheme but the elements focused in this paper are:

- IMU aided GNSS positions
- Bridging GNSS outages by using IMU based positions
- IMU aiding of GNSS tracking loops

It is assumed that these focal points will be the most important driving parameters for GNSS/IMU integration for DP applications. However, it should be noted that IMU integration will be useful for antenna lever arm compensation and improved GNSS integrity capabilities.

For a maritime application it is important to note that IMU sensor errors typically will propagate through attitude errors (roll- and pitch angles) before transformed into position errors by using a Kalman filter. Therefore, an IMU implementation for integration with GNSS typically needs to include a 3-axis gyro and a 3-axis accelerometer sensor cluster. The most important IMU sensor performance parameters are:

- Gyro in-run bias (represents bias instability, unit of deg/hour)
- Gyro angular random walk (represents gyro noise and has a unit of deg/ $\sqrt{\text{hour}}$)
- Accelerometer bias and noise

It is important not to focus only on gyro performance but also include the contribution from accelerometer performance even of gyros will be the main topic covered by this paper.

MEMS Based Gyro Developments

The principle behind MEMS based gyro implementations corresponds to the oscillating pendulum used by the French physicist Léon Foucault to demonstrate the rotation of the Earth in 1851. An MEMS based implementation of this “pendulum” is achieved by using a small, vibrating structure where the “pendulum” usually is fixed relative to a resonator. Physical rotation of the structure causes transfer of energy to a pick-off axis, 45° or 90° to the “pendulum” axis, depending on in which way the resonator is constructed. Then the pick-off amplitude will be proportional to the rotation rate according to impact from the Coriolis force.

While Foucault’s famous pendulum in Phantéon in Paris was 67 m long carrying a 28 kg bob, a modern MEMS gyro resonator typically will have the following physical characteristics:

- Resonator area: 5 – 50 mm²
- Excitations: < 5 μm
- Frequencies: 4 – 20 kHz

MEMS based gyros have been implemented in many different variations over the past 10 years and a lot of innovation and ingenuity has lead to increasingly better performance (improved price/performance). It seems like MEMS based gyros are about to close the technology gap that alternative technologies like Fiber Optic Gyros (FOG) has had for many years. It can be claimed

that MEMS based gyros represents a so-called disruptive technology that eventually will open up for new utilizations of gyros where price so far has been prohibitive for wide-spread use.

A gyro recently developed by Kongsberg Seatex AS, optimized for use in the high-end of the Seatex MRU (Motion Reference Unit) product range, is one example of a novel MEMS based gyro design that demonstrates new levels of performance for this kind of technology (see Figure 2). The gyro consists of supporting electronics and advanced Digital Signal Processing (DSP) to achieve the required performance from the enclosed MEMS based resonator.



Figure 2: MRG 15-04 – a gyro designed by Kongsberg Seatex AS

The Allan Variance technique is a useful method for assessing the performance of any gyro in relation to the dynamics of the application. It takes into account bias, noise, drift and long term sensor instability. The fundamental principle is to average successive data samples over different time intervals. Averages taken over shorter intervals will be dominated by noise while averages taken over longer intervals will be dominated by longer term drift. The variation from one averaged time period to the next is calculated and plotted against the averaging interval on logarithmic axes. An Allan Variance Graph will typically have a characteristic bathtub shape and can be used to compute angular random walk and bias instability.

An example of Allan Variance Plots for three real samples of the MEMS based MRG 15-04 model is shown in Figure 3 together with data from a typical FOG. MRG is characterized with lower noise than the FOG since the three MRG curves is well below the FOG curve for shorter averaging intervals (up to about 5-6 minutes). For averaging intervals of more than 5-6 minutes Bias instability will start to dominate the Angle Drift for the MRGs. As seen from the Allan Variance plot this particular FOG does not have any Bias instability that contributes to the Angle Drift. However, the curves do not cross until at about 10-15 minutes averaging intervals where the total drift of the MRG and FOG equals each other.

Wave induced motion typically has periods of up to 15-25 seconds. This means that a Kalman filter combining gyro and accelerometer data for maritime applications needs to be given filter

periods longer than this with some additional margin. Kalman filter periods of 1 – 3 minutes have shown to give good results. Since the relevant Kalman filter period is below the point where the Bias instability starts to dominate the MRG (MEMS) error the relevance of the lower Bias instability for the FOG will be negligible.

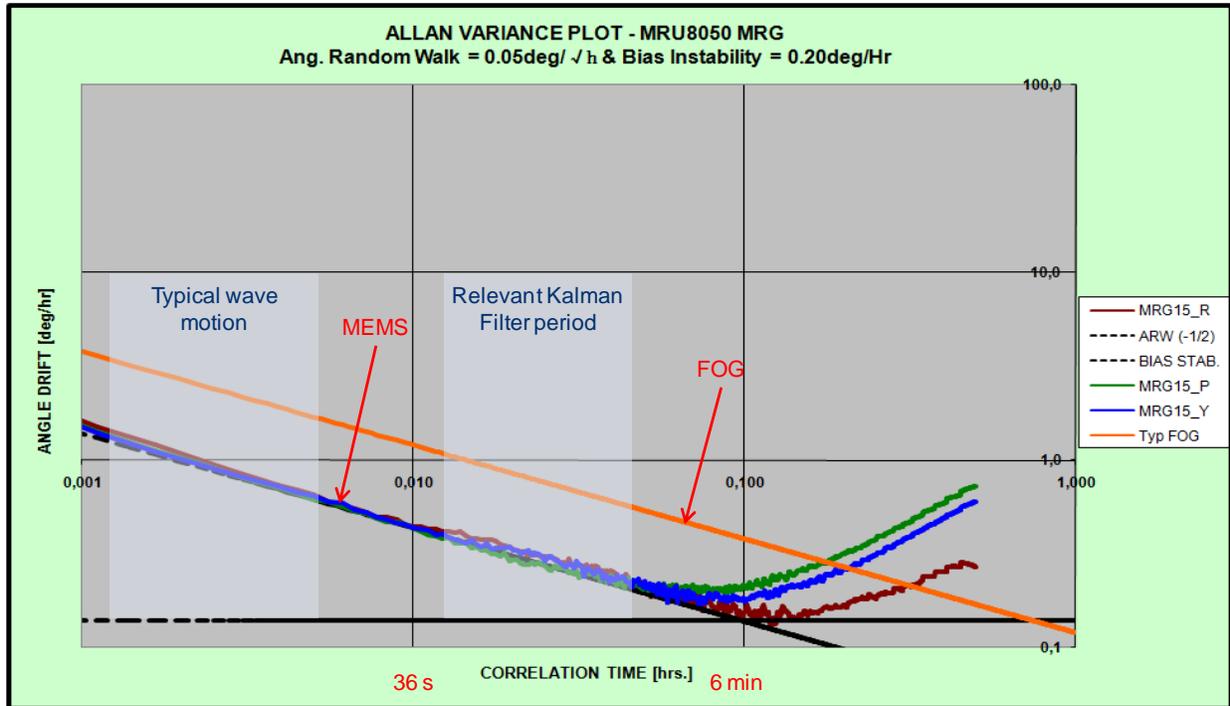


Figure 3: Allan Variance for 3 x MRG and a typical FOG

Assuming that the error budget is dominated by gyro noise (Angular Random Noise) gyro error can be approximated to position error (assuming no GNSS position available) according to the following formula:

$$\Delta X = \frac{1}{2} * \frac{\pi}{180} * \frac{g}{60} * ARW * t^{2.5} [m]$$

where

ΔX is position error in meters (one direction, RMS)

ARW is angular random walk in deg/ $\sqrt{\text{hour}}$

t is elapsed time in seconds

The formula should be considered as a rule-of-thumb since a real implementation of a position filter might utilize e.g. a vessel model and result in a more complicated connection. It is also assumed that the formula will be used for $t \ll 84$ minutes (The Schuler period).

Filling in some values of ARW and t gives the following table:

Table 1: ΔX as a function of ARW and t

<i>ARW/Period</i>	<i>10s</i>	<i>30s</i>	<i>60s</i>
<i>0,10 deg/ \sqrt{h}</i>	0.05m	0.70m	3.98m
<i>0,05 deg/ \sqrt{h}</i>	0.02m	0.35m	1.99m

The table shows that an IMU can be used to maintain a position with appropriate accuracy for short intervals. However, it will be important to limit t as far as possible since the power to 2.5 always will be the limiting factor. Therefore, using IMU data to aid GNSS tracking is essential to achieve a good integrated solution.

In-run bias needs to be low enough compared to ARW to prevent significant contribution to angle drift (the lowest point on the Allan Variance curve is at a long correlation time)

The impact of accelerometer errors should also be considered according to following logic:

1. Accelerometer measurements are needed to estimate in-run bias by use of a Kalman filter
2. Accelerometer measurement noise propagates into in-run bias estimation
3. High quality accelerometers (with low absolute bias) are needed to prevent attitude (hence position-) errors

Developments of MEMS based gyros have gradually been closing the performance gap towards FOG based solutions with regards to the most relevant parameters for GNSS integration as shown in Table 2. FOG will still outperform MEMS with regards to bias instability but this difference in performance will not be relevant for these kinds of solutions.

Another advantage for MEMS technology compared to FOG is the limited life-time of optical components. An instrument like the Seatex MRU 5 has over the years demonstrated a MTBF of more than 120 000 hours.

Integration Results

Degradation of GNSS performance caused by ionospheric activity will especially be noticeable in locations close to the geomagnetic equator and in Polar Regions. The activity in the ionosphere is usually following the intensity of sun spot eruptions that for a long time has been following an 11-year cycle. The previous sun spot Cycle 23 maximum was observed in 2000-2001 while the next one is expected to occur in 2011-2012. Among the effects of increased ionospheric activity is heavy degradation of differential GNSS accuracy. To demonstrate the potential of minimizing this effect by using an IMU aided GNSS solution data recorded in Brazil in year 2000 have been reprocessed with two IMUs representing different performance levels.

Table 2: Performance development of MEMS based technology

	Seatex MRU (MEMS)			FOG AHRs
	2003	2007	2008	(typical)
	Analog	DSP	DSP	
Angular Random Walk	<0.3°/√h	<0.1°/√h	<0.05°/√h	<0.1°/√h
In-run Bias Stability @360 s	<2°/h	<0.6°/h	<0.2°/h	N/A
Accelerometer Bias	<300 μg	<300 μg	<150μg	<1000 μg
Accelerometer Noise (0 Hz - 10Hz, RMS)	10 μg	10 μg	3 μg	150 μg

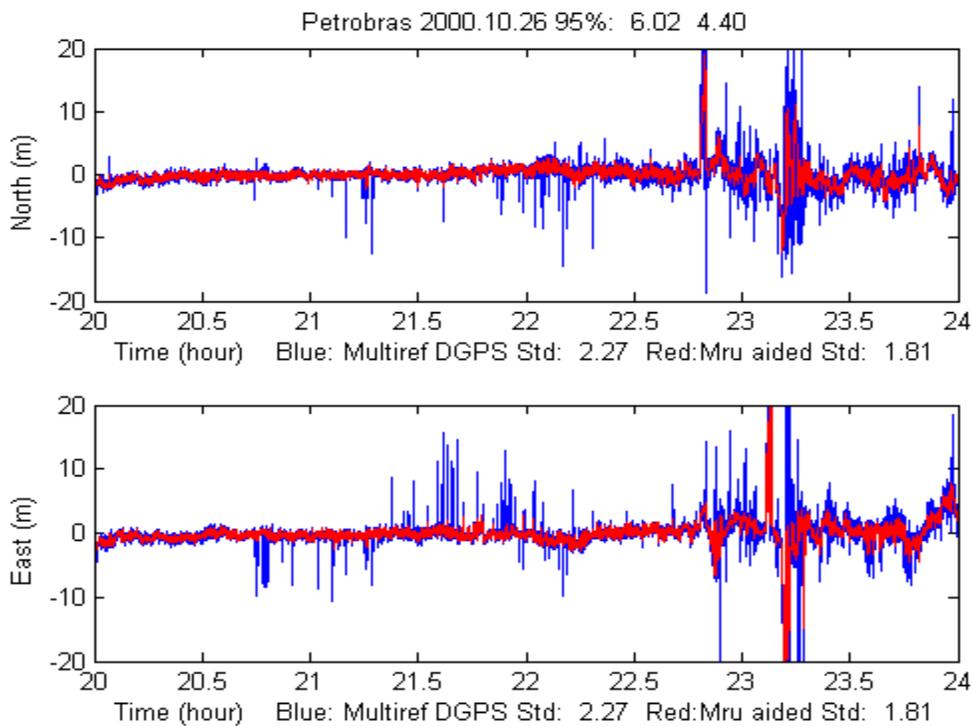


Figure 4: IMU aiding of GNSS using a “low grade” IMU

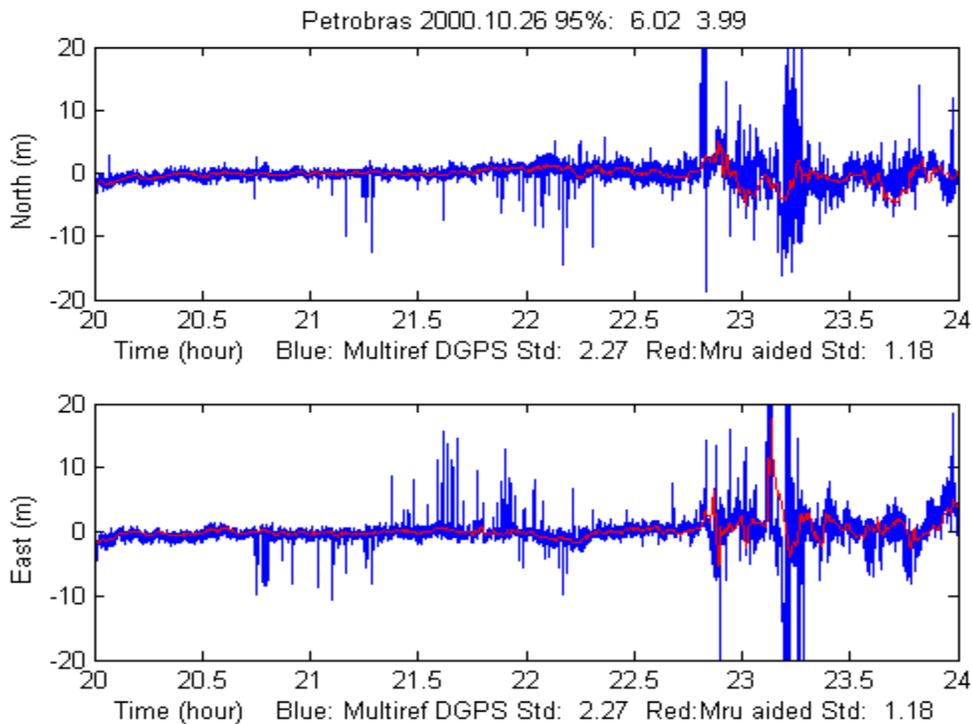


Figure 5: IMU aiding of GNSS using an improved IMU

The figures show that a DGPS multiple reference station position accuracy (95% CEP) is improved from 2.27m to 1.81m and 1.18m for the two types of IMU's. The quality of the IMU consequently is significant for reducing the noise level caused by ionospheric disturbances.

Demonstration of IMU based position to bridge outages of GNSS solutions have been done by driving a car on roads where GNSS signal has temporarily been obstructed or disturbed. Figure 6 plots positions while driving under dense foliage and Figure 7 plots positions while driving through a tunnel. Both plots clearly indicate significant improvements both with regards to bridging outages and reducing the effect of inaccurate GNSS measurements.

The direct effect of aiding the tracking loops of the GNSS receiver with IMU data has also been studied. Some results are plotted in Figure 8. The test has been done by disconnecting/reconnecting the GNSS antenna and the reacquisition time has been measured several times. It should be noted that significant improvements are achieved on L1 but the improvement is even better with regards to L2. L2 tracking will especially critical for high accuracy solutions based on clock and orbit corrections and solutions relying on dual-frequency GPS data.



Figure 6: GNSS and IMU/GNSS position driving under dense foliage

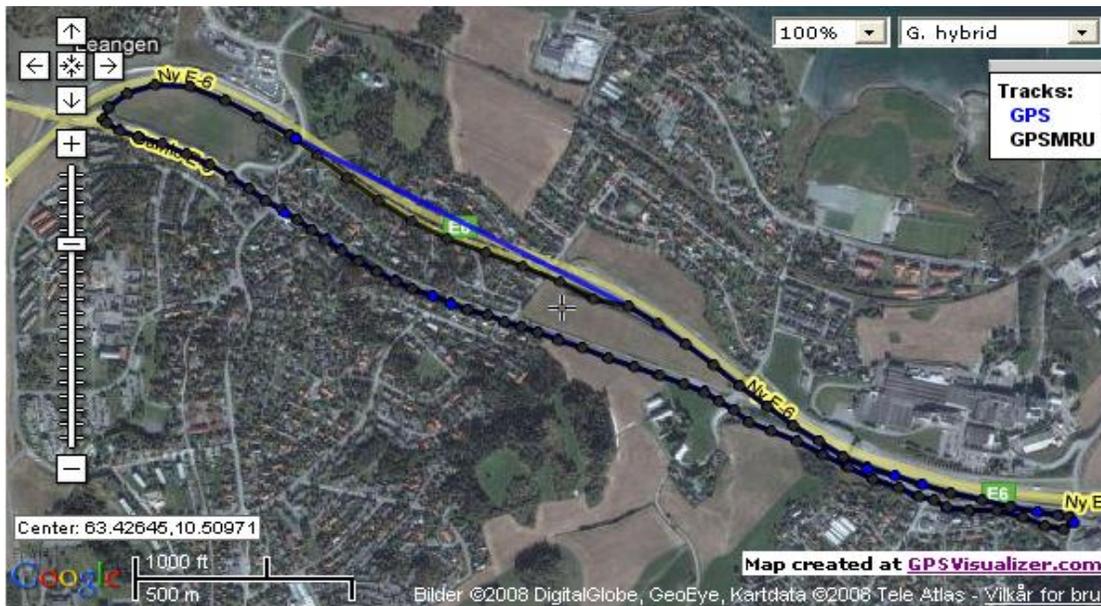


Figure 7: GNSS and IMU/GNSS position driving through a tunnel

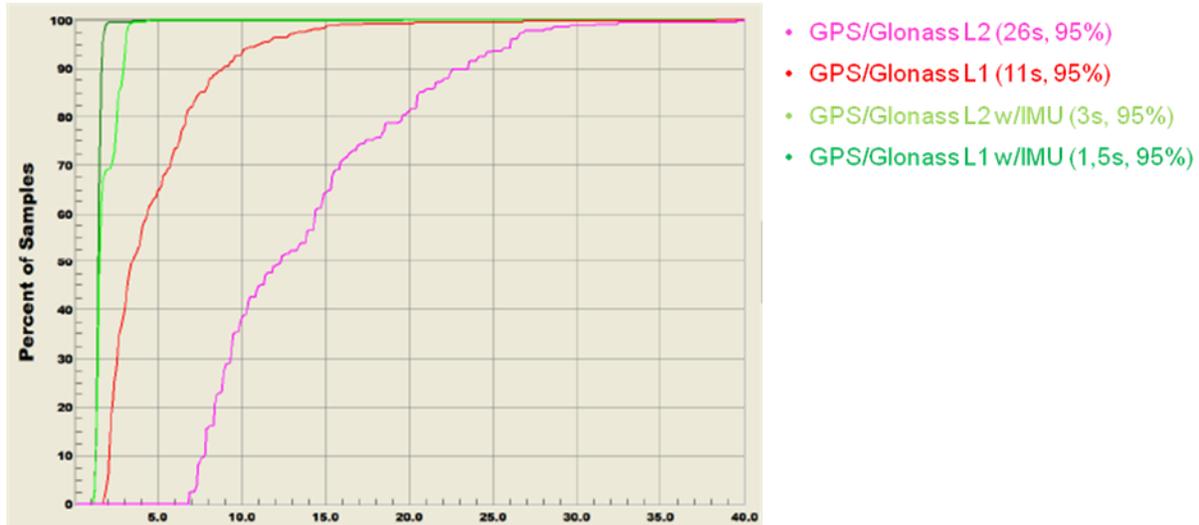


Figure 8: Reduced re-acquisition time by IMU aiding of GNSS tracking loops

Conclusion

Performance of MEMS based gyros in IMUs used for integration with GNSS solutions have been demonstrated to give promising results used as the basis for DP position reference systems. It has been demonstrated that MEMS based gyros is very competitive to FOG based solutions with regards to relevant parameters defined by the application. Practical demonstrations indicate that an integrated solution will provide improved accuracy and availability by appropriate filtering of GNSS positions, bridging of GNSS position outages and improving tracking by aiding of GNSS tracking loops.

Utilizing all these capabilities requires integration not only by the sensors, but also integration of the development process since considerations need to be taken into account across the different technologies.