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Sensors

Qualification of a Hybrid GNSS and IMU Solution

Arne Rinnan, Marit E. Sigmond, Andrew Robertsen, Nina Gundersen

Kongsberg Seatex AS, Trondheim, Norway

Abstract

Advanced GPS and GPS/Glonass solutions utilizing modern clock/orbit correction services provide accurate and reliable positions under almost all conditions. However, there still are failure modes and risks related to e.g. high ionospheric activity, HDOP spikes caused by signal blocking or variations in the satellite coverage and interference either caused by other radio frequency emitting equipment or hostile jammers.

An approach to further improvement of GNSS solutions is to combine satellite observations with inertial measurements. An overall integration scheme and a proposed system configuration are described and exemplified by the DPS 4D product.

The challenge of improving already accurate and reliable GNSS solutions by using inertial technology is considerable and an insight into the quality management process with explicit focus on test activities during the development cycle, is presented. Some of the advanced simulation and different test platforms for inertial and GNSS equipment are described. Extended verification and validation also involve pre-release installations and operation onboard large vessels to ensure full performance and operational capabilities.

Examples of results from the verification and validation activities demonstrating the increased capabilities of a hybrid GNSS/IMU solution compared to advanced GNSS-only solutions, are covered. The scenarios covered are performance achievements under normal conditions, satellite signal obstruction, signal scintillations, possible re-init of clock/orbit solutions and temporarily access denial of satellite signals (e.g. jamming) is presented. The integrated GNSS/IMU solution demonstrates improvements under all these scenarios.

The final section of the paper highlights some aspects regarding installation and surveying of the sensors constituting a hybrid GNSS/IMU solution, since installation aspects will be crucial to maintain optimum performance.

Introduction

Since GPS reached its Full Operational Condition (FOC) almost 15 years ago, it has clearly become the most recognized navigation system ever. Accuracy and reliability have reached levels unthinkable in the pre-GPS era. Even if system and satellite failures have occurred they have been so rare that most users have no personal experience with such faults. Not much of our essential modern infrastructure like power, telecommunication, public transportation, waste management and supply of water can refer to a track record like the GPS ground and space segment.

However, users requiring a 365/24/7 service still cannot consider GPS 100% reliable under all circumstances. There are still possible failure modes like ionospheric turbulence, tropospheric variations, blocking and multipath from objects near to the antenna and the increasing threat from accidental or intentional jamming.

The upcoming sunspot cycle 24 is expected to cause problems in the ionosphere induced by large currents of charged particles from the sun. This type of faults were frequently observed e.g. outside Brazil during the previous sunspot cycle 23.

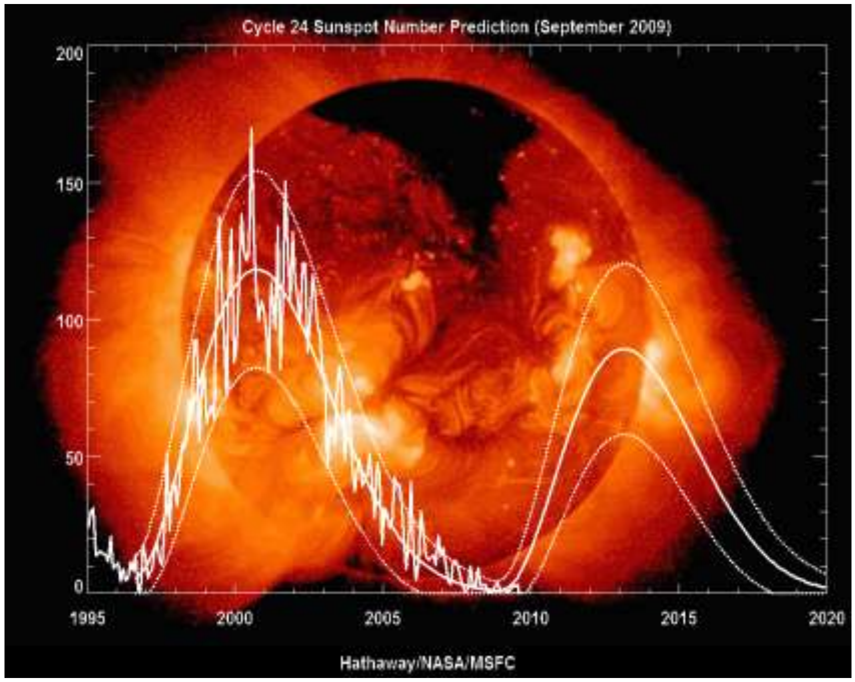


Figure 1: Sunspot period prediction

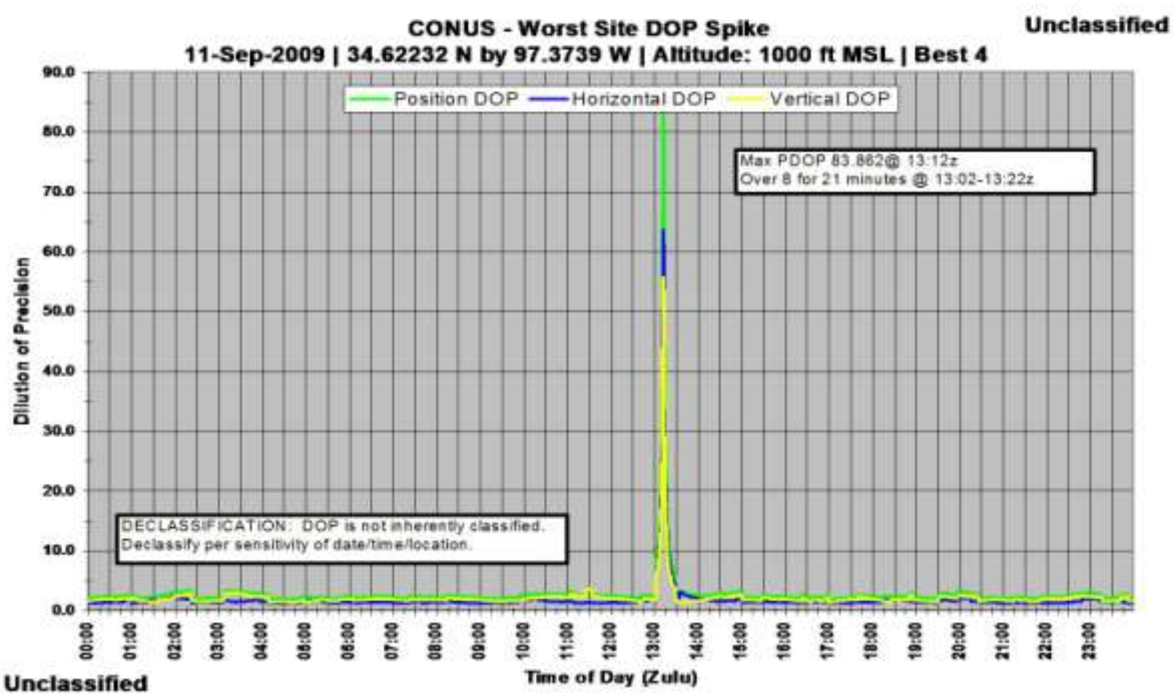


Figure 2: USCG Navigation Center high HDOP warning

The lifetime of GPS satellites has shown to exceed the design lifetime by far. Of the 31 satellites flying in the current constellation 11 are more than 10 years old. If a few of these satellites fail without being replaced within short notice, a weakened constellation might lead to HDOP spikes in certain areas. Since HDOP represents an amplification of the GPS ranging error, degraded position accuracy will be the result. The USCG Navigation Center even announced such an HDOP spike at 9/11/2009 caused by repositioning of a GPS satellite. In a worst case scenario this event could possibly degrade the GPS or DGPS accuracy by tens of meters. A GPS satellite constellation consisting of fewer than 30-31 satellites would increase the risk for such HDOP spikes.

Another increasing risk is the risk of interference and jamming. A modern offshore vessel usually represents a very complex electromagnetic environment and interference with the GPS L1 and/or L2 signal is reported more and more frequently. An increasing concern is also the threat of being intentionally jammed by low cost jammers intended to interfere with the GPS signal. Such jammers are now available for a few $ on the Internet and some of them will be capable of jamming a GPS signal over distances of several km.

Figure 3: GPS jammer

The L1 and L2 signal from such a jammer is shown in **Figure 4**. The emitted power is about 0.5W.

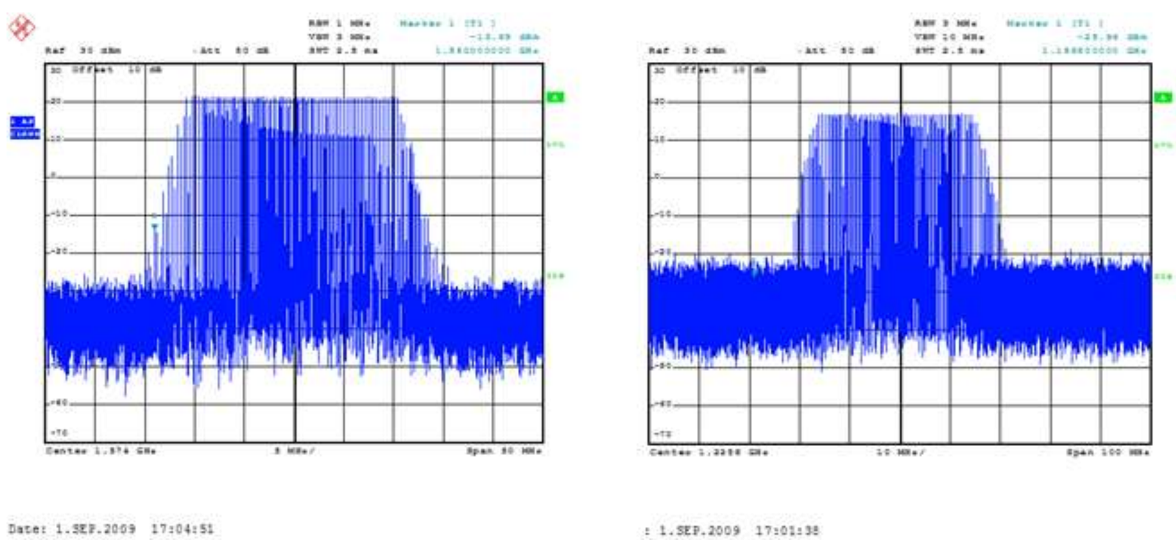


Figure 4: GPS jammer L1 and L2 signal

A strategy to minimize these risks will involve several elements like utilizing the combined GPS/Glonass satellite constellation, using global high precision corrections (e.g. Fugro G2/XP/HP) and relying on redundant onboard GPS equipment.

Another element in this strategy is integrating GPS with data from an IMU (Inertial Motion Unit). The DPS 4D developed by Kongsberg Seatex AS represents a solution where such an integration is achieved by combining high precision GPS/Glonass measurements with data from the new MRU 5+.

INS-GNSS Integration

The DPS 4D is based on an integration scheme shown in ***Figure 5***.

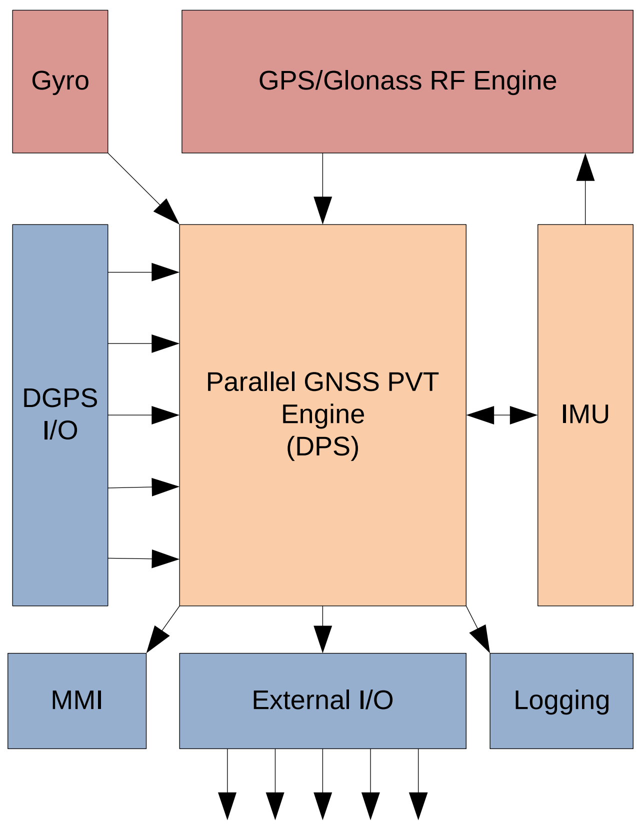


Figure 5 GNSS/IMU integration scheme

As the figure illustrates, it is possible to interface the MRU 5+ directly to the GNSS RF engine to be able to support aiding of the tracking loops and to a parallel GNSS PVT including a Kalman Filter for combination of inertial and GPS range-domain data.

The system configuration of a DPS 4D is shown in **Figure 6**.

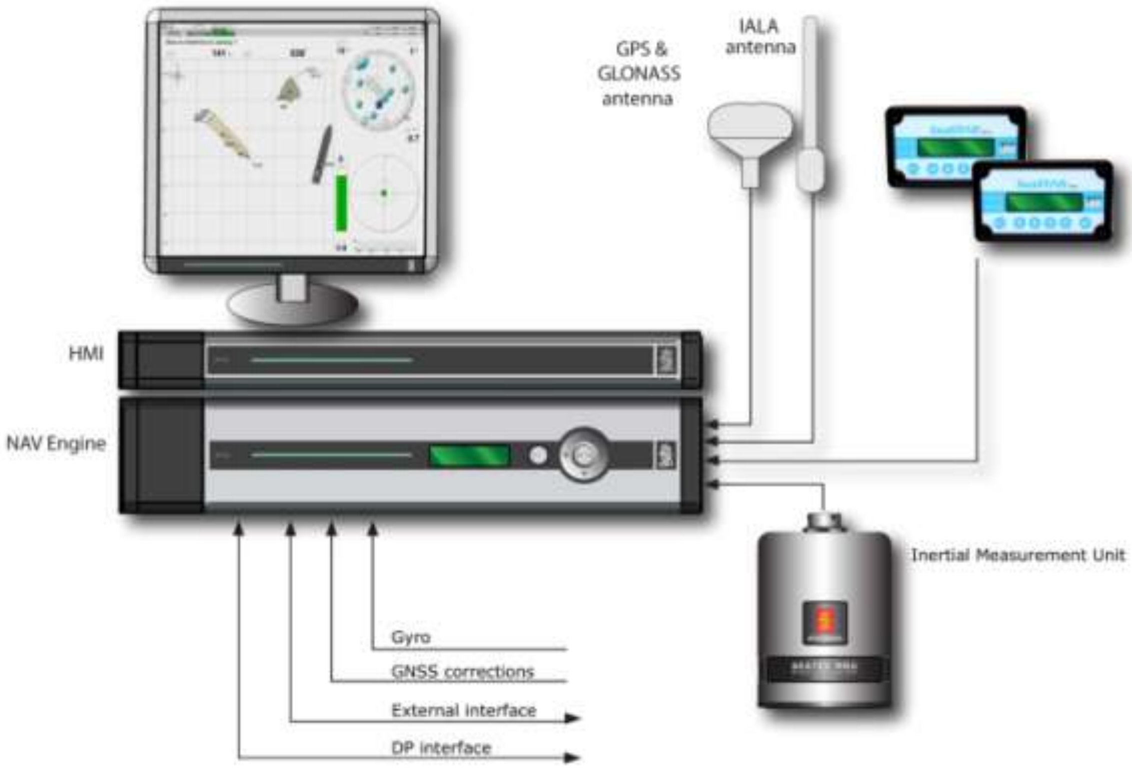


Figure 6: DPS 4D system configuration

Quality Management

A hybrid GNSS and IMU system is a complex piece of technology with many possible pitfalls that have to be considered to avoid introducing new failure modes. Testing of such a system requires running through thousands of large data-sets to be able to find the optimal trade-offs and elimination of risk factors. The most important parameter in the development of such a solution is therefore the quality and skills of the development team. This team has to be members of a strong and positive culture to be able to develop and utilize their competence and commitment.

The development process also needs to balance between innovation and incremental improvements. These two processes must then be supported by a robust and strong technical architecture and professional process support. Some of the elements needed for a successful development are presented in **Figure 7.**

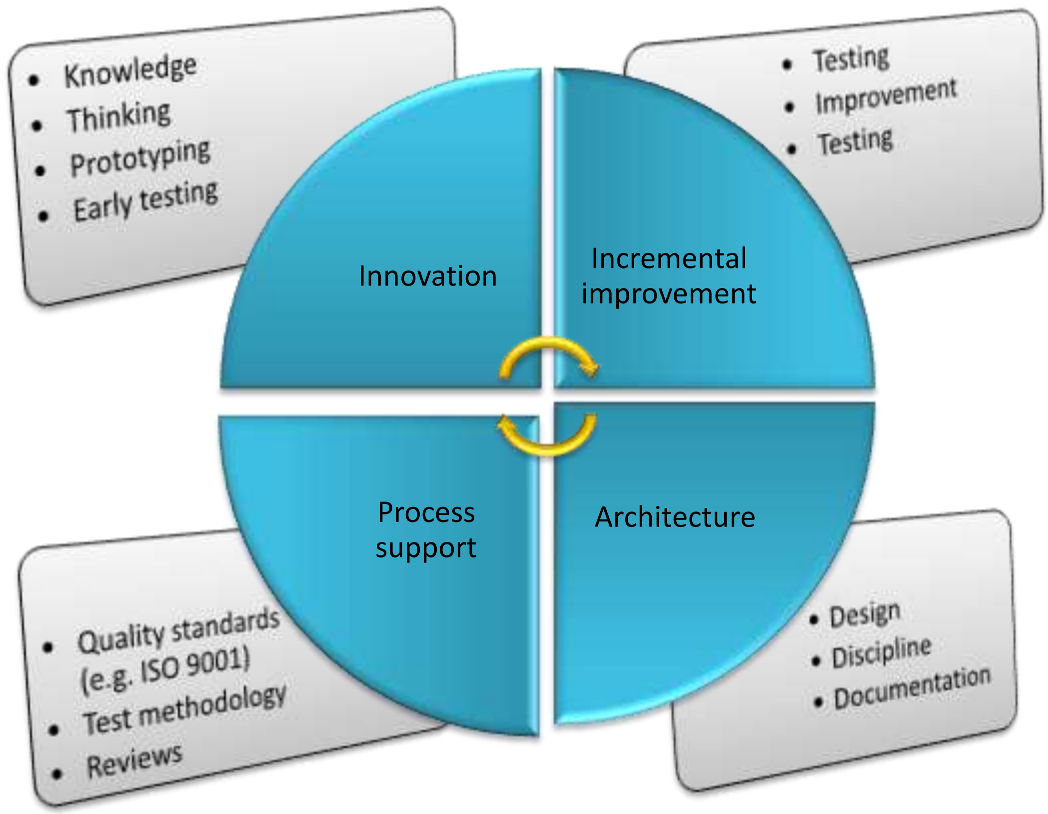
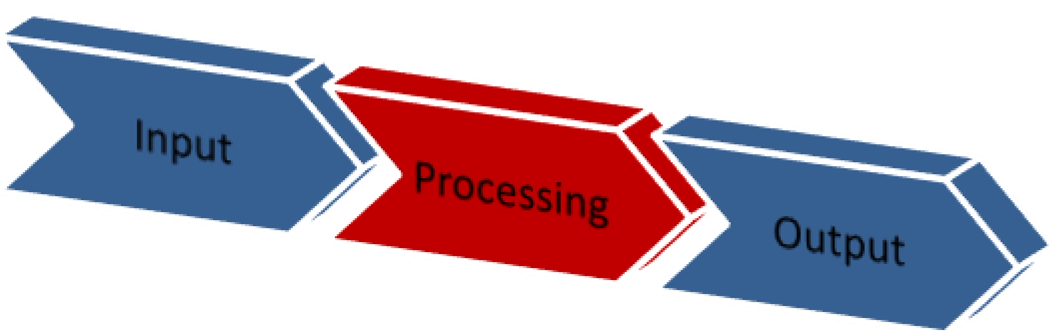


Figure 7: Key element of a successful development process

<u>Test platform</u>

Developing a hybrid GNSS/IMU solution has to rely on different types of advanced test equipment. One fundamental problem is to know exactly what the processing algorithms do when sensor input includes measurement errors and noise.



A GPS/Glonass signal simulator is an invaluable tool for exactly controlling the input for testing of the processing algorithms. In addition to generating "perfect" GPS and Glonass signals, a signal simulator can also be used to manipulate the signal in a controlled manner to test for events occurring very rarely with the operational satellites.

Testing of an IMU is requiring equipment that is capable of inducing controlled movements with very high accuracy. Figure 9 shows a position/rate table for two axis motion simulation with a rate stability of 0.0001% and position accuracy of 0.0008°. The rate table also has the capability of controlling temperatures from -45°C to +90°C. Rotation rates are 200°/s for the outer chamber and 900°/s for the inner mount.

Figure 8: GPS & Glonass simulator equipment

Figure 9: Position/Rate table for IMU testing

The rate table is also used to test and calibrate each individual IMU which is documented by a calibration certificate.

Seatex MRU Calibration Certificate

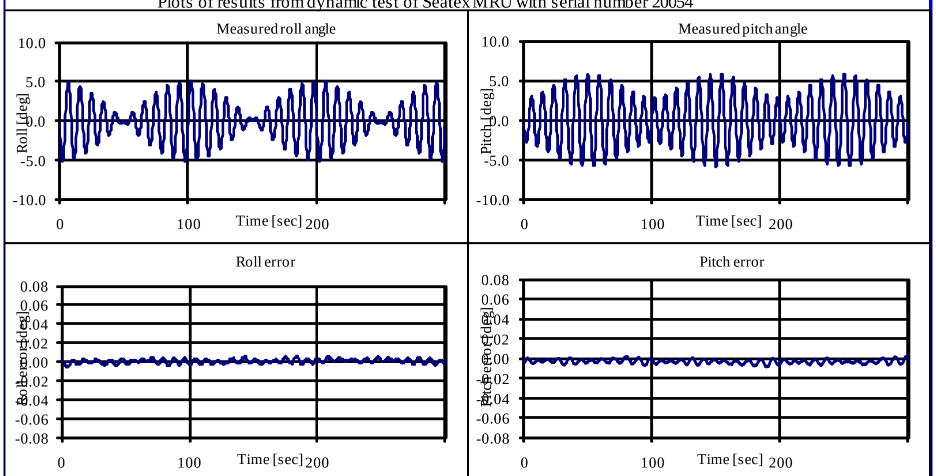
Seatex MRU model number:	5
Serial number:	20054
Calibration certificate number:	20090910-20054

1. Roll and Pitch Accuracy Tests

Roll and pitch accuracy	Test requirement	Roll	Pitch	Approval
RMS static roll and pitch [deg]	0.01	0.003	0.001	*Passed*
RMS dynamic roll and pitch [deg]	0.01	0.002	0.004	*Passed*

The static accuracy was measured by sampling at 4 Hz for 30 minutes, when the Seatex MRU is stationary.
The dynamic accuracy was measured in a rate table test with simultaneous sinusoidal exitation in two axes for 10 minutes.

Plots of results from dynamic test of Seatex MRU with serial number 20054



2. Rate Gyro Accuracy Tests

Angular rate accuracy	Test requirement	R-axis	P-axis	Y-axis	Approval
RMS rate sensor noise [deg/s]	0.025	0.007	0.009	0.008	*Passed*
RMS rate sensor scale factor error [%]	0.08 %	0.00 %	0.01 %	0.00 %	*Passed*

The angular rate sensor noise level was measured by sampling at 4 Hz for 30 minutes, when the Seatex MRU is stationary.
The rate gyro scale factor error was tested by single-axis rotations on a rate table at ±10°/s and at ±30°/s.

3. Accelerometer Accuracy Tests

Linear acceleration accuracy	Test requirement	R-axis	P-axis	Y-axis	Approval
STD acceleration sensor noise [m/s^2]	0.0017	0.0000	0.0001	0.0001	*Passed*
RMS acceleration sensor scale factor error [%]	0.020%	0.002%	0.000%	0.004%	*Passed*

Figure 10: MRU calibration certificate

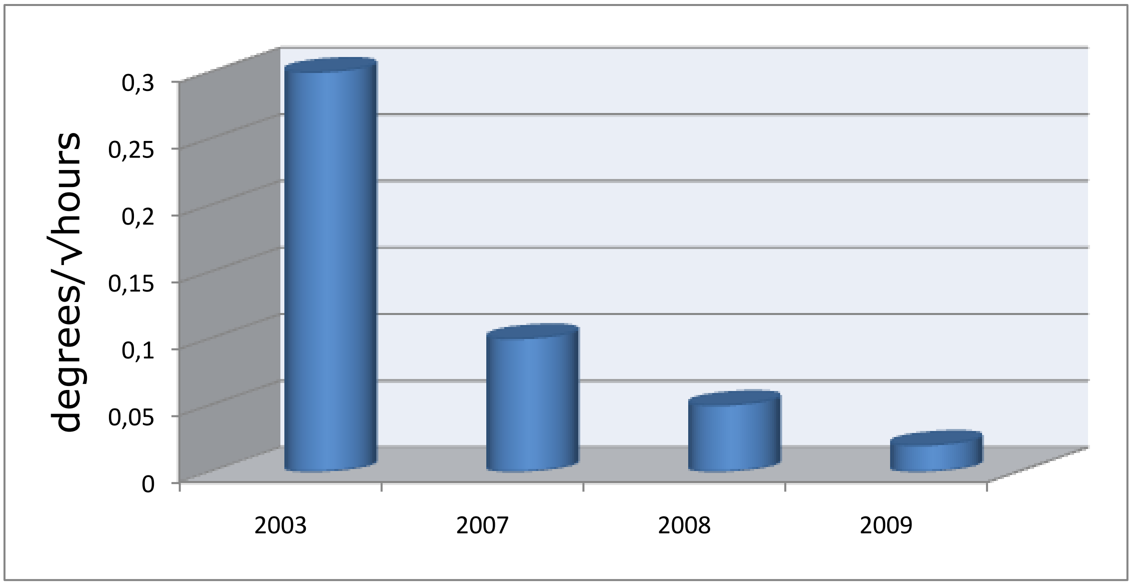


Figure 11: Improvement of angular random walk

A hybrid GNSS/IMU system performance relies among many other factors on the level of angular random walk. The value of incremental development over several years is illustrated in **Figure 11**. The significance of this parameter is indicated by the following equation

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

The interpretation of the equation is that extrapolation of position based on measurements from an IMU will be proportional to angular random walk (ARW) multiplied by elapsed time to the power of 2.5.

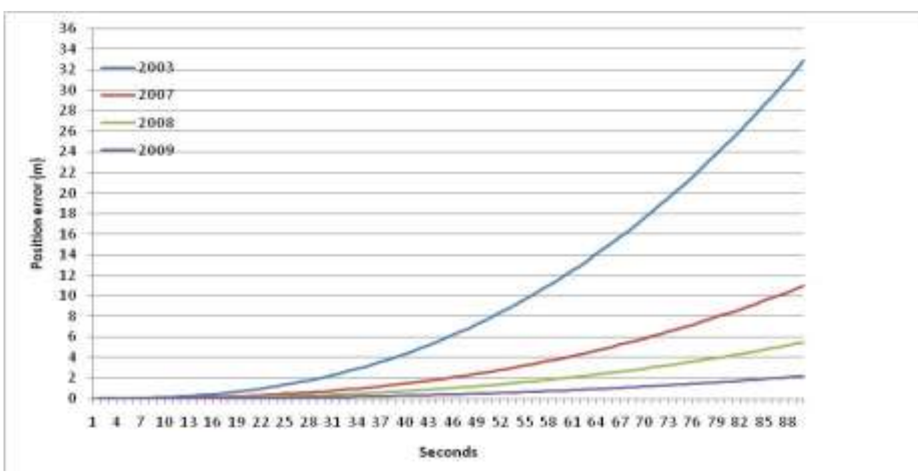


Figure 12: Position error caused by angular random walk

Verification and validation

Figure 13: Lab test equipment

An advanced hybrid GNSS/IMU solution requires thousands of hours of verification and validation before a commercial product can be released. For this purpose several test platforms are utilized:

- in-house equipment with continuous logging and analyses of data
- a car used to collect data under different types of dynamics
- test vessels of different sizes to be able to adapt algorithms to realistic dynamics
- installation onboard relevant types of vessels for validation and further optimization of algorithm parameters

Figure 14: Test vehicle and test pilot

Figure 15: Small test vessel

Figure 16: Test vessel (R/V Gunnerus)

Figure 17: DPS 4D validation platforms (Bourbon Topaz and Bourbon Oceanteam 101)

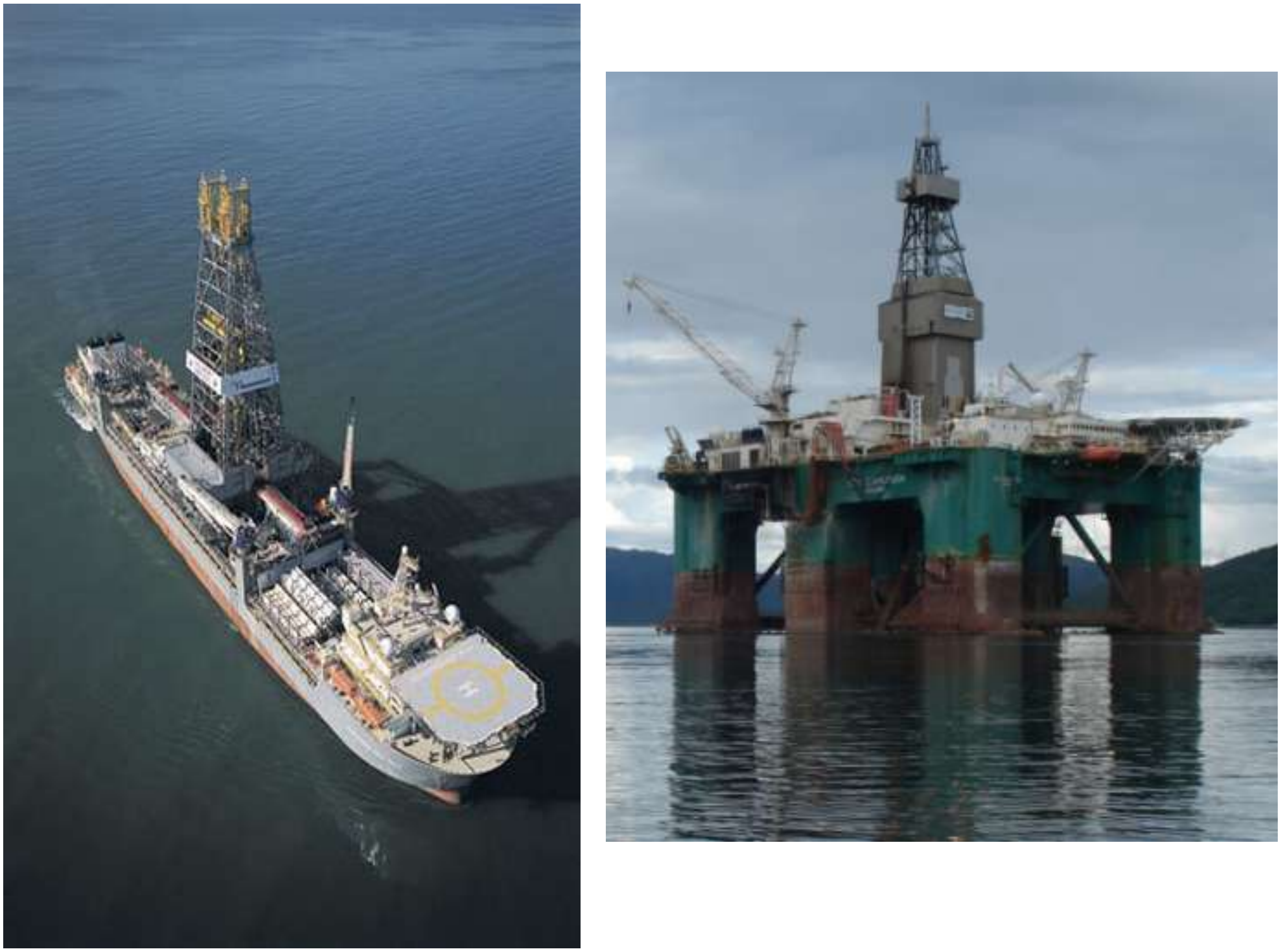


Figure 18: DPS 4D validation platforms (Discoverer Deep Seas and Leiv Eriksson)

Test results

This chapter gives some examples of test results from the verification and validation work of DPS 4D. It should be noted that some of the datasets are selected to demonstrate the capabilities of DPS 4D and therefore do not necessarily represent situations that will commonly occur.

The plots in Figure 19 show a comparison of Northing position between a standard DGPS solution and DPS 4D. Since GPS conditions are normal, it can be seen that the curves follows each other almost all the time. Note that the variations in position represent real measurements of a vessel (recorded onboard Discoverer Deep Seas).

The plots in Figure 20 show a zoomed in section of the same time-series. At about 12:05-12:08 it is seen that the DGPS position gets some distortion caused by a low elevation satellite toggling in and out of the solution. The variation from the low elevation satellite is handled by the GNSS/IMU filter and no addition of noise to the position solution can be observed.

The plots in Figure 21 show an example of a situation with blocking of the GPS signal. Blocking causes a decrease in the number of tracked satellites and a corresponding increase in HDOP. It is shown that the DPS 4D solution is very little affected by the blocking. Plots in Figure 22 show a zoomed in version of the same time-series.

In Figure 23 noise is added to the GPS signals by simulating measurements errors for a period of 6-7 minutes. This might typically happen during large instabilities in the ionosphere. The DGPS position is shifted by several meters while the DPS 4D solution maintains the correct position of the vessel during these periods.

Figure 24 data is recorded in a situation where clock/orbit corrections are used to keep the position error typically within 20 cm under normal conditions. The plots represent a section of the time-series where the clock/orbit solution is forced to be reinitiated. The reinitiating of the clock/orbit solution caused a position error of about 1 m. The DPS 4D solution detects this position jump and maintains the correct position with very slight position error increase for the plotted section of the time-series. However, the Estimated Position Error parameter (EPE) for the DPS 4D solution is slowly increasing during this period to reflect the increasing uncertainty of the position solution.

Figure 25 shows a situation where the GPS/Glonass signal is completely lost for a period of about 40 seconds. The DPS 4D position shows a drift that is increasing as the time elapses more or less according to the expectations. After about 40 seconds the position error is still just about 1 m and the corresponding EPE is overbounding the actual position error with a factor of about 2.

It is important to note that DPS 4D is capable of logging all sensor data for later replay and analyses. This includes logging of:

- GPS and Glonass raw measurements
- Clock/orbit corrections (e.g. Fugro XP/HP/G2)
- IMU data (MRU 5+)

Real-time replay makes it possible to analyze all kinds of deviations on data recorded under realistic conditions and even manipulate these to simulate special situations.

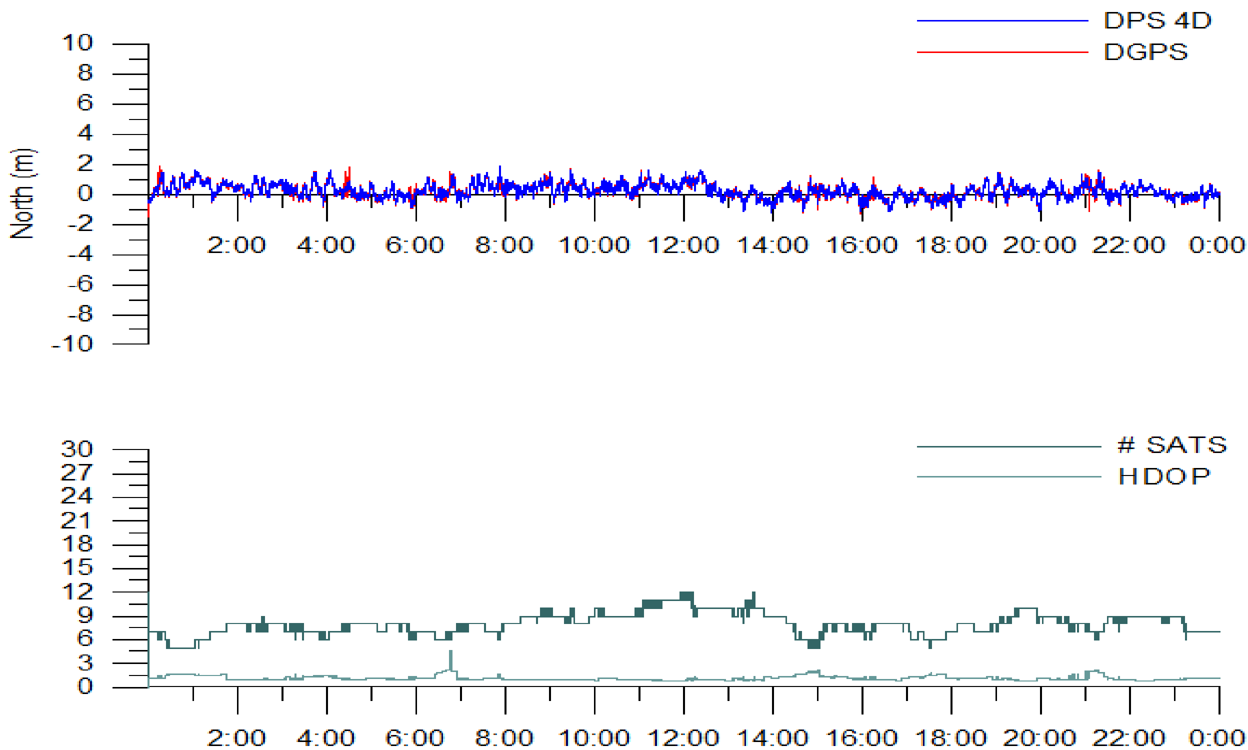


Figure 19: DPS 4D and DGPS, normal conditions

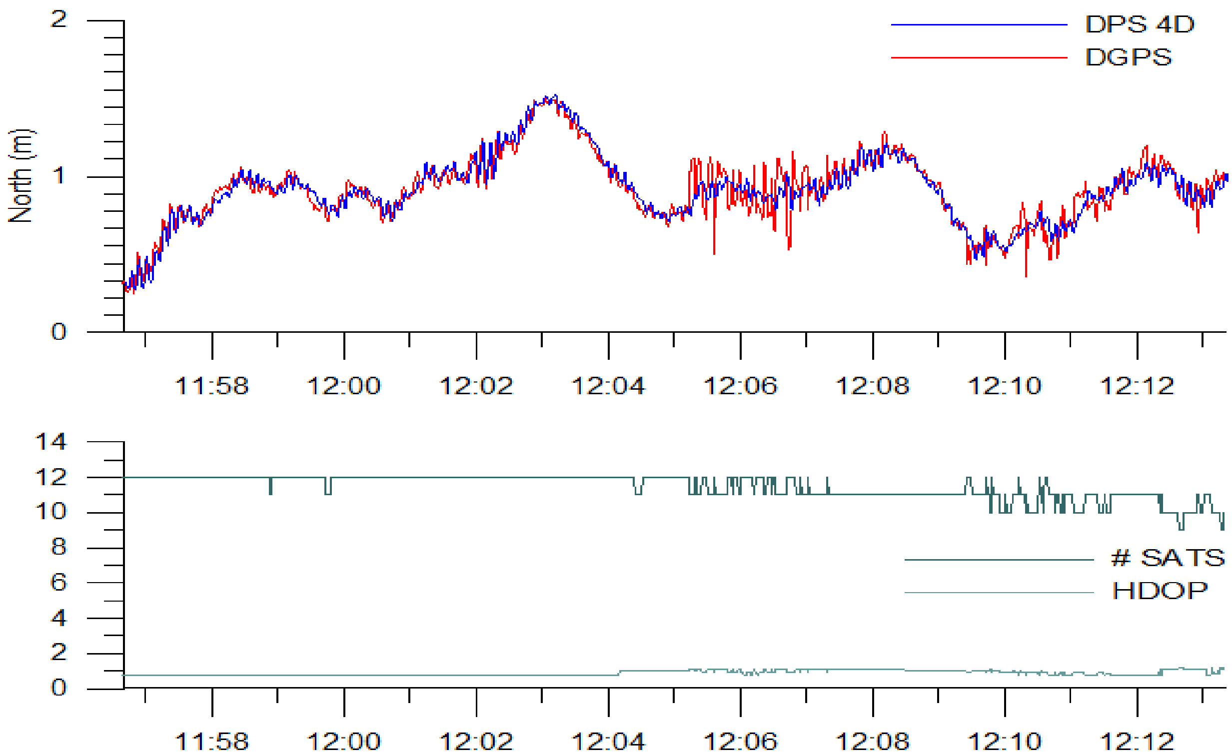


Figure 20: DPS 4D and DGPS, normal condition, zoomed

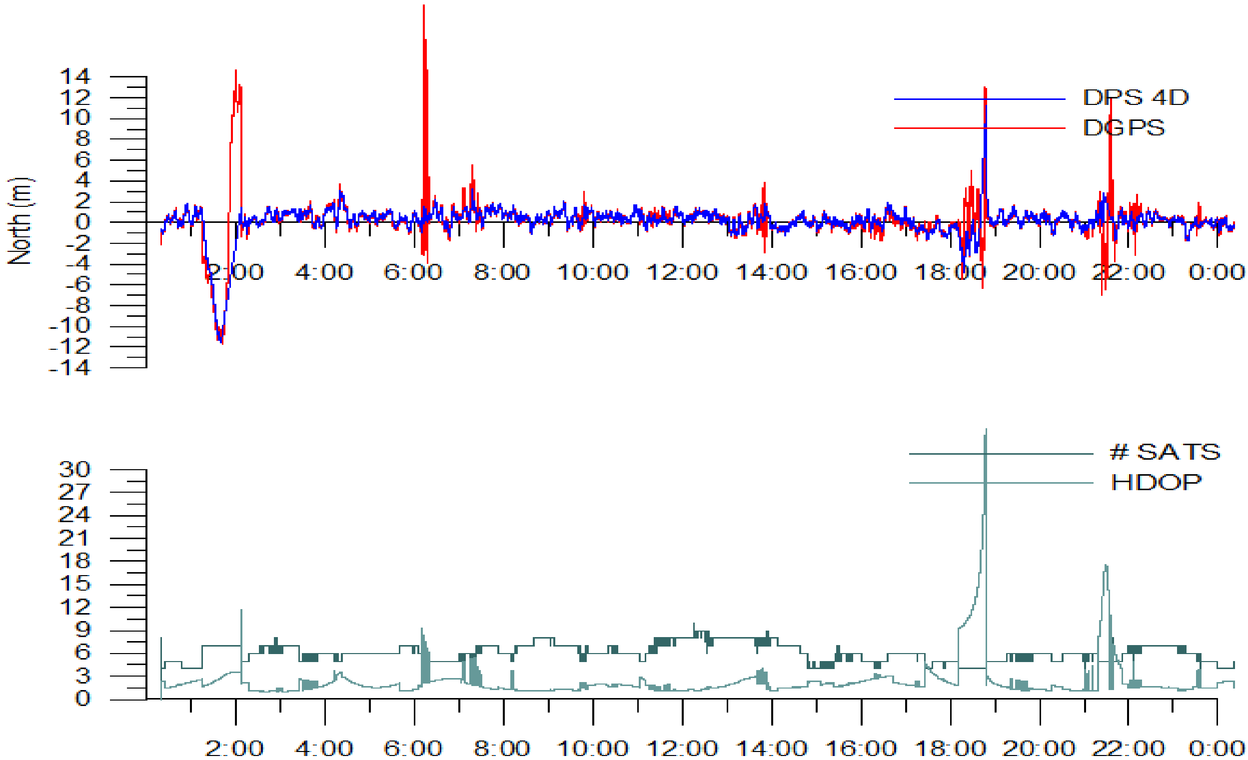


Figure 21: Satellite signal blocking

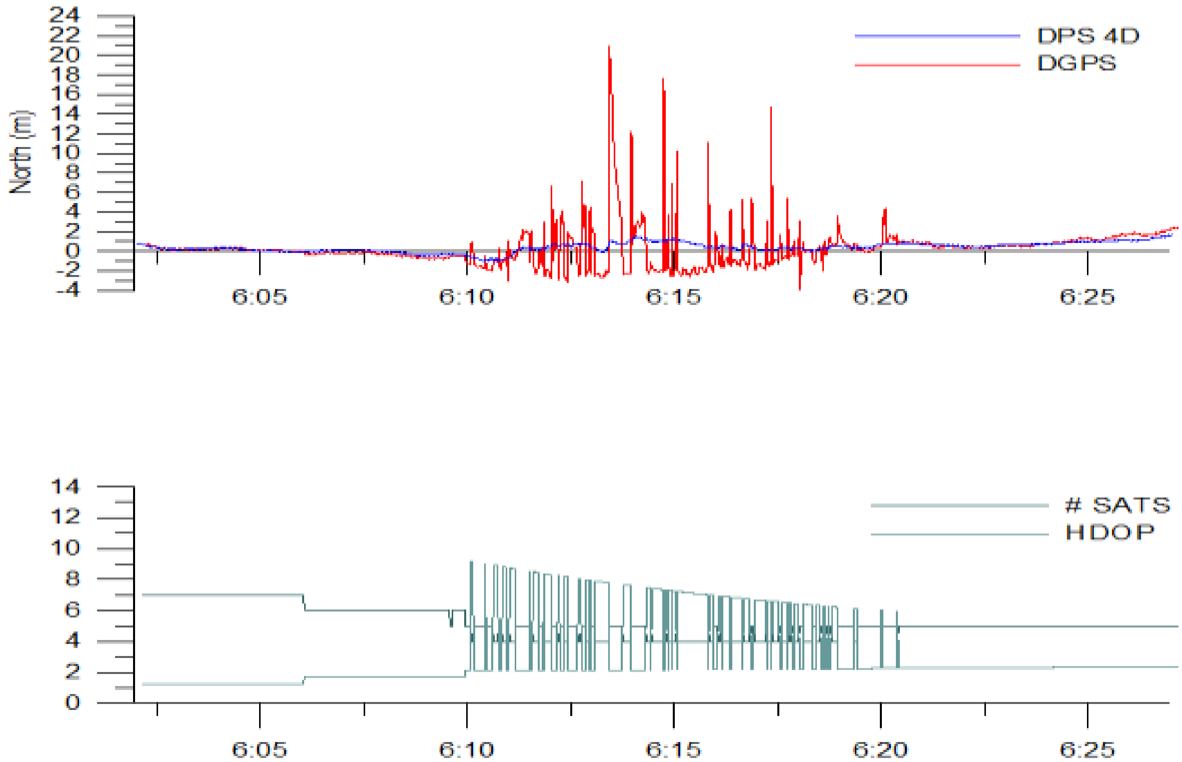


Figure 22: Satellite signal blocking, zoomed

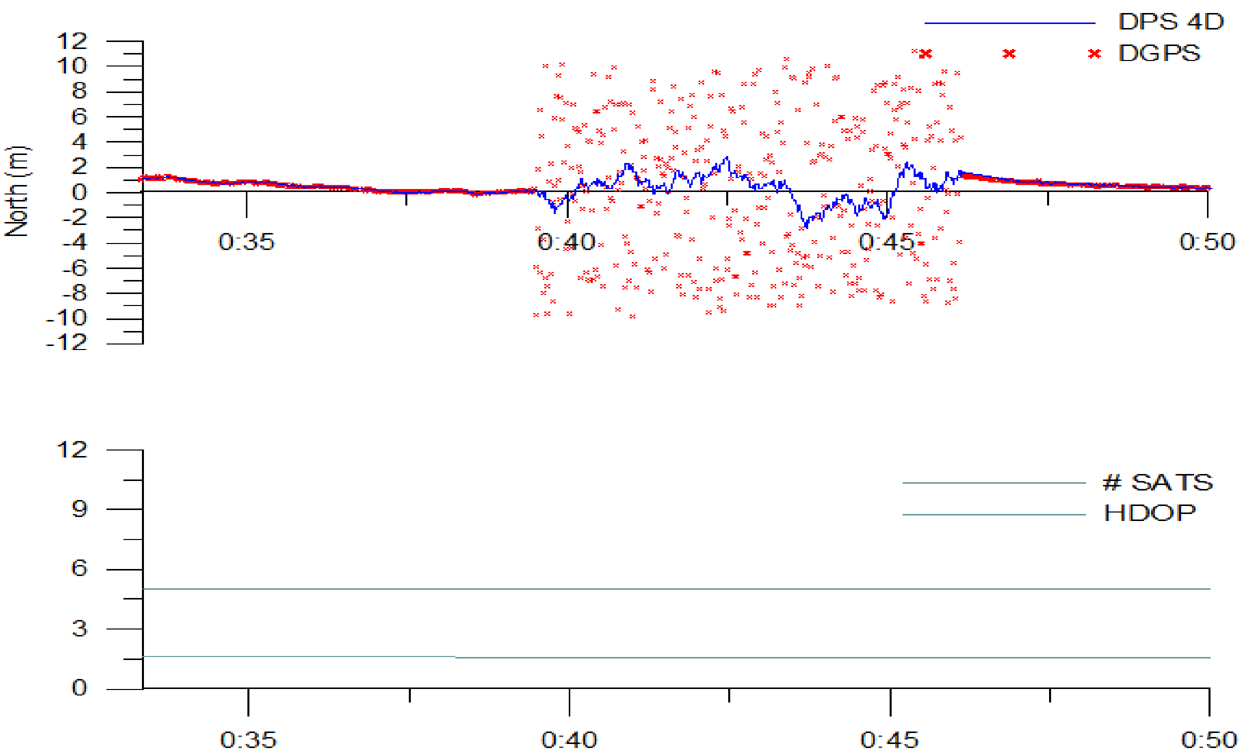


Figure 23: GPS / Glonass measurement noise

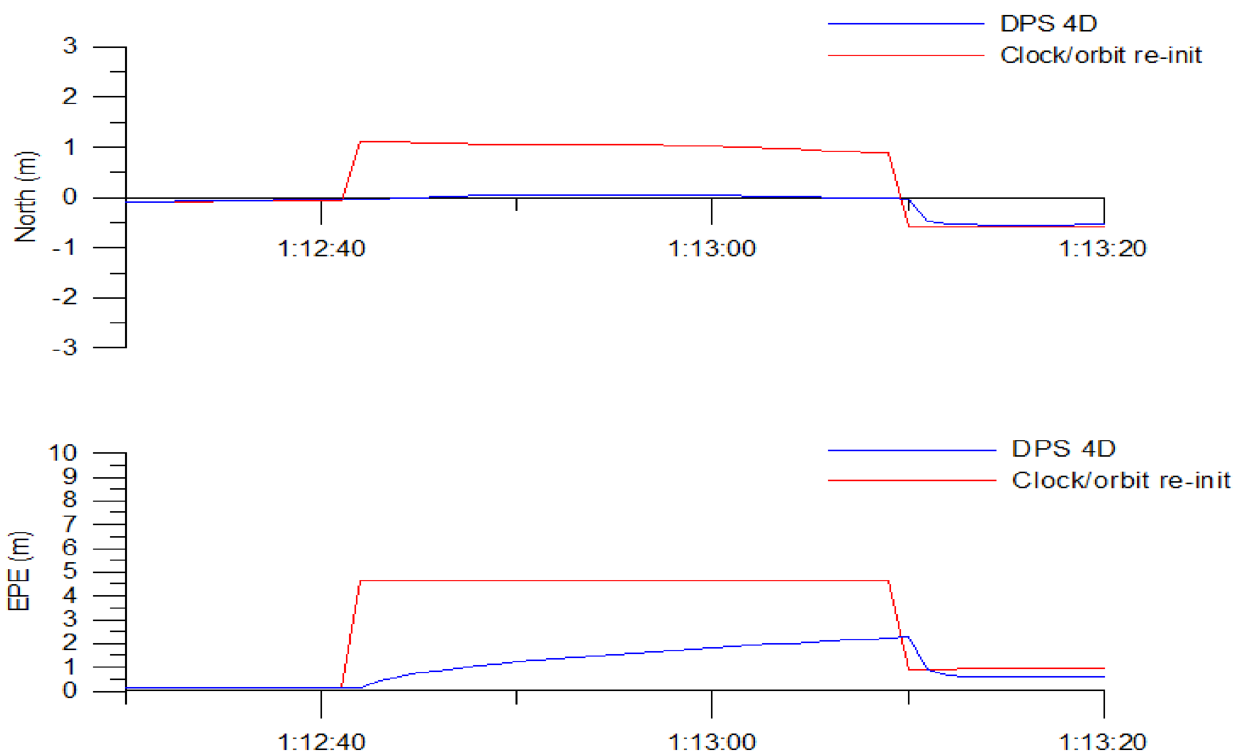


Figure 24: GPS/Glonass clock/orbit re-init

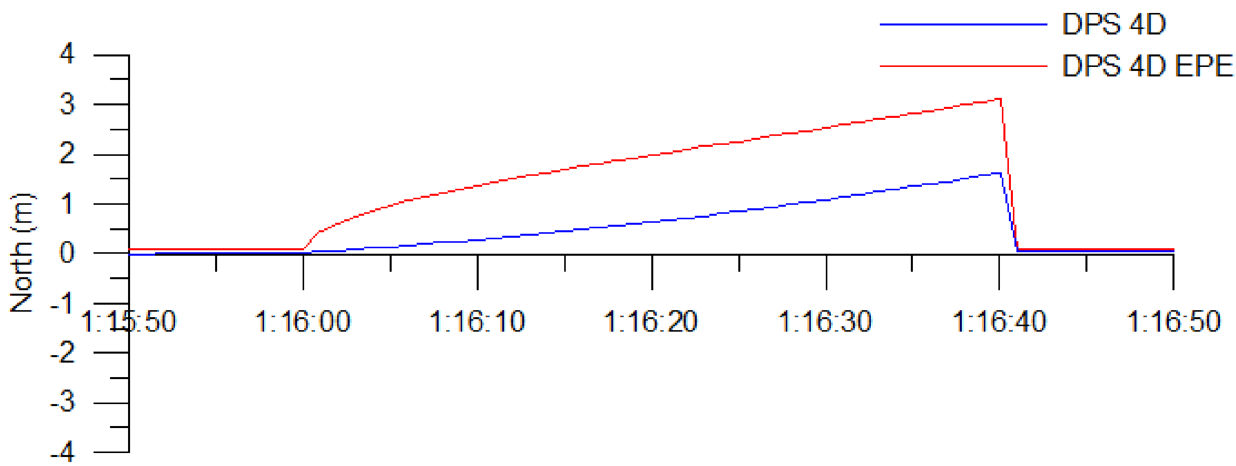


Figure 25: GPS/Glonass loss-of-signal

Installation aspects

Since a hybrid GNSS/IMU system relies on data from two different sensors (GNSS antenna and IMU) that usually cannot be located in exactly the same point, special care has to be taken with regards to installation of such a system. The performance and capabilities of such a system is easily undermined by a careless installation.

All sensors need to be surveyed in a well-defined and uniform vessel reference system with origo in a Common Reference Point (CRP). The MRU 5+ sensor point (X, Y, Z) should be surveyed together with the mounting angles (Roll, Pitch and Yaw). The GPS/Glonass antenna point (X, Y, Z) should also be surveyed.

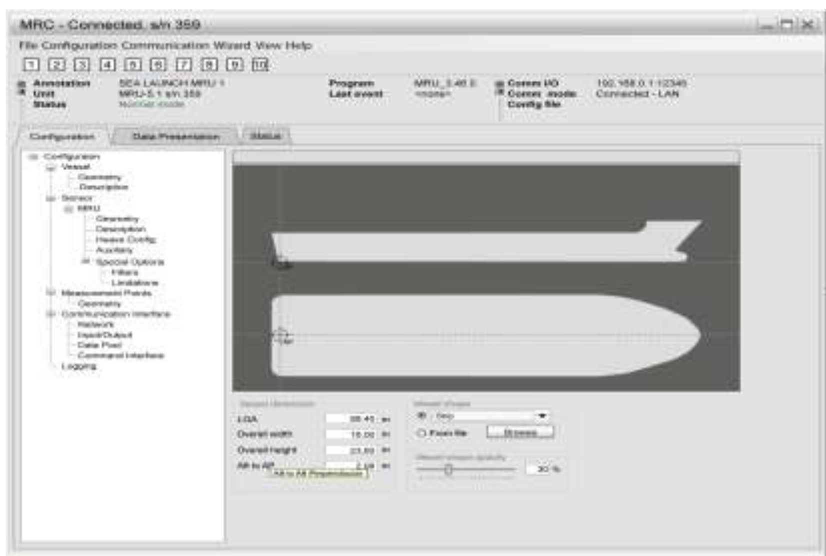


Figure 26: DPS 4D sensor survey assistance display

To maintain the specified accuracy and performance of the DPS 4D, the lever arm vector from CRP to the GPS/Glonass antenna position (X, Y, Z) should be surveyed with an accuracy of < 0.5 m. The lever arm from CRP to the MRU 5+ should be surveyed with similar accuracy. MRU 5+ misalignment angles (Roll, Pitch, Yaw) should be surveyed with an accuracy of < 0.1°.

The quality of a reference system installation is also dependent on the physical location of antennas, cables, lightening protection etc. For installation where redundant GNSS based systems are required, it is usually preferred to locate the GNSS antennas at different locations. This minimizes the risk of a source of interference to become a common failure mode. An example of a proposed configuration is shown in Figure 27.

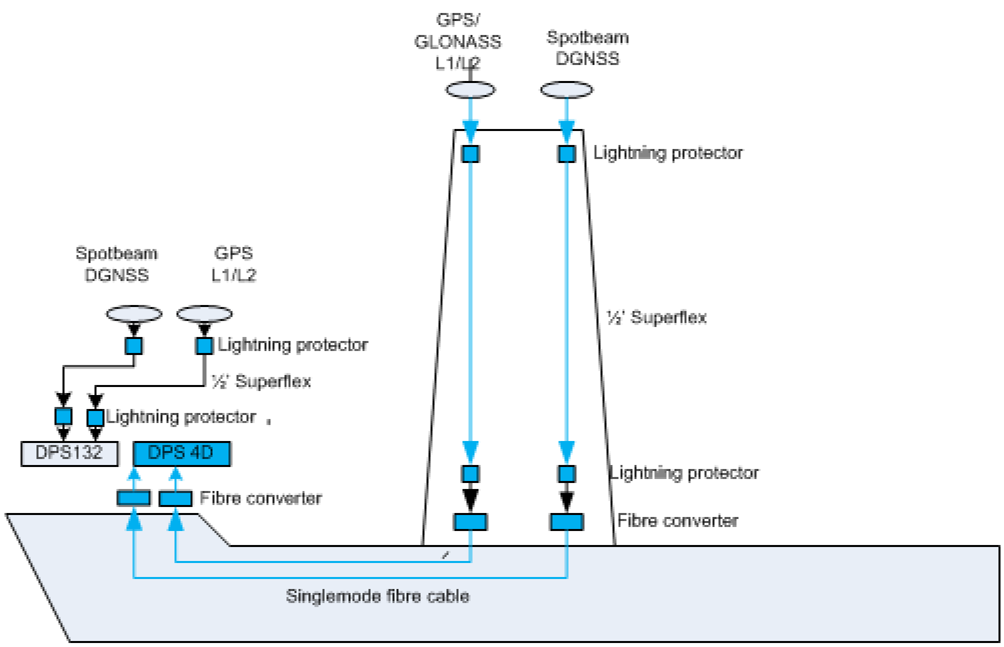


Figure 27: Proposed redundant GNSS installation

Conclusion

The quality of a hybrid GNSS/IMU solution like the DPS 4D needs to be focused during the entire development process. The complexity of the underlying technology and the challenges of integrating these technologies without introducing new failure modes, require extensive testing by using advanced test equipment and thousands of hours of observations under different conditions. The quality of a solution like DPS 4D also depends on the installation of the sensors and installation aspects should be addressed as a part of the quality cycle.

Numerous simulations and tests verify that a hybrid GNSS/IMU solution like the DPS 4D outperforms the most advanced solutions relying only on GPS/Glonass observations. Accuracy under normal conditions is not very different but DPS 4D comes to its right under extraordinary and difficult conditions.