ONBOARD AUTONOMY IN THE SPACE SERVICE VOLUME

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Abstract

The presentation demonstrates the feasibility of on-board autonomous orbit determination using GNSS for spacecraft in transfer to geostationary orbit focusing on chemical and electrical propulsion. GNSS navigation performance is analyzed by HW-in-the-loop tests using different transfer scenarios. Transfer scenarios are derived from realistic spacecraft orbit, attitude and acceleration profiles in particular of the Electra spacecraft, which were kindly provided by OHB Sweden. The HW-in-the-loop tests are done with the Airbus Defence and Space LION Navigator GNSS receiver engineering model (EM) featuring enhanced software and the Spirent Simulator GSS 9000.

1. INTRODUCTION

Autonomous navigation based on GPS receivers is widely used for satellites in low Earth orbits. By missions like Equator S and AMSAT OSAR-40 GPS signals were received and acquired at distances up to 68 800 km (apogee), which encouraged spacecraft and space mission designers to consider navigation at orbits higher than GPS constellation altitude, receiving the spill over the limb of the Earth.

Navigation in GEO using on-board GNSS receivers is foreseen for several geosynchronous satellites, e.g. SmallGEO/SGEO [01] and GOES-R [02]. The first SGEO satellite Hispasat AG1 is flying an Airbus Defence and Space MosaicGNSS Receiver on its communication platform as a first flight test [03].

Preliminary investigation of the requirements and constraints for navigation on the transfer to GEO [04] indicated that GNSS navigation may be feasible, but needs further investigation. New missions emerged for geosynchronous satellites due to the introduction of electrical propulsion for orbit raising and station keeping. Examples are the fully-electrical satellite platforms Boeing B702SP, Airbus Defence and Space Eurostar 3000, and OHB's Electra. For electrical propulsion transfer time to geosynchronous orbit is several months making on-board autonomous navigation during transfer increasingly desirable.

The goal of an ongoing development [04], [05] is to enlarge the application area of the LION Navigator GNSS receiver product line to launch and early operation phases (LEOP) on transfer up to and including the nominal on orbit operation in geosynchronous orbit. The focus of this activity is on electrical transfer to GEO where the improvement of using on-board autonomous GNSS navigation is expected to have a major impact due to the long transfer time of several months in comparison to the few days in case of chemical propulsion.

2. MAIN BENEFIT OVER STATE OF THE ART

Currently, trajectory/orbit determination of launch vehicle and spacecraft in transfer to GEO is performed by S-Band or C-Band TT&C ranging, using ranging antennas on the ground and on-board TM/TC transponders. The increased transfer duration using electrical propulsion (i.e. several months) implies costly scheduling and coordination of operations and maintenance and calibration of the required ground network of widely distributed antennas. By on-board autonomous orbit determination, ground station contacts may be reduced to TM/TC traffic, avoiding the use of tracking antennas, spread all over the world. This is expected, particularly in case of electrical transfer, to result in considerable reduction of overall operational complexity and costs.

The main contribution of this HW-in-the-loop (HIL) simulation campaign is the demonstration of on-board autonomous orbit determination by real time tests using the LION Navigator GNSS receiver EM in electrical transfer scenarios to GEO based on Electra. The transfer scenarios were provided by OHB Sweden. Successful HW tests are essential for the acceptance of on-board autonomous navigation using GNSS in LEOP by potential customers and a last step before flight tests.

3. CHALLENGING PHYSICAL ENVIRONMENT

Challenges to on-board autonomous navigation by GPS stem from the physical environment. Another obstacle to global acceptance presents the formal lack of specifications of signal power and antenna pattern for the upper space environment. This uncertainty has been overcome. First specifications for signal strength and beam width are included in the GPS Block III ICD up to geosynchronous altitude.

Technical challenges are:

- Availability of few measurements, simultaneously only less than 4 SVs above ~ 12 000 km,
- Long gaps between measurements, up to several hours,
- Wide variation of signal strength,
- Extreme range of orbit parameters, possibly distances up to the moon,
- Unfavorable distribution of SVs in main beam as seen from high Earth orbits,
- Varying and unfavorable spacecraft attitude as demanded by thrust vector profile and electrical power generation in particular in all-electrical transfer to GEO.

The challenging environment from 3000 km to GEO altitude has been defined as the Space Service Volume in a joint effort of US Airforce and NASA. Starting with GPS Block III the GPS constellation will be characterized by the following parameters: User Range error (URE), minimum received power, minimum signal availability of the GPS main lobe signal.

These performance specifications are also the basis for a Multi-GNSS SSV. There are currently four GNSS constellations in operation or under deployment, worldwide: GPS of USA, GLONASS of Russia, Galileo of European Union, and BeiDou of China. Combining signals from 2 or more constellations improves visibility and as a consequence accuracy and resilience of the solution. This requires interoperability of GNSS systems. GNSS interoperability is pursued by a number of ongoing bilateral and multilateral, international efforts, such as the International Committee on GNSS (ICG) Most important for Europe is the "EU-US Cooperation on Satellite Navigation", Working Group 10, dating back to 2004, which among others defines transmitting the GPS to Galileo Time off-set (GGTO) in the GPS data message. The benefit to users in the SSV is improved performance and better resilience to potential disruptions of GNSS signals.

4. KEY ISSUES

Figure 1 shows the geometric relationship between a user spacecraft in GEO and/or transfer to GEO (GTO), and the Space Vehicles (SVs) in the GPS constellation. Spacecraft in transfer orbits pass through both the Terrestrial Service Volume (TSV) and the Space Service Volume (SSV) [06].

Satellites in geosynchronous altitude are flying above the GPS constellation. To receive signals that spill around the rim of the earth, the receive antenna of a user satellite in GEO must point downwards to the earth (Nadir direction). The path length from a GPS SV to a user satellite in GEO is approx. 67488 km at 13.9° off-bore-sight angle. This corresponds to a path loss of -167.57 dB.

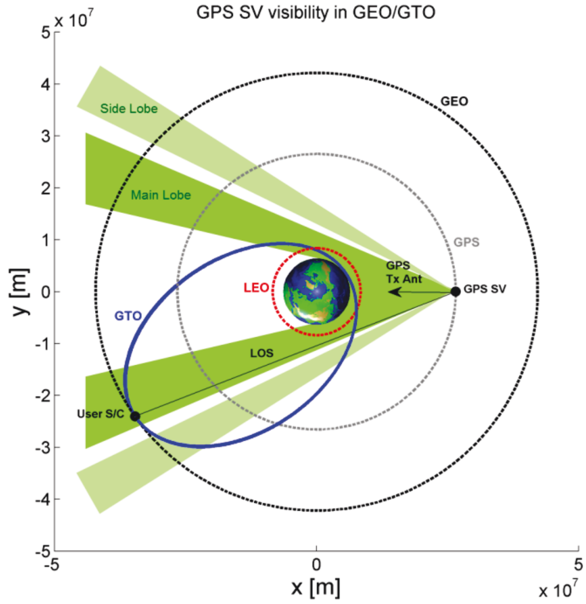

Figure 1: GPS SV visibility in geostationary orbit (GEO) and transfer to GEO (GTO).

The visibility depends mainly on the attitude of the user spacecraft in combination with the mounting of the receive (Rx) antenna(s). Transmit (Tx) antenna side lobe signals may significantly increase the visibility.

In comparison, the path length to a GPS SV from a user in a 500 km earth orbit is approx. 19689 km at 0° off-bore-sight angle, resulting in a path loss of -156.88 dB, which is 10.7 dB more received power. Satellites in GEO orbit require a high gain receive antenna to compensate for the extra signal loss.

In LEO and GEO orbits, Earth pointing orientation of the user spacecraft may be assumed in a first approach to assess navigation accuracy. The user spacecraft is generally aligned with the local-vertical local-horizontal (LVLH) reference frame.

This is not the case in transfer orbits. User spacecraft attitude in transfer orbits is determined by solar power demand and the thrust vector maneuver profiles, which in turn are the results of sophisticated optimization procedures; e.g. for electrical transfer [07], [08]. The effect on a GNSS receiver is a constantly changing field of view with sub-optimal conditions for GNSS signal reception, because the bore sight vectors of the user receive antennas do not always point towards the GNSS constellation satellites. The maneuver profile may change depending on launch vehicle, launch strategy and launch location.

Additional demands on trajectories and navigation accuracy are enforced by collision avoidance during GEO belt crossing. Particularly challenging w.r.t. navigation are low altitudes (< 900 km), and the altitude of GEO belt crossing, which are populated with many operational satellites as well as orbital debris.

To avoid interference with active telecom spacecraft in their GEO slots, the GEO belt with an extension of +/- 75 km in north/south direction and +/- 35 km in radial direction is declared a protected region, only to be entered for insertion into the assigned box.

The optimal placement of the receive antenna(s) depends on the maneuver profile, and may differ for use in transfer and on-station. As indicated in Figure 1, GNSS transmit antenna side lobe signals may significantly increase the signal availability.

5. TRANSFER TO GEO USING CHEMICAL VS ELECTRICAL PROPULSION

There are different types of transfer orbits to GEO, depending among others on the orbit injection type, i.e. the launch vehicle. The main types of transfer orbits are:

- Geostationary Transfer Orbit (GTO), e.g. with Ariane 5 injection
- Super Synchronous Transfer Orbit (SSTO), e.g. with SpaceX Falcon 9 injection

A typical geostationary transfer orbit has an apogee close to but not beyond geostationary altitude. A super synchronous transfer orbit has the apogee significantly higher than geostationary altitude, and generally involves an inclination w.r.t. the Earth's equator. Inclination correction maneuvers are done at apogee for fuel-efficiency.

The actual spacecraft attitude and thrust vector profiles in transfer to GEO may differ significantly depending on:

- the propulsion system (electrical, chemical, hybrid),
- the injection/transfer type (e.g. equatorial GTO, SSTO with inclination), and
- the launch vehicle, launch strategy and launch location.

Up to now, the transfer to geostationary orbit is typically done using chemical propulsion systems with high thrust levels; with chemical propulsion the transfer to GEO typically takes several days and involves a few firings of relatively short duration, e.g. approx. 40 minutes.

For electrical propulsion, the situation is quite different; Electrical thrusters are an interesting alternative for transfer to GEO since they achieve a very high specific impulse (Isp), therefore increasing fuel-efficiency and decreasing the total mass of the satellite. A typical specific impulse is approx. 1600 s for electrical propulsion, compared to approx. 310 s for chemical propulsion. But the relatively low thrust levels, compared to chemical propulsion, imply an almost continuous application of thrust throughout the transfer. A typical thrust level is approx. 0.5 N for electrical propulsion, compared to approx. 400 N for chemical propulsion. The associated transfer duration is typically several months.

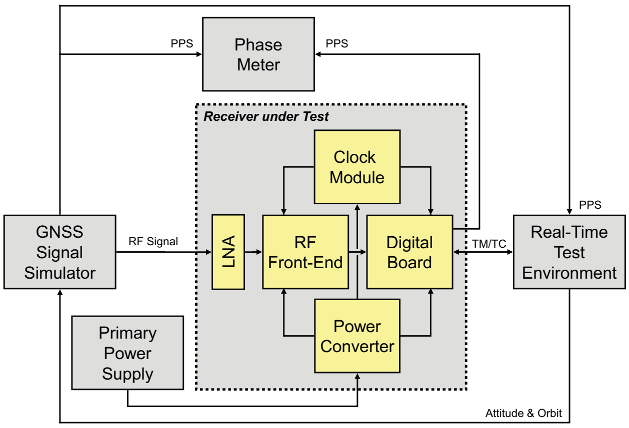

Figure 2: Real-Time Test Environment

The spacecraft attitude and thrust profiles in transfer to GEO using electrical propulsion are the result of complex orbit raising techniques implementing guidance laws optimized w.r.t. fuel consumption and solar power generation; in addition, the thrust vector profile, and therefore also the user spacecraft attitude profile, differ significantly for different orbit injection types, e.g. equatorial GTO or SSTO with inclination.

6. GNSS CONSTELLATIONS, FREQUENCY BANDS, AND SIGNAL SELECTION

The use of GNSS in geosynchronous and higher orbits is facilitated by the availability of GNSS signals from multiple GNSS constellations and upcoming constellation modernizations, e.g. GPS Block III with L2C and L5. The LION Navigator GNSS receiver real-time tests were performed for GPS [09] and Galileo [10] signals generated by the Spirent GSS 9000 signal generator under control of the Real-Time Test Environment, Figure 2.

The Galileo nominal constellation is assumed with 24 SVs. GPS is expected to maintain a constellation with a minimum of 24+3 SVs. The modernized GPS and Galileo constellations offer powerful new signals beyond L1 C/A. The GPS interface specification defines modernized GPS signals, e.g. L2C and L5, and a Space Service Volume (SSV) beyond the Terrestrial Service Volume (TSV). In particular, the transmit antennas' power and reference beam width are specified; c.f. [11], [12].

At the core of the tasks is the isolation of a very weak ranging signal from a jumble of RF signals incident on a satellite antenna in a difficult and greatly varying environment and to use it for navigation in space to bring the satellite safely to its desired target position in orbit and to keep it in the assigned GEO position box.

Based on minimum power, half beam width and chipping rate GPS L5 and Galileo E5a are preferred signals. Faster chipping rate leads to higher band width, higher processing gain, smaller in-band interference, sharper autocorrelation peaks, more precise estimate of the time of arrival, higher accuracy, and smaller errors due to multipath.

L5 and E5a have data and pilot signals which allow for coherent tracking of carrier phase by PLL with 3 dB SNR net benefit. Long codes minimize auto- and cross-correlation side lobes and prevent false signal acquisition. Code length of L5 is 10230 chips and in addition L5 uses Secondary codes with the benefit of reducing cross-correlation peaks further. In addition synchronization of receiver with data bits is supported and the impact of narrow-band interference reduced by 13 dB (important for the operation of electrical thrusters).

The visibility in GEO and GTO is evaluated as percent of time over one characteristic orbit arc assuming one RX antenna in Nadir directions [13]. For the example, the evaluation shows a visibility of over half of the time and the tendency is as expected. Simultaneous use of L5/E5 gives still better visibility.

Signal	L1	E1	L5	E5a
Visibility ≥ 2 at GEO	48%	39%	6%6	85%
Visibility ≥ 2 at GTO	61%	67%	75%	97%

Table 1: Visibility ≥ 2 for GEO and GTO

7. LION NAVIGATOR GNSS RECEIVER

The Airbus Defence and Space LION Navigator product line is a modular family of multi-GNSS-constellation multi-frequency receivers for spacecraft that is space qualified for operation in low Earth orbits and intended for geosynchronous Earth orbits; c.f. [14], [15].

The LION Navigator uses a next generation GNSS core supporting GPS and Galileo, and a powerful LEON2-FT processor architecture. These two elements are combined in a single ASIC, i.e. the AGGA-4. The design goal was to provide 36 single frequency channels, which can be used for multi-frequency purposes. In addition, the LION Navigator hardware and software design is strictly modular in order to facilitate re-use, upgrading, and re-configuration;

The LION Navigator is designed to make at least use of the GPS signals L1, L2C, and L5 and of the Galileo signals E1, and E5a. As long as enough channels are available, all GPS and Galileo satellites in view will be tracked.

The LION Navigator demodulates the navigation data messages of the GPS and Galileo navigation signals and uses this information for determining the spacecraft position, velocity, and time (PVT).

There are two major navigation solution modes:

- The instantaneous kinematic least-square (LSQ) solution requires at least four GNSS satellites in track.
- The dynamic sequential filter solution (Kalman filter) requires at least two GNSS satellites in track.

The dynamic navigation solution implements an extended Kalman filter (EKF) based on highly accurate orbit models and statistical knowledge of process and measurement noise. This Kalman filter solution uses pseudorange and range rate measurements. By using dual-frequency measurements, the ionospheric errors can be effectively eliminated. The filter update is performed using the difference of two measurements. This effectively eliminates the influence of receiver clock errors. This makes the filter vary robust in a wide range of initial conditions and model parameters. An update requires that at least two GNSS satellites are in track. If less than two GNSS satellites are in track the PVT solution is based solely on propagation using the orbit model; this is referred to as signal outage. The Kalman filter models include gravitational forces from Earth, Sun and Moon, as well as solar radiation pressure, air drag. The acceleration due to thruster activation can be applied via TC input.

8. EXTENSION OF THE KALMAN FILTER TO ESTIMATE UNKNOWN ACCELERATION

One major source of error, especially in GTO using electrical propulsion, is the uncertainty in modelling/providing the thrust vector magnitude and direction (misalignment). Therefore, the standard LION Navigator Kalman filter was extended in order to estimate also the unknown/external acceleration vector (x, y, z) due to thrust maneuvers. This increases navigation solution performance, in terms of position/velocity errors, in the presence of considerable thrust errors.

Contributions to acceleration:

- The *total acceleration* acting on the user spacecraft is the combination (sum) from various perturbation forces acting on the spacecraft. Some of these perturbations are modelled in the Navigation module, e.g. gravity of Earth, Sun, Moon, Solar radiation pressure, air drag.
- The *external acceleration* from thrust maneuvers is generally commanded via TC and used as additional part in the total acceleration.
- The *empirical acceleration* is the unmodelled acceleration acting on the spacecraft which we try to estimate. In the case of continuous thrust maneuvers in GTO, the empirical acceleration is expected to be mostly due to the un-commanded thrust acceleration, i.e. error in the thrust acceleration commands.

The electrical acceleration vector (x, y, z) in spacecraft body frame is estimated when GNSS updates are possible (> 2 SVs in track).

Since the acceleration remains approx. constant, the estimate of the acceleration vector is expected to improve the navigation solution performance, especially during signals outages when the PVT is propagated.

9. ELECTRA GTO AND GEO TEST SCENARIOS FOR REAL TIME HIL SIMULATION

Table 2 specifies the reference GNSS constellations used as baseline for the tests. Differences are the number of SVs in the GPS constellation and only main lobe or main and side lobes are uses. Reference GNSS constellation 1 is a conservative approach considering the reduced SV/signal availability for a launch planned in 2019, based on assumptions from 2015, and main lobe only for increased conservatism. Reference constellation 2 is a favorable approach considering the full constellation availability and also side lobes.

Reference Constellation	GPS L5	Galileo E5a
Constellation 1 (conservative): Reduced constellation (planned launch in 2019)	18 SVs Main lobe only	21 SVs Main lobe only
Constellation 2 (favorable): Full constellation availability with side lobes	24+3 SVs Main and side lobe	24 SVs Main and side lobe

Table 2: Reference GNSS constellations for the HW tests.

The test scenarios used are selected subsets of the Electra transfer trajectories, since the whole transfer phase is too long for real-time HW tests.

The scenario data were provided by OHB and comprise user spacecraft orbit, attitude, and thrust profiles.

The transfer scenarios are based on the following launch vehicles:

- **SSTO with Falcon 9 injection**: The initial orbit perigee height is approx. 250 km, the apogee is approx. 71322 km (i.e. well above GEO height). C.f. scenario in Figure 3.
- **GTO with Ariane 5 injection**: The initial orbit perigee height is approx. 250 km; the apogee is approx. 35670 km (i.e. approx. GEO height). C.f. scenarios in Figure 4, Figure 5, Figure 6.

The baseline is to use multi-constellation (GPS and Galileo) single-frequency signals, i.e. GPS L5 and Galileo E5a, and a single receive antenna.

The receive antenna is mounted in spacecraft body frame +X axis for all transfer orbits (green arrow). For comparison, the receiver antenna for use on-station in GEO is mounted in spacecraft body frame +Z axis, i.e. Nadir-pointing.

The navigation solution baseline is the standard Kalman filter. Some tests used the (new) extended Kalman filter estimating also the external acceleration vector; c.f. Table 2. The signals travelling through the ionosphere are excluded in the GNSS receiver by using a mask over the Earth, assuming 600 km ionosphere height.

The following data TCs need to be sent throughout the test, generally every second:

User spacecraft attitude: quaternions from earth-centered inertial (ECI) to spacecraft body frame.

External acceleration due to thrust maneuvers: acceleration in (x, y, z) w.r.t. ECI.

The electrical thrusters are mounted in spacecraft body frame –Z axis and provide a total, constant thrust of 540 mN (specific impulse Isp = 1624 s) in +Z direction w.r.t spacecraft body frame. All electrical transfer orbits assume constant thrust with 540 mN in spacecraft body +Z direction throughout the test duration (electrical thruster is continuously ON). Errors in the commanded thrust w.r.t. the real thrust used in the spacecraft reference propagation are considered with 1% error on the thrust levels.

10. RESULTS

The HW-in-the-loop (HIL) tests were done with the Airbus Defence and Space LION Navigator GNSS receiver engineering model (EM) featuring enhanced software. The LION Navigator was configured in single-frequency mode using GPS L5 and Galileo E5a with up to 36 channels. The Spirent RF signal simulator (GSS 9000) was used to simulate GNSS signals and the receive antenna.

The results Electra for GTO B5 week 1 day 1 based on Falcon 9 injection are shown in Figure 8. The perigee is passed two times (one full orbit of approx. 24 h). Signal outages are the main performance driver when using main lobe only. The signal outages are greatly reduced by using side lobes. The signal outages (< 2 SVs tracked) are reduced by using side lobes. When the extended Kalman filter is used, estimating also the external acceleration, the performance is improved significantly (using main lobe only).

The results for Electra GTO C1 week 1 day 1 based on Ariane 5 injection are shown in Figure 7. The perigee is passed 3 times (two full orbits of approx. 10.5 h), resulting in spikes of higher number of tracked GNSS SVs. During the rest of the orbit, signal outages are the main performance driver. When the extended Kalman filter is used, estimating also the external acceleration, the performance is slightly improved, but only after the first orbit (using main lobe only).

The results for Electra GTO C1 week 9 day 1 based on Ariane 5 injection are shown in Figure 9. The performance is mainly driven by one long signal outage. The performance is improved by using side lobes. Corresponding simulation tests suggest a significant improvement in performance by using the new extended Kalman filter with estimation of the external acceleration vector.

The results for Electra GTO C1 week 15 day 1 based on Ariane 5 injection are shown in Figure 10. The performance is mainly driven by one very long signal outage (approx. 16 h). The performance is not improved significantly by using side lobes. The signal outage starts soon after the thrust maneuver. This short duration of valid measurements was not enough to estimate the external acceleration. Therefore, using the estimation of the external thrust did not improve the performance in this case as shown by corresponding simulations. In this scenario, using a second receive antenna could improve the GNSS SV visibility and therefore the performance.

For comparison, results in GEO with a nadir-pointing receive antenna and without thrust/attitude maneuvers are shown in Figure 11. Signal outages are the main performance driver if only the main lobe is used. No signal outages occur when using side lobes and the navigation solution performance and settling time are considerably improved.

11. CONCLUSION

In the course of this work, the orbit determination performance of the Airbus Defence and Space LION Navigator GNSS receiver in transfer to GEO is analyzed by HW-in-the-loop tests using electrical transfer scenarios. These electrical transfer scenarios are derived from realistic spacecraft orbit, attitude, and acceleration profiles of the Electra spacecraft.

The HW-in-the-loop tests are done with the LION Navigator GNSS receiver engineering model - featuring an enhanced sensor and navigation software - and the Spirent signal simulator.

The LION Navigator was configured in single-frequency mode using GPS L5 and Galileo E5a. Acquisition and tracking based on L5/E5a was performed with sufficient stability in all scenarios.

Signal acquisition and tracking behavior is better than expected with an observed min. acquisition limit < 27 dB-Hz and a min. tracking limit < 25 dB-Hz.

As a baseline, only the GNSS transmit antenna main lobe is used for conservatism. Side lobes are considered separately as possible yet unreliable improvement.

This provides a sound analysis of achievable in-orbit performance under the stringent conditions of the transfer to GEO with electrical propulsion. In particular, the navigation performance is achieved under the varying user spacecraft orientation conditions, as required by the optimal thrust vector guidance laws and solar power generation.

The main drivers for performance in transfer to GEO are signal outages due to the spacecraft attitude in combination with the imperfect knowledge of the thrust maneuvers, assuming 1% error in the commanded thrust levels. This situation was improved by estimating the propulsion system behavior in the extended Kalman filter. For this purpose, the Kalman filter of the LION Navigator was adapted to estimate also the unknown external acceleration vector, i.e. the error in the commanded thrust vector. The estimation of the external thrust may improve orbit determination performance, especially in the presence of signal outages, when the knowledge of the external acceleration is used to improve the propagation of the state vector. The estimation of the external thrust generally increases the navigation solution settling time.

An important finding is that navigation in transfer to GEO may be performed with one single receive antenna. Using a second receive antenna could improve the GNSS SV visibility and therefore the performance for specific parts of the transfer, but it increases the complexity and cost of the GNSS navigation system. An additional nadir pointing antenna is required.

This study confirmed that GNSS-based orbit determination performance strongly depends on the particular ascend scenario. For an optimal design of the navigation system it is mandatory not only to know the trajectory but also the performance required along the trajectory for fuel-efficient guidance and collision avoidance.

It is to be noted that, in case of using star attitude sensors, the spacecraft position is needed for conversion of the attitude from the inertial to the Earth-referenced system. Hence, the accuracy of the spacecraft position impacts the accuracy of the attitude and therefore the performance of the thrust vector alignment.

12. ACKNOWLEDGEMENTS

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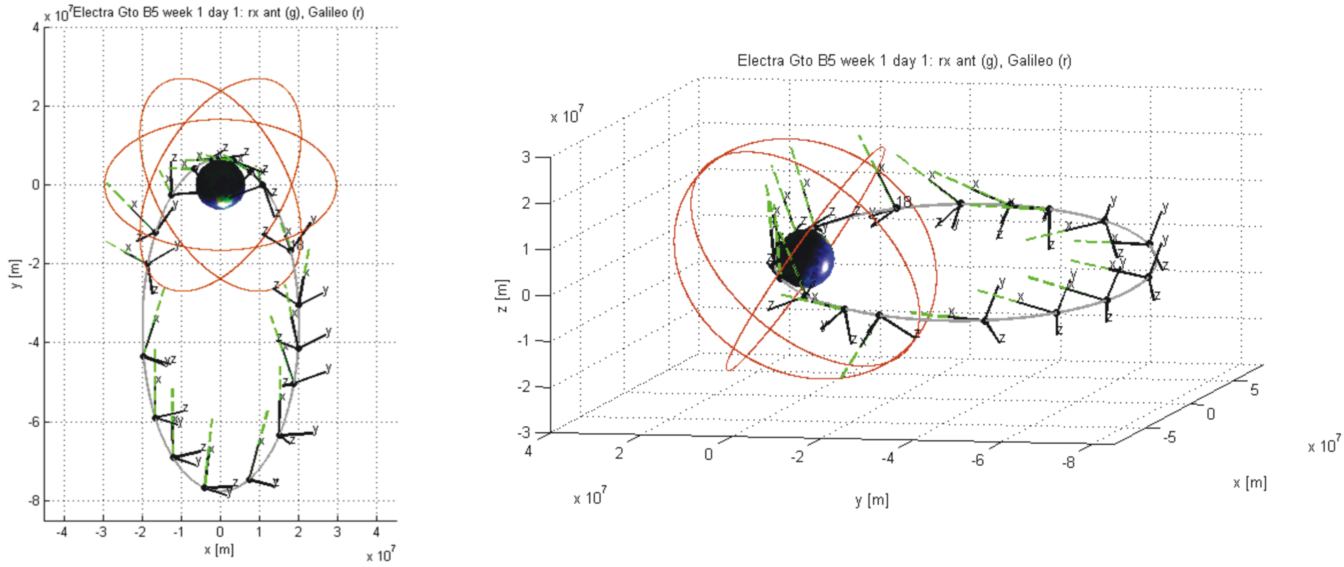

Figure 3: Electra GTO Week 1 Day 1 with Falcon 9 injection (top view, side view)

This test case is the first day after launch with approx. 24h orbit period. Of specific interest here is the tracking and PVT performance at high altitudes followed by the long visibility gap afterwards.

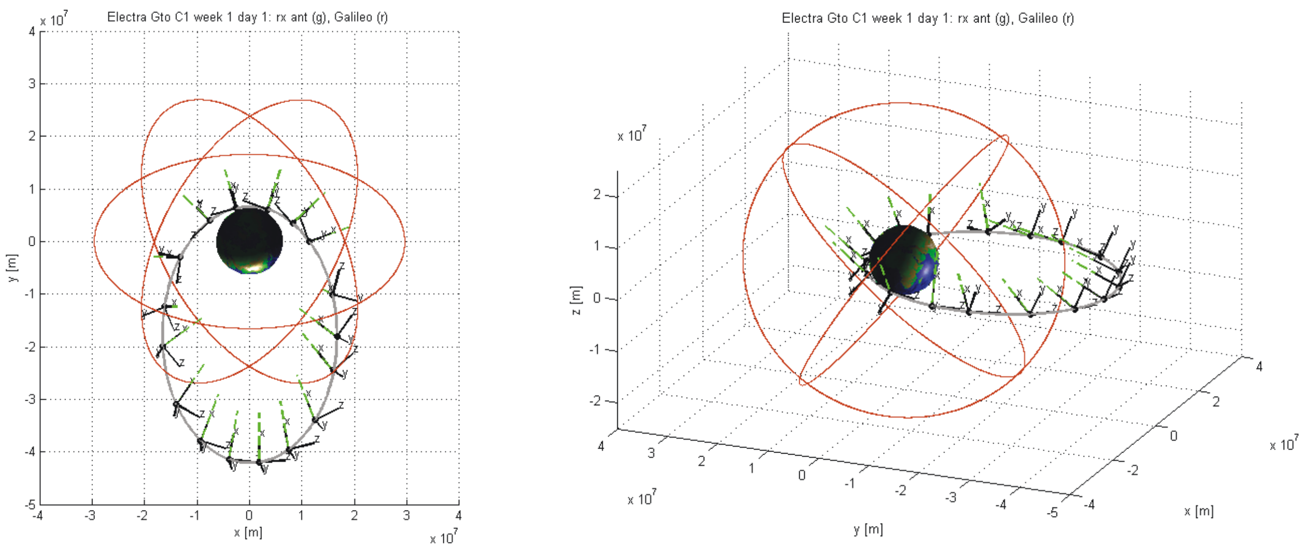

Figure 4: Electra GTO Week 1 Day 1 with Ariane 5 injection (top view, side view)

This test case is the first day after launch with approx. 10.5h orbit period. It covers altitudes from LEO (perigee) to approx. GEO height (apogee).

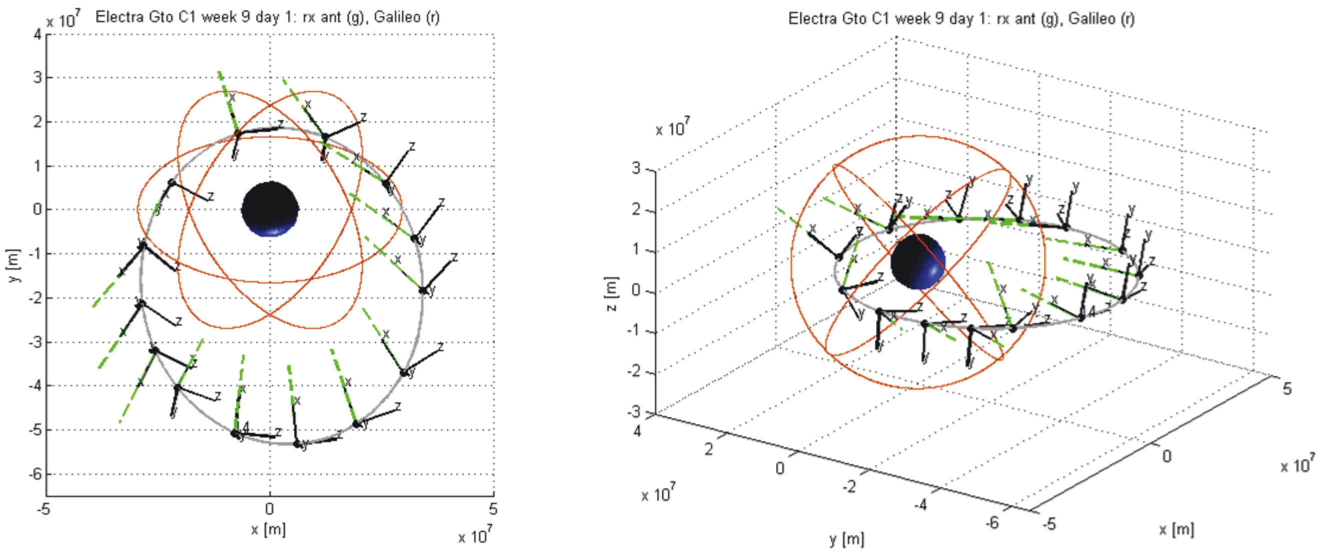

Figure 5: Electra GTO Week 9 Day 1 with Ariane 5 injection (orbit period approx. 19h) (top view, side view)

This test case involves an increased perigee still below the GNSS constellations which is of interest w.r.t. the possible near-far effects (especially when the user spacecraft is crossing the GNSS orbit height).

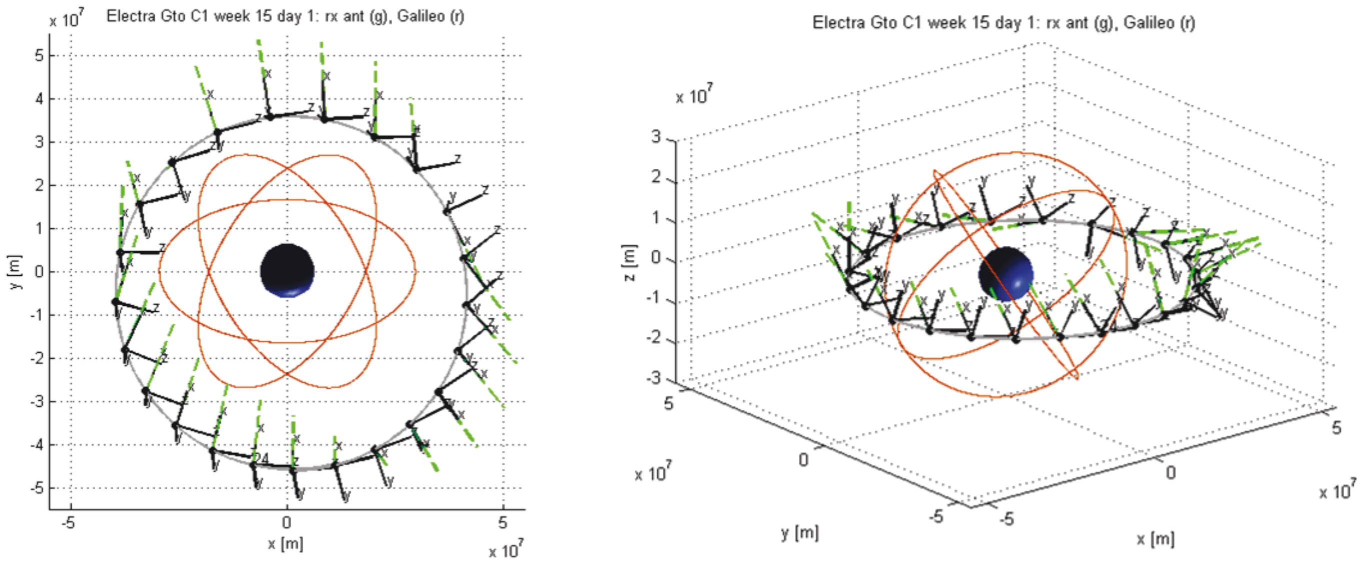

Figure 6: Electra GTO Week 15 Day 1 with Ariane 5 injection (orbit period approx. 23h) (top view, side view)

The orbit height is already close to GEO, and there are long visibility gaps due to the spacecraft attitude profile (i.e. eccentricity reduction manoeuver with an approximately inertially fixed attitude).

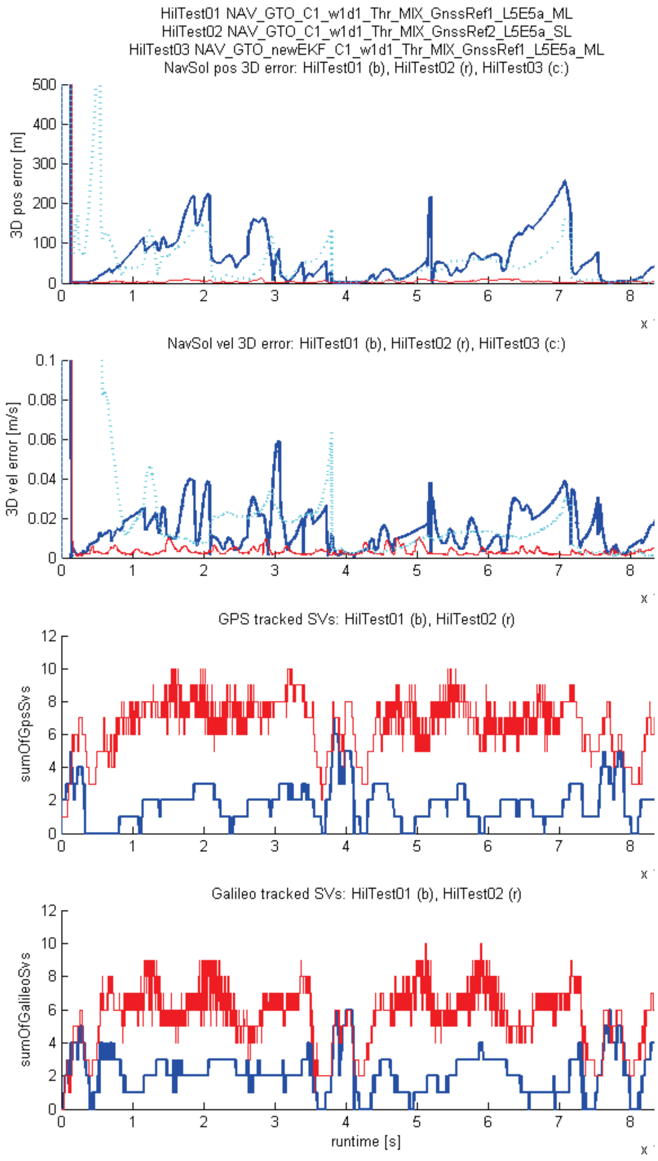

Figure 7: Comparison of HilTest 01, 02, and 03

Electra GTO C1 week 1 day 1, based on Ariane 5 injection; using GPS L5 and Galileo E5a; using the standard Kalman filter with GNSS reference constellation 1 (blue) and 2 (red); using the extended Kalman filter with estimation of the external acceleration with reference constellation 1 (cyan).

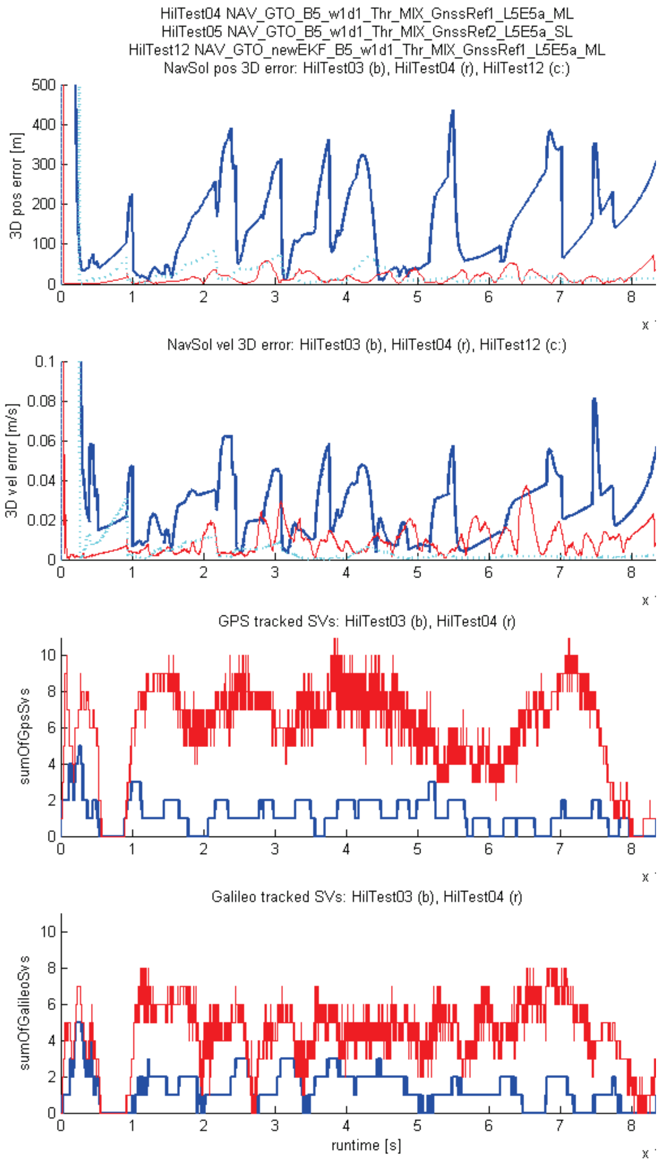

Figure 8: Comparison of HilTest 04, 05, and 12

Electra GTO B5 week 1 day 1, based on Falcon 9 injection, using GPS L5 and Galileo E5a; using the standard Kalman filter with GNSS reference constellation 1 (blue) and 2 (red); using the extended Kalman filter with estimation of the external acceleration with reference constellation 1 (cyan).

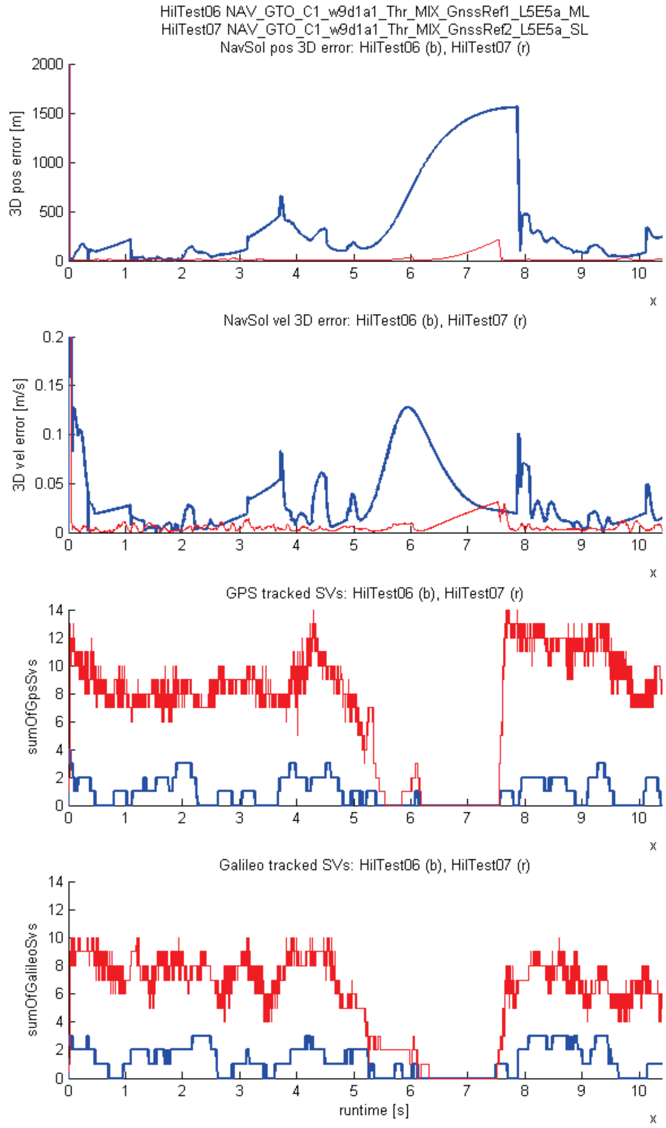

Figure 9: Comparison of HilTest 06 and 07

Electra GTO C1 week 9 day 1, based on Ariane 5 injection, using GPS L5 and Galileo E5a; using the standard Kalman filter with GNSS reference constellation 1 (blue) and 2 (red).

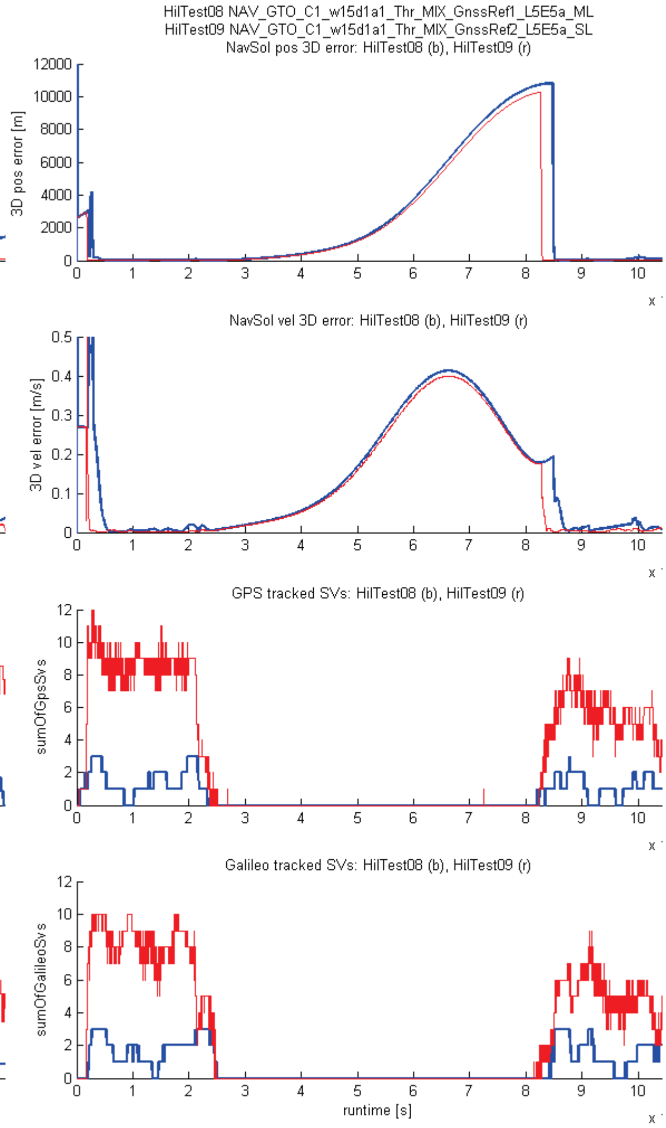

Figure 10: Comparison of HilTest 08 and 09

Electra GTO C1 week 15 day 1, based on Ariane 5 injection, using GPS L5 and Galileo E5a; using the standard Kalman filter with GNSS reference constellation 1 (blue) and 2 (red).

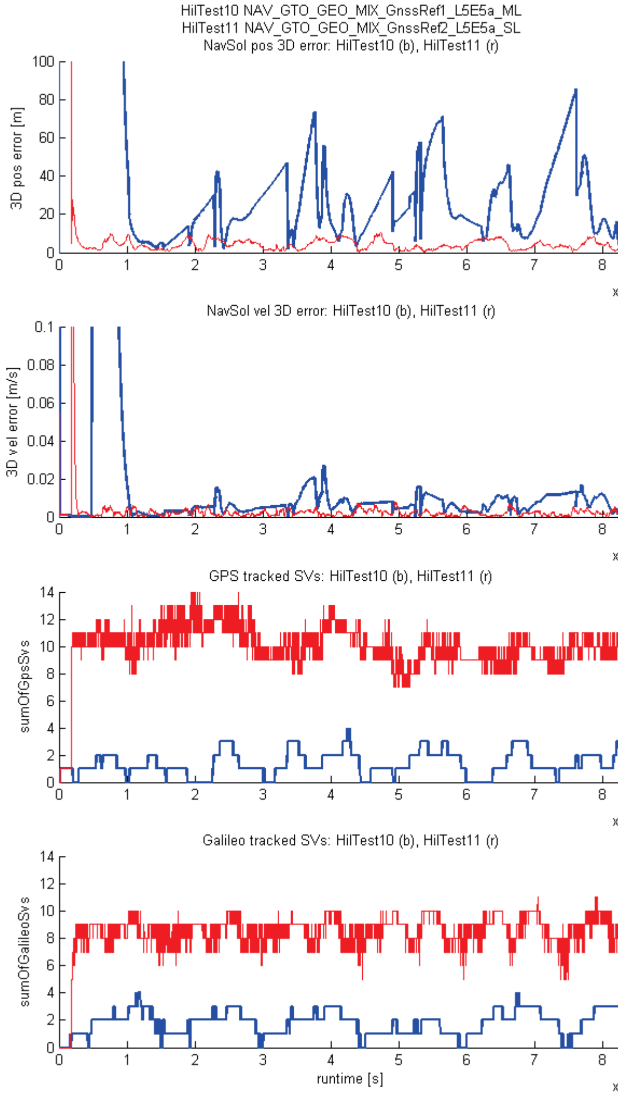

Figure 11: Comparison of HilTest 10 and 11

GEO (on-station, no maneuver, Nadir-pointing) using GPS L5 and Galileo E5a; using the standard Kalman filter with GNSS reference constellation 1 (blue) and 2 (red).