AAS 10-038

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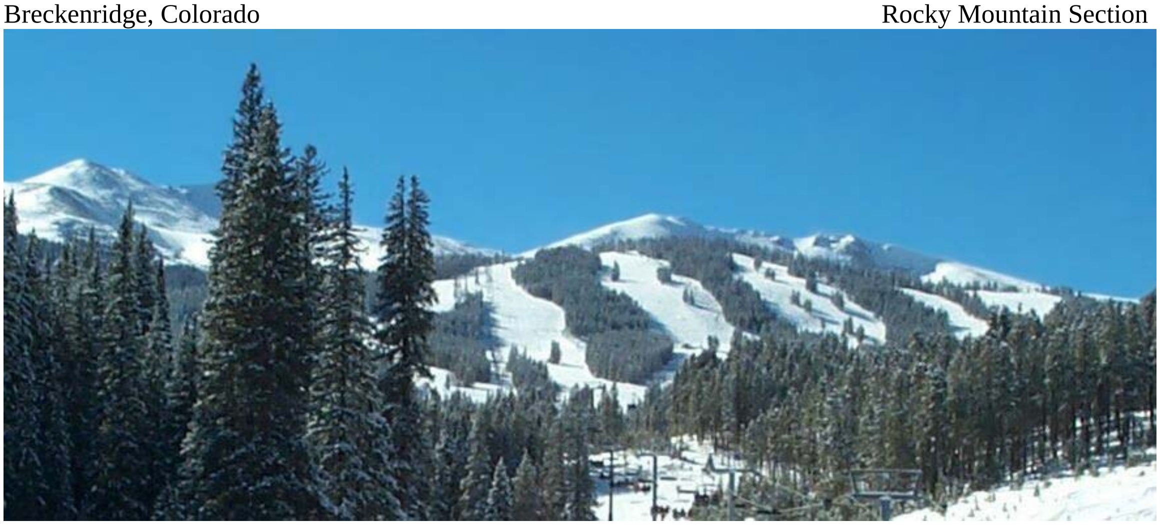

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This paper deals with the preparation of the Small GEO mission and the accommodation of a GPS receiver as an experiment. The expected benefits of using the GPS receiver for Small GEO are explained. The feasibility of using GPS for position determination is investigated by simulation using a MosaicGNSS receiver, which was stimulated by a Spirent RF signal generator. A procedure, how to evaluate flight data on ground is outlined. Success criteria of the experiment and the minimal size of the downlink stream required and reserved for the receiver TM are presented.

INTRODUCTION

Already in 2002 the geosynchronous test satellite STENTOR carried a GPS receiver onboard. Unfortunately a launcher failure destroyed the mission and the hope to open a new era in the field. Ten years after, the telecommunication satellite Small GEO which is planned to be launched in 2012 will carry again a GPS receiver as an experiment onboard. This will then be a novelty, and it is a consequence of the rapidly growing interest of satellite operators for further optimizing operations. Once the feasibility to use GPS signals in 36.000 km altitude for satellite position determination is proven in orbit, the expectations of the satellite operators are to reduce ground infrastructure complexity and ground station involvement i)during the 15-years mission life time, ii) by reducing the cost intensive GTO phase with several ground stations collaborating in a network in order to track the satellite, iii) by increasing the mission safety through less man-machine interactions, i.e. higher satellite autonomy.

Beyond these advantages, the Small GEO mission has some further motivation to fly a GPS receiver: First, the satellite will rely fully on electrical propulsion thrusters to perform the long lasting station keeping maneuvers, At least a full day without any maneuver is necessary every week to determine the satellite position from ground with sufficient accuracy. We are confident, that the future use of a GPS Receiver onboard the satellite will radically change this situation. Second, Small GEO does not use an Earth sensor but a star tracker and the onboard estimated position to determine the Earth pointing angle. This means, knowledge of the position has a direct impact on the pointing budget as well and therefore it has to be higher than in the case of a direct Earth vector measurement.

The paper will deal in detail with the expected benefits of using the GPS receiver for Small GEO. Another challenge is to select the significant parameters to be transmitted to the ground via telemetry without disturbing the platform TM downlink stream.

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THE SMALL GEO MISSION

Mission Objective

The Small GEO telecommunications satellite is a new development by a consortium led by OHB-System AG under overall management of the European Space Agency (ESA) to fill a niche in the telecom satellite market for small platforms weighing about 1.5 tons and targeting payloads of 300 kg and 3 kW. The platform design provides the capability for direct injection into geostationary orbit as well as injection into Geostationary Transfer Orbit (GTO), both with high mass efficiency. In GTO configuration, the platform will weigh approximately 2.5 tons. The platform is compatible at minimum with the following launchers: Ariane 5 (secondary passenger under Sylda), Soyuz GSC (from Guiana Space Centre), LandLaunch and Proton from Baikonour, as well as Atlas V. Potential future launchers like GSLV MkII, Falcon 9, and Angara 3A are considered as well.

The prime contractor for Small GEO is OHB-System AG (Germany). The Swedish Space Corporation (Sweden) is a partner in the consortium and supplies the AOCS and EP subsystems as well as the EP-based mission analysis. The other partners are RUAG AG (Switzerland) and LuxSpace Sàrl (Luxembourg).

The project for platform development, ESA's ARTES 11, is currently in the implementation phase (Phase C/D). Negotiations are complete for nearly all equipment. The first Structural and Thermal Models arrive in 2009 and the first Engineering Models will arrive in early 2010. The first release of the AOC Core software flight code was in October 2009. Launch is expected in 2012.

The contract for the first commercial mission was signed in November 2008 between ESA and HISPASAT S.A (Figure 1). The second mission is currently under development.

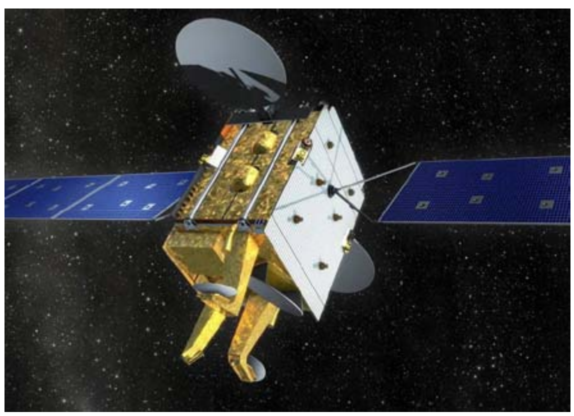


Figure 1. Hispasat AG1 (OHB-System)

The first Small GEO mission will be the HISPASAT Advanced Generation satellite (Hispasat AG1). Its main payload of Ka-band transponders will serve Spain, Portugal, the Canary Islands, and America. An advanced Ku-band payload will also be carried. It will also carry a GPS receiver as a demonstrator.

The satellite will be launched into a Geostationary Transfer Orbit. A bi-propellant system on-board will provide the injection into geosynchronous orbit. Final orbit transition and placement is however performed with the Electric Propulsion (EP). Electric propulsion is then used for all nominal station-keeping and momentum management for the entire lifetime of 15 years.

Platform

The Small GEO platform is in many ways a conventional telecom platform but with a number of unique characteristics that make it one of the most advanced telecom platforms on the market. The structure is built around a conventional central tube. The MMH (Mono-Methyl Hydrazine) and MON (Mixed Oxides of Nitrogen) tanks are inside the central tube, while the two GHe (Gaseous Helium) pressurant tanks and the two Xenon tanks are mounted outside the tube. The rest of the Platform Module is built around the bottom of the central tube. The Payload Module is mission specific and fits onto the top of the Platform Module. The Liquid Apogee Engine which will be used for GEO transfer is mounted on the bottom of the satellite.

The platform relies upon EP for station-keeping and angular momentum management. Therefore, there are only four nominal and four redundant 10N chemical propulsion thrusters. Chemical propulsion is only used with the Liquid Apogee Engine for transfer to geostationary orbit. The Electric propulsion is much more efficient, but has a much smaller thrust (44 mN to 75 mN) resulting in more firing time. The electric propulsion must be fired for 2-4 hours per day as opposed to the chemical propulsion which is only fired for few minutes every few weeks.

In fact, two EP thruster assemblies will be flown. The primary system is a new development called HEMP-T which promises high impulse and long life. The back-up system is based upon the proven SPT-100 EP thruster which has flown on numerous satellites for several decades. The eight EP thrusters are mounted in pairs on the East and West panels with thrust directions symmetrically ordered around the nadir direction (Figure 2). In nominal operations each thruster has thrust vector components in the directions orthogonal to the orbital plane and tangential to the satellite velocity vector.

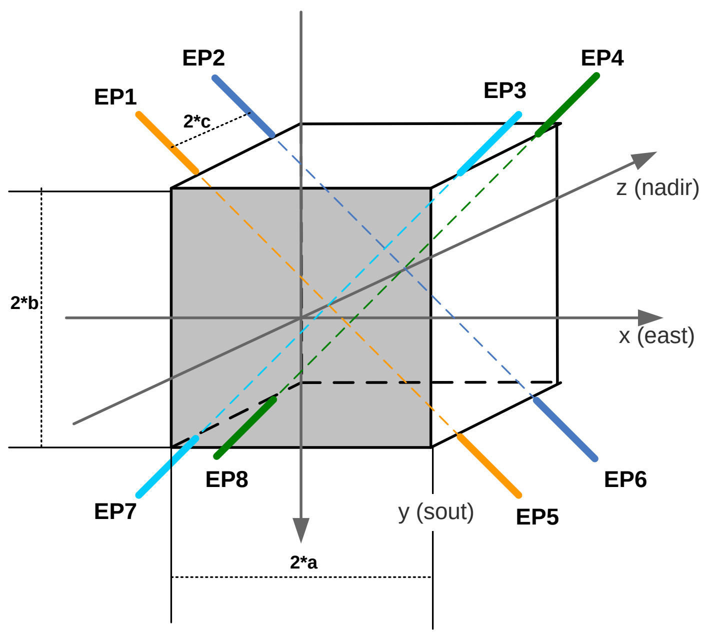


Figure 2. EP Thruster Configuration

The platform relies upon star trackers for Earth pointing; no Earth sensor is carried. This simplifies the system drastically. Highly accurate sun sensors are replaced by coarse sun sensors used only for safe modes. The highly accurate sun sensors were necessary together with the Earth sensor to resolve the 3-axis attitude which is now done automatically by the star tracker. And the star trackers function during eclipse as opposed to the sun sensors which do not. The star tracker can off-point from the Earth, whereas the Earth sensor could lose attitude measurements during antenna mapping phases or in inclined orbits that exceed the Earth sensor field of view. The star tracker simplifies all non-Earth pointing phases where the Earth sensor based satellite must rely upon an advanced gyro.

Modern telecom satellites are slowly abandoning the Earth sensor in favor of the star tracker because of its many positive benefits. However, there is one negative aspect of star tracker based Earth pointing. The position of the satellite must be known relative to the Earth. Orbit determination is classically done by the ground station which also generates the weekly or bi-weekly Chemical propulsion commands. To implement an equivalent scheme for Small GEO, Electric propulsion commands are still calculated on-ground based upon ground-based orbit determination. The Electric propulsion commands for the next seven days are then sent up to the satellite along with the current position. Then the satellite must propagate its position in the presence of the actually commanded EP thrust which could potentially differ as a result of failure or other unforeseen event. A GNSS receiver onboard could simplify the operations even further.

The Mosaic GNSS Receiver

The before mentioned GPS receiver demonstrator is the Mosaic GPS receiver. In 1997, EADS Astrium started the development of GPS receivers for space applications. Key requirements for such a navigation receiver were low cost, low power consumption, low mass, small size, and radiation hardened components to withstand the space environment[1]. Further more, there was a need for an easy access to all software for modifications and adaptations, even after launch. Since a hardware correlator for space application was not available on the European market at that time, a software based correlator for GPS signal reception using a digital signal processor (DSP) was developed. Resulting from this development was a software based sensor module, capable of receiving simultaneously the L1 C/A signal from up to eight GPS satellites.

Today the MosaicGNSS Receiver, as shown in Figure 3, is available as a product. It has been sold many times and several receivers are operating successfully in orbit. Key performance parameters of the redundant MosaicGNSS receiver are given in Table 1.

Mass [kg]	*Power [W]*	*Dimensions [mm]*	*Expected accuracy in GEO [3 Sigma, m]*	*Data Output*
3.9	10.0	272 x 284 x 92	150	PVT and raw measurements at 1 Hz, point and/or dynamic solution, ECEF or ECI, GPS Time

Table 1. Key Performance Parameters of Mosaic GNSS Receiver

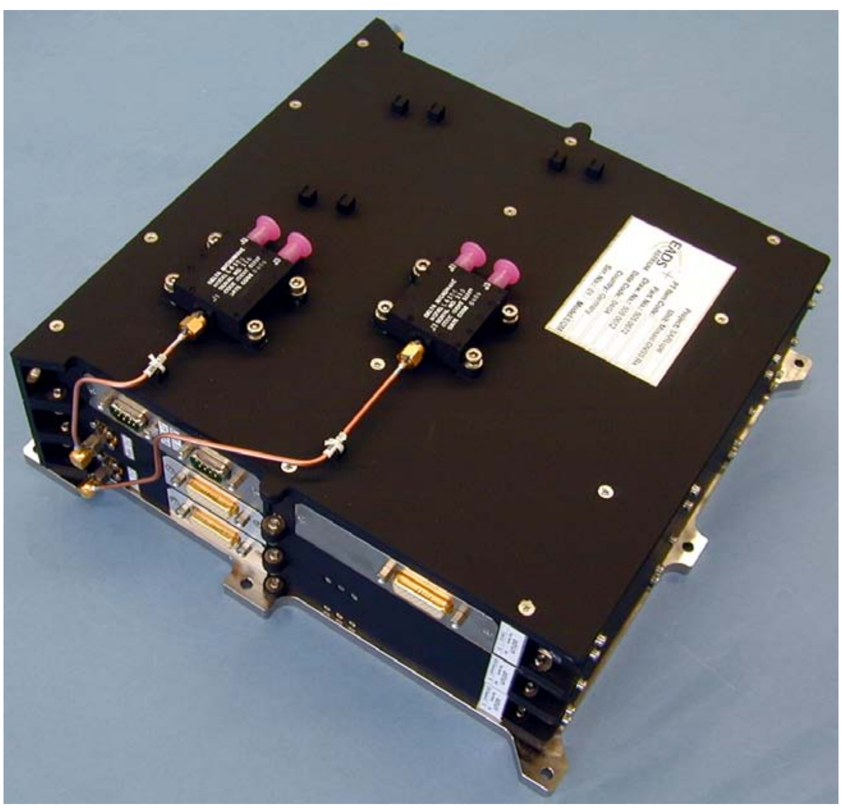


Figure 3. Flight Unit Box of redundant MosaicGNSS Receiver

Accommodation and Usage of the GPS Receiver in the Next Missions

In Normal Mode, the spacecraft attitude determination is based on Star Tracker measurements (two Jena-Optronik APS star trackers are used in cold redundancy). This allows a lot of freedom in attitude maneuvers: it is indeed not required to follow limited profiles, accounting for the Sun / the Earth to be in the Sun / Earth sensors fields of view. One limitation remains: to avoid blinding of both Star Trackers by the Earth and the Sun simultaneously. This is however not very restrictive. Additional gyroscope measurements are used during some of the mission phases, in particular during LEOP operations. On the other side, the reference attitude profile is computed directly from the spacecraft position. In Earth Pointing Mode, no other information or TC is required from ground. If necessary, a pointing offset can be added to the perfectly Earth pointing reference, without limitation. Finally, the estimated spacecraft attitude is compared to the reference one. The difference feeds the attitude control function which commands adequate commands to the Reaction Wheel Assembly (four Rockwell-Collins Teldix wheels mounted on a pyramid are used in hot redundancy).

The spacecraft position knowledge is therefore a key element in the onboard AOCS architecture, and position determination errors will be directly translated into pointing errors (Figure 4).

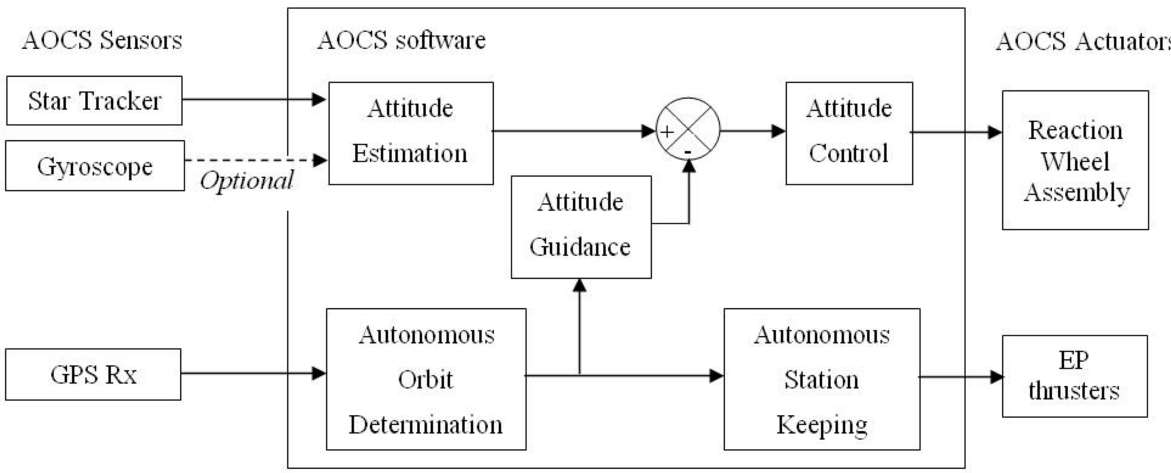


Figure 4. GPS Receiver in the AOCS architecture

For the first mission, an Onboard Orbit Propagator is used to propagate the spacecraft position and velocity. The propagator is re-initialized on a weekly basis, after one full day of ground orbit determination. The spacecraft position and velocity are then propagating using models of the spacecraft dynamics. The typical position propagation error sources are given by the following table[2]:

Error source	Propagation error (3σ after 1 week)	Associated pointing error
Model and natural disturbances	0,5 km	2 arcsec
Initialization errors	4,7 km	23 arsec
EP thruster force uncertainty	6,7 / 11.5 km 1% / 2% thrust error	33 / 56 arcsec
Total (root sum square)	**8.3 / 12.5 km**	**41 / 61 arcsec**

Table 2. Onboard orbit propagation errors and associated pointing error contributions

This contribution is significant in the whole AOCS budget (180 arcsec allocated to AOCS). These values are to be compared with the expected GPS accuracy 150m (associated pointing error: 0.7 arcsec), which is 2 orders of magnitude smaller[3].

Another positive impact of the GPS receiver on the AOCS architecture will be the possibility to integrate the Station Keeping algorithms onboard. Indeed, the satellite position will be known better onboard than on ground and also in a continuous way, and the efficiency of the Station Keeping maneuvers could be improved by thruster calibration which would then be possible accurately. The maneuvers could be performed everyday, which will remove the weekly full day of free drift, during which the spacecraft position is not controlled. It will be a gain in terms of both autonomy and performance.

THE GPS EXPERIMENT ON HISPASAT AG1

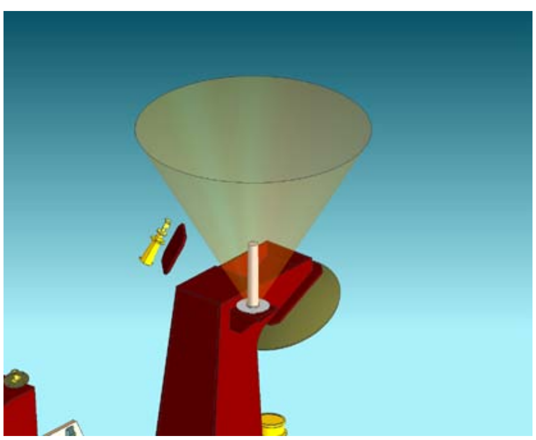
In spite of the aforementioned demonstration/experimental character, the use of the GPS receiver during the HAG-1 mission will be, provided a nominal mission development, almost permanent. In particular, the GPS receiver is expected to deliver a PVT solution from the GTO up to the graveyard phase, i.e. throughout the station keeping phase. Consequently the epithet of experimental should be correctly understood.

At a high level the GPS receiver assembly for the HAG-1 mission will comprise a GPS receiver board with a communication interface together with a patch and a helix antenna, with the corresponding low noise amplifiers (LNA). The need of two antennas is driven by the use of the GPS receiver during the GTO and station keeping phase. In particular, the patch antenna will be used during the former phase and the helix antenna for the latter.

The success of the experiment relies significantly on a suitable accommodation of the GPS antennas. In order to guarantee their necessary field of view, a significant effort has been made to accommodate them suitably, whilst minimizing the impact on other subsystems. As an example, for the helix antenna, used during the station keeping phase, an accommodation above the whole payload antenna farm was chosen. In fact, the helix antenna represents the uppermost limit of the spacecraft, on top of a FSA. This fact poses stringent constraints on the loads this antenna has to be qualified for.

Figure 5 shows the GPS antennas together with their field of view cone to ensure no obstructions impair the GPS signal reception.

An additional issue is the accommodation of the LNAs with respect to their corresponding antennas. The accommodation of the helix antenna on top of the FSA coupled with the necessary accommodation of its LNA inside the spacecraft yields a coax cable length possibly larger than 1.5 meters. The cable losses herewith have to be assessed thoroughly, once the final accommodation of the LNA is in place.



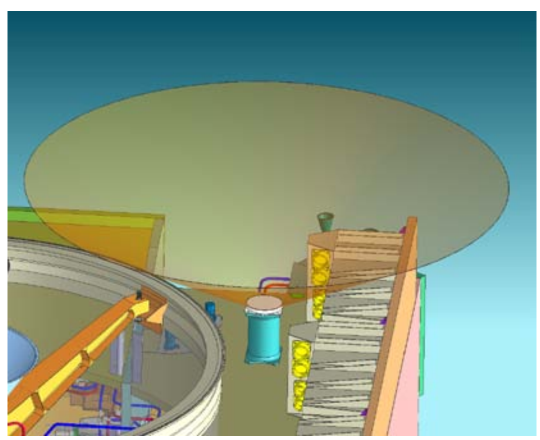


Figure 5. Helix antenna on top of FSA (left) and patch antenna on opposite spacecraft side (right)

As far as the future is concerned, the inclusion of the GPS receiver in the operational scenario will take place gradually. In particular, the following three steps are foreseen:

1. HAG-1 will fly a GPS receiver without including it in the operational scenario, i.e., as an experiment (object of the present paper)

2. In the case that the first step is successful, a second Small GEO mission would fly a GPS receiver using the resulting PVT for the operations. Nevertheless, the use of the aforementioned PVT would not have a mandatory nature.

3. In the case that the second step is successful, a third Small GEO mission would include a GPS receiver fully in the operational scenario and therefore the operational scenario would be designed on the basis of the provided PVT.

These steps reflect the caution exercised when it comes to including new technology in the telecom sector, especially when more spacecraft autonomy is the issue at stake.

Hopes and Worries of the Satellite Operators on Usage of GPS in GEO

Satellite operators can benefit greatly from use of GNSS receivers in geosynchronous orbit. Soon there will be three GNSS systems in place: GPS, GLONASS, and Galileo. On-board usage of a GPS receiver will give the telecommunications satellite operator a number of advantages:

- reduce the daily workload of ground stations during the 15 years mission lifetime,
- reduce the cost intensive GTO phase with several ground stations collaborating in a network in order to track the satellite,
- increase the mission safety through less man-machine interactions, i.e. higher satellite autonomy.

There are also worries about the use of GPS in GEO. The biggest concern is whether or not it will work. The HAG1 mission will hopefully put this doubt to rest. Methods of improving the performance in GEO are being researched for example by usage of the side-lobes of the GPS signal. The Small GEO platform will also be improved by gaining continuous access to on-board orbit determination. Specifically for the Small GEO mission this has additional advantages:

- The pointing error will not increase over the week due to increasing orbit propagation error.
- The influence of EP thrust errors will be reduced. Robustness will increase since larger thrust errors will be measurable.
- It will no longer be necessary to prevent EP thruster firing for one day every week to support orbit determination by ground-based tracking.
- Improved position knowledge combined with on-board station-keeping guidance should increase precision and reduce fuel consumption.

On-board station-keeping guidance will remove the need for ground-based EP command profile generation and up-link.

Constraints on the GPS TM Downlink-Stream

Since the GNSS receiver is an experiment on Small GEO it has also no priority for the TM downlink stream. Therefore, it is required to estimate what the real minimal stream is which is absolutely necessary to perform a meaningful experiment.

The TM of the Mosaic GNSS Receiver is grouped[4] into four categories, where category 1 is absolutely necessary to retrieve the complete PVT and to verify it from ground, category 2 is helpful for computation improvement at ground station, category 3 is helpful for easier processing and category 4 is for more detailed information. The complete list of the entire available receiver TM can be found in Table 3 [5]. The next category includes all variables of the previous category.

Please note that the categorization is also subject of iteration. For instance, “integrated carrier phase” and “carrier noise ratio” are now better seen in “1” than in “2” and “3”, respectively, but this was revealed shortly before the paper deadline and was not considered in the relevant plots.

Necessary Sampling Rate of the TM

The amount of the TM is dependant on the sampling rate. The highest possible sampling rate of the receiver output is 1s. It has been estimated in section “GROUND-BASED ORBIT DETERMINATION AND VERIFICATION“ that a sampling rate of **30 s** yields still the best possible result with negligible deterioration for the position determination of the satellite on ground using this TM. In order to evaluate the size of the receiver TM a 3-day long every-second-sampled GPS receiver TM data set including all variables from Table 3 has been provided [4].

TM variable	Category: 1: absolutely necessary 2: helpful for computation improvement 3: helpful for easier processing 4: just for information	Data Type: double: 64 bit single: 32 bit uint32: 32 bit	Values per Sample
x_position	1	double	1
y_position	1	double	1
z_position	1	double	1
x_velocity	1	double	1
y_velocity	1	double	1
z_velocity	1	double	1
gps_week_number	1	uint32	1
gps_time_of_week	1	uint32	1
x_position_rms	4	single	1
y_position_rms	4	single	1
z_position_rms	4	single	1
x_velocity_rms	4	single	1
y_velocity_rms	4	single	1
z_velocity_rms	4	single	1
time_bias_error	2	double	1
time_bias_error_rms	4	double	1
clock_drift	2	single	1
clock_drift_rms	4	single	1
gps_sv_deselect	3	uint32	1
gps_sv_raim_isolated	3	uint32	1
gps_sv_raim_alm_eph	3	uint32	1
gps_sv_visible	3	uint32	1
gps_sv_tracked	3	uint32	1
gps_sv_used_in_pvt	3	uint32	1
validity_flags	1	uint32	1
channel	3	uint32	8
sv_id	1	uint32	8
Measurement_week_number	1	uint32	8
measurement_time_of_week	1	uint32	8
pseudorange	1	double	8
range_rate	1	double	8
integrated_carrier_phase	2	double	8
channel_status	1	uint32	8
carrier_noise_ratio	3	uint32	8
time_of_sig_transmission	1	double	8
range_rms	4	single	8
range_rate_rms	4	single	8
delta_rate_rms	4	single	8
Compression_factor	4	single	8

Table 3. List of GPS receiver TM and its categorization

Original TM

The standard TM for the GPS raw data takes into account 8 different channels to pick up GPS signals as shown in Table 3. However, since in GEO orbit maximally only 4 GPS satellites (i.e. 4 channels) can be seen, the remaining channels provide literally zero-information. Therefore, in order to reduce the TM size, a modification on either the receiver SW or the OBCU SW is recommended to select for the TM output the desired number of channels. The result in TM size is given in Figure 6. The result is an almost factor of 2 improvement as shown in Table 4, approach A2.

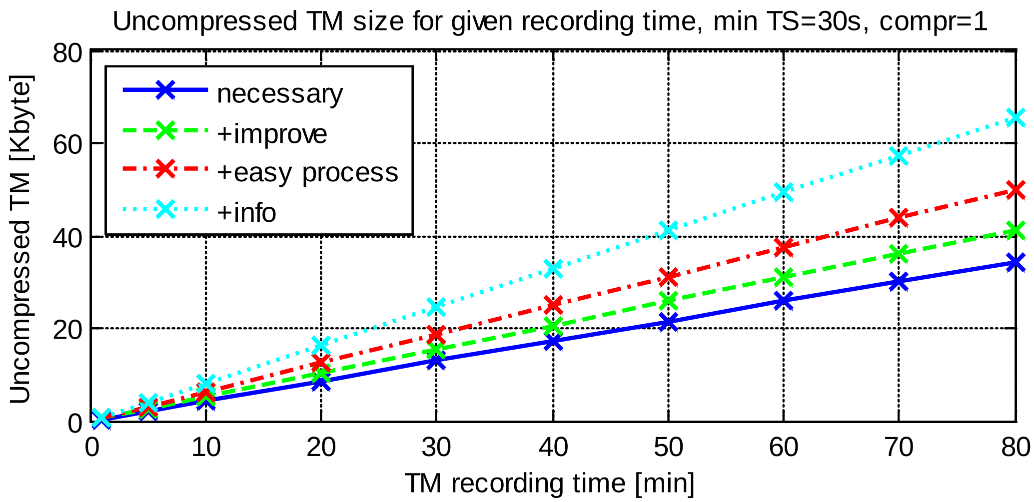


Figure 6. Size of sampled original TM recorded for a given recording time (4 channels)

Compression of TM

There is a potential to save even more TM, since all 4 channels very seldom provide at the same time information, in most cases there are only 1 or 2 channels with useful measurements. Therefore, only those channels are kept which provide useful information and the rest is discarded. This means, that the TM size is no longer constant wrt time.

In addition to that the tailored TM and thus the downlink rate can be even further reduced when the receiver TM is compressed using data compression algorithms [5]. The results of all approaches are shown in Table 4: The best results for the smallest possible downlink rate are achieved with Approach A3, i.e. a downlink rate of about 30 bit /s is required. For this case a SW modifications needs to be performed which should preferably done inside the GPS receiver. Since the effort in implementation and testing is non-negligible, for Small GEO Approach A2 using category 4 is selected and accordingly a TM rate allocation of **120 bit/s** is foreseen.

Approaches (A1, A2, A3) to taylor the TM	**Category 1: absolutely necessary**	**Category 2: helpful for computation improvement**	**Category 3: helpful for easier processing**	**Category 4: just for information**
A1: Use all 8 channels	101.3	121.6	145.1	188.8
A2: Use only 4 channels	58.7	70.4	85.3	**112.0**
A3: Select channels with measurements only, record for 80 min and store on-board, then compress the TM	17.8	20.5	21.7	29.7

Table 4. Downlink rates [bit/s] for receiver TM

GPS TM Analysis and Evaluation of the Feasibility to Use GPS in GEO

Kind of Telemetry

The GPS Receiver is an experiment on Small GEO. Accordingly its telemetry is not required for the nominal operation, allowing long term and post factum evaluation of collected telemetry packages. The contents of the GPS telemetry can be subdivided into two categories:

1. **Regular Telemetry** values, such as the solutions for position, velocity and time (PVT), the

quality marker for the solution and administrative values. This telemetry would be as well available for the satellite board computer and is used to update the precise knowledge about orbit position and velocity.

2. **Specific Telemetry**, such as the pseudo ranges, satellites in track, signal strengths. These values are sent to ground on request. They are used for diagnostic purposes and to understand better the receiver performance and behaviour for specific situations.

Telemetry analysis

The primary purpose of telemetry evaluation is to get a clear picture about the in orbit performances of the receiver, which are essential for the practical suitability for on board orbit determination and control. The corresponding performance parameters are given in Table 5:

Performance Parameter	**Expected values**
Acquisition time for first fix	0.5 days for cold start, full accuracy after one day
Accuracy of the PVT solution	150m, 3d(imensional), 3 Sigma, no thrust 200m, 3d, 3 Sigma, with thrust, applying thrust compensation
Availability of the acquired solution	one of the experiment subjects the PVT accuracy is stable over 20 min without sat. visibility

Table 5. Performance Parameters of GPS Receiver

Further, the following general characteristics are of interest are in Table 6:

Characteristic	**Expected values**
Needed accuracy for a priori information	position 3d within 70 km cube
Actual receiver link margins	one subject of experiment
Robustness for different satellite states (during station keeping, for different thermal situations, during orbit transfer, on transfer orbit etc.)	confirmation is one of the experiment subjects
Ageing effects	none

Table 6. General Characterizing Parameters of GPS Receiver

Feasibility evaluation

The identified performance parameters and characteristics are fed into a simulation set up for automated orbit control, using the

- modeled and parameterized GPS receiver as sensor
- filter algorithms for augmented orbit parameters determination
- a set of specific orbit control laws for the control function
- and the parameterized satellite model as plant

This simulation shall demonstrate the feasibility of automated orbit control in GEO, shall identify the sensitivities of these process and shall give guidelines for filter design and control laws for different propulsion configurations. Filtering and control functions will be kept simple, in order to allow later transfer to an on board computer.

FEASIBILITY INVESTIGATION BY SIMULATION

The GPS experiment for the small GEO mission will be based on the use of the GPS L1 signal as specified for terrestrial users[6]. The use of GPS was successfully extended to the position determination of spacecraft in low Earth orbits as early as 1982 [7].

The extension of GPS to critical GEO missions was hampered in the past by the lack of specifications governing GPS signal strength and availability at GEO altitudes.

The GPS Operational Requirements Document (ORD) [8] incorporates space user requirements including a first description of a Space Service Volume (SSV) up to equatorial geosynchronous altitudes. The ORD was released to support the modernization and up-grade of GPS Block IIF satellites. Until then, it has been stated, that the present capability offered by the system for GEO users now will be maintained with a constellation of at minimum 27 satellites.

For the Small GEO investigations, GPS constellation parameters can be chosen at will from the Yuma Almanac File.

The quality of GPS performance for the SSV is specified as accuracy on the pseudo-range observable. The pseudo-range accuracy or User Range Error (URE) is an error bound on the GPS range measurement. It was improved from 4-5 m in 1990 to approximately 1.1 m by November 2004[9]. This value will be used as 1σ value of URE.

Using GPS on satellites at altitudes higher than the GPS constellation altitude is based on acquiring and tracking signals crossing the limb of the Earth by Nadir pointing antenna (Figure 7)

Technical challenges to be overcome for navigation by GPS in GEO are the weak GPS signal levels caused by the maximum range between GPS and geosynchronous satellite (r_{max} = 67463 km, received power ~ -166 dBW). In addition, the signals received at GEO are at large angle w.r.t. to the nominal pointing direction, the GPS signal coverage is poor (less than 4 satellites) and the Geometrical Dilution of Precision (GDOP) of GNSS satellites is high, which is caused by the unfavourable satellite distribution.

The receivers developed for use on GEO orbit must be capable of acquiring and tracking GPS signals that are much weaker than signals received in LEO and include orbit navigation filters to sequentially cope with sparsely available pseudorange measurements and unfavourably distributed satellites (high GDOP)

Visibility and GDOP are limited by the half beam angle under which the Earth is seen from GPS altitude (±13.9º) and the half-beam angle of the GPS transmit antenna (for the L1 signal γ = 21.3°).

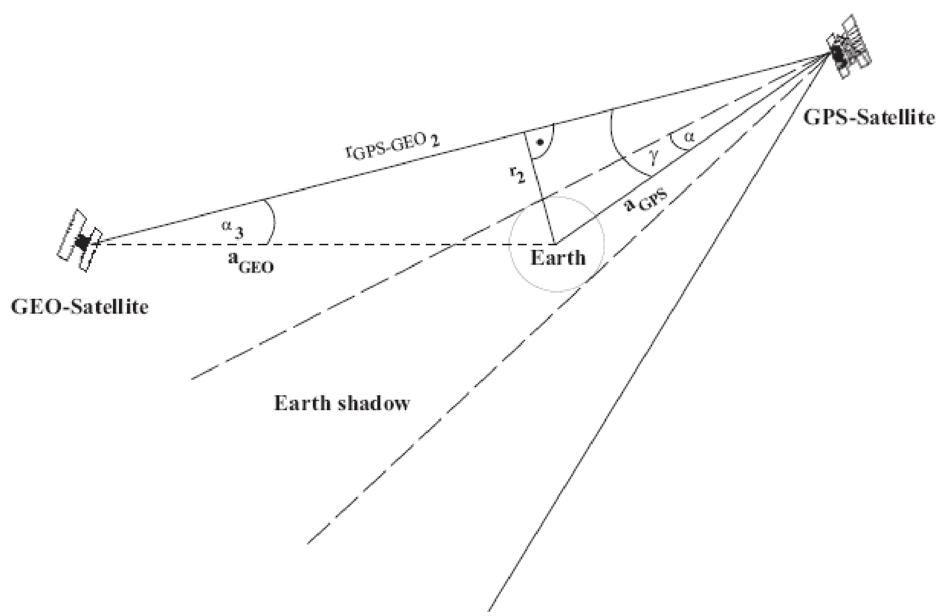


Figure 7. GPS visibility from Geosynchronous Orbit

In order to compensate for the additional free space loss a nadir pointing helical antenna is foreseen (Figure 8). Figure 9 shows the matching of transmit and receive antennas half-beam angles.

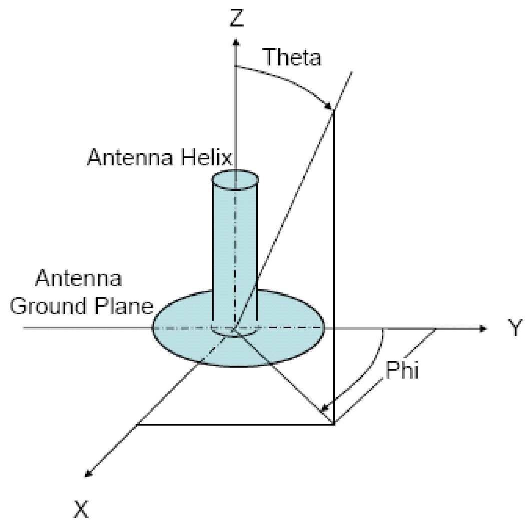


Figure 8. Antenna Helix, Antenna Gain 10 dBic for 8° < Θ < 25°

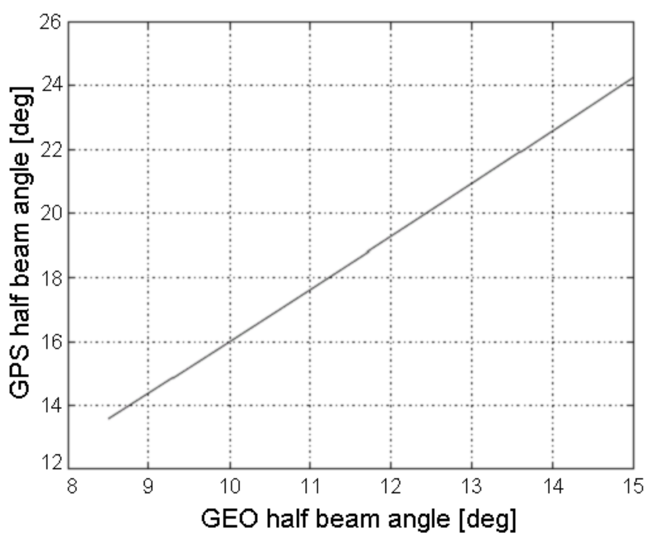


Figure 9. Dependency of GPS and GEO Satellites Half-Beam Angles

Figure 10 shows the antenna attenuation diagram for a GPS Block IIA satellite[10]. The data are based on F. Czopek[10].

When using a single frequency receiver the Earth radius is masked to prevent use of rays, which have been delayed by the Ionosphere. The penalty is the loss of ~ 2° half-beam angle as seen from the GPS satellite, which could be recovered when a dual-frequency receiver is used.

Results from Figure 9 are used to calculate the collection area in Figure 10 for a receive antenna half-beam angle of 25°. The collection area is compatible with the SNR tracking threshold of the receiver. A word of warning however, concerning the use of side lobes in critical programs: There is no future intention to formally specify antenna side lobes.

The use of GPS for orbit determination during Geosynchronous Transfer Orbit (GTO) is of particular interest, because it eliminates the need for a network of worldwide tracking stations, with all its scheduling and coordination problems. The GPS experiment on Small Geo therefore also includes the GTO phase. During GTO the satellite is partially flying above and partially below the GPS satellite constellation orbits.

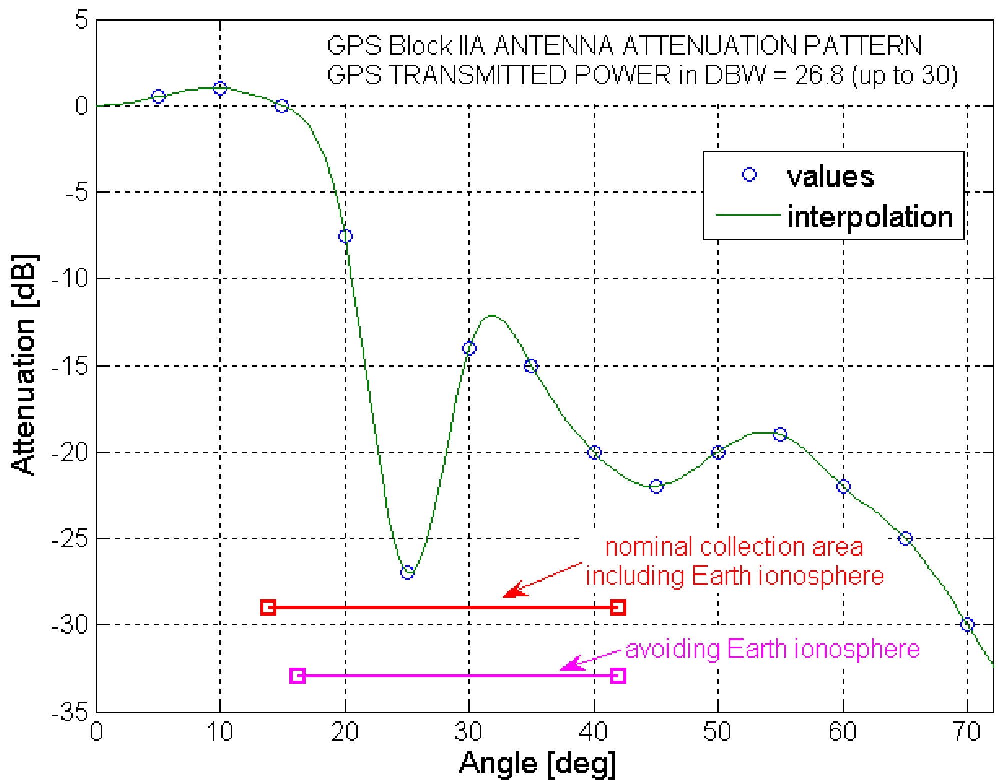


Figure 10: GPS IIA Antenna Attenuation Pattern

In addition the satellite orientation is determined by power requirements (sun pointing), apogee maneuvers and maneuvers for gyro calibration. For tracking of GPS signals at low altitudes an additional patch antenna (Figure 11) is required.

Figure 11. GNSS Patch Antenna

The mounting of the patch antenna is to be optimized based on the mission specific attitude profile to be flown during the geosynchronous transfer orbit. Signals from both antennas are either permanently combined by power combiner or intermittently switched by RF switch dependent on the orbit segment in which the S/C is flying. The navigation algorithm to determine satellite position and orbit from GNSS sensor raw data has to be adapted accordingly.

Closed-loop performance evaluation

The performance of Astrium's MosaicGNSS Receiver was investigated under geosynchronous orbit conditions. The receiver RF input was stimulated by representative L1 signals from a SPIRENT RF-signal generator. The settings in the receiver software were the standard settings, as e.g. used for LEO satellites. This leaves some margin to the possible performance, while providing a certain robustness to external disturbances (e.g. orbit maneuvers), which needs to be considered carefully when designing the filter and setting its parameters.

A major improvement is made when using the GPS-satellites' sidelobes in addition to the main lobe of the antenna characteristic. This has been implemented on simulator side in the second set of tests. The different antenna attenuation patterns with respect to an isotropic antenna are shown in Figure 12. The purpose of the tests was to investigate the improvement to be gained, when also the side lobes of the GPS Constellation satellites are used for position, velocity and time determination.

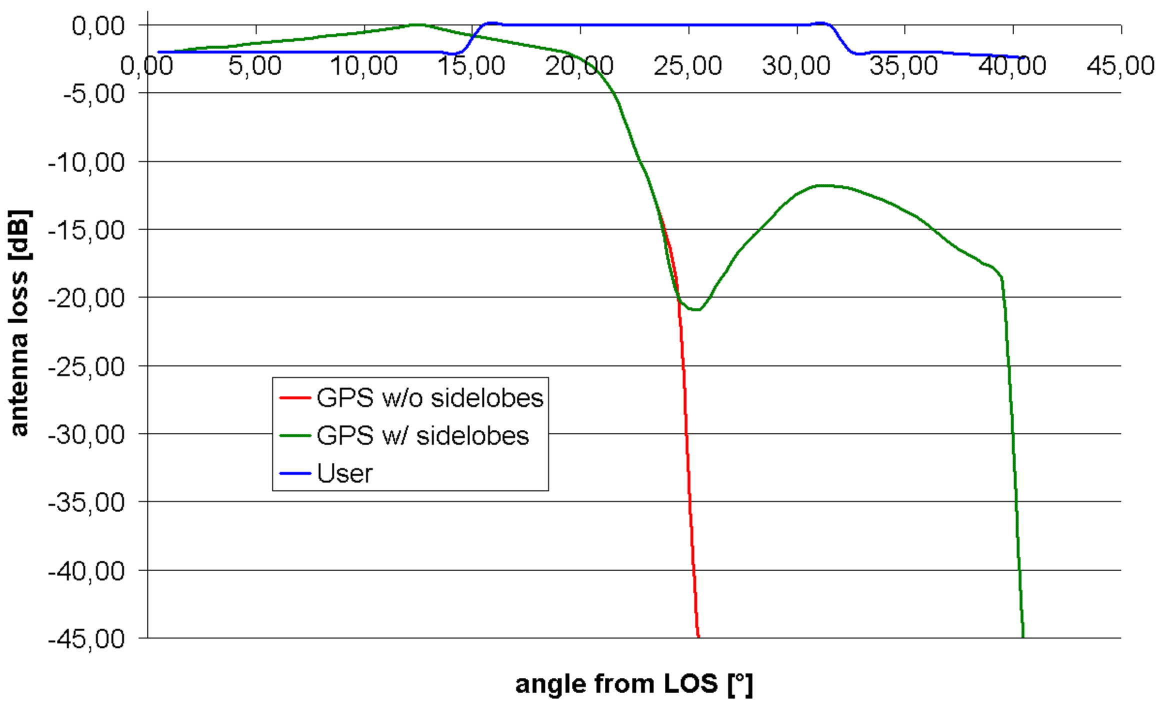


Figure 12. Antenna patterns of user satellite and GPS SVs with and without side lobes. A global off-set of 18 dB is considered in the simulation in order to take into account the user antenna gain, the non-present atmospheric losses, and the higher signal power of GPS in comparison to the ICD [6]

The settings in the SPIRENT simulator were the following:

- Start Time : 23.Sep.2008, 12:00 GMT
- Start Parameters: circular orbit with a=42164000 m; starting at 0 ° lat,0 ° lon
- Satellite Parameters: Surface Area = 20m^2, Mass = 1500 kg
- Orientation: Earth Pointing,

- Reference System: J2000
- Gravity Model: JGM 3, order = 40
- SV Ids 12, 19 and 32 are switched off
- Sv ID 23 has a parity error

Dedicated receiver settings were

- Atmospheric radius: WGS84 radius + 200 km (limit for observation of GPS satellites)
- No dedicated ionosphere model was used in this evaluation.

The initialization was performed via TC with a correct ECEF position at a time-accuracy of approximately 1 sec.

In each test, the number of tracked satellites, the position error and the associated pseudo ranges were recorded over a 72 hour time span (3 days ≈ 3orbits) as shown in Table 7 and Figure 13.

The advantage of using side lobes in addition to the main lobe of the GPS satellite antenna is clearly shown by comparing the number of tracked satellites over time. For instance more than one satellites are tracked for over 78.1 % of the time (mean number of tracked satellites is 2.2) when side lobes are used versus only 29.8 % (mean number of tracked satellites is only 1.3) when the main lobe only is employed as shown in Table 7. The seeming inconsistency, showing a larger number of maximum tracked GPS signals when using main lobes only, is a result of the MosaicGNSS Receiver’s processing architecture: since the correlation is performed by software, the number of acquired and tracked signals depends on the signal power. Since in the case with sidelobes in general signals of lower power are tracked, this reduces the number of instances when additional signals can be acquired. It needs to be noted, though, that the overall benefit of using sidelobes is still dominant when looking at the mean number of tracked signals. Furthermore it should be noted that the next generation receiver, which is currently under development, features a flexible hardware correlator, which allows for an increased use of signals.

Number of tracked satellites	*Occurrences (equals seconds),* ***with*** *sidelobes*	*Occurrences (equals seconds),* ***without*** *sidelobes*
0	5197 [2.0 %]	45205 [17.1 %]
1	51842 [19.9 %]	140040 [53.1 %]
2	117343 [45.1 %]	45957 [17.4 %]
3	75261 [28.9 %]	19492 [7.4 %]
4	6809 [2.6 %]	8569 [3.2 %]
5	3848 [1.5 %]	4714 [1.8 %]
More than 1 satellite	203261 [78,1 %]	78732 [29.8 %]
Mean number tracked satellites	2.1467	1.3193
3 D position error (rms after 2 orbits)	60.3 m	174.3 m

Table 7. Histogram and Statistics on the number of tracked satellites over 3 orbits

The position error (rms value) after about two orbits is 60.3 m in case of side lobes versus 174.3 m when only the main lobe is used (Figure 13).

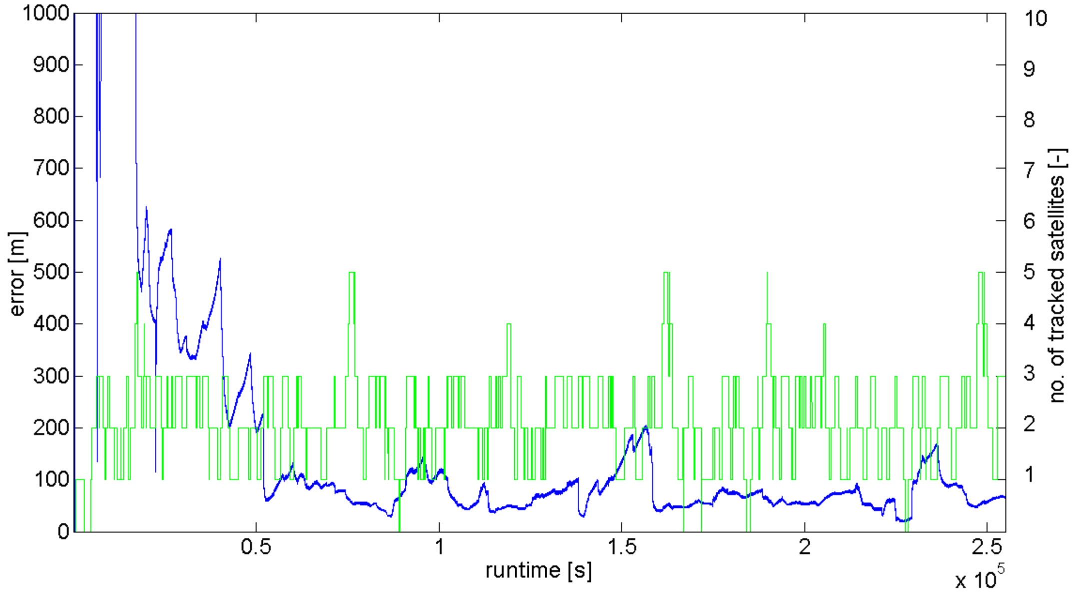


Figure 13. 3D position (blue) and number of tracked satellites (green, meter scale/100) error over 72 hours (with side lobes)

GROUND-BASED ORBIT DETERMINATION AND VERIFICATION

In view to the experimental nature of the GPS navigation system on the first Small GEO missions, an independent ground based tracking using Ku-Band range (and angle) measurements from one or two ground stations is foreseen. It supports the overall mission operations and provides the required a priori orbit information for the onboard orbit propagator and the initialization of the MosaicGNSS receiver. Due to the lack of a consolidated ground station concept, concise values for the achievable orbit determination cannot be given at present, but overall positioning accuracies at the level of 200 m and 2 km can be expected with single and dual-site tracking, respectively, during thrust free arcs. While this appears inferior to the envisaged accuracy of the GPS onboard navigation solution at first sight, it will still meet all mission requirements.

Obviously the ground based ranging represents a measurement technique that is highly complementary to GPS. Other than GPS pseudoranges, the ranging from terrestrial ground stations is based on a two-way technique and does not depend on an unknown receiver clock offset. Furthermore, the ground station (G/S) ranging is conducted at line of sights close to the nadir vector that are never covered by GPS tracking. Even though the signals from the G/S pass through the Earth atmosphere, the resulting media effects can either be compensated through adequate models (tropospheric paths delays) or are sufficiently small (ionospheric delays) due to the high frequency of the Ku-band signal. Noise and bias values of the Ku-band ranging are expected to lie in the 1 to 10 m range. This is compatible with the 5-10 m pseudorange noise assumed for the MosaicGNSS pseudoranges in case of main and sidelobe tracking from geostationary altitudes.

An optimum concept for based orbit determination should therefore make use of both GPS raw measurements (pseudorange and carrier phase data) as well as Ku-band ranging. Both data types will be made available at the mission control center through the telemetry and the ground data system, respectively. While the Ku-band ranging is typically performed in short slots of 5 min duration separated by intervals of about 2 hours, the GPS measurements will be provided on a quasi-continuous basis. Despite the orbital period of the GEO satellites, which is roughly 15 times higher than that of a LEO, a similar sampling rate of the GPS raw data must be foreseen to support (a) a smoothing of the pronounced pseudorange and (b) to properly resolve potential thrust and thrust vector variations during electric propulsion maneuvers. A

30s sampling interval is currently considered as the best compromise between these goals and the limitations of the data downlink.

Aside from the additional incorporation of ground based ranging measurements the basic concepts for the Small GEO orbit determination closely match the well established methods of GPS based LEO orbit determination [11] [12]. Other than the onboard navigation solution generated by the MosaicGNSS receiver, which employs an extended Kalman Filter, a batch least squares estimation is considered as baseline for the ground based precise orbit reconstruction. It offers a higher robustness and can well cope with the mixture of different data types and the discontinuous availability of the ground station ranging.

The dynamical model for the motion of a geostationary satellite considers the gravitational field of the Earth (up to degree and order 10-15) as well as third body accelerations of the Sun and Moon. A cannonball or, preferably, box-wing model is furthermore incorporated for the modeling of solar radiation pressure effects. Finally, constant thrust arcs have to be incorporated to propagate across orbit keeping maneuvers. However, a reduced dynamic approach is strongly favored over a fully deterministic dynamical model in view of obvious uncertainties in the a priori modeling of both the solar radiation pressure effects and the electric propulsion. In the reduced dynamic approach piece wise constant empirical accelerations in radial, along-track and cross-track acceleration are incorporated into the trajectory model and adjusted from the observations.

The measurement model for the GPS data leaves the choice of pseudorange-only processing or the more advanced processing of GRAPHIC (Group and PHase Ionospheric Correction) measurements. The latter are formed as the arithmetic mean of the single-frequency code and phase range [13] and are free of ionospheric path delays due to the opposite change of group and phase velocity in an ionized medium. This enables a processing of MosaicGNSS measurements in the immediate vicinity of the Earth limb and results in a larger number of tracked satellites compared to the 1000 km (2° boresight angle) exclusion zone applied in the standard processing. Also, the noise of the GRAPHIC measurements is only half as large as that of the underlying C/A code pseudoranges, which favorably affects the orbit determination accuracy. On the other hand, the GRAPHIC processing requires the adjustment of carrier phase biases, which increases the overall number of estimation parameters in the orbit determination process.

Due to the lack of an ultrastable oscillator in the MosaicGNSS receiver, the clock offset must be determined individually at teach measurement epoch. This requires a minimum of two GPS satellites tracked at the same time. Overall, the normal equations involve a total of about 3000 estimation parameters per day if measurements are collected at 30s intervals. The presently envisaged design of a combined GPS+Ku-ranging orbit determination process assumed a 6-dim position/velocity vector, 1-2 global solar radiation pressure parameters, 3 thrust parameters for each of the daily electric propulsion maneuvers and roughly 150 empirical acceleration parameters (assuming half-hour intervals). In case of GRAPHIC processing about 200 phase biases would have to be estimated if one assumes that each GPS satellite is tracked in three continuous arcs per orbit in either the main or side lobe. On top of the above 2880 clock parameters need to be determined but can be pre-eliminated. The normal equations can thus be reduced to 300-400 parameters which poses no problems for present desktop computer systems. For the Ku-band ranging a priori station coordinates will be employed and atmospheric corrections will be based on external models and data. As such only one additional estimation parameter for the adjustment of the ranging transponder delay is envisaged.

The actual design of the Small GEO orbit determination system will be performed after consolidation of the ground tracking concept. Furthermore, extended simulations of the MosaicGNSS main and sidelobe tracking performance using the planned antenna system as well as a performance characterization of the electrical propulsion (concerning thrust level and direction errors) are deemed necessary for an optimum design of the orbit determination process.

CONCLUSIONS

The Small GEO satellite has good chances to be the first commercial platform to test a GNSS receiver in geostationary orbit. Hopefully the results will show that ground control operations can be simplified by increasing the onboard autonomy. As a consequence, the costs to perform the satellite maintenance will be lowered.

Satellites using electric propulsion as Small GEO will be benefit from the unique calibration potential of the thrust vectors which can be done using the GNSS receiver. Similar, for satellites carrying star trackers instead of Earth sensors depend heavily on the orbit position in order to perform Earth pointing. The paper showed in detail all these expected benefits of using the GPS receiver for Small GEO and how the feasibility is planned to be evaluated on ground. Simulations using real transmitted GPS signals using a SPIRENT simulator have been successfully performed.

The Small GEO team is well prepared and waits for the launch.

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