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A GPS TRACKING SYSTEM WITH ONBOARD IIP PREDICTION FOR SOUNDING ROCKETS

Oliver Montenbruck, Markus Markgraf

German Space Operations Center (GSOC), Deutsches Zentrum für Luft- und Raumfahrt (DLR),
82230 Weßling, Germany, markus.markgraf@dlr.de Tel. +49 (8153) 28-3531, Fax +49 (8153) 28-1450

Abstract

The development and verification of a dedicated GPS sensor for sounding rocket missions is described. It is based on the hardware design of a terrestrial low cost L1 C/A code receiver but operates an enhanced software that has been specifically adapted for high dynamics applications. Besides the navigation and timing function provided by traditional Global Positioning System receivers, the prediction of the instantaneous impact point (IIP) has for the first time been integrated into the receiver software. Making use of a newly developed perturbed-parabolic trajectory model the receiver can directly perform real-time IIP predictions with an accuracy that is compatible with operational ground software and is only limited by atmospheric forces. It is expected that the availability of onboard IIP prediction will both simplify existing range safety systems and contribute to a future increase of the onboard autonomy of sounding rocket missions. The overall receiver performance is demonstrated with hardware-in-the-loop simulations and actual flight data for representative mission profiles.

1. Introduction

In parallel with the tremendous growth of terrestrial and airborne GPS applications an ever increasing number of space missions nowadays utilizes the Global Positioning System for navigation and scientific measurements. Likewise, GPS receivers offer numerous prospective benefits onboard a sounding rocket. During the various flight phases, GPS measurements can support range safety monitoring, geolocation and time tagging, event triggering, recovery operations and, finally, a post-mission performance and trajectory analysis[1,2].

Right after launch, GPS position and velocity measurements allow for a rapid recognition of boost and guidance problems through real-time prediction of the instantaneous impact point (IIP). This information can directly be used by the range safety officer to decide on the need and feasibility of an abnormal flight termination. In the post-mission analysis, the GPS navigation data can furthermore be used to compare the actual performance of a boost motor with pre-mission models and to infer the aerodynamic properties of the rocket. This enables a refined planning of future missions based on improved parameter sets. In the subsequent free flight phase precise position and timing data collected jointly with the science measurements are essential for the study of regional and temporal variations in the atmosphere and magnetosphere and a comparison with experiments performed at other sites. In case of multiple payloads separated during the mission or flown simultaneously on different rockets, GPS can provide highly accurate relative state vectors and timing information for the science data synchronization[3]. Time and position information can likewise be employed to activate experiments and service systems precisely at a desired flight stage. A GPS receiver may thus take over functions traditionally performed by mechanical timers and barometric switches. Finally, the instantaneous payload position measured by a GPS receiver can continuously be relayed to the control center during the final descent and parachute phase to allow a rapid and reliable recovery even in the presence of pronounced wind fields. Aside from a high accuracy of the basic navigation and timing information, which is nowadays already available with single-frequency C/A code receivers, GPS has the additional benefit of an onboard data availability. This offers the prospect of an increased autonomy in future rocket systems and may e.g. be applied for onboard geocoding or onboard IIP prediction. Furthermore the overall system cost are considered to be notably lower than that of alternative tracking systems[4].

All of the aforementioned benefits come at the expense of dedicated enhancements of the GPS receiver design, required to ensure proper tracking at the extreme signal dynamics encountered during the boost phase and reentry. In the sequel, the hard- and software of the Orion-HD high dynamics GPS receiver is described, which has been adapted by DLR's German Space Operations Center (GSOC) from a prototype for low cost, mass market applications to the highly specialized use on sounding rockets. Motivated by the needs of its Mobile Rocket Base (MORABA), which plans, prepares and performs sounding rocket launches at various international launch sites, a research and development program for GPS tracking systems has been set-up in an effort to ultimately replace or minimize conventional radar stations. In a first step, the Orion-HD receiver has received basic software extensions and modifications for high dynamics use[5] and undergone a preliminary flight qualification together with a novel antenna system[6]. In a next step, which is addressed by the present report, the system has been upgraded for carrier phase tracking and supplemented by a simple, yet efficient, IIP prediction algorithm. It computes the expected touch down point of the sounding rocket based on the latest state vector and outputs the result in real-time along with the navigation solution. The mathematical formulation of the IIP prediction algorithm, which makes use of a perturbed parabolic trajectory model and can well be applied with limited computing resources, is described in Sect. 4 of this report. Finally, we discuss the overall navigation and IIP prediction performance of the Orion-HD GPS receiver as obtained in ground based signal simulator tests and actual sounding rocket flights.

2. GPS Hardware

The GPS Orion receiver, which serves as a platform for the IIP prediction system, has originally been designed by Mitel (now Zarlink) as a prototype of a low-cost receiver for mass market applications based on the GP2000 chipset[7]. It comprises a GP2015 front-end chip, a DW9255 saw filter, a GP2021 12-channel correlator for L1 C/A code and carrier tracking and an ARM60B 32-bit microprocessor. The chipset is similarly used in industrials receivers (e.g. CMC Allstar) but has more recently been superseded by the combined GP4020 correlator and microprocessor, which allows more tightly integrated receiver designs (Superstar II, SigTec MG5001).

While the Orion itself receiver has never reached the commercial production stage, the open design information[8] and the temporary availability of a source code level software development kit have resulted in a variety of rebuilds by universities and research centers to support specialized scientific and technological applications. In the context of spaceborne navigation, the Orion receiver has been flown on Surrey's SNAP-1[9] and USNA's PCsat[10] nano-satellites, dual front-end versions for attitude determination and pseudolite applications have been developed at Stanford University[11] and Johnson Spaceflight Center[12], and sounding rocket experiments have been performed by Cornell University[3] and DLR/GSOC[6].

The key receiver elements are combined on a single printed circuit board of 95 x 50 mm size, which holds a 10 MHz TCXO reference oscillator, the front-end, correlator, and processor as well as RAM (512 kB) and ROM (256 kB) memory. At a regulated 5V supply the receiver consumes a power of 2 W (or 2.4 W including typical switching regulator losses), which is well compatible with the onboard power systems of typical sounding rockets. Two serial interfaces (TTL level) allow for flexible communication with the telemetry and telecommand system, an umbilical or onboard data recorders. Finally, a discrete input pin is available to provide a lift-off signal to the GPS receiver. Using appropriate receiver software, this signal can be used to measure the accurate launch time and to compute auxiliary information that depends on the actual flight time (e.g. reference trajectory evaluation)

In the original receiver design, the main board is complemented by an equally sized interface board providing support elements like a voltage regulator, RS232 line drivers and a rechargeable backup battery for real-time clock operation and non-volatile memory retention during off-times. To comply with mission specific space, power and communication requirements, the auxiliary board has been replaced by a tailored version on most of the experimental sounding rocket flights conducted so far. As an example, Fig. 1 shows the Maxus-4 flight unit of the GPS Orion-HD receiver integrated by Kayser-Threde.

Fig. 1 Maxus-4 flight unit of the Orion GPS receiver with mission specific interface board (Kayser-Threde)

The GPS receiver hardware is complemented by a dedicated antenna system[6] made up of one or more passive antennas, optional R/F relays and a preamplifiers with a typical gain of 28 dB for each individual antenna string. While still on ground, an external antenna mounted at the launch pad and connected via the umbilical (or, alternatively, a re-radiation device) is used to provide unobstructed GPS signals and ensure a proper initialization of the receiver.

During the early flight, the receiver is connected to a helical antenna in the tip of the ogive (Fig. 2), which ensures optimum visibility of the GPS constellation and makes the signal reception insensitive to spin about the longitudinal axis. The tip antenna is thus well suited to support the use of GPS as an IIP prediction system for range safety purposes.

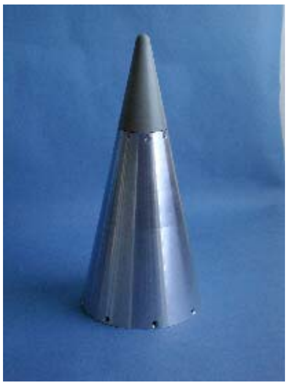

Fig. 2 Helical tip antenna with radome for GPS tracking of sounding rockets during the early flight phase (DLR Mobile Rocket Base)

After tip separation, a dual blade (or patch) antenna configuration has been proven to provide acceptable GPS tracking conditions even during the spin and reentry phase at considerably lower manufacturing and integration cost than traditional wrap-around antennas.

3. GPS Receiver Software

A basic software for the GPS Orion receiver has earlier been made available by Mitel Semiconductor as part of the GPS Architect Development Kit[13]. In contrast to alternative GPS software packages for operation of GP2015/GP2021 cards inside a host PC (GPS Builder[14], OpensourceGPS[15]) the GPS Architect software is specifically designed for use in a standalone GPS receiver employing the ARM60B microprocessor.

Despite its maturity, however, the GPS Architect code is essentially limited to terrestrial operations in a low dynamics regime and no effort has been made by the original developers to support its use in aerospace applications with intrinsically high velocities. Most notably, the prediction of line-of-sight Doppler shifts has therefore been modified by the authors to account for a non-negligible receiver velocity, the navigation solution has been reformulated in terms of Cartesian coordinates to avoid errors resulting from a neglected motion of the local horizontal frame in the spherical formulation, and the simple navigation filter assuming linear motion has been deactivated. Furthermore, a one millisecond timing error introduced by the bit-synchronization algorithm has been fixed.

To support a flexible operation of the receiver during pre-launch testing and in actual missions numerous enhancements have been performed to the command and telemetry interface. Output messages can be freely configured in accord with the available downlink capacity. Both NMEA type message formats and proprietary ASCII message strings are supported. Other than the original Orion firmware, which collects measurements at equidistant but otherwise arbitrary time steps after power up, the revised software provides for an active alignment of measurements epochs and navigations solutions to integer GPS seconds with a representative accuracy of 0.2 μs (S/A off). Along with this, a hardware signal (pulse-per-second) of 1 ms duration is generated at the occurrence of each integer second that can be used for onboard clock synchronization purposes. While raw measurements are internally collected at a 10 Hz sampling rate, the navigation solution and data output is performed at an update rate of either 1 Hz or 2 Hz.

The high dynamics of the relative motion of user and GPS satellite as well as the rapidly varying GPS constellation visibility pose a major obstacle for the space based use of a conventional GPS receiver. Dedicated modifications for high dynamics applications have therefore been made, which include an open loop aiding of the Doppler and visibility prediction[5] and the upgrade of the carrier tracking loops[16]. In view of the low signal levels and the time consuming correlation process special precautions have to be taken to achieve a rapid acquisition and an optimal channel allocation. This is readily accomplished by aiding the receiver with nominal trajectory information, if continuous GPS signal availability or operation of the receiver cannot be ensured. For sounding rockets or other ballistic missions the trajectory is represented by a piecewise, low order polynomial approximation stored within the non-volatile memory of the Orion-HD receiver. If code or carrier tracking should be lost during the flight, this information is used to compute the GPS satellites in view and the expected Doppler shift required to allocate and pre-steer the tracking channels.

While the original firmware implementation of a 2nd order frequency tracking loop (FLL) for the Mitel Architect and Orion receiver can essentially be used to track GPS signals even under high dynamics conditions, it suffers from an SNR dependent bandwidth and does not support accurate carrier phase tracking. It has therefore been supplemented by a 3rd order phase lock loop (PLL) with FLL assist[17] that is fully described in Montenbruck[16]. The tracking loop employs an arctan and Δarctan discriminator to sense the phase and frequency offsets. For terrestrial and low Earth orbit applications the loop filter is configured for noise bandwidths of B_F~2Hz and B_P~7Hz, whereas appropriately relaxed loop settings are employed for the increased dynamics encountered in sounding rocket applications. To ensure a reliable acquisition, the 3rd order PLL with FLL assist is only activated after proper frequency lock has been achieved with a pure 2nd order FLL using a cross-product discriminator. Its estimates of frequency and frequency change are used to initialize the corresponding values of the 3rd order PLL prior to activation. In this way, a robust acquisition of carrier phase tracking is obtained.

Both the 2nd order FLL and the 3rd order PLL do not exhibit acceleration dependent steady state errors and are only sensitive to high jerk. By combining both types of tracking loops one benefits from a favorable acquisition performance and the availability of carrier phase measurements. These are used to compute smoothed pseudoranges based on a simple filter operated at a 10 Hz measurement update rate and a characteristics averaging time of 20 s. The smoothed pseudoranges are subsequently used to compute the single point position solution and clock offset correction which thus exhibit a notably smaller noise level than in the unsmoothed case. Delta-ranges derived from carrier phase measurements between consecutive epochs are furthermore used to obtain the line-of-sight range rates at the instance of the latest measurement and the corresponding velocity with a much smaller noise level than achieved with instantaneous Doppler measurements.

4. IIP Prediction

Range safety at the launch site of a sounding rocket requires a continued monitoring of the instantaneous impact point (IIP). Following Koelle[18], the IIP designates the expected landing point following an immediate termination of the boosted flight. It represents a contingency, in which the rocket motor is intentionally deactivated by the mission control center following a guidance problem or other failure error during the propelled flight phase. The real-time computation and display of the IIP allows the range safety officer to discern whether the rocket would eventually land outside the permissible range area and thus necessitate an abort of the boosted flight or even a destruction of the malfunctioning vehicle.

To comply with the restricted computational resources of common real-time systems, a simple, yet accurate, analytical IIP prediction method has been developed by the authors[19]. It is based on a plane-Earth parabolic trajectory model with first order corrections for surface curvature, gravity variation and Earth rotation. Despite the implied simplifications the resulting model is more complete and of higher accuracy than conventional IIP algorithms based on a flat Earth approximation with Coriolis correction (see e.g. Regan et al.[20]). Overall the agreement with the full modeling of conservative forces is high enough to introduce IIP prediction errors of less than 1.5% of the ground range for sounding rockets reaching altitudes of up to 700 km and flight times of about 15 min. On the other hand the model is less complex than a perturbed Keplerian trajectory model or numerical integration and thus well suitable for real-time computations.

For the description of the rocket trajectory, we employ a local horizontal coordinate system which is aligned with the instantaneous East, North, and up direction and originates in the foot point of the satellite at time t_0. Starting from the initial position $\boldsymbol{s}_0=(0,0,h_0)^T$ and velocity $\boldsymbol{u}_0=(u_{0,\mathrm{E}},u_{0,\mathrm{N}},u_{0,\mathrm{up}})^T$, the sounding rocket performs a parabolic trajectory under the action of a constant vertical acceleration $-g$ and impacts at

$$\boldsymbol{s} = (u_{0,\mathrm{E}}\tau, u_{0,\mathrm{N}}\tau, 0)^T \tag{1}$$

after a flight time

$$\tau = \frac{1}{g}\left(u_{0,\mathrm{up}} + \sqrt{u_{0,\mathrm{up}}^2 + 2h_0 g}\right) \ . \tag{2}$$

A proper value of g is given by the effective surface acceleration[21]

$$g_{\mathrm{eff}} = 9.7803\ \mathrm{m/s^2}\ (1 + 0.005279 \sin^2(\varphi)) \ , \tag{3}$$

which accounts for the cumulative effects of the Earth's central, centrifugal and J_2 attraction. For extended ground ranges $d = (u_{0,\mathrm{E}}^2 + u_{0,\mathrm{N}}^2)^{1/2}\tau$ the local horizontal plane is no longer a good approximation of the geoid and the actual impact point is located at a negative height $h = d^2/(2R_\oplus)$. Along with an increase of the total flight time, the impact point is changed by a small amount

$$\Delta\boldsymbol{s}_{\mathrm{IIP}} = \frac{(u_{0,\mathrm{E}}^2 + u_{0,\mathrm{N}}^2)\tau^2}{2R_\oplus} \begin{pmatrix} u_{0,\mathrm{E}}/u_{\mathrm{imp}} \\ u_{0,\mathrm{N}}/u_{\mathrm{imp}} \\ -1 \end{pmatrix} \ , \tag{4}$$

where

$$u_{\mathrm{imp}} = \left|\dot{h}(t_0+\tau)\right| = -(u_{0,\mathrm{up}} - g\tau) \tag{5}$$

is the magnitude of the vertical impact velocity.

In the sequel, linearized expressions are provided to account for various perturbations that are not considered in the parabolic approximation of the trajectory. A first correction is required to account for the Earth's rotation and the fact that the chosen reference frame is non-inertial. This results in apparent forces known as centrifugal force (which is already considered in the effective gravitational acceleration) and the Coriolis force. Upon integrating the perturbing acceleration along the flight path, one obtains corrections to both the horizontal and vertical position components. While the East and North component of the above expression translate directly into a corresponding correction of the predicted impact point coordinates, the vertical component implies an increment to the computed flight time and an associated extension of the ground track. Upon combining both terms, the total IIP correction for Coriolis forces is given by the expression[19]

$$\Delta \boldsymbol{s}_{\mathrm{IIP}} = \omega_\oplus \begin{pmatrix} +u_{0,\mathrm{N}} \sin\varphi + (u_{0,\mathrm{E}}^2 / u_{\mathrm{imp}} - u_{0,\mathrm{up}}) \cos\varphi \\ -u_{0,\mathrm{E}} \sin\varphi + (u_{0,\mathrm{N}} u_{0,\mathrm{E}} / u_{\mathrm{imp}}) \cos\varphi \\ 0 \end{pmatrix} \cdot \tau^2 + \frac{\omega_\oplus g}{3} \begin{pmatrix} \cos\varphi \\ 0 \\ 0 \end{pmatrix} \cdot \tau^3 \quad .(6)$$

where $\omega_\oplus = 0.729 \cdot 10^{-4}$ rad/s denotes the Earth's angular velocity. The along-track shift of the IIP caused by the change in flight time (i.e. terms proportional to $u_{0,E}/u_{imp}$), which is commonly ignored in the discussion of the Coriolis correction is mainly relevant for a rocket launched in an eastern or western direction, whereas it has no effect for northbound or southbound trajectories.

A further correction is required to account for the non-constant gravitational acceleration. Here two independent effects must be considered for extended ground ranges and high altitude missions. First, the gravity vector is no longer perpendicular to the horizontal plane of the reference coordinate system, as the horizontal separation of the rocket from the initial foot point increases. This deflection of the plumb line results in an ever increasing deceleration and an associated shortening of the impact range by

$$\Delta \boldsymbol{s}_{\mathrm{IIP}} = -\frac{g}{6R_\oplus} \begin{pmatrix} u_{0,\mathrm{E}} \\ u_{0,\mathrm{N}} \\ 0 \end{pmatrix} \tau^3 \quad . \quad (7)$$

Secondly, the decrease of the gravitational acceleration g with altitude h results in an increased flight time, which again increases the resulting flight range. By linear expansion (which is justified for altitudes of less than 10% of the Earth radius) and integration along the flight trajectory, one finally obtains the following expression for the associated IIP shift:

$$\Delta \boldsymbol{s}_{\mathrm{IIP}}(t_0) = \frac{1}{3R_\oplus} \frac{(h_0 + u_{0,\mathrm{up}}\tau)(5h_0 + u_{0,\mathrm{up}}\tau)}{u_{\mathrm{imp}}} \begin{pmatrix} u_{0,\mathrm{E}} \\ u_{0,\mathrm{N}} \\ 0 \end{pmatrix} \quad .(8)$$

The two effects described by (7) and (8) are partly counteracting, which explains the reasonable accuracy of IIP predictions assuming a constant gravitational acceleration along the vertical. However, the net effect depends on the actual flight profile and it is therefore advisable to always include the respective corrections.

The perturbed parabolic IIP prediction model is simple enough to allow a computation of the instantaneous impact point inside the Orion-HD GPS receiver at the 2 Hz navigation update rate. As a rule-of-tumb, 2-3% of the available ARM60B processing power are required for the IIP computation as compared to 5-10% for a single navigation solution. After converting the results from the instantaneous horizontal local vertical frame to the global WGS 84 systems, the geodetic impact point coordinates are output along with other navigation and status data. For compatibility with the National Marine Electronics Association (NMEA) standard a special message format illustrated in Fig. 3 has been defined.

```
$PDLRM,IIP,120228.50,1,6834.2656,N,
02044.8612,E,0614.35*17
```

Fig. 3 Example of an NMEA compatible IIP data message providing the UTC time (12:02:28.5), the latitude (+68°34.2556') and longitude (+20°44.8612') of the predicted instantaneous impact point as well as the expected time to impact (614.35 s) for a simulated Maxus trajectory originating from the Kiruna launch site.

Table 1 Flight parameters for simulated VS-30 and Maxus scenarios

Parameter	VS30 (Cuma)	Maxus
Launch site	λ=-44.4° φ= -2.3°	λ=+21.1° φ=+67.9°
Boost duration	30 s	64 s
Flight time (to parachute)	415 s	870 s
Apogee altitude	180 km	710 km
Horizontal range	130 km	80 km
Max. velocity	1680 m/s	3330 m/s
Max. acceleration (ECEF)	12.1 G	12.5 G
Max. jerk	29 G/s	15 G/s

5. Simulator Testing

To assess the navigation and IIP prediction performance of the Orion-HD GPS receiver, hardware-in-the-loop simulations have been carried out using a Spirent STR4760 GPS signal simulator. Two scenarios with notably different flight parameters were considered to cover a representative set of mission profiles: a VS-30 rocket launched from the Brazilian Alcantara site and a Maxus rocket launched from Esrange, Kiruna (Table 1). The VS-30 scenario is based on the Cuma mission, which used a single stage S30 motor to carry its payload to a nominal apogee altitude of 180 km within 210 s from lift-off. During the 30s boost phase, the rocket reaches an altitude of 31 km and builds up a speed of 1680 km/s with a peak acceleration of 12 G. After a flight time of approximately 415 s, the parachute is opened and the payload ultimately touches down in the Atlantic ocean at a distance of about 130 km east of the launch site. The second scenario represents the standard flight path of the Maxus rocket, which provides the main platform for the European microgravity program (Fig. 4). The guided rocket achieves an apogee altitude of roughly 700 km with an 800 kg payload using a single stage Castor-4B booster and allows for a total µG time of 12 min.

Fig 4 The Maxus rocket has an overall length of 15.8 m and a total mass of 11.4 tons. It employs a Morton Thiokol Castor 4B motor, which develops a thrust of 430 kN over a 64 s burn time.

In accord with restrictions of the Spirent signal simulator, simulation trajectories approximating the nominal flight profile for both scenarios have been modeled by a continuous sequence of 3rd order position polynomials representing piecewise constant jerk (acceleration rate) over time intervals of 0.1 s to 5 s. The resulting acceleration and jerk profiles are illustrated in Fig. 5.

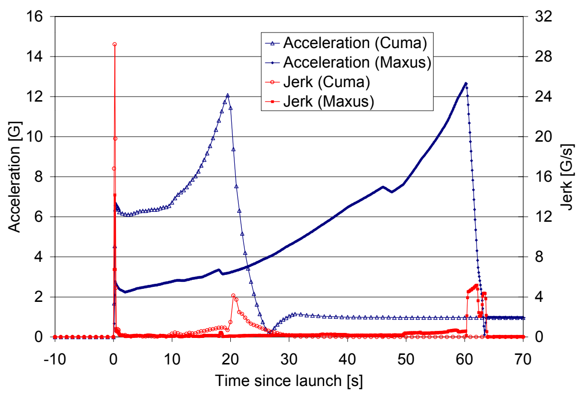

Fig 5 Total acceleration and jerk (in the Earth-fixed reference frame) for the simulated VS-30/Cuma and Maxus scenarios

Maximum jerks of 29 G and 15 G occur at boost start in the VS30/Cuma and Maxus scenario, respectively, while more moderate values of up to 4 G/s are encountered near boost termination. During the boost phase, the acceleration increases from 6 G (VS30/Cuma) and 2 G to a maximum of roughly 12 G in both missions.

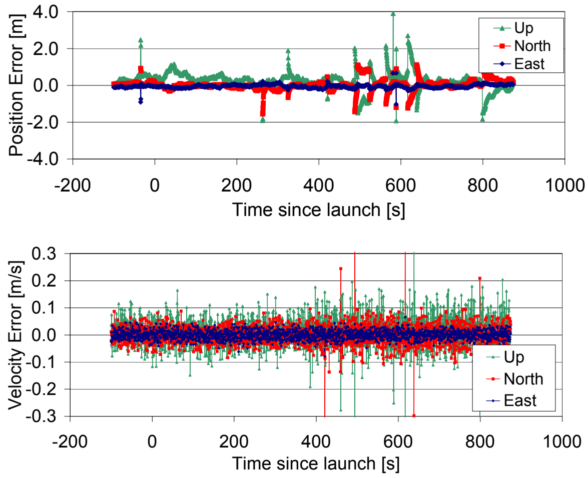

Fig 6 Position and velocity errors in East, North, and up direction for simulated Maxus scenario in the absence of tropospheric and ionospheric path delays.

A comparison of measured positions and velocities for the Maxus scenario with the simulated reference trajectory is shown in Fig. 6. In the absence of Selective Availability and broadcast ephemeris errors the position determined by the Orion-HD GPS receiver exhibits an r.m.s. scatter of 0.1 m, 0.3 m, and 0.5 m in East, North and up direction. Sudden jumps in the position solution at irregular intervals are caused by restarts of the carrier phase smoothing process on individual channels and reflect the inherent pseudorange accuracy of about 1 m.

The velocity noise amounts to roughly 2 cm/s, 4 cm/s, and 6 cm/s, respectively in the East, North and vertical axes, which includes contributions due to carrier phase noise and simplifications in the onboard velocity solution. No indications of an acceleration or jerk dependence of the navigation solution are obvious from data collected during the boost phase of the simulated Maxus trajectory. In case of the VS30/Cuma scenario (which exhibits a two times higher initial jerk value) navigation solutions with a similar accuracy as in the Maxus scenario were collected throughout the flight.

Overall, the tracking performance is in good accord with results reported previously[22] for a less demanding low Earth orbit application with line-of-sight accelerations of up to 1 G. As a result of the increased tracking loop bandwidth, however, the carrier phase noise (0.8-1.5 mm) and range-rate noise (0.25-0.5 m/s) is somewhat larger than in the low-dynamics application.

Results of the IIP prediction performed within the Orion-HD GPS receiver are shown in Figs. 7 for the Maxus scenario. Compared to an offline computation (using the true state vectors and a rigorous numerical trajectory integration accounting for all gravitational forces), the onboard IIP results differ by less than 2 km from the reference values and even better results are obtained for the shorter VS30/Cuma flight range (Fig. 8).

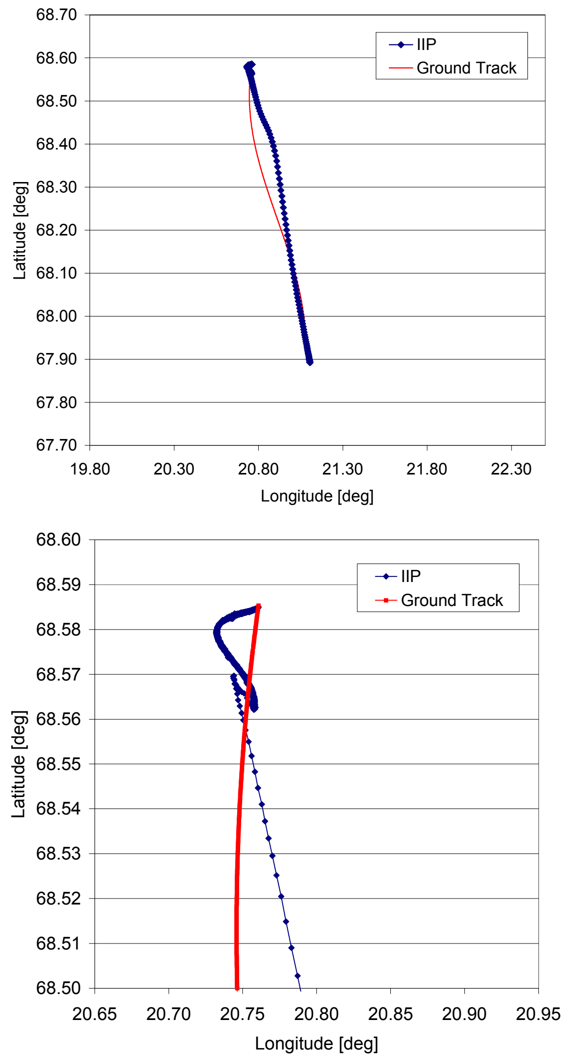

Fig 7 Onboard IIP results and ground track for simulated Maxus trajectory (*top*: complete flight path; *bottom*: close-up view of landing area). 0.01° in latitude correspond to roughly 1 km.

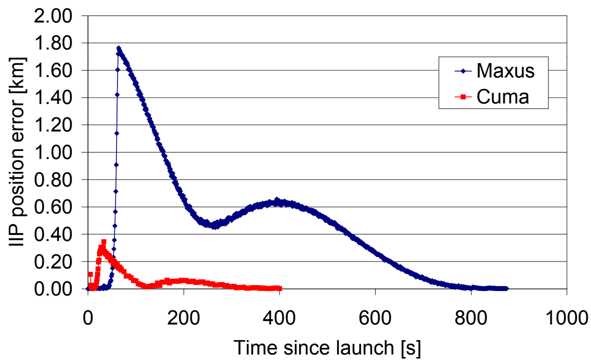

Fig 8 Error of onboard IIP prediction with respect to offline IIP computation using true state vectors and numerical trajectory model (Maxus and VS30/Cuma scenarios).

The onboard IIP prediction thus provides an adequate accuracy for range safety purposes and even slightly outperforms the operational, ground based IIP prediction used at Esrange Kiruna[23]. It has to be emphasized, however, that the neglect of atmospheric drag and lift forces may ultimately introduce a much higher uncertainty than implied by the above figures.

6. Flight Results

The Maxus-5 sounding rocket was launched on 1 April 2003 from Esrange Kiruna. It carried a scientific payload of 795 kg and reached an altitude of 701 km with a total µG phase of 736 s. GPS tracking was provided by two independent receivers, an Ashtech G12 HDMA and an Orion-HD. Continuous GPS coverage from launch to landing was ensured by a three-stage antenna system. It comprised a tip antenna (employed during the boost phase), a single patch antenna ("can antenna") mounted on the parachute can (available after deployment of the nose cone), and, finally, a dual-patch antenna combination (used during the descent and re-entry phase).

For redundancy, GPS data were transmitted to the ground via two independent S-band telemetry systems (payload and motor telemetry). The position and velocity measurements from both GPS receivers were used on ground to perform real-time predictions of the instantaneous impact point for range-safety purposes. In addition the onboard IIP prediction provided by the Orion receiver were transmitted as part of the telemetry data stream, but not yet used operationally.

In accord with the expected performance, the GPS measurements from both receivers agreed to 5 m and 0.5 m/s (3D rms) during the entire free-flight phase. Occasional outliers of up to 100 m and 10 m/s in the Orion-HD data can be attributed to an immature screening of bad pseudorange and range-rate measurements near the begin of track of new satellites. These (re-)acquisitions affect a single, low elevation satellite during the boost phase but are otherwise most frequent during operation of the dual patch antenna system, which suffers from pronounced gain drops at certain viewing angles. A more elaborate editing scheme is under consideration to reject bad measurements in future software versions.

No degradation of the tracking accuracy could be observed during the high jerk at boost end, where the acceleration dropped from 12 G to 0 G in about 2.5 s. At the beginning of the re-entry (with a peak jerk of ca. 6.5 G and a significant spin of ca. 0.8 Hz) a brief outage (4 s) with invalid Orion-HD navigation data occurred. After reacquisition of all channels the receiver yielded trustworthy navigation data through the re-entry shock with a maximum deceleration of ca. 35 G. Due to a loss of tracking of the G12 receiver at spin-up, no GPS based reference information is available during the final flight phase and the performance assessment of the Orion-HD receiver is exclusively based on the consistency with onboard accelerometers.

Overall, the Orion-HD receiver provided reliable tracking for IIP prediction throughout all flight phases. Following eqn. (1), position errors translate directly into IIP errors, whereas the effect of velocity errors scales with the remaining time to impact. For the given mission profile, GPS measurement noise therefore contributes less than 0.5 km to the IIP prediction error, which is in fair accord with results reported for the Ballistic Missile Range Safety Technology (BMRST) system[24]. It should be emphasized, however, that the IIP error budget is dominated by uncertainties in the modeling of atmospheric drag[19], compared to which the impact of GPS tracking errors can generally be neglected.

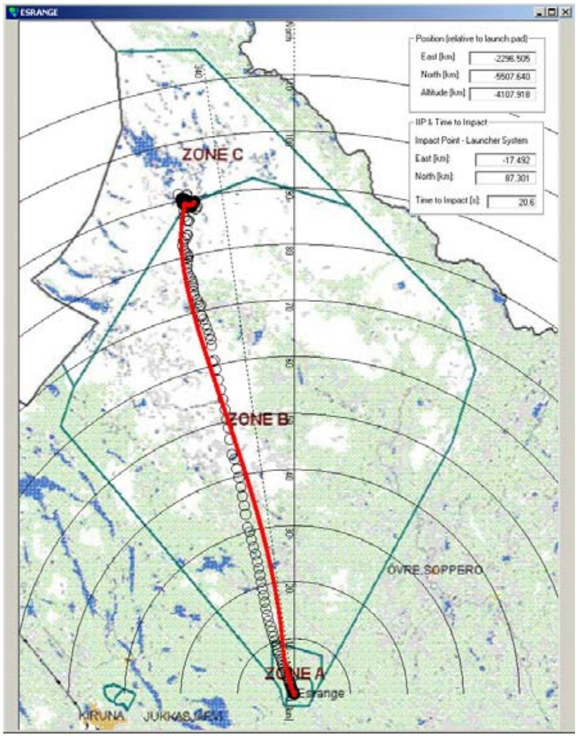

Fig 9 Plot of Maxus-5 ground track (solid line) and instantaneous impact point predictions (open circles) computed within the Orion-HD receiver.

Results of the onboard IIP prediction performed by the Orion-HD receiver are shown in Fig. 9. After burn-out of the Castor 4B engine, the predicted impact point matches the re-entry point and the actual landing point within about 3 km. This underlines a good overall modeling of the free-flight trajectory in the simplified onboard IIP prediction algorithm.

For further comparison, Fig. 10 shows the results of other real-time IIP predictions used for operational range safety purposes during the Maxus-5 mission. The IIP values computed inside the Orion-HD receiver are barely discernible from the GPS based predictions performed on ground. They notably outperform both the radar based IIP predictions computed on ground and the onboard IIP predictions provided by the inertial measurement unit (IMU) of the Maxus guidance system.

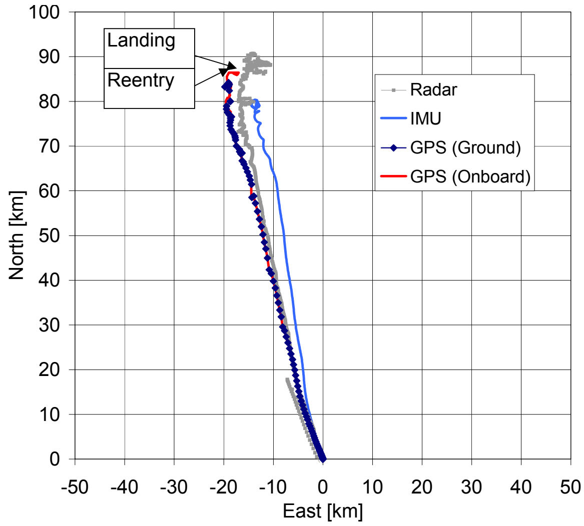

Fig 10 Comparison of IIP predictions for Maxus-5 using GPS, radar and inertial platform (IMU) data

7. Summary and Conclusions

The design and verification of the Orion-HD GPS receiver providing onboard IIP prediction for sounding rockets has been presented. Starting from a terrestrial low cost receiver design, the GPS Orion-HD receiver has received numerous modifications for high dynamics applications. Important enhancements include an aiding of the signal acquisition through coarse a priori trajectory data and the use of a 3rd order PLL with FLL assist that tolerates high accelerations. Furthermore, an analytical model for the prediction of the instantaneous impact point has been implemented in the receiver software. Starting from a simple parabolic trajectory model, various corrections are made to account for the curvature of the surface of the Earth as well as the integral effects of the Coriolis force and gravity field changes along the trajectory. Its accuracy is competitive with computationally more involved algorithms in existing range safety systems and can thus be used to make compatible IIP information available onboard the sounding rocket itself. Simulation results and actual flight data confirm the proper operation of the receiver as concerns both the fundamental navigation accuracy and the onboard IIP prediction.

Compared to the BMRST system[24], which employs an integrated GPS/IMU as well as a dedicated processor and RF transmitter in the space segment, the present solution is considerably less hardware intensive and makes a maximum re-use of existing onboard hardware. Despite its simplicity and low cost, the GPS-only solution has been shown to provide accurate IIP predictions in real-time and onboard the host vehicle. It is therefore considered as a valuable supplement for future onboard navigation systems of guided sounding rockets. Beyond the encouraging flight results obtained so far, further tests are under preparation to fully assess the robustness of Orion-HD receiver in critical situations and improve the overall maturity of the system.

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