

A LOW COST GPS SYSTEM FOR REAL-TIME TRACKING OF SOUNDING ROCKETS

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ABSTRACT

This paper describes the development as well as the on-ground and the in-flight evaluation of a low cost GPS system for real-time tracking of sounding rockets. The flight unit comprises a modified ORION GPS receiver and a newly designed switchable antenna system composed of a helical antenna in the rocket tip and a dual-blade antenna combination attached to the body of the service module. Aside from the flight hardware a PC based terminal program has been developed to monitor the GPS data and graphically displays the rocket's path during the flight. In addition an Instantaneous Impact Point (IIP) prediction is performed based on the received position and velocity information.

In preparation for ESA's Maxus-4 mission, a sounding rocket test flight was carried out at Esrange, Kiruna, on 19 Feb 2001 to validate existing ground facilities and range safety installations. Due to the absence of a dedicated scientific payload, the flight offered the opportunity to test multiple GPS receivers and assess their performance for the tracking of sounding rockets. In addition to the ORION receiver, an Ashtech G12 HDMA receiver and a BAE (Canadian Marconi) Allstar receiver, both connected to a wrap-around antenna, have been flown on the same rocket as part of an independent experiment provided by the Goddard Space Flight Center. This allows an in-depth verification and trade-off of different receiver and antenna concepts.

1. INTRODUCTION

The Mobile Rocket Base (MORABA) of DLR's German Space Operations Center plans, prepares and implements scientific sounding rocket and balloon campaigns in the fields of aeronomy, magnetospheric research, astronomy and microgravity. Tracking services are currently performed using C-band radars (AN/MPS-36, RIR-774C), which are relocatable but comprise bulky equipment and result in costly ground operations. As an alternative, the development of a low cost, GPS based tracking system for sounding rockets has therefore been initiated at DLR.

Available experience with commercial-off-the-shelf (COTS) GPS receivers shows that various models can provide continuous tracking of sounding rockets, provided that no hard-coded altitude or velocity limits are implemented. On the other hand, large tracking gaps have likewise been observed, which indicates that temporary signal losses cannot be handled properly by some receivers and that a reacquisition under highly dynamical motion is hard to achieve.

To enhance the tracking robustness and reliability, adaptations of the standard receiver software need to be performed, which prohibits the use of most COTS receivers. The Mitel Orion receiver [1] has therefore been selected for the implementation of a GPS based tracking system for sounding rockets, since it supports software modifications through the Mitel Architect development system [2].

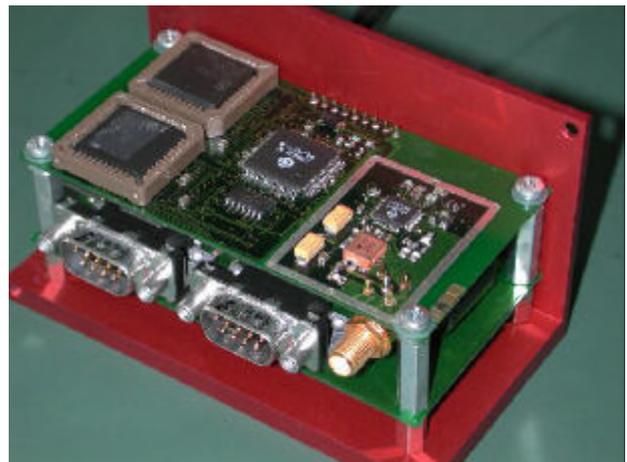


Fig. 1 The Mitel ORION receiver comprises a main receiver board (top) with RF front end, correlator, processor and memory as well as an interface board with power regulator, battery backup and serial interfaces (bottom). Physical dimensions are 95 x 50 x 30 mm³.

2. RECEIVER DESIGN AND MODIFICATION

The Orion receiver itself has been built by DLR based on Mitel design information [1]. It makes use of the GP2000 chipset, which comprises a GP2015 RF down-converter, a DW9255 SAW filter, a GP2021 correlator and a 32-bit ARM-60B microprocessor. Using a single active antenna and RF front-end, the receiver supports C/A code tracking of up to 12 channels on the L1 frequency. It is hardware and software compatible with the off-the-shelf GPS Architect Development System [2], but designed to act as a stand-alone receiver. To this end, the main receiver board is supplemented by an interface board, which comprises a power regulator, a backup battery for real-time clock operation and memory retention as well as a TTL-to-RS232 serial interface converter (Fig. 1).

The small size and the open-source policy makes the Orion receiver particularly interesting for the envisaged application on a sounding rocket. Here, most functions of the interface board are taken over by the on-board power system and data handling system, allowing a total receiver size of roughly 10 x 5 x 1 cm³.

To cope with the highly dynamical environment, various modifications of the standard receiver software have been made. While initial tests showed that the unmodified receiver is able to track GPS signals up to constant accelerations of about 15g and provides continuous tracking throughout the boost and free-flight phase of a sample sounding rocket trajectory, it cannot properly reacquire the tracking signals in case of a temporary signal loss. A position-velocity aiding concept has therefore been developed, which makes use of a piece-wise polynomial approximation of the nominal

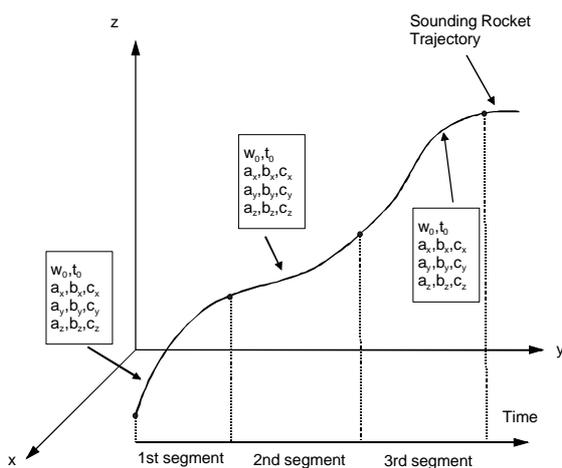


Fig. 2 Piecewise polynomial approximation of the reference trajectory of a sounding rocket. Each time interval is represented by its start epoch (GPS week and seconds) and three coefficients per axis.

flight path in Cartesian WGS84 coordinates [3]. To minimize the computational workload of the ARM processor, second-order polynomials in position have been selected, which provide a first-order approximation of the sounding rocket velocity (Fig. 2).

Up to 15 polynomials can be configured and stored via a suitably modified command interface, which is sufficient to provide a position accuracy of about 2 km and a velocity accuracy of roughly 100 m/s. Based on the polynomial approximation of the nominal trajectory, the reference position and velocity of the sounding rocket in the WGS84 reference frame are computed once per second. The result is then used to obtain the line-of-sight velocity and Doppler frequency shift for each visible satellite, which in turn serve as initial values for the steering of the delay and frequency locked loops. The position-velocity aiding thus assists the receiver in a fast acquisition or re-acquisition of the GPS signals and ensures near-continuous tracking throughout the boost and free-flight phase of the sounding rocket trajectory.

Further modifications comprise corrections to software limits for altitude and velocity, an extension of the Doppler computation to properly account for the receiver velocity and a replacement for the kinematic position and velocity determination. By default the least-squares estimation of the host vehicles state vector is carried out in spherical coordinates to support the implementation of an altitude hold-mode in case of lacking GPS satellite visibility. Since the frame rotation of the co-moving North-East-Up system is not properly accounted for in the original firmware, the velocity estimation exhibits a severe degradation in case of fast moving host vehicles. This is particularly notable for near-polar trajectories and high ground velocities. As a remedy, a traditional, Cartesian formulation has been implemented, which does not support fixed-altitude operation but provides accurate navigation solutions (WGS84 position and velocity) even for ballistic trajectories and orbiting spacecraft.

3. RECEIVER ON-GROUND EVALUATION

The modified receiver has been extensively tested in a signal simulator environment for a wide spectrum of different scenarios to validate the proposed trajectory aiding concept. Fig. 3 shows the offset of the predicted and NCO measured Doppler shift for PRN 7 in a simulation of the Texus-37 flight. Despite a 210 Hz overall frequency offset resulting from a known but unavoidable frequency error of the GPS Orion reference oscillator, the Doppler offset differs by at most 150 Hz (\cong 50 m/s) from the steady state value during the parabolic free-flight phase. Larger errors occur only after parachute deployment, which results in extreme accelerations and is not modeled by a suitable number of trajectory polynomials.

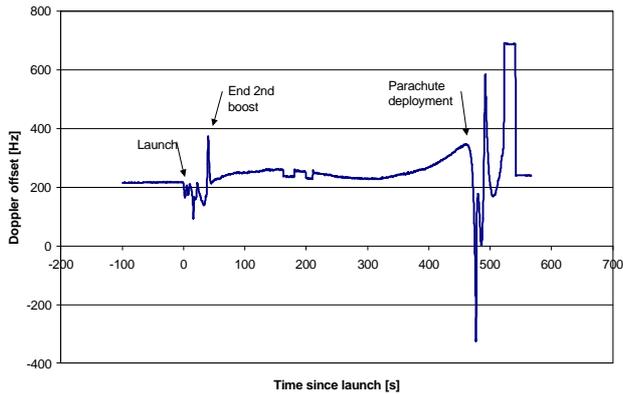


Fig. 3 Difference of predicted Doppler shifts and measured NCO values for PRN 7 in a Texus test scenario.

During the tests the signal was intentionally interrupted for several seconds at well-defined points of the trajectory. In all cases, the aided receiver was back on track much faster than the unaided receiver (Table 1).

Table 1 Reacquisition capability with and without trajectory aiding (times since launch for Texus scenario)

#	Interrupt From	Interrupt To	Reacquisition unaided	Reacquisition aided	Remarks
1	20s	30s	92s (1sat) 162 (3sat) 175s (nav)	32s (nav)	2 nd boost
2	76s	105s	n/a	106s (nav)	Ascent
3	181	240s	258s (nav)	245s (nav)	max. altitude

4. TEST MAXUS-4 CAMPAIGN

As part of the Test Maxus-4 campaign, carried out at Esrange, Kiruna, on 19 Feb. 2001, the Orion GPS receiver was first flown on a sounding rocket. The experiment served as a validation of a flexible antenna concept as well as GPS receiver technology.

The Orion receiver was placed inside the DLR service module, which housed a data handling unit and telemetry system. In addition the two blade antennas were attached to the walls of the service module. Two independent modules provided by GSFC and SSC kept two NASA GPS receivers, a Globalstar modem and a secondary TM unit. The complete payload section is shown in Fig4.

The Test Maxus-4 rocket was powered by a single stage Improved Orion motor (*note*: by accident the rocket motor and the GPS receiver shared the same name). During the 24s boost phase, the rocket built up a spin rate of 3.8 Hz along the longitudinal axis. Accordingly, the rocket maintained a constant and stable attitude with a near zenith-facing tip.

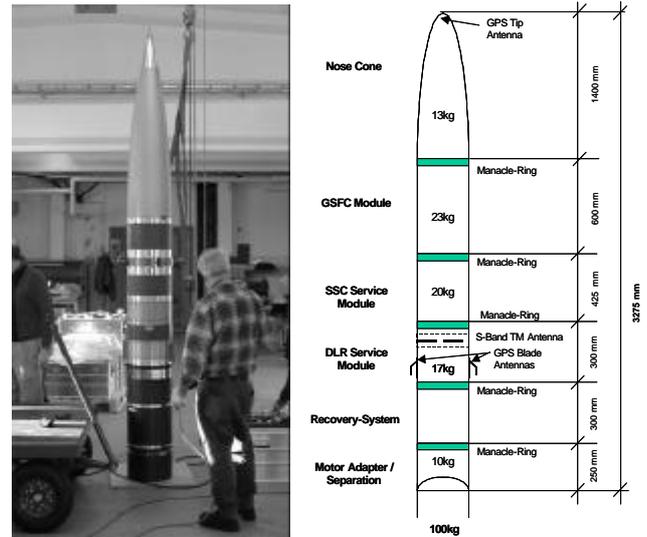


Fig. 4 The completely assembled payload before integration with the motor (*left*) and schematic view of the payload arrangement (*right*).

During the first 6s boost phase a maximum acceleration of 18g was reached, followed by a sustenance phase of 1g and 5g. After burnout a maximum rate of climb of 1100 m/s and a speed over ground of 280 m/s were measured. The rocket reached the apogee 2 minutes and 17 seconds after lift-off at an altitude of 81 km. Briefly thereafter the spin was removed by a yo-yo system and the top cone as well as the motor have been separated (Fig. 5). The service and recovery module started a tumbling motion from about h=40 km downwards. Between 25 and 15 km altitude the module decelerated to sub-sonic speed before parachute deployment at h=5 km. The payload and nose cone landed at a distance of 60 km from the range and were finally recovered by helicopter.

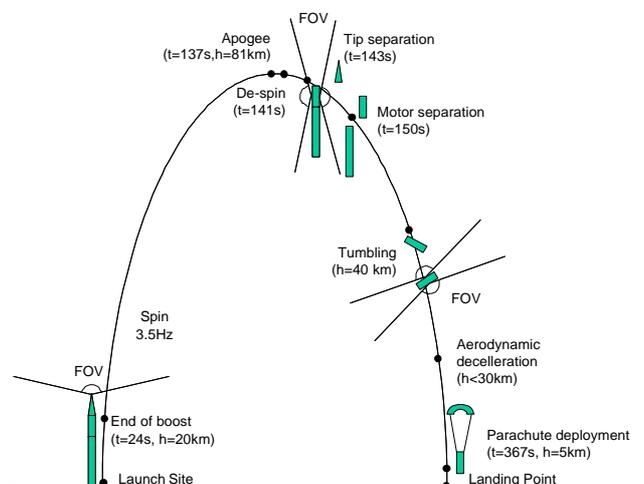


Fig. 5 Test Maxus-4 mission profile

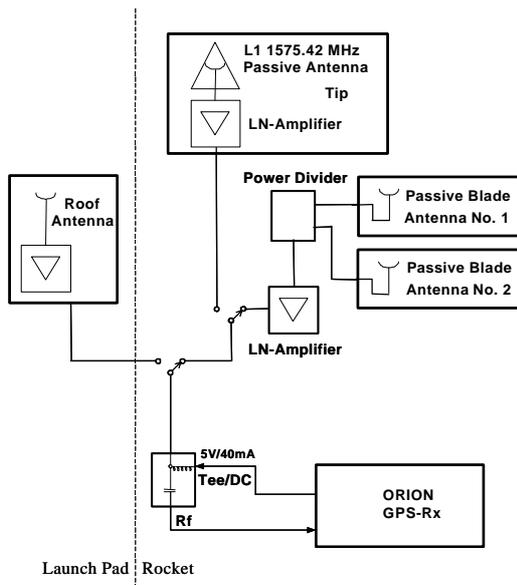


Fig. 6 Schematic view of the GPS antenna system.

5. ANTENNA SYSTEM

To support the different mission phases and to assess the suitability of different antenna concepts, the rocket was equipped with the multi-antenna system illustrated in Fig. 6. A helical antenna mounted in the tip of the rocket cone provides a near hemispherical coverage during the ascent trajectory. After separation of the cone, an R/F switch connects the GPS receiver to a pair of antennas mounted opposite to each other at the walls of the service module and combined via a power divider. This results in a near omni-directional coverage and can thus be applied even in case of a tumbling motion of the module [4]. Compared to wrap-around antennas that are otherwise used for GPS tracking of launchers, a blade antenna system can be manufactured at less than 10% of the overall system cost and does not require special milling of the sounding rocket structure for mounting.

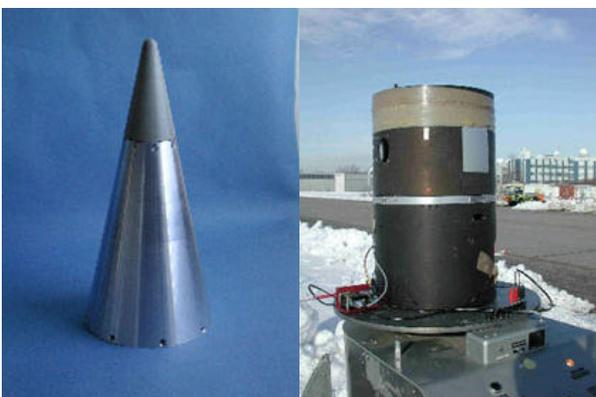


Fig. 7 Tip antenna(left); Test Maxus-4 module with attached blade antennas(right)

Finally, a separate antenna was mounted on the arm of the launch pad and connected to the receiver through a supplementary R/F switch prior to lift-off. Thus the receiver could be properly initialized and acquire all visible GPS satellites prior to launch.

5.1 Tip antenna

For GPS tracking during the first flight phase a helical antenna mounted in the tip of the rocket cone has been designed and manufactured by DLR (Fig. 7). The tip antenna provides near hemispherical coverage during the ascent trajectory. As long as the rocket keeps its initial zenith-facing attitude, an antenna mounted in the rocket tip ensures the best possible signal reception. Since the rocket built up a spin rate of about 4 Hz along the longitudinal axis during the burn phase, the initial attitude was maintained up to apogee. Due to the near-isotropic radiation pattern of the employed antenna, the system is insensitive to rotation around the symmetry axis

5.2 Blade Antennas

Blade antennas (Fig. 7) have previously been used for S-band telemetry data transmission and can easily cope with much higher temperatures than common GPS patch antennas. On the other hand, a blade antenna exhibits linear polarization, which implies a 3dB gain loss when used with right-hand circularly polarized GPS signals and a lacking multipath suppression. This is not a fundamental detriment, however, since the total gain of the antenna system can be adjusted by suitable amplifiers and since no reflecting surfaces other than the rocket body are present during the flight. Another potential drawback of the envisaged dual antenna system is the fact that destructive interference may result in pronounced gaps in the overall antenna diagram (Fig. 8). The latter effect should be most evident, if the diameter of the supporting structure and the resulting separation of the antennas is of similar order as the wavelength of the R/F signals [4].

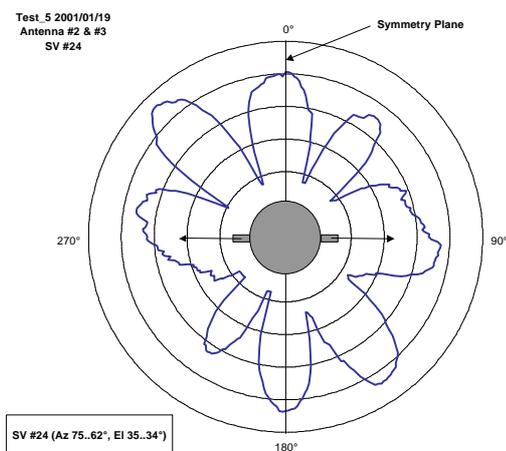


Fig. 8 360° antenna radiation pattern obtained during the on-ground evaluation of the blade antenna system (azimuth plane).

For the Maxus-4 test flight, the 14" diameter of the ORION rocket and the overall size of the antennas imply a separation of roughly two wavelengths between the phase centers at the L1 frequency ($\lambda=19.0$ cm). Preliminary ground testing with a 14" mockup has verified the expected antenna diagram with local maxima separated by azimuth angles of 30° to 60° (Fig. 8). Nevertheless, it could be demonstrated that a sufficient number of satellites can continuously be tracked by the combined antenna system both in a static configuration and a rotation around the symmetry axis of up to 0.5 Hz.

6. FLIGHT DATA ANALYSIS

6.1 Tracking Status

Analysis of the Orion GPS data recorded during the Test Maxus-4 campaign shows that the receiver and the antenna system worked well during the entire flight. The receiver has continuously been in 3D-navigation mode from payload activation on the launch pad (20 minutes before lift off) to the time when DLR telemetry lost contact near landing. Typically, the receiver had 10 to 11 GPS satellites in lock. Only during the first few seconds of the boost phase and during the reentry into the atmosphere a loss of some satellites can be observed (Fig. 9). Continuous tracking was even available near apogee, where short outages had to be expected due to the antenna switching at this time.

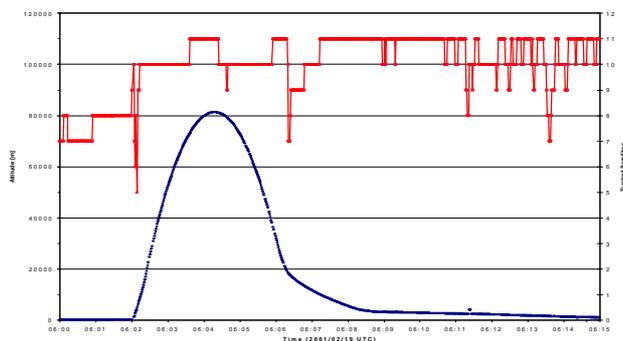


Fig. 9 History of the number of tracked satellites (solid line) and rocket altitude during the mission (diamonds).

Likewise, the tracking behavior during atmospheric reentry was expected to be critical due to the uncontrolled tumbling motion of the payload and the pronounced sensitivity gaps in the antenna diagram described above. While the performed ground tests indicated a moderate robustness in case of single axis rotation, the actual body motion and system performance during reentry could neither be simulated nor tested on ground prior to the mission.

Further information on the receiver and antenna performance during the different flight phases can be obtained from the signal to noise ratios (SNR) recorded during the flight for the various channels. Fig. 10 illustrates SNR values of four representative satellites.

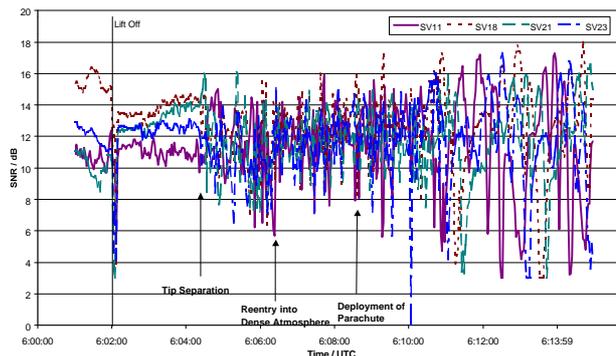


Fig. 10 SNR values for PRN 11, PRN 18, PRN 21 and PRN 23 in dB measured during the Test Maxus-4 flight.

The switching from the tip antenna to the blade antenna system at tip separation is clearly discernible from the suddenly increased SNR variation. The residual rotation rate of about 0.5 Hz left after the de-spin of the rocket, results in random like changes of the signal levels due to the antenna pattern. The average signal level, however, was at any time high enough to allow continuous tracking on all active channels down to an altitude of 40 km. Following the start of the atmospheric reentry the SNR variations exhibit a higher frequency and a moderately larger average value. Similar variations were also observed in the S-band telemetry link and are most likely related to orientation and spin rate changes during this mission phase. Several minutes after the main parachute deployment the payload system stabilized and the spin rate decreased to a few revolutions per minute. At the same time, however, more pronounced signal drops are encountered, which results in a rapidly changing number of tracked satellites below an altitude of about 2.5 km.

6.2 Receiver Performance Under High Dynamics

As mentioned above, a sudden drop in the number of tracked satellites occurred right after lift-off at 6:02 UTC. During this phase accelerations of up to 18g were encountered. While the receiver had constantly enough satellites in lock to compute a navigation solution, the obtained position and velocity values are notably degraded during the initial flight phase. This may be recognized both from a comparison of measured velocities with the nominal mission profile and a self-consistency test of velocity measurements and differenced position measurements. As shown in Fig. 11 for the WGS-84 z-velocity, the Orion navigation data exhibit a pronounced scatter for about 10 s that cover the primary boost phase. Thereafter the consistency of Doppler based velocity values and those derived from consecutive position measurements improves notably. An overall offset with respect to the nominal trajectory is readily explained by a 3% underperformance of the Improved Orion motor.

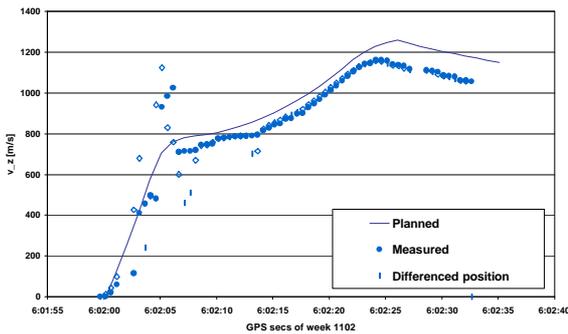


Fig. 11 Comparison of measured velocities with the nominal mission profile and a self-consistency test of velocity measurements and differenced position measurements during the thrust phase.

The observed phenomenon can be attributed to the physical acceleration forces during this phase and their impact on the GPS receiver's reference oscillator. Since the effect of the pure signal dynamic on the tracking behaviors has extensively been tested and analyzed in a wide spectrum of different simulation scenario it can be excluded as a cause for the observed phenomenon. In Figure 12 the oscillator error measured during the TestMaxus4 flight is displayed.

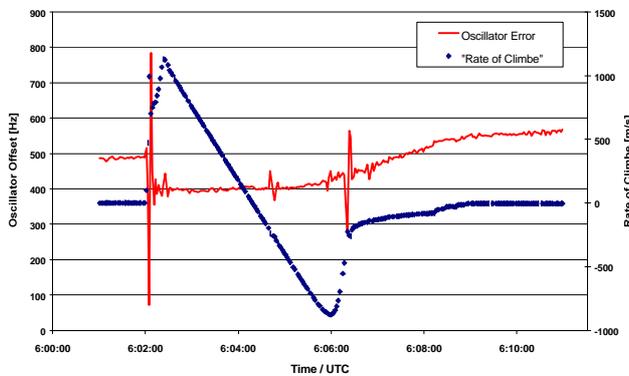


Fig. 12 Oscillator error in Hz in respect of L1 (*left scale*) and vertical speed (*right scale*) during the TestMaxus-4 flight.

Briefly after ignition one can observe large spikes in positive and negative direction in the frequency plot. After a few seconds in flight the oscillator offset stabilized on a value of about 100 Hz below the initial value. A similar but less intense effect appeared during the strong deceleration at reentry into the dense part of the atmosphere around 6:06:25 UTC.

Simultaneously with the beginning of the deceleration phase at 6:06:00 the average value of the frequency offset starts to increase slowly and stabilizes again during the parachute phase at a value of about 50 Hz

above the initial offset. Until now no detailed explanation for this behavior is known. Since there are a lot of possible sources for this phenomenon like e.g. acceleration, vibration, and temperature changes, it is hard to conceive which perturbation affected the oscillator in which way. A further investigation of the oscillator behavior and a potential means for a improvement will be performed as part of future flight experiments.

6.3 Navigation Accuracy and Performance Comparison

Since GPS is usually more accurate than ground based radar tracking, its absolute accuracy is difficult to prove if only one GPS receiver is flying on a sounding rocket. In the case of the Test Maxus-4 flight three different and independent GPS receivers were providing data. This gave the unique chance to make a detailed analysis of the accuracy of the obtained GPS solutions. Likewise it was a good opportunity to find out the pro and cons of each individual sounding rocket tracking systems. The Ashtech G12 HDMA flown by NASA in combination with a commercial wrap-around antenna [5] can be considered as a kind of reference in performance and accuracy for the other systems, since from technical point of view it is the most advanced and best evaluated GPS receiver for the use on high accelerated vehicles. For the sake of completeness the GPS data are also compared against radar tracking data to allow a more general statement about the performance as well as the future chances of this new technique in exchange for expensive and bulky radar tracking systems.

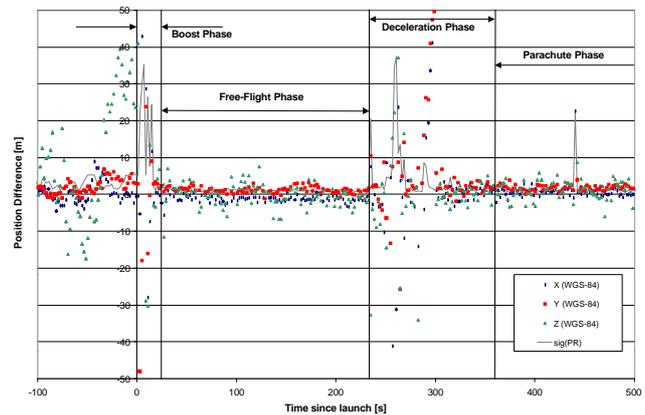


Fig. 13 Difference between the Ashtech G12 and the Orion position solution.

The differences between the Ashtech G12 on-board computed single point solution and the unfiltered Orion single point solution recorded during the TestMaxus-4 flight is illustrated in Fig. 13. In addition the r.m.s. values for the total position difference are given in Table 2, for the different flight phases.

During the good quality periods the GPS solutions obtained from the two receivers match each other to

better than 6.5 meters, which is in good accord with the expected overall accuracy of a GPS tracking system. The large perturbations after lift-off and during the re-entry phase can be attributed to the oscillator behavior already described above as well as a temporary loss of satellites during the descent. Due to the use of a dual antenna system the number of tracked satellites varied rapidly during the tumbling motion of the payload. As a consequence, the position dilution of precision (PDOP) and the associated noise of the position solution showed frequent spikes prior to the parachute deployment.

Table 2 R.M.S. values for the difference between Ashtech G12 and Orion position solution

#	Time / UTC From To	R.M.S [m]	Remarks
1	6:00:00 6:01:59	0.9	Before lift-off
2	6:02:00 6:02:24	90.0	Boost phase
3	6:02:27 6:05:52	1.5	Free-flight phase
4	6:05:55 6:06:44	29.0	Re-entry (h=39..14km)
5	6:07:00 6:09:19	3.4	Descent (h=12..2km)

The difference between the Ashtech and Orion position solutions exhibit a noise level of 1-29 m outside the boost phase (see Table 2). This is mainly attributed to the fact that the Orion single point position solutions are entirely unfiltered, whereas both filtering and carrier phase smoothing is applied within the Ashtech receiver. As may be recognized from inspection of Fig. 13, the average noise in the WGS-84 Z-direction is much higher than that observed in X- and Y-direction. At the high geographic latitude of the Kiruna site (71°) the majority of the visible GPS satellites reaches only a small elevation above the 0° horizon. This limits the achievable position accuracy in the vertical direction due to poor geometry. On average, the vertical position accuracy and noise is roughly 3 times larger than the corresponding values for the horizontal component of the position. Since the zenith facing axis of the local ENU coordinate system has a small angle toward the Z-axis of the WGS-84 coordinate system the reduced accuracy in the upwards-direction is likewise evident in an increased noise of the Z-position component.

Another critical point in the accuracy discussion is the refraction model used for the correction of the pseudorange errors due to ionospheric and tropospheric path delays. While tropospheric refraction can safely be neglected at altitudes above 10 km, the total vertical electron content varies only slightly from ground to apogee. However, the standard Klobuchar model implemented in representative GPS receivers does not allow proper modeling of ionospheric refraction corrections for satellites below the mathematical horizon. A different treatment of low elevation satellites will therefore cause significant changes in the estimated receiver positions at high altitudes.

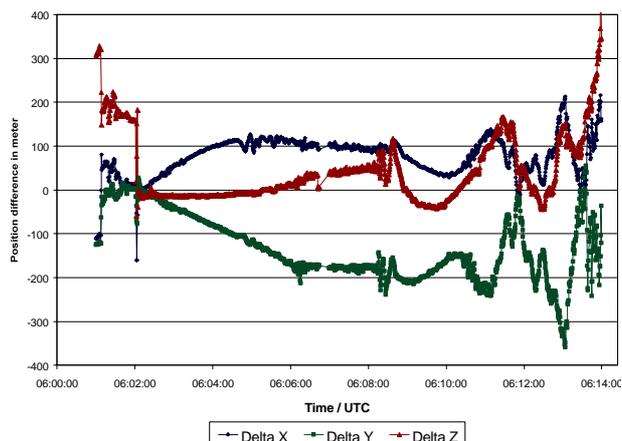


Fig. 14 Comparison of radar measurements and GPS solutions recorded during the TestMaxus-4 campaign.

A comparison between the GPS and the radar measurements (Fig 14) yields an overall r.m.s of about 200 m for the total position difference. A more detailed analysis has shown, that the position error of the radar tracking system can be attributed to an offset in the radar angle measurements. Since the radar system computes the rocket position from measured range and angle data and due to the fact that the accuracy of the angle determination is limited by mechanical constraints, the observed position error is not surprising. At the same time this shows the limits of the position accuracy achievable with a commonly used radar tracking system.

7. INSTANTANEOUS IMPACT POINT PREDICTION

Besides the use of GPS derived position data for the post-mission analysis of scientific experiments onboard a sounding rocket, GPS can also contribute to range-safety operations. An experimental Instantaneous Impact Point (IIP) prediction has therefore been performed during the Test Maxus-4 campaign. It employed position and velocity data provided by the Orion receiver to compute (in real-time) the expected touch down point under the assumption that the booster is no longer active. A major benefit of using GPS for impact point predictions lies in the simultaneous availability of 3-dimensional position and velocity information. While the current rocket position is determined from pseudorange measurements with an accuracy of about 10m (after the switch-off of Selective Availability S/A in May 2000), the velocity is obtained from line-of-sight Doppler measurements in the Orion receiver. Typical r.m.s. accuracies of 0.5 to 1 m/s in each axis have been demonstrated in signal simulator tests for representative sounding rocket trajectories. Other than ground based radar stations no filtering of subsequent positional measurements is required to obtain the complete 6-dimensional state vector of the rocket. A screenshot of the display is shown in Fig. 15.



Fig. 15 Screenshot of the Instantaneous Impact Point (IIP) prediction display. Ground track (line) and IIP (circles) for the TestMaxus-4 flight.

During the initial phase of the ascent trajectory a notable scatter of the predicted IIP can be observed. This may both be attributed to the real motion of the rocket and the fact that no filtering or screening of the position-velocity vector obtained by the GPS receiver has been performed. Further analysis, making use of other independent data sources, will therefore be required to separate both effects. The simplified (ballistic) model used in the present implementation of the IIP prediction is furthermore responsible for the fact that the IIP predicted briefly after burnout is about 10 km further away from the launch site than the value obtained briefly thereafter. Since the burnout takes place at an altitude of 24 km, the atmospheric drag reduced the ground speed by roughly 15 m/s during the subsequent ten seconds. As a result, the impact point distance is reduced by the above mentioned value.

After validation of the ground computation, the IIP prediction shall ultimately be carried out inside the Orion GPS receiver itself to minimize the ground interface and achieve an utmost independence from the particular launch site environment.

8. SUMMARY AND OUTLOOK

A GPS based real-time tracking system for sounding rockets has been developed. The chosen receiver architecture and antenna system provide increased flexibility for mission specific adaptations and reduced overall system cost. Aside from a description of the receiver hard- and software, the results of various hardware-in-the-loop simulations and ground tests are described. In addition, results from the first test flight on an Improved Orion rocket as part of the Test Maxus-4 campaign in February 2001 are presented and discussed. The GPS measurements are compared against flight data of a secondary receiver and radar tracking data. It is shown that the system performance and the position solution accuracy is competitive to that obtained by the more expensive system comprising an Ashtech G12

HDMA receiver and wrap-around antenna system. It is further confirmed that the use of GPS on sounding rockets results in a pronounced improvement of the achievable position accuracy compared with radar tracking. Further flight tests are planned for the mid of 2001. In addition to sounding rocket applications, preparations for a utilization of the described system on a LEO satellite as well as a re-entry vehicle have been started.

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