GPS Tracking of Sounding Rockets – A European Perspective

Oliver Montenbruck(1), Markus Markgraf(1), Peter Turner(1)
Wolfgang Engler(2), Günter Schmitt(2)

(1)Deutsches Zentrum für Luft. und Raumfahrt (DLR), German Space Operations Center(GSOC)
Oberpfaffenhofen, 82234 Wessling, Germany
Email: oliver.montenbruck@dlr.de

(2)Kayser-Threde GmbH
Irschenhauser Str. 48, 81379 München, Germany

ABSTRACT

Following a series of initial qualification flights, GPS is today considered as a promising and feasible tracking technology within the European sounding rocket program. Compared to traditional radar systems, GPS offers an improved accuracy as well as the onboard availability of navigation and timing information. Difficulties in the use of GPS on sounding rockets stem from the high dynamics and the environmental conditions that necessitate special receiver and antenna systems. To reduce the dependence on US providers, dedicated antenna systems and a high-dynamics GPS receiver have been developed by the authors. As part of the Texus/Maxus program these system components have demonstrated their performance and are now expected to find their way into a regular operational usage. The paper outlines the requirements for GPS tracking of sounding rockets, describes available commercial and in-house technology and presents a performance valuation based on actual flight results. Future development lines are identified based on the needs of both science users and range safety standards.

INTRODUCTION

Sounding Rockets take their name from the nautical term *to sound* which means to take measurements. They are basically comprised of a solid fuel rocket motor and the payload. The payload is the section which carries the instruments to perform the experiment and to send data back to Earth. After burn-out and separation from the motor the payload follows a parabolic trajectory with flight times of less than 30 minutes. When the experiments are completed, the payload re-enters the atmosphere and a parachute is deployed, bringing the payload gently back to Earth. The payload is then retrieved for experiment recovery and subsequent refurbishment. A representative mission profile is illustrated in Fig. 1.

While sounding rockets make up a small fraction of the European space programs, only, they provide an essential complement and supplement to other research opportunities. By their nature, sounding rockets can access altitudes that are neither reachable by airplanes and balloons on one side nor by orbiting satellites on the other side. Within a range of 30 km and 250 km, in-situ measurements of the atmosphere are almost exclusively obtained by sounding rocket probes. While the duration of individual experiments is limited by typical flight times of 5 to 15 minutes, sounding rockets provide a high flexibility and affordable mission cost. Experiments can be scheduled on short notice, which is likewise important for the various kinds of solar and astrophysical observations conducted on sounding rockets. Last but not least, sounding rockets provide an established platform for biological, physical and technological experiments in weightlessness, which is well accepted even in the age of the manned space stations.

Within the European micro-gravity programs, sounding rocket launches are routinely performed in northern Sweden from the Kiruna launch site. Common systems include the dual stage Skylark 7 rocket flown in the Texus and Maser missions with a peak altitude of 250 km as well as the more powerful Maxus/Castor-4B rocket (Fig. 2) that is capable of carrying an 800 kg payload up to an altitude of 700 km. In addition to these, a variety of other motors (Viper, Orion, Nike, Super Loki) are employed in atmospheric and astrophysical research projects conducted for European scientists from launch sites in Europe, America and Australia and Antarctica.

The launch of sounding rockets is traditionally supported and monitored by ground based tracking radars. They provide trajectory information for a variety of applications, including range safety monitoring, scientific data analysis and payload recovery. Due to the pronounced operations and maintenance cost of radar systems, the interest in alternative, GPS based tracking systems has continuously increased since the first flight demonstrations [1]. Benefits of GPS include the provision of both position and velocity information, the high accuracy and onboard availability of navigation data as well as the provision of a precise timing reference [2]. Recently, the US National Research Council has recommended GPS as a key technology for future range safety installations [3].

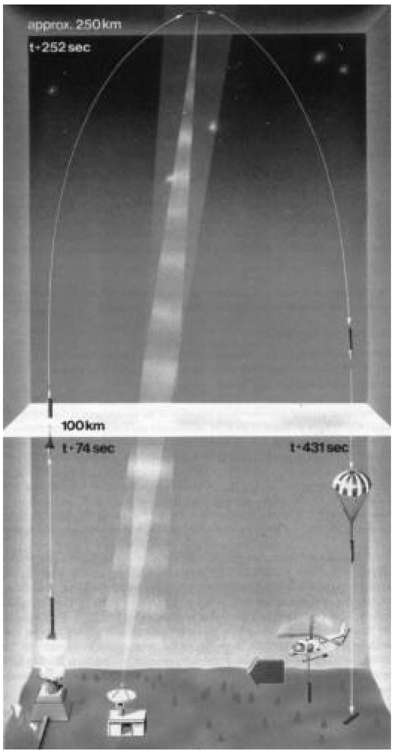

Fig. 1. Texus mission profile (© Astrium)

Fig. 2. Maxus rocket at Kiruna launch site (© SSC)

Within the European sounding rocket community, Kayser-Threde (KT) and the Mobile Rocket Base of DLR's German Space Operations Center have actively promoted the use of GPS on sounding rockets and performed a series of flight demonstrations. Following the first successful flight of an Astech G12 HDMA receiver onboard the Texus 37 rocket in 2000, GPS tracking systems have been employed on all subsequent Texus and Maxus missions. While the use of GPS as a sole means of navigation information is still under discussion, sufficient progress in receiver and antenna technology has been made to consider GPS tracking of sounding rockets a market ready technology and a valuable complement to existing ground facilities.

In view of prevailing US export restrictions that seriously hamper access to commercial-off-the-shelf equipment, independent receiver and antenna systems have been developed as part of an ongoing research and development program. The employed receiver is based on the Mitel Orion design and makes use of the GP2000 chipset. It provides 12 channel C/A code tracking on the L1 frequency to determine the user position and makes use of Doppler measurements to derive the instantaneous velocity of the host vehicle. The basic firmware has received various modifications and fixes to safeguard the receiver against signal losses and improve its tracking performance and accuracy. Supplementary to the Orion GPS receiver, new antenna concepts have been introduced as an alternative to costly wrap around antennas. These comprise the use of a helical tip antenna as well as a dual blade antenna configuration attached to the body of the payload service module.

The above GPS tracking system has been tested on three sounding flights launched from Esrange, Kiruna, in the first half of 2001. The employed launch vehicles utilized an Improved Orion motor (Test Maxus-4 campaign), a Castor-4B engine (Maxus-4 mission) and a dual stage Goldfinch/Raven booster (Texus-39). The overall suitability of the new receiver and the employed antenna system could thus be successfully demonstrated over a wide range of dynamic conditions.

GPS SYSTEMS FOR SOUNDING ROCKETS

GPS Applications

A GPS receiver may serve multiple purposes on a sounding rocket during the individual mission phases. Possible applications include e.g.

- *Range Safety*: During the boosted ascent trajectory, the GPS position and velocity measurements allow for a rapid recognition of guidance errors and real-time prediction of the instantaneous impact point (IIP) [4]. Based on this information, the range safety officer may decide on the need and feasibility of an abnormal flight termination.

- *Geolocation and time tagging*: absolute 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.
- *Event triggering*: using absolute time and position data, experiments and service systems may precisely be activated at the desirable flight stage. A GPS receiver may thus take over functions traditionally performed by mechanical timers and barometric switches.
- *Recovery*: during the final descent and parachute phase a GPS receiver can continuously relay the instantaneous payload position to the control center to allow a rapid and reliable recovery even in the presence of pronounced wind fields.
- *Performance and trajectory analysis*: the position and velocity measurements of a GPS receiver can 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.

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 [3]. For completeness we mention that GPS receivers with multiple frontends can be used to determine e.g. the main body axis orientation and spin state of a rocket (see e.g. [5]). Attitude related applications will not, however, be addressed in this report.

Antenna Systems

Ideally, a GPS antenna for sounding rockets should provide a near omni-directional coverage and be mounted on the payload module to allow GPS tracking during all flight phases independent of the instantaneous body orientation. These requirements are almost ideally met by wrap-around antennas that consist of properly coupled individual patches mounted like a belt around the circumference of the rocket. Despite the superior technical characteristics, wrap-around antennas exhibit various draw backs, which have triggered the search for alternative concepts. Wrap around antennas are difficult to design and manufacture for large diameters and are typically available for common 14” to 17” tubes, only. In addition to the high cost of the stand-alone wrap-around antenna that are well on the order of 10000 US$, specialized tubes with enhanced wall thickness and a milled grove are required to hold the antenna ring. Last but not least, wrap around antennas are subject to US export restrictions which further limit or complicate their use for European providers of sounding rocket services.

Fig. 3. Tip antenna

Fig. 4 Blade antenna

Various alternative antenna systems that support tailored mission requirements at reduced system engineering cost have, therefore, been developed by the authors and qualified on European sounding rockets:

- *Tip antenna*: A helical antenna mounted under a conic radome in the rocket tip provides a full sky coverage during the ascent of a sounding rocket. Tip antennas have first been used in 1998 within the Maxus-3 flight. Due to the particular antenna placement, the GPS signal reception is independent of the rocket’s spin about the body axis. A tip antenna, therefore, provides an ideal choice for GPS based range safety systems that require reliable tracking during the boost phase of a sounding rocket flight. The right-hand circular polarization, narrow bandwidth and optimum separation from onboard transmitters make the tip antenna particularly robust and easy to use in a sounding rocket environment. On the other hand, its use may conflict with sensor experiments requiring a tip position or an early tip separation during the mission.

- *Can and parachute antennas*: During the free flight phase and the final descent GPS tracking can conveniently be obtained by simple patch antennas placed on top of the parachute canister and in the leashes of the parachute. Before and after the hot reentry the environmental conditions are benign enough to allow use of commercial-off-the-shelf antennas and no space qualified hardware is required. The concept was first demonstrated by KT during the Maxus-3 flight in 1998. It offers remarkably low system cost but lacks the capability to monitor the high deceleration during the atmospheric reentry phase.
- *Blade antenna combinations*: In an effort to minimize antenna switches and improve the overall mission coverage, the use of combined blade antennas has been studied by DLR [6]. The most elementary configuration comprises two blade antennas attached to the body of the payload segment and connected in a phase coherent way via a power combiner. The coverage resembles that of a wrap around antenna but exhibits pronounced gaps due to destructive interference of signals from the two antennas. The detailed shape of the combined antenna diagram depends on the tube diameter (in relation to the 19.5cm wavelength of the L1 signals) and can be measured in ground experiments. These as well as the initial flight demonstration within the Test Maxus-4 mission [7] indicate that a sufficient number of satellites can always be tracked despite the interference gaps and that the system can also be used at moderate spin rates. The simple design makes the antennas environmentally robust and enables tracking also during the hot reentry phase. Disadvantages include the linear polarization of the blade antennas, which implies a 3dB gain loss and increased multipath errors in the launch site environment. Furthermore, the large band width of the blade antennas makes the GPS reception more sensitive to jamming signals.

Switching between individual antennas in a multi-antenna system can be accomplished by R/F relays controlled by timers, break-wires or barometric switches. Depending on the relative location and center frequency of GPS antennas and onboard transmitters the use of narrow band-pass filters or notch filters may, furthermore, be required in a GPS antenna system for sounding rocket applications.

Receivers

GPS tracking of sounding rockets differs in various ways from terrestrial GPS applications. Evidently, the receiver must be operated at higher speeds and altitude than imposed by International Traffic in Arms Regulations (ITAR), which restrict the use of publicly available receivers to a height of less than 60000 feet (ca. 20 km) and a velocity of less than 1000 knots (ca. 500 m/s). For the use of commercial receiver systems onboard a sounding rocket, the hardcoded firmware restrictions have to be disabled by the manufacturer and an appropriate waiver by the US government is required for the receiver operation. Leaving aside these legal issues, the high vehicle dynamics poses a major obstacle for the GPS based tracking of sounding rockets. A suitable mechanical protection is clearly required to avoid a receiver damage due to vibration and high accelerations (up to 30 g) in the boost and reentry phase. This is less concerning, however, than the signal dynamics caused by the relative motion of user and GPS satellite. Tracking loops must be able to follow rapid changes in the signal frequency and yet provide accurate measurements. Likewise, signal acquisition algorithms have to allow for an increased Doppler search interval to account for the high speed of the host vehicle (e.g. more than 3000 m/s on a Maxus mission).

Out of various receivers that have been tested in a signal simulator environment or flown in early trials after deactivation of the altitude and velocity constraints, the Ashtech G12 HDMA receiver has emerged as the adopted standard for sounding rocket applications within NASA [2]. It has likewise been applied by KT in the Texus and Maxus program from 2000 onwards. Within these flights, a good tracking performance has generally be obtained, even though dropouts related to antenna switching have been observed in some cases, that indicate problems in the signal re-acquisition after occasional interrupts. Given these technical limitations, the high unit cost (presently 15000 US$) and the tedious and unpredictable export procedures for US receivers, a development program for an independent GPS tracking system has been initiated at DLR in 1999. Within this program a Mitel GPS Orion receiver has been specifically modified and adapted to support sounding rocket applications.

The Orion receiver itself has been built by DLR based on Mitel design information [8]. 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 [9], but designed to act as a stand-alone receiver. The receiver board measures roughly 10 x 5 cm^2 and is supplemented by a mission specific interface board for accessing the onboard power and telemetry/telecommand system. Also the I/F board will usually carry a backup battery for non-volatile memory retention and real-time clock operation. A sample flight receiver is shown in Fig. 5.

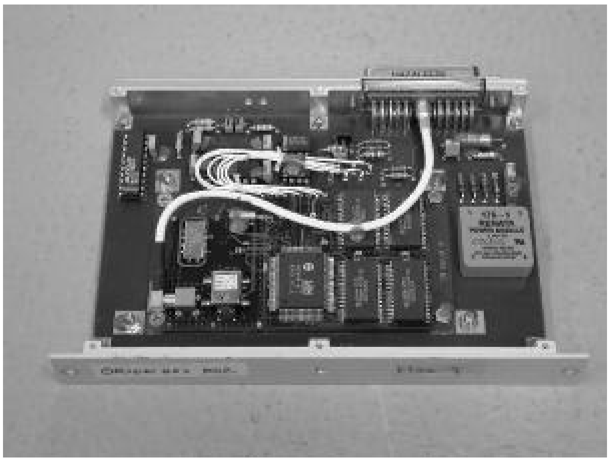

Fig. 5 ORION GPS unit for the Maxus-4 mission.

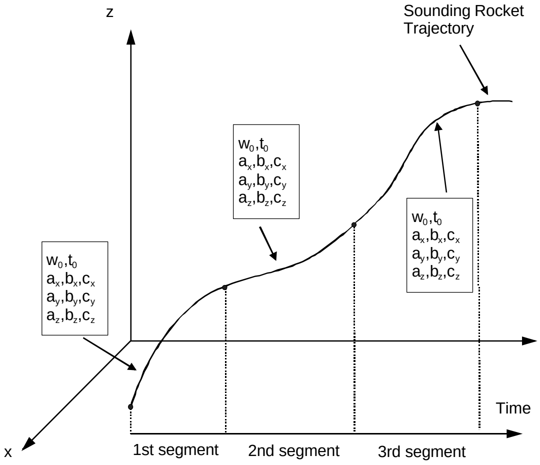

Fig. 6 Piecewise polynomial approximation of the reference trajectory of a sounding rocket. Each time interval is represented by its start epoch (GPS week and seconds) and three coefficients per axis.

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 flight path in Cartesian WGS84 coordinates [10]. 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. 6).

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. For increased flexibility, the reference time of the trajectory polynomials can either be configured by command or automatically be set at lift-off via a discrete input.

Further modifications comprise an extension of the Doppler computation to properly account for the receiver velocity, a replacement of the kinematic position and velocity determination (which deteriorates at high velocities near polar regions), a pulse-per-second synchronization and a correction of the measurement time tagging.

FLIGHT EXPERIENCE

Test Maxus-4 Flight

A first flight valuation of the GPS Orion receiver was performed on 19 February 2001 during the test flight of an Improved Orion rocket in Kiruna. The primary mission goal consisted in the validation of existing range safety facilities (radar and one-way slant-range system) prior to the Maxus-4 campaign. As an add-on various GPS receivers (Ashtech G12 HDMA, BAe Allstar and Mitel Orion) have been tested in experiments conducted by NASA/WFF [11] and DLR. During the 24 s boost phase a spinrate of 3.5 Hz was built up, which ensured a stable attitude of the rocket during the ascent trajectory. Within the first six seconds the peek acceleration of the single stage engine amounted to 18g, while it varied between 1g and 5g thereafter. At burnout in 20 km altitude a climb of 1100 m/s and a ground velocity of 280 m/s have been achieved. Near apogee (80km altitude) the motor and nosecone were from the payload, which was safely returned to ground by a parachute recovery system.

Aside from a qualification of the Orion GPS receiver, the test flight also served for the analysis of an antenna system made up of tip and blade antennas. During the boost and ascent phase a helical antenna mounted in the rocket tip allowed reception of GPS satellites visible above the apparent horizon. Following the separation of the tip near apogee the receiver was switched to a system of two blade antennas mounted on opposite sides of the payload segment with an in-phase combination of the received signals.

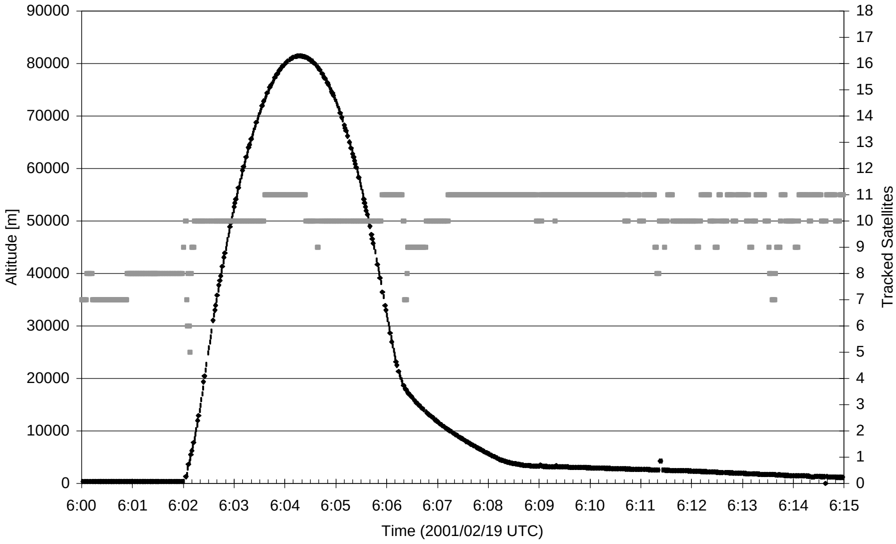

Fig. 7. Altitude and number of GPS satellites tracked by the Orion receiver during the Test Maxus-4 flight

Within the test flight the overall suitability of the receiver and the employed antenna system could successfully be demonstrated. Throughout the entire flight from launch to landing pseudoranges from five and more GPS satellites (9-11 typical) have continuously been measured (Fig. 7). This is particularly remarkable in view of the blade antenna system used during the descent phase, which is characterized by pronounced drops in the cumulative antenna diagram. Despite notable signal-to-noise ratio variations caused by the tumbling motion of the payload module a sufficient number of satellites could be tracked in this part of the mission. Likewise, it was demonstrated that the receiver would not loose tracking during the boost phase with peak accelerations of 18g. In comparison to the Asthech G12 HDMA receiver carried on the same flight, individual single point solutions of the two receivers were shown to match each other to a level of few meters during the free flight phase.

Aside from the positive results described above, it is evident, however, that the measurements collected during the initial boost phase are notably deteriorated by frequency variations of the reference oscillator. A similar but less pronounced degradation is again observed during the atmospheric reentry. Due to the use of off-the-shelf components with mechanical tuning elements the observed behavior is not, however, entirely unexpected. As a corrective measure, qualified oscillators for highly dynamical loads will be employed in future receiver models.

Maxus-4

The Maxus-4 rocket (cf. Fig. 2) was launched from ESRANGE, Kiruna, on April 29, 2001 (11:28 UTC). The payload segment weighed a total of 803 kg and comprised seven material sciences experiments in five different experiment units. A single stage Castor-4B motor carried the payload to an altitude of 703.4 km and allowed for a zero-g time of more than twelve minutes. Due to problems in the guidance system, the flight path started to deviate from the planned trajectory from about 10 s after lift-off. As a result, the ground track was shifted in a westerly direction and the payload ultimately crossed the border before landing in Norway. Furthermore, the main parachute was destroyed after being deployed too early due to a malfunction, which resulted in a final sink rate of about 90 m/s. While the payload segment was badly damaged due to the abrupt deceleration, valuable data and samples required for the scientific post-mission analysis could still be recovered. Likewise, the Orion GPS receiver experienced no evident damage during touch down and was found to be electrically functioning after disassembly of the payload module.

The Orion receiver tracked the position and velocity of the Maxus-4 payload from lift-off to landing with the exception of two outages related to antenna switching. 3D navigation was first lost for 5.5 seconds after the boost end (t=65.4 s to 70.4 s), even though one to two satellites were continuously tracked throughout this interval. Prior to the reentry, no tracking was available for 92 s after separation of the can, which took place at t=851 s. Position and velocity information was regained at 943 s, before telemetry transmission was ultimately terminated at t=961 s. Throughout the boost and free flight phase the Orion receiver tracked between 9 and 12 satellites, yielding PDOP values better than 2.0. The slow decrease in the number of tracked satellites correlates with changes in the signal-to-noise (SNR) ratios, which indicate a slow but notable change in the antenna boresight direction during the parabolic flight.

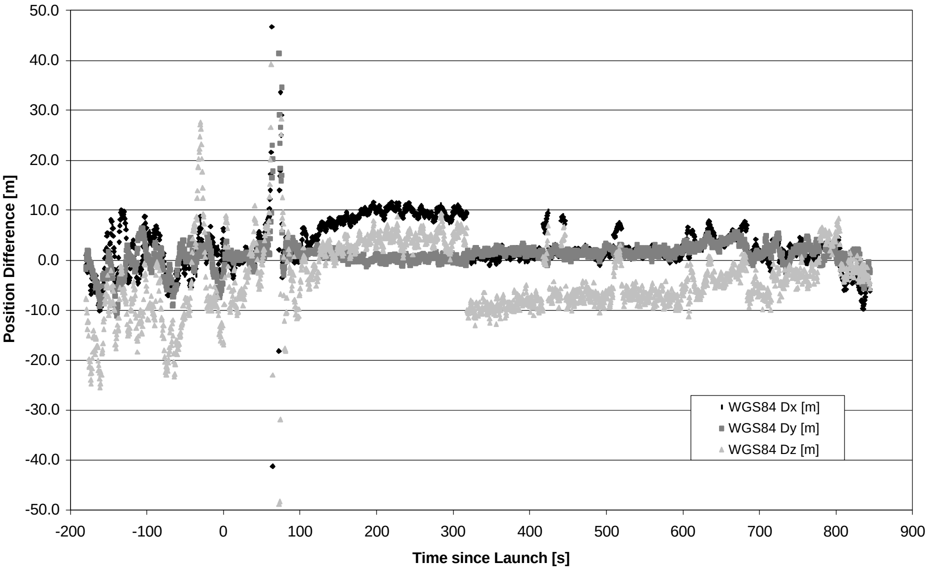

Fig. 8. Mean offsets of the Orion position solution as compared to G12 reference data during the Maxus-4 mission

The accuracy of the GPS Orion navigation solution was assessed by comparison with Ashtech G12 HDMA data collected on the same flight. The navigation solutions agree to roughly 10 m (Fig. 8) and 0.5 m/s during the pre-launch and free flight phase. Slightly increased position errors during the pre-launch phase can be attributed to multipath effects caused by reflections in the vicinity of the launch pad. Only moderately increased velocity errors are encountered during the boost phase, and major tracking errors may only be observed right after the end of boost. This behavior is again related to mechanical stress of the quartz oscillator at the time of maximum yerk and can be overcome by the use of qualified oscillators for high dynamics applications. Overall, the observed differences between the Orion and G12 navigation solution are within expectations and readily understood by differences in the set of tracked satellites as well as the modeling of atmospheric path delays. In addition, no filtering or carrier phase smoothing is applied in the Orion navigation solution, which results in a somewhat higher noise level.

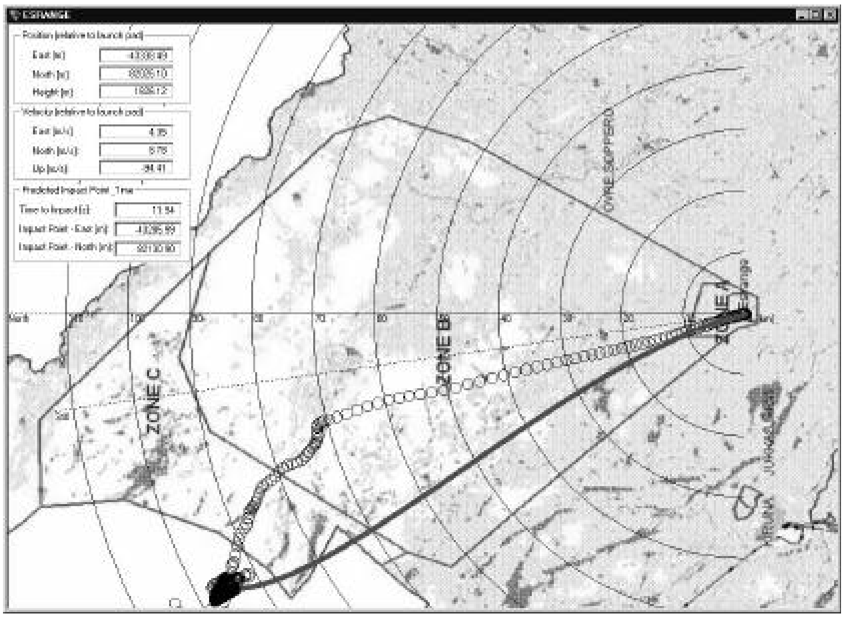

Fig. 9. Ground Track (solid line) and Instantaneous Impact Point (IIP; open circles) of Maxus-4 as derived from the GPS Orion navigation data.

The Orion GPS telemetry was processed in real-time to obtain a graphical representation of the ground track and the instantaneous impact point (IIP). As illustrated in Fig. 9, the Maxus-4 rocket followed the nominal flight path for approximately 35 s. Thereafter, an increased West component of the thrust vector built up, which resulted in a sharp left turn of the instantaneous impact point. The online IIP prediction provided a rapid indication of the off-nominal performance of the guidance system and the landing point across the Norwegian border. The cross-track deviation between the nominal and actual trajectory amounted to roughly 30 km near the landing point. Obviously, the differences between the actual flight path and the reference trajectory used for aiding inside the Orion GPS receiver had no negative impact on the overall tracking performance.

SUMMARY AND CONCLUSIONS

German aerospace industry and the national aerospace research center have made a joint effort to promote and implement GPS tracking within European sounding rocket projects. To reduce the dependence on US providers and avoid project delays caused by applicable export restrictions, an independent development program has been established. Novel antenna concepts as well as a tailored GPS receiver for high dynamics applications have been developed and qualified in various test flights, which offer technical alternatives and lower recurrent system cost than other systems available on the market. Likewise, they increase the flexibility for mission specific adaptations and enable new and innovative applications of GPS on sounding rockets. Future fields of work comprise the use of dual or quadruple patch antenna arrays, the build up of dual frontend receivers and the assembly of an autonomous IIP prediction system for range safety purposes. These developments will be carried out in close coordination with the needs of European sounding rocket scientists and applicable program requirements.

REFERENCES

[1] Selser A. R., *The first Flight of a GPS Receiver on a NASA Sounding Rocket*; NASA Report for Flight 12.046, NASA Goddard Space Flight Center Wallops Flight Facility (1994).

[2] Bull B., *A Real Time Differential GPS Tracking System for NASA Sounding Rocket Flights*; ION-GPS-2000, Salt Lake City (2000).

[3] NRC; *Streamlining Space Launch Range Safety*; National Research Council, Aeronautics and Space Engineering Board; National Academic Press, Washington (2000).

[4] Montenbruck O., Markgraf M., Jung W., Bull B., Engler W.; *GPS Based Prediction of the Instantaneous Impact Point for Sounding Rockets*; Submitted to Aerospace Science and Technology (2001).

[5] Felton P.C., Kunysz W., Garbe G.; *Using GPS For Position & Attitude Determination Of the Canadian Space Agency's Active Rocket Mission*; ION-GPS-1998, Nashville, September 15-18, A6-6, p.1791 (1998).

[6] Markgraf M., Montenbruck O., Hassenpflug F.; *A Flexible GPS Antenna Concept for Sounding Rockets*; DLR-GSOC TN 01-04; Deutsches Zentrum für Luft- und Raumfahrt, Oberpfaffenhofen (2001).

[7] Markgraf M., Montenbruck O., Hassenpflug F., Turner P., Bull B.; *A Low cost GPS System for Real-time Tracking of Sounding Rockets*; 15th European Symposium on European Rocket and Balloon Programmes and Related Research, Biarritz, 28 May - 1 June (2001).

[8] *GP2000 GPS Receiver Hardware Design*; Mitel Semiconductor; AN4855 Issue 1.4, Feb. 1999.

[9] *GPS Architect 12 Channel GPS Development System*; Mitel Semiconductor; DS4605 Issue 2.5; March 1997.

[10] Montenbruck O., Enderle W., Schesny M., Gabosch V., Ricken S., Turner P.; *Position-Velocity Aiding of a Mitel ORION Receiver for Sounding-Rocket Tracking*; C5-5; ION GPS 2000, Salt Lake City, 19-22 Sept. 2000.

[11] Diehl J.; *Post-flight data analysis report for PTO P113E;* NSROC Documentation #NSROC–01-00459; NSRCO Program Office, Wallops Island, Virginia; 16 March 2001.