A FLEXIBLE GPS TRACKING SYSTEM FOR SUB-ORBITAL AND SPACE VEHICLES

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Abstract

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This paper describes the development of a GPS based navigation system for the use on highly dynamical platforms, comprising sounding rockets, re-entry vehicles and low earth orbit satellites. The tracking system comprises the GPS receiver itself as well as a mission specific antenna system. So far, the system has successfully been tested during several sounding rocket campaigns and on a small radio amateur satellite. In the near future the first flight onboard a re-entry capsule will be performed. For all three mission types a brief introduction to the employed system is provided. Besides this, a performance valuation based on actual flight results is presented where available.

Introduction

GPS based tracking systems for all kind of vehicles have become increasingly important over the recent years. Even though a major effort has been put into the development of GPS systems for mass market applications, there is still a strong demand for receiver for high dynamic platforms. While a large number of GPS systems for ground based and civilian aeronautic applications can nowadays be purchased at low prices all over the world, commercial-off-the-shelf systems for highly dynamical environment are still rare and costly. Nearly all of these systems are produced in the US and access to those systems is limited due to rigorous export limitations resulting at least in unacceptably long delivery times.

Motivated by these restrictions and the need for GPS based tracking systems within DLR internal projects, the development of an independent GPS system for high dynamics applications has been initiated. A first goal of the project was to build up a receiver system for the use on sounding rockets [1]. The Mobile Rocket Base (MORABA) of DLR’s German Space Operation Centre plans, prepares and carries out sounding rocket missions and balloon campaigns in the whole world. Traditionally tracking services for those vehicles are provided utilizing bulky and costly C-band radar equipment. As an alternative, a GPS based tracking system can help to minimize expenses and the maintenance requirements. In 2001, such a system has successfully been flown onboard three sounding rockets (TestMaxus-4, Maxus-4 and Texus-39) launched from Kiruna, Sweden. The results obtained from these flights are presented and discussed to demonstrate the actual receiver performance.

Aside from the use on sounding rockets, a nearly identical system will be flown on an experimental re-entry vehicle IRDT-2 in 2002. The mission serves for the conceptual validation of a download system that has been developed by German and Russian space industry as an alternative for returning small payloads from the International Space Station. The Orion GPS navigation system has been supplemented by a dedicated data handling unit for this mission. Due to differing mission requirements in comparison with the sounding rocket campaigns, a software adaptation to the new constraints became necessary. Aside from a short mission and system description, the results of various signal simulator tests, performed to assess the receivers tracking performance during all mission phases, will be presented.

Aside from ballistic flight trajectories the GPS tracking system can likewise support the navigation of satellites in low Earth orbit. As part of a demonstration project a taylored Orion system has been made available to the US Naval Academy (USNA) for the flight onboard the Pcsat radio amateur satellite. Several additional working payload has been activated and started providing highly accurate navigation data. The paper provides a short system overview as well as an analysis of the so far received tracking data. steps had to be carried out to adapt the hardware to the satellite's environment. PCsat has successfully been launched on 30 September 2001 from Kodiak Island, Alaska. One month after the launch the GPS receiver.

1. Receiver System

Despite obvious differences in the characteristics of the various space applications demanding a GPS tracking system, all missions described in the following share the common problem of host vehicle dynamics and environmental conditions. This suggests the development of a single GPS platform supporting a wide range of different mission types. Traditional GPS systems are mainly designed for usage near the Earth's surface and onboard of relatively slow host vehicles. Furthermore, in accordance to the regulations of the US department of defence (DoD), all GPS receiver built for export purposes must have height and velocity limits implemented, disabling the computation of a navigation solution above these limits. Hence, almost all available commercial systems are unsuitable for use onboard sub-orbital and space vehicles. Moreover, signal simulator tests with various GPS receiver showed big problems in acquiring new satellites at high velocity, even if continuous tracking at high velocities is possible.

The Mitel Orion receiver has been selected as base for the development of a GPS based tracking system for space applications, since on the one hand the availability of detailed design information allowed a fast manufacturing of the required hardware platform in the DLR workshop. On the other hand, a development kit [2] could earlier be obtained from Mitel. The kit included the source code for a simple ground based application, resulting in an essential simplification of the development of a firmware version ensuring accurate and reliable tracking under a highly dynamical environment. The GPS Orion receiver (Fig. 1) makes use of the GP2000 [3] 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. 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.

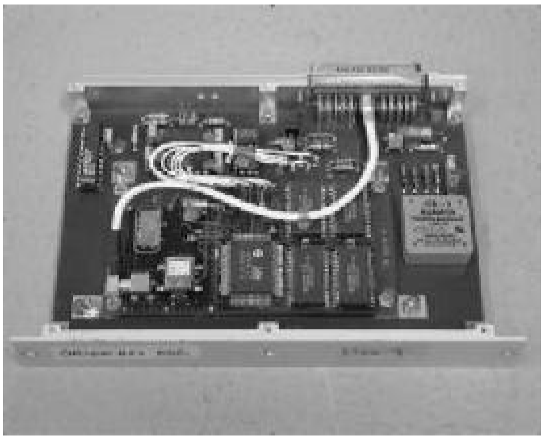


Fig. 1 Orion GPS unit for the Maxus-4 mission.

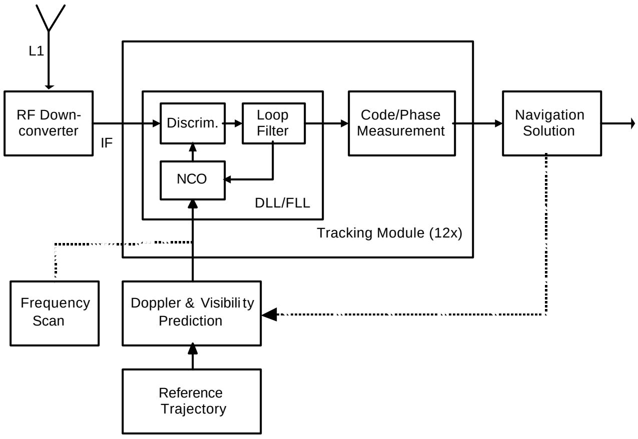


Fig. 2 Doppler and visibility prediction for code and frequency tracking on highly dynamical host vehicles. An open-loop prediction based on the nominal flight path (bold line) replaces the cold start frequency search and the feed back of the receiver's navigation solution (dashed line).

Numerous modifications have been applied to the standard receiver software in order to adapt the system to the requirements of a use in a space mission. Above all, a pronounced improvement of the acquisition capability under high dynamics could be achieved by implementing a novel position-velocity-aiding algorithm, making use of a piece-wise polynomial approximation of the nominal flight path in Cartesian WGS84 coordinates [4]. 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.

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 a sounding rocket or a re-entry vehicle 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 (Fig. 2). 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 all flight phases.

For satellite applications, the above described piece-wise approximation is replaced by an SGP4 analytical orbit model for the prediction of the receiver's coarse position and velocity required for the prediction of visible satellites and the steering of the Doppler search [5]. The model is fed by standard two line elements that are for most satellites routinely generated by NORAD and distributed for public use. At the orbiting altitude of LEO satellite, updates of the twoline elements need to be commanded at intervals of about one to two weeks, which provides an only minor effort for the ground operations.

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.

Besides, several hardware modifications have been performed, mainly concerning the interface module, to adapt the system to the particular requirements of each envisaged mission. A short description of these mission specific modifications can be found in the following chapters. Likewise, specific antenna concept has been developed for each application. Since the antenna has to be considered as the "eye" of the GPS sensor, the importance of the antenna subsystem as an integral part of each GPS unit and therewith the influence on the performance of the entire system may not be neglected. In particular notable effort has been put into the design of a sophisticated antenna concept for sounding rocket missions. A brief introduction to the various, mission specific antenna systems is provided within each corresponding chapters.

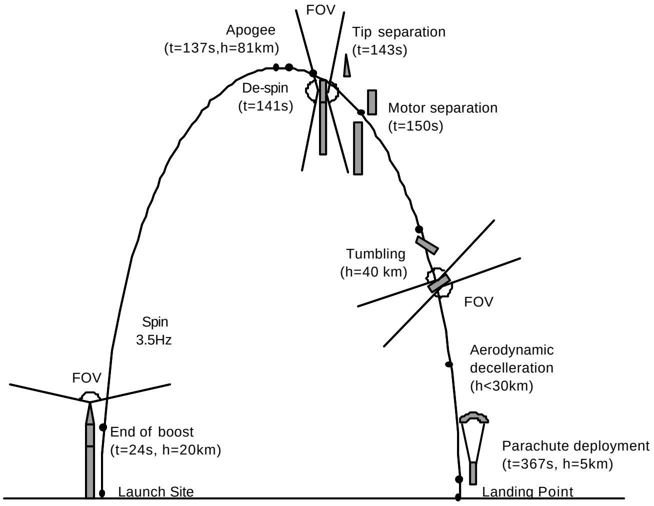
2. Sounding Rockets

The first assessment of the modified GPS Orion system in a real mission has been performed during three sounding rocket flights, conducted in 2001. All missions have been carried out from the European rocket range Esrange near Kiruna, Sweden. The qualification flights were performed on an Improved Orion rocket (Test Maxus-4 campaign [6]), a Castor-4B rocket (Maxus-4), and a dual stage Goldfinch/Raven rocket (Texus-39)). The results obtained throughout the three flights convincingly demonstrated the great benefit of the soft- and hardware modifications applied to the Orion receiver regarding the tracking and acquisition capability under high dynamic. In all missions the receiver kept lock throughout the entire flight except during outages caused by an intentional switching of GPS antennas. Re-acquisition times after interrupts amounted to at most five seconds. The number of tracked GPS satellites was sufficient for a stable and continuous determination of a 3-D navigation solution. As a representative example for all test flights, the Test Maxus-4 mission will be presented in more detail with a discussion of the achieved results.

2.1 Test Maxus-4 Campaign

The 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.

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. 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. 3). 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.



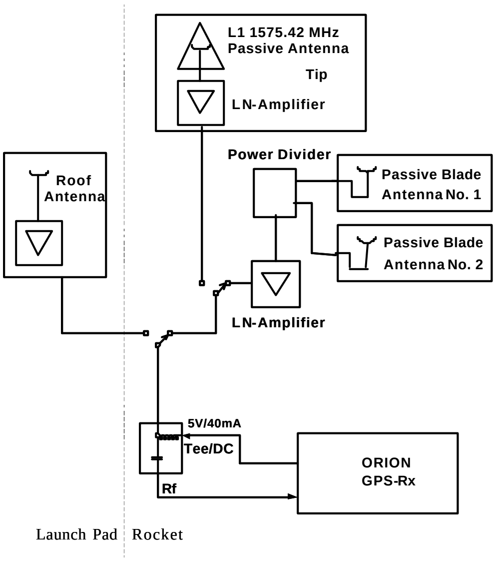


Fig.3 Test Maxus-4 mission profile.

Fig.4 Schematic view of the GPS antenna system.

The Orion receiver was placed inside a DLR/MORABA provided service module, which housed a data handling unit and telemetry 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. 4 [7]. 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. 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. 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.

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 allowed an in-depth verification and trade-off of different receiver and antenna concepts.

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. 5). Continuous tracking was even available near apogee, where short outages had to be expected due to the antenna switching at this time. 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.

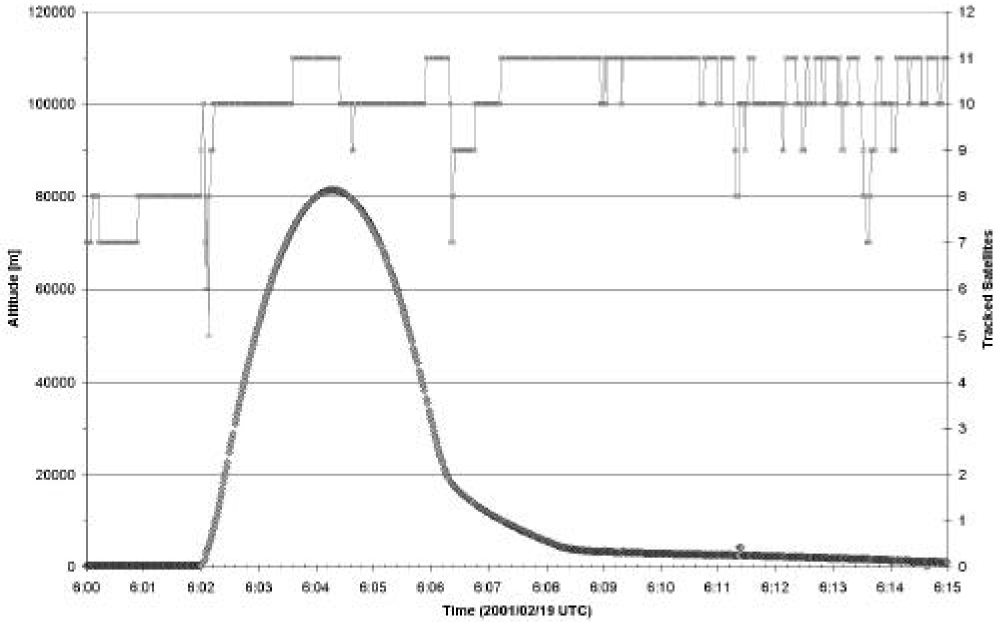


Fig. 5 History of the number of tracked satellites (solid line) and rocket altitude during the mission (diamonds).

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. As mentioned above, 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 can be considered as a reference in performance and accuracy for the other systems, since from a technical point of view it is the most advanced and best evaluated GPS receiver for the use on highly accelerated vehicles.

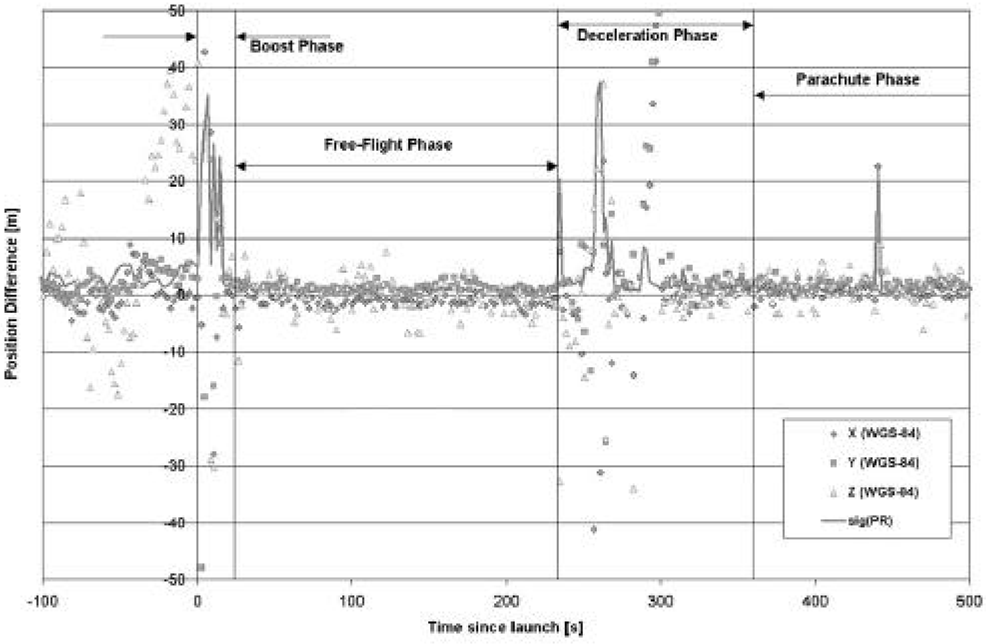


Fig. 6 Difference between the Ashtech G12 and the Orion position solution.

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. 6. In addition the r.m.s. values for the total position difference are given in Table 1, for the different flight phases.

Table 1 R.M.S. values for the difference between Ashtech G12 and Orion position solution

#	Time / UTC		R.M.S	Remarks
	From	To	[m]	
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)

During the periods of good tracking the GPS solutions obtained from the two receivers match each other to better than 6.5 meters, which is well in 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 frequency variations of the reference oscillator as well as a temporary loss of satellites during the descent. Furthermore, deficiency the receiver tracking loops has been identified, which contributes to the degradation of the obtained navigation solution. A further verification flight with a modified receiver software and a better suited quartz oscillator is planned for September, 2002.

3. Re-entry Experiment

Under contract of ESA and the European Community the German Astrium GmbH is presently preparing the second test flight (Inflatable Rentry and Descent Technology IRDT-2) for the demonstration of a novel reentry technology making use of an inflatable aerobraking shield [8]. The project conducted jointly with the Babakin Space Center, Moscow, aims at the development of a download system for the International Space Station, which is able to return small payloads to the ground independent of the US Space Shuttle. IRDT makes use of technologies originally developed within the Russian Mars program and differs from common recovery systems for reentry capsules or sounding rockets. Instead of a parachute an inflatable heat shield is employed to decelerate the capsule and land it safely on ground.

The launch has originally been scheduled for 2001 but had to be postponed to the year 2002 due to a failure in the electronic of the sensor module found during the final check-out at the launch site in Severomorsk. Presently, the IRDT-2 capsule is planned to be launched in the last week of May 2002 by a Volna rocket from a Kalmar type submarine in the Baltic sea north of Murmansk and injected into a ballistic trajectory passing across the arctic sea and northern Siberia (Fig. 7). Following deployment of the first shield, the capsule reaches the rentry

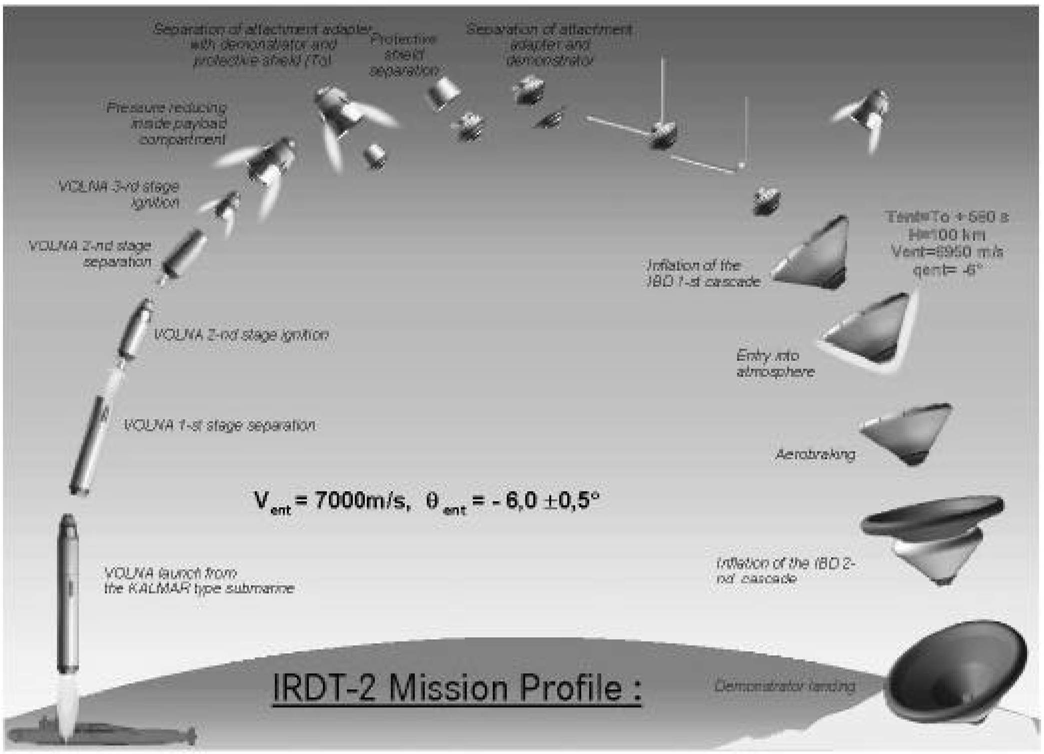


Fig. 7 IRDT-2 mission profile

point at a 100 km altitude and a velocity of roughly 7 km/s. Here, a second shield is deployed which introduces a steep descent of the capsule. The actual landing takes place on the Kamshatka peninsula within 25 min after separation.

As part of the IRDT-2 payload, a DLR/GSOC provided Orion GPS receiver system will be flown and the resulting navigation data will complement other sensors and experiments in the post mission analysis [9]. Within the IRDT flight unit, the main receiver board is supplemented by a tailor-made interface unit, which comprises basic support functions (power regulator, backup battery and serial interface converters) as well as a dedicated data handling system (Fig. 8). It provides a separate micro-controller and an EPROM memory, which are used to store GPS navigation data during the flight of the IRDT-2 capsule for read-out after landing. The available storage volume of 900 kByte is sufficient to hold 2 Hz samples of position and velocity as well as raw data (pseudoranges, pseudorange rates) and status information at a reduced data rate. Thus a dynamical post mission adjustment of the reentry trajectory is even possible in case of limited tracking conditions with less than 4 satellites in lock. The receiver and interface board measure 95 x 50 mm each and are stacked on top of each other inside the housing shown in Fig. 9. The power consumption of the complete GPS unit amounts to roughly 3W.

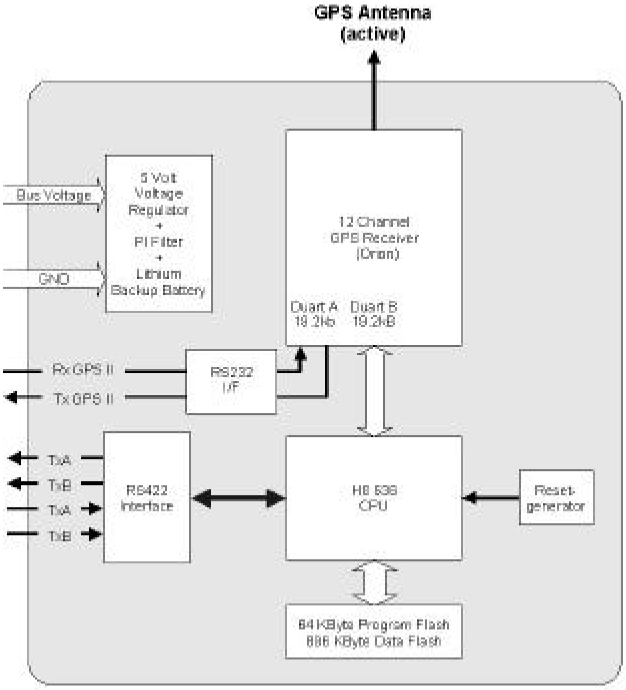


Fig. 8 Schematic view of the IRDT GPS system.

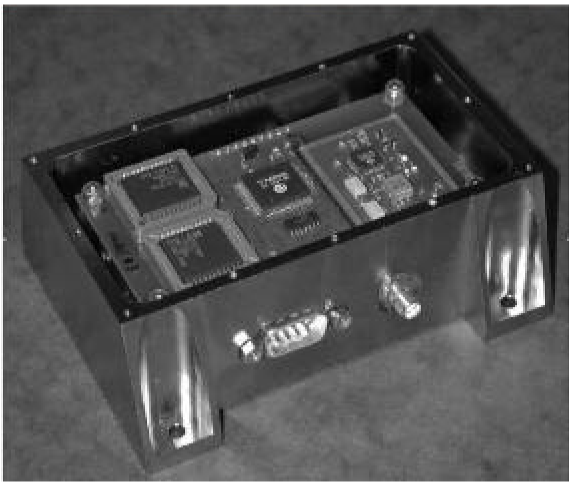


Fig. 9 IRDT-2 GPS flight unit.

Even though the mission scenario resembles a sounding rocket flight at first sight, it involves a much higher maximum speed and critical differences in the receiver initialization. In a sounding rocket campaign the receiver is switched on several minutes prior to lift-off, which allows a proper initialization of the system at the launch pad. In contrast to this, the activation of the GPS system onboard the re-entry capsule takes place shortly after separation when the vehicle has reached its maximum speed. Furthermore, the exact launch time and thus the receiver boot time is not known in advance. Due to these facts, a slightly different initialization procedure had to be implemented in the receiver software. Prior to the final integration the receiver will be briefly activated and connected to an outside antenna. This allows the receiver to synchronize itself to the current time and to receive a recent almanac of the GPS constellation. Following the subsequent power-down the correlator's internal real-time clock is kept alive by a backup battery. Likewise, relevant auxiliary data like the almanac and the IRDT reference trajectory are stored in a non-volatile part of the memory. Using the above information, the absolute time is available to the receiver at start-up with an accuracy of a few seconds, which in turn allows the prediction of the GPS satellite constellation. Likewise the time since boot (i.e. the time since separation) is available within the receiver, which is required to read-out the nominal trajectory. In this way the receiver is both able to predict its approximate position and velocity as well as the position and velocity of the GPS satellites. Using these data the channel allocation and the Doppler offset for the signal acquisition are determined. This allows a full warm start of the receiver irrespective of the actual launch date and time of the mission. Based on corresponding signal simulator tests, it is expected that position, and velocity measurements are available within a minute after activation, provided that the tumbling of the capsule after separation does not impose major restrictions to the GPS satellite visibility.

Using a GPS signal simulator, different hardware-in-the-loop simulations were carried out to validate the receiver design and operations concept. The simulation scenario was configured to start at separation of the IRDT capsule from the upper stage and continue up to the time of landing. In accord with the operations concept described above, the IRDT GPS receiver had to be switched on simultaneously with the start of the simulator and it had to be ensured that the time propagated by the battery buffered real-time clock matched the simulated separation epoch.

An initial test that matched these requirements to within about a second provided an overall conceptual verification of the receiver design and showed that the receiver is nominally able to perform a warm start under the given conditions. Within 15 s, the receiver achieved frame lock for eight satellites but was still unable to produce a navigation solution due to the lack of suitable broadcast ephemeris parameters. At 37 s after the boot, 3D navigation was obtained with 7 satellites in use. Since then the receiver provided uninterrupted tracking troughout the free-flight phase and atmospheric reentry down to the landing point.

Additionally, an off-nominal test has been performed, simulating a complete loss of real-time clock and non-volatile memory as a consequence of a battery failure. In addition an offset of roughly 11 s was introduced between the simulator start and the receiver boot. As a result the receiver started with a default date (2000/07/30) and an 80 km position offset, but was nevertheless able to acquire a first satellite after 23 s and adjust its clock to the scenario time. Using the hardcoded almanac and reference trajectory, the receiver started searching for other visible GPS satellites in highest elevation mode and achieved 3D navigation within about 2 minutes.

4. Satellite Application

While space borne GPS receivers can in general be considered as a well established tracking tool for low Earth orbit (LEO) satellites, their use on micro- or nano-satellites poses multiple problems from a systems engineering point of view. Representative examples include the mass budget, the lack of a suitable attitude stabilization, antenna allocation problems, restricted command and telemetry links as well as limited onboard power resources. The recent flight of a DLR built GPS system onboard the PCsat Prototype Communications satellite (Fig. 10) provides an illustrative example of GPS operations on a 25 kg class of micro-satellites.

Fig. 10 The Prototype Communication Satellite (PCSat) built by the US Naval Academy

The Prototype Communication satellite PCsat has been designed and built by midshipmen of the US Naval Academy (USNA), Annapolis. It serves as a space borne extension of the terrestrial Amateur Radio Automatic Position Reporting System (APRS), which allows the distribution of position/status reports and short messages using handheld or mobile radios. PCsat is a cubic satellite of 10” (25 cm)size. Solar cells on five faces of the spacecraft provide a typical power of 7 W in full Sun, which is buffered in a set of 12 NiCd cells to allow operations during eclipses (with minimum GPS receiver activities). The minimum power consumption amounts to 3 W when sending only safe mode beacon messages, thus leaving a best case value of 4 W for thermal control, digipeating, and experiment operations. PCsat has been launched on an Athena 1 rocket on 30 September 2001 from Kodiak Island, Alaska. It orbits the Earth at an altitude of 800 km and an inclination of 67° with respect to the equator. US and European radio amateurs can access the satellite for up to six passes of 10-15 min each per day.

While the main purpose of PCsat consists in the relaying of APRS communication messages, it also carries an experimental Orion GPS receiver provided by DLR/GSOC (Fig. 11). Prior to the integration into the satellite, the position-velocity-aiding concept for LEO satellites has extensively been tested in a signal simulator environment. These tests have demonstrated that the receiver is able to perform hot starts with a typical time to first fix of better than 20s under adequate GPS visibility conditions. During the actual mission, where the output sampling interval was reduced to 30-60 s, the receiver was found to be back on track within 60 s after various power cyclings due to temporary battery shortages. In case of extended off times that exceeded the validity of broadcast ephemeris parameters stored in non-volatile memory, representative times-to-first fix of 3 minutes were observed during the actual mission.

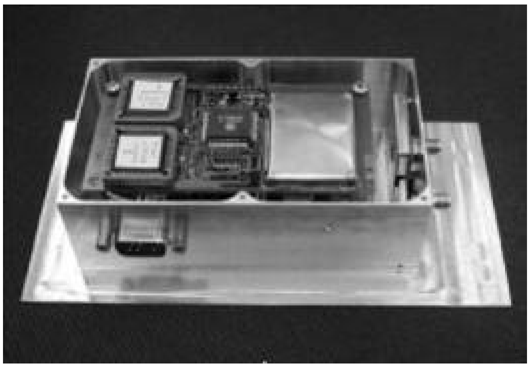


Fig. 11 PCsat GPS Orion flight unit

Fig. 12 Monopole antenna (λ/4) for GPS reception.

Compared to terrestrial or big LEO applications, the signal acquisition onboard PCsat is seriously hampered by the use of a low gain antenna and the uncontrolled attitude of the spacecraft. Due to lacking surface area for the accommodation of a standard antenna patch, a quarter-wavelength monopole mounted in the corner of the cubic spacecraft structure is used instead (Fig. 12). It provides a roughly toroidal antenna diagram with a sensitivity dip in the boresight direction, but allows tracking down to negative elevations with respect to the antenna equator. Other than a patch or helical antenna, the monopole is linearly polarized and does not provide a proper impedance matching. As a result of the sub-optimal antenna system, signal-to-noise ratios are, on average, 4-5 dB less than observed otherwise with the same receiver.

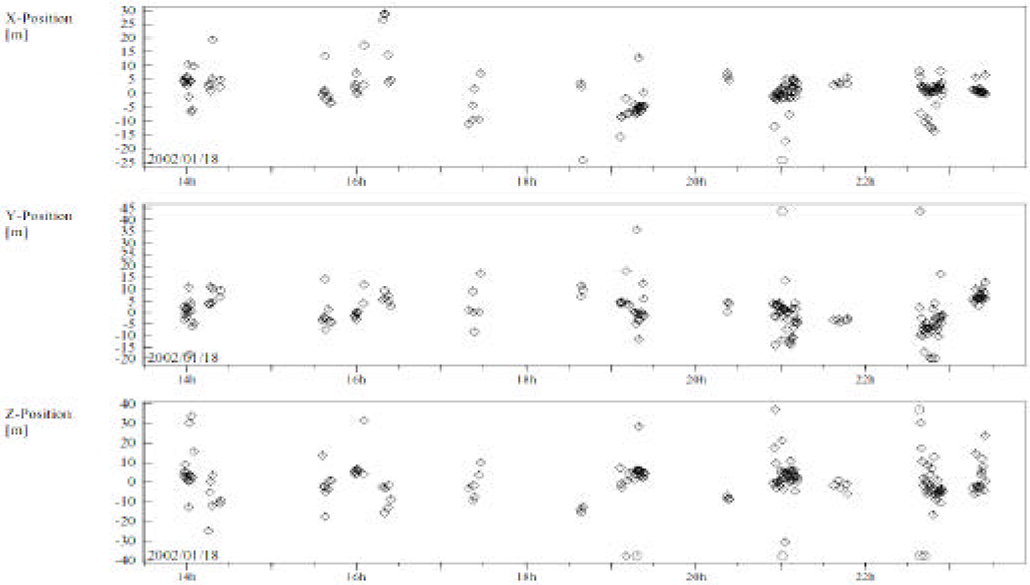


Fig. 13 Position residual plot (from single point code range solutions) for a 12 hour data arc recorded in mid-January, 2002.

A near continuous activation of the GPS receiver became possible in mid-January, when PCsat was in a full-Sun orbit for about on week. NMEA type GPGGA position message as well as state vectors, raw measurements (pseudorange and Doppler), and channel status data were collected by a worldwide net of radio amateurs. Batch filtering of the GPS position data in a dynamical orbit determination system indicates an 3-D r.m.s. accuracy of 15 m (Fig. 13). This is slightly worse than observed in other missions but can be understood by the large fraction of low (including negative) elevation pseudoranges that are affected by media effects (ionospheric path delay) and tracking errors near signal acquisition.

5. Summary and Outlook

Starting from a prototype design of a terrestrial receiver, a GPS tracking system for high dynamics applications has been developed. A preliminary qualification of the Orion GPS receiver has been performed in various test flights onboard sounding rockets and a small low Earth satellite. A first flight on a re-entry capsule is planned in the summer of 2002. Compared to commercial receivers, the in-house developments offers a notably improved flexibility and a reduced time to mission. Aside from sounding rocket missions benefiting from a robust tracking under high dynamics, the receiver is also well suited for small satellite missions in view of its small size and power requirements. New applications under study include the onboard computation of the expected impact point of a sounding rocket to improve range-safety operations at the launch site [10] and the precision relative navigation of spacecraft in close proximity [11].

Acknowledgment

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