A GPS Receiver for Space Applications

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BIOGRAPHY

Oliver Montenbruck is head of the GPS Technology and Navigation Group at DLR's German Space Operations Center (GSOC). He received his Ph.D. from Munich's University of Technology in 1991. Since 1987 he's been working as a flight dynamics engineer with focus on satellite orbit determination. His current field of work comprises the development of on-board navigation systems and spaceborne GPS applications. He has written various text books on computational astronomy and satellite orbits as well as numerous papers on related topics.

Markus Markgraf is a GPS development engineer at DLR/GSOC. He has prepared and conducted various sounding rocket flight experiments at Esrange, Kiruna, and is in charge of the mission preparation and operations for the IRTD-2 GPS experiment.

Sunny Leung is currently preparing his Ph.D. thesis on spaceborne GPS and relative navigation under supervision of DLR/GSOC and RMIT, Melbourne. He is the principal engineer for the PCsat GPS experiment and responsible for the receiver software design and ground operations.

Eberhard Gill is a scientific staff member at GSOC's Spaceflight Technology section, where he is in charge of autonomous navigation. He received his Ph.D. in Physics at the University of Tübingen, in 1989. At DLR, he has been working in the field of satellite orbit determination and consider covariance analysis. He recently completed the development of the Onboard Navigation System for the German BIRD satellite. He is author of numerous papers and a text book an satellite orbits.

ABSTRACT

This report presents the development of a cost effective GPS receiver for space applications conducted at DLR's German Space Operations Center (GSOC). Building up on the existing GPS Orion receiver design by Mitel Semiconductor multiple units for sounding rockets and satellite usage have been built up. Developments specific to the space application comprise software modifications to ensure signal acquisition and precise navigation under high dynamics as well as hardware modifications for integrating the receiver into existing bus systems. Aside from hardware-in-the-loop simulations for a lab-based receiver validation, first flight results obtained during sounding rocket missions are described. In addition, current missions in which the receiver will be utilized are presented and future development lines are described.

INTRODUCTION

Today, the use of spaceborne GPS receivers is a widely accepted alternative to traditional tracking methods for artificial satellites. Its fundamental technical advantages comprise the global coverage, the achievable accuracy, and the immediate onboard availability of orbit information. In addition, the wide acceptance is also driven by cost considerations, even though reliable figures on the overall system cost including procurement, integration and operation are barely available

In the frame of the German national space program, GPS receivers have been (or are) used within the MIR/MOMSNAV, EQUATOR-S, ABRIXAS, CHAMP, and BIRD missions. Furthermore, GPS receivers have successfully been applied for sounding rocket tracking within the TEXUS-37/38 and MAXUS-3 missions. In all cases American receivers have been employed exclusively, the purchase of which is seriously hampered by applicable export restrictions. Aside from this major differences in the suitability of individual receivers for space applications as well as the required operations effort and the available technical documentation may be observed. In particular, outdated „bargain sales“ have been shown to bear the risk of an excessive integration effort or a non-adequate utilization. Overall, spaceborne GPS receivers are at present supported by only a few industrial providers in view of a modest market segment.

On the background of the above situation the "GPS Technology and Navigation" group of the German Space Operations Center is taking an effort to support the application of spaceborne satellite navigation receivers and promote its use by independent developments. Current core projects comprise the provision of an autonomous navigation system for the BIRD small satellite mission [1] as well as the build up of a simple and flexible GPS receiver for sounding rocket and satellite applications. The development of this receiver as well as its validation in laboratory tests and flight experiments is further described in the sequel.

RECEIVER DESCRIPTION

As a basis for the development of a space GPS receiver use has been made of the GPS Orion receiver design of Mitel Semiconductor. It serves as a prototype for industrial GPS receivers built around the Mitel GP2000 chipset [2] and is supplemented by the GPS Architect Software Development Kit [3]. A major advantage over other development kit is the availability of the receiver's source code, which is a fundamental prerequisite for the required software adaptations.

Fig. 1 GPS Orion receiver (IRDT flight unit)

Core components of the GPS Orion are the frontend made up of the GP2015 R/F down converter and the DW9255 saw filter, the GP2021 correlator and an ARM-60B 32-bit microprocessor. The receiver allows L1 C/A-Code measurements in 12 parallel channels and can be operated with common active antennas. For use with passive systems, a preamplifier with an 18-28 dB gain is required.

Fig. 1 shows a sample flight unit built up at DLR. The main receiver board is supplemented by an interface board lying underneath, which, by default, provides two serial interface converters, a power regulator as well as a backup battery for real-time clock operation and non-volatile memory retention. The small size and the moderate power consumption of 2 W make the Orion receiver an ideal starting point for spaceflight applications. Here most functions of the standard interface board can be taken over by independent on-board systems, thus leaving a total receiver size of roughly 10 x 5 x 1 cm^3.

Leaving aside the hardcoded limitations that restrict the use of commercial GPS receivers to an altitude below about 20 km, the high dynamics of the relative motion of user and GPS satellite as well as the rapidly varying constellation pose the major obstacle for the space based use of GPS receivers. In view of the low signal level and the time consuming correlation process special precautions have to be taken to allow a rapid start of the receiver and an optimal channel allocation. Aiding the receiver with nominal trajectory information that is available for all space missions is therefore a core concept of GSOC's development.

To this end, the reference trajectory of a sounding rocket or other ballistic missions is represented by a piecewise low order polynomial approximation and stored inside the receiver [4]. Using this information the GPS satellites in view and the expected Doppler shift can be computed at any time after launch.

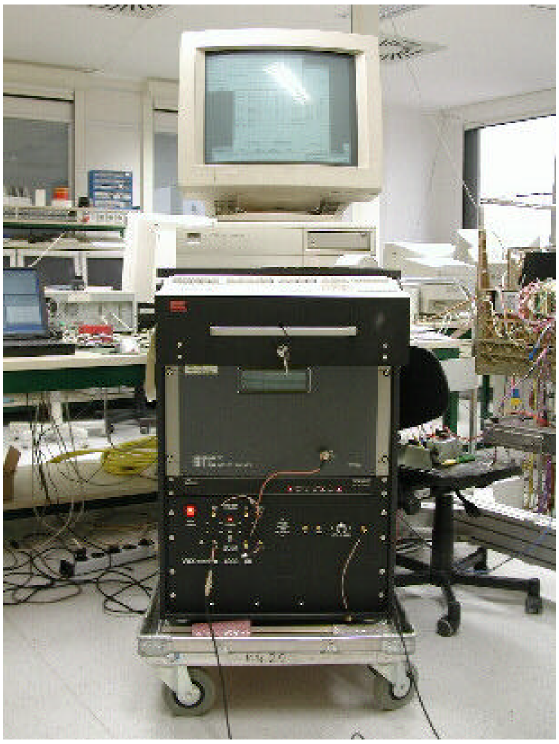

Fig. 2 GPS signal simulator (Kayser-Threde Corp.)

For a validation of the software concept and the receiver hardware comprehensive tests have been conducted with a GPS signal simulator (Fig. 2) provided by Kayser-Threde corporation. Within these tests it has been verified that a fast acquisition or reacquisition is ensured even under high dynamics and after short signal interrupts.

FLIGHT VALUATION

Sounding Rockets

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 of 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/GSFC [5] and DLR.

During the 24 s boost phase a spin-rate of 3.5 Hz was built up, which ensured a stable attitude of the rocket during the ascent trajectory. During 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 nose-cone were from the payload, which was safely returned to ground by a parachute recovery system.

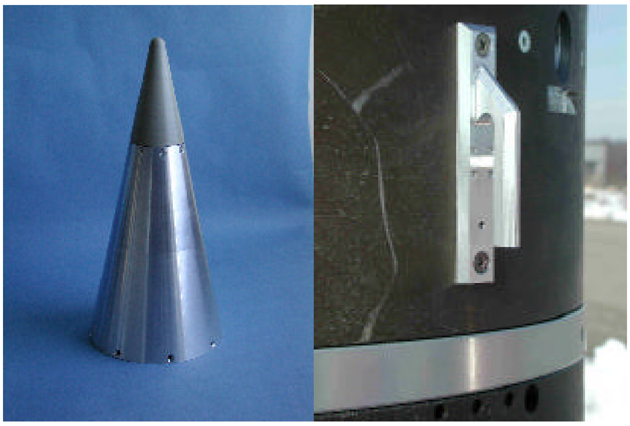

Fig. 3 Tip and blade antenna for GPS usage on sounding rockets

Aside from a qualification of the Orion GPS receiver, the test flight also served for the analysis of a novel antenna system made up of tip and blade antennas, which provides a cost effective alternative to common wrap around 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 (Fig. 3). 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 [6].

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. 4). This is particularly remarkable in view of the blade antenna sys-tem 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.

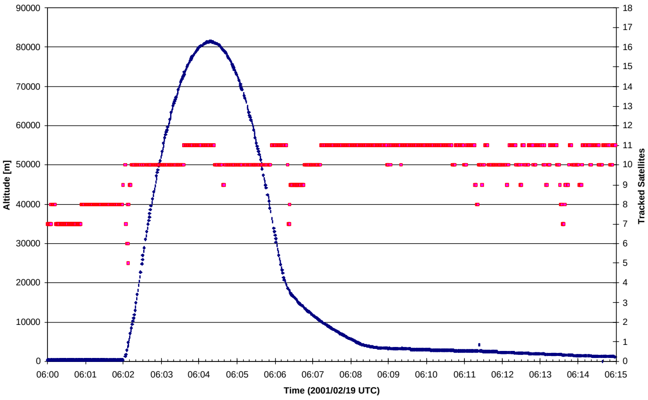

Fig. 4 Number of tracked GPS satellites (right hand scale) and geodetic height during the Test Maxus-4 campaign

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 for about ten seconds. 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, which may, however, imply a need for modifications of the standard printed circuit board layout. For further information on the Maxus-4 test flight the reader is referred to [7] and [5].

An important application of GPS receivers consists in the provision of precise positions during the free-flight phase for the analysis of scientific (e.g. TIGER). Aside from an increased accuracy and the onboard availability of tracking data, the use of GPS receivers is particularly promising to reduce the overall system cost compared to the use of conventional ground based radar stations.

In addition, GPS measurements provide a suitable basis for the prediction of the instantaneous impact point (IIP), which is required for range safety purposes. As an example, Fig. 5 shows the results obtained for the Maxus-4 mission in April 2001. Based on the Orion GPS measurements, a small guidance offset could be detected right after launch and a landing point near the Norwegian border was predicted. It is planned to perform this prediction autonomously inside future versions of the GPS receiver.

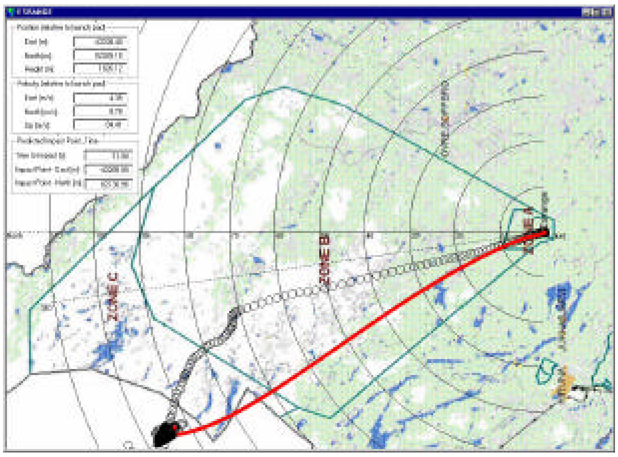

Fig. 5 Instantaneous Impact Point prediction for the Maxus-4 sounding rocket mission at ESRANGE (Kiruna) based on Orion GPS measurements

Both applications will be further qualified in subsequent test flights conducted jointly with Kayser-Threde and DLR'S mobile rocket base. For future applications on spinning rockets the build up of a dual front-end receiver is envisaged to allow an interference free combination of signals from a dual antenna system.

Reentry Missions

Under contract of ESA and the European Community the German Astrium GmbH is presently preparing the second test flight (Inflatable Reentry and Descent Technology IRDT-2) for the demonstration of a novel reentry technology making use of an inflatable aerobraking shield ([8], [9]). 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 IRDT-2 capsule will be launched in early October 2001 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. 6). Following deployment of the first shield the capsule reaches the reentry point at a 100km 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 service module a modified GPS Orion receiver (Fig. 1) will be employed to provide navigation data for the post mission analysis supplementary to other sensors and experiments. Here, it is desired to cover the complete trajectory from separation to landing. In view of the short mission duration and the fact that the service module is only powered-up at separation, special precautions are required to ensure an immediate operation of the GPS receiver after switch-on even under the high dynamics of the ballistic reentry trajectory.

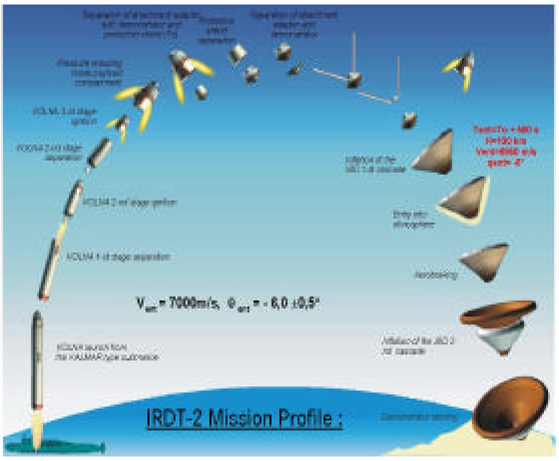

Fig. 6 IRDT-2 mission profile

To this end the receiver is briefly activated prior to the final integration. 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 of the GPS satellite visibility.

During the flight of the IRDT-2 capsule the GPS navigation solutions obtained by the Orion GPS receiver are stored in a dedicated EPROM memory, from which they can be read-out after landing. This memory is accessed via a separate micro-controller which is part of an extended Orion interface board developed by Vectronic Aerospace. 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.

Satellite Applications

In view of its physical parameters (volume, power consumption) the GPS Orion receiver recommends itself in particularly for small and micro-satellite missions with limited onboard resources. As the Abrixas-2 mission could not be realized within the German small satellite program, a first flight validation is now planned for the US PCSat (Prototype Communication Satellite) radio amateur satellite to be launched in September 2001. In addition, its use onboard the Leonides-Inspector is presently discussed, which is derived from the TubSat bus.

Fig. 7 The Prototype Communication Satellite (PCSat) built by the US Naval Academy

As has already been demonstrated in [10], the components of the employed GP2000 chipset are sufficiently radiation proof to allow a meaningful use in low Earth orbits (500-800 km altitude) without major modifications. Considering a shielding of e.g. 3 g/cm2 Al as provided by representative bus structures, a lifetime of several years may be expected before the total radiation dose results in a significant degradation of the components. As a limited protection against latch-up effects a supplementary electronic fuse is, however, recommended to limit the total current consumption.

On the background of the envisaged applications the modifications of the receiver design performed by GSOC focus on an extension of the aiding concept for orbital trajectories. Instead of approximating polynomials an analytical orbit model is employed to compute coarse values of the user spacecraft's position and velocity in a background process. Thus a rapid signal acquisition under warm- or hot-start conditions can always be obtained, which in turn allows a discontinuous receiver operation in selected parts of the orbit [11]. In view of the limited power budget of common microsatellites the GPS usage can thus be reduced to the absolute minimum required for a reliable orbit determination.

For a pre-flight verification of the above concept, multiple GPS signal simulator tests (Fig. 2) covering periods of up to 24h have been conducted. Here the receiver's capability to acquire GPS signals and to provide valid navigation solutions within a short time (<20 sec) after power-up has been confirmed. In addition the achievable accuracy of single point position and velocity solutions has been determined. For unfiltered navigation solutions, accuracies of <10 m and <1 m/s have been demonstrated.

Supplementary developments for satellite usage comprise the synchronization of raw measurements and navigation solutions with GPS or UTC seconds as well as the generation of an associated pulse per second signal for on-board time distribution. For smoothing of pseudorange measurements as well as differential tracking techniques and extension to carrier phase measurements is, furthermore, under preparation.

SUMMARY AND OUTLOOK

Starting from the existing design of a GPS receiver for terrestrial applications, the German Space Operations Center has developed a receiver for use on sounding rockets and satellites. The presented projects illustrate the range of application of spaceborne receivers as well as the need for suitable devices within the national space program. Through close cooperation with German aerospace industry necessary developments could be performed in short time and applied for practical applications.

Future efforts aim at a fully operational use of GPS on sounding rockets as well as flight applications and experiments on satellites. As a key goal the use as relative navigation sensor for autonomous formation flying has been formulated in the recent GEMINI project proposal by Astrium and DLR.

Aside from the provision of cost effective GPS receivers for national space projects, the in-house developments provide valuable experience on the operational GPS utilization for sounding rocket and satellite projects. Thus, the German Space Operations Center continuously extends it its expertise gained in previous missions and provides its competence in the field to project scientists, aerospace industry, and the space agency.

ACKNOWLEDGEMENT

The laboratory and flight tests of the presented receiver have been performed in close contact with and support by DLR's mobile rocket base as well as German aerospace industry, including Astrium GmbH, Kayser-Threde GmbH and Vectronic-Aerospace GmbH. We'd like to express our thanks to all individuals involved in the associated projects for their continued interest and generous help.

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