GPS TRACKING OF THE IRDT-2 RE-ENTRY CAPSULE

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ABSTRACT *– The paper describes a GPS based tracking system for the IRDT-2 re-entry capsule. 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 IRDT capsule will be launched from a submarine and perform a short ballistic flight before re-entering the atmosphere. Using an inflatable aero-braking shield, the capsule will finally be landed on the Kamshatka peninsula. The navigation system is based on a Mitel GPS Orion receiver that is supplemented by a dedicated data handling unit. The paper describes the design of the receiver and the required software modifications for reliable tracking and rapid acquisition under high dynamics. In addition various signal simulator tests and sounding rocket flight results are presented that demonstrate the actual receiver performance.*

KEYWORDS: GPS, Reentry, IRDT

INTRODUCTION

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 [1]. 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 is planned to be launched in late 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. 1). Following deployment of the first shield, the capsule reaches the rentry 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.

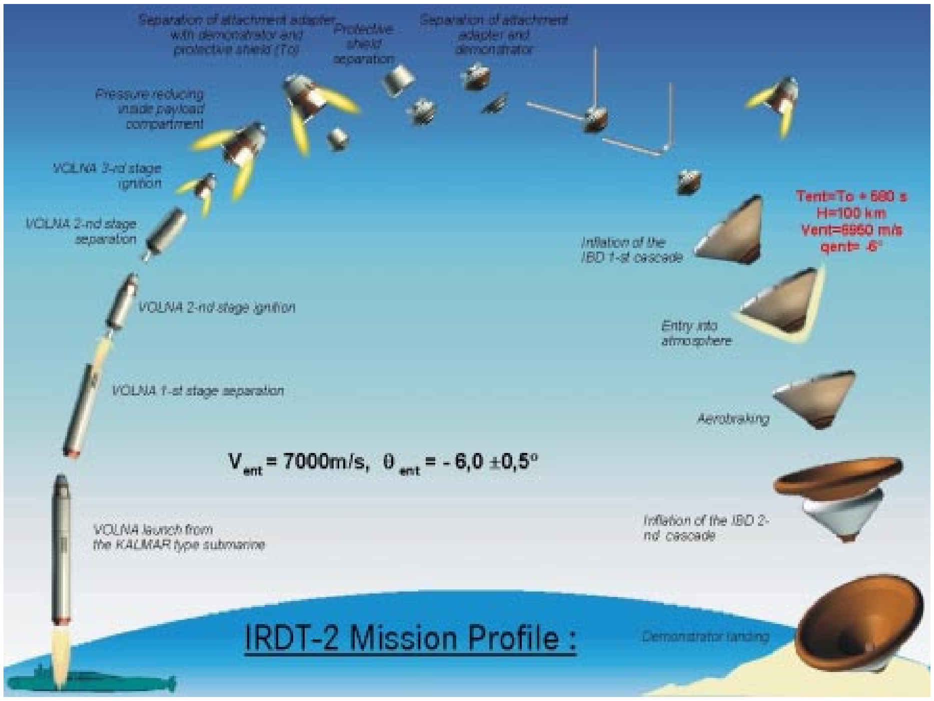

Fig. 1 IRDT-2 mission profile

As part of the IRDT-2 payload, a modified Orion GPS receiver for space applications will be flown by DLR/GSOC and the resulting navigation data will complement other sensors and experiments in the post mission analysis. In view of the short mission duration and the fact that the IRDT power system will only be switched on at separation from the upper stage, special precautions have to be taken to allow for a hot start of the GPS receiver at boot time even under the high dynamics of the re-entry trajectory. The Mitel Orion receiver has been selected for the IRTD tracking system, since it supports necessary software modifications through the Architect development system. The Orion receiver itself has been built by DLR based on Mitel design information [2] and is described in the subsequent section along with relevant software changes.

GPS RECEIVER DESIGN

The GPS Orion receiver 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 [3], but designed to act as a stand-alone receiver.

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. 2). 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. 3. The power consumption of the complete GPS unit amounts to roughly 3W.

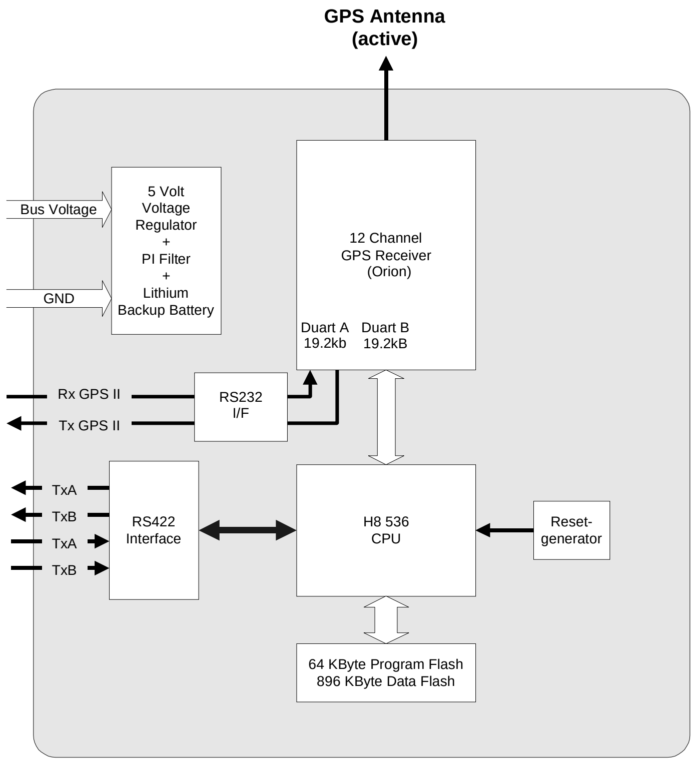

Fig. 2 Schematic view of the IRDT GPS system

The standard Mitel firmware has received numerous changes to improve the tracking performance under highly dynamical conditions and to allow a fast acquisition of the receiver. These include updates of various receiver parameters (operational limits, filter parameters) as well as fixes of the Doppler computation and the kinematic navigation solution for fast moving host vehicles. Also, a small time offset that would otherwise introduce a measurable along track error in space applications has been corrected in DLR's receiver software.

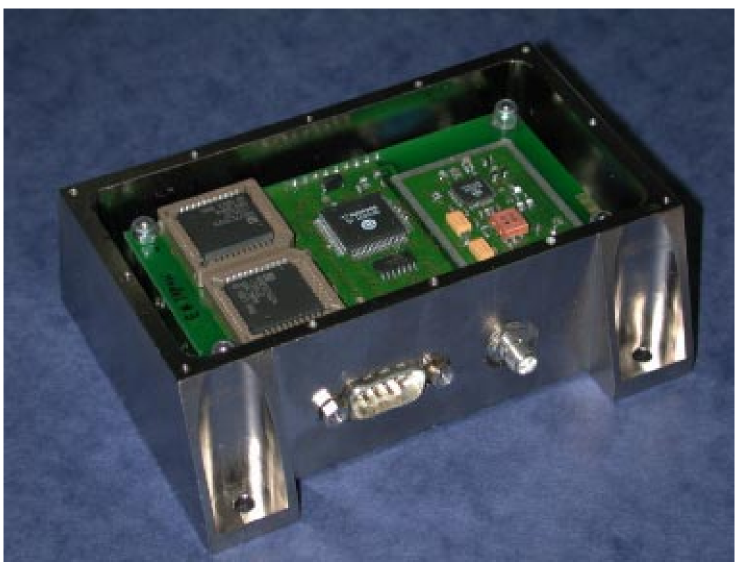

Fig. 3 Orion GPS receiver (IRDT-2 flight unit)

A major modification concerns the use of a position-velocity aiding concept, which makes use of a piece-wise polynomial approximation of the nominal flight (Fig. 4, [4]). Based on this, the reference position and velocity of the vehicle in the WGS84 reference frame are computed approximately 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. For use on IRDT-2, the polynomials are referred to the instant of separation from the launcher, which coincides with the boot time of the receiver.

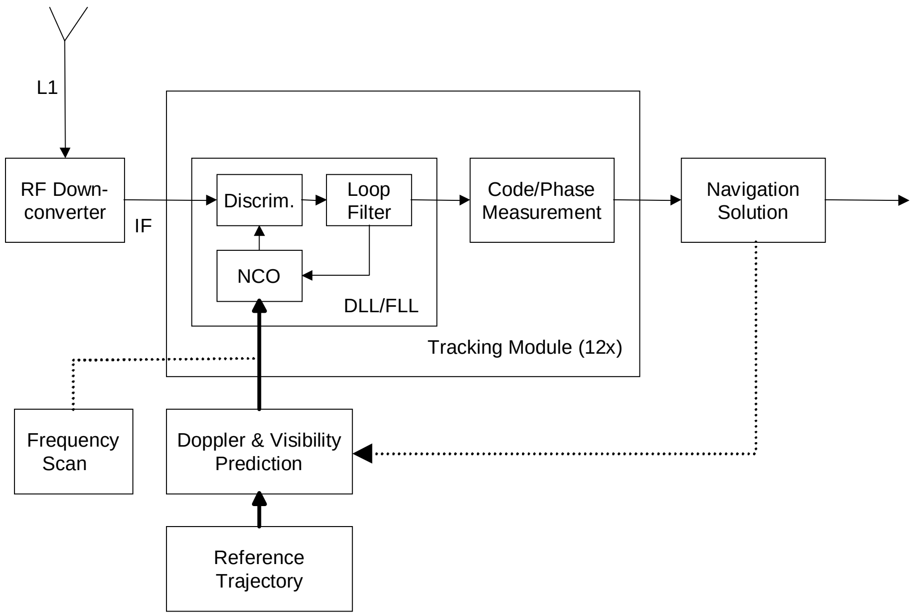

Fig. 4 Doppler and visibility prediction for code and frequency tracking on highly dynamical host vehicles [4]. An open-loop prediction based on the nominal flight path (bold line) replaces the cold start frequency search and the feed back of the receiver's navigation solution (dashed line).

OPERATIONS CONCEPT

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.

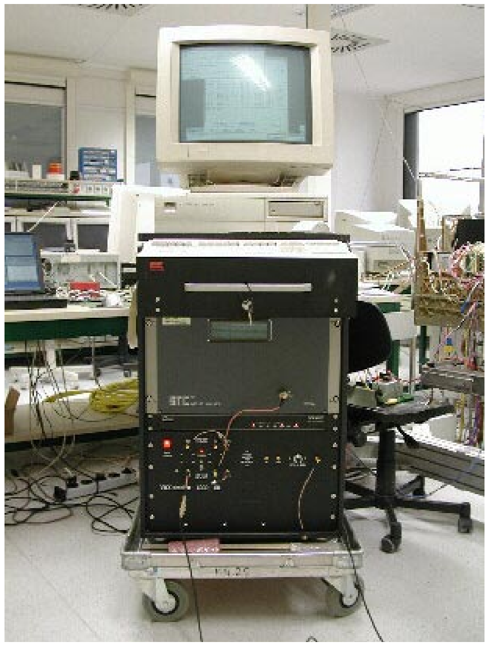

Fig. 5 STR2760 10 channel GPS signal simulator

SIGNAL SIMULATOR TESTS

Using a GPS signal simulator (Fig. 5), different hardware-in-the-loop simulations were carried out to validate the receiver design and operations concept described above. Prior to the tests, a trajectory file giving the Cartesian position and velocity of the IRTD-2 capsule at 10 s intervals has been made available by the Babakin Space Center. The trajectory served as reference for the signal simulator and formed the basis of the hardcoded trajectory polynomials in the receiver software. Key parameters of the IRTD- 2 trajectory are summarized in Table 1.

Table 1 Key parameters of the IRDT-2 mission

Parameter	IRDT-2
Simulated Launch Epoch	2001/03/21 6:00 GPS Time
	(GPS week 1106, t_{ow} 280800s)
Separation	λ=+54.3°, ϕ=+76.2°, h=264km
Flight time	ca. 1600 s
Max. altitude	411 km
Max. velocity	7000 m/s
Max. deceleration	16 g

All tests were performed using Kayser-Threde's STR2760 GPS signal simulator. A software amplification of 10 dB and a dual stage hardware amplification (2 x 24 dB nominal) was used to generate an adequate signal level for radiation via a passive Procom GP2000 antenna. Signals were received by an active M/A COM ANPC131 antenna with an LNA gain of +26dB at a distance of about 0.5-1.0m from the transmitting antenna and boresight angles of 30°-60°. Representative SNR figures indicated by the receiver range from 11 db to 17 dB.

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. The number of observed GPS satellites varied between five and ten as a result of inconsistencies between the signal simulator configuration (10 channels, dynamically switched) and the receiver elevation mask setting (0°) used within this test case. Due to the absence of rigorous attitude models and obstruction patterns, the actual antenna field of view during the various mission phase is not known concisely. Experience with sounding rocket missions performed at northern latitudes does, however, indicate that a sufficient number of satellites for 3D navigation should always be within the field of view. Otherwise, a dynamical orbit determination based on pseudorange and Doppler measurements will be used to establish the actual flight path of the IRDT capsule in a post mission analysis.

A complete loss of real-time clock and non-volatile memory as a consequence of a battery failure was simulated by a reset of the receiver (using the CS cold start command) prior to switch off. 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 (Fig. 6).

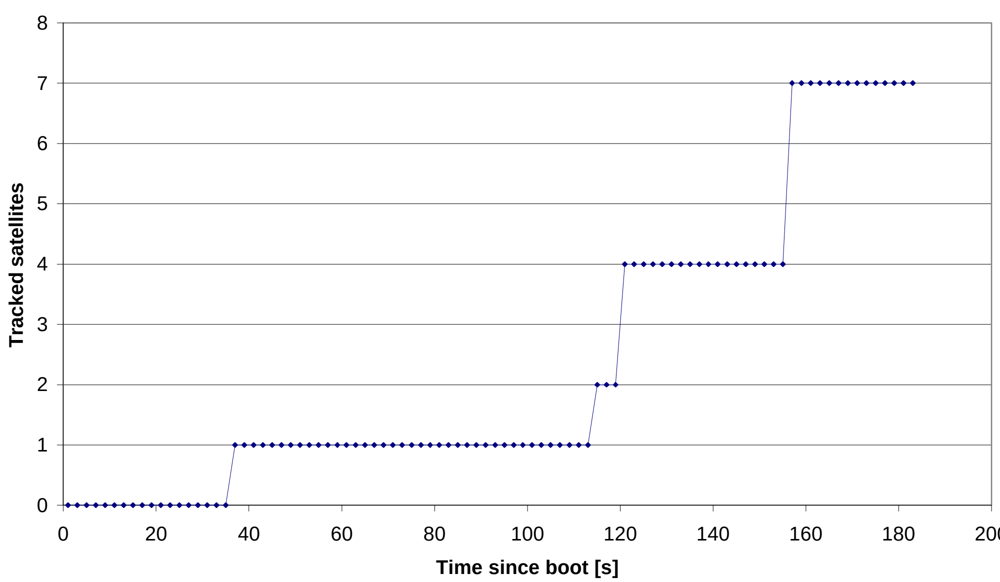

Fig. 6 Acquisition performance in case of real-time clock and non-volatile memory failure. Tracking conditions for the first satellite (frame lock and ephemeris available) were achieved at 37s after boot. Four satellite navigation was available after two minutes.

Supplementary to the assessment of the signal acquisition process, a dedicated test was performed to determine the errors of the GPS navigation solution in comparison to the simulator's reference trajectory (Fig. 7). Here, 3D navigation was achieved within 14 s after scenario start, since valid ephemerides were

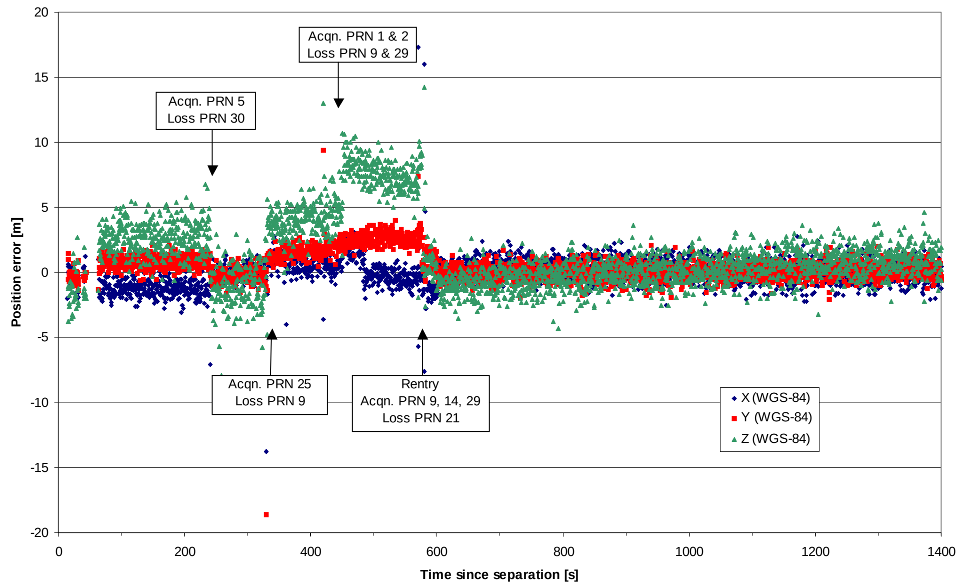

Fig. 7 Errors of Cartesian WGS-84 position for IRDT-2 scenario

still stored in non-volatile memory from previous simulations. Around 40 s a small data gap occurred due to the download of trajectory and almanac data from the receiver that disabled the regular data output. The position accuracy is 3 m on average while velocities are typically accurate to 0.3 m/s, which meets all expectations. Jumps in the position solution coincide with changes in the channel allocation and reflect the expected uncertainty of a real-time position solution in the presence of broadcast ephemeris errors and ionospheric refraction model uncertainties. During the reentry phase systematic velocity errors of ±1 m/s may furthermore be observed, which correlate with phases of high acceleration changes and most likely reflect a limitation of the tracking loop bandwidth.

SOUNDING ROCKET FLIGHT TESTS

Aside from the signal simulator tests described above, the Orion receiver has been qualified in a series of sounding rocket flights carried out at Esrange, Kiruna, in spring 2001. The three flights were performed on an Improved Orion rocket (Test Maxus-4 campaign [5]), a Castor-4B rocket(Maxus-4), and a dual stage Goldfinch/Raven rocket (Texus-39)). 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.

As shown by comparison with the results of an Asthech G12 HDMA receiver flown jointly on the Test Maxus-4 mission [6], a 3D tracking accuracy of better than 10 m could be demonstrated during the parabolic free flight and the final descent. During the boost phase and atmospheric re-entry different levels of degradation have been observed that indicate a sensitivity of the temperature controlled crystal oscillator (TCXO) on mechanical stress. Here, yerk, i.e. a rapid change in acceleration appears to be more important than high acceleration itself. This is e.g. illustrated by the Maxus-4 mission, where the acceleration increased almost linearly up to a peak value of 14 g at the end of the 60 s boost phase. Tracking problems were only encountered at burn end, when the acceleration suddenly dropped backed to zero level. During the reentry of the Test-Maxus-4 payload, a peak acceleration of 5 g was achieved within about 15 s, giving a yerk of 0.33 g/s. In comparison with the G12 tracking data, a maximum position offset of 120 m and a velocity error of 77 m/s were determined during this phase of the mission.

In view of a peak yerk of 0.7 g/s expected during the atmospheric re-entry of the IRDT-2 capsule, a temporary degradation of the GPS navigation solution is therefore foreseen with the employed oscillator. However, due to a lack of flight test results for alternative TCXOs and a tight project schedule, it was decided not to perform any last minute changes to the GPS flight hardware prior to launch.

SUMMARY AND CONCLUSION

As part of the second Inflatable Reentry and Descent Technology demonstration mission, a GPS navigation unit will be employed to track the capsule's trajectory from separation to landing. The unit is based on a Mitel Orion receiver built by DLR/GSOC and a supplementary data handling system used to record GPS navigation data and raw measurements throughout the entire ballistic flight. The original receiver firmware has received numerous modifications to support a robust signal acquisition and accurate tracking under the highly dynamical conditions of a reentry mission. Tests conducted in a signal simulator environment as well as existing experience on sounding rockets indicate that the receiver should be able to provide a tracking accuracy of better than 10 m during the free flight phase, if a sufficient number of GPS satellites is within the antennas visibility cone. The flight data from the actual mission are expected to provide valuable information on the vehicle dynamics as well as the GPS signal conditions during the reentry phase of the mission.

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