IGAS (INNOVATIVE GPS ANTENNA SYSTEM) – A NOVEL GPS ANTENNA CONCEPT FOR SPIN-STABILIZED SOUNDING ROCKETS

M. Markgraf (1), F. Hassenpflug (1), J. Ettl (1), P. Turner (1)

(1) (1)Deutsches Zentrum für Luft- und Raumfahrt (DLR), D-82234 Wessling, Germany
tel: +49.8153.28.3513, fax: +49.8153.28.1450, Email: markus.markgraf@dlr.de

ABSTRACT

This paper addresses a novel GPS antenna system for spin-stabilized sounding rockets and launch vehicles. It describes the concept as well as the first realization of the newly developed system. Furthermore it presents the results of on-ground tests conducted on a turn-table with the system installed into a mock-up of a rocket section. The promising outcome of these tests justified the subsequent preparation of a flight experiment. In the second part of this paper, the results of the maiden flight of the IGAS system onboard a real sounding rocket, the Rexus-4 vehicle, are summarised and discussed. The qualification flight has demonstrated that the system, in general, performs well and even outperforms the traditionally used combination of tip and blade antennas. However, it has also been recognized, that further adaptations in the GPS receiver software are required to gain full profit of the novel concept.

1. INTRODUCTION

Over the recent years, GPS sensors have become an integral part of many sounding rocket projects. GPS receivers onboard such vehicles can serve a multitude of purposes, from the support of flight safety operations, post-mission analyses, time-tagging and geo-coding of scientific data up to the use in integrated navigation systems.

However, in a vast number of projects a main obstacle to using a satellite-based navigation system is the spin about the longitudinal axis build-up during the boosted phase of the flight. While a number of suitable GPS sensors have been developed, able to cope with the linear motion of the rocket, this is typically not the case for spinning vehicles, where an additional rotational motion is superimposed to the translational motion. In general, the antenna system has been identified as the major weak point in these applications.

A well established solution to this problem is the use of wrap-around antennas [1]. Despite the superior technical performance, these antennas exhibit various drawbacks, such as high cost, need for specialized tubes with enhanced wall thickness and a milled grove and, last but not least, US export restrictions and long lead times.

In a first attempt to overcome these inherent drawbacks, the authors have previously developed a dedicated multi-antenna concept, composed of a tip antenna and a pair of blade antennas, connected to the receiver via R/F relay [2]. While the former provides satisfying results during spinning phases, and is therefore well suited for tracking during the boost phase, the latter suffers from a highly anisotropic antenna diagram, and is used for tracking after de-spin and tip release. Even so it has successfully passed flight qualification, and has been used during many past missions, the system is not always an appropriate choice. In numerous missions, the tip section is occupied by experiments and thus not available for the installation of a GPS antenna.

As a remedy to this problem, an effort has been made to further improve and refine the above concept. A spin-insensitive multi-blade-antenna system has been developed, which actively compensates the spin of the vehicle by switching among different antenna sets in such a way as to maintain a roughly constant orientation of the active antennas. An even number of blade-antennas is mounted around the circumference of the rocket and linked together such that always two or more antennas form an individual antenna pair. These pairs are then connected to the receiver through a pin-diode switch and at any time only one pair is active. The switching is controlled via a rate sensor, depending on the actual spin rate of the rocket. As a result, this yields a quasi-static antenna pattern in an inertial reference frame.

The present paper describes the concept and design of the novel antenna system. Furthermore it presents the results of on-ground tests conducted with a mock-up of a rocket section on a turn-table. Finally, the results of the first flight validation onboard the Rexus-4 vehicle are analysed and discussed. The ground tests as well as the qualification flight have demonstrated that the system in general performs well but further adaptations in the GPS receiver software are apparently required to gain full profit of the novel concept. In the subsequent section, the basic concept and implementation of the novel IGAS antenna system are presented.

Proc. '19th ESA Symposium on European Rocket and Balloon Programmes and Related Research, Bad Reichenhall, Germany, 7–11 June 2009 (ESA SP-671, September 2009)

2. IGAS - SYSTEM OVERVIEW

2.1. Problem Description

To reduce the costs of a GPS antenna system for spinning rockets, simple but efficient blade antennas are traditionally mounted around the circumference of sounding rocket. The signals received by the individual antennas are combined together via a powered divider, before they enter the GPS receiver. Due to strong interference of the individual antenna patterns, the resulting overall antenna diagram exhibits a highly anisotropic sensitivity characteristic. Fig. 1 provides a 3D illustration of the overall antenna pattern for a four-antenna system, with antennas mounted at azimuth angles of 0°, 90°, 180° and 270° for a 14 inch payload.

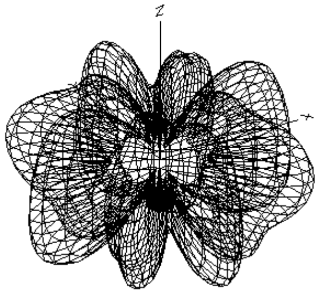

Fig 1. Overall 3D-Antenna diagram for a GPS antennas quadruple.

For practical applications, the system nevertheless provides a good overall global coverage and allows tracking of a sufficient number of GPS satellites irrespective of the sounding rocket orientation, al least, as long as the spin rate remains below 1 Hz.

In case of unguided ballistic rockets, however, it is necessary to spin up the vehicle about the vertical axis to much higher rates in order to maintain a stable vehicle orientation during the boost phase. Previous experiences have shown, that during the spinning flight phase a normal GPS receiver connected to the above described system is not able to synchronize to the incoming navigation signals and thus not able to deliver continuous navigation solutions.

During the spinning phase the rotating antenna pattern, with its numerous minima and maxima along all axes, produces an amplitude modulation on the incoming signal with a dynamic range of up to 20 db. These amplitude and also phase variations influence the GPS receiver in a severe and adverse way which, in the end, leads to a loss of synchronisation in the GPS receiver to the incoming satellite signals. To overcome this problem, a tip antenna mounted in the nose cone of the rocket is typically used during the spinning flight phase. However, the tip section is not always available for mounting a tip antenna e.g. because an experiment requires the space or the tip is even part of the experiment itself (e.g. SHEFEX-2,[3]).

2.2. Concept

A possible solution to the above problem is to modify the blade antenna system in such a way as to minimize the amplitude and phase modulations on the signals feed to the GPS receiver to a level that can be tolerated by the receiver. In this case, the use of an additional tip antenna during the boost phase would be superfluous and a single antenna system could be employed for tracking the entire flight trajectory.

In order to achieve this goal, the above described four-blade antenna system is supplemented by a second, identical system mounted with a 45° azimuth offset with respect to the first system. Both systems are connected to the radio-frequency front-end of the GPS receiver via a pin-diode switch. At any time, only one of the both subsystem is connected to the receiver

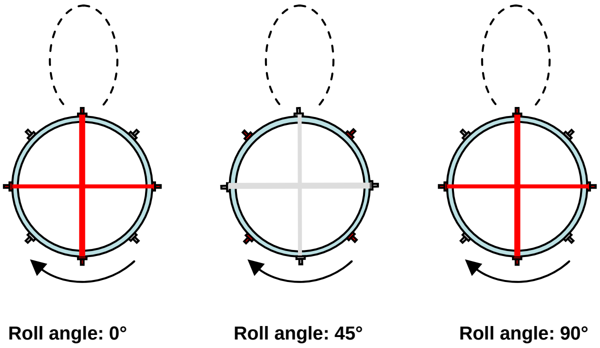

Fig 2. Schematic illustration of the switching between the different antenna quadruples (A=red; B=grey). When the rocket has turned about 45° the pin-diode switches from system A to sub-system B. After another 45° turn, the switches back to system A, and so on….

Switching between the different sub-systems is controlled via a rate sensor, depending on the actual spin rate and the roll angle of the rocket in such a way as to maintain a roughly constant orientation of the antenna pattern. In other words, the actual roll motion of the rocket is compensated by a virtual rotation of the antenna pattern in the opposite direction. As a result, this yields a quasi-static antenna pattern with respect to an inertial reference frame and reduces the amplitude and phase variations on the signal to a minimum.

In general, the novel antenna concept is not confined to the above described implementation with two times four antennas. Each subsystem could comprise more or less antennas and the number of subsystems could vary. The minimum number of antennas, however, has to be chosen such that the resulting phase shifts are reduced to values less than 90 degrees. Larger phase jumps during the switching could be understood by the GPS receiver as a change of the data bit modulated onto the navigation signal. The total number of antennas therefore depends mainly on the diameter of the payload segment.

2.3. Implementation

This section describes the IGAS experiment module which has been build up to validate and qualify the above introduced concept in a real flight mission.

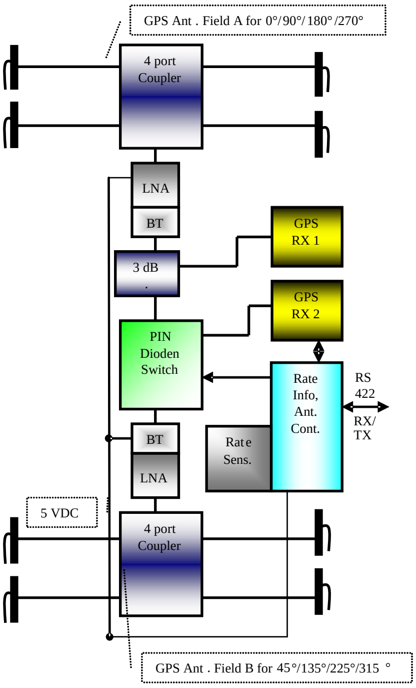

Fig 3. Architectural diagram showing the IGAS experiment configuration.

The IGAS flight system consists of two antenna sub-systems, each comprising four flight antennas. The four flight antennas are passively combined through a 4 port coupler. The output signal of the coupler is amplified by a low noise preamplifier to compensate the losses due to the power divider and the R/F lines. The amplified signal is then connected to the GPS receiver via a pin diode switch. A rate gyro accommodated in the IGAS experiment module is used to determine the rotation rate of the spinning rocket. Based on this information, the board computer calculates the corresponding attitude angle and activates the pin-diode switches in such a way that the amplitude and phase modulations are minimized. During a complete revolution the board computer switches eight times between the both antenna sub-systems.

Apart from the main GPS receiver, the IGAS flight module contains a second receiver used as independent reference data source. This second receiver is directly connected to one of the both passively coupled antenna quadruples, before the pin-diode switch (see Fig. 3). The data provided by both GPs receiver as well as a set of house keeping data are collected and sent to the ground via TM/TC system RF link. On ground the data are received, monitored and archived by the ground system.

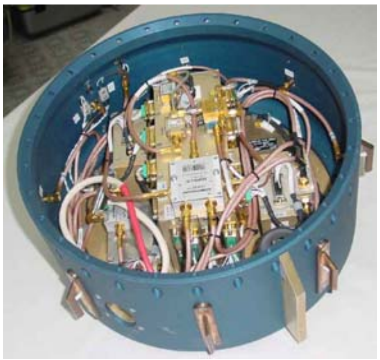

Fig 4. Photograph of the IGAS module with two GPS receivers, LNAs, rate sensor, switching relay and the blade antennas attached to the outer structure.

3. ON-GROUND TESTING

Parallel to the development of the novel antenna system, numerous ground tests have been conducted with a turn-table placed on an open field near the air-filed in Oberpfaffenhofen (Fig. 5). During these tests various system configurations have been assessed with different numbers of antennas, connected together to antenna couples, triples and quadruples and mounted in several geometries. While in the beginning a mockup structure has been utilized for these activities, the final tests have been performed with the experiment module described above and later on flown in the framework of the Rexus-4 rocket project. In the sequel, the results of the final ground tests are presented and discussed.

Fig 5. Picture of the test setup used for the on ground validation of the IGAS concept

Fig. 5 above shows a photograph of the turn table with the IGAS experiment module installed on top, taken during the testing. In order to enable a real-time monitoring of the system performance during the test, a radio link has been set up between a monitoring computer and the experiment module.

The test was initiated by a short phase of several minutes without spin, in order to allow the receiver to do a proper initial acquisition and to download a complete Almanac through the air. This corresponds well with the situation during a real sounding rocket flight, where the electrical systems are typically activated a few minutes before lift-off, to do a final system checkout at the launch pad. Thereafter, the system has been spun up in steps of 1 Hz to a total spin rate of 3 Hz which is the maximum rate the test table supports.

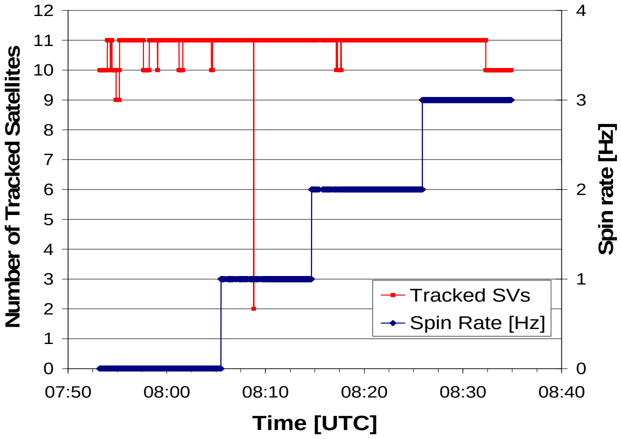

Fig 6. Plot of the number of tracked satellites (red line) and the spin rate in Hertz (blue line).

The graph in Fig. 6 shows the number of tracked satellites along with the current spin rate. This parameter provides a good indication for the overall tracking performance and robustness of the navigation system. The number of tracked satellites remains almost constant during the entire test run, which was not the case in earlier tests with a non-switched dual-antenna system as it has traditionally been used in past rocket missions.

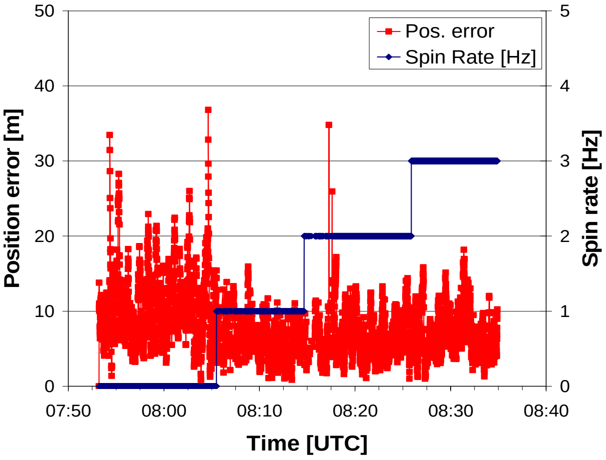

Fig 7. Position errors (red) and spin rate(blue).

In addition to the number of tracked satellites, the navigation accuracy has been analyzed. For this purpose the position and velocity errors on the kinematic navigation fixes obtained from the Phoenix-HD GPS receiver have been computed and are illustrated in Fig. z and Fig. a.

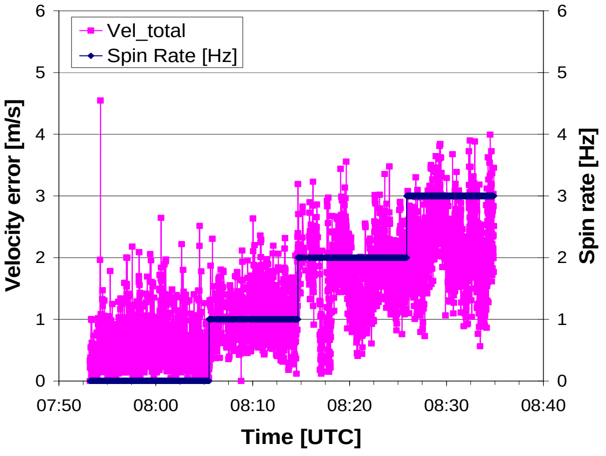

Fig 8. Velocity errors (pink) and spin rate (blue).

While for the position errors, no dependence on the spin rate is obvious, this is not the case for the velocity error. The magnitude of the overall velocity error is directly correlated with the actual spin rate and increases with the rotation speed. This might be explained by the fact, that the satellite signals entering the receiver front-end are still affected by a certain level of amplitude and phase variations. This results in an increased noise level on the carrier phase, Doppler measurements and thus the velocity fixes.

However, in total, the observed errors on the navigation solutions are still on a tolerable level and sufficiently accurate to serve for operational purposes such as e.g. flight safety operations and post flight vehicle performance analysis.

4. FLIGHT VALIDATION

Following the successful on-ground validation of the IGAS concept, the maiden flight onboard a real sounding rocket has been conducted in the frame of the REXUS-4 project. A short overview about this mission and the obtained results is provided subsequently.

4.1. REXUS-4

The German-Swedish sounding rocket program Rexus provides periodically recurring flight opportunities for student and young scientist experiments under space conditions. The Rexus-4 rocket was launched at Esrange Sweden, on October 22, 2008 at 12:30UTC (Fig. 9) [4].

Apart from the IGAS experiment module, the Rexus-4 vehicle carried five technological experiments onboard designed and built up by different German and Swedish universities.

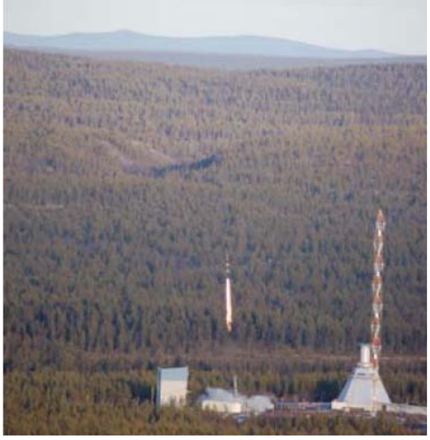

Fig 9. Rexus-4 student rocket at lift-off.

The Rexus-4 mission marked also the maiden flight of a newly developed service system for rockets. As part of this new system, a third, independent GPS receiver was flown onboard the rocket, utilizing a traditional antenna system composed of a tip antenna and a dual-blade antenna combination.

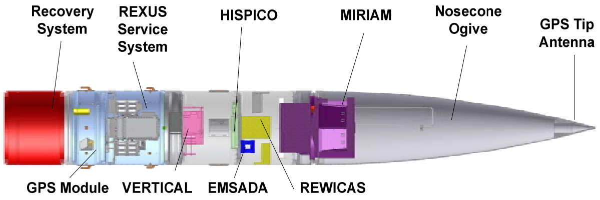

Figure 10. Schematic view of the payload segment of the Rexus-4 vehicle.

The dual-stage motor system, consisting of a Nike/Improved Orion combination, carried the 152 kg heavy payload to an apogee height of 175 km (Fig. 10). To maintain a stable attitude during the ascending flight phase, a spin of approximately 4.6 Hz was built up about the longitudinal axis. After the burn-out of the 2nd stage a yoyo system de-spun the rocket at an altitude of 66 km to a rate of only a few degrees per second.

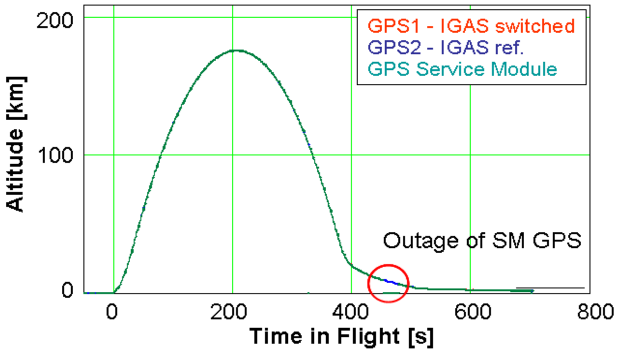

Figure 11. Altitude profile of the Rexus-4 payload.

The plot in Fig. 11 shows the altitude measurements of the vehicle obtained from the three different GPS systems on board the Rexus-4 rocket. While the both GPS receiver in the IGAS experiment module were able to continuously provide navigation fixes during the entire flight, the standard GPS system lost track during the flat spin phase at the atmospheric re-entry.

The following graph in Fig. 12 displays the number of tracked GPS satellites. In average, the both IGAS GPS receiver had more satellites in lock than the third receiver in the service system, especially during the high dynamic phases.

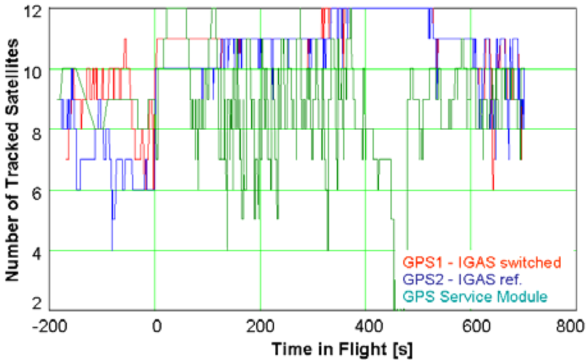

Figure 12. History of number of tracked satellites.

During the high dynamics ascending phase both experimental GPS system in the IGAS module achieved improved results compared to the standard tip/dual-blade GPS system in the service system.

A direct assessment of the navigation accuracy is generally hampered by the lack of accurate reference position and velocity data for a comparison. However, there are some ways to indirectly assess the collected data. The following graphs, for example, illustrate the flight angle (elevation angle to the earth surface), a parameter directly derived form the velocity fixes during the first 200 seconds in flight (Fig. 13).

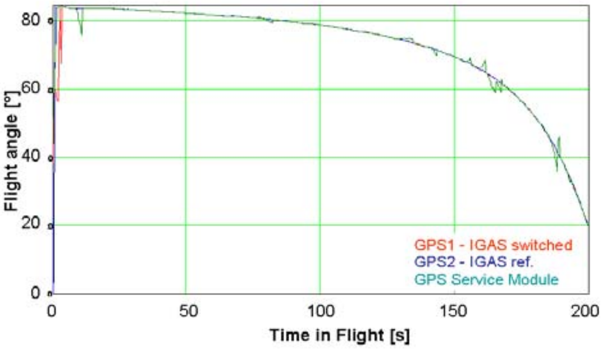

Figure 13. Flight angle derived form GPS velocity data.

It is noticeable that the flight angles obtained by the IGAS GPS receivers show a smoother curvature than the flight angle of the standard GPS system, which is located in the Service Module. Furthermore, the graph GPS 1 (red line), which results from the GPS system with the switching antenna, indicates the best and smoothest behaviour.

In summary, it can be stated that both GPS systems flown as part of the IGAS experiment module exhibit a superior performance compared with the standard system flown as part of the service module. During the boost phase, for instants, where an extreme dynamic is observed, both IGAS GPS receivers revealed an improved performance over the standard GPS system. Additionally, the GPS system with the switched antenna system generates smoother data with less noise especially on the velocity data which might be used for the determination of flight and heading angles in guidance systems. These angles can furthermore be used for the calibration of attitude angles of rocket vehicles during the boosted phase.

5. LESSONS LEARNED AND FUTURE IMPROVEMENTS

It is obvious, that the IGAS module as it is described above might not be really suited for the utilization in sounding rockets due to its size, weight and complexity. This, however, is mainly attributed to the fact that the unit has been designed as self-contained experiment module with a number of auxiliary sensors and elements. An operational system can be built much smaller.

Typically, a standard service system already contains most elements required to realize the proposed concept, such as rate gyros, an onboard computer and a GPS receiver. Only an additional pin-diode switch needs to be added, to select which sub-system is connected to the receiver front-end. In the next version of the standard GPS receiver for high dynamic applications, this pin-diode switch will be an integral part of the design.

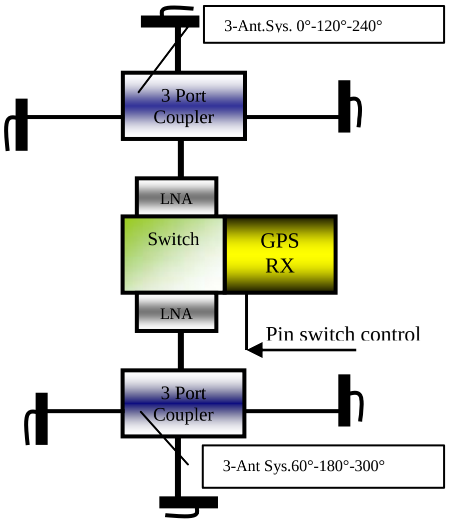

Fig 14. Architectural diagram showing the IGAS experiment

The structural diagram in Fig. 14 shows a "two times three" implementation of the IGAS concept, as it could be used for operational purposes in future flight missions. Each triple-blade antenna system consists of three antennas mounted with an azimuth offset of 120° to each other. Both triple flight antenna systems have a distance of 60 deg to each other. This system can be used for payload with a maximum diameter of 0.5m. The preamplifier and the pin diode switch are integrated into the GPS receiver. The switching between the sub-systems will be controlled via the existing board computer in the service system.

6. SUMARY AND OUTLOOK

This paper has introduced a novel multi-blade-antenna concept for spin-stabilized sounding rockets. It describes the architectural design of the system and presents and discusses the results obtained in on-ground and flight tests. The system actively compensates the spin of the vehicle by switching among different antenna sets in such a way as to maintain a roughly constant orientation of the antenna pattern. As a result, this yields a quasi-static antenna diagram in an inertial reference frame which has been identified as a prerequisite for a successful operation of a GPS receiver onboard a spinning rocket.

The results of the numerous conducted ground test as well as the maiden flight onboard of the Rexus-4 rocket have substantiated the validity of the proposed concept and shown the superior overall performance compared to the traditionally used antenna concept composed of tip and blade antennas. However, the tests have also revealed, that further fine-tuning of the system and a tailoring of the GPS receiver software might help to further improvements of the performance above the already reached level.

A first operational use of the IGAS concept in a sounding rocket mission is planned for the SHEFEX-2 project, due for launch in the second half of 2010.

7. REFERENCES

1. Haigh-Farr Inc., *GPSAntennas Data Sheet*, http://www.haigh-farr.com/datasheets/gps.pdf, 2009
2. Markgraf, M. and Montenbruck, O., *Phoenix-HD - A Miniature GPS Tracking System for Commercial and Scientific Rocket Launches*, 6th International Symposium on Launcher Technologies, 8-11 Nov. 2005, Munich Germany, 2005.
3. Turner J., *SHEFEX 2. Development Status of the Vehicle and Sub-Systems for a Hypersonic Re-Entry Experiment*, 19th ESA Symposium on European Rockets and Balloon Programmes, Bad Reichenhall, Germany, 2009.
4. Stamminger A., et al., *REXUS-4: Vehicle & subsystem design, flight performance & experiments*, 19th ESA Symposium on European Rockets and Balloon Programmes, Bad Reichenhall, Germany, 2009.