FLIGHT TEST RESULTS OF A NOVEL INTEGRATED GPS RECEIVER FOR SOUNDING ROCKETS

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ABSTRACT

DLR/GSOC's Phoenix-HD receiver is a flight-proven GPS receiver for sounding rockets. Commercial of the shelf (COTS) receiver hardware is combined with specifically designed software, which allows for a low cost navigation system to be used on low budget to high end missions. The Phoenix-HD receiver has flown on major european and international sounding rocket missions. With Galileo, new GPS signals and Glonass on the horizon and the flight experience gathered in recent years there are two main fields of improvement for a possible successor: one aspect is the implementation of new GNSS signals; the reduction of system complexity while maintaining performance under high acceleration and spin-rates is the other aspect. This paper describes the developments for a reduction of the GPS receiver system complexity. The current system uses one antenna on the tip of the nosecone and two antennas mounted on the side of the rocket body. The antenna in the nosecone is necessary because the receiver with two side-mounted antennas is spin sensitive and does not work during the boost phase on spin stabilised rockets. The forward part of the rocket below the nosecone fairing is usually required for experiments which have to be exposed to the environment. It is therefore in many missions necessary to separate the nosecone after burn out and switch to the lateral antennas. This setup has shown a good tracking performance during the boost and free flight phases and a relatively poor performance during re-entry. In experiments like Shefex II it is not possible at all to use a tip-antenna[1]. The alternative in this case is to use wrap-around antenna system with a high integration effort. The goal of the ongoing development is to get rid of the antenna in the nosecone and rely exclusively on the two side-mounted antennas. The development shall result in a reliable and low-budget alternative to both the current 3-antenna system and the wrap-around antenna. A digital diversity signal combining scheme has been developed in order to improve the performance of the current analogue combining. A first demonstration version of this receiver has been developed using the flexible FPGA-based Namuru GPS receiver [2]. Ground testing has been conducted with a Spirent signal simulator and a turn table setup in the field. A prototype version has been launched successfully on the Rexus 7 rocket and showed clear performance improvements over the current system. The paper provides a description of the rocket flight experiment and compares the flight experiment results with the ground test results. Conclusions of the experiment are drawn and the further work is discussed.

Key words: GPS; Sounding Rocket; Phoenix Receiver.

1. INTRODUCTION

The Namuru V2 receiver [2] has been developed by the University of New South Wales in Sydney, Australia. It uses a Field Programmable Gate Array (FPGA) to include the digital signal processing logic for the correlator and the microprocessor. The system has two analogue GPS L1 frontends. The FPGA design is very similiar to the Zarlink GP4020 correlator chip which is used for the DLR's Phoenix receiver. In a first step, the Phoenix receiver software had been ported to the Namuru platform. The Namuru V2 hardware together with the Phoenix software provides an excellent basis for further developments of the flight-proven Phoenix receiver. The Namuru-HD (High Dynamics) receiver presented in [3] has been developed in order to test new features and technologies for a future Phoenix-HD successor. As it has been before, the aim of the development is to provide a small and reliable receiver at low costs.

The traditional Phoenix receiver as shown in Figure 1 (top) uses a set of three antennas, a radio frequency (RF) power coupler and a RF switch for operation on a typical sounding rocket. One antenna in the nose-cone is used to track during the boost phase. The nose-cone is usually ejected after burn-out and de-spin in order to enable other experiments which need to be exposed to the environment. Before ejecting the nose-cone the receiver is switched over to two blade antennas, mounted adjacently on the sides of rocket body.

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We are therefore developing a system which is using the to RF inputs of the Namuru hardware to implement a digital antenna diversity approach [4]. This system reduces the external RF components and therefore points of failure as well as the effort for integration and operation of the receiver. Figure 1 (bottom) shows a block diagram of the developed Namuru-HD setup.

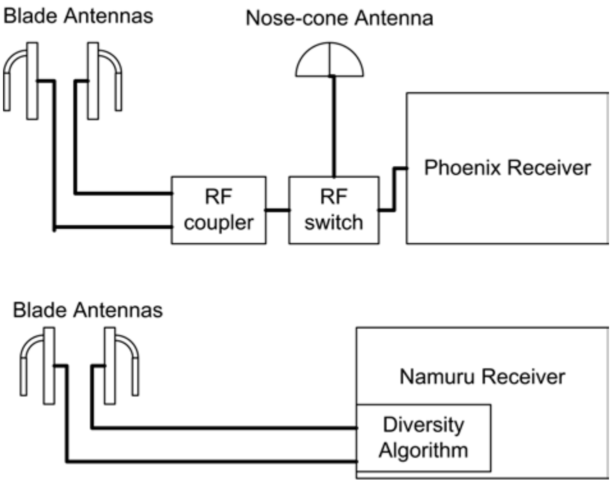

Figure 1. Block Diagram with external components: Phoenix (top); Namuru (bottom)

This paper describes the system tested on the Rexus 7 sounding rocket mission. Section 2 describes the experiment hardware and software as flown on the mission. In 3 the flight result are presented and discussed. Section 4 describes the changes implemented after analysing the results of the flight and describes testing of the changes in a signal simulator environment. A conclusion is finally drawn in Section 5.

2. EXPERIMENT DESCRIPTION

There are two downsides of the current system which are addressed in the ongoing development. First, the antenna in the nose-cone adds weight, complexity and a point of failure. Secondly, the current two-antenna system is sensitive to spin and tumbling motion and has problems to track during the atmospheric re-entry of the rocket.

The Namuru-HD receiver is using a digital antenna diversity switching system in order to remove the need for a third antenna on the nose-cone while providing stable tracking throughout the complete flight. A preliminary implementation of this system has be tested in flight. In addition to the flight data it is used to assess and improve the means of simulating the rocket flight with a Spirent GPS signal simulator.

The following subsections describe the experiment as flown and gives information on the flight of the Rexus 7 mission.

2.1. Test Setup

The FPGA hardware flown on Rexus has been described in [3]. The receiver firmware had some minor improvements regarding the tracking loops. In general, a very early version of the development has been flown on the rocket. Figure 2 shows a schematic of the hardware/FPGA design.

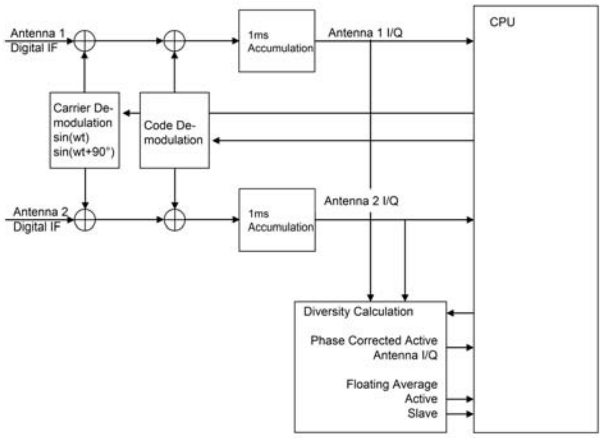

Figure 2. Diversity receiver schematic

The code and carrier demodulation is performed by one tracking loop respectively. From the two demodulated signals from both antennas a signal to noise ratio (SNR) calculation is performed. The software selects the stronger signal automatically. During the process of switching from one antenna to another the phase of the signal is corrected in order to allow a continuous decoding of the navigation data bitstream. The receiver hardware is mounted in an aluminium enclosure. A circuit board containing a DC/DC converter, RS422 level translator and EMI filter is included to provide the interface to the service module. Figure 3 shows the Namuru-HD receiver with the power and communications circuit board on top.

Figure 3. Experiment receiver hardware

2.2. Rocket Flight

The Rexus 7 consisted of a one-stage rocket with an Improved Orion rocket motor. The rocket launched 93 kg

Figure 4. Assembled experiment ring with GPS antenna

of payload to an apogee of 83 km. Figure 5 shows the GPS and radar trajectory together with the precomputed trajectory. The rocket's service module contains a traditional Phoenix GPS receiver system which is used as a reference throughout this paper. The Namuru-HD receiver has been powered about 10 minutes before launch. It had been loaded with a current almanac and acquired 11 satellites before launch.

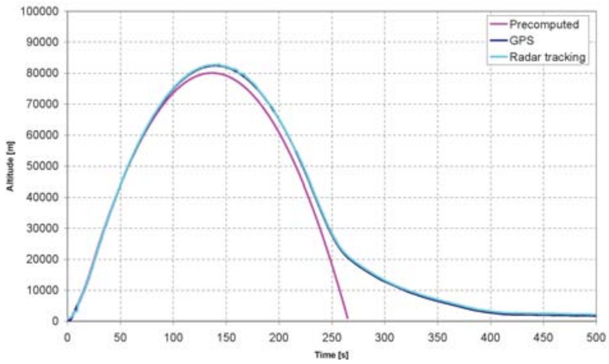

Figure 5. Altitude vs. time plot from Rexus 7 housekeeping data and radar tracking [5]

3. FLIGHT RESULTS

The receiver has provided a good navigation solution for the most parts of the flight. The receiver had some tracking outages throughout the boost phase with high accelerations and spin-rates but outperformed the Phoenix-HD in every aspect as soon as both receivers tracked on an identical antenna system. The flight has been an important step towards a working and tested system. The flight performance is further analysed in this chapter.

3.1. Analysis of flight performance

As the reference receiver is expected to produce position errors in the same range as the Namuru-HD receiver, a comparison with the service module's Phoenix-HD can not provide accurate error measures. It is however a suitable way to assess the general quality of the navigation solution. A comparison with the radar tracking results would be possible but the errors of radar tracking exceed the trajectory computed by GPS. Figure 6 shows the difference in meters on the x, y and z axes between the Namuru-HD and the onboard reference receiver from the rockets service module. Differences of up to 100m can be observed before launch. This phenomenon has been observed earlier on sounding rocket missions and is most likely to be attributed to multipath interference due to numerous metallic launcher structures and buildings on the launch site. Once the rocket leaves the launcher, the multipath error has shown to decrease in earlier missions. This behaviour has been expected and can be observed on the Namuru receiver as well as the reference receivers position solution. It can be seen from the data that the RMS difference between the two receivers remains below 20 m for almost all parts of the flight.

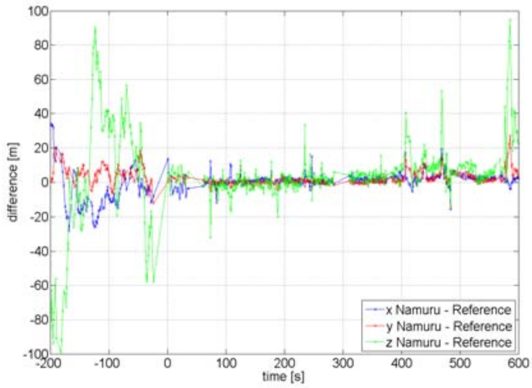

Figure 6. Difference of Namuru-HD and reference receiver

Figure 7 shows the velocity in z-direction derived from the reference receiver and the number of tracked satellites of both receivers. During $t = 46s$ and $t = 69s$ the Namuru-HD receiver did not provide a navigation solution because it lost track of too many satellites. This is the boost phase with high acceleration and a spin-rate of up to 4 Hz. The Phoenix-HD managed to track in this phase because the signal has been received with the nose-cone antenna. During reentry the Phoenix-HD lost tracking and subsequently provided no navigation solution during $t = 298s$ until $t = 322s$. The payload of the rocket showed a tumbling about all axes of up to $600°/s$. The blade antenna system in the configuration with a power combiner as used for the Phoenix-HD had problems with tracking the signals. The Namuru-HD however tracked constantly 10 satellites through the reentry. This shows that the digital antenna diversity system presents a clear improvement over the current system.

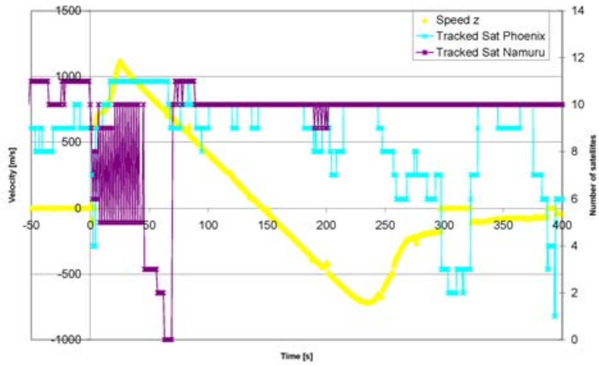

Figure 7. Velocity in vertical direction vs. the number of tracked satellites with Phoenix and Namuru receivers

3.2. Comparison of flight results with simulations

The Namuru-HD showed a loss of tracking during the boost phase at high spin rates. This came somewhat unexpected as the ground testing and simulations have shown no such problems. The testing and simulations however have not been completely accurate as the turn-table setup is limited to approximately $1000°/s$ has obvious difficulties in accurately reproducing the high longitudinal accelerations of a rocket. The scenario for simulator testing replicated the turn-table setup regarding the spin-rate and did not simulate the dynamics of the rocket flight. This was an intentional setup to be able to compare the developments in the laboratory to the testing on the turn-table. Further time constraints did not allow to repeat simulations with a realistic rocket scenario.

To analyse the data and reproduce the flight, the simulation scenario has been changed to include the rockets dynamics. New simulations show that the system flown on Rexus 7 is indeed sensitive to the combination of spin and acceleration which lead to a subsequent loss of tracking during the boost phase.

4. NEW DEVELOPMENTS

After analysing the flight data it became evident that the tracking behaviour during the boost-phase requires further improvement. This came somewhat surprising after the working ground tests. To simplify the development and debugging a system that allows a high speed transfer of arbitrary data to a personal computer has been developed. This system uses the Namuru's USB port in order to transfer data such as correlation values or tracking loop parameters. It has been implemented in the FPGA in order to minimise the effort needed by the receiver software. Data rates of more than 1 MB/s are possible with minimal impact on the software run times.

The rocket trajectory and spin-rates have been simulated on a Spirent GSS7700 GPS signal simulator. The simulation scenario has been changed to include a trajectory with an acceleration of 18 g and 4 Hz spin rate. Figure 8 shows the inphase and quadraphase correlation results at 18 g and 4 hz with a 1 ms integration time. It can

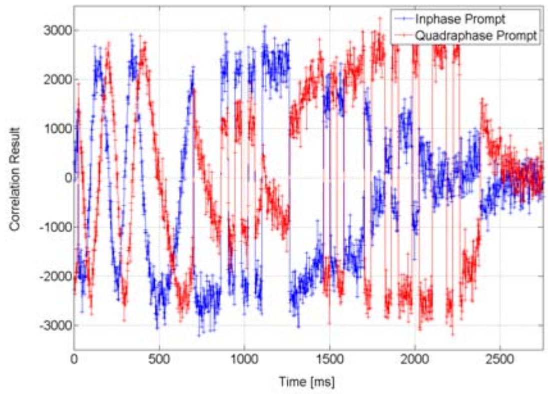

Figure 8. Tracking at 3 Hz in simulation scenario with system flown on Rexus 7

be seen that the PLL fails to lock intermittently which in turn presents problems to the bit synchronisation process. The receiver can still provide code tracking in this case but acquisition of new signals and stable tracking can not be guaranteed during the boost phase. As a conclusion, the design has to be improved in order to ensure robust tracking and acquisition.

4.1. Modified diversity processing

During tests with the updated simulation scenario, it became clear that a smooth transition between the antenna in use and the antenna coming into the field of view is very important to provide the ability of decoding data from the GPS signal. It has to be ensured that the I/Q-vectors of both antennas match before performing the switch the reception between the two antennas. This can be achieved in two different ways. If the final downconversion stage is the same for both antennas, the signal from only one antenna is actively tracked and therefore phase-controlled. The signal from the passive antenna, in case both antennas are in the field of view, has a slightly different phase and frequency depending on the spin rate and the angle of the spin axis and the GPS satellites elevation. Vector rotation can be used to align both the active and passive antennas I/Q-vectors. The second alternative is to use different final downconversion stages for each antenna with slightly different frequencies of the numerically controlled oscillator (NCO). In combination with a locked PLL on both channels, the same vector rotation is performed in this case by the carrier tracking loop.

Based on the simplicity of implementation, the second approach has been implemented in the improved version of the Namuru-HD receiver. A short handover phase of 10-15 ms in which both antennas are in the field of view is required for the transition between antennas. During this phase the inactive antennas tracking loop is started with estimated parameters and converges to stable tracking before the now inactive antenna is declared active. The estimated starting parameters for the passive loop are the internal states of the tracking loop taken at the last switch of the antennas. A combination of a limited maximum differential frequency and a lock indicator for the passive channel ensures that the passive channel is only allowed to track whenever a valid signal is detected. The I/Q vectors of both antennas are subsequently summed for code tracking. This allows for a up to 3 dB higher signal to noise ratio compared to a single antenna in case of both antennas looking at the GPS satellite and subsequently a lower code tracking noise. To simplify the interaction of the channels, a new NCO hardware has been developed. Figure 9 shows a schematic of the implemented diversity hardware including the NCO with two different offset frequencies.

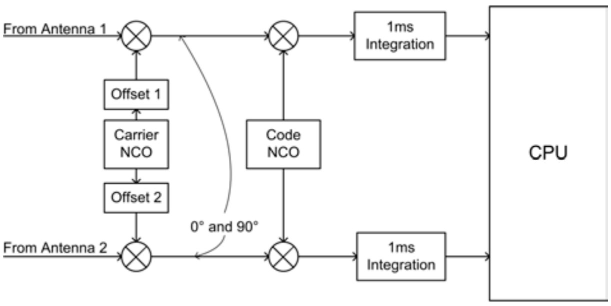

Figure 9. Schematic of the improved system. (N.B.: The inphase and quadraphase signal paths are not drawn separately)

The main oscillator has two offset registers which can generate an arbitrary offset from the main oscillator. The software uses the main oscillator to track the signal from the active antenna and the appropriate offset to track the passive signal. The allowed frequency difference is limited by software.

4.2. Simulator testing

Figure 10 shows signal tracking with the improved system on a simulation run at approximately 3 Hz. The simulation has been changed to use the full rocket dynamics as described in 3.2. The upper plot shows the inphase correlation wheras the lower plot shows the quadraphase correlation results. The blue signal is received from antenna 1 and the red signal from antenna 2. At $t = 44700ms$ antenna 1 turns into view of the GPS satellite. The signal power can be seen to gradually increase. Immediately after exceeding the threshold, the PLL locks the signal and adjusts the phase to the currently still active antenna 2. As soon as the signal power exceeds antenna 2, antenna 1 is declared active and used as master input for the carrier tracking loop. The now slave antenna 2 is still tracked until signal power fades below the threshold. Now the slave channel is preset with the estimated tracking parameters and waits until the signal exceeds the threshold at $t = 45150ms$. The I and Q portions of both antennas are subsequently summed while both signals are above the threshold. The combined signal is then used as an input for the code tracking loop and can provide a more robust code tracking. It can be observed in the lower plot

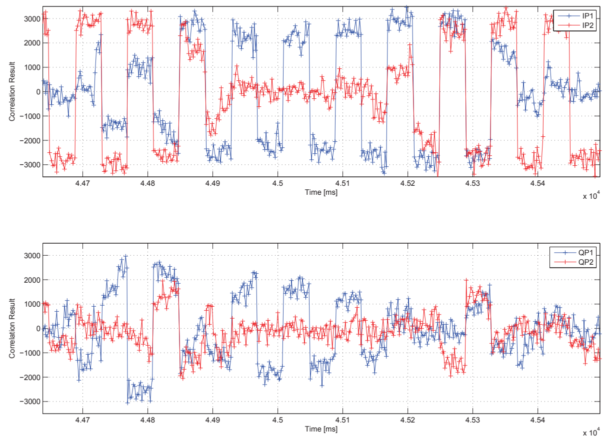

Figure 10. Tracking at 3 Hz with new algorithms

that the PLL is not able to steer the vector quickly enough to provide a completely real signal amplitude. This does not matter as long as the PLL manages to keep the vector within $\pm 90°$. The remaining phase error is removed by calculating the signal magnitude and phase to provide the maximum available signal power to the bit decoding process.

5. CONCLUSIONS

It has been shown on the Rexus 7 flight that the digital dual antenna diversity system can provide an improvement over the traditional Phoenix receiver. The tracking during the reentry clearly outperformed the reference system. During the boost-phase, the Namuru-HD with the side-mounted blade antennas was not able to match the performance of the reference using the nose-cone antenna. The rocket flight has been an excellent opportunity to test the implemented diversity algorithms and is a vital step in development of an improved GPS receiver. Further developments in order to improve tracking during the boost-phase have been implemented and tested in a simulation environment.

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