KODIAK: A VERSATILE SPECIAL PURPOSE MULTI-GNSS RECEIVER FOR HIGHLY DYNAMIC SOUNDING ROCKET APPLICATIONS

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ABSTRACT

The Kodiak GNSS receiver is a modular and versatile GNSS receiver platform that has been developed by DLR specifically for high dynamic space applications such as sounding rockets, launch vehicles or re-entry vehicles. It is a successor to the widely used Phoenix GPS receiver. Its flexible design allows various use cases like rocket- or other high dynamic applications. Features are: estimation of the 6DoF state of vehicles by fusing the receivers' position and velocity with the inertial navigation solution, orientation estimation from relative carrier phase measurements of signals of two or more antennas, adaption of tracking depending on the flight phase forecasting of Doppler frequencies based on current velocity estimations of the IMU solution. This paper presents first flight results of the Kodiak receiver.

1. MOTIVATION

For almost twenty years, the Phoenix GPS receiver, developed by DLR, was a reliable PVT sensor for space applications. It had its maiden flight on the German-Brazilian VSB30 sounding rocket in 2004 and has quickly established as a receiver for orbital and suborbital satellite and rocket missions. It has been successfully flown on numerous satellite missions like PROBA-2, PROBA-V, PRISMA, TET-1, BIROS/BEESAT-4, or EuCROPIS and rocket missions like TEXUS, MAXUS, REXUS, SHEFEX. WADIS, MaxiDusty 1&2, PMWE 1&2, or Ariane-5 VA 219. The Phoenix GPS receiver consists of a radio-frequency (RF) frontend chip, an application-specific integrated circuit (ASIC) for baseband signal processing, and an ARM7 microcontroller running the navigation algorithms. The baseband signal processing chip is capable of tracking twelve GPS L1 C/A signals simultaneously. The Phoenix GPS receiver evolved from the MITEL Orion GPS receiver design, which was adapted for the unique requirements of space applications, such as the implementation of more dynamic tracking loops, trajectory aiding, and instantaneous impact point (IPP) prediction.

However, the technology of the Phoenix GPS receiver is not up-to-date anymore. The GNSS market has changed quite a lot since the maiden flight of the Phoenix GPS receiver. Since then, several new constellations have been launched, and numerous more advanced and complex navigation signals have been added in different frequency bands. With the new generation of GNSS satellites, multi-constellation, multi-frequency GNSS receivers featuring increased navigation accuracy and robustness have become state-of-the-art.

To keep up with the technological progress and to take advantage of the numerous benefits of modern GNSS, it was decided to develop a successor model.

The new design should be as flexible as possible to support all current and even future features of modern GNSS. It should allow full access to the hardware and the software. Like its predecessor, the new system should be adaptable to the specific requirements of satellite and rocket missions. Finally, the new system should be powerful enough to run advanced navigation algorithms and additional software for real-time sensor data fusion.

There is no such open and flexible device available on the commercial market, especially designed for the purpose of research and development of GNSS for space applications. That is why the Kodiak GNSS receiver has been newly developed as the successor to the proven Phoenix GPS receiver (Fig. 1).

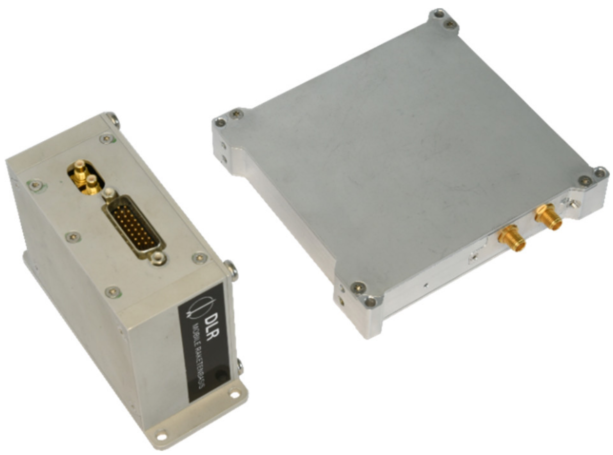

Figure 1. Phoenix GPS and Kodiak GNSS receivers

2. DESIGN

The Kodiak GNSS receiver is designed to be used as a standalone GNSS receiver or to be integrated with external sensors such as a high-grade inertial measurement unit (IMU). The concept allows custom radio frequency (RF) frontends and precise time synchronization of external sensors.

With its 32 independent tracking channels, each divided into pilot and data channels, and up to five correlators per channel, it can track 32 satellite signals of multiple constellations and frequencies simultaneously.

In addition to the GPS L1 C/A signal, which the Phoenix receiver was already able to receive, the Galileo E1 BC signal has also been implemented. The Kodiak GNSS receiver is backward compatible with the Phoenix GPS receiver, so that it can be easily integrated into existing systems without requiring any adjustments to the connected devices.

The core of the Kodiak GNSS receiver is a powerful Intel Cyclone V system-on-a-chip (SoC), consisting of a field programmable gate array (FPGA) and a dual-core ARM Cortex hard processor system (HPS) with floating point unit. The signal correlation and accumulation part of the baseband processing is implemented in the FPGA, while the tracking loops and the computation of the navigation solution run on the HPS. Compared to the lower-performance Phoenix receiver, which had only fix-point capabilities and came without an operating system, a full-stack operating system such as Linux or real-time operating systems such as µC/OS can now be used on the Kodiak GNSS receiver.

Data can be served to the processor using various bus systems like CAN, SPI, I^2C, or serial. Other interfaces can be added simply by implementing further IP cores in the FPGA without having to modify the hardware. The interfaces are also used to connect additional navigation sensors to the Kodiak GNSS receiver, such as a tactical IMU or small microelectromechanical (MEMS) IMUs that are already integrated into the receiver's hardware. Furthermore. external equipment can be connected via general-purpose input/output (GPIO) pins, which can also be used to deliver interrupts to the processor.

An internal 10 MHz temperature-controlled crystal oscillator (TCXO) is used to generate all required frequencies, but can be replaced by an external oscillator such as a more-accurate oven-controlled crystal oscillator (OCXO) or an even more accurate chip-scale atomic clock (CSAC). With a wide input voltage range of 15–40 V, the receiver can be used in a variety of applications.

The baseband signal processing can handle up to four independent antennas. The signals at one of the four antenna inputs are fed into the pilot and data channels that have been assigned to that antenna. Tab. 1 lists once again some specifications of the Kodiak GNSS receiver.

Table 1. Specifications

GNSS signal tracking	
Hardware channels	32 (pilot + data)
Correlators	256
Signals[1]	- GPS L1 C/A - Galileo E1 BC
Physical	
Size[2]	110 × 115 × 20 mm³
Weight[2]	328 g
Input voltage	15 – 40 VDC
Power consumption	4.5 W
Operating temperature	-40 – +75 °C
Interfaces	
Antenna	up to four, with LNA power supply
Communication[3]	RS422 (2×), CAN, SPI, I^2C, JTAG
Timing	- configurable PPS output - configurable PWM signal output for time sync - external clock input (10 MHz)

[1] The Kodiak GNSS receiver is prepared for most of the current and future signals due to the generic memory and LFSR code generators and flexible hardware channel design in the FPGA module
[2] If integrated in the small Kodiak GNSS receiver box
[3] Other interfaces can be implemented in the FPGA module

3. MODULAR HARDWARE

The Kodiak GNSS receiver is characterized by its modular design. Not only can the physical dimensions of the receiver be customized, but new modules can be added or existing modules can be replaced with updated versions without having to completely redesign the layout. The receiver can thus be adapted to specific requirements of an application by selecting the individual modules.

Fig. 2 illustrates the modular design of the Kodiak GNSS receiver. The FPGA module is the core of the receiver, housing the HPS, main memory, non-volatile eMMC storage and the FPGA itself. This module is commercial off-the-shelf (COTS) hardware. Thanks to the standardized connector, it can be easily replaced by more powerful or less energy consuming versions that will be available in the future. Also, different modules with different firmware can be quickly exchanged without having to flash the device. Nevertheless, the HPS is capable of running a Linux distribution for embedded systems that also allows easy access to the file system, making the exchange of firmware very simple.

The FPGA module, the RF frontend modules and all other available modules are mounted on the baseboard. The baseboard manages the communication between the various modules and with the outside world, contains a wide-range power regulator and houses the 10 MHz TCXO. For external communication with the satellite or rocket bus, the baseboard has two Micro-D connectors. For testing and development purposes, an interface board can be conveniently connected to these two connectors, providing several additional connectors and a JTAG programming interface.

On the baseboard, there are two general purpose interface connectors for mounting extension modules. These interface connectors are primarily used to connect RF frontend modules. Due to the multitude of signals on these interface connectors, it is also possible to connect other navigation sensors, controllers or actuators to the Kodiak GNSS receiver. Since the pins of the interface connectors are directly coupled to the FPGA, it is also possible to partially modify the pin layout as well as the bus systems that are bound to IP cores on the FPGA.

The RF frontend modules consist of one or two GPS and Galileo receiver chips with integrated bandpass filters, amplifiers, frequency down conversion and sampling and power supply for active antennas and/or inline low noise amplifiers (LNA). Depending on the application, up to two RF frontend modules, each with two antenna inputs, can be used at the same time. This means that measurements of signals from up to four different antennas are simultaneously possible. To reduce the mechanical footprint of the Kodiak GNSS receiver, a reversed version of the RF frontend module, with the antenna connectors on the other side, is available, as illustrated in Fig. 3. If only one interface connector is occupied by an RF frontend module, the remaining interface connector can be used for another extension module such as a MEMS IMU module, as shown in Fig. 3 top right. The IMU module consists of two sets of three-axis accelerometers and three-axis gyroscopes with different measurement ranges and a three-axis magnetometer. For the Kodiak GNSS receiver configuration shown in Fig. 3, a small-sized enclosure measuring 11×11.5×2 cm is readily available. With this small footprint, it easily fits into the service module of a sounding rocket.

4. KEY FEATURES

Because of the unrestricted access to all hardware and software components and the availability of plenty of computing power, the Kodiak GNSS receiver can be adapted to the specific requirements of highly dynamic applications. This makes the Kodiak GNSS receiver an ideal platform for research and rapid prototyping. Some examples are:

- Estimation of the six degree-of-freedom (DoF) state of the vehicle by fusing the receiver's position and velocity estimates with the inertial navigation solution which is computed from the IMU measurements.
- Estimation of the vehicle orientation from relative carrier phase measurements of signals from two or more antennas, which are fed into specifically modified tracking loops.
- Adaption of the tracking loop bandwidth depending on the flight phase, with widened bandwidths during the propelled and atmospheric re-entry flight phases to withstand the effect of the dynamics.
- Aiding of tracking loops with expected Doppler frequencies, which are derived from the current velocity estimate of the inertial navigation solution to increase the robustness of the signal tracking against high acceleration and jerk.

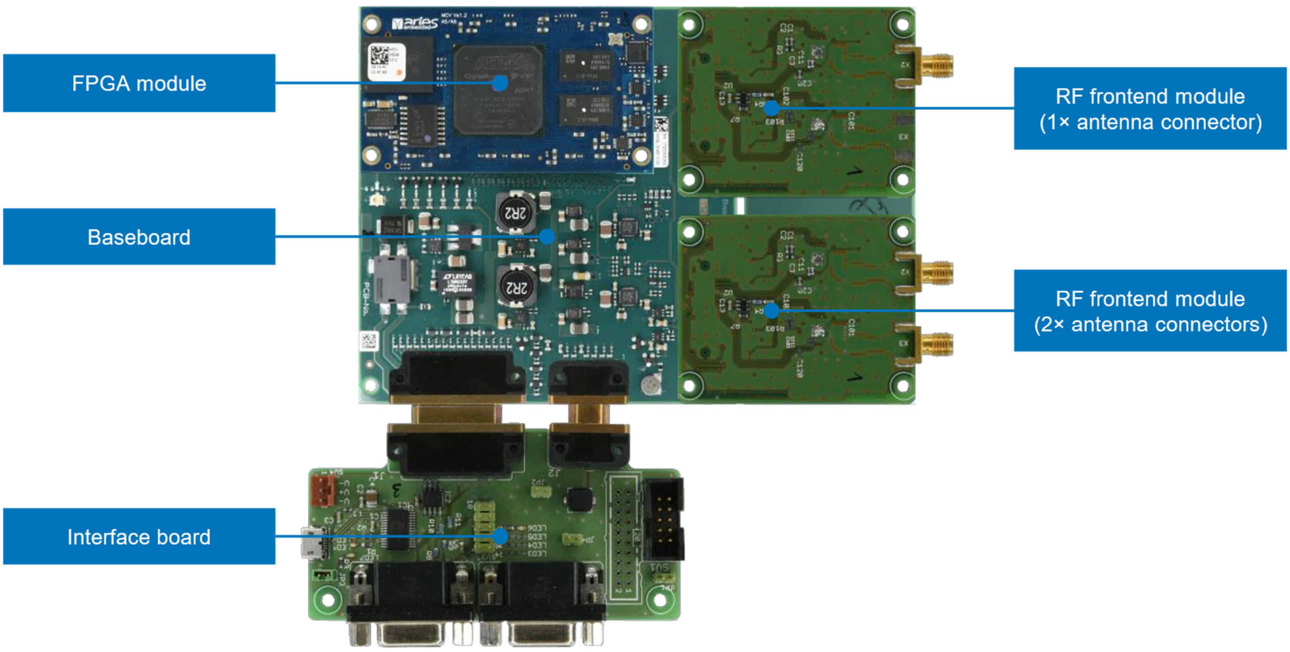

Figure 2. Modular design of the Kodiak GNSS receiver

The key features of the Kodiak GNSS receiver can be summarized as:

- High level of modularity due to two flexible and freely configurable interface slots for RF frontend modules, IMU modules, or other sensor modules
- Large number of interfaces for connecting additional external navigation sensors
- Powerful dual-core floating-point processor, with the tracking and navigation algorithms on the first core and optional algorithms on the second core (e.g. real-time data fusion)
- High capacity internal storage for recording of measurement data at high rate for post-processing such as raw GNSS observations and IMU samples
- Flexible allocation of tracking channels to up to four antenna inputs
- Coupling of tracking channels for highly accurate relative carrier phase measurements
- Simple adaption to new navigation signals due to the versatile tracking channel design with memory based and shift register based PRN code generation
- Configurable PWM signal output for time synchronization of internal and external sensors
- Interface for external reference oscillator (e.g. CSAC)

Due to the full access to the software and navigation algorithms, new features such as the Galileo Open Service Navigation Message Authentication (OSNMA) can be easily implemented and tested.

5. SIMULATION AND FLIGHT TEST

Qualification and flight testing of the receiver was performed on the Polar Mesospheric Winter Echo (PMWE) sounding rockets [1]. The maiden flight of the Kodiak GNSS receiver was on the PMWE1 sounding rocket, which was launched from Andøya Space in April 2018 [2]. A second flight took place on the PMWE2 sounding rocket in October 2021.

The development of the Kodiak GNSS receiver has been accompanied by various tests in the laboratory using a GNSS signal simulator to consistently evaluate the performance of the receiver, for example in terms of accuracy. One important aspect for sounding rocket applications that needs to be validated by simulation is the rapid acquisition of lost or newly visible satellites. This is crucial for not losing the navigation solution particularly during the high dynamic phases of the relatively short flight of the rocket. High dynamics, including high jerk and vibration, usually occurs immediately at lift-off and at motor burn-out.

5.1. Simulation

Signal acquisition was tested by means of signal simulator tests. Fig. 4 shows the tracking status of GPS L1 C/A and Galileo E1 signals just after a cold start of the receiver, which is stationary. After a cold start, the receiver no longer has prior knowledge of its position and time, and all stored satellite ephemerides are erased. The receiver has only the satellite almanac, which is loaded from a file at power-up.

The receiver starts searching for signals on all available 32 tracking channels. The first 18 channels are assigned to GPS and are occupied by the search for GPS satellites with PRN1 to PRN18. The remaining 14 channels are assigned to Galileo and are used for the search of Galileo satellites with PRN1 to PRN14. Since there is no information about which satellites are currently visible in the sky, the receiver simply starts searching for signals from the PRN1 satellites onwards. GPS satellites G03 and G12 are the first satellites to be acquired after eight seconds, and properly tracked and flagged as valid after 14 seconds after the cold start. 18 seconds after the cold start, GPS satellites G01 and G06 have been additionally

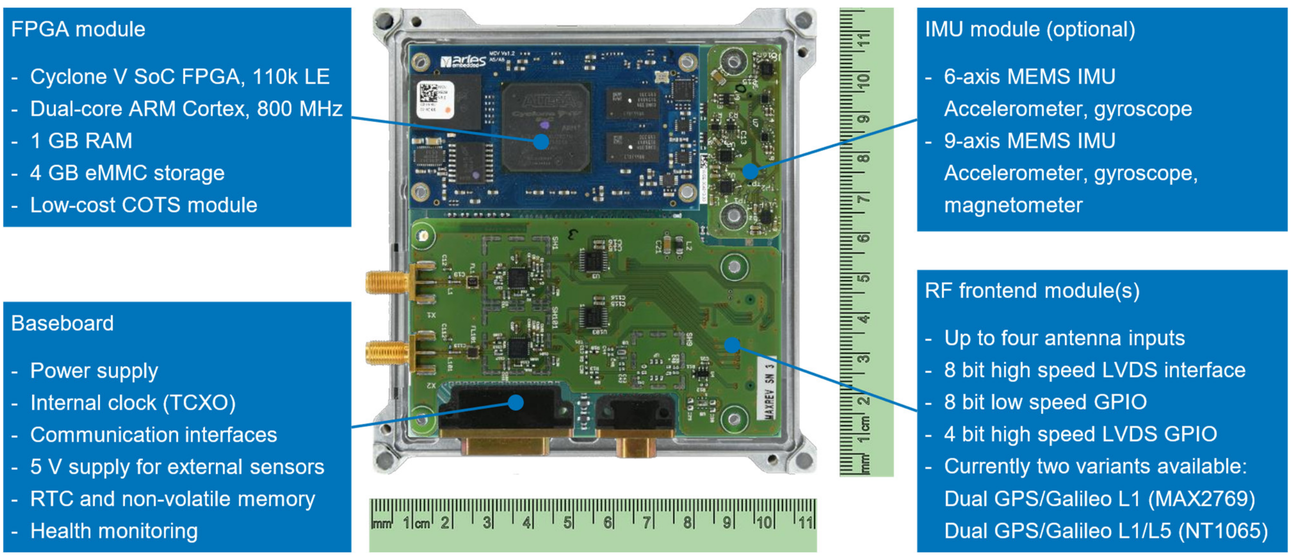

Figure 3. Kodiak GNSS receiver in a small enclosure with IMU module and reverse dual-antenna RF frontend module

acquired and are now tracked. After downloading the ephemerides included in the navigation messages of each satellite signal, the receiver can compute a position and time solution 34 seconds after the cold start. With the known position and time, and the available almanac, the receiver can immediately determine which satellites are visible in the sky, and reassigns all non-tracking channels to visible satellites accordingly. Satellites that are not visible are not searched anymore. 58 seconds after the cold start, all twelve visible GPS satellites are correctly tracked and flagged as valid. Due to the longer ranging codes, Galileo satellites take a little longer to acquire.

Fig. 5 shows the signal acquisition for a typical sounding rocket mission, where the signals were again generated by a signal simulator. A cold start of the Kodiak GNSS receiver is performed approximately 280 seconds before lift-off, which occurs at second 0. In the time before lift-off, the receiver is stationary. All visible satellites are tracked and flagged as valid at least 205 seconds before lift-off. Satellites E09 and E24 are close to the horizon and only become visible and trackable as the flight altitude increases. Especially in the propelled flight phase during ascent, signal tracking is not interrupted by high dynamics and jerk occur immediately after lift-off and at motor burnout.

This proves that the filter bandwidth of the tracking loops has been chosen wide enough to cope with the high dynamics of a sounding rocket. The widened filter bandwidth of the tracking loops comes along with the disadvantage of larger noise on the pseudorange, Doppler, and carrier phase measurements and consequently larger noise on the position and velocity solution, as illustrated in Fig. 6.

5.2. PMWE2 flight

The Kodiak GNSS receiver was tested for the second time on the PMWE2 sounding rocket, which was launched from Andøya Space on October 1, 2021, at 10:03:00 UTC. The sounding rocket payload was equipped with three different GNSS receivers, all three connected to a wrap-around antenna and a navigation-grade inertial navigation system. The GNSS receivers were the Kodiak GNSS receiver, a Phoenix GPS receiver, and a Novatel OEM7 receiver. The launch site is shaded by a 468 m high mountain located in the southeast. Before lift-off and during the first seconds of flight, the mountain blocks signals from satellites in the southern part of the sky.

Fig. 7 shows the number of tracked GPS and Galileo satellites. Lift-off is marked by the vertical grey line. With increasing altitude of the rocket, the number of visible and tracked satellites increased, too. In the end, during the coasting phase, the Kodiak GNSS receiver tracked eleven GPS and nine Galileo satellites. Briefly after lift-off at motor burnout, tracking of some signals, mainly from highly elevated satellites, was only briefly interrupted due to the short moment of negative acceleration and jerk. This proves that the Kodiak GNSS receiver is capable of acquiring new signals without difficulty even in highly dynamic flight lost phases.

Fig. 8 is a skyplot of the GPS and Galileo satellites during the flight. The satellites whose signals were received at lift-off are marked in green. The remaining satellites primarily in the south became visible and were tracked as the sounding rocket cleared the mountain's shadow.

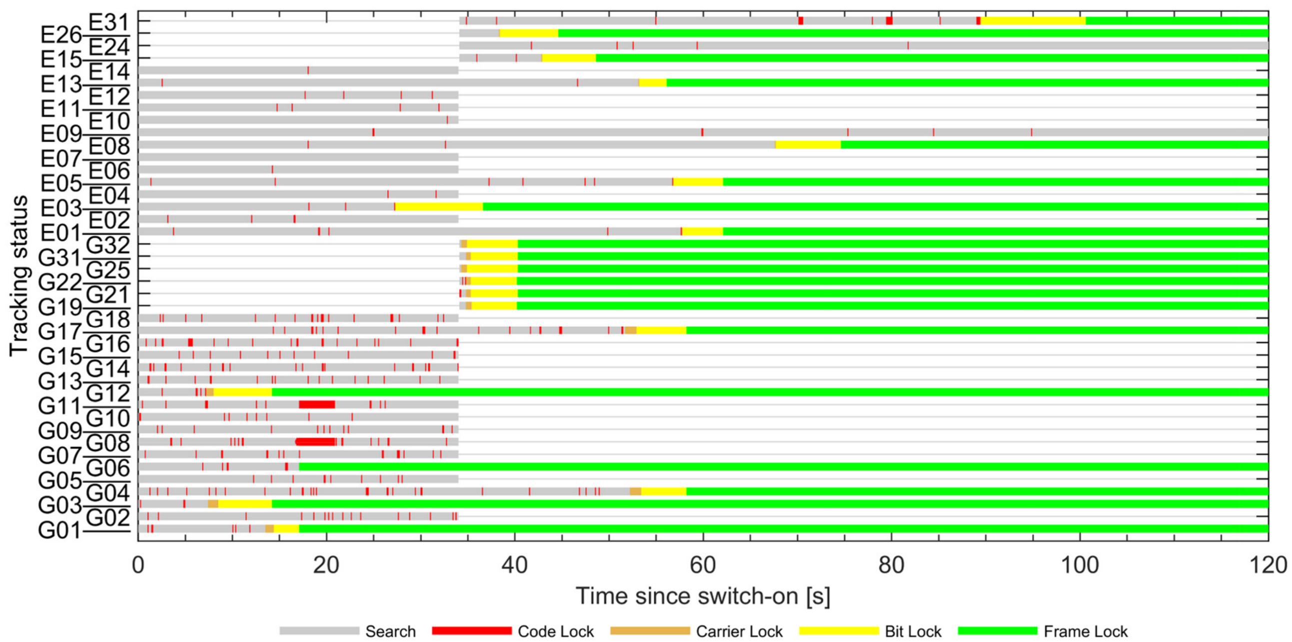

Figure 4. Satellite acquisition and tracking after a cold start of the Kodiak GNSS receiver, which is stationary

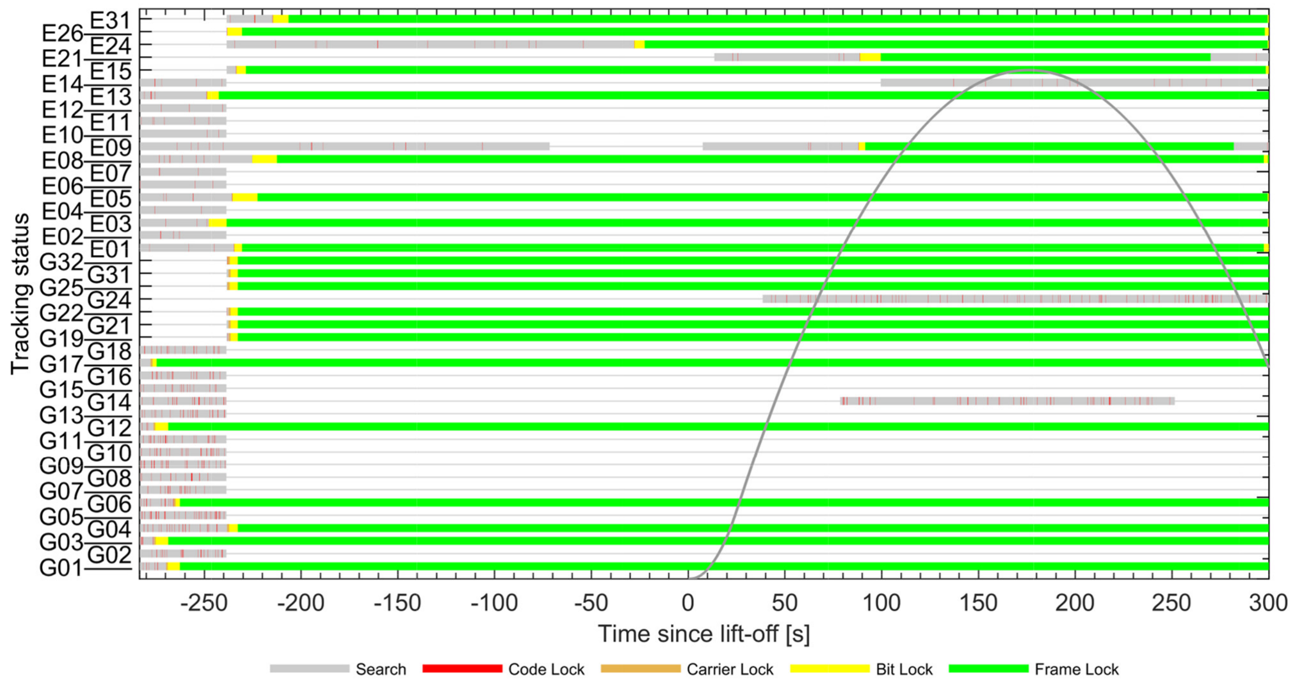

Figure 5. Satellite acquisition and tracking before and during the flight of a typical sounding rocket mission

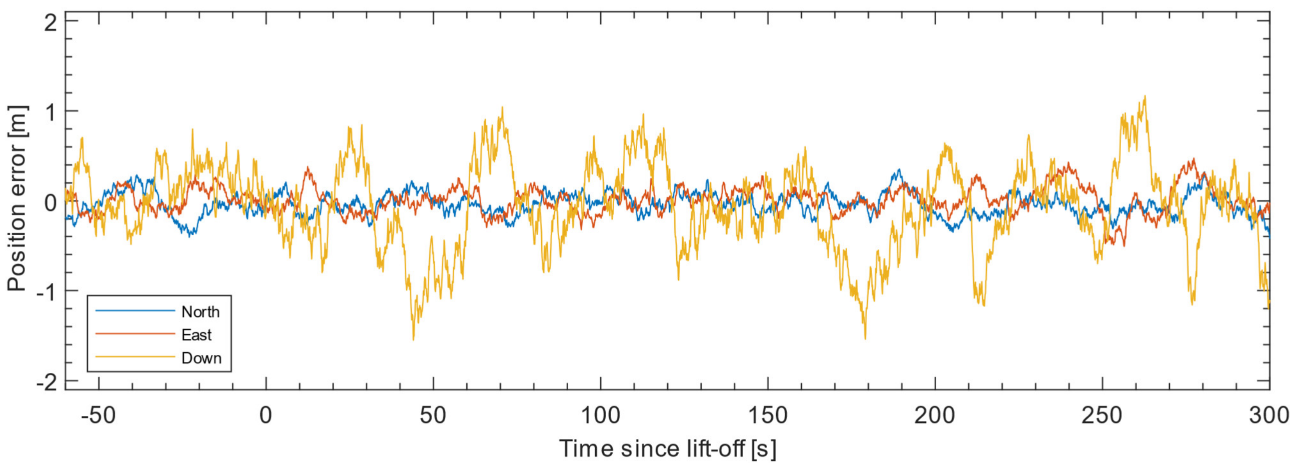

Figure 6. Position error during the simulated flight of a sounding rocket

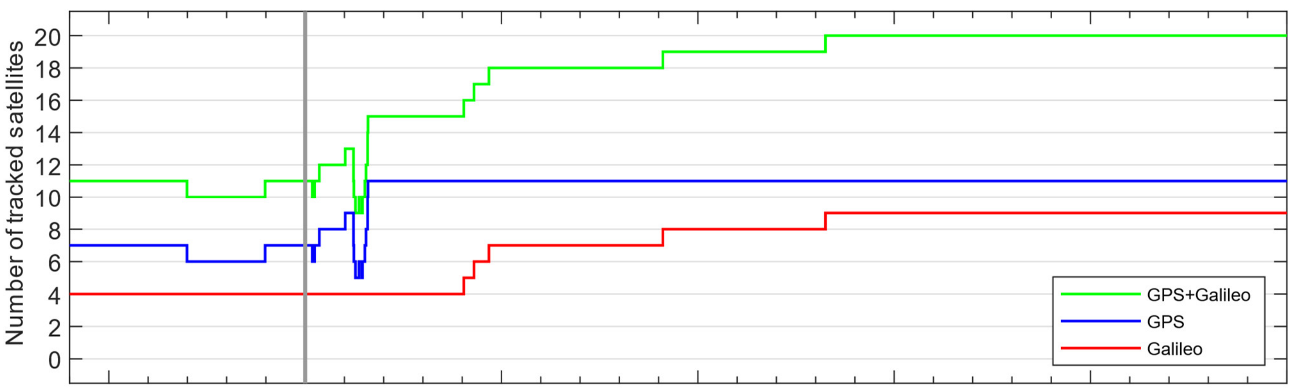

Figure 7. Number of GPS and Galileo satellites tracked during the PMWE2 flight

The second and third antenna inputs of the Kodiak GNSS receiver were connected to two additional sideways oriented blade antennas, which were arranged with an angle of 100 deg to each other about the longitudinal axis. The signals of these two antennas were fed into specially modified tracking loops so that the relative phase between the signals from the wrap-around antenna and each of the blade antennas could be measured. This setup was part of an experiment to estimate the 3D orientation of a spinning sounding rocket using GNSS by appropriately slaving tracking channels.

6. INTEGRATED NAVIGATION SOLUTION

For the PMWE2 flight, a Safran Sensing Technologies STIM300 IMU was connected to the Kodiak GNSS receiver. The sensor time was synchronized with the receiver time by a 2 KHz pulse signal generated by the Kodiak GNSS receiver FPGA. The IMU provided 200 Hz angular rate and acceleration measurements about all three axes. By fusing the inertial measurements with the position and velocity solution from the Kodiak GNSS receiver, a 6DoF navigation solution (position, velocity, and orientation) was computed in post-processing. Fig. 9 shows an example of the 3D orientation of the payload of the sounding rocket at a particular time during ascent. The green arrow represents the longitudinal axis, the blue and red arrows the two orthogonal lateral axes. The grey ellipses at the tips of each arrow represent the current 3σ uncertainties of the axis orientations estimated by the navigation error filter. While for PMWE2 the integrated navigation solution was post-processed after the flight, it is foreseen to implement the data fusion algorithm on the second, currently spare core of the CPU and to compute the navigation solution in real-time in the future. The 6DoF navigation solution is of interest not only to the principal investigators of the experiments flown on the sounding rocket to better understand their results, but also to the launch provider to analyse the flight performance and also investigate possible anomalies after the flight.

7. CONCLUSION

The Kodiak GNSS receiver is a modular GNSS receiver platform for scientific research and rapid prototyping of innovative software and hardware features. Without redesigning the system, individual modules and algorithms can be easily adapted to the fast-paced GNSS world. Sensor data fusion and other computationally demanding computations such as image processing can be executed in real-time. Furthermore, the Kodiak GNSS receiver is capable of using signals from multiple antennas, for example, to measure relative phase shifts and derive attitude information, which in turn can be fused with IMU measurements to provide a 6DoF navigation solution. Open access to software and hardware allows the receiver to be best adapted to the specifics of rocket and satellite applications.

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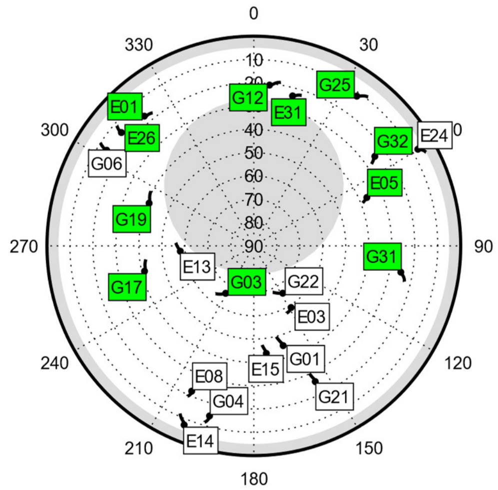

Figure 8. Skyplot during the PMWE2 flight

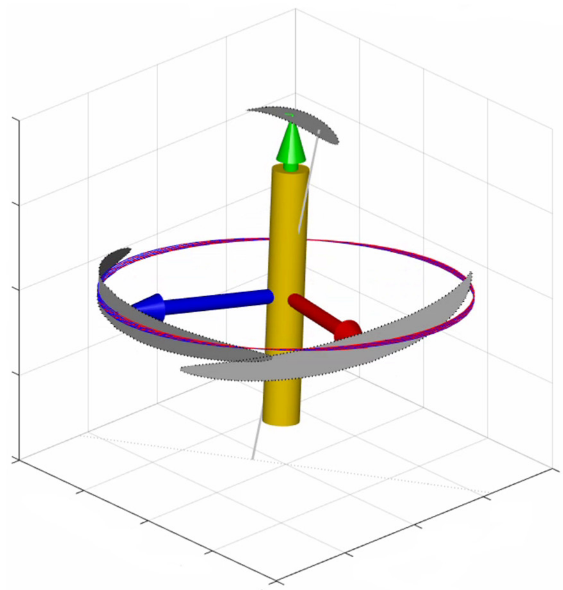

Figure 9. 3D orientation of the PMWE2 payload