GPS FOR MICROSATELLITES – STATUS AND PERSPECTIVES

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ABSTRACT

GPS receivers nowadays provide a well established system for tracking of spacecraft in low-Earth orbit (LEO). In addition, GPS receivers serve as instruments for geodetic and atmospheric research on an ever growing number of science missions. The paper provides an overview of existing GPS receivers for LEO satellites, covering both fully space qualified as well as commercial-off-the-shelf (COTS) systems. The needs of pure navigation receivers and advanced science instruments are independently discussed and directions for future systems are identified. Potential benefits of the new Galileo constellation are addressed and recommendations for future receiver developments are given.

1. INTRODUCTION

More than 30 years have past since the first spaceborne GPS receiver was flown on-board the Landsat-4 satellite. Since then, GPS has become a well accepted tool for spacecraft navigation and scientific investigations. With at least four GPS satellites in view, a spaceborne GPS receiver can provide instantaneous position and velocity as well as timing information onboard a user spacecraft. This enables new and powerful applications and promises relevant cost savings in ground operations and space equipment.

Besides the navigation oriented applications, GPS sensors are more and more employed as science instruments for geodetic and atmospheric research. GPS tracking has enabled the generation of high-fidelity gravity field models and GPS radio occultation (RO) measurements support a global near-real-time monitoring of the troposphere and ionosphere. Finally, new science opportunities emerge through the analysis of ground reflected GPS signals.

So far, the distinction between the navigation and science applications is almost unambiguously reflected in the choice of single- versus dual-frequency receiver technology. The vast number of GPS receivers in orbit are designed to provide navigation and timing information with an accuracy that is well compatible with the GPS Standard Positioning Service (SPS) and thus the use of single-frequency technology. Science applications, on the other hand, demand the availability of dual-frequency measurements to measure (or eliminate) ionospheric path delays and to enable purely carrier-phase based navigation. In fact, high precision navigation marks

IAA-B6-0501; 6th IAA Symposium on Small Satellites for Earth Observation, April 23-26, Berlin (2007)

the boundary between both receiver classes and a growing tendency to support these needs may be recognized in the receiver market.

Following a more detailed discussion of navigation and science applications, an overview of current single-and dual-frequency receiver technology is given in the subsequent sections. Thereafter, future technology needs and trends are discussed, giving proper attention to the upcoming Galileo system. In view of limited space, the presentation is confined to the use of Global Navigation Satellite System (GNSS) receivers on LEO satellites. These constitute the majority of missions and offer the largest market segment for spaceborne GNSS technology. Special applications, such as GEO and HEO missions are beyond the scope of this survey and left for future studies.

2. SPACEBORNE GNSS APPLICATIONS

2.1 Navigation and Timing

With at least four GPS satellites in view, a spaceborne GPS (SGPS) receiver can provide instantaneous position and velocity as well as time information onboard a user spacecraft. The four-dimensional nature of the GPS navigation information distinguishes it from other spacecraft tracking systems. This enables new and powerful applications and promises relevant cost savings in ground operations and space equipment [1]. So far, the usefulness of GPS has already been demonstrated for

- precise orbit determination [2],
- onboard time synchronization and geocoding of payload information [3],
- autonomous orbit control and maneuver planning [4],
- spacecraft formation flying ([5],[6]), and
- onboard attitude determination ([7],[8]),

to mention just the most popular applications.

Following the deactivation of Selective Availability (S/A), representative accuracies for GPS based real-time navigation of spacecraft in low Earth orbit (LEO) are on the order of 10 m for kinematic single-frequency solutions. Associated timing accuracies for onboard clock synchronization are generally better than 1µs. Using dual frequency receivers and dynamical filtering the real-time navigation accuracy can further be improved to 1 m and below. In post-processing, accuracies of down to 5 cm have been achieved using dual-frequency GPS measurements in combination with sophisticated reduced dynamic orbit determination algorithms [2]. For relative navigation of two spacecraft based on carrier-phase differential GPS (CDGPS), accuracies of down to 1 mm have been demonstrated in real-time hardware-in-the-loop simulations [5] as well as offline analyses of actual flight data [6].

As illustrated by these examples, spaceborne GPS sensors offer remarkable positioning accuracies, that are hardly achieved with alternative tracking devices at competitive cost. Unfortunately, the same does not apply for GPS-based attitude determination, which generally suffers from short baselines and signal reflections at the spacecraft structure. Even though various successful flight demonstrations have been reported in the literature ([7],[8]), the achieved accuracies of 0.1° to 1° are easily outperformed by other attitude sensors such as star cameras and optical gyros. Attitude capable GPS receivers have therefore gained little attention by spacecraft designers and have not reached a fully operational status.

2.2 Radio Science

Besides the navigation oriented applications, GPS sensors are more and more employed as science instruments for geodetic and atmospheric research [9]. This is nicely exemplified by the German CHAMP satellite, which carries a BlackJack dual-frequency GPS receiver. GPS measurements collected onboard this satellite have enabled the independent generation of high-fidelity gravity field models that notably outperformed the results derived from all previous space missions [10]. GPS radio occultation measurements, furthermore, enable a tomographic and low-latency monitoring of the troposphere and ionosphere for weather forecasts and atmospheric studies [11]. GPS instruments for occultation measurements are flown on the latest generation of European meteorological satellites (METOP,[12]) and a global constellation (COSMIC) of five satellites carrying GPS occultation receivers has been launched by the Taiwanese government in 2006.

While the use of GPS measurements for gravimetry and atmospheric research is now a well established technology, new science opportunities emerge through the analysis of ground reflected GPS signals. The GPS constellation offers a particularly large number of “natural” signal sources for bistatic altimetry and surface roughness or wind speed measurements. The feasibility of these techniques has been demonstrated the onboard CHAMP satellite ([13],[14]) and with a dedicated GPS receiver onboard the UK satellite of the Disaster Monitoring Constellation [15] and a variety of future space experiments has already been proposed by the science community.

3. RECEIVER SURVEY

A non-exhaustive list of present and planned GPS receivers for space applications is provided in Tables 1 and 2 for single- and dual-frequency receivers, respectively. Compared to terrestrial GPS receivers, the environmental robustness of space equipment is a continued source of concern. Key issues to be considered in this context include the resistance to thermal-vacuum conditions, vibration and shock loads as well as ionizing radiation and single event effects. Besides a cost driving test and qualification effort that is implied by applicable space engineering standards, suitably qualified electronic components are often less powerful and require higher resources (mass, power) than state-of-the-art consumer electronics.

The small market segment and high specialization of SGPS receivers as well as the associated test and qualification effort inevitably results in high unit cost ranging from roughly 100 k€ to 1 M€. Various companies and research institutes have therefore made efforts to come up with low cost solutions based on the use of commercial-off-the-shelf (COTS) components. Following the early work of SSTL, miniature single-frequency GPS receivers based on COTS components are now considered for numerous micro-satellites projects. An advanced example of these is DLR’s check-card sized Phoenix GPS receiver, which has been selected for the Proba-2, Flying Laptop, TET, ARGO, and X-Sat missions. The receiver offers a power consumption of less than one Watt and can provide real-time and offline navigation down to the 1m level [16]. It will also provide high-accuracy relative navigation for the first European formation flying mission, PRISMA.

Table 1 Single-frequency GPS receivers for space applications

Manufact.	Receiver	Chan	Ant	Power Weight	TID [krad]	Missions, References
Alcatel (F)	TopStar 3000	12-16 C/A	1-4	1.5 W 1.5 kg	>30	Demeter, Kompsat-2;
EADS Astrium (D)	MosaicGNSS	6-8 C/A	1	10 W 1 kg	>30	SARLupe, TerraSAR-X Aeolus; [17]
General Dynamics (US)	Viceroy	12 C/A	1-2	4.7 W 1.2 kg	15	MSTI-3, Seastar, MIR, Orbview, Kompsat-1
SSTL (UK)	SGR-05	12, C/A	1	0.8W, 20g	>10	
	SGR-20	4 x 6 C/A	4	6.3 W 1 kg	>10	PROBA-1, UOSat-12 [8], BILSAT-1
DLR (D)	Phoenix-S	12 C/A	1	0.9 W 20 g	15	Proba-2, X-Sat, FLP, ARGO, PRISMA; [16]
Accord (IND)	NAV2000HDCP	8 C/A	1	2.5W 50 g		X-Sat

Table 2 Dual frequency GPS receivers for space applications

Manufact.	Receiver	Chan	Ant	Power Weight	TID [krad]	Missions, References
SAAB (S)	GRAS/GPSOS	12 C/A,P1/2	3	30 W 30kg		METOP [11]
Laben (I)	Lagrange	16 x 3 C/A,P1/2	1	30 W 5.2 kg	20	ENEIDE, Radarsat-2, GOCE; [18]
General Dynamics (US)	Monarch	6-24 C/A,P1/2	1-4	25 W 4 kg	100	
JPL (US) / BRE (US)	BlackJack / IGOR	16 x 3 C/A,P1/2	4	10 W 3.2/4.6kg	20	CHAMP, GRACE, Jason-1 / COSMIC, TerraSAR-X; [19]
Alcatel (F)	TopStar 3000G2	6 x 2 C/A,L2C	1			Under development; PROBA-2; [20]
Austrian Aerospace (A)	Inn. GNSS Navigation Recv.	Up to 36 C/A,P1/2	2		>20	Under development; SWARM; [21]
BRE (US)	Pyxis Nautica	16-64 C/A,P1/2 L2C, L5	1-4	20 W 2.5 kg		Under development
NovAtel (CA)	OEM4-G2L	12 x 2 C/A,P2	1	1.5 W 50 g	6	CanX-2; CASSIOPE; [22]
Septentrio (B)	PolaRx2	16 x 3 C/A,P1/2	1 (3)	5 W 120 g	9	TET; [19]

Based on promising experience with single-frequency receivers, DLR has taken the initiative to investigate the use of commercial-off-the-shelf (COTS) dual-frequency receivers for space applications and perform a basic qualification program as well as initial flight demonstrations. As part of this effort, NovAtel's OEM4-G2L receiver and Septentrio's PolaRx have been demonstrated to cope with the signal dynamics and the environmental conditions of a low Earth satellite ([19],[22]). Extended flight demonstrations of these receivers are planned for 2008-2009 onboard the Canadian CASSIOPE mission and the German TET technology demonstration micro-satellite.

4. TECHNOLOGY NEEDS AND TRENDS

The applications and available receiver equipment discussed in the previous sections nicely demonstrate that GNSS is a mature and well accepted technology for space missions. Despite these achievements, continued research and development are deemed necessary to properly respond to needs of future mission designers and scientists. Even though the evolution of the spaceborne receiver market is not expected to parallel the explosive evolution of the terrestrial GNSS market, a continued growth and technical evolution are likewise expected. Aside from an overall need for cost-reduction, the four key challenges have to be met: miniaturization, increased accuracy and robustness, support of new signals, and advanced science applications. These are addressed in more detail in the subsequent paragraphs.

4.1 Miniaturization

Shrinking space programs and the interest in faster mission implementations have raised the attractiveness of small and micro-satellites that can be implemented by individual research institutes or Small and Medium sized Enterprises (SMEs). These missions are generally characterized by limited engineering (and financial) budgets and benefit most from a further reduction in the size, mass and power consumption of avionics equipment. As a guideline, power consumptions below 1 W appear desirable for onboard radio navigation receivers that are continuously operated. This requirement can presently only be met by COTS-base receivers such as the SGR-05, Phoenix and CCA-370HJ [23] receivers. Further efforts will thus be required to achieve a similar performance with fully space hardened electronic components.

An extreme case of miniature satellites is represented by the CubeSat initiative, which has resulted in numerous student projects around the world. At a nominal size of $10\times10\times10$ cm^3, and an average power budget of 1 W, the use of a GPS receiver onboard such satellites becomes highly demanding. Modified Garmin and Trimble receivers as well as Phoenix receivers are considered in some upcoming CubeSat missions, but no successful flight demonstration has yet been reported. Despite serious technical concerns and risks, the operation of GPS receivers onboard CubeSat satellites would ultimately be of benefit for the space community. Even sparse position fixes could assist a proper orbit determination and prediction in the absence of continuous and reliable NORAD tracking and thus facilitate a better maintenance of space object catalogues.

4.2 Accuracy and Robustness

Applications such as remote sensing, altimetry, and SAR interferometry drive the need for sub-decimeter orbit information that is traditionally served by dual-frequency GNSS receivers and ground-based precise orbit determination (POD) systems [2]. So far, a 10m level accuracy has well been accepted for onboard purposes, but a 1m or better position knowledge already becomes desirable for onboard geocoding of high resolution imagery and open-loop altimeter operation. For comparison, a 0.5m accuracy (3D rms) is presently achieved by the DORIS tracking system onboard Jason-1 using the DIODE real-time navigation function. In case of spaceborne GPS, ionospheric errors can well be eliminated through the use of dual-frequency tracking or the GRAPHIC combination of code and phase date in single-frequency receivers [16]. This leaves the GPS broadcast ephemeris errors with a representative Signal-In-Space-Error (SISRE) of 1-1.5 m as the limiting factor. Even though a 0.5m real-time position accuracy is within reach of a GPS based navigation system, this performance has so far only been validated in lab experiments and flight demonstrations are still pending. As a major step forward, JPL and NASA have implemented a service for transmitting real-time corrections to the GPS broadcast ephemerides via the TDRSS satellites. In combination with the Real-Time GIPSY navigation software, these corrections should enable decimeter position accuracies onboard a LEO satellite [25].

In terms of robustness, the long cold-start time (typically 10-15 min) of many spaceborne GPS receivers represents a limiting factor. In particular, GPS receivers presently don't lend themselves as safe-mode sensors that can deliver immediate position and/or attitude information after being switched on. GPS tracking is hardly feasible today on heavily tumbling spacecraft. Among others, fast signal acquisition techniques will be required to extend the application range of GPS receivers for these purposes.

4.3 New Signals

The prospect of new GPS signals (L2C, L5, L1C) and the build-up of the Galileo Constellation causes great attention by terrestrial and spaceborne GNSS users alike [26]. Key benefits include the larger number of satellites transmitting navigation signals and the improved signal characteristics. The larger number of satellites improves

- the geometric dilution of precision,
- the redundancy and data screening capabilities, and
- the number of occultation and reflection events for scientific applications.

The new signals and navigations data in turn offer

- direct (versus-semi-codeless) tracking of dual-frequency signals,
- lower tracking noise and enhanced multipath suppression,
- data & pilot codes and an moderate increase in total signal power,
- tri-carrier ambiguity resolution,
- more accurate broadcast ephemerides,
- integrity information.

It remains to be seen, which of these advantages can ultimately be materialized in future space missions. The improved multipath reduction, for example, applies only for reflecting objects more than several meters from the antenna and is thus primarily of interest for GNSS navigation in the vicinity of the International Space Station (ISS). On the other hand, radio occultation measurements will clearly benefit from the unencrypted ranging codes that enable improved signal-to-noise ratios and dual-frequency tracking down to very low tangent point altitudes.

Most other benefits come at a notable increase in hardware cost and complexity. Compatibility with the new signals and the increased number of visible satellites will trigger the demand (even though not necessarily a serious need) for a 2-3 times increase in the processing power of correlators and micro-processors. With a total of four frequency bands (L1, L2, E5, E6) and an "inflationary" number of different signals, a variety of different receiver designs are possible. It remains to be seen, which types of spaceborne GNSS receivers will ultimately evolve and find a sufficiently large market. Likely candidates include an L1 single-frequency receiver as well as a L1+E5a dual-frequency receiver for tracking open service signals from up to 24 GPS and Galileo satellites. For an intermediate transition time, the need to support L2 signals of the GPS constellation, might even result in tri-band receiver designs. Given the mass and power budgets of current space-grade GPS receivers, major efforts will, however, be required to keep the resulting receivers within reasonable limits.

4.4. Advanced Science Applications

LEO satellite-based Global Navigation Satellite System (GNSS) receivers for bistatic altimetry/reflectometry and radio occultation measurements are of great interest as a possible component of future tsunami and Earth observation systems [27]. The general idea is that densely spaced grids of sea surface heights with a few centimeters precision could be established fairly rapidly using multi-frequency GNSS receivers as add-on payload to independently planned Earth observation missions. The required performance of such a space-based monitoring system requires highly advanced GNSS receivers with improved algorithms and quasi real-time data processing capabilities to satisfy the needs of a future spacebased Tsunami Early Warning System. To support these activities, GFZ and DLR have recently launched a study for the development of a GNSS Occultation, Reflectometry and Scatterometry receiver (GORS) in the frame of GITEWS project [28]. A close cooperation between research organization and industry is considered as a key factor for a successful development of a cost effective science instruments. In view of limited projects budgets and the restricted technical capabilities of current space-grade receivers, the development activity and initial flight demonstrations will be based on the modification of a COTS based dual-frequency GNSS.

SUMMARY

The status and prospects of GNSS receiver technology for space applications have been described. Miniaturization, increased performance and the support of new navigation signals have been identified as needs for future missions. GNSS reflectometry and scatterometry are considered as emerging scientific applications that deserve proper attention by receiver system designers.

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