TOPSTAR 3000 – An Enhanced GPS Receiver for Space Applications

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This article discusses the main attractions of using GPS receivers for space applications, as well as the specific features of spaceborne and terrestrial and airborne receivers. The performances achievable for several types of space mission are also highlighted with the results of engineering-model simulations performed with the Alcatel TOPSTAR 3000 GPS receiver.

Introduction

GPS receivers are now widely used for Low Earth Orbit (LEO) spacecraft applications for both scientific and commercial programmes. New applications are also under study, such as navigation in Geostationary Earth Orbit (GEO) and Geostationary Transfer Orbit (GTO), space rendezvous manoeuvres and atmospheric re-entry, for which GPS receivers are promising candidates as navigation sensors. Between 1997 and 1999, under a joint ESA/CNES contract, Alcatel developed TOPSTAR 3000, a new generation of GPS receiver dedicated specifically to spacecraft applications (Fig.1). This receiver uses the L1-C/A GPS service and can serve both modular and multi-mission applications.

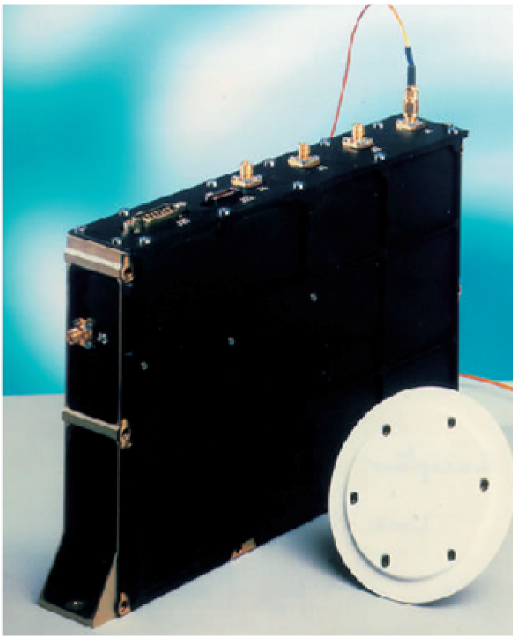

Figure 1. Alcatel TOPSTAR 3000 GPS receiver

The TOPSTAR 3000 receiver has been designed as an autonomous unit, allowing easy adaptation to particular mission requirements and spacecraft interfaces. Intended to cover the radio-navigation needs of both telecommunications and Earth-observation satellites, it features a fully parallel architecture providing 24 signal-processing channels over 1 to 4 antennas with very high sensitivity performances. An embedded orbital navigator provides reliable and highly accurate navigation, and is able to cope with poor visibility as well as complex spacecraft manoeuvres.

Space radio-navigation

Space GPS receiver services

The use of GPS receivers for space missions is becoming quite a common technique, the main applications being:

- *Real-time orbit-determination services:* The receiver provides three-dimensional position and velocity information for both on-board and ground-station use, thereby improving spacecraft autonomy and simplifying the ground tracking and ranging segment. As an example, real-time positioning can be used on-board for computing the Local Orbital Frame co-ordinates, thus improving attitude pointing accuracy versus up-linked filtered position. On-board position determinations can also be down-loaded to ground stations for the monitoring of the spacecraft orbit. This feature is particularly interesting in the case of constellations, where avoiding saturation of the localisation system would require costly duplication of the ground tracking stations.

- *Reference-time services:* The receiver provides accurate reference time synchronised with UTC to better than 1 µs. This level of accuracy can be useful for both telecommunications and Earth-observation missions, as well as for multi-spacecraft time synchronisation.
- *Raw-measurement services:* The receiver provides raw GPS measurements that can be either transmitted to another spacecraft (for relative navigation) or downloaded for ground processing. One example of such ground processing of raw GPS measurements is Kalman-filtering for very precise orbit determination. The accuracy achieved for the radial component is better than 10 cm for a single-frequency receiver and 3 cm for a dual-frequency receiver, and may therefore be useful for scientific Earth-observation missions. Raw measurements from dual-frequency L1/L2 GPS receivers can also be used for atmospheric analyses.
- *Attitude determination services:* This requires the use of three or four GPS antennas connected to the receiver. The latter performs GPS signal-carrier measurements, which can be used to compute the attitude of the spacecraft in real time. Accuracy is mainly limited (0.5° rms) by the effect of multi-paths on the spacecraft structure. Performance can be improved (0.1°) by combining GPS with other attitude sensors.

Space GPS receiver features

In terrestrial or airborne GPS receivers, position and velocity are usually computed by a ‘snapshot least-square’ method. Position and velocity are considered independent and resolved separately: position is computed from code range measurements and velocity from carrier Doppler measurements. This provides a high degree of robustness, but accuracy is limited by GPS Selective Availability to 100 m and 1 m/s (3D rms)*.

In orbital flight, a spacecraft’s motion is governed by Kepler’s laws, which define a predictable trajectory for which position and velocity are closely linked. This predictability of movement allows time filtering of the trajectory, leading to an improvement in orbit prediction accuracy. A Kalman filter, called the ‘GPS Orbital Navigator’ is used, which combines GPS measurements and an orbital force model to improve the availability and integrity of spacecraft localisation as well as the accuracy.

Spaceborne GPS receivers also have to cope with strong signal dynamics during their orbital flight, which requires adapted signal-processing algorithms and dedicated strategies for satellite search and selection.

Space mission applications

Navigation in LEO is the most widely-used application of GPS in space, as these missions involve similar visibility and link-budget constraints to terrestrial applications. For Earth-pointing missions, typical navigation requirements can be met using only one antenna. In the case of large spacecraft roll/pitch manoeuvres, or the likelihood of masking of the single GPS antenna, use of a second antenna can be useful. For Sun- or inertial-pointing missions, the receiver encounters visibility holes during the Earth-shadowing phases, which degrades the accuracy during these periods. Again, the use of a second antenna or the inclusion of an accurate clock within the receiver can limit this drawback.

GPS-based navigation in GEO is still in the experimental phase, due to the present low GPS-signal availability and weak signal-to-noise ratio. These limitations are due to the fact that the GEO satellites are above the GPS constellation and the receiver has to process signals coming from the other side of the Earth (Fig. 2). Very good signal sensitivity in the receiver and the ability to compute position with less than four GPS measurements are therefore required. The lack of visibility also requires the use of a very stable clock inside the receiver to maintain time accuracy during the visibility holes.

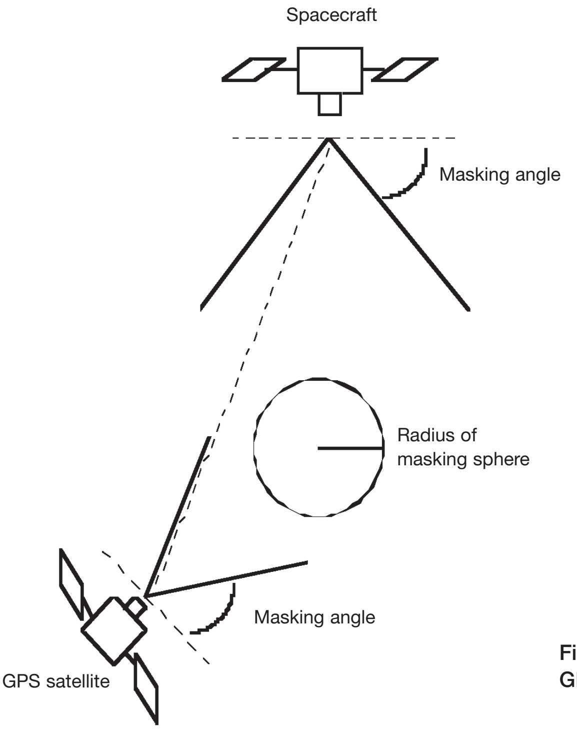

Figure 2. Use of GPS for GEO navigation

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* Recent de-activation by the US Dept. of Defense (DoD) of GPS Selective Availability (except during times of crisis) allows an improvement in accuracy by a factor of 4 (approx.)

For attitude applications, the GPS receiver is connected to three or four antennas to provide GPS carrier interferometric measurements. A wide variety of antenna configurations are possible, as well as in-flight upgrading of the antenna configuration.

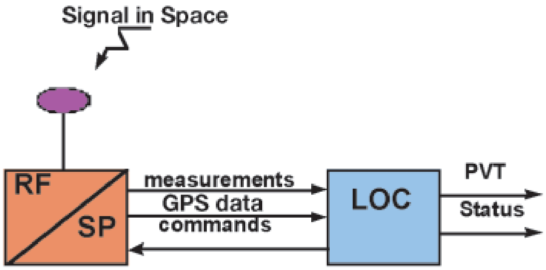


Figure 3. Receiver functional architecture

Relative navigation enables real-time precise positioning of two spacecraft (to better than a few tens of centimetres) and will be used for rendezvous manoeuvres between the Automated Transfer Vehicle (ATV) and the International Space Station (ISS). During the recent flight of ESA's Atmospheric Re-entry Demonstrator (ARD), use of the Alcatel GPS receiver coupled to the inertial sensor significantly improved the navigational accuracy throughout the flight, including the orbital and atmospheric phases.

The TOPSTAR 3000 GPS receiver

A joint ESA-CNES-Industry collaboration

TOPSTAR 3000 has been developed by Alcatel Space Industries, with funding from an ESA, CNES and Matra-Marconi Space partnership. Development was completed in mid-1999 and the first flight model has been delivered for the Stentor geosynchronous mission. Several further flight models are being delivered in 2000–2001 for commercial LEO missions.

The main features of the receiver are:
- 30 C/A code channels, 1 to 4 antennas, fully parallel architecture
- very high sensitivity
- embedded orbital navigator, providing highly accurate and reliable navigation, and able to cope with poor visibility conditions and spacecraft manoeuvres
- modular design, able to accommodate a variety of interface and mission requirements in terms of number of antennas, number of processing channels, class of receiver clock (TCXO or OCXO), data interfaces (RS422 or MIL-STD-1553B), power interfaces (20–50 V primary power bus or secondary voltages)
- fully space-qualified.

The receiver can be operated in two ways: a so-called 'fire and forget' mode, in which the receiver starts as soon as it is switched on and works autonomously (this mode is required for most typical commercial missions), and a 'ground control' mode in which the receiver parameters are closely controlled from the ground via the telemetry/telecommand link (this mode is mainly interesting for advanced experimentation purposes).

Functional architecture

The receiver consists of a signal-processing and a localisation module (Fig. 3).

Signal-processing module

The signal-processing consists of a set of channels that perform GPS signal acquisition and tracking and produce measurements and 50 bps demodulated GPS message data. The measurements include pseudo-range, integrated Doppler, carrier phase and C/N_o.

The main feature of the signal-processing module is the receiver's high sensitivity and hence its ability to acquire and track signals with low C/N_0 (Table1). The signal-acquisition process is a time/frequency search, which involves estimating the energy of the input signal inside a Doppler slot for each C/A code position. The sensitivity of the search is governed by the time spent in integrating the signal in order to extract it from the noise. The integration time is also linked to the *a priori* knowledge of the signal dynamics, and thus also depends on the localisation accuracy.

Table 1. TOPSTAR 3000 sensitivity

Cold-start acquisition	40 dB.Hz
Warm-start acquisition	35 dB.Hz
After-first-fix acquisition	19 dB.Hz
Tracking in code and carrier	29 dB.Hz
Tracking in code only	19 dB.Hz

In order to cope with the wide signal dynamic range of space missions, TOPSTAR 3000 includes several acquisition algorithms:
- 'General acquisition' is used during cold starts when no supporting data are available. The integration time is short, so that the searched for signal does not move out of the Doppler slot during the search. It allows the acquisition of signals with $C/N_o > 40$ dB.Hz.
- 'Normal acquisition' is used during warm starts when external supporting data are available (approximate position, velocity, time, almanac). It allows the acquisition of signals with $C/N_o > 32$ dB Hz.
- 'Direct acquisition', which requires that the pseudo-range is known *a priori* to ± 10 µs (this occurs when the receiver tracks GPS satellites and computes the spacecraft's position). It allows long integration times and therefore provides very good sensitivity, with acquisition of signals down to $C/N_o > 19$ dB Hz.

After the signal has been acquired, the code tracking is performed with a delay-locked loop, and that of the carrier with a third-order modified Costas loop.

Localisation module
The localisation module is dedicated to position, velocity and time computation, GPS SV visibility computation, and signal-processing management. Spaceborne GPS receivers usually rely on two concurrent localisation algorithms: snapshot-least-square resolution and the orbital navigator.

The snapshot resolution uses least-square resolution for computing position, velocity, clock bias and clock drift from pseudo-range and pseudo-range-rate measurements. It requires at least four satellites to be in view and its accuracy is determined by the geometry (GDOP) and by the GPS satellite range error. When Selective Availability is ON, the accuracy is 100 m and 1m/s (3D 1σ) for GDOP = 2.

The benefits of the snapshot resolution for space applications are that it provides:
- a first-fix position after a cold start as soon as four satellites are tracked; this first fix can then be used for the initialisation of the orbital navigator
- localisation during non-orbital phases (re-entry, rendezvous).

The CNES-developed orbital navigator implemented in TOPSTAR 3000 is called DIOGENE (Détermination immédiate d'orbite par GPS et navigateur embarqué). Based on a Kalman filter, it propagates the state vector with an accurate force model and updates it with all available GPS measurements. The state vector consists of the six orbital parameters, the clock drift and the clock bias. The propagation model includes a 40 x 40 Earth gravitational field model, Moon and Sun gravitational effect, and solar pressure effect. DIOGENE can also take into account the description of manoeuvres provided to the receiver (date and duration, amplitude and orientation of the thrust, estimated error, specific impulse, initial mass), and also includes an integrity monitoring function (RAIM). DIOGENE's performance is 10 m in position and 1 cm/s in velocity (3D 1-sigma) for LEO missions. With GPS Selective Availability ON, the time needed for convergence is less than two orbital periods (Table 2).

The orbital navigator provides:
- high accuracy, even with a strong Selective Availability
- embedded integrity function, providing protection against potential GPS constellation anomalies.

Both localisation algorithm outputs are continuously monitored and the receiver provides the best solution (the one with the lowest estimated error). Typically, the snapshot-resolution output will be selected as long as the orbital navigator has not converged or during manoeuvres with large thrusting errors.

The visibility computation is designed to determine which GPS satellites are in the spacecraft GPS antenna's line of sight. For this, the spacecraft attitude is either provided by the on-board computer or defined as a by-default pointing law in the receiver.

The signal-processing management commands and controls the signal-processing module (PRN allocation to GPS channels) and provides supporting data for signal acquisition.

Hardware architecture
The spaceborne GPS receiver consists of a GPS core for signal processing and navigation computation, and optional modules that adapt the receiver to the particular spacecraft interfaces and mission requirements (power supply, data interface, etc.) (Fig. 4).

GPS core
The GPS core is composed of one radio-frequency (RF) and one digital-processing (DP) unit.

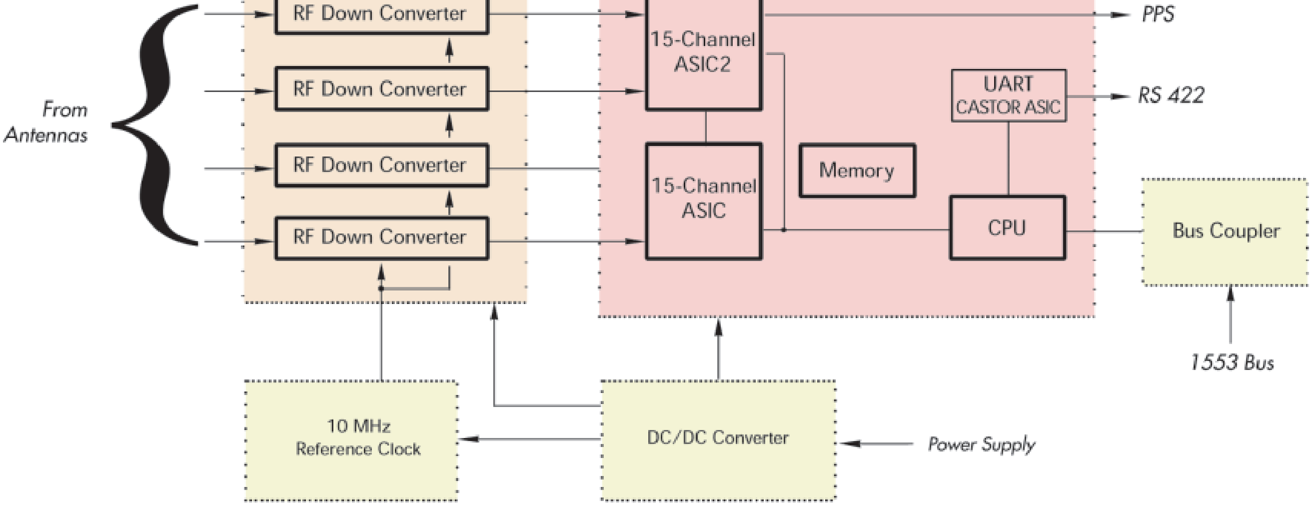
The RF unit consists of one to four RF/IF down converters, each of which receives the RF signal from one antenna and performs low-noise pre-amplification and filtering, frequency down-conversion and analogue-to-digital conversion. The key component of each RF/IF down-converter is a bipolar RF ASIC, which features double down-conversion, a low-noise local oscillator, and high-rate multi-bit A/D conversion. The RF unit also includes a medium-class 10 MHz reference clock (TCXO).

The DP unit controls the digital processing of the GPS signal and all the navigation-related computations. It is based on the SPARC Embedded RISC Processor ERC32, and the

Table 2. TOPSTAR 3000 accuracy

In LEO	Position	10 m (3D – 1σ)
	Velocity	1 cm/s (3D – 1σ)
	Time transfer with OCXO	200 ns (3 σ)
	Time transfer with TCXO	1 µs (3 σ)
	Orbital navigator full accuracy	2 orbital periods
In GEO	Position	100 m (3D – 1 σ)
	Velocity	2 cm/s (3D – 1 σ)
	Time transfer with OCXO	1 µs (3 σ)
	Orbital navigator full accuracy	1 orbital period

Figure 4. TOPSTAR 3000 receiver design



key component for GPS signal processing is the signal-processing ASIC called PEGASE. This ASIC was developed under an ESA contract in 1995 and features 15 multi-standard channels (GPS, GLONASS and GIC) and interfaces with two RF/IF down-converters.

The GPS core is housed in a compact module powered by secondary supply voltages. Communication is via full-duplex asynchronous RS422 links.

Optional modules

The MIL-STD-1553B interface is a hardware module that can be plugged onto the GPS core. It provides a remote-terminal interface with a redundant MIL-STD-1553 communication bus.

The DC-DC converter is a hardware module that can be stacked on the GPS core. It provides the necessary secondary voltages to the GPS core and other optional modules from a primary 22 to 50 V DC power bus.

A temperature-controlled oscillator (OCXO) can be used to provide a high-stability 10 MHz reference clock for the receiver for missions involving poor GPS visibility or requiring high time-transfer performances.

Space-qualified design

The TOPSTAR 3000 GPS receiver has been designed to fulfil the reliability requirements and cope with space launch and mission demands, including vibration, thermal vacuum, radiation and long lifetimes. It provides resistance to single-event upsets thanks to intensive use of an error-detection-and-correction system, and features latch-up immunity.

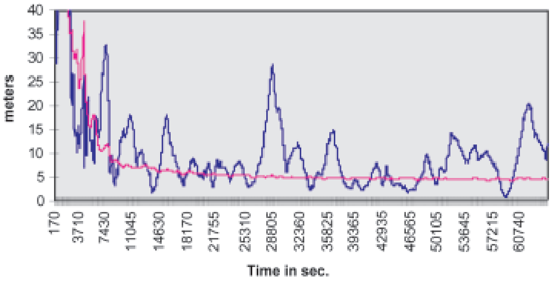
Mission analysis

Navigation in LEO

Performance in LEO mainly depends on measurement availability and the accuracy of the orbital filter. Assuming that 6 to 12 GPS satellites are permanently visible in LEO, the availability of the measurements depends primarily on appropriate GPS antenna implementation and orientation, and on receiver sensitivity.

Figure 5 shows the 3D-position true error of the orbital filter resolution for a typical LEO mission (altitude 800 km, inclination 98° and antenna zenith-pointed). The 3D-position accuracy reaches 10 m (rms). The estimated figure of merit (FOM) accuracy computed by the orbital filter is also plotted.

Figure 5. Positioning accuracy (LEO Earth-pointed)



For LEO inertially pointed missions, the number of visible GPS SVs varies between 0 and 8 at the same rate as the spacecraft orbital period, because the GPS constellation is no longer visible to the inertially pointed antenna when the spacecraft is in the Earth's shadow.

Figures 6 and 7 show the number of tracked signals and the true 3D-position error in the orbital filter resolution for a LEO mission with a Sun-pointed GPS antenna (altitude 800 km, inclination 98°). The best 3D-position accuracy is again 10 m (rms).

Navigation in GEO

Performance in GEO depends primarily on the ability of the receiver to cope with very weak

GPS signals and with poor visibility conditions. Navigation in GEO using the GPS antenna main lobe results in 0 to 3 visible satellites, and the minimum signal power is limited to 30 dB.Hz. Navigation in GEO using the GPS antenna main and side lobes results in 2 to 6 visible satellites, but the minimum signal power falls to 20 dB Hz.

Navigation in GEO using side lobes of GPS SV transmitting antenna

Navigation in GEO is dependent on the GPS antenna transmission pattern, which typically involves a 22° main-lobe aperture and a 38° second-side-lobe aperture (Fig. 8).

Figure 9 shows the number of tracked GPS signals when using both the main and side lobes of a GPS SV transmitting antenna (the number of available measurements is doubled compared with using the main lobe only). The signal received from the GPS antenna side lobes is very weak.

Figure 10 shows a GPS signal tracked successively on the main and the side lobes. The signal is first tracked in the main lobe after acquisition at a C/N_0 of 45 dB.Hz. The signal power then decreases as the GPS antenna main lobe decreases and is lost when the C/N_0 falls below 19 dB Hz. The signal is reacquired 30 min later when the C/N_0 reaches 22 dB.Hz and is tracked for 1 h on the side lobe with a level varying between 22 and 27 dB.Hz. Thus, the GPS signal was tracked for 1 h on the main lobe and 1 h on the side lobe, thereby increasing measurement availability and navigation accuracy. With such a weak signal, the receiver uses the code-only acquisition and tracking technique and the velocity provided by the orbital navigator (patented technique).

Use of on-ground pseudolite beacons for GEO navigation

Navigation in GEO with GPS-like on-ground pseudolite beacons is also under study because it brings the advantages of constant geometry, higher signal power, and a signal free from any Selective Availability constraints.

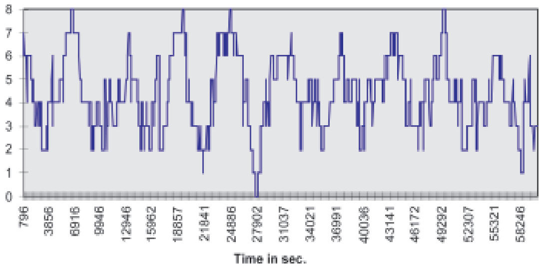


Figure 6. Tracked signals (LEO Sun-pointed)

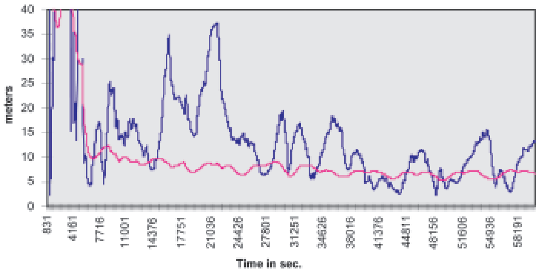


Figure 7. Positioning accuracy (LEO Sun-pointed)

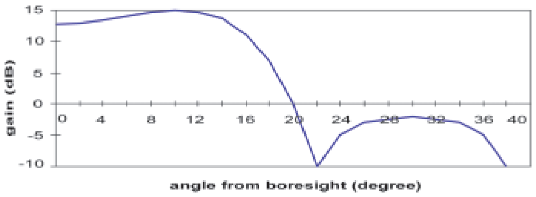


Figure 8. GPS satellite antenna gain pattern

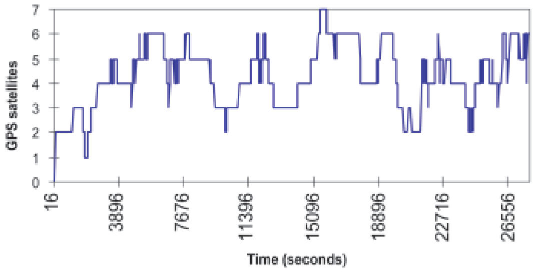


Figure 9. Tracked GPS signals in GEO

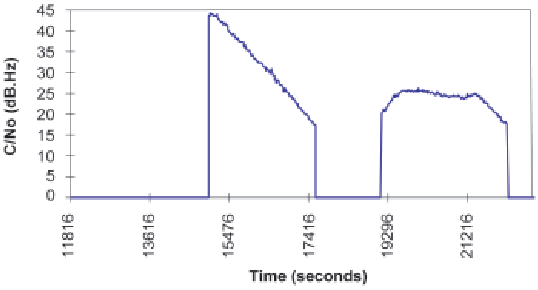


Figure 10. Signal tracked in GEO

Conclusion

GPS receivers are already being widely used for navigation in LEO. For GEO/GTO applications, the use of high-sensitivity and high-accuracy receivers such as TOPSTAR 3000 seems very promising for future commercial applications, and will be demonstrated during the Stentor mission. The use of GPS-like signals transmitted from on-ground beacons and processed by the TOPSTAR 3000 will also be experimented with during the Stentor flight (so-called 'ranging-per-pseudolite' experience).

The de-activation of GPS Selective Availability allows the real-time positioning accuracy in LEO to be improved to 1 m (rms), whilst the availability of two GPS civil frequencies in the near future will further facilitate atmospheric scientific studies. The advent of the Galileo constellation will also contribute substantially to the development of space radio-navigation services.