New space GNSS navigation experiments

Jean-Luc Issler, Laurent Lestarquit, Michel Grondin, Marie-Claire Charmeau, Denis Laurichesse, Alain Lamy, Claude Vincendet, Christian Cazaux (CNES, The French Space Agency)

Fabrice Legrand, Abdelahad Benhallam (ENAC)

Yves Domaine (Aerospatiale) ; Xavier G'sell (MMS)

Gilles Potignat, Nicolas Wilhelm, Christian Mehlen, Christian Valpard (Alcatel)

BIOGRAPHY

Jean-Luc Issler, Laurent Lestarquit and Michel Grondin are in the RadioNavigation Department [1] at CNES. They are involved in the mission analysis and the developement of STENTOR and DEMETER satellites GNSS receivers.

Denis Laurichesse, in the Orbital Metrology and techniques Department at CNES, works on space navigation projects. He his responsible for the multimission GNSS orbital navigation filter called DIOGENE.

Marie-Claire Charmeau is in the CNES On board Software Department, responsible for the R&D and experiments concerning autonomous spacecraft applications.

Alain Lamy is, at CNES orbital Mission Analysis Department, in charge of the AOC experiment of the STENTOR geostationary satellite.

Claude Vincendet is, at CNES STENTOR project, in charge of the GNSS receiver and the associated experiments.

Christian Cazaux was the CNES ARD project leader.

Fabrice Legrand is presently a doctoral applicant at ENAC (French civil aviation school), in the LTST (Signal Processing and Telecommunication Laboratory). His thesis is suported by CNES and Alcatel, and dedicated to radionavigation raw measurements integrity and accuracy improvements.

Abdelahad Benhallam is the responsible of LTST at ENAC.

Yves Domaine, at Aerospatiale, has a long experience in using GPS receivers in space, and was responsible for the ARD capsule GPS equipment.

Xavier G'sell is, at MMS, responsible for the GNSS receiver for STENTOR. He his experienced in space GPS receiver procurements.

Gilles Potignat is, at Alcatel, the TOPSTAR 3000 GNSS spaceborne receiver project leader.

Nicolas Wilhelm is, at Alcatel, the TOPSTAR 3000 product responsible.

Christian Mehlen is, at Alcatel, responsible for the functional performances of the TOPSTAR 3000.

Christian Valpard is, at Alcatel, a spaceborne GNSS receiver software expert. He was involved in the TOPSTAR 3000 development.

ABTRACT

CNES (The French Space Agency) enter in an active GPS space navigation experiments period. The use of GPS has been decided for operational navigation of the CNES/Alcatel PROTEUS platform. CNES also decided to participate in the GPS navigation experiment of the ARD capsule (Atmospheric Reentry Demonstrator : ESA/CNES program) launched by the third ARIANE 5. The successfull GPS navigation and raw measurements results in orbit and during the reentry are presented, as the details of the threshold improvement signal processing technique used in the ARD GPS receiver.

The new GPS space navigation experiments prepared are also detailed, as threshold and multipath errors reduction techniques implemented in the used receivers, improved compared to the one implemented in the ARD receiver.

The first experiment is the GPS navigation and timing of the HETE2 spacecraft. The receiver includes the DIOGENE orbital navigator (: Immediate Orbit Determination on board a GNSS receiver) developed by CNES. The receiver navigation performances has been tested using a GPS simulator, and are presented.

The second experiment is STENTOR, a geostationary satellite carring a different GNSS receiver, also provided with DIOGENE. This equipment will be used in GTO and in GEO. GPS satellites and ground pseudolites will be tracked in GEO.

The third experiment will be in LEO, on a microsatellite called DEMETER. Acquisitions with very low thresholds will be used, as DIOGENE.

INTRODUCTION

CNES (The French space agency) enter in an active GPS space navigation experiments period. The use of GPS has been decided for operational navigation of the PROTEUS platform, and the associated first mission called JASON1 (NASA/CNES project). This platform is provided with a propulsion subsystem, and GPS navigation is expected to be used within and during the manœuver phases. The JASON1 flight is scheduled mid 2000.

CNES also decided to implement an acquisition threshold improvement technique in the GPS receiver of the ARD capsule (Atmospheric Reentry Demonstrator : ESA/CNES program) launched by the third ARIANE 5 in 1998. The ARD was built by Aerospatiale. This first GPS experiment is described hereafter. In the next 2 years, CNES will also perform GNSS new navigation experiments in LEO, GEO and GTO on board the HETE2, STENTOR and DEMETER spacecrafts.

THE ARD GPS EXPERIMENT

The Atmospheric Reentry Demonstrator has proven the European capability to launch and recover a space capsule which could have been manned. After injection, it performed nearly one complete orbital revolution and an automated reentry phase (fig 1).

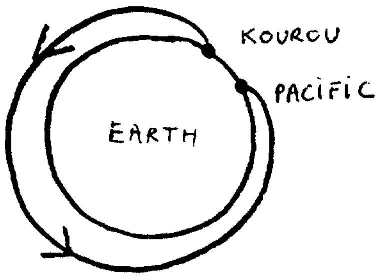

Fig 1 : ARD trajectory

The nominal ARD reentry attitude is shown on fig 2.

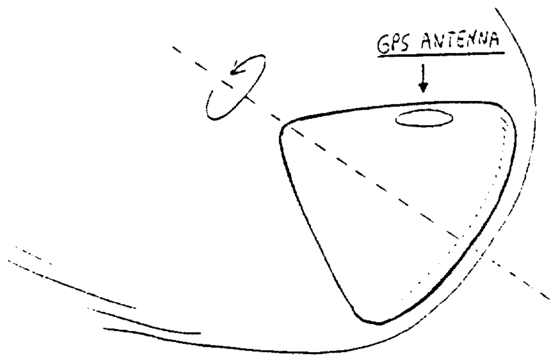

Fig 2 : Nominal ARD reentry attitude

The roll reversal manoeuvers was expected to present the antenna patern main axis in a lateral direction instead of a zenithal direction. Thus, it was decided to implement a specific signal processing, dedicated to acquisition thre shold reduction, in the receiver. The receiver TOPSTAR 100 ARD and the thre shold reduction software were developed by Alcatel.

The threshold reduction performance is achieved using the « Code Only acquisition » technique [2].

The « Code Only acquisition » threshold $[C/No]_{co}$ is approximated at the DLL level using the following formula, demonstrated in [2] :

$$\left[\frac{C}{No}\right]_{co} > \frac{2a}{f(N_{cb}).\tau}\left(\sqrt{B.\tau.f(N_{cb})}+a\right)L_{co}.L_{ss}.L_{bt}$$

This formula uses the following energy detection model of the receiver (fig 3).

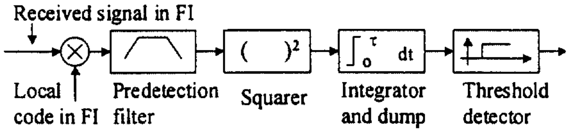

Fig 3 : Energy detection model

B = Predetection bandwith (Hz)

τ = Integration constant (s)

If a = 3, we have a good detection at about 3 sigma, that is for 99.9 % of the cases.

If a = 2, we have a good detection at about 2 sigma, that is for 95 % of the cases.

If a = 1, we have a good detection at about 1 sigma, that is for 65 % of the cases.

N_{cb} = Number of used correlator branches for acquisition. The function f dependson the type of used receiver.

L_{co} = Code Only threshold losses due to the pseudovelocity error ($L_{co} > 1$)

L_{ss} = Losses due to the Sweeping Speed α of the DLL local code.

A chip of the DLL local code is swept in $1/\alpha.\tau$. This correspond to a local code sweeping speed equal to α chip/τ. For instance, if α = ½, the one chip sweeping time is $2.\tau$.

L_{bt} = Losses due to bit transitions

Assuming the integration period is centered within the correlation pic, we have :

$$L_{ss} = \frac{2}{\alpha.\tau}.\int_{(1-a/2)T}^{T}\left(x^2/T^2\right)dx$$

$$L_{ss} = =1-\frac{\alpha}{2}+\frac{\alpha^2}{12}$$

For ARD, we have selected :

α = 1 chips/s

If the predetection filter is an integrator and dump, the losses L_{co} on the C/No tracking threshold in « code only » tracking mode are given by :

$$L_{co}\ \ (dB)\ \ = 10*\log\left[\frac{\sin\left(\frac{\pi.\Delta V.f_o}{B.c}\right)}{\left(\frac{\pi.\Delta V.f_o}{B.c}\right)}\right]^2$$

ΔV = Pseudovelocity aiding error (m/s)

For ARD, the Pseudovelocity aiding is computed from IMU data (Inertial Measurement Unit)

c = Speed of light (m/s)
f_o = Carrier frequency (Hz)

A nominal « code only » tracking is considered when L_{co} is below # 3 dB. In such a case, the following condition has to be verified :

$$abs[\Delta V] < \frac{0.443.B.c}{f_o}$$

In the case of ARD, we have defined :

ΔVmax = Maximum Pseudovelocity aiding error expected in the ARD design phase (m/s)

ΔVmax = 25 m/s

Thus, we have selected :

B = 250 Hz

The practical acquisition threshold of ARD receiver is close to 25 dBHz at the DLL level.

The ARD mission profile is given hereafter (fig 4) :

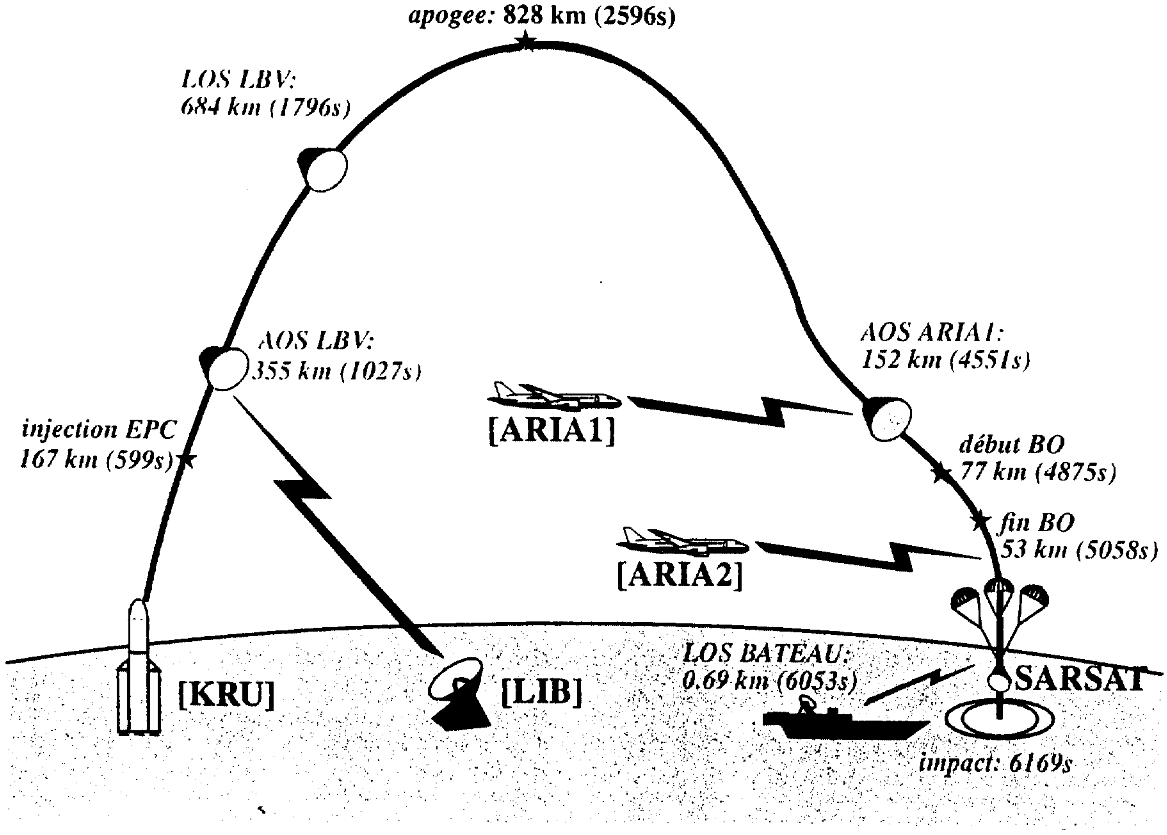

Fig 4 : Planed Atmospheric Reentry Demonstrator mission profile

THE ARD GPS EXPERIMENT RESULTS

If the launch relative date is 0s, the capsule splash down in the Pacific ocean occured at arround 6000 s. The first ARD GPS experiment results are presented hereafter. A valid GPS position/velocity/time fix was continuously obtained during all the registered phases of flight, except during the radioelectrical black out. Generally, 9 GPS SVs were tracked (fig 5)

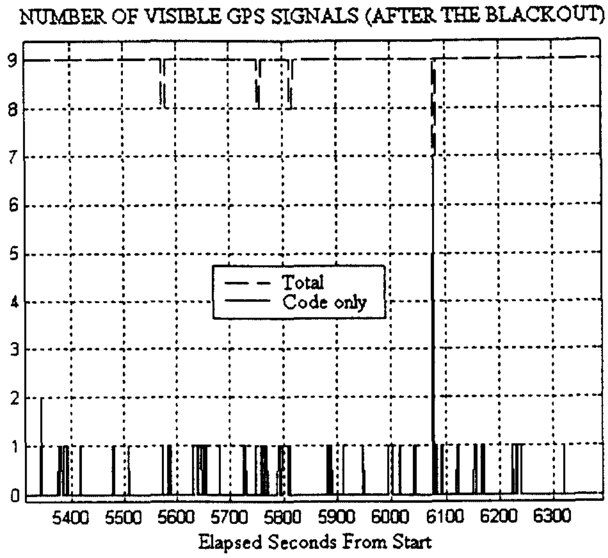

Fig 5 : Visible GPS satellites after black out

The On Board Computer (OBC) compared permanently the GPS and IMU navigation solutions. The GPS was permanently selected by the OBC as the nominal navigation and guidance mean : ARD really flew with GPS.

During the black out, the number of tracked GPS SV decreased as expected. However, some SV's were still tracked (fig 6, 7).

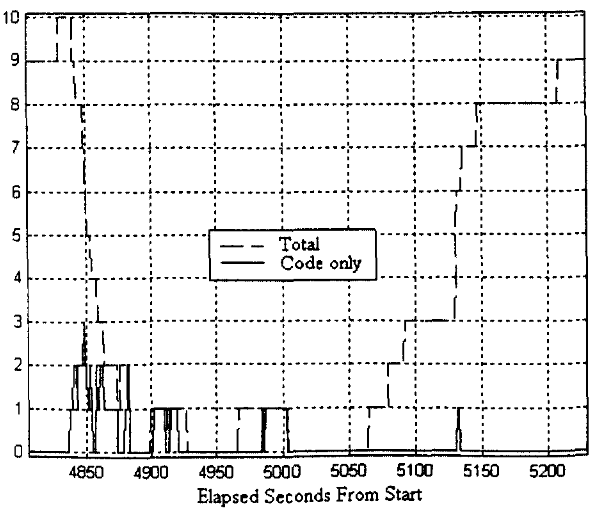

Fig 6 : Visible GPS SV's during black out

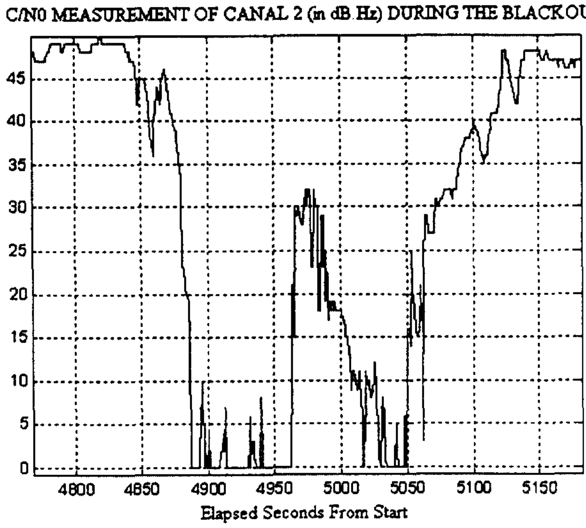

Fig 7 : Channel 2 tracking during black out

The « Code Only » acquisition and tracking clearly make more robust the navigation solution. On ARD, it enable to acquire generally one extra SV compared to classical processings and thresholds, and some times 2 or 3 more (fig 6), and rarely 5 or 7 more (fig 5).

The Automatic Gain Control (AGC) voltage is a very interesting data available in Alcatel receivers. It allowed to observe the noise increase during the black out (fig 8).

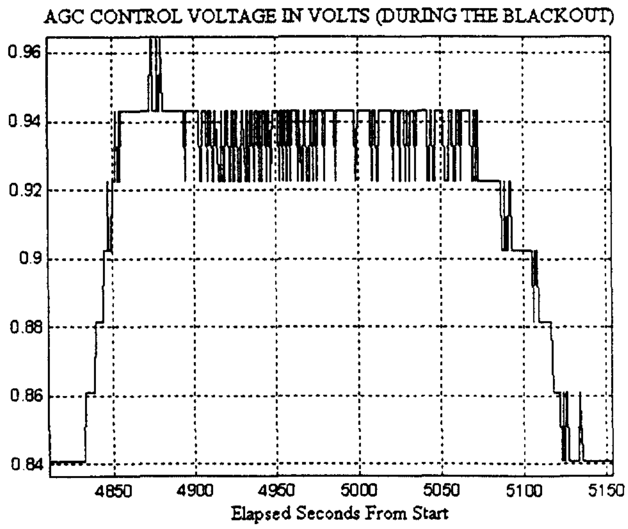

Fig 8 : AGC voltage during ARD radio black out.

The AGC voltage curve defines precisly the black out time interval : Start at 4825 s , end at 5125 s, that is 300 s at GPS L1 band. The receiver was in « research mode » (i.e less than 4 GPS SV's tracked) during 282 s. The mean loss duration of a GPS satellite is 265 s. The TTFF (Time To First Fix) after black out is close to only 5 seconds. This is better than the specification (30 s). The noise temperature of the plasma generated by the blackout, computed from the AGC measurements, is close to 6000 K.

The raw GPS pseudovelocity measurements were as expected, in space (fig 9). The SA (Selective Availability) has been removed by post processing, in order to observe the thermal and oscillator noise measurements (fig 9).

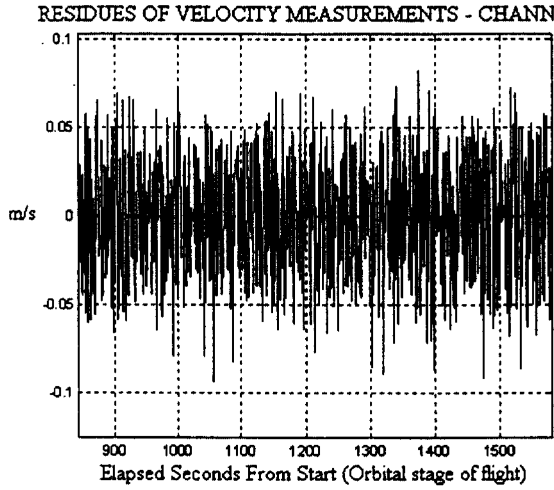

Fig 9 : Doppler Thermal and oscillator noise in space

The C/No associated to orbital measurements is also nominal, with the present GPS IIA constellation (fig 10).

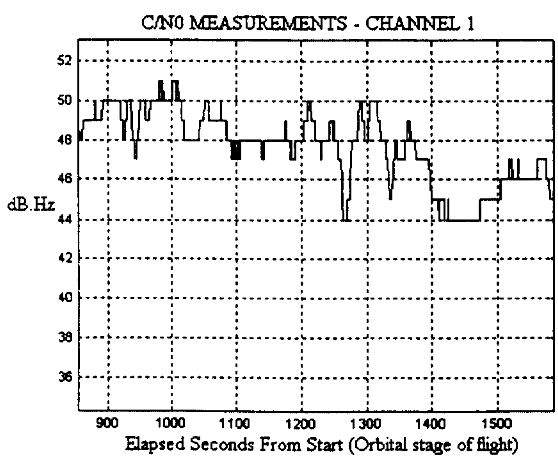

Fig 10 : C/No measurement on the orbital arc

The raw measurements were also continuously produced during the free descent, parachute, splash down and floating phases, despite numerous rotations of the capsule, creating important fadings (fig 11, 12). The « code only » technique allowed this continuity, despite these link budget degradations.

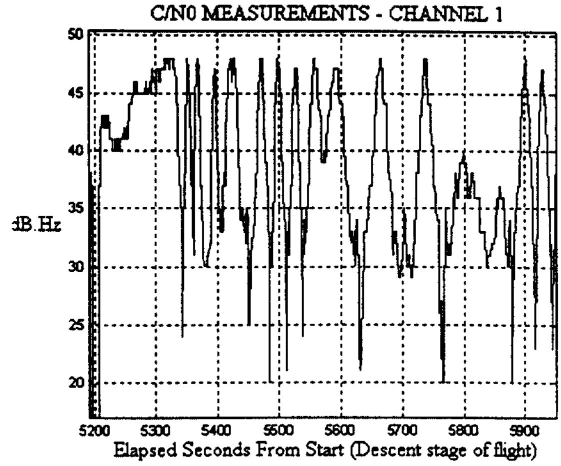

Fig 11 : C/No measurements during descent phase

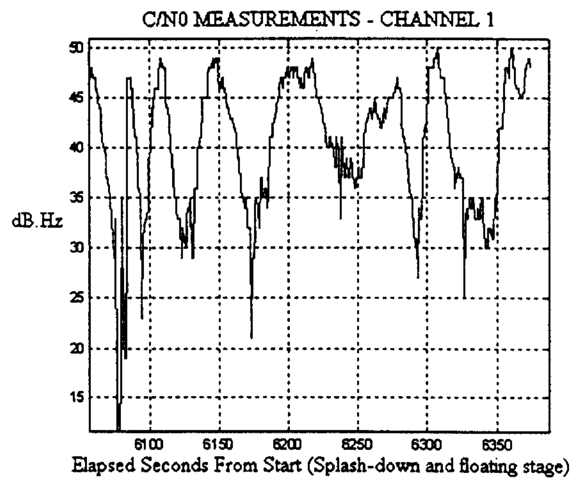

Fig 12 : C/No measurements on the see surface

The ESA/CNES GPS navigation experiment with ARD was thus a complete success. The PVT navigation filter (geometric resolution of Position, Velocity and Time) provided a 3D solution with one sigma standard deviations close to 30 m in position and 0,4 m/s in velocity. The GPS position at splash down was only 4,93 km away from the predicted position before launch, taking into account the drift phase under parachute.

THE HETE2 GPS NAVIGATION EXPERIMENT

HETE2 is a NASA spacecraft, manufactured by the Center for Space Research (CSR) of MIT. A Pegasus launch is expected in the begining of year 2000. CNES procured a TOPSTAR 300 receiver of Alcatel for MIT. CNES already supplied in january 94 to MIT a first TOPSTAR 300 receiver for the HETE1 spacecraft [3]. This receiver was one of the first equipment provided with both an orbital model on board and a cold start capability, but, the Pegasus launch unfortunatly failed in november 1996.

The HETE2 (High Energy Transcient Experiment) mission, dedicated to observation of astronomical gamma and ultraviolet bursts, will be on an equatorial orbit, at about 700 km above the Earth. The receiver is provided with a single GPS antenna (Rayan), sun pointed. The RF semi-regid cable is provided by Alcatel. As HETE is a microsatellite, power saving is performed by alternating standby modes and operational modes of the GPS receiver (fig 13).

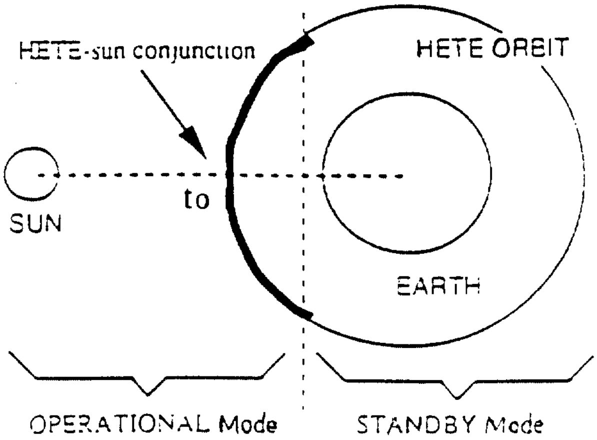

Fig 13 : HETE2 GPS mission phases

The only difference between the GPS receivers of HETE1 and HETE2 is the introduction of the DIOGENE fine orbital navigation software (DIOGENE : Détermination Immédiate d'Orbite par GNSS Et Navigateur Embarqué ; *Immediate Orbit Determination on board a GNSS receiver*).

DIOGENE is an operational Kalman filter developed by CNES in ADA and in C languages. It can process most of the Earth orbits like circular or elliptic Low Earth Orbits (LEO), Geostationary Transfer Orbits (GTO) and Geostationary orbits (GEO). The used orbital parameters are equinoxial, expressed in the Veis frame, and dated in UTC time. DIOGENE supplies also the UTC time

The DIOGENE state vector includes as a minimum the 6 equinoxial orbital parameters of the carrier spacecraft, the bias and drift of the receiver clock. Other parameters, like solar pressure, can be liberated on user request. DIOGENE takes also into account the orbital manoeuvers, to be described by the characteritics of the thrust, and the associated uncertaincy. Thrusts can also be liberated in the filter.

The processed raw measurements are the pseudoranges, and the pseudovelocities, if they are available (i.e : not in « code only tracking » mode).

DIOGENE performs an orbital RAIM, and rejects measurements due to unhealthy satellites or uncoherent measurements coming from false acquisitions. This advantage enables integrity of the orbital navigation.

The data provided by the host receiver to DIOGENE are the corrected raw measurements, an associated quality factor and the position of the transmitter. Thus, it can process any measurement coming from GPS , GLONASS, GNSS1 GEOs , ground pseudolites or other radionavigation references, like GALILEO in the future.

The DIOGENE pseudovelocity aiding performances are excellent, and can be used for the patented « Autonomous Orbital Code Only » technique [2], [4]. The accuracy is a few cm/s (1 σ) with a 25 m RMS Selective Availability. This allow to reach acquisition thresholds so low as 20 dBHz [2], with a 50 Hz predetection bandwith. This capability is a dramatic advantage in any degraded link budget situation.

THE TOPSTAR 3000 FAMILY AND DIOGENE

The DIOGENE Navigator is also integrated in the TOPSTAR 3000 Next Generation of GNSS receiver, already developed by Alcatel. The first tests with a GSSI GPS simulator, provided with a LEO scenario and connected to a TOPSTAR 3000 receiver, presented a 3D one sigma accuracy close to 1 meter without SA, and close to 8 meters with a strong SA.

The development of the TOPSTAR 3000 family of GNSS receivers was performed in the frame of a partnership between CNES, ESA, MMS and Alcatel.

This receiver can manage directly 1, 2, 3 or 4 antennas. A fully parallel RF architecture has been selected, in order to minimize the implementation losses at the receiver input. The size of the receiver is not penalized by the parallel architecture, since miniaturized integrated RF chips are used.

The TOPSTAR 3000 hardware is thus a multistandard spaceborne receiver able to process any C/A code and message coming from GPS, GLONASS and the associated GNSS1 GEO overlays. It should be able to process the Open Access Signal (OAS) C/A code which should probably be selected for GALILEO [17]. It is also able to process ground pseudolites.

The RF chips of the TOPSTAR 3000 have a programmable user carrier frequency. The GLONASS or GPS L1 or L2 frequency can thus be choosen. A wide range of carrier frequencies can be choosen from about 1200 to 1600 MHz ; only a very few micro elements has to be adapted (LNA, filters) in such a case. For instance, the TOPSTAR 3000 hardware is nearly a GPS block II F L1/L2 radiooccultation receiver.

The signal processing ASIC is provided with programmable numerical frequency translators (fig 14), also enabling to manage the user carrier frequency selection in the previously mentioned wide band. This ASIC is also provided with the Double Delta Correlator (DDC), enabling important multipath error reduction, during space rendez vous for instance.

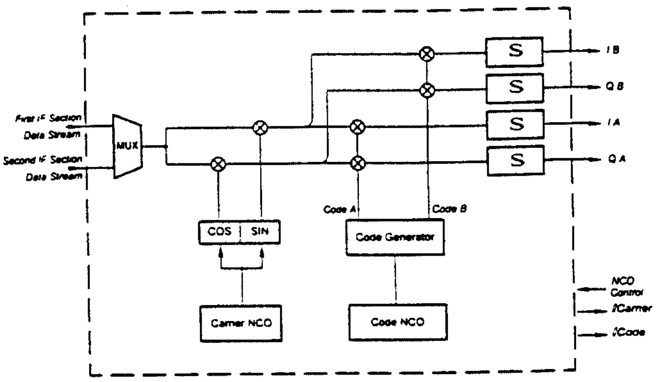

Fig 14 : TOPSTAR 3000 signal processing ASIC

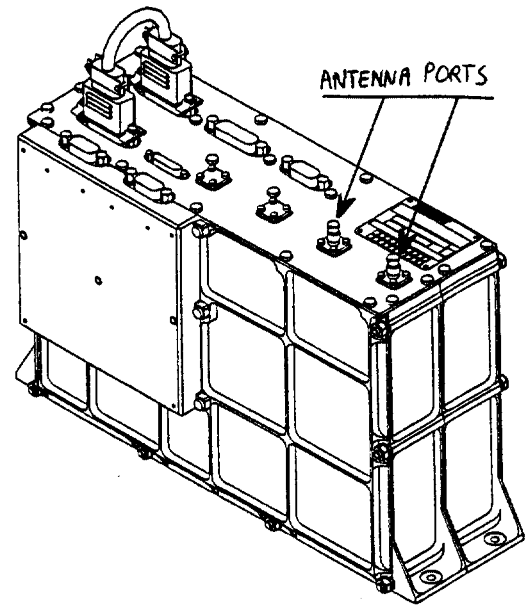

Fig 15 : STENTOR TOPSTAR 3000 RECEIVER

The on board software is fully uploadable from the ground.

The used on board processor is a radiation tolerant ERC 32 SPARC. The configuration of the receiver is fully selectable in order to provide best compromise between performances and cost/mass/consumption (number of RF reception chains, number of channels, memory size, quality level of the components, oscillator : TCXO or OCXO, numerical interface : RS422 or 1553B).

The main functional characteristics of this equipment are :

- Navigation/Time softwares : DIOGENE

- Integration of autonomous code and carrier threshold reduction software enabling high robustness of operational applications.

- Navigation with 1or 2 master antennas on every type of orbit (LEO, MEO, HEO, GTO or GEO).

- Attitude determination with 3 or 4 antennas

- Possibility to operate at various predefined attitudes (Anti Earth pointed antenna, Sun pointed, Anti sun pointed , variable or unkown).

THE STENTOR GNSS EXPERIMENTS

The STENTOR GEO spacecraft will be launched end 2000. This satellite is dedicated to in orbit experiments (ionic propulsion subsystem ; new power amplifier and antenna technologies, ...) and telecommunication services demonstrations. The STENTOR spacecraft is provided with a GNSS TOPSTAR 3000 receiver (fig 15).

This receiver will be connected to 2 GNSS antennas. One antenna (Matra Bae Dynamics) is a semi-directive helix pointed toward the earth during station keeping, enabling to receive the GPS constellation from the GEO orbit. The other antenna (Starec) is semi-omnidirectional, used during the GTO phase, as the first antenna previously mentioned. Each antenna is connected to one independant RF module of the receiver. The principle of operation of these two antennas in GTO is shown hereafter (fig 16).

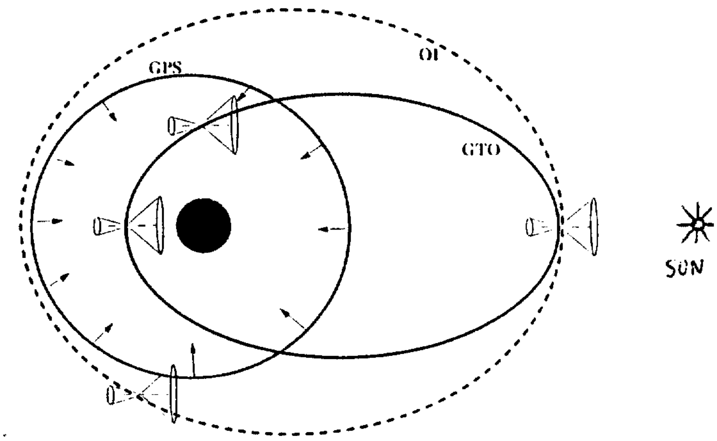

Fig 16 : Use of GPS in Geostationary Transfer Orbit

The use of GPS navigation on board GEO has been studied by numerous authors [5], [6], [7], [8], [9], [10]. One of the more important system parameter of a GEO GPS navigation subsystem is the C/No acquisition threshold. The number of GPS satellites visible from GEO has been estimated, with a C/No acquisition threshold of 20 dBHz at the receiver input, compatible with the TOPSTAR 3000 performances (fig 17)

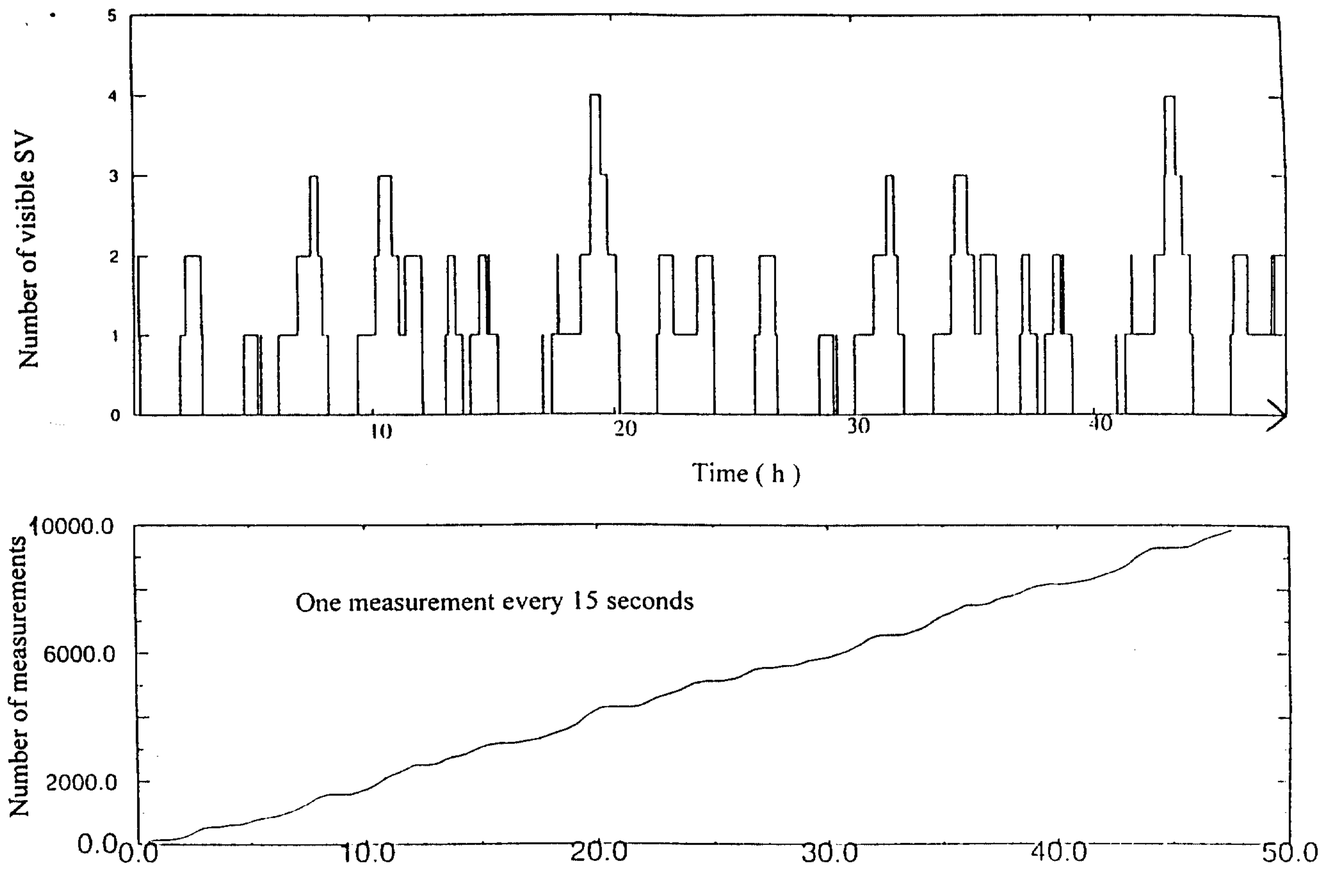

Fig 17 : Analysis of GPS SV visibilities from STENTOR GEO spacecraft

The specifications of the DIOGENE navigation (position, velocity) one sigma accuracy in GEO and in GTO were made with the following hypothesis : SA one sigma standard deviation of 25 meters, and short term clock noise $\Delta F/F = 10^{-9}$.

In GEO, we have 80 meters and 5 milimeters/s

In GTO, we have 160 meters and 2.6 cm/s

Simulation results present performances better than specification.

CNES will also perform a pseudolite navigation experiment on board the STENTOR geostationary satellite. This experiment is called Ranging Per Pseudolite (RPP). The TOPSTAR 3000 receiver, as a multistandard equipment (fig 14) [2], will be used to track 3 ground pseudolites (fig 18), which will be located in Toulouse (France), Kourou (French Guyana) and Hartobeeshoek (South Africa). These pseudolites will be provided with a directive antenna, pointed toward the satellite, and transmiting a GPS-like C/A code modulating a shifted carrier, out of the GPS frequency band. The pseudorange and pseudovelocity raw measurements made on board will be used on ground to perform several orbit determination processings. The experiment will be tested with a GSSI simulator, already developped, able to simulate a network of up to 64 pseudolites on earth, accessible from planes or spacecrafts [11].

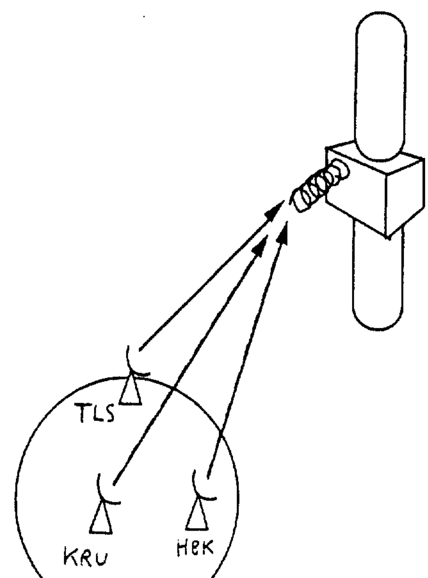

Fig 18 : The RPP STENTOR pseudolite experiment

The goals of these experiment, are :

- determine an experimental precise orbit of STENTOR, using an accurate orbit restitution software. This reference orbit will enable to evaluate the navigation performance of the DIOGENE navigation used in "GPS constellation" mode.

- perform an experimental precise calibration of the plasmic propulsion station keeping manoeuvers of STENTOR.

- test of an experimental on board navigation system, independant of the GPS system (if more than 3 pseudolites are used), but reusing the GNSS signal format to reduce the coast of the on board receiver. The on board raw measurements will be used to evaluate on ground the navigation accuracy of the DIOGENE navigator, in "pseudolite" mode.

In the future, an operational pseudolite navigation system for geostationary platforms could be based on the frequency bands used by the telecommand stations (Ku or Ka band). Therefore, the existing TC stations can be reused (a C/A channel should be added in these stations), and the global coverage on board TC antenna as well (a frequency translator should be used outside or inside the receiver). The geostationary spacecraft could thus be provided with a generic GNSS navigation/timing receiver, used in "GPS constellation" mode for users not concerned by the independance with GPS, and in "pseudolite mode" for users willing a low coast proprietary navigation system.

The RPP STENTOR pseudolite experiment is a first concrete step in orbital GNSS navigation using ground pseudolites and/or DORIS Next Generation (DORIS NG) beacons [12]. These new navigation techniques are now emerging and promising. Mrs C. Altmayer, S. Martin and S. Theil, in Germany, published several papers on GEO and high altitude navigation using pseudolites [13], [14]. Mr R. L. Easton, in USA, presently studies a reversed GPS system [15].

CNES patented worldwide navigation systems made of ground pseudolites accessible from air and space, enabling particulary on board satellite ephemeris determination [16].

The DEMETER GNSS EXPERIMENT

The DEMETER spacecraft is the first of the Next Generation of CNES microsatellites. Its science mission consists in detecting correlations between ionospheric parameters variations and earth natural catastrophes, like earthquakes or volcanic activity. Such correlations might help to predict the mentioned earth phenomenons in the future. A technological payload will also be placed on board DEMETER, to be launched end 2001, at an altitude of about 600 km.

A TOPSTAR 3000 GNSS receiver will be included in this payload (fig19).

A single antenna will be used. This will allow to test the TOPSTAR 3000 receiver provided with DIOGENE in Low Earth Orbit. The DEMETER GPS navigation experiment will include single frequency ionospheric parameter determination and GPS radiooccultations. The « autonomous orbital code only » technique will also be tested in LEO thanks to DEMETER.

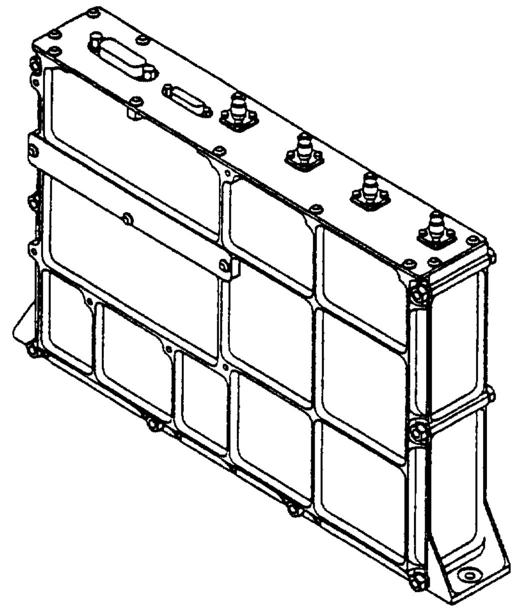

Fig 9 : DEMETER TOPSTAR 3000 RECEIVER

CONCLUSIONS

CNES presented its spaceborne GNSS receivers in orbit test plan. The goal is to qualify in orbit the TOPSTAR 3000 GNSS receiver and DIOGENE, to allow operational use of these products. This test plan will also increase CNES experience in GPS and Pseudolite space navigation and derived science results.

ACKNOWLEDGMENTS

The Authors whould like to thank all the colleagues of their company contributing to the spaceborne GNSS receivers test plan, and particulary, all of them who made the ARD and its GPS experiment a complete success.

REFERENCES

[1] CNES Magazine (English and French editions) – Satellite Navigation ; N°6. July 1999.

[2] High reduction of acquisition and tracking thresholds of GPS spaceborne receivers. J-L. Issler, J. Fourcade, L. Lestarquit, C. Mehlen, G. Garnier. ION GPS NTM january 98.

[3] Orbital Navigation with a GPS receiver on the HETE spacecraft. J-L. Issler, M. Tello, R. Mesnard, E. Peragin (CNES), G. Ricker, F. Martel (MIT/SCR), A. Auphan, G. Caillet, C. Mehlen, C. Valpard (Alcatel). ION GPS NTM 94.

[4] CNES Patent n° 95 14031. 27 november 1995. Procédé de réduction autonome des seuils d'acquisition et de poursuite des codes d'étalement de spectre reçus en orbite.

[5] Orbit determination of geostationary satellites using the GPS. M.P. Ananda and P.S. Jorgensen. Symposium on Space Dynamics for Geostationary Satellites, CNES, France, august 1985.

[6] Tracking geostationary satellites with GPS. J. M. Legido Riba, R. Lucas Rodrigez, ESA-preparing the future, vol .5 N°1, march 1995.

[7] GPS Techniques for Navigation of Geostationary Satellites. Jean-Luc Issler, Pascale Ferrage, Genevieve Campan, Jean-Claude Durand (CNES). ION GPS ITM 95.

[8] GPS Receiver Architecture and expected performances for Autonomous GPS Navigation in Highly Eccentric Orbits. Michael Moreau, Penina Axelrad, James L. Garrison, David Kelbel, Anne Long. ION Annual Meeting. June 99.

[9] GPS/IMU/LASER space mission for global change sensing & 21^{st} centery satellites. David Gleason. ION GPS NTM 94.

[10] GPS-based position determination for geosynchronous satellites. Roger Bryan, Scitor Corporation.

[11] Development of a GNSS2 navigation signal simulator. Jean-Luc Issler, Laurent lestarquit (CNES), Mark Wilson, Peter Boulton (GSSl). GNSS98 + ION GPS NTM 99 (update).

[12] DORIS, the Next Generation. A new and complementary GNSS2 element. J-Luc Issler and all. ION GPS NTM 98.

[13] Autonomous Onboard Orbit and Attitude Control of Geostationary Satellites Using Pseudolites. C. Altmayer, S. Martin, S. Theil. ION GPS ITM 98.

[14] Pseudolite-Based Position and Attitude Control of Satellites in High Earth Orbits. C. Altmayer, S. martin, S. Theil. ION Annual Meeting 99.

[15] ION Annual Meeting 99 Awards brochure.

[16] CNES Patent n° 95 13478. 14 november 1995. Système mondial de radiolocalisation et de radionavigation spatiale, balise, et récepteur mis en œuvre dans un tel système.

[17] CNES technical note on Galileo Open Access Service signals : Etude des performances en multitrajets des options de signaux de navigation de type C/A GPS et 3 Mchips/s – SRC. P. A. Brison, L. Lestarquit. 5 may 1999.