Global/Regional Advanced Autonomous Localization system (GRAAL)

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BIOGRAPHY

Eric Sénant is senior engineer in navigation at Thales Alenia Space France (TAS-F). He graduated from ENAC in 1997. After his doctoral course in image compression, he worked from 2000 to 2004 on on-board compression and joint source/channel algorithms for the CNES Pléïades project. Then he worked for three years in radar altimetry, and joined the TAS-F Navigation Business Unit in 2007 at the engineering department in charge of navigation, transmission, payload and receiver activities.

Charles Fernet is technical manager of GNSS system studies in the Transmission, Payload and Receiver group of the Navigation Engineering Department of Thales Alenia Space France, Navigation Business Unit. He graduated from ENAC in 2000. He started as a test engineer in the digital laboratory of TAS-F, and then joined the Research Department on signal processing activities. Since 2002, he works in the Navigation Engineering Department of TAS-F where he is in charge of signal & system studies involving Galileo and GPS.

Daniel Brocard is senior expert in Navigation Systems at CNES, the French Space Agency. He started his career in 1983 as radio navigation and telecommunication engineer at Aerospatiale/Airbus design office. Then he joined CNES to work in telecommunication and guidance systems for the European space plane project HERMES. In 1996 he joined the satellite system navigation department of CNES and became system architect on the EGNOS Project at ESA. He now works on the future missions of the European GNSS (EGNOS and GALILEO) for CNES and ESA.

Lionel Ries has been a navigation expert in the Transmission Technique and signal processing (TT) Department at **CNES** since June 2000, where he coordinates navigation technical activities. He is responsible for research activities on GNSS2 signals, ground and spaceborne receivers, payloads, and systems. He contributed to the invention of the CBOC signal. He provided support to the 2004 US-EU agreement on GPS and Galileo. He was responsible for the development of the L1-L2C signal processing algorithms now implemented in the ASIC and processor of the TOPSTAR 3000 receiver, in the frame of a CNES R&D activity.
He graduated from the Ecole Polytechnique de Bruxelles, at Brussels, and received an M.S. degree from Supaero in Toulouse.

Damien Joly is an engineer in the navigation system engineering department of TAS-F since 2004. He received in 2004 a M. Sc engineer degree in space system engineering and Telecom from TELECOM Paris France. He was first involved in activities on EGNOS integrity, and then has worked in the Galileo Mission Segment performance team. Since 2007 he is deeply involved in the performance allocation management activity of the Galileo Mission Segment.

INTRODUCTION

The first phase of GRAAL system study was initiated by CNES in the frame of R&T CNES 2006 activities, laying the basic principles of Inter Satellite Links to identify potential improvements of the GALILEO system, in terms of robustness, integrity, and autonomy with the definition of associated functions (communications, ranging and data repatriation). This study was co-financed by CNES and Thales Alenia Space France for a duration of 16 months. The present article deals with the second phase of this study, started in the end of 2007. The purpose of this phase was to refine the assumptions of the first phase for the ranging and communication functions from a system point of view, to derive specifications of the proposed technical solutions for future versions of European

GNSS (evolutions of 2nd generation GALILEO system).

The navigation performance offered by the 1st generation GALILEO system (IOV then FOC) strongly depends on the ground segment ability to continuously perform monitoring and control of the MEO constellation (orbit, navigation signals, etc) in nominal conditions.

In case of degraded ground segment (i.e. failure or unavailability at ground stations, or ground network, or operation levels, interferences problems at L-band at GSS level, etc.), this navigation performance can be impacted.

The GRAAL system study consisted in conceiving, prototyping and validating a set of solutions allowing to obtain a more robust GNSS system (i.e. less vulnerable to degraded modes of ground segment) by increasing autonomy performance and functional abilities of the space segment through the addition of communication and ranging links between MEO satellites, with the aid of on-board functions such as clock and signal integrity monitoring, separately analyzed in the GRAAL study.

This paper is organized in three sections, that expose the main analysis and conclusions drawn in by TAS-F concerning ISL.

The 1st section briefly presents an overview of the GALILEO system to remind of the required basics as input for this study. It also identifies the main points of GALILEO system responsible for the limited autonomy performance of space segment and for the ground segment complexity.

The 2nd section proposes a set of functions to be implemented as potential answers to the points identified above. Technical solutions are mainly located on board MEO satellites payloads but have strong indirect impacts on ground segment architecture.

Inter satellite links are proposed for communication (navigation data broadcast, GSS data repatriation…) and ranging between satellites. Signal observables are improved from 1st version of GALILEO (due to easier signal conditions), and may allow the ability of autonomous navigation.

The 3rd section presents the mains conclusions of the GRAAL study in terms of integrity, autonomy and complexity (ground segment). Finally, further activities to be performed are presented.

1. GALILEO SYSTEM OVERVIEW

The considered GALILEO system is composed of three entities which are the Space Segment, the Ground Segment and the Users Segment, the last one being potentially composed with terrestrial or space users. Regarding the *Space Segment*, GALILEO FOC satellites constellation is a Walker 27/3/1 type, composed of 30 MEO satellites (27 nominal and 3 redundant) with homogeneous repartition within three spaced orbital plans having the same inclination of 56°.

GALILEO satellites broadcast 4 navigation services (OS, SoL, CS and PRS) at L-band, a Regional Integrity data dissemination Service, and a Search And Rescue (SAR) service.

The GALILEO Ground Segment is composed of 3 entities:

- GCS (Ground Control Segment) for control of satellites and associated means
- GMS (Ground Mission Segment) for generation / transmission of data (up link) for users and control of associated means and system performances
- MDDN (Mission Data dissemination Network) to link components of the two previous entities

The main GCS components are:

- 5 TCR stations at S-band performing telemetry/telecommand/ranging functions for all MEO satellites (ex: command of manoeuvres, reception of plateform and payload telemetries, etc); TCR stations are all equipped with two 11m diameter antennas (1 nominal, 1 for back-up).
- SCF (Satellite Control Facilities)

The main GMS components are:

- 40 GSS (Galileo Sensor Station) at L-band, wide spread over the world, receive navigation signals transmitted by the MEO satellites in visibility and send measurements and messages to GCC; each GSS is equipped with 3 RX chains (1 for navigation function, 2 for integrity function with a 1/2 redundancy scheme)
- 9 ULS (Up Link Station) at C-band performing synchronized transmission of navigation parameters to up to 4 MEO satellites (3 in FOC conditions), with 4 TX chains (in a 4/3 redundancy scheme). The 5 TCR stations are co-localized with some of the ULS.
- 2 GCC (Galileo Control Centre) with a 1/2 redundancy scheme in charge of operability/data processing/security aspects composed of numerous specialised sub-components:

  - OSPF (Orbit & Synchronization Processing Facilities)
  - IPF (Integrity Processing Facilities)
  - MGF (Message Generation Facilities)
  - PTF (Precise Time Facilities)

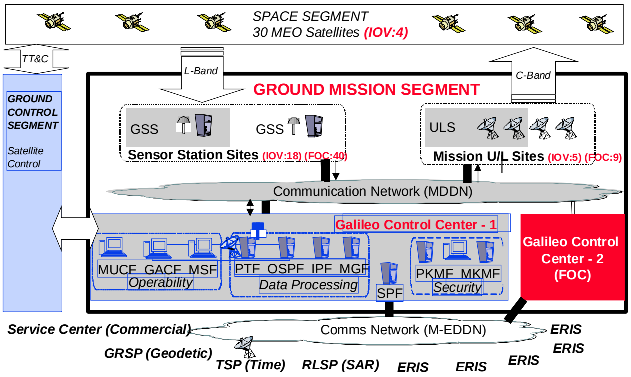

Figure 1 GALILEO system architecture

MDDN links GSS, ULS and TCR stations to GCCs with tripled connections within ground network. Measurements performed by all GSSs are sent to GCCs via VSAT stations and GEO satellites, eventually via additional ground network (not property of the GALILEO system) for some GSS not in view of a GEO satellite.

This communication segment is a critical part of the system, as the integrity monitoring function performed for SoL and PRS at GCCs (IPF) needs real time measurements/navigation data from the 40 GSS to process the integrity of all satellites in the required Time To Alarm (TTA) of 6s. Besides, these links represent high repetitive costs, and a strong dependency on private telecommunications operators, which is potentially sensitive considering the PRS case.

As a consequence, the GRAAL study aimed at both:

- Proposing a Galileo scheme using ISL to increase the constellation autonomy in strongly degraded conditions (reduced ground segment)
- Proposing evolutions of the Galileo system with comparable performances and integrity levels, more cost effective at long term.

These solutions can be derived in two improvements described hereafter.

2. STUDIED FUNCTIONS DEFINITION

The first improvement is the concept of backbone. It should be dedicated to back-up :

- the up-link communication network, in case of malfunction, by transmitting navigation and integrity messages toward all the satellites from a reduced number of ULS, then broadcast through the MEO constellation via ISL, which is the first function identified as **Broadcast**
- the GSS raw measurements repatriation necessary to process orbit/synchronization determination and integrity computation in case of network malfunction. This function is identified as **Repatriation**.

The second improvement deals with the navigation signals monitoring. It is today limited to a systematic and permanent analysis of PN correlation for all navigation signals received by GSS with omni directional antennas (with occasional spectrum analysis for some navigation signals requiring very directive antennas of 12 m diameter typically). Besides, the conditions of monitoring are not optimum (iono/tropo effects, thermal noise, etc). The signal monitoring may also be performed on-board (which was a dedicated part of the GRAAL study) or through Inter Satellite **Ranging** links (ISR), which constitutes the last studied function.

2.1 Broadcast function

In case of current Galileo scheme Up-Link, the proposed back-up solutions consist in using a reduced number of ULS and ISL broadcast. This considers the MEO constellation as a spatial communication network in replacement of failed MDDN.

The ideal scheme would be composed with a single ULS co-localised at GCC, with a redundant ULS/GCC couple. Nevertheless, the three MEO plans are not systematically reachable at the same time from the currently defined GCC locations, with a cyclic loss of coverage for a plan during several minutes, which is not compatible with the required constraints on TTA for SoL and PRS. Therefore, from a GCC/ULS couple to 27 MEO satellites, 2 options remain:

- ISL com are limited between MEO satellites part of the same orbital plan, thus discarding the unique ULS solution
- ISL com are allowed between any MEO satellites in visibility (particularly with different orbital plans)

The first option was preferred because of :

- The relative geometry is constant between MEO satellites in same orbital plan which simplifies the broadcast scheme
- The broadcast scheme is quite simple to conceive and operate.

Therefore, the proposed up-link scheme is composed with 4 ULS each having 3 TX chains in C-Band (2 active, 1 redundant). 2 of the 4 ULS are planned to be localised at GCCs, in a cold redundancy scheme, while the last one should be in favourable locations considering access to all plans. Kiruna (Sweden) or Kourou (France), already planned to be ULS are good candidates as they can access any plan at any time. Nevertheless, this trade-off remain totally open.

Now, the method to connect nominal ULS to 27 MEO satellites consists in performing in parallel *for each orbital plan* the same following steps :

1. establish 2 up links at C-band from 2 different ULS to 2 reference MEO satellites in visibility/plan (active redundancy scheme)
2. received signal by 2 reference MEO satellites are then:
   - demodulated to extract data to be temporarily saved on board
   - retransmitted in specific band to other MEO satellites (ISL broadcast); as some remaining MEO satellites in same plan are not in optical visibility (due to Earth mask) or within instantaneous antenna coverage of reference MEO satellites, it is necessary to have at least 2 master MEO satellites/plan used as repeaters

Figure 2 illustrates geometry of ISL Broadcast with minimum necessary links to support at least a single failure when considering a given orbital plan.

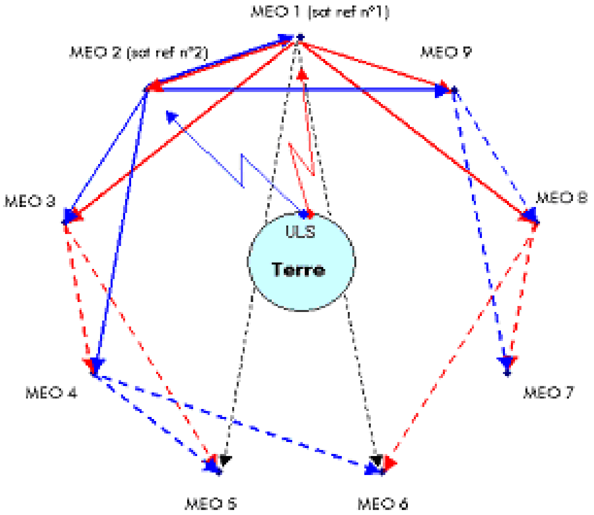

Figure 2: Geometry of ISL broadcast function

Notice that any MEO satellite (excepted references) can receive navigation messages (at large sense) issued directly or not from each of 2 reference MEO satellites. Each reference MEO satellite must also be able to receive navigation messages at large sense from ULS on ground and other reference MEO satellite. The use of 4 simultaneous links as proposed allows to overcome few cases of double failures. This scheme forces to have a schedule allowing each MEO satellite to get the integrity table every second.

Besides, in the GRAAL system design the uplink has to convey messages for a set of 9 (up to 11) active satellites at once, which dramatically increases the uplink data rate.

2.1.1 Uplink

The currently defined Galileo Up-Link scheme accesses each satellite, with a zero Doppler steered signal that does not allow ranging from MEO with ground stations, which is a necessary function in the GRAAL system design.

The proposed signal to overcome these issues is to use a multiplex derived from Galileo CASM principle with a pilot signal on I and a Code shift Keying (CSK) modulated difference of two coherent data channels (allowing to reach up to 100ksps with a 1023 chips PRN) on the Q axis, all gathered in the navigation 5000-5010 MHz band.

In nominal mode, each ULS (1 at GCC + 2 extra ULS) addresses two MEOs from two different plans, to have an active redundancy on ground as well, as shown in figure 3.

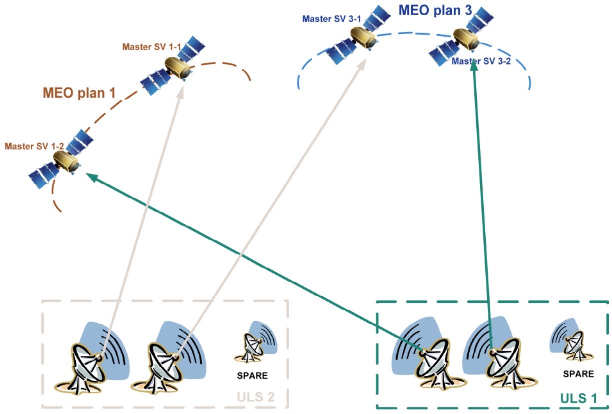

Figure 3: Reduced Up-Link principle

2.1.2 Inter Satellite Link

The baseline broadcast scheme is inner plan broadcast, thus with a constant geometry, with four simultaneous links in two opposite azimuth directions. In practise, we will establish 2 simultaneous links in a same instantaneous beam having:

- a quite constant gain over 20° in elevation
- a 1 dB width in azimuth to be computed

Within 1 dB width limit in azimuth and for any elevation (nominal off pointing from nadir) in the range [50°; 70°], antenna gain must be 18.5 dBi at C-band with F # 5 GHz for an elevation shift of 0° (from min elevation of 50°). This antenna gain value of 18.5 dBi at C-band with mobile beams in azimuth has to be compared to 7.5dBi at instantaneous coverage limit in azimuth for F = 400 MHz with fixed beams (GPS ISL band).

	Spec. at C-band
Directivity max at elevation shift 0°	***18.5 dBi***
Directivity max at elevation shift 10°	***17.4 dBi***
Directivity max at elevation shift 20°	***15.8 dBi***

Table 3: Gain specifications at C-band

To answer to ISL broadcast needs (4 links through 2 opposite beams), the proposed electronic antenna (C-band or Ka-band) is composed of a mechanical structure and an electronic structure.

The proposed mechanical structure is of truncated cone type and used to put radiative components grouped by column as illustrated on figure 4.

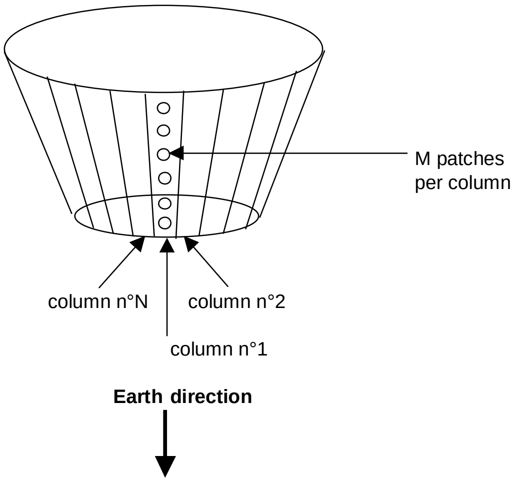

Figure 4: View of antenna mechanical structure

The electronic structure contains:

- 2 TX BFN (1 per TX beam)
- 2 RX BFN (1 per RX beam)

TX and RX antennas (C-band or Ka-band) have common components:

- Patches (owning to mechanical structure)
- Combiner + Phase shifters (owning to electronic structure - TBC)

Table 2 illustrates the RX/TX antenna performances (gain, instantaneous coverage in elevation and 1 dB beam width in azimuth) and size obtained after optimization number of columns and number of patches per column in C-band:

Parameters	C-band case
Number of columns (N)	39 (3 patches per column)
RX/TX antenna gain	18.5 dBi
Instantaneous coverage in elevation	[50°; 70°]
1 dB beam width in azimuth:	10° (±5°)
Antenna size:	
• Height	150 mm
• Diameter (towards Earth)	300 mm
• Diameter on PF	450 mm

Table 2: Antenna performances and size at C-band

The aperture in elevation is constant (20° at 3*dB*) for any azimuth direction, off pointing is 60° from nadir, targeting the middle of first and second row neighbours. Besides, any azimuth direction is reachable in a few tenths of *ns* with stable amplitude and phase, which allows very fast changes for tracking MEOs in different plans, as discussed in the ranging function section.

2.1.3 Choice of ISL band

Two bands exist for navigation purposes in C-band : the 5000-5010MHz for Up-Link, that is used as well in GRAAL and the 5010-5030Mhz for downlink. The spatial separation brought by the proposed antenna with up-link, even with eventual opposite polarisations or other optimizations seems too weak to guarantee no coupling between Rx and Tx chains on-board, as the bands are very close to each other. The GRAAL system proposes a simple solution to avoid solving this constraint in using a slot in the 5100-5150MHz band.

This band is **not** currently dedicated to navigation purposes, but used by GlobalStar for downlink to its gateways. Therefore, with the proposed antenna pattern, this band could be used without specific dedication to navigation purposes.

2.1.4 MEO Time division scheme

The constant inner plan geometry allows the definition of a simple schedule to allow communications in the two opposite directions.

Time slot definition

The shorter propagation delay between two inner plan neighbour satellites (MEO n°1 and 2 in figure 2) is 68*ms*. The second row neighbours (MEO n°1 and 3) are separated by 129*ms*. Therefore, as each MEO satellite is alternatively transmitting and receiving, a Time Division Multiplex must be defined for all SVs. The Tx slot was set at 50*ms*, which allows a 18*ms* margin before reception. These delays allow a time slot definition of 200*ms* including Tx and Rx, represented in figure 5.

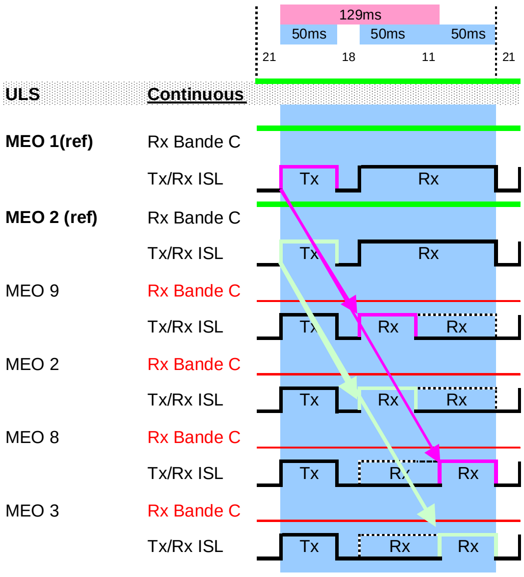

Figure 5 : 200*ms* time slot definition

This TDM scheme is given is repeated each 200*ms* which allows any SV to get navigation and integrity data in a maximum 600*ms* for a constellation with 9 active satellites per plan (with 1 spare between two active SV), and 800*ms* for eventual evolutions with up to 11 active SV per plan.

Nevertheless, as the two master SV of each plan have to relay data for all remaining SV, the needed data for ISL is at least equivalent to up-link, but in only 50ms, which makes a instant rate 20 times higher. This makes impossible to use CSK in a 10MHz bandwidth, which is the maximum width target.

Signal definition

As a consequence on the required data rate in 50*ms*, the proposed signal is composed with a pilot signal (Galileo E6C-like) on I and a purely data signal (without spectrum spreading) on Q, coherently with the pilot, allowing to reach a theoretical 5Msps data rate in a 10MHz width modified CASM scheme. Power sharing between pilot and data channels is driven by separate link budgets as the pilot signal is dedicated to ranging with a C/No constraint at Rx level (and also synchronisation allowing coherent demodulation of the data channel) while the data channel budget is constrained by its data rate and coding scheme, with an associated Eb/No.

Time sharing between functions

As shown in figure 6, only one 200*ms* time slot is necessary for navigation and integrity data broadcast through the plan. This means than the remaining 4 time slots are available for ranging or data repatriation functions. The Galileo specified possibility of 36 satellites (interpreted as 11 active + 1 spare per plan) requires to keep four consecutive 200*ms* time slots dedicated to inner plan. Within inner plan, only one time slot is actually used for Tx on the four available. Besides, as the pilot channel is always on (in the 50*ms* slots), inner plan ranging is possible in any time slot, in a first approach (see ranging section). Besides, the first GRAAL study showed that at least one outer plan ranging link is required. Thus, one 200*ms* slot is completely dedicated to outer plan ranging. Then, the three remaining 200*ms* time slots could be used for the data repatriation function.
Figure 6 shows this time sharing scheme between function in 1*s*.

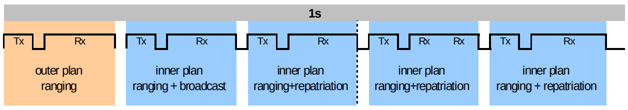

Figure 6 : Time sharing scheme between functions

2.2 Repatriation function

The current GSS data repatriation to GCC uses a network which is not entirely the property of Galileo. It has to be noted that even a partial loss of GSS measurements due to GSS or MDDN failure leads per principle to a higher value of SISMA parameter and an eventual inability to monitor navigation performances.
Moreover ground exploitation costs are high (including GEO channels rentals) due to multiplication of redundant paths to overcome risks about of unavailability (even short) with civil infrastructure. As a consequence, the GRAAL study aimed at proposing solutions to yield a higher independence level for this function, combined with costs reduction.

The major issue of measurement and navigation data repatriation to GCC through the Galileo constellation via ISL is the data rate, associated with a severe multi-point (40 GSS) to point (6 satellites in visibility of GCC), in a tight schedule imposed by SoL TTA constraints. Our analysis concluded that using the constellation to repatriate GSS data to GCC with the currently defined GSS network was not considered reasonably feasible. Nevertheless, the GRAAL study proposed two options detailed hereafter.

2.2.1 Ground segment evolution solution

The proposed solution (figure 6) envisions GSS as “ground linked regional satellites” of ULS, already connected to GCC for uplink. A full duplex should be developed between ULS and GCC to allow this return link. In figure 7, TCR are separated from ULS in terms of function, but stations should be common, as in the current Galileo design. This solution allows more (whereas not complete) independence, but is limited in terms of costs reduction.

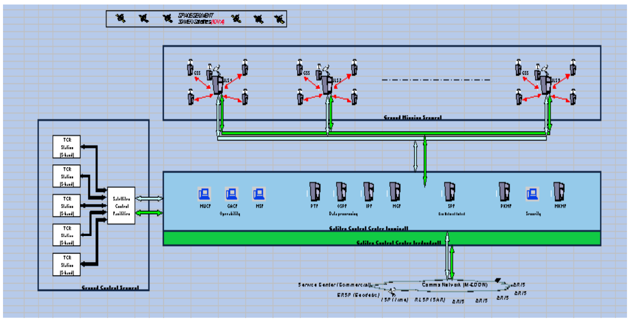

Figure 7 : Gnd segment based repatriation solution

2.2.2 ISL based solution

The alternative GRAAL solution is based on ISL, but requires deep evolutions (though envisioned as progressive) of ground segment, principally GSS.

Indeed, the GRAAL study has also estimated the impact of on-board clock and signal monitoring on the GSS network dimensioning, that showed the number of GSS could be reduced with an equivalent integrity level, even without considering ISL aid.

Besides :

- the ISL ranging functions allow a very precise estimation of SV clocks and should be able to provide a good estimation of orbit (not precisely studied in GRAAL, but argued in [2]), even with fewer GSS on ground
- on-board monitoring function (if considered as an on-board receiver) may be able to play the role of GSS with a simplified repatriation scheme to GCC (no Up-Link)

Inter Satellite links

The slots used are the three available 200*ms* time slots from figure 6, shared with ranging data (negligible). As the ISL in the constellation are managed in a global TDM scheme accesses to a given SV from several GSS can be dispatched in different time slots, to limit the final data rate at SV in visibility of GCC. Inner and outer plan TDM scheme are naturally protected from unwilling emissions. Besides, only one link is expected to exist at once for a given antenna lobe. Therefore, this allows to consider single frequency non CDMA signals for ISL data link.

Uplink

The current data rate of GSS data repatriation was estimated around 200ksps. Some optimizations (as these messages were not designed for air broadcast) allowed to reduce it to 25ksps, with equivalent content. This reduced data rate is largely compatible with the specifications of ULS Tx section described before, with use of the same CSK modulation.

As a consequence all currently defined ULS sites shall be re-used as GSS with common (but reduced) ULS Tx chains, which makes a minimum of 9 GSS, with possibly 2 (or 3?) extra GCC potentially used as GSS without need for up-link.

Downlink

As a consequence of the reduced number of GSS, the amount of data to repatriate to GCC is far reduced : with a minimum of six satellites in visibility of each GCC (27 SV configuration), with 30 ksps per GSS, 3 solutions were proposed:

- modifying the current E6B(CS) signal definition, allowing an additional CSK modulation with a reduced chips PRN thus allowing to reach the required 50ksps to downlink data from 2 GSS per SV in visibility, e.g. 12 GSS. This solution has the great advantage that it does not increase the SV emitted power, nor modifies the spectral occupation.
- creating an additional communication signal around E6BC, with a dedicated TDM scheme between the SVs in visibility of GCC (complexity when taking failures cases into account).
- adding a dedicated downlink RF chain on-board (in Ku-band).

The last two solutions have the drawback of increasing power consumption on-board, and the last one to require a dedicated Ku Rx chain at GCC. So the first solution was preferred.

Note that on-board signal and clock monitoring were also analysed in the GRAAL study, providing higher quality observables than those collected on ground. These observables could be downlinked to GCC for integrity processing via this same link, which could justify the decrease of the number of GSS.

2.3 Ranging function

The method proposed by TAS-F is based on halved additions and differences of pairs of one way pseudo range measurements between MEO satellites as defined in [2].

Pseudo range errors between MEO satellites via ISL ranging are caused by:

- MEO satellite ephemeris and clock errors
- multi-paths effects
- on board receiver (RX) measurement errors due to noise (including software contribution)

It has to be noted that, with the proposed design :

- no group delay errors due to tropo/iono effects exist due to our choice to limit ISL ranging between close MEO satellite and not 3rd row neighbour MEO satellites

- group delay bias caused by on-board equipments are eliminated with the proposed method
- errors due multi-paths effects are reduced (but not fully eliminated) due to spatial filtering with a quite selective instantaneous coverage in azimuth and elevation and specific disposals on the antenna. The impact on pseudo range differences and their derivatives are very limited anyway.

Under assumptions of uniform, uncorrelated and zero mean ranging errors, basic relation in navigation field between standard deviation of pseudo range errors σ_{PR} and standard deviation of position error σ_{POS} is quite applicable to ISL ranging:

$$\boxed{\sigma_{POS} = PDOP * \sigma_{PR}}$$

where PDOP (Position Dilution Of Precision) is a factor only depending on relative MEO satellites geometry. To take into account specificities of proposed ranging method and geometry between MEO satellites, it is proposed to :

- separately study cases where pseudo range measurements are performed between MEO satellites owning or not to a same orbital plan
- use in any case 3 components (along track, radial and cross track) to describe position error of MEO satellites

Inner plan geometry performance

The inner plan Dilution of Precision coefficients must be computed by considering geometry between central MEO satellite (MEO$_n$) to be positioned and its 4 nearest MEO satellites used for pseudo range measurements, as shown in figure 8.

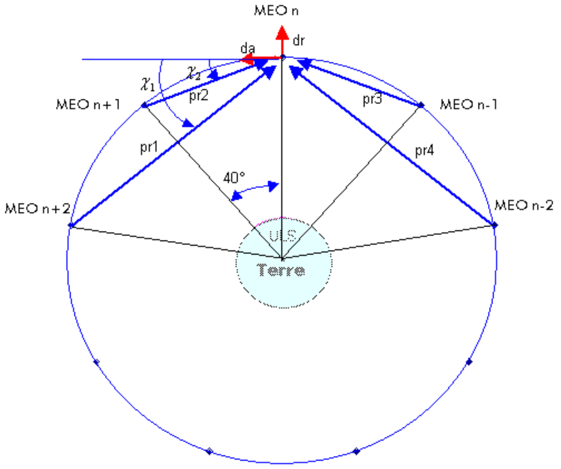

Figure 8: Geometry for inner plan MEO SVs

MEO$_n$ position change is breakdown in 3 components d$_a$ (along track variation), d$_r$ (radial variation) and d$_c$ (cross track variation).A change in MEO$_n$ position (d$_a$, d$_r$, d$_c$) results in a change of each pseudo range dpr$_k$ given by:

$$dpr_k = \frac{\partial pr_k}{\partial a} * da + \frac{\partial pr_k}{\partial r} * dr + \frac{\partial pr_k}{\partial c} * dc$$

A direct system axis having its origin on MEO$_n$ is used to define direction of 4 other MEO satellites through conventional polar angles (χ_k, φ_k) such as:

- $(\chi_1 = -40°, \varphi_1 = 0°)$ for MEO$_{n+2}$
- $(\chi_2 = -20°, \varphi_2 = 0°)$ for MEO$_{n+1}$
- $(\chi_3 = -20°, \varphi_3 = 180°)$ for MEO$_{n-1}$
- $(\chi_4 = -40°, \varphi_3 = 180°)$ for MEO$_{n-2}$

It can be easily demonstrated that:

$$\frac{\partial pr_k}{\partial a} = -\cos(c_k) * \cos(j_k) = \pm\cos(c_k)$$

$$\frac{\partial pr_k}{\partial r} = -\sin(c_k)$$

$$\frac{\partial pr_k}{\partial c} = -\cos(c_k) * \sin(j_k) = 0$$

It is then obvious that pseudo ranges between MEO satellites in a same orbital plan are sensitive to along track and radial variations but not to cross track variation. By using previous relations and introducing noise components n_k per pseudo range, we obtain:

$$(dpr) = \begin{pmatrix} dpr_1 \\ dpr_2 \\ dpr_3 \\ dpr_4 \end{pmatrix} = G * \begin{pmatrix} da \\ dr \end{pmatrix} + \begin{pmatrix} n_1 \\ n_2 \\ n_3 \\ n_4 \end{pmatrix}$$

$$\text{with } G = \begin{pmatrix} -\cos(40°) & \sin(40°) \\ -\cos(20°) & \sin(20°) \\ \cos(20°) & \sin(20°) \\ \cos(40°) & \sin(40°) \end{pmatrix}$$

If all noise components are independent, zero mean and of equal variance s^2, it is well known that:

$$\operatorname{cov}\begin{pmatrix} da \\ dr \end{pmatrix} = (G^T * G)^{-1} = \begin{pmatrix} Caa & Cra \\ Car & Crr \end{pmatrix}$$

It can then be demonstrated that :

- Dilution of Precision factor for along track component noted A_DOP is given by:

$$\text{A\_DOP}=\sqrt{Caa} = \frac{1}{\sqrt{2*\left[\cos^2(40°)+\cos^2(20°)\right]}}$$

$= \mathbf{0.58}$

- Dilution of Precision factor for the radial component noted R_DOP is given by:

$$\text{R\_DOP}=\sqrt{Crr} = \frac{1}{\sqrt{2*\left[\sin^2(40°)+\sin^2(20°)\right]}}$$

R_DOP=**0.97**

- Dilution of Precision factor for the along track and radial components, A&R_DOP, is given by:

$$\text{A\&R\_DOP}=\sqrt{Caa+Crr} = \mathbf{1.13}$$

DOP factors (A_DOP, R_DOP and A&R_DOP) have also been computed for all degraded cases where only 3 or 2 of pseudo range measurements (instead of 4 in nominal case) are available. Results in nominal and degraded cases, are all very good (low X_DOP value even in degraded cases). As expected, the use of PR measurements with close (respect. far) MEO satellites is favourable for A_DOP (respect. R_DOP). Thus, the geometry is particularly good for measurements in the same plan. Besides the almost null dynamics in the inner plan geometry allow very precise two way phase measurements

Nevertheless, it is recalled that cross track component can not be estimated with ISL ranging between MEO satellites owning to a same orbital plan, which leads to study outer plan links.

Outer plan geometry

The first idea analysed in the GRAAL study was a systematic and exhaustive outer plans MEOs access to minimize the scheduling complexity. This lead to assess the theoretical cross visibility of outer plans MEOs with the proposed antenna pattern, which is represented as cumulated time in visibility over half an orbit (repetitive geometry) in figure 9 :

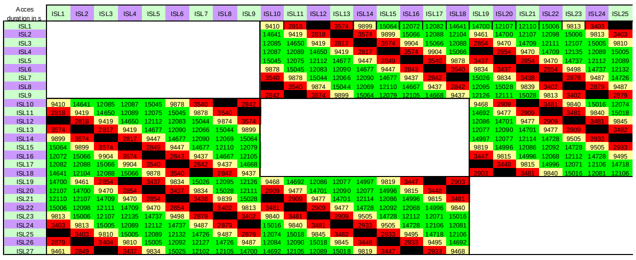

Figure 9 : Cross visibility of different plans SVs

Black cells correspond to “no link”, red cells to “very short links” and green cells to “reliable links”. This analysis showed that around 30% of links were useless in terms of ranging. That assessment lead to consider the selection of the best MEO amongst the reliable links. To evaluate impact of additional pseudo range measurements between MEO satellites in different orbital plans, we considered a basic case where 1 additional pseudo range is available. The direction of additional MEO in a different orbital plan is defined by 2 polar angles:

- $c \in -[40°, -20°]$ due to antenna coverage limitation
- $j = [-180°, 180°]$ due to full azimuth coverage capability (not instantaneously)

In this case, we can write:

$$(dpr) = \begin{pmatrix} dpr_1 \\ dpr_2 \\ dpr_3 \\ dpr_4 \\ dpr_5 \end{pmatrix} = G * \begin{pmatrix} da \\ dr \\ dc \end{pmatrix} + \begin{pmatrix} n_1 \\ n_2 \\ n_3 \\ n_4 \\ n_5 \end{pmatrix}$$

$$with\ \ G = \begin{pmatrix} -\cos(40°) & \sin(40°) & 0 \\ -\cos(20°) & \sin(20°) & 0 \\ \cos(20°) & \sin(20°) & 0 \\ \cos(40°) & \sin(40°) & 0 \\ -\cos(c)*\cos(j) & -\sin(c) & -\cos(c)*\sin(j) \end{pmatrix}$$

If all noise components are independent, zero mean and of equal variance s^2, it can be derived that :

$$\mathrm{cov}\begin{pmatrix} da \\ dr \\ dc \end{pmatrix} = (G^T * G)^{-1} = \begin{pmatrix} Caa & Cra & Cca \\ Car & Crr & Ccr \\ Cac & Crc & Ccc \end{pmatrix}$$

The dilution of precision factor for cross track component noted C_DOP can then easily be obtained as :

$$\mathrm{C\_DOP} = \sqrt{Ccc}$$

$$= \frac{\sqrt{m*n + m*\sin^2(c) + n*\cos^2(c)*\cos^2(j)}}{\sqrt{m*n*\cos^2(c)*\sin^2(j)}}$$

with $m = 2*[\cos^2(40°) + \cos^2(20°)]$

and $n = 2*[\sin^2(40°) + \sin^2(20°)]$

The selection method at this point was to select the lowest DOP MEO SV in a given outer plan, over a half orbit, as the geometrical configuration is completely symmetrical. Figure 10 shows the MEO indexes providing the optimal C_DOP for a given outer plan.

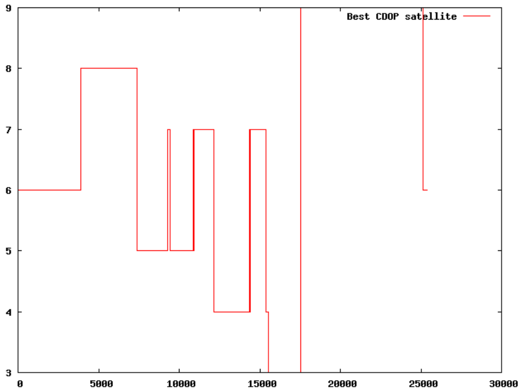

Figure 10: index of MEO providing optimal C_DOP

This optimization then allows to define a simple scheduling as the same outer plan MEO is tracked for quite long time. Besides , scheduling could be sub-optimal but still with good C_DOP performances by considering long time intervals in order to lower its complexity

Besides, the proposed antenna design allows to form two simultaneous lobes, so that links with two different plans are feasible. The selection of best couple of MEO for each outer plans in terms of minimum C_DOP leads to the results of figure 11.

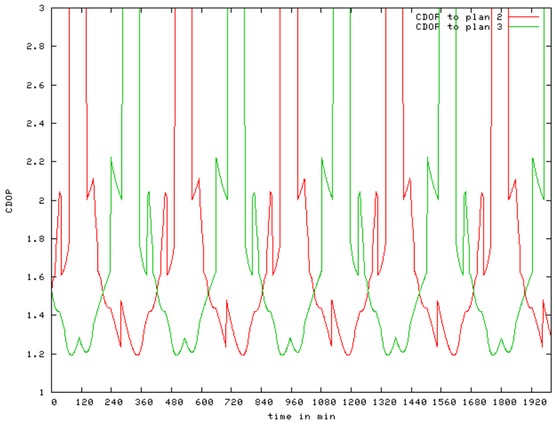

Figure 11: Optimal C_DOP of 2 outer plan MEO

This figure clearly shows that when C_DOP is optimal with the aid of a satellite in one outer plan, it is opposite in the other outer plan. This can be explained by the fact that C_DOP due to an additional outer plan MEO is optimal when the MEO which position is being computed has the outer plan MEO on its side. Indeed, as orbital plans cross with an angle close to 90°, to C_DOP is optimal when the studied MEO is at plans crossing. Nevertheless, as the considered measurements are two way pseudo-ranges, we should also consider the C_DOP brought to the outer plan MEO. This time, the outer plan MEO sees the first considered MEO very close to its along track direction, thus with a huge C_DOP. From this assessment, we can derive that, when considering outer plan ranging, two simultaneous MEO in different plans are necessary to compute pseudo range : one providing optimal C_DOP for the considered MEO, and the other which is provided a good C_DOP by the considered MEO.

On-board navigation receiver

The specifications of on board receivers loops directly depend on the Doppler dynamics between satellites (or with pseudolites, as GSS and ULS). The Doppler range with ground stations is well known to be of ±5kHz. Doppler range between MEO in the same plan is null, and the Doppler range between two satellites in different plans is about ±12kHz. Nevertheless, all positions are pretty well known as all satellites are supposed to know each others' ephemeris, thus reducing the Doppler search range to the Doppler error range due to position errors and not to the Doppler range itself.

Therefore, very narrow bandwidth loops can be used. Typically, measurement are performed at 1 Hz in the GRAAL scheme.

Orbit Determination

This function was not precisely analysed in the GRAAL study. The envisioned method to get observables for orbit determination is the double difference with 4 satellites (or pseudolites) of two way observables proposed by ESA in [2].

With this method, orbit determination (with purely geometric “observables” not sensitive to clock errors and group delay bias) can be separated from time determination (not sensitive to geometry).

In our case the GRAAL study, the number of ground stations available for ranging is lower, which should be taken into account. Nevertheless, in an increased autonomy strategy, the GRAAL study is closer to degraded cases with partly inoperative ground segment.

Time Synchronisation

The clock monitoring through ISL is performed using clock observables obtained as follows :

- Bias : by halved difference of 2 one way pseudo ranges (using precise phase measurements) as in [2]
- Drift : estimated with the half difference of each Rx estimated Doppler on each one way measurement. This measure is not affected by multi-paths.
- Aging : estimated as time difference of previously estimated drift, neither affected by multi-paths.

These very accurate estimations are performed for each pair of inner plan linked SV, which means four estimations by SV. This clock estimation is completely geometry free, but takes advantage of the very low geometry dynamics in the receiver loop dimensioning.

Integrity monitoring

The observables used for orbit determination and time synchronisation are already used for autonomous integrity monitoring, as clock frequency jumps can be easily detected with high levels of performances. The major cause of failures or errors on board is clearly identified as the clock. Besides, the presented GRAAL study also proposed and simulated autonomous on-board monitoring solutions that can take advantage of the Inter Satellite Links to downlink these on-borad observables to GCC, and to have a double check with inter satellite ranging based integrity monitoring. The future work shall assess the actual impact on the number on GSS on ground to have an equivalent level of integrity.

CONCLUSIONS

The GRAAL system allows to strengthen the robustness of the system by providing a backbone for the broadcast of mission data through the constellation and by adding supplementary raw measurements. These raw measurements are combined to derive very precise synchronisation and orbit determination in completely separated processes. Besides, these measurement allow a performing clock monitoring. These two enhancements allow to improve the autonomy of the whole system.

The constellation is seen as an in-orbit network managed through inner and outer plan inter satellite links.

The same high performance antenna is used for broadcast and ranging inter-satellite link dedicated to raw measurements. These two functions benefit from a particularly favourable geometry, which is exploited by the proposed antenna design.

The inter satellite links allow to monitor very precisely the clocks of the neighbour satellites without the impairments due to the propagation encountered by GSS on the earth.

ACKNOWLEDGEMENTS

[1] “New, improved GPS” extracted from GPS World march 2006

[2] Appendix 1 to ESA AO/1-5041/06/NL/HE, Navigation and Integrity Autonomous Navigation Satellite System