Autonomous Satellite Navigation System

GNSSPLUS

Final Report Abstract

	Name	Function	Signature
Prepared by	L. Arona	Project Engineer (DMS)	
	J.A. Pulido	Project Engineer (DMS)	
	F. Soualle	Project Engineer (AST-D)	
Reviewed by	A.J. Fernández	PA Manager (DMS)	
Approved by	M. Sánchez-Nogales	Project Manager (DMS)	
Signatures and approvals on original			

GNSSPLUS

Final Report Abstract

Code : GNSSPLUS-DMS-TEC-FIR02-E-R

Issue : 1.1

Date : 15/12/2008

Page : 2 of 21

This page intentionally left blank

DMS-DQS-QRE0603-ADD-11-E

Document Information

Contract Data	
Contract Number:	ESTEC contract no. 20105/06/NL/HE
Contract Issuer:	ESA/ESTEC

Internal Distribution		
Name	Unit	Copies
M. Sánchez Nogales	Advanced Projects	1
A.J. Fernández	Advanced Projects	1
J.A. Pulido	Advanced Projects	1
L. Arona	Advanced Projects	1
Internal Confidentiality Level (DMS-COV-POL05)		
Unclassified ☐ Restricted ☑ Confidential ☐		

External Distribution		
Name	Organisation	Copies
Francisco Amarillo	ESA / ESTEC	1

Archiving	
Word Processor:	MS Word 2000
File Name:	GNSSPLUS-DMS-TEC-FIR02-E-R-11.doc

GNSSPLUS

Final Report Abstract

Code : GNSSPLUS-DMS-TEC-FIR02-E-R

Issue : 1.1

Date : 15/12/2008

Page : 4 of 21

Document Status Log

Issue	Change description	Date	Approved
1.0	First Issue	03/11/2008	
1.1	Earth-fixed position accuracy included in performance table (section 3.2.2)	15/12/2008	

GNSSPLUS
Final Report Abstract

Code : GNSSPLUS-DMS-TEC-FIR02-E-R
Issue : 1.1
Date : 15/12/2008
Page : 5 of 21

Table of Contents

GNSSPLUS

Final Report Abstract

Code : GNSSPLUS-DMS-TEC-FIR02-E-R
Issue : 1.1
Date : 15/12/2008
Page : 6 of 21

List of Figures

List of Tables

1. INTRODUCTION

This study is aimed at investigating alternative and innovative technologies and methods in the satellite navigation area to improve the current navigation systems and future evolutions of GNSS systems. These improvements are focused on the following fields:

Goal 1): Enhancement of satellite autonomy,

Goal 2): Reduction of ground segment infrastructure,

Goal 3): Improvement of orbit and clock determination data,

Goal 4): Increment of update rate of navigation data,

Goal 5): Reduction of operational cost.

In order to achieve those challenging targets, various technologies will be investigated in the framework of the current study, such as:

- Inter-satellite ranging and communication signals,
- Onboard orbit and clock determination.

1.1. Purpose

The objective of this document is to provide an overview of the baselined system architecture for the *autonomous satellite navigation system* and to introduce the results of the simulations run.

1.2. Scope

This document was initially produced during the Final Experimentation Phase (issue 1.0): minor changes have been included after the Final Review (issue 1.1), in order to include costumer's comments.

This document is organised as follows:

❑ Section 1 contains this introduction.

❑ Section 2 contains the list of applicable and reference documents and standards.

❑ Section 3 provides a quick summary of the GNSSPLUS Final Report.

1.3. Acronyms and Abbreviations

The acronyms and abbreviations used in this document are the following ones:

Acronym	Description
AD	Applicable Document
AGI	Analytical Graphics Inc.
ARNS	Aeronautical Radio Navigation Service
CPU	Central Processing Unit
DLL	Delay Lock Loop
DMS	DEIMOS Space
DOP	Dilution of Precision
DR	Design Review
ECEF	Earth-Centred Earth-fixed
EIRP	Equivalent Isotropically Radiated Power
ERR	Experimentation Readiness Review
ESA	European Space Agency
FER	Final Experimentation Review
FGUU	Frequency Generation Unit
FOV	Field Of View
GNSS	Global Navigation Satellite System
GS	Ground Segment
GSS	Galileo Sensor Station
GSP	Geodetic Service Provider
IER	Intermediate Experimentation Review
ISL	Inter-Satellite Links
ITT	Invitation To Tender
LEO	Low Earth Orbit
LNA	Low Noise Amplifier
LSQ	Least SQuares
MEO	Medium Earth Orbit
NAPEOS	NAvigation Package for Earth Observation Satellites
OD&TS	Orbit Determination & Time Synchronisation
OFA	Off-Axis Angle
PLL	Phase Lock Loop
PM	Progress Meeting

GNSSPLUS
Final Report Abstract

Code : GNSSPLUS-DMS-TEC-FIR02-E-R
Issue : 1.1
Date : 15/12/2008
Page : 9 of 21

Acronym	Description
RAAN	Right Ascension of Ascending Node
RD	Reference Document
RF	Radio-Frequency
RNSS	Radio Navigation Satellite Service
SADF	System Architecture Definition File
SAJF	System Architecture Justification File
SC	Spacecraft
SGU	Signal Generation Unit
SMA	Semi-Major Axis
SOW	Statement Of Work
SRIF	Square Root Information Filter
STD	STandards Document
STK	Satellite Tool Kit
SW	Software
TBC	To Be Confirmed
TBD	To Be Defined / Decided
TBW	To Be Written
TRM	Transmit Receiver Module
WP	Work Package

GNSSPLUS

Final Report Abstract

Code : GNSSPLUS-DMS-TEC-FIR02-E-R

Issue : 1.1

Date : 15/12/2008

Page : 10 of 21

This page intentionally left blank

GNSSPLUS

Final Report Abstract

Code : GNSSPLUS-DMS-TEC-FIR02-E-R
Issue : 1.1
Date : 15/12/2008
Page : 11 of 21

2. RELATED DOCUMENTS

2.1. Applicable Documents

The following table specifies the applicable documents that shall be complied with during project development.

Table 1: Applicable documents.

Reference	Code	Title	Issue
[AD 1]	Appendix 1 to AO/1-5041/06/NL/HE	*Navigation and Integrity Autonomous Satellite Navigation System*. Statement of work	3.7
[AD 2]	GAL-ICD-GLI-SYST-A-0258	*Galileo Signal-In-Space Interface Document*	12.0

2.2. Reference Documents

The following table specifies the reference documents that shall be taken into account during project development.

Table 2: Reference documents

Reference	Title
[RD 1]	*Intersystem and Intrasystem Interference Analysis Methodology*. Lt Bryan M. Titus, John W. Betz, Christopher J. Hegarty, Rick Owen. ION 2003 Oakland.
[RD 2]	*Design and Performance of Code Tracking for the GPS M Code Signal*. J. Betz. MITRE. ION 2000
[RD 3]	*Understanding GPS. Principles and applications* Kaplan. ISBN 0-89006-793-7
[RD 4]	*Comparative System Study. Intersatellite Link-Trade-off*
[RD 5]	*Inter-satellite ranging and inter-satellite communication link for enhancing satellite broadcast navigation data*. F. Amarillo et al. First Colloquium Scientific and Fundamental Aspects of the Galileo Programme. 1-4 October 2007. Toulouse (France)
[RD 6]	*Alternative Frequencies For Use By Public Safety Systems*. Response to Title XVII, Section 1705 of the National Defense Authorization Act for FY2001. Thomas L. Chirhart, Charles T. Hoffman, Richard J. Orsulak, Edward F. Drocella. December 2001. (*http://www.ntia.doc.gov/osmhome/reports/sp0148/sp0148_012502.htm#SECTION2*)

GNSSPLUS

Final Report Abstract

Code : GNSSPLUS-DMS-TEC-FIR02-E-R

Issue : 1.1

Date : 15/12/2008

Page : 12 of 21

This page intentionally left blank

GNSSPLUS

Final Report Abstract

Code : GNSSPLUS-DMS-TEC-FIR02-E-R

Issue : 1.1

Date : 15/12/2008

Page : 13 of 21

3. THE GNSSPLUS PROJECT

3.1. System Top-Level Architecture

In order to achieve the goals listed in section 1 at page 7, the following improvements to the currently baselined Galileo architecture are envisaged:

1) Ability of each MEO satellite to establish double-frequency communication links with the other satellites of the same constellation, and to perform spacecraft-to-spacecraft range measurement,

2) On-board orbit and clock offset determination,

3) Ability of the Ground Stations to perform ISL-like MEO↔GSS links.

Although the satellites will be endowed with enough computational capability to perform autonomous orbit and clock offset determination (taking linear combination of MEO↔MEO and MEO↔GSS pseudo-range measurements as an input), in nominal conditions the estimation processes will be carried out on ground in a dedicated processing facility. On ground, there will be no limitation over the computational power and, therefore, more complex models and algorithms will be used.

In what follows, the two aforementioned conditions will be referred to as **Autonomous Scenario** and **Nominal Scenario** respectively.

Table 3: Processing and Filtering in the Different Scenarios.

Object	Nominal Scenario	Autonomous Scenario
Processing	On Ground	Onboard
Filtering	Centralised	Distributed

In the Nominal Scenario, the goal is to maintain a position accuracy constantly below a one-centimetre threshold while, in the Autonomous Scenario, a slow decay of performances can be accepted, as long as the position accuracy remains below a one-metre threshold after fourteen days of navigation.

Table 4: Accuracy Goals of the Different Scenarios.

Object	Nominal Scenario	Autonomous Scenario
GOAL in terms of satellite position accuracy	1 cm	1 m after 14 days of navigation

The estimation process will be fed with MEO↔MEO and MEO↔GSS pseudo-range measurements: those kinds of observables are always affected by errors due to the transmission chain, as well as the troposphere and ionosphere. The last contribution is neglected by using links in double-frequency, while some of the others can be discarded by building linear combinations of observables, like two-way measurements or double-differences, shown in Figure 1.
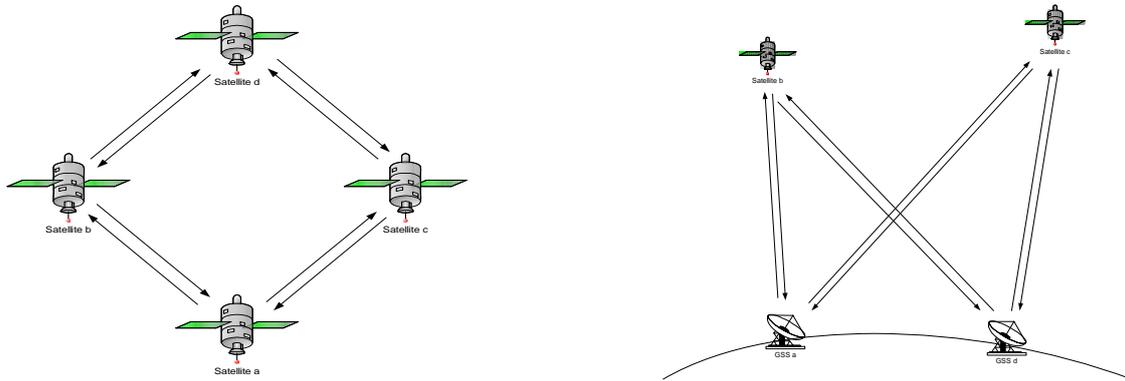
Figure 1: MEO-MEO and MEO-GSS Double-Differences Schemes.

Apart from the tropospheric contribution, all the double-differences observables are purely geometrical so, in the Nominal Scenario, there is no need to deal with any other considered bias. The tropospheric contribution must be estimated, and it has been modelled as the variation of the zenithal delay of each GSS over an average value: since the tropospheric mapping function depending on the satellite elevation over the local horizon is known, the parameters to be estimated are just one per every ground station.

On the other hand, in the Autonomous Scenario, the halved two-way observables used for orbit estimation are corrupted by unwanted contributions of the group delays of MEO and GSS: the former must be treated as considered biases, while the latter are supposed calibrated at hardware level.

Table 5: Observables of the Different Scenarios.

Object			Nominal Scenario	Autonomous Scenario
Observables	MEO-MEO	Obs. Type	Double-Differences	Halved Two-Way
		Unwanted Terms (And Treatment)	None	MEO GD (Considered Biases)
	MEO-GSS	Obs. Type	Double-Differences	Halved Two-Way
		Unwanted Terms (And Treatment)	Tropospheric Delay (Estimated $\Rightarrow$ one parameter for each GSS is included in the augmented state vector)	Tropospheric Delay (Cons. Biases) MEO Group Delay (Cons. Biases) GSS Group Delay (HW Calibration)

So far, the elements of the augmented state vector that have been identified are the degrees of freedom of the satellite (three for position and three for velocity for every satellite) and, in the Nominal Scenario, one parameter for every ground station, in order to take into account the tropospheric correction.

Nevertheless, in order to identify the other parameters of the augmented state vector, more information must be provided over the perturbations taken into account when modelling the orbit. The perturbations to be taken under consideration have been chosen and artificially collected into four main groups, according to their order of magnitude, namely consisting in:

1) Third body perturbations of Sun & Moon, and 2nd order term of Earth's gravity potential,

2) SRP & additional terms of the Earth's gravity potential (up to 5th order),

3) Albedo and IR radiation, Relativistic Effects, Solid Tides, 6th-to-8th order terms of Earth's gravity potential, 2nd and 4th order ocean tides and Jupiter gravitational influence,

GNSSPLUS

Final Report Abstract

Code : GNSSPLUS-DMS-TEC-FIR02-E-R
Issue : 1.1
Date : 15/12/2008
Page : 15 of 21

4) Third body perturbations of other planets, additional terms of the Earth's gravity potential (up to 12th order) and 6th order ocean tides.

For the usual constraints over the computational load onboard the satellites, in the Nominal Scenario, when each spacecraft is in charge of its own state vector estimation, only the perturbations included in the first two groups are included in the orbit model. Furthermore, different models of solar radiation pressure have been used in the Nominal and in the Autonomous Scenario: in the former case, a nine-parameters CODE model was employed, while in the latter case, a simpler one-parameter Cannonball model has been considered accurate enough.

The model coefficients will be estimated in both cases but, in the Nominal Scenario, the nominal values have been derived in a heuristic way, by post-processing the orbital and navigational data of the Galileo single pre-series satellite GIOVE-A: since four of these parameters are known to be null, only five per each satellite are left to be estimated.

Table 6: Perturbations Taken into Account in the Different Scenarios.

Object			Nominal Scenario	Autonomous Scenario
Perturbations	Third Bodies	Sun	YES	YES
		Moon	YES	YES
		Mercury	YES	NO
		Venus	YES	NO
		Mars	YES	NO
		Jupiter	YES	NO
		Saturn	YES	NO
		Uranus	YES	NO
		Neptune	YES	NO
	Earth Gravity		YES, up to 12th Order	YES, up to 5th Order
	SRP		YES, 5 Coefficients	YES, 1 Coefficient
	Albedo		YES	NO
	Relativity		YES	NO
	Solid Tides		YES	NO
	Ocean Tides		YES, up to 6th Order	NO

Since, in the Nominal Scenario, high-order contributions of the Earth gravitational potential are used, a very precise modelling of the Earth Rotation Matrix (ERM) is needed. The ERM is the product of three matrices corresponding to the effects caused by Precession, Nutation and polar motion respectively: since the first two matrices do not depend on estimation parameters, the only parameters that must be estimated are the values of the polar offsets and the difference between the current time and the UTC. Thus three additional parameters have to be included in the estimation vector.

Table 7: Augmented State Vector in the Different Scenarios.

Object		Nominal Scenario	Autonomous Scenario
Augmented State Vector	MEO Initial Condition	162 Parameters	6 Parameters per Satellite
	SRP Coefficients	135 Parameters	1 Parameter per Satellite
	Tropospheric Delays	40 Parameters	Not Included
	Earth rotation parameters	3 Parameters	Not Included
	Total Dimension	340 Parameters	7 Parameters per Satellite

GNSSPLUS

Final Report Abstract

Code : GNSSPLUS-DMS-TEC-FIR02-E-R

Issue : 1.1

Date : 15/12/2008

Page : 16 of 21

Now that the model of the satellites dynamics has been quickly introduced, it is worth mentioning that also the ground stations dynamics model is rather accurate. In the current model, the following effects are considered: instantaneous deformation of the solid Earth under the tidal potential of the Sun and the Moon, the periodic variations due to ocean loading, the polar motion and the Earth plate motion drift. The formulations contained in the IERS Conventions are used to compute the site displacement effects.

The simulation of the ground stations dynamics does not require including any further parameter in the augmented state vector, but was integrated in order to guarantee a proper modelling of the MEO↔GSS pseudo-range measurements, with the long-term objective of turning the GNSSPLUS tool into an operational tool whose output will be compared with real data.

The ground stations and satellite dynamics, as well as the MEO↔GSS measurements, have been validated with the DEIMOS Space operational tool RDG.

As in the orbit determination case, the clock determination takes as observables linear combinations of measurements, but in this case the combination (semi-sum) is such that the geometrical terms are cancelled out in the observation equation. No dynamical correlation is assumed in the behaviour of the clocks at different times, and the clock determination consist on computing a first degree polynomial that best fits the clock offsets. In the nominal scenario the process is centralised, and the number of variables is twice the number of clocks (one per satellite and per ground station, minus the ground station representing the PTF). In the autonomous scenario each satellites determine its own two linear parameters by comparing its clock offsets with those of the other visible satellites and ground stations.

3.2. Communications and Hardware Chain

The MEO↔MEO pseudo-range measurements and inter-satellite communications links are supposed to use the same hardware, and therefore are not simultaneous. The communications within the space segment and between the space segment and the ground segment are scheduled through a TDMA scheme. The first TDMA slots are assigned to pseudo-range measurements, while subsequent slots are assigned to communications: in these slots, every satellite has to provide the others with the best estimate of its position and velocity, plus some other parameters useful to build the linear combinations of observables. Time-slots will be one second wide, so the pseudo-range measurements are acquired at a 1 Hz rate, even if the duration of the ranging signal is just 30 ms.

The choice of the transmission chain was ruled by the constraint over the size of the antenna: the maximum allowed diameter is 40 cm, therefore the need to achieve a certain signal-to-noise ratio claimed for using frequencies in the X-band. A noise amplification factor of about 3 was used to choose the spacing of the two channels required to compensate the ionospheric error in the MEO↔GSS links; in order to preserve the same structure for the group delays, dual-frequency communications have been considered baseline also for the MEO↔MEO links.

A sufficiently wide spacing between the two transmitting frequencies allowed the choice of a wide pulse shape, that provides the best ranging performances when considering the contribution of the thermal noise: the chosen pulse shape is BOC(15,10), with a frequency occupation of 90 MHz. This choice allowed reaching sub-centimetre ranging accuracy even with just 30 ms of measurements and a closed loop noise bandwidth of 33 Hz (corresponding to 1/30 ms)

A transmitted power of 20 W has been considered baseline for every channel.

An active antenna has been considered the best compromise between performances and technological issues: the beam forming in the digital domain outperforms the analogical beam forming option in terms of accuracy of the generated beam, but the high input power required (i.e. roughly 400 W per channel)

claims for the use of two different solid-state power amplifiers (one per channel). The extremely high input power is due to the fact that the number of radiating elements in an active antenna increases when the frequency increases, and the losses associated to those elements are not negligible. It is worth noting that the baseline SSPA efficiency is about 45%, expected to be achieved within the next ten years.

The simulations show that it is possible to achieve a root mean square error below one centimetre in both MEO↔MEO and MEO↔GSS pseudo-range measurements (as long as the diameter of the ground antenna must be of at least 80 cm): preliminary DOP analyses proved that such an error over the observables can translate in a position accuracy in the sub-centimetre range.

An overview of the baseline architecture is provided in Table 8.

Table 8: Review of the Transmission Chain Architectural Baseline.

Parameter		BASELINE	
MEO Antenna Diameter		40 cm	
Bean Forming		Digital	
Transmission Frequencies	First MEO-MEO	8.1 GHz	
	Second MEO-MEO	10,1 GHZ	
	First MEO-GSS	8.1 GHz	
	Second MEO-GSS	10.1 GHz	
	NAF [1]	2.8	
MEO Antenna Gain (Tx or Rx) [dB]		27.35 @ 8.1 GHz	29.27 @ 10,1 GHz
GSS Antenna Diameter		80 cm	
Power Consumption per Frequency [W]		337	480
Overall Power Consumption [W]		817	
Nbr Radiators		91	142
Output Power per Carrier [W]		20	
Pulse Signal		BOC(15,10)	
Symbol Rate (for secondary codes) [Ksps]		2	
Code Period [ms]		0.5	
Tx Bandwidth [MHz]		52	
HPA Efficiency [%]		45%	
Minimal Available (C/N$_o$) [dB-Hz]		65	67
Closed Loop Bandwidth [Hz]		33	
Measurement Error [cm]	MEO↔GSS	~0.6 cm	
	MEO↔MEO	~1.0 cm	

---

[1] Noise Amplification Factor associated to the two frequencies; $NAF = f_2^2 (f_2^2 - f_1^2)^{-1}$

GNSSPLUS

Final Report Abstract

Code : GNSSPLUS-DMS-TEC-FIR02-E-R

Issue : 1.1

Date : 15/12/2008

Page : 18 of 21

3.2.1. Software Tool

The GNSSPLUS software tool is a FORTRAN tool with C and C++ built-in subroutines.

The tool in divided into four main functions:

1) Measurements Generation,

2) Measurements Combination,

3) State Vector Estimation,

4) Parameter Comparison.

The *Measurements Generation* function generates all the "real world" one-way pseudo-range measurements between space segment and ground segment and within the space segment itself. The disturbances taken into account are the clock offset, the group delays in transmission and reception, and the troposphere (ESA Blind model): the ionospheric effect is not taken into account since a double-frequency measurement is used.

The *Measurements Combination* function is in charge of combining the one-way measurements into two-way measurements and double-differences. Measurements derivatives are used to map all the non-simultaneous observables at the beginning of every mapping time and, after that, a specific routine selects the minimum sub-set of linearly independent combination of measurements.

In the *State Vector Estimation* function, which represents the core of the software tool, the aforementioned linearly independent observables are fed as input to the square root information filter, in order to let it update the predicted values of the parameters listed in Table 7.

The *Parameter Comparison* function organises the main outputs in such a way to be easily plotted: in this way, immediate information over the actual quality of the solution can be delivered.

A top-level overview of the input/output relationships among the main functions of the GNSSPLUS tool is depicted below.
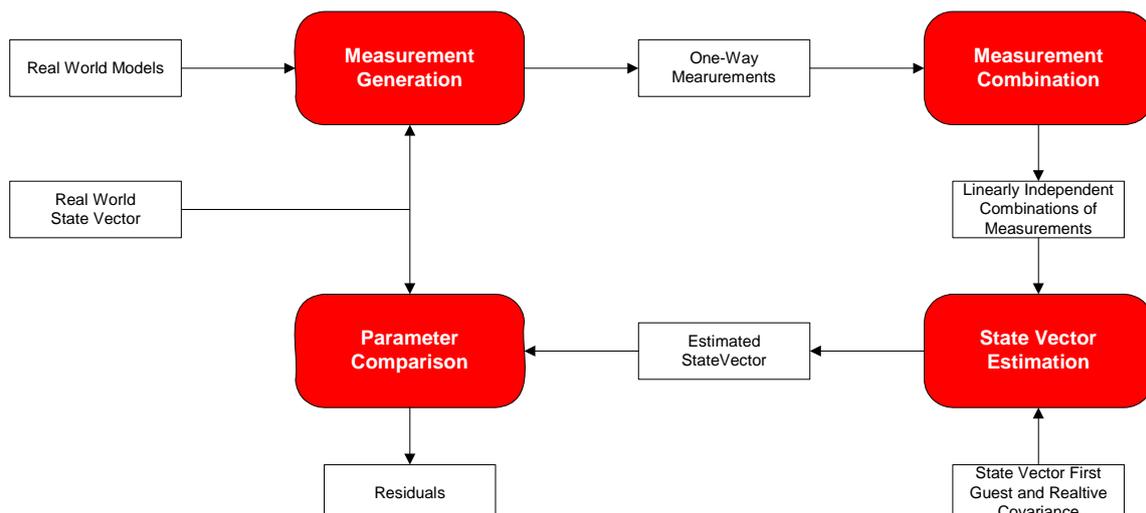

Figure 2: I/O Relationships among the Main Functions of the GNSSPLUS Tool.

DMS-DQS-QRE0603-ADD-11-E

GNSSPLUS

Final Report Abstract

Code : GNSSPLUS-DMS-TEC-FIR02-E-R
Issue : 1.1
Date : 15/12/2008
Page : 19 of 21

3.2.2. Performance Assessment

Three different simulations campaigns have been run at DEIMOS Space.

The first one aimed at testing and validating specific features of the software tool like satellite dynamics, GSS dynamics, or pseudo-range measurements generation.

The second campaign was made up of several tests simulating the behaviour of the full-scale system for two days in both the Nominal and the Autonomous Scenario. The different test cases simulated the nominal conditions, as well as the failure of some satellites and/or some of the ground stations. The results were extremely promising and proved two important points: that the goals in terms of accuracy for the Nominal and Autonomous Scenarios could be met, and that the system was extremely robust. The results, in fact, did not change much even when the number of ground stations out-of-order was a considerable portion of the entire FOC ground network. Actually, a relatively simple ground network, as for example the ESA ESTRACK network, would be enough to meet the accuracy goals, as long as the space segment of the system remains fully operational.

The results mentioned above can be extended up to state that it is pretty likely that a Galileo system endowed with inter-satellite links and autonomous navigations capabilities will have a minor dependence on the ground segment, which might be simplified, with positive consequences over the operational cost. This would translate in the achievement of the goals listed in section 1 at page 7.

The third simulation campaign differs from the second campaign for the length of the simulation period, given that it consists of full-scale simulations over a period of two weeks, and that the analysis was focused on the reduction of number of ground stations.

These simulations provide three main graphical outputs:

1) Minimum, medium and maximum inertial and Earth-fixed position and velocity errors at constellation level, with respect to time,

2) Minimum, medium and maximum error over the solar radiation pressure CODE model parameters, at constellation level, with respect to time,

3) Estimated Earth rotation parameters, with respect to time.

The following table has been obtained from the third simulation campaign, and shows the achieved performances (average inertial position error) as function of scenario and ground segment size.

Scenario and Ground Segment Size		Orbit Determination		Clock determination
		Inertial	**Earth-Fixed**	
Nominal	40GSS	2 to 6 cm	2 to 3 cm	12 cm
	6 GSS	7 to 11 cm	2 to 8 cm	15 cm
	1 GSS	12 to 18 cm	2 to 20 cm	18 cm
Autonomous	40 GSS	2 m	10 cm	18 cm
	6 GSS	2 m	0.2 to 0.8 m	24 cm
	1 GSS	No convergence		-

In the nominal scenario with full ground segment the 1-cm target accuracy is almost reached. This solution could be further improved by providing more accurate predictions of ERPs, which are determined with a limited accuracy.

GNSSPLUS

Final Report Abstract

Code : GNSSPLUS-DMS-TEC-FIR02-E-R

Issue : 1.1

Date : 15/12/2008

Page : 20 of 21

In the autonomous scenario each satellite uses the predicted ERPs, without trying to determine them. The error in these predictions translates directly into a rotation of the complete constellation, and that rotation becomes the main source of error in the inertial position. Reducing the ERPs prediction error could improve the inertial position accuracy to a few centimetres in the 40-GSS case, and to 1 m in the 6-GSS case.

The clock determination achieves result of 12 to 18 cm in the nominal cases, and 18 to 24 cm in the autonomous ones.

End of Document