Galileo Science Opportunity Document

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Introduction

Context

This document describes the opportunities offered by satellite navigation systems (and more specifically, the Galileo system) and their signals to different scientific communities, as well as the potential benefits for the Galileo system resulting from its scientific exploitation.

Objectives

The purpose of the Science Opportunity Document (SOD) is to provide an overview of scientific endeavours benefiting from the Galileo system and to establish a common background for the scientific exploitation of the Galileo system and possible future versions. Its writing was initiated by the Scientific Programme Committee of the Galileo Science Colloquium in 2007. It is a continuously evolving document that is maintained by the GNSS Scientific Advisory Committee (GSAC) to advise the ESA directorate and to stimulate research related to Galileo in the wider scientific community.

More specifically, the SOD shall provide:

- An overview of all areas of science where Galileo signals and data can be used.
- A summary of the existing capabilities of Galileo.
- Identification of areas where a specific ESA intervention can lead to effective evolution of the system.
- A starting point for the first Announcement of Opportunity for scientific activities inside the Galileo Evolution Programme.
- The basis of a database of companies/institutes/universities that are interested in participating in ESA activities;

1. General Information

1.1 Galileo Specifications

The high level requirements for Galileo have been defined by the European Commission in the "Galileo Mission Requirements Document" (MRD), first released in 2001. ESA developed, based on the MRD, the Galileo System Requirements Document (SRD) and derived the corresponding space and ground segment requirements from the SRD. The signal-in-space has been defined in the Signal-in-Space Interface Control Document (SIS-ICD). The one for the Open Service has been published by the European GNSS Supervisory Authority [GSA, 2008].

1.1.1 Galileo Services

The Galileo system will provide a total of five distinct services:

1. Open Service (OS) is intended for the mass market; the signals are un-encrypted and can be freely used. Receivers can be either single or dual frequency and are optimised for fast acquisition and multipath suppression.
2. Commercial Service (CS) is intended for professional users. The users will subscribe to the service, will obtain a guaranteed performance and will utilise dual frequency receivers which are optimized for accuracy.
3. Safety-of-Life Service (SoL) is designed for civil aviation and other mass transport systems. The service will be certified to provide the necessary level of integrity and the user receivers (either single or dual frequency) will also have to be certified.
4. Public Regulated Service (PRS) will be provided to government users. Access will be limited to authorised entities and the service will be optimized for continuity and robustness.
5. Search and Rescue (SaR) is not strictly speaking a navigation service, it will be used in conjunction with certified emergency beacons.

1.1.2 Galileo Satellite Constellation

The Galileo constellation consists of 27 satellites (plus 3 spares) in three orbital planes which are offset by 120 degrees. The nominal inclination of the orbital planes is 56 degrees and the orbit altitude is

23,222 km. Each satellite makes 17 orbits in 10 days. The average number of satellites visible from the ground (without obstructions) is 12.

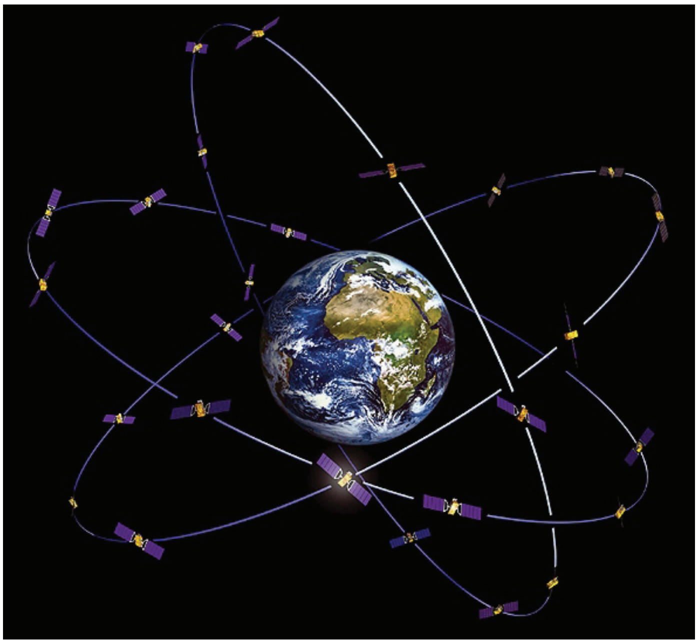

Figure 1: Diagram showing the Galileo orbits

The typical mass of a Galileo satellite is approx. 700 kg and the solar panels deliver a power of 1.6 kW at the end of a nominal lifetime of 12 years. The body of the spacecraft is 2.7 x 1.2 x 1.1 m in size; the span of the solar panels is 17.5 m. The navigation payload has a mass of approx. 140 kg and consumes about 900 W of power. The onboard clocks will consist of a combination of rubidium and passive hydrogen maser sources. [Hahn, 2007].

1.1.3 Galileo Frequency Plan

The Galileo navigation signals are transmitted in four bands between 1.1 and 1.6 GHz as indicated in the figure below (Figure 2). For more information on the signal characteristics see [GSA, 2008].

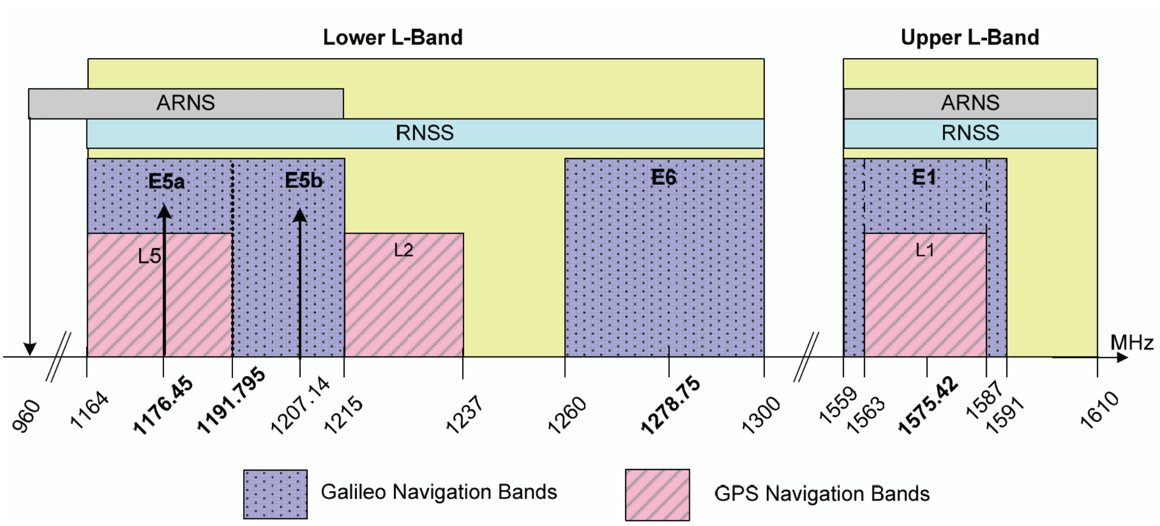

Figure 2: Galileo Frequency Plan. ARNS: Aeronautical Radionavigation Service, RNSS: Radionavigation Satellite Service

For future generations of Galileo, additional radio navigation frequency bands are being considered, namely in S-band (2483.0 – 2500.0 MHz) and in C-band (5010.0 – 5030.0 MHz). ESA is undertaking system studies as well as supporting in-depth investigations of the propagation conditions and the interference environment at these frequency bands [ITU, 2008; Irsigler et al., 2004].

1.2 Availability of GNSS Data to the Scientific Community

In the start up phase of the Galileo programme, operational data of GIOVE-A and GIOVE-B were restricted to the members of the project. There were several reasons for this restrictive data policy; one was the limited capacity of the data server. In some exceptional cases, data have been made available to scientists and this limited exposure already provided important insights.

For the future, a science data server is envisaged which will give access to important operational information and to (historic) data collected at Galileo Sensor Stations. The policy for the use of such data is being formulated.

1.3 References

[GSA, 2008] GSA "The Galileo Open Service Signal In Space Interface Control Document Draft 1 (OS SIS ICD Draft 1, February 2008)", http://www.gsa.europa.eu/go/communications-center/publications

[Hahn, 2007] Hahn, J. "GALILEO – Overview and links to the Scientific Communities", Proc. 1st Coll. Scientific & Fundamental Aspects of the Galileo programme, Toulouse 1-8 Oct 2007.

[Irsigler et al., 2004] Irsigler, M., Hein G.W., Schmitz-Peiffer, A., "Use of C-Band frequencies for satellite navigation: benefits and drawbacks", GPS Solutions, Vol 8, No 3, Sept 2004, pp. 119-139, doi: 10.1007/s10291-004-0098-2.

[ITU, 2008] ITU Radio Regulations ITU RR, Article 5, http://www.itu.int/pub/R-REG-RR/en.

2. Earth Sciences

This chapter covers sciences related to understanding the planet Earth, but focuses on the aspects of physics (as opposed to chemistry or biology) for which the use of GNSS signals is most relevant.

2.1 Geodesy and Geodynamics

2.1.1 Global Geodetic Observing System

Modern Earth sciences require acquisition and analysis of large data streams stemming from different disciplines and can use a variety of instruments located all over the world. In order to meet these requirements the International Association of Geodesy (IAG) organized the Global Geodetic Observing System (GGOS) composed of IAG technique-services, such as the International GNSS Service (IGS), the International Very Long Baseline Interferometry (VLBI) Service for Astrometry and Geodesy (IVS), the International Laser Ranging Service (ILRS), and the International Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) Service (IDS), and services combining the products of the technique-specific services, such as the International Earth Rotation and Reference Systems Service (IERS). The GGOS enables research in three fundamental areas of geodesy:

- The geometric shape of the Earth (land, ice and ocean surface) as well as its variation in time.
- The orientation of the Earth in inertial space as a function of time as described by three Euler angles, namely precession and nutation in longitude and latitude, and Universal Time (UT) (Length of day (LoD) is the first time derivative of UT, and polar motion essentially defines the rotation axis of the Earth in an Earth-fixed reference system).
- The Earth's gravity field and its temporal variations.

These three large fields of research are related by the joint problem of the definition and maintenance of the global geodetic reference system [Rummel, 2002; Drewes, 2007].

One of the main information sources of satellite geodesy is provided by the dynamics of satellite orbits. Satellite motion is conveniently described in a geocentric but otherwise inertial coordinate system. This system may be called quasi-inertial. As the gravitational attraction of a non-spherical Earth is the dominant constituent of the force field acting on the satellite, the Earth's orientation in the quasi-inertial system must be known as a function of time in order to generate the ephemerides of a satellite.

The Earth's rotation is described by the three Euler angles mentioned above. They solve the so-called Liouville-Euler equations of motion in the case of an elastic planet [Beutler, 2005]. Precession and nutation in longitude and latitude and UT cannot be established directly by satellite geodetic methods because of correlations with the satellite orbital elements. The quantities related to the first time derivatives of the three Euler angles can, however, be established rather accurately by satellite-geodetic methods. Thus, GNSS-based nutation rates are valuable contributions to determine high frequency terms of the nutation model but usually nutation is retrieved from VLBI observations. The remaining three quantities frequently denoted as Earth Rotation Parameters (ERP), namely the coordinates x and y of polar motion in an Earth-fixed coordinate system and Length of Day (LoD) are determined by GNSS with unique accuracy. Concerning the determination of sub-daily variations in Earth rotation, mainly caused by ocean tides, Galileo will be a valuable contributor because of the satellites' revolution period of about 14 h and therefore not in resonance with Earth rotation.

The Earth's gravitational potential was determined and estimates were gradually improved in the 20th century through the observation of a large number of artificial satellites by astrometric and laser techniques, notably the two LAGEOS satellites. In the first decade of the 21st century our knowledge of the Earth's gravity field and its time variations was dramatically improved by the dedicated gravity field missions CHAMP (CHAllenging Minisatellite Payload) [Reigber et al., 2004], GRACE (Gravity Recovery And Climate Experiment) [Tapley et al., 2004], and GOCE (Gravity field and steady-state Ocean Circulation Experiment) [Drinkwater et al., 2006]. As today's GNSS satellites orbit the Earth at heights of typically 20,000 km, the gravity field established by the Low Earth Orbiters (LEOs) in the past fifty years may be assumed as known when analysing GNSS orbits.

GNSS satellites emit signals (codes) on several carriers of different wavelengths in the microwave part of the electromagnetic spectrum. The signals are coherently derived from a rather accurate atomic clock onboard the satellites. These signals and, for scientific applications, the carrier phases, are the primary observables of GNSS. The satellites' orbit and clock corrections (synchronization with respect to a synthetic system clock), the coordinates of ground tracking networks (including their time development), LoD, polar motion, etc. are determined using GNSS observables.

The carriers and signals as recorded by receivers on or near the Earth's surface have to cross the Earth's atmosphere, causing signal delay and phase changes. These refraction effects, namely ionospheric and tropospheric refraction, have to be compensated for through measurements or by models. As the ionosphere is a dispersive medium, this part of refraction may be eliminated by forming the so-called ionosphere-free linear combination of the corresponding observables at two wavelengths. Tropospheric refraction is not dispersive at GNSS frequencies and usually is taken into account by adopting an a priori model of the hydrostatic content and adopting in addition an elevation-angle-dependent mapping model. Especially high accuracy applications solve in addition for model parameters covering in principle the wet part of the tropospheric refraction as well as deficiencies in the approximation of the hydrostatic part.

In the 1980s, the orbit errors of the partially deployed Global Positioning System (GPS) were the dominant accuracy-limiting element for high-accuracy applications of GPS. This insight was the motivation to create the International GPS Service for Geodynamics (IGS), as it was called at that time. Originally, the IGS was designed as a pure orbit determination service. The coordinates of the ground tracking network and the Earth rotation parameters should be taken over from the other space geodetic techniques (and emerging from the IVS and the ILRS). The concept failed. It proved to be necessary to solve for all parameters accessible to the GNSS. Starting in the late 1990s some of the IGS Analysis Centers incorporated GLONASS observations gathered by combined GPS/GLONASS receivers into the analysis. The IGS intends to incorporate Galileo, as well, using combined receivers. Today, the IGS is a service making available consistent products to a wide user community. For an overview of the development and achievements of the IGS see [Beutler et al., 2009]; for a recent description of products, see [Dow et al., 2009]. The IGS makes its products, in particular the time series of receiver coordinates and ERPs, available to the IERS, which combines the IGS products with those of the other technique-specific services (ILRS, IVS, and DORIS) to generate consistent and highly accurate series of ERPs and the International Terrestrial Reference Frame, supposedly the most accurate and robust global reference frame

2.1.2 Measurement of Tectonic Motions and Local Deformations

Scientists started measuring the large-scale deformation of the Earth, notably plate tectonics and changes in the overall shape of the globe, before the first GNSS appeared. But GNSS have brought greater precision and above all enabled sustained monitoring at an acceptable cost and in a very efficient and timely way. For instance, we can now monitor variations of geodetic station positioning induced by various geophysical processes. The global network of IGS stations can provide continuous information about motions of the continents or smaller tectonic plates.

At a local or regional scale, the ease with which a GNSS can be used and combined with positioning precision (particularly in differential mode) means that the number of measurement points in areas of seismic or volcanic activity can be increased to monitor changes that might warn of coming disasters. After an earthquake or volcanic eruption, the extent of deformation can be measured too. GNSS also provides a means of aligning local deformation with the ITRF and aids the attempt to understand the forces behind it on a worldwide scale. In regions of significant seismic activity (e.g. California, Japan), local GNSS networks are used for permanent monitoring of the ground deformations. The provided data are used to develop or to validate models of crustal movements and earthquakes prediction.

It is right to mention that other space geodesy techniques – laser ranging, VLBI, DORIS – also make important and crucial contribution to the above mentioned research, but the GNSS method is the most substantial and the most productive [Springer et al., 2006].

2.1.3 Earth's Gravity Field and Ocean Surface Determination

The geoid is the equipotential surface of the Earth's gravity field that approximates the mean sea surface. By definition, the local vertical (plumb line) is perpendicular to this surface. Its form is represented by differences in altitude in relation to a theoretical surface adopted by convention: a geocentric ellipsoid whose dimension is chosen to fulfil the condition that the global integral of geoid undulations is zero.

In the early days of satellite geodesy, it was discovered that there were bumps and hollows in the geoid (with respect to a reference ellipsoid) with deviations of as much as 100 metres over distances of about 1000 kilometres. These results were obtained by analysing the trajectories of many artificial satellites over long periods. As analytical methods improved it became possible to study structures without it being possible to consider details less than a few hundreds of kilometres in size. Very large scale undulations and their possible variations in time remain within the scope of this perturbation method.

The orbit of a satellite tracked by systems such as GPS or DORIS may be transformed to a geocentric reference frame rotating with the Earth. At any given time the model indicates the satellite's altitude above the reference ellipsoid. A radar altimeter on board a satellite (e.g. Envisat, Jason-1 or -2) therefore indicates the (positive or negative) altitude of the surface of the sea (or the ice) with respect to this ellipsoid. The altitude reading has two components: the contribution of irregularities in the geoid (the geophysical component) which may attain several tens of meters, and the difference between the geoid and the actual sea level. We can distinguish these components by the way they vary in time and space. The geoid itself only varies very slowly. In contrast, oceanic effects, caused by changes in temperature, salinity, current dynamics and tides, vary over intervals ranging from a single day to a decade and over distances from several tens of kilometres to several hundred. We can, however, often only obtain data about temporal variations in the oceanographic component, and not its absolute value.

New satellite missions allow modelling of the gravity field in greater detail. The CHAMP mission (launched in 2000) is based on a space-borne GPS receiver and an accelerometer to separate gravitational from non-gravitational forces. The GRACE mission (launched in 2002) uses twin satellites in the same orbital plane. Each satellite is equipped with a GPS receiver and an accelerometer. In addition the (biased) distance between the satellites is monitored on the micrometer level using a K-band microwave link. The European GOCE mission (launched in 2009) is also equipped with a GPS receiver and with a three-dimensional gradiometer measuring gravity gradients inside the satellite and delivering very short wavelength static information of the gravity field.

Satellite altimetry is a challenge for space geodesy since it requires satellites in a sufficiently low orbit for accurately measuring the distance between the satellite and the ocean surface. The orbits are heavily perturbed by the detailed gravity field, by drag, and by radiation pressure. One should, however, achieve centimetre precision in the radial direction. Precision of this kind can only be achieved by using various space techniques. Space-borne GNSS receivers make a direct and very efficient contribution. Using onboard GNSS receivers and the GNSS orbits and clock corrections issued by the IGS, the position of the LEO satellite may be established as a function of time with centimetre accuracy.

The use of GNSS for tracking LEOs is a significant improvement in orbit determination because of the following two reasons:

1. Continuity and homogeneity

The LEO is tracked permanently, 24 hours per day without interruptions. Such coverage could never be achieved with ground tracking systems, where weather conditions (for laser) or visibility limitations (due to the sparseness of the observatories) produce long data gaps.

2. Accuracy

The new generation of space qualified GNSS receivers together with the ephemerides and GNSS clock corrections provided by the IGS enables precise positioning of the low orbiting satellite. The most advanced instruments used for the CHAMP, GRACE and GOCE missions deliver position precision on the few cm-level per coordinate. Relative precision (either in space or in time) is even more accurate.

GNSS is also essential to connect the space-geodetic networks of VLBI, SLR, tide gauges, etc., with cm accuracy [Springer et al., 2006; Reigber et al., 2003].

2.1.4 Multi-constellation GNSS analysis

The distinction should be made between (a) global geodetic analysis including orbit and clock determination for all openly available GNSS and (b) user analysis based on known GNSS orbits, clocks, Earth rotation parameters, etc. An analysis of type (b) is either based on information broadcast by the GNSS (for real-time applications in remote areas often the only available option) or information made available, e.g., through the IGS. Analysis of type (b) is simple, but limited by the accuracy of the broadcast and IGS products, respectively.

Analysis of type (a) thus provides the basis for all applications of type (b). One should make the distinction between the analysis performed by the GNSS providers, which result in broadcast orbit elements in an Earth-fixed reference frame and clock predictions and the analysis performed by scientific institutions. Today, these institutions collaborate (or compete) as Analysis Centers of the IGS. The scientific analysis is much broader and shall be briefly outlined here. It covers at the minimum the following parameter types:

- orbit parameters,
- GNSS clock corrections with respect to a conventional system time for each GNSS satellite,
- ERPs,
- coordinates of the tracking sites,
- clock corrections of the tracking sites,
- troposphere parameters,
- initial phase ambiguity parameters.

As a convenience to the user, the orbits are made available as ephemerides (rectangular coordinates spaced by 15 min) in the IGS realization of the ITRS. The ephemerides allow a user to reconstruct the scientific orbit with sub-mm precision using simple interpolation polynomials.

Ideally, the parameters of all types are solved for in one adjustment step. The parameters, which have to be determined when analysing a global network of 100+ sites for one day of data, are counted in the thousands. All estimated parameters are correlated. Parameter estimation may be based on conventional least-squares (LSQ) or on Kalman filtering techniques (KFT). The parameters are assumed to be static in the case of LSQ; they may represent stochastic processes in the case of KFT – where it is the analysist's duty to define the stochastic properties of the processes. We do not discuss the mutual benefits of LSQ and KFT here, but assume an LSQ environment and add a few remarks concerning specific parameter types.

Orbit parameters: The orbit of a satellite is assumed to be a solution of the equations of motion, which are second order non-linear differential equations with time *t* as the independent variable. Strictly speaking, the orbits should be generated in the framework of the General Theory of Relativity. In practice, the orbits are based on classical Newtonian mechanics and the corrections to general relativity are treated as known perturbations. If the force field acting on a particular satellite is assumed known, one set of only six parameters (e.g., components of the initial position and velocity vectors or six initial osculating orbit elements) per arc defines a particular solution. The arc length in principle may be defined by the analyst, where it is an unwritten law in the IGS that the arc length is one day or longer. Due to the height of the GNSS satellites, drag can be safely ignored. Radiation pressure, however, must be taken into account. Despite the fact that the surface properties and the orientation of the GNSS satellites are in principle well known, it proved to be necessary to solve for about 10-20 empirical force parameters per satellite and arc (e.g., the famous y-bias in the case of GPS).

The orbit parameterisation is an important issue and has to be studied carefully for each GNSS, i.e., also for the Galileo system. Such studies require good knowledge of the satellite properties (e.g., mass, surface sizes, shapes, and reflection/absorption properties). High precision orbit modelling requires in addition sub-cm 3-d-knowledge of the satellite (and receiver) phase centres with respect to the centre of mass of the satellite. Such aspects must be studied carefully for Galileo. For validation purposes using the SLR technique it is also necessary to have available the 3-d position of the SLR reflector array with respect to the satellites' centres of mass.

Satellite and receiver clock parameters: A global analysis usually is based on one (or few) reference clocks of highest quality, which are kept fixed (which serve as system clocks). For each epoch (usually with spacing between 10 s and 15 min) clock corrections with respect to the system clock are determined (ideally) in the parameter adjustment process together with all other parameters. For GPS and GLONASS one usually selects the clock of a ground-based receiver driven by a hydrogen maser as a reference. The Galileo space clocks may allow us to review this concept, e.g., by using space clocks as reference. In addition, all space clocks might be used to define an epoch-overarching Galileo system clock as a function of time.

Site coordinates: As "normal" station motion is small (a few cm per year), it is usually sufficient to generate one set of coordinates per day or even per week. An analysis of the time series of station coordinates allows it to derive station motion with respect to a conventional "non-rotating frame" of an ensemble of stations. Sub-daily site motion (e.g., due to tides, loading) are assumed as known using *a* *priori* models. Different IGS Analysis Centres use different tracking sites. Therefore, several hundred IGS sites are available as input into the ITRF (see Sect. 4.3).

ERPs: Currently, the basic sampling interval for ERPs (x, y, LoD) is one solar day. This may not be the best choice. From the perspective of Earth rotation, one sidereal day (the rotation period of the Earth in inertial space) would be more appropriate. Usually, not only one set of pole coordinates x and y are set up, but polar motion is modelled by rectilinear motion with constant velocity for each day.

Phase ambiguity parameters: The phase ambiguity parameters on the double difference level (involving two satellites and two receivers) referring to a particular carrier may be resolved to integer values. There are different techniques to do that, e.g., by forming special linear combinations of code and phase observations. The issue will be very complex for Galileo. It will be in particular necessary to determine and monitor differential code biases (DCBs) for all possible wavelengths and code types. The issue of ambiguity resolution and of DCB determination is quite complex but of vital importance to make use of the full potential of Galileo. DCB determination is, by the way, also necessary to achieve the highest precision for time and frequency transfer.

When combining the observations of different GNSS gathered by combined receivers, new analysis aspects will show up:

- Is it possible to have one receiver clock for all GNSS or are different clocks needed for different systems?
- Is it necessary to introduce inter-system biases for code and/or for phase?
- Is it possible to resolve ambiguities (on the double difference level) involving satellites of different systems?
- Etc.

The goal of a global analysis based on a network of receivers gathering the observations of the satellites of all GNSS in view is one consistent set of parameters of all types allowing the user to generate results based on all observations "as if they had emerged from only one GNSS". This goal will be hard to achieve and requires a lot of research work to be performed.

Under a multi-GNSS scenario, additional research will also be required to further improve the accuracy and efficiency of user software products for demanding applications. Such products include enhanced real-time kinematic (RTK) software, precise point positioning (PPP) software (including real-time implementations) and the merger of these two positioning modes.

2.1.5 Atmospheric Waves Generated by Earthquakes and Tsunamis

Severe weather fronts, nuclear explosions, volcano eruptions, and earthquakes are known to produce energetic infrasonic pressure waves, which may propagate upward. Since the atmospheric density decreases almost exponentially with altitude, energy conservation implies that the wave amplitude also increases exponentially. Such amplification of the wave amplitudes can reach a factor of up to 100 causing detectable traces in the ionospheric plasma. Due to the absorption and acoustic cut-off, only waves with frequencies between about 3.7×10^{-3} Hz to 10^{-2} Hz can reach the ionospheric layers [Lognonne et al., 1998]. Acoustic waves excited at the ground need approximately 10 minutes to reach the F-layer of the ionosphere, where close coupling between the neutral atmosphere and ionized plasma may result in a wavelike modulation of the electron density.

Since dual-frequency measurements of navigation signals from GNSS such as GPS and Galileo are very sensitive to small plasma changes along the ray path, earthquake signatures may be detected. The sensitivity of GPS-based ionospheric measurements to earthquakes was first reported by Calais and Minster in 1996 [Calais and Minster,1996] by analyzing the extremely strong Denali Park Alaska Earthquake of 3 November 2002. A more detailed analysis of this magnitude 7.9 earthquake has provided objective evidence that seismic-wave-induced upward propagating atmospheric acoustic waves significantly modify the ionospheric plasma measurable by differential GNSS phases [Ducic et al., 2003; Jakowski et al., 2006]. Whereas earthquakes may excite acoustic waves, tsunamis induce atmospheric gravity waves, which can reach the ionosphere where they may be detected [Artru et al., 2005]. The time required to manifest a detectable tsunamigenic signature in GNSS-based ionospheric observations may be as short as 20 to 30 minutes but further research is required to confirm this [Hickey et al., 2009; Galvan et al., 2009].

Since natural disasters such as earthquakes are of serious concern to the public, great attention is paid to any plausible approach having a potential for reducing the impact of such catastrophes. Among such approaches also ionospheric precursors of strong earthquakes are intensively discussed by many authors (e.g. [Pulinets and Boyarchuk, 2004] and references therein).

High quality signals of Galileo will enormously improve the GNSS data availability for ground- and space-based measurements and so essentially contributes to the study of solid Earth-atmosphere-ionosphere couplings and energy transfers.

2.2 Remote Sensing Using GNSS-R

2.2.1 GNSS Reflections

The concept of GNSS-R (GNSS-Reflectometry) or PARIS (Passive Reflectometry and Interferometry System) is that of a bi-static radar, where the transmitter is a GNSS satellite and where the receiver can receive both the signal coming directly from the source and the signal reflected from the Earth's surface. In spite of the fact that the properties of GNSS signals have been optimized for navigation applications, the reflected signal contains information about the state of the reflecting surface.

An illustration of such a concept is presented in the following figure.

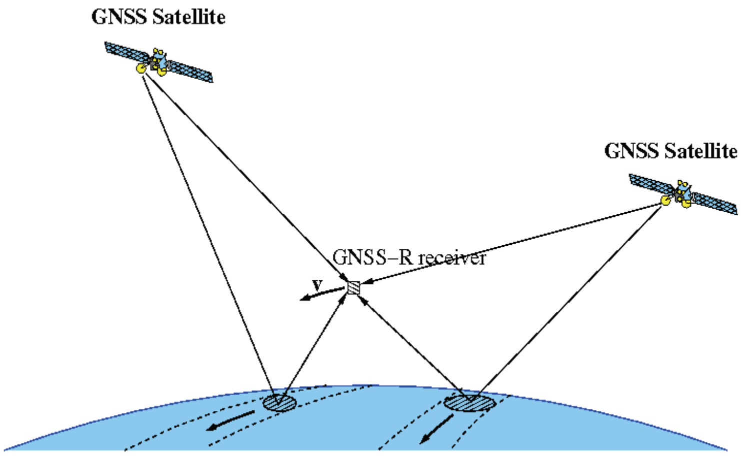

Figure 3. A vehicle flying over the Earth's surface observes the GNSS signals emitted by the GNSS constellations, both direct and reflected, using a GNSS-R receiver. The correlation function of the reflected and direct signals (or suitable replicas) provides altimetric and scatterometric information

When the signals are reflected at grazing angles, as is the case in the lower parts of the GNSS radio occultations, they maintain coherence and interfere with the direct signal. This is a common situation, observable in a large number of GNSS radio occultation events using space GNSS receivers in open loop mode. While these reflected signals contain useful geophysical information [Beyerle and Hocke, 2001; Cardellach et al., 2004], the term GNSS-R is usually reserved for the non-grazing reflections were the reflected signal is essentially incoherent. Many different institutions have contributed to the development of the technique.

The concept GNSS-R was proposed in 1993 by ESA [Martín-Neira, 1993] to provide additional measurements of the sea surface to increase the spatial and temporal resolution provided by radar altimeters. In 1998, the application to remote sensing of the sea roughness and winds was demonstrated [Garrison et al., 1998]. Most of the applications are based on a bi-static radar model adapted to the GNSS-R, as described in [Zavorotny and Voronovich, 2000].

Research to demonstrate the potential of the technique has been initiated by different groups, mainly in the U.S.A., Europe, and China. These studies are based on experiments performed with receivers placed at fixed locations [Treuhaft et al., 2001; Helm et al., 2005], on aircraft [Garrison et al., 1998; Lowe, 2002a; Rius et al., 2002; Ruffini et al., 2004], on high altitude balloons [Cardellach et al., 2003] and on LEO satellites [Lowe et al., 2002b; Gleason et al., 2005]. Gleason et al. [2009] provide a review of the GNSS-R technique and the mentioned applications. Additionally, this reference includes a data set acquired by the GNSS-R receiver on board the UK-DMC SSTL satellite and basic software tools to process such data.

2.2.2 GNSS-R Instrumentation

In the current implementations of the GNSS-R concept, the primary observables are the cross-correlations, termed waveforms, of the recorded signal after its reflection with replicas of the GNSS transmitted signals. The replicas are generated locally within the GNSS-R receivers. For civil applications, the generation of the replicas is limited to the codes with civil open access. Different algorithms have been proposed to extract from the measured waveforms estimated quantities which could be related with geophysical variables, providing the basis for the different applications of the GNSS-R technique, as discussed in the next section.

Different architectures have been proposed, built, tested and used at different institutions to implement such concepts. In the open literature, more than twenty GNSS-R research instruments are described, with different functionalities and performances. Implementation details for some of these instruments could be found in the references [Martín-Neira et al., 2001; Lowe et al., 2002c; Heckler and Garrison, 2004; Nogués-Correig et al., 2003 and 2007; Akos, 2004; Dunne et al., 2005; Gleason et al., 2005; Brown and Mathews, 2005; Helm et al., 2005].

A different approach has been proposed recently by ESA, to demonstrate primarily the suitability of the PARIS concept to perform mesoscale altimetry. The main difference between the ESA proposal, the PARIS In-Orbit-Demonstrator (or PARIS IoD), and the instrumentation mentioned previously is that a) the waveforms are obtained by cross-correlating directly the direct and the reflected signals and b) it includes functionalities to increase the signal to noise ratio and to obtain a good characterization of the instrumental delays, needed to reduce the measurement uncertainties. An overview of such an approach can be found in [ESA, 2009].

2.2.3 Some GNSS-R Applications

The GNSS-R concept has been developed to remotely sense the different components of the Earth surface: water, soil moisture, ice, snow, etc. In the present section some of the work done is reviewed and a more complete account is given in the cited references.

2.2.3.1 Ocean Surface Altimetry

One of the first applications conceived for GNSS-R was altimetry – the measurement of the ocean surface height and topography. Conventional satellite radar altimeters typically only measure the ocean height at the sub-satellite point (using a nadir-looking real-aperture radar) – the GNSS-R altimeter measures the ocean height at many points at the same time, namely the specular reflection points of all GNSS satellites which are visible above a predefined masking angle. This passive wide-swath altimeter concept lends itself to new applications, such as the detection of tsunamis, ocean eddies or other mesoscale features in ocean height [Martin-Neira et al., 2005; Buck and D'Addio, 2007]. The experiments already described have demonstrated that the achieved precision of few centimetres is suitable for the intended altimetric application if the uncertainties in the instrumental delays are evaluated by using properly calibrated instruments (e.g: [Rius et al., 2010]).

2.2.3.2 Monitoring Sea State

As previously mentioned, in 1998, the application to remote sensing of the sea roughness and winds was demonstrated with data acquired in aircrafts experiments [Garrison, 1998], by measuring properties of the probability distribution function (PDF) of the sea surface slopes. A method to observe non-Gaussian features of the sea state have been demonstrated by Cardellach and Rius [2008].

Because the brightness temperature measured by L-Band radiometers is affected by the sea roughness, the GNSS-R measurements could be utilized to reduce the uncertainties of the sea-surface temperature and salinity retrievals obtained with space missions like the ESA SMOS Mission [Sabia et al., 2007].

For static coastal platforms an estimation of the sea-state can be obtained by analyzing the interferometric complex field coherence time [Ruffini and Soulat, 2008]

2.2.3.3 Remote Observation of Soil Moisture

The power level of the reflected signal, appropriately normalized, contains information about the soil moisture of the reflecting surface. The GNSS-R data collected from aircraft and/or spacecraft detects different soil types; urban areas, dry-soil, wetlands [Masters et al., 2000].

The retrieval of soil moisture with GNSS-R systems is based on the variability of the ground dielectric properties associated with soil moisture. Higher concentrations of water in the soil yield a higher dielectric constant and reflectivity, which incurs in signals that reflect from the Earth surface with higher peak power. The importance of soil moisture relies in the fact that it is a prime parameter for the surface hydrology cycle, which is one of the keys for the understanding of the interaction between continental surfaces and the atmosphere in environmental studies. Water storage in the soil, either in the surface layer or in deeper levels, affects not only the evapotranspiration but also the heat storage ability of the soil, its thermal conductivity, and the partitioning of energy between latent and sensible heat fluxes.

2.2.3.4 Sea Ice and Dry Snow

A theoretical model to interpret the GNSS signals after reflection by the cryosphere in terms of the firnpack characteristics, accumulation rates and snow roughness and structure is provided in [Wiehl et al., 2003]. Promising results obtained in field experiments from aircraft [Komjathy et al., 2000; Belmonte Rivas, 2007] and from space [Gleason et al., 2005] have been published.

2.2.3.5 TEC Monitoring over the Ocean

Another interesting application of GNSS-R is the global mapping of the ionospheric total electron content (TEC) over the ocean. While ground-based GNSS receivers provide good maps of TEC over the populated land masses, there are virtually no observations done over the oceans (apart from the ionospheric profiling done by occultation missions) – leading to severe gaps in the TEC maps which are needed to better understand the spatial and temporal variability of the ionosphere. The GNSS-R altimeter concept described above utilizes at least two frequencies in order to remove the ionospheric delay from the altimetry solution. This delay can be used to reconstruct slant TEC values, one for the link between the GNSS satellite and the LEO platform and one for GNSS-to-ground-to-LEO link in which the two contributions from the ionosphere below the height of the LEO orbit are present. This technique can be suitably combined with a tomographic retrieval algorithm [Pallares et al., 2005].

2.2.4 Benefits of Galileo Signals for GNSS-R

Upcoming satellite navigation systems, such as the European Galileo, will represent an excellent opportunity for GNSS-R-based remote sensing for various reasons. Due to the high number of signals, an increase of spatial coverage will be achieved by using all available GNSS signals.

Moreover, the availability of Galileo E1 and E5 signals will allow the multi-spectral analysis of the reflected signals and the development of inversion models, which will be able to account more precisely for adverse effects, such as surface roughness and vegetation canopy. The availability of such signals as well as those with an even higher bandwidth (up to 50 MHz with the E5 signal) provided by the European Galileo system will further increase the potential of the GNSS-R techniques. http://naca.central.cranfield.ac.uk/dcsss/2004/E03_mutistaticSARa.pdfhttp://arxiv.org/PS_cache/physics/pdf/0406/0406084v2.pdfhttp://igscb.jpl.nasa.gov/overview/pubs/06_darmstadt.htmlhttp://www.iers.org/iers/publications/tn/tn33http://www.insidegnss.com/node/1157http://coll.cc/http://arxiv.org/abs/0710.3880http://arxiv.org/abs/0910.3413

2.3 Physics of the Ionosphere and Magnetosphere

The ionosphere is a region of electrons and electrically charged atoms and molecules that surrounds the Earth, stretching from a height of about 50 km to more than 1000 km. It owes its existence primarily to ultraviolet radiation from the sun. The magnetosphere of the Earth is a region in space whose shape is determined by the extent of Earth's internal magnetic field, the solar wind plasma, and the interplanetary magnetic field (IMF). In the magnetosphere, a mix of free ions and electrons from both the solar wind and the Earth's ionosphere is confined by magnetic and electric forces that are much stronger than gravity and collisions. The inner part of the magnetosphere (bordering the ionosphere) is called the plasmasphere, which extends to a height of 20 000 to 40 000 km.

2.3.1 Ionospheric Effects on Galileo signals

Galileo signals are transmitted at L-band, as is the case of GPS signals. The main ionospheric effects on L-band signals are:

- Phase advance and group delay
- Additional contribution to the geometric Doppler shift

- Faraday rotation
- Ray bending
- Amplitude and phase scintillation

The main problem for GNSS caused by the ionosphere is the difficulty of predicting and modelling its contribution due to the high variability [Arbesser-Rastburg and Jakowski, 2007]. An additional problem is the lack of complete observability of a given region and that has its largest impact in systems like a space-based augmentation system (SBAS) where it can cause loss of integrity at the user level.

The relation between the Galileo system and the ionospheric effects goes in both directions:

- Galileo data are affected by the ionosphere and this effect needs to be estimated or minimised.
- Galileo data can be used to study ionospheric behaviour and for analysis of ionospheric effects on radio signals.

At the Galileo system level, it is important to improve ionospheric information and correction because of the high precision (e.g. orbits and clocks) and availability that it is expected from the system.

The main contributions of the Galileo system to ionospheric research are:

- The availability of additional data from the Galileo constellation. These data could be used alone or in combination with other GNSS to have denser network information.
- The third frequency in Galileo. Being a dispersive medium, the ionosphere's effects are frequency dependent; therefore, data available at an additional frequency can improve some ionospheric analysis.

2.3.2 Total Electron Content

Most of the ionospheric effects listed above depend on the ionospheric total electron content (TEC).

The total electron content is the number of electrons in a column of 1 m^2 cross section. Values for the TEC are usually considered to be between a few TEC units (10^{16} e/m^2 = 1 TEC unit) and a few hundred TEC units along the propagation path, depending on local time, position, season, solar and geomagnetic activities, etc. There is a long-term variation of the TEC with the solar cycle, in such a way that the largest values of TEC occur during the solar maximums. The next one is expected to occur around 2013. There is also a diurnal variation of the TEC, and there can be more than one order of magnitude of difference between daytime and nocturnal TEC values. There are also regional changes in the ionosphere due to geographic-geomagnetic relationships. In this case, the most relevant phenomenon is the equatorial anomaly crest, a region of enhanced electron density at both sides of the geomagnetic equator. This is the region with the largest horizontal TEC gradients, and where rather high values of TEC can be observed even during low solar activity.

Apart from those relatively well-known dependencies of the TEC, there are other irregular effects that affect the behaviour of the TEC like ionospheric storms, ionospheric irregularities, TEC depletions, scintillations, etc., and these are largely unpredictable.

A radio signal crossing the ionosphere suffers a delay that can be expressed as:

$$d_{ion}^{gr} = \frac{q}{f^2} + \frac{s}{f^3} + \frac{r}{f^4} + \ldots \qquad (1)$$

The main effect, q/f^2, depends directly on the TEC and inversely on the frequency (f) squared, and can be on the order of 1-30 meters at zenith for the frequency E1. This term can be removed using a linear combination of dual frequency data, but those combinations do not remove the effects of the higher-order terms.

The second and third order effects (s/f^3, r/f^4) depend on the TEC and the second order effect also depends on the relative geometry of the magnetic field. For example, typical values of the higher-order ionospheric effects for the GPS f_1 = 1574.42 MHz are $s/f^3 \sim 1.6$ cm and $r/f^4 \sim 0.86$ mm at zenith for a TEC = 10^{18} el/m^2 [Bassiri and Hajj, 1993]. That value of TEC can be reached at mid-latitudes in a period of solar maximum.

In all cases we must consider that the portion of the ionosphere crossed by low elevation angle observations is larger than for zenithal observations, so a factor depending on the elevation angle must be applied. The ionospheric effect is about 3 times greater for low elevation angles (lower than 10°) than at zenith.

In most applications, the higher-order ionospheric effects can be neglected because they are relatively small. This is the standard approach, and then, using a linear combination of dual frequency data, it is possible to obtain an ionospheric-free observable. But if very precise positioning is required, the higher-order terms of the ionospheric effect should be considered.

Thus, various approaches have been developed to correct the residual range errors in GPS applications, for example [Bassiri and Hajj, 1993], [Hoque and Jakowski, 2007] and [Hoque and Jakowski, 2008].

If more than two frequencies are available as planned for Galileo, higher order effects can be mitigated by using suitable frequency combinations. Since combinations of phase measurements at different frequencies often amplify the noise level, such a procedure requires a careful analysis of the noise budget.

The impact of the high order ionospheric terms in the Galileo data and their implementation should be carefully studied.

The effect of the ionosphere on a radio signal introduces additional complications in the integer ambiguity resolution procedure even using dual frequency data. Some algorithms for ambiguity resolution use combinations of phase and code measurements in which the ionospheric term appears, so this term must be modelled. The most common approach is to assume a smooth behaviour of that parameter and model it with a polynomial. Such an assumption of smoothness is frequently not suitable, particularly in equatorial or polar regions or under special ionospheric conditions.

The ionospheric effect also limits techniques like the on-the-fly resolution algorithms to implementation only over very short baselines. In order to extend the use of that method to longer baselines, a regional differential ionospheric model could be applied, although the accuracy of such models may be currently insufficient [Kim and Langley, 2008a and 2008b].

The use of three modulated carriers is an alternative to reduce the convergence time in the resolution of integer ambiguities, which can improve the accuracy of relative navigation in real-time. The availability of a third frequency will not only allow improvements to the positioning accuracy but also to develop improved real time TEC monitoring techniques [Spits and Warnant, 2007]. The three-carrier concept could be further studied and improved.

2.3.3 Use of C-band for Navigation

For improved navigation, use of a frequency located in the C-band (5010.0 – 5030.0 MHz) has been considered as a supplement to the current Galileo frequencies in the L-band [Schmitz-Peiffer et al., 2009]. A frequency in the C-band will, in combination with the current frequencies, improve positioning and navigation performance because of improved possibilities for handling of the ionospheric effects.

Presently, linear combinations of observations in the L-band are used for reduction of ionospheric effects. This approach can be expanded with new linear combinations of observations from both the L-band and the C-band, leading to a reduction in the residual ionospheric delay as well as a reduction in the noise level of the resulting observations, compared to the present conventional ionosphere-free linear combinations of observations in the L-band.

Also, signals in the C-band are less susceptible to ionospheric scintillation and therefore will especially improve positioning and navigation performance in the equatorial and arctic regions.

A few research projects have been carried out in order to evaluate the benefits of the use of the C-band for navigation. But no comprehensive analysis with the use of real satellite data has been performed, and this is important for a thorough verification of existing models and algorithms.

Also, the effect caused on satellite signals in the C-band by the neutral atmosphere (stratosphere and troposphere) remains to be investigated. As the effects of attenuation caused by the neutral atmosphere increases with increasing satellite signal frequency, it is expected that the effect of the neutral atmosphere will be larger for satellite signals in the C-band. But more research is necessary in order to develop models and algorithms, and also to reveal the size of the residual effects of the neutral atmosphere on the C-band signals in the positioning process.

2.3.4 Phase and Amplitude Scintillation

Ionospheric scintillations are revealed as rapid variations in signal amplitude and phase. They can produce loss of signal and phase-lock problems. Scintillations are caused by irregularities in the ionospheric electron density. There is a dependency of the occurrence of scintillation on location, the equatorial region being the one with the strongest scintillation effects. Amplitude and phase scintillations are produced by refractive and diffractive scatter by ionospheric plasma-density irregularities, especially at equatorial and auroral-to-polar latitudes. Transionospheric communication and navigation signals may be strongly degraded due to amplitude and phase scintillations.

Multi-frequency observations have indicated that ionosphere-induced radio scintillations show a varying frequency dependence. The frequency dependence of scintillation depth varies between f^{1} in the frequency range 1.5 up to 4 GHz and f^{2} in the frequency range 4-10 GHz. Using such relationships, measurements and systematic studies of radio scintillations at the L-band frequencies transmitted by the GPS satellites may be used to get valuable information also about the impact of ionospheric induced radio scintillations on communication bands, e.g. that of satellite UMTS (Universal Mobile

Telecommunication System). Ionospheric scintillations usually occur in equatorial and auroral/polar regions but occasionally they can be observed also at mid-latitudes.

Systematic studies of radio scintillations and the development of prediction tools can help to avoid problems in communication with satellites, e.g. by substituting the receiving station by another station in an unperturbed region. In any case, users of the communication link should be informed about transionospheric propagation problems. Safety critical applications based on the use of these radio links should be cancelled during the perturbation period.

Several networks of GPS-based scintillation receivers have been established, some in conjunction with other ionosphere monitoring tools such as ionosondes, to better understand the occurrence of scintillations and the effects they have on transionospheric radio signal propagation (see, e.g., [Jayachandran et al., 2008]).

Reliable scintillation models are not yet available and they are particularly needed to forecast the behaviour of ionospheric parameters some hours in advance to ensure high reliability of the communication and navigation systems.

It must be noted that within Galileo ionospheric scintillations affect both the user level and the system level.

Some of the Galileo Sensor Stations (GSS) are located in the equatorial region, and therefore could be subject to high levels of scintillations. The quality of the GSS carrier-phase measurements is a fundamental aspect for the Galileo integrity monitoring scheme, and therefore, it has to be assessed continuously in order to prevent the Galileo integrity algorithms to work out of specifications. This is why the Galileo Integrity Processing Facility (IPF) implements a real-time scintillation detector [Hernández et al., 2007]. The idea of a real-time scintillation detector could be used in other applications and the approach could be improved.

At the user level, it has to be noted that the final effect of scintillation also depends on the Galileo receiver characteristics. Further research could be performed for the improvement of Galileo receivers to be robust against scintillations.

2.3.5 Ionospheric Tomography

Ionospheric tomography based on GPS data has been successfully used in regional and wide-area differential GPS to improve the location precision and to allow greater distances between the rover and the reference stations. In those cases, ionospheric tomography contributes to the improvement in the resolution of carrier-phase ambiguity.

Ionospheric tomography can provide fast and accurate estimates of TEC under conditions of high electron density variability, such as those observed close to the geomagnetic equator, during solar maximum [Colombo et al., 2002].

Tomography modelling is based on a set of three-dimensional cells that covers spatially the sampled ionosphere. In these cells, the electron density is considered constant at a given time. Despite other possibilities to choose the cell distribution, a regular distribution is adequate for describing a region with samples from a more or less homogeneously distributed network of reference stations. The estimate of ionospheric electron density in each cell is based on the ionospheric data obtained from the satellite-receiver ray paths crossing that particular cell.

An ideal situation for tomography methods would be that in which there is a continuous data and continuous coverage of all view angles. However, the experimental data are usually given at discrete points and some data may be unavailable.

Promising tomographic and assimilation techniques for three-dimensional imaging of the ionosphere were developed in recent years such as the 'Multi-Instrument Data Analysis System' (MIDAS) [Mitchell and Spencer, 2002], the 'Global Assimilation of Ionospheric Measurements' (GAIM) [Schunk et al., 2004], and the radio occultation method 'Electron Density Assimilative Model' (EDAM) [Angling and Cannon, 2004]. When completed, the physics-based data assimilation model GAIM will provide 3-dimensional electron density distributions from 90 to 25,000 km altitude with a horizontal resolution of up to 25 km. A review of tomography and data assimilation is given by Bust and Mitchell [2008].

With the availability of Galileo data, the situation can be very much improved due to the increase of data availability and the improvement in the density of data when combined with GPS data.

It is expected that ionospheric tomography modelling can be applied to Galileo data as it has been done in the past for GPS data. The performance of Galileo ionospheric tomography should be analysed, as well as the improvement obtained when combining GPS and Galileo data.

2.3.6 Ionospheric Profiling Using Occultation Measurements

The availability of L-band radio signals permanently transmitted by a fleet of satellites belonging to GNSS such as GPS has opened a new dimension for ionosphere sounding.

After the proof-of-concept GPS/MET experiment on Microlab-1, flown within the years 1995 -1997, had demonstrated the huge potential of the limb sounding technique on LEO satellites for atmosphere/ionosphere sounding [Hajj and Romans, 1998], the development of improved inversion techniques, assimilation methods and powerful processing systems made significant progress in the last decade [Hernandez-Pajares et al., 2000; Syndergaard, 2002].

The radio occultation technique enables the retrieval of the vertical refractivity profile of a planetary atmosphere travelled by an electromagnetic wave in the limb sounding geometry. Measured is the change of ray path bending, phase or signal strength of the radio wave while approaching the planetary surface until it is completely occulted by the Earth.

As pointed out earlier, the refractive index of the ionosphere is mainly determined by the electron density. Thus, the inversion of measured radio occultations or limb sounding data provides the vertical electron density profile from the LEO orbit height down to the bottom side of the ionosphere.

The GPS/MET experiment on Microlab-1 was successfully followed by other missions such as Oersted [Hernandez-Pajares et al., 2000; Syndergaard, 2002], CHAMP [Jakowski et al., 2002], IOX [Straus, 2007], GRACE [Wickert et al., 2009] and COSMIC [Rocken et al., 2000].

The six Formosat3/COSMIC satellites, launched in April 2006, provide unprecedented data coverage for detailed studies of the vertical ionospheric structure [Schreiner et al., 2007] capable of providing more than 1000 vertical electron density profiles per day on global scale. Several other satellites featuring GNSS occultation experiments are under construction or in the planning stages, for example e-POP/CASSIOPE [Langley et al., 2004] .

Since the space-based receiver on board a LEO satellite is mainly used for accurate positioning and precise timing, the dual frequency navigation measurements can be used to get information on the topside ionosphere above the LEO satellite orbit too. The data enable reconstructing the 3D electron density distribution of the topside ionosphere/plasmasphere in the vicinity of the LEO orbit plane [Heise et al., 2002]. The more data links from GNSS satellites that are available, the more accurate and higher resolved is the tomographic or assimilative reconstruction of the electron density distribution.

Whereas the ground-based measurements are especially suited for imaging the horizontal distribution of plasma, the spaceborne measurements are suited to map the vertical distribution of the ionospheric plasma.

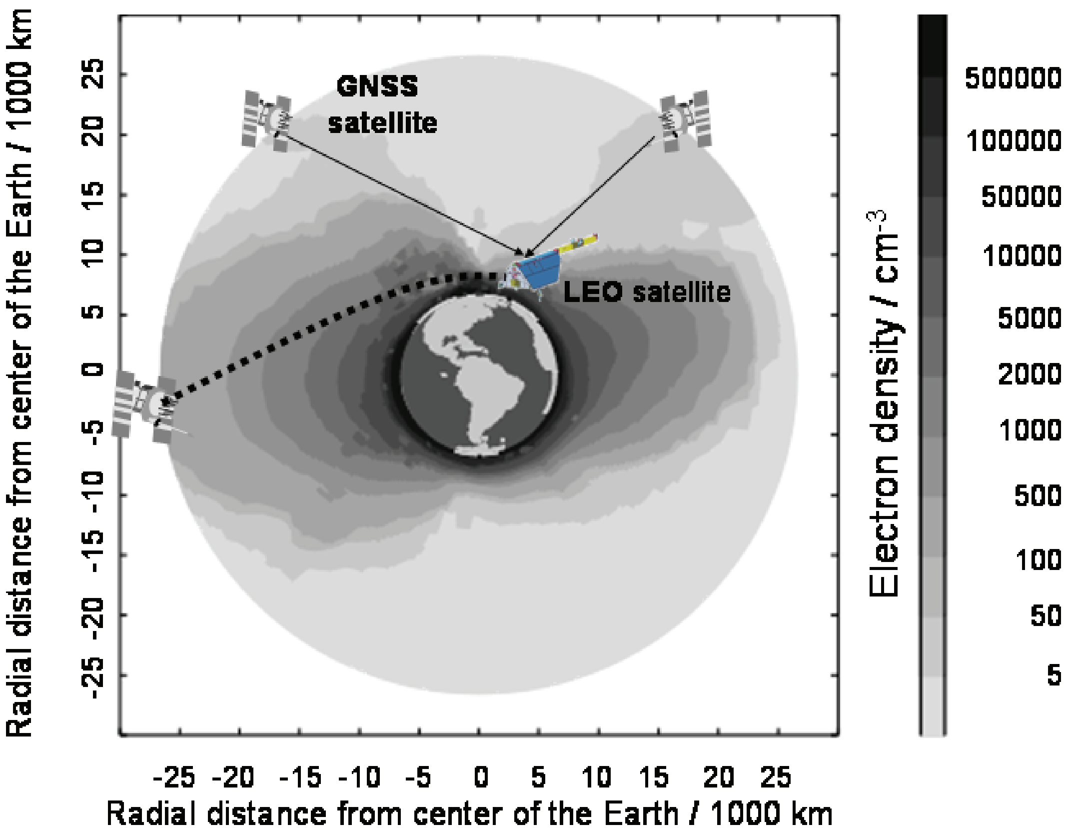

Figure 5: Ionospheric radio occultation measurements in the limb sounding mode (dotted line) and topside measurements (solid line)

Figure 5 shows the geometry of combined limb-sounding and topside-sounding geometries for reconstruction of the topside ionosphere as it is shown in the background figure based on CHAMP data [Jakowski et al., 2006].

To fully use the high potential of space-based Galileo measurements for monitoring and sounding the ionosphere, space-certified Galileo receivers should be available in the near future.

Test calculations have shown that utilization of one complete GNSS in MEO like GPS or Galileo in combination with one additional LEO-satellite equipped with an occultation-capable receiver allows for about 500 occultation profiles per day.

The additional availability of Galileo signals increases the number of measurable radio links for radio occultation measurements at one LEO satellite. The use of all GNSS signals in radio occultation and navigation mode with a multi-satellite mission like COSMIC, would enable an instantaneous global reconstruction of the geo-plasma, being able to now-cast space weather related ionospheric behaviour.

2.3.7 Space Weather Forecasting

There is a close relationship between Galileo and space weather. On the one hand, the functionality of Galileo is directly related to space weather effects. On the other hand, Galileo may essentially contribute to monitoring and forecasting space weather.

Before discussing the benefit of Galileo for space weather monitoring, it should be mentioned that the functionality of Galileo may be affected by space weather impact mainly due to:

- High-energy radiation of solar or galactic origin (particle + electromagnetic wave) degrading the satellite payload
- Ionospheric impact on navigation signals
- Interference of signals by solar radio emission

Therefore, monitoring systems for detecting, tracking and forecasting the above mentioned perturbation sources need to be established. High energy particles can be detected directly onboard Galileo satellites by the Radiation Hazard Monitor [Taylor et al., 2007]. The monitor data inform the Galileo system operator about the degradation risk due to the high energy particle radiation environment at the Galileo orbit height. On the other hand, if these data are public, the radiation data are valuable for space weather science; e.g., modelling, or related operational space weather services. To complete the radiation environment data, it would be useful to install X-ray and EUV solar radiation spectrometers on at least two satellites for continuous monitoring of solar activity. Such data would also essentially contribute to improving space weather information.

Since the ionosphere is an integral part of the geo-space environment, ionospheric processes are strongly related to space weather issues. Besides the dominating solar control, there is a strong interaction with dynamic processes in the thermosphere and magnetosphere thus reflecting the high complexity of space weather physics and resulting difficulties in describing and understanding space weather issues. As pointed out in the previous sections related to the ionosphere, GNSS-based techniques–especially Galileo-based–are well suited to monitor medium to large scale ionospheric processes in time and space.

Thus, storm-induced changes of the ionospheric plasma developing at characteristic times of a few days and scale lengths of up to several thousand kilometres can be monitored effectively both by ground- and space-based measurements [Jakowski et al., 2007].

Space weather information and data systems must operate robustly, accurately, and automatically to fulfil the user requirements. As the use of GPS data clearly shows, ground- and space-based GNSS data can be processed automatically to a high degree thus being capable to provide essential space weather warnings and forecasts in a timely fashion. The availability of Galileo data will enormously increase the number of radio links usable for extracting direct or indirect ionospheric information. Furthermore, as stated earlier, Galileo multiple frequencies allow better estimating the total electron content which is a key parameter characterizing the ionospheric weather. Here, the meaning of TEC is comparable in importance with the meaning of air pressure for characterizing the troposphere weather.

As already stated in the previous chapter, the availability of space-certified Galileo receivers would be extremely useful to contribute to space and ionospheric weather.

2.4 Physics of the Troposphere

The troposphere is the lowest part of the Earth's atmosphere – it covers the region from the Earth's surface up to the tropopause which ranges from about 7 km at the poles to almost 20 km at the equator. At microwave frequencies, the troposphere is a non-dispersive medium, which means that the group delay does not vary with frequency (as opposed to the ionosphere, where the dispersion can be used to estimate the total electron content).

2.4.1 Tropospheric Effects on Galileo Signals

The typical effects of the troposphere on radio wave signals are:

- Attenuation (clear air attenuation, cloud attenuation and rain attenuation)
- Depolarisation (due to ice crystals in clouds and oblate raindrops)
- Scintillations (due to turbulent layers)
- Excess path delay (hydrostatic plus wet delay)

At frequencies between 1 and 1.5 GHz, most tropospheric effects affecting signal strength are barely perceivable. Rain attenuation, even at tropical, high-rainfall rate locations, typically remain below 1 dB. Depolarisation does not create a link budget problem when the signal (as is the case for Galileo) is circularly polarised. Scintillations due to eddies in the troposphere do not affect these low frequencies (as opposed to ionospheric scintillations).

The only significant propagation effect of the troposphere is therefore the excess path delay. Even though it is typically less than the ionospheric delay, due to the fact that the troposphere is not dispersive and therefore there is no receiver-autonomous procedure to correct for it, the correction has to be provided to navigation receivers either by means of an inbuilt blind model, by a model which allows for local meteorological data to be used or by means of differential corrections.

The "blind" tropospheric correction model built into the receiver has the advantage that no external input of any kind is required. In GPS, the RTCA-MOPS blind tropospheric model [RTCA,1998; Collins and Langley, 1999] provides global tropospheric corrections dividing the world into latitude belts but without distinction of ocean or land or other climatic features. The Galileo model [Krüger et al., 2004] uses a gridded database (1.5° x 1.5° grid) where the key meteorological statistics (derived from 15 years of re-analysed ECMWF data) for each grid point are stored in the Galileo receiver. Seasonal and diurnal variations are modelled by cosine functions; the altitude of the receiver above sea level is considered by using the model lapse rates of air and water-vapour temperature and the receiver's position with respect to adjacent grid-points is taken into account by a bi-linear spatial interpolation of latitude and longitude. The conversion for zenith delay to slant delay is performed using a mapping function [Niell, 1996].

2.4.2 Retrieval of Total Water Vapour Content

Water vapour is an important constituent of the atmosphere, contributing strongly to the weather and playing a critical role in the global climate system. It absorbs and re-radiates energy from the sun and it influences the formation of clouds. Despite its importance to atmospheric processes over a wide range of spatial and temporal scales, it is one of the least understood and poorly described components of the Earth's atmosphere. Furthermore, it is the most abundant of the greenhouse gases and a better understanding of its role in climate change is needed.

Total tropospheric water vapour content can be measured directly by means of a radiosonde (a small meteorological sensor attached to a balloon) or by ground-based microwave radiometry. The radiosonde approach is typically restricted to about one thousand locations worldwide with 1 – 2 measurements per day. Water vapour radiometers are rather expensive instruments which require frequent calibration.

GNSS receivers can measure the slant delay in the direction of a satellite, remove the contribution of the ionosphere and with some considerable post-processing estimate the system-related errors (such as clock, orbit, phase centre) and obtain the total tropospheric delay. In order to arrive at vertical total delay (also called zenith total delay ZTD), the slant values are mapped to the vertical. To extract the water vapour content, the zenith hydrostatic delay (which can be obtained by measuring the pressure at the surface) is subtracted from the ZTD, giving the zenith wet delay (ZWD). The water vapour can be estimated from ZWD and the atmospheric temperature.

It is obvious, that for near real-time applications (such a weather forecasting) the precise orbit parameters have to be established in a very short time (IGS ultra rapid orbits), and this can only be done with a collaborative network of receivers.

As a result of the capability of obtaining basic information on troposphere, GNSS is nowadays very widely used in operational meteorology for weather forecasting, everyday and everywhere. Such applications are extremely important from a societal point of view; they are illustrated for example in [Barlier, 2008]. It is a very import basic field of research to be developed.

2.4.2.1 Radio Occultations for Sensing of the Neutral Atmosphere

GNSS to LEO satellite signals can be used to take atmospheric measurements through the technique of radio occultation as described in section 3.4.6, and this can also be used for probing of the neutral atmosphere. Such sensing of the neutral atmosphere is based on precise measurements of the excess phase path or Doppler shift caused by atmospheric refractivity gradients. The measurements can be related to temperature, density and water vapour integrated along the signal path. The Doppler shift of the signal can be related to the bending angle and this in turn inverted to estimate the profile of refractivity. This has been used extensively for global study of atmospheric structure and dynamics in the troposphere and stratosphere and is also utilised for operational meteorology. The observations, in the form of refractivity or bending angle, are now used for long term weather prediction by leading weather prediction centres around the world as for instance ECMWF, NCEP, Meteo-France, Met Office, and Environment Canada.

In order to derive observations of meteorological conditions in the neutral atmosphere, the ionospheric effects on the signal propagation must be estimated and eliminated. Today, this is normally done by linear combinations of the observations on the L1 and L2 GPS frequencies. The same technique can be implemented for Galileo, using combinations of observations of the Galileo frequencies.

For Galileo it has been discussed whether a signal in the C-band (5010.0 – 5030.0 MHz) should be implemented [Schmitz-Peiffer et al., 2009]. This would be highly beneficial for the future use of radio occultations for profiling of the upper part of the neutral atmosphere.

Adding a third frequency provides the opportunity for generating new linear combinations of the observations from the frequencies to compensate for higher order ionospheric effects. With a new third frequency in the C-band the noise amplification and ionospheric scintillation levels in such combinations will be considerably lower (several orders of magnitude) compared to using a new third frequency in the L-band [Syndergaard, 2009]. Additionally, a systematic higher order effect caused by dispersion can be eliminated using three frequencies, which means that a small erroneous signature of the 11 year solar cycle in the stratosphere and mesosphere in radio occultation data [Kursinski et al., 1997; Rocken et al., 2008] can be eliminated. This could be very important for future climate applications.

In practice, this means that information on for instance refractivity and temperature can be extracted with a much better accuracy at higher altitudes with a signal in the C-band than what is possible with frequencies in the L-band only. It is therefore recommended that more research is carried out on the use of the C-band for radio occultations as this is expected to be beneficial for numerical weather predictions, atmospheric science and climate research.

2.4.2.2 Ground-Based Troposphere Monitoring

As mentioned in section 3.4.1, microwave signals of the GNSS satellites (GPS, GLONASS and in future GALILEO) are time delayed when passing through the atmosphere. Based on this, signal delay parameters, such as the humidity distribution within the troposphere, can be determined. It has already been shown by several international and national projects that the delivery of zenith wet delays (ZWD) derived from a GNSS-network solution with hourly resolution and an accuracy of 1mm in precipitable water vapour (PWV) is achievable. These ZWD-estimates have been successfully assimilated into meteorological models [Karabatic et al., 2010].

Preconditions to derive accurate ZWD estimates are accurate satellite orbit and clock information and an almost complete and successful fixing of ambiguities of the chosen phase linear combination. The optimal signal linear combination in terms of wavelength and noise level depends on the baseline length. Typical baseline lengths within RTK-GNSS-networks which are frequently used for ground-based tropospheric monitoring are between 50 km and 120 km. The set of new signals provided by Galileo as well as GPS/GLONASS ongoing modernization programs will allow for improved ambiguity resolution techniques over such long baselines. Furthermore, GNSS signals at three frequencies will allow modelling of the higher order terms of the ionospheric refraction (on the order of 1 cm), which in turn reduces the error of the tropospheric wet delay estimates.

In terms of tropospheric monitoring, also the increased number of available observations as well as improved satellite geometry will be beneficial. Utilization of Galileo signals will allow for an increased temporal resolution of the respective ZWD-products without degrading their current level of accuracy. Thus the accuracy of derived delays due to the wet component of the troposphere (ZWD) could be improved by up to 40% compared to the current level of +/- 4mm (< +/- 1mm in PWV) by inclusion of Galileo data. The temporal resolution might be increased to 30 min and less. This close to real-time availability of ZWD-estimates is an urgent need for GNSS contributions to weather forecasting. The combination of GPS, GLONASS and Galileo observations will allow the operation of 3D- or 4D-tomography models without the need of tight constraints between the vertical estimation levels. Although in case of multi-system use the number of signal rays passing through high altitude voxels will significantly increase, reliable tomography is still in need of denser ground networks to retrieve delay information within the low altitude voxels. Recent investigations are in favour of dense (and cheap) single-frequency networks with a mean inter-site distance of about 10 km embedded in the sparse dual-frequency receiver networks already in place. Interpolation techniques will allow recovery of the ionospheric delay of all stations from the dual frequency sites and subsequently estimation of the tropospheric delays.

2.5 References

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3. Space-time Metrology

For space and time, metrology (the "science of making measurements") covers three main activities:

- The definition of internationally accepted units of measurement; e.g., the metre and the second;
- The realisation of units of measurement by scientific methods; e.g., the realisation of the second through the operation of atomic clocks;
- The establishment of traceability chains by determining and documenting the value and accuracy of a measurement and disseminating that knowledge, e.g. the relationship between time scales realised in different scientific establishments.

Natural sciences are completely dependent on measurements. Geologists measure shock waves when the gigantic forces behind earthquakes make themselves felt, and atomic physicists use local frequency references (lasers, microwave sources) to do spectroscopy on atoms, molecules and ions, just to give a couple of examples.

Accurate time and frequency measurements form the backbone of a variety of studies in the fields of geodesy, astronomy, and space exploration, either by measuring the time of arrival of propagation of a radio or light signal, or by measuring the change in frequency incurred by a propagating signal. This is also the case regarding the operation of a GNSS in general and therefore also of Galileo. On one hand, the successful operation of such systems relies on time and frequency metrology and, on the other hand, the availability of such systems supports several scientific activities. In section 4.1, we show how GNSS/Galileo improve techniques used in space-time metrology and in sections 4.2 and 4.3, we show the relations between GNSS/Galileo and the time and space references used for all fields of science. In the concluding section, we highlight the main areas where useful interactions should exist between science and Galileo.

3.1 Galileo's Impact on Space-time Metrology

Time and frequency metrology is involved twofold in the context of scientific exploitation of the Galileo Programme. The comparison of distant clocks has always been an important part of time metrology and has for a long time been based on GPS time comparisons. They allow the assessment of the properties of (primary) frequency standards; e.g., to judge whether they agree within their assigned uncertainties. They are needed also for providing the data which are subsequently used in the calculation of time scales on the basis of the readings of clocks located in different institutes spread world-wide. As soon as the Galileo constellation is completed, Galileo signals can and will be used in this activity. Looking from another perspective, function and performance of a GNSS are strongly dependent on the quality of clocks on the ground, onboard the satellites, and on the means of synchronization of the various elements. Therefore a strong interest exists in research aimed at improving clocks and time comparison techniques in support of Galileo evolution.

We discuss subsequently research areas related to Galileo development and those depending on the availability of Galileo.

Time metrology will rely primarily on the Open Service, and a combination of the three signals/frequencies will cancel simultaneously the first order ionospheric delays and the geometrical path delay. Such a combination can be written either for the code modulated on the signals, or for the carrier frequencies. For both combinations, the first order ionospheric delays, which are proportional to $1/f_i^2$ where f_i is the signal carrier frequency, are cancelled, and the geometrical path can also be cancelled by the simple difference of two signals, provided the antenna phase centres of all signals are at the same point. The most severe drawback is that the noise of the combination results would be higher than when using just one single code/phase signal. It remains to be studied whether these techniques are competitive compared to one single signal ameliorated by Galileo products to be provided in the future by the International GNSS Service.

Three different carrier signals available at a time should also help to solve for the phase ambiguities, one of the problems when using carrier phase for time and frequency transfer.

One should keep in mind that GPS III will also openly provide three coded signals to the civil users: one on L1 (the current C/A signal), one on L2 (which will carry the L2C code), and one on L5, primarily (but not exclusively) for SoL purposes. The Galileo signal codes have been designed to exhibit better performance than the GPS C/A code. The possibility to exploit different GNSS systems simultaneously will be of highest interest. The increased number of satellites tracked simultaneously would help to reduce the short term noise. Potential biases induced by one of the GNSS might be discovered and compensated for using the data based on another GNSS. Last but not least, a multi-GNSS approach would be more resistant to potential interference and jamming.

The multi-system approach will require advanced GNSS receivers, able to perform multi-GNSS satellite tracking with respect to the same internal reference point, whose relation to an external reference clock would need to be known. A number of geodetic quality receivers from several manufacturers with the capability to use signals from GPS, GLONASS, and the GIOVE satellites are already on the market.

3.1.1 Progress in Time Transfer, Positioning and Navigation

GNSS systems offer important contributions in a variety of scientific research domains, as illustrated in the other chapters of this document. As a matter of fact, a good part of the progress achieved in recent years is due to new or improved data analysis techniques, jointly with a growing variety of available measurements (use of all GNSS signals, including GLONASS). In this respect, Galileo will definitively contribute to further improvements.

Significant progress has been already achieved by the scientific community through the use of GPS (and also GLONASS) data. The international cooperative work developed since a decade ago around the IGS has played a leading role in this respect. A working group on GNSS systems established by the IGS specifically focuses on new systems such as Galileo (and the Chinese Compass system).

The processing of GNSS data enables estimation of several types of parameters. Those of interest in the present context are the position of the GNSS reference point (typically denoted as the antenna phase centre) and the time difference between the local reference clock and the GNSS time reference. Other parameters are of interest for other chapters of this document, such as tropospheric delay for meteorology, ionospheric delay, etc.

We focus here on the clock parameter, which is the observable for time and frequency transfer, and on the position information, the observable for precise positioning (geodesy, surveying, geo-information) and navigation (aeronautics, marine, rail, road, low Earth orbiting satellites, people). Numerous research topics are stimulated by the availability of new kinds of GNSS data:

- Quality issues (precision, reliability, integrity);
- For time transfer: the impact of a lower multipath level due to better code characteristics.
- For positioning and navigation: better coverage and faster convergence in difficult situations (e.g. urban canyons) due to the larger number of satellites available.
- For all applications: better ambiguity resolution techniques due to various linear combinations available with more frequency bands; a better separation of correlated effects; e.g., clock parameter versus radial orbit parameter; vertical position and tropospheric delay;

In terms of processing, the main domains of research are:

- Combined use of code and phase measurements, ionosphere-free combinations, ambiguity resolutions;
- Physical modelling: relativity, geophysics, satellite force modelling;
- Processing strategy: data from global versus regional networks, differential solutions, single point analysis including externally provided satellite parameters. Precise point positioning (PPP) [Kouba and Héroux, 2001; Lahaye et al., 2006], to mention one important development, uses GPS dual frequency carrier phase and code measurements to compute the link between a local clock and a reference time scale with the precision of the carrier phase and the accuracy of the code. The time link between any two stations can then be computed by a simple difference.

3.1.2 Progress in Clock Development

The Galileo navigation performance will depend highly on the frequency stability (predictability) of Galileo System Time (GST)–see below–as well as of that of the clocks operated on the spacecraft from which the signal in space is derived.

Europe has a long-established tradition in the making of atomic clocks: The first caesium clock was developed at the National Physical Laboratory (NPL) in the UK, Physikalisch-Technische Bundesanstalt (PTB) in Germany has designed and successfully operated thermal beam standards for over 30 years, and the Paris Observatory (now Laboratoire National de Métrologie et d'Essais–Système de Références Temps-Espace or LNE SYRTE) is the forerunner of the use of cold atoms in primary clocks. Only in Switzerland, however, has commercialization of high-level atomic-clock technologies been supported successfully for many years. The Observatoire de Neuchâtel produced active hydrogen masers for almost three decades, and later stepped into the research on miniaturized rubidium gas cell frequency standards. The passive hydrogen maser development has followed more recently. All initiatives led to space-qualified products: the active hydrogen maser will be part of ESA's Atomic Clock Ensemble in Space (ACES) mission. The rubidium clock and the passive hydrogen maser are the current Galileo space clocks. The Observatoire de Neuchâtel's clock research was recently transferred to the Laboratoire Temps–Fréquences (LTF) of the Université de Neuchâtel.

If the space passive hydrogen maser continues to function as it is reported today for the unit on board GIOVE-B [Waller et al., 2009], Galileo will be ahead of all other concurring GNSSs in terms of its space clock performance. In the long term, the study of alternative systems, simpler and cheaper but giving the same performance, or more advanced ones – such as optical space clocks, has to be pursued in order not to rely exclusively on one technology. Research activities in this direction are pursued in several European research institutes [Boudot et al., 2009; Esnault et al., 2006; Godone et al., 2006]

During the Galileo In-Orbit-Validation phase, the clocks used on the ground for the realization of GST represent mature technology and 10 out of 12 of them are of U.S. origin. Several venues for improving the stability and accuracy of ground clocks have been shown, based on laser-cooled "fountain clocks" [Wynands and Weyers, 2005; Bize et al., 2005] and optical clocks [Lea, 2007]. ESA has initiated studies for "space optical clocks" and on the "feasibility and applications of optical clocks as frequency and time references in ESA deep space stations." For the time being, such advanced clocks are operated in the European metrology institutes, and the transfer of the technology into an operational environment, such as a GNSS or even a scientific space mission, imposes severe challenges. Whether such clocks will ever be converted to commercial products is an open question. The realization of GST (and other GNSS reference time scales) will more likely benefit from such advanced clocks by time and frequency transfer to the GNSS ground control centres (see 4.2.4). The use of better clocks in space and on the ground for Galileo (as an example) has been discussed on a theoretical basis in [Moudrak et al., 2008]. It was shown that clock prediction and user range error could be improved compared to the presently expected values. A more realistic assessment of their performance in terms of reliability and ease of operation, however, would be needed. Improving GST performance would require substantial research and engineering efforts regarding the latter aspect.

3.2 Galileo and the Establishment of Time References

In this section, we describe the internationally agreed references for time, how they are realized for the use of Galileo and how Galileo could help improve them. As much as possible, a similar organization has been chosen in section 4.3 dealing with space references.

3.2.1 Introduction

A mission conferred to the Bureau International des Poids et Mesures (BIPM) by the Conférence Générale des Poids et Mesures (CGPM) is that of providing the basis for a coherent system of measurements adopted worldwide which should be traceable to the International System of Units (SI). One of the responsibilities mandated to the BIPM is that of maintaining and disseminating International Atomic Time (TAI) and Coordinated Universal Time (UTC), and this is done by its Time, Frequency and Gravimetry Section (in short "the BIPM" in the following) [Guinot and Arius, 2005]. Next we briefly describe the realization of TAI and how Galileo System Time is related to it.

3.2.2 TAI: the International Conventional Reference for Time

TAI and UTC are post-processed time scales; they are the result of worldwide cooperation of more than 65 national metrology laboratories and astronomical observatories that operate commercial caesium standards and hydrogen masers. The data are regularly reported to the BIPM by timing centres which maintain a local realization of UTC. Results are calculated on the basis of data acquired in the previous month and are published in the monthly *BIPM Circular T*.

All contributing laboratories operate industrial atomic clocks and are equipped with devices for their comparison at a distance. The BIPM keeps long-term track of the clock behaviour, and assigns weights to clocks according to their individual stabilities. About ten national metrology institutes (NMIs) develop and maintain primary frequency standards that realise the SI second, with a substantial number of caesium fountains that contribute more or less regularly to improve the accuracy of TAI.

The algorithm used for the calculation of TAI has been designed to guarantee the reliability, the long term frequency stability, the frequency accuracy and the accessibility of the scale. Nevertheless, the quality of TAI rests critically on the methods of clock comparison which may bring significant instability mostly at short averaging time (5-10 days). The BIPM organizes the international network of time links to compare local realizations of UTC in contributing laboratories and uses them in the formation of TAI. The network of time links presently used by the BIPM is non-redundant and relies today on the observation of GPS satellites and on Two-Way Satellite Time and Frequency Transfer (TWSTFT) [Kirchner, 1999].

As of 2009, most of the links in TAI are obtained by using GPS equipment (about 60% by single-frequency code-only receivers, 25% by dual-frequency receivers providing either code-only ionosphere-free or so-called P3 links or, since September 2009, providing phase+code PPP links), while about 15% of the links are provided by TWSTFT observations and one link is obtained with GLONASS single-frequency code. It should be noted that the best techniques (GPS dual frequency and TWSTFT) contribute more than 80% of the clock weight and all primary frequency standards used for TAI.

It is expected that GNSS techniques remain an essential tool in the TAI computation in the foreseeable future and that research along the lines mentioned in 4.1.2 will also yield progress for the realization of TAI. As an example, the uncertainty in the frequency comparison between TAI and a Cs fountain is generally limited to about 3-5 parts in 10^{16}, even on 20-30 day intervals. This is of the same order as the intrinsic accuracy of the fountains, so that the frequency transfer now limits the accuracy of TAI.

3.2.3 Galileo System Time

The operation of a satellite navigation system requires accurate synchronization among the various elements in the ground and space segments. The core navigation function of Galileo will be based on

Galileo System Time (GST) as realized in the two Precise Timing Facilities (PTFs). They will be located in the Galileo Control Centers (GCCs) which are part of the Ground Mission Segment (GMS). The major functions of the PTFs are:

- Maintain an ensemble of ground clocks in a well-controlled environment;
- Compute GST as a weighted average of all clocks operated in the PTF and provide steering of the Master Clock to this ensemble in the case of PTF autonomous operation;
- Accept steering corrections provided by the Galileo Time Service Provider–see below–and steer GST – derived from the Master Clock to Coordinated Universal Time (UTC) (modulo 1 s);
- Provide a physical realization of GST (1 PPS, 10 MHz, time of day) and distribute it in the Galileo GMS and within the GCC. A Galileo Sensor Station (GSS) will be co-located with each of the PTFs, thereby making GST available as time reference in the Orbit Determination and Time Synchronization (ODTS) process;
- Operate time transfer equipment for the mutual synchronization of the two PTFs and in support of the TSP activities.

3.2.4 The Role of the Galileo Time Service Provider

The additional use of Galileo as a time dissemination service requires that the relation between GST and international references such as UTC and TAI, is well defined and broadcast in the Galileo navigation message. The required support for such ”metrological time-keeping” shall be provided by the so-called Galileo Time Service Provider (TSP).

The main TSP function from the Galileo perspective is to provide the PTF with the so-called UTC correction so that GST can be steered to UTC. UTC differs from TAI only by an integer number of seconds because of the introduction of leap seconds into UTC, but both scales have the same scale unit. GST differs itself by another integer second offset from both scales because of the choice to let the GST epoch agree with the epoch of GPS Time. An equally important TSP function is the provision of a prediction of the time offset GST-UTC: Its specifications call for an uncertainty of 28 ns (2 sigma) but it is expected that a much better uncertainty may be realized. This information shall be broadcast in the Galileo navigation message. In order to fulfil such function, the TSP shall carry out different tasks which were described in [Achkar et al., 2007]. Briefly, the TSP manages the synchronization links between the master PTF and slave PTF, and the two PTFs and a small number of European timing institutes each of which provides the link to the timing community. In the long term it should support scientific activity, in collaboration with European NMIs and academia, to obtain an improved accuracy of GST (better than currently specified). As part of this mission, the most effective way (in terms of effort versus performance) of ensuring the metrological properties of GST should be studied.

The TSP is supposed to provide access to GST performance monitoring data on a dedicated web interface. This could allow GST users in calibration laboratories to obtain traceability of their calibration facilities to national standards, as often prescribed in national legislation. The use of UTC via prediction with respect to GST as a reference should be advocated, not the direct use of GST itself. The content of the Galileo navigation message in this respect needs to be continuously monitored. This would require that a TSP structure be established and maintained during the Galileo Full Operations phase.

3.2.5 Galileo Internal Synchronization and Interoperability with Other GNSS

From a technical point of view, it is most important that time scale comparisons between both PTFs and the associated timing laboratories be maintained. TWSTFT was identified as the prime means in this context. It provides time scale comparisons with sub-nanosecond precision in quasi real time. One of the connected laboratories, at least during the coming In-Orbit-Validation campaign, is the United States Naval Observatory, which supports the determination of the GPS to Galileo Time Offset (GGTO). Accurate time comparisons are needed, which requires that repeated calibration of the time links, including the two PTFs, following the approach explained in [Piester et al, 2008] have to be arranged. TWSTFT has been studied by several groups in Asia, Europe, and the U.S., and strategies for improvement of its performance have been proposed. In practice, progress is limited by the dependence on the available transponder capacity on geostationary satellites which is costly and inconvenient to get. The availability of a dedicated geostationary satellite – or of a payload on a general purpose satellite, would be very supportive for the progress in this direction.

Instrumental delays in GNSS receivers differ with the code used, the frequency band and the characteristics of the band-pass filter. They affect the accuracy of time transfer, and should be correctly assessed both for the GGTO determination and at the user level, in order to ensure interoperability of the systems. Absolute values may, in principle, be determined by calibration. But in general, differential code biases are determined by a global analysis, e.g. by the IGS, with a global rank deficiency which is conventionally removed. As new modulations are added to the GPS signals and still others will exist on Galileo, it is expected that the determination of inter-signal biases will become a major task. The calibration of user equipment is more specifically addressed in the next sub-section.

Time and frequency transfer over regional distances, including the central European countries, may well be possible through fiber networks established for communication purposes. Transport of optical frequencies - signals of lasers emitting in the telecommunication bands, stabilized to atomic references - has been demonstrated in urban fiber networks of about 100 km length [Narbonneau et al., 2007]. Remarkable frequency transfer stability of 10^{-17} over one day was demonstrated. More recently, the first stage of an optical fiber network in Germany that will eventually link optical frequency standards at PTB with those at the Institute of Quantum Optics (IQO) at the Leibniz University of Hanover, and the Max Planck Institutes in Erlangen (MPL) and Garching (MPQ) has been put into operation. A phase coherent comparison of clock lasers at the few 10^{-15} level during a few minutes has been accomplished between two lasers more than 100 km apart [Schnatz et al., 2009]. Several groups are engaged to increase the distances bridged step by step, using commercially deployed, but currently unused (dark) fibers. Other studies address the transfer of time information over such networks, which could become extremely interesting for time synchronization of the two Galileo PTFs.

3.2.6 Improving GNSS Time Transfer and Time References with Galileo

GPS Receivers of the first generation used for time comparison were single-channel, single-frequency C/A-code (Coarse/Acquisition) receivers. Receiver manufacturers later developed multi-channel receivers, operating also at one frequency, but allowing simultaneous observations of several satellites at a time. The propagation of the signal is affected by atmospheric effects. The ionosphere provokes delays that introduce significant errors, particularly during periods of high solar activity (see 3.4). Dual-frequency reception eliminates most of the ionospheric delays. Multi-channel, dual-frequency receivers have thus started to replace older equipment in a number of laboratories. Such receivers and the P3 evaluation method [Defraigne and Petit, 2003] have helped to increase the accuracy of long-distance time transfer.

The most advanced use of GPS signals is based on the carrier phase [Schildknecht et al., 1990; Kouba and Héroux, 2001; Ray and Senior, 2005]. This allows frequency comparisons among remote standards with the lowest transfer noise of all current common methods [Bauch et al., 2006]. Such techniques are now common in the time and frequency community [Cerretto et al., 2009] and, for example, they enter into the computation of time links for TAI [Petit, 2009].

The use of Galileo with its variety of carrier frequencies and phase modulation schemes has to our knowledge not been fully assessed, but without doubt, an improvement of the time and frequency comparison performance can be expected. The most obvious advantage is the increased number of observations, which will become possible. In addition, improved performance is expected for the new codes available in the Galileo signal [Hein and Avila-Rodriguez, 2006; Simsky et al., 2008] which should improve the medium-term stability of time transfer using carrier phase and code. Recently, a review of the requirements for future GNSS receivers to be used for precise time and frequency transfer was published [Defraigne et al., 2009]. The goal is to transfer time with an accuracy of 1 ns or better, and to compare remote frequency standards without degradation of their frequency due to the receiver architecture. It appears essential that the receiver functions be described in detail by the manufacturer. A correct definition of the physical point corresponding to the internal reference clock inside the receiver must be given. The complete relation between this physical point and the input/output signals, and between this physical point and the point to which the measurements are reported (if it is not the same) has to be revealed. Receivers should provide the measurements using the standard geodetic format RINEX, and if delivering the Consultative Committee for Time and Frequency (CCTF) Group on GNSS Time Transfer Standards (CGGTTS) files [Allan and Thomas, 1994], then the manufacturers should follow the future updates of this format.

3.3 Galileo and the establishment of terrestrial reference frames

3.3.1 Introduction

The positions of stations over the Earth's surface can now be determined with a precision at the level of a few millimetres and their variation over time at the level of, or better than, 1 mm/yr. This performance is only possible thanks to the tremendous progress achieved by space geodesy techniques and the high level scientific software packages developed by various analysis centres dealing with the accumulated geodetic observations over the last three decades [Blewitt, 2007]. Continuous geodetic observations become more and more fundamental for many Earth science applications at the global and local levels: large scale and local Earth crust deformation; global tectonic motion; redistribution of geophysical fluids on or near the Earth's surface, including the ocean and atmosphere, cryosphere, and the terrestrial hydrosphere; and by no means the least of these applications is the monitoring of mean sea level and its variability given its impact on global warming. All of these important applications depend fundamentally on the availability and accuracy of a truly global terrestrial reference system (TRS to be associated with the concept of ITRS, International Terrestrial Reference System) that only space geodesy can realize, [Altamimi et al., 2001; 2002; 2007]. In addition to these geoscience applications, a TRS, through its realization by a terrestrial reference frame (TRF), is an indispensable reference needed to ensure the integrity of GNSS, such as GPS, GLONASS, Galileo, etc. In the following we summarize the current status of the contribution of the individual techniques to the reference frame, their limitation factors and future requirements, through the currently available results of the International Terrestrial Reference Frame (ITRF).

It is believed that the science requirement, including the main stringent one, the mean sea level variability, is the availability of the reference frame that is reliable and accessible at the level of 1 mm and with a stability of 0.1 mm/yr. Stability of the reference frame means here that no discontinuity or drift should occur in its time evolution, especially for its defining physical parameters, namely the origin and the scale. Unfortunately, the current level of reference frame accuracy (based on ITRF current achievement) is at least ten times worse than the science requirement. Some pertinent limiting factors are given below.

3.3.2 The International Terrestrial Reference Frame, ITRF

The implementation of the ITRF is fundamentally based on the rigorous combination of the main space geodetic techniques, where co-location sites allow their interconnection. The space geodetic techniques that provide measurements for the realization of the ITRF include in addition to GNSS, SLR, VLBI, and DORIS. These techniques are organized as scientific services under the umbrella of the International Association of Geodesy (IAG): the International Earth Rotation and Reference System Service (IERS) [IERS, 2003], the International GNSS Service, formerly the International GPS Service (IGS) [Dow et al., 2005], the International VLBI Service (IVS) [Schlüter et al., 2002], the International Laser Ranging Service (ILRS) [Pearlman et al., 2002] and the International DORIS Service (IDS) [Tavernier et al., 2005].

None of space geodetic techniques is able to provide all the parameters necessary to completely define a TRF (origin, scale and orientation). While satellite techniques are sensitive to the Earth centre of mass (the point around which a satellite orbits; a natural TRF origin), VLBI is not (whose TRF origin is arbitrarily defined). The scale is dependent on the modelling of some physical parameters and the absolute TRF orientation (unobservable by any technique) is arbitrary or conventionally defined through specific constraints. The utility of multi-technique combinations is therefore recognized for the reference frame implementation, and in particular for accurate TRF datum definition. In principle, the particular strengths of one observing method can compensate for weaknesses in others if the combination is properly constructed, suitable weights are found, and accurate local ties at co-location sites are available.

The ITRF is the standard frame that is widely used in Earth science applications as well as for satellite navigation. For the first time in ITRF history, the ITRF2005 frame uses as input data time series (weekly from satellite techniques and 24-hour session-wise from VLBI) of station positions and daily Earth orientation parameters (EOPs). Time series analysis allows:

- monitoring station non-linear motion, and, in particular, discontinuities, which are accounted for by piecewise modelling,
- improving the consistency between the ITRF and the EOPs and
- examining the temporal behaviour of the frame physical parameters (namely the origin and the scale) [Altamimi et al., 2007].

Expected contributions of Galileo to the ITRF are largely outlined in [Altamimi, 2007].

GPS was introduced in the ITRF combinations for the first time in 1992 with the release of ITRF91, involving 21 sites. Since then, continuous enhancement of the GPS network with the creation of the IGS in 1994 extended dramatically the ITRF to include now 250 GPS sites in ITRF2005. However, the GPS site distribution is still far from optimal between the two hemispheres, with only 20% of the sites located in the southern hemisphere.

As was the case when GPS was introduced in the ITRF combinations, we expect that future development of the Galileo network of receivers will certainly lead to the inclusion of Galileo data in IGS activities, and consequently contribute to the extension and enhancement of the ITRF itself. Particular interest would be the balance of the Galileo network distribution between the two hemispheres and in remote areas that is necessary for the determination of the time evolution of the ITRF orientation as well as to improve our knowledge of tectonic plate motion. Having more satellites together with GPS and GLONASS, Galileo (and Compass) will contribute to improving the quality and accuracy of the estimated orbits via which precise access to the ITRF everywhere, anytime, e.g. by precise point positioning, will be enhanced.

3.3.3 The ITRF and Current Status of Co-location Sites

The key-element of a multi-technique combined frame such as the ITRF is the availability of a sufficient number and worldwide distributed co-location sites [Altamimi, 2005]. A co-location site is defined by the fact that two or more space geodesy instruments occupy simultaneously or sequentially very close locations, which are very precisely surveyed in three dimensions, using geodetic classical surveys or the GPS technique. Classical surveys involve usually direction angles, distances, and spirit levelling measurements between instrument reference points or geodetic markers. Adjustments by least squares of local surveys are generally performed by national geodetic agencies operating space geodesy instruments yielding differential coordinates (local ties) connecting the co-located instruments' reference points.

Figure 6 illustrates the status of co-location sites where stations from the four techniques (VLBI, SLR, GPS, and DORIS) are currently operating. All in all there are 58 sites with two techniques, 16 sites with three techniques, and only two sites with all four techniques. The Greenbelt (MD, U.S.A.) 4-technique site includes an old VLBI mobile antenna of very low performance. Among the 58 two-technique sites, 38 are GPS-DORIS co-locations. We note also that about 15% of the available local tie vectors have discrepancies larger than 1 cm with space geodesy estimates. There are only 8 sites where VLBI and SLR are co-located, a very poor number to ensure optimal connection between these two techniques. In ITRF combinations, GPS now plays a major role connecting both techniques, given the fact that all SLR and VLBI sites are co-located with permanent GPS stations. The drawback of this situation is that if there is any GPS-related bias, this would contaminate the ITRF defining parameters, mainly the origin and the scale, being determined by SLR and VLBI. One of the major GPS weaknesses is the existence of position discontinuities due to equipment changes that affect more than 50% of the IGS network. In addition, there are a certain number of GPS stations with uncalibrated radomes. Given these preponderant weaknesses and the currently available local ties and their uncertainties, we estimate the quality of the local ties to be at the level of 4 mm, as the weighted mean of the tie residuals resulting from the current ITRF combinations.

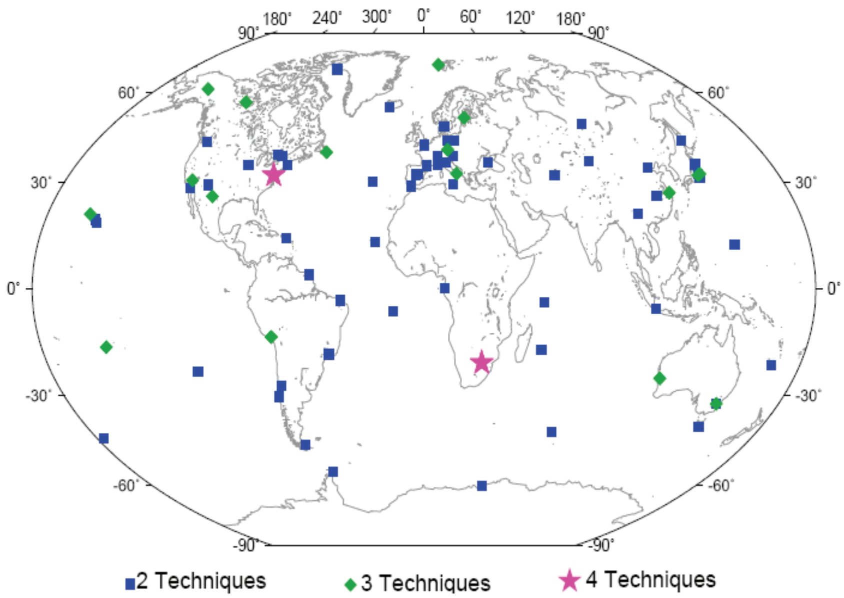

Figure 6: Currently available co-location sites (2008)

3.3.4 Space Reference for Galileo: the Galileo Terrestrial Reference Frame

As for any satellite navigation system, Galileo should rely on a global terrestrial reference system and its realization by a frame, necessary for the overall system integrity. The main function of the GTRF is to allow the expression of satellite orbits and the positions of ground sensor stations tracking the Galileo satellites with high precision anywhere, anytime. The realization and maintenance of the GTRF is the main function of the Galileo Geodetic Service Provider (GGSP), serving both the Galileo Core System as well as the Galileo users. The GGSP will enable all users of the Galileo system, including the most demanding ones, to rapidly access the GTRF with the precision required for their specific application.

In its definition, the GTRF is fully compatible with, and aligned to, the ITRF in origin, scale, orientation, and their time evolution. In order for the GTRF to be maintained over time, the GGSP is (and should continue) operating in a continuous and routine analysis [Gendt et al., 2007]. The GGSP is currently (at the time of writing) composed of, essentially, three processing facilities (PFs), and combination and validation facilities (CFs and VFs). A full and operational GGSP prototype has been established and has been running for almost three years [Gendt et al., 2007]. Weekly solutions of stations positions of a network composed of more than 100 globally distributed stations are generated by the three PFs, analysed, combined, aligned to the current ITRF (ITRF2005) and validated. The GTRF network includes (at the time of writing) 13 Galileo Experimental Sensor Stations that should ultimately be replaced by the effective Galileo Sensor Stations. The current GTRF network weekly solutions are based on GPS observations for the prototype implementation, with the intention and software upgrade to include Galileo observations as soon as the Galileo satellites are fully operational. The weekly GTRF maintenance is fundamental in order to update the station positions in case that equipment changes occur and geophysical phenomena happen, such as earthquakes, so that the GTRF and ITRF compatibility is ensured at the centimetre level or better.

As is the case for GPS, it is expected that Galileo will contribute significantly to the ITRF and enhance its accessibility anywhere, anytime. In the same way, no doubt Galileo will also contribute to various geoscience applications as GPS does. In the meantime, the weaknesses of GPS underlined above should be taken into account in the design of both the space and ground segments in order for Galileo to be a performing tool in minimizing the GNSS systematic errors and significantly contribute to the ITRF datum specifications.

3.3.5 The Role of Galileo and GNSS in Improving Space References

Each one of the four techniques used in the ITRF combination has its own strengths and weaknesses. Therefore the ITRF combination benefits from the strengths of all four techniques, while mitigating, and underlining, their weaknesses.

Among the currently operating GNSS systems, only GPS is contributing to the ITRF. It is expected that other GNSS systems (Galileo in the near future) will also contribute to the ITRF. Given the fact that all the GNSS systems operate under the same principles, we take here the example of GPS to underline its strengths and weaknesses as seen from the ITRF combination activities. Starting with the strengths of GPS for the ITRF, we can mention the following main points:

- the spatial density and distribution of the IGS/GPS sites result in a very good coverage and sampling of the main tectonic plates. This is an important aspect because it allows a precise determination of the ITRF orientation time evolution. In effect, the ITRF should satisfy the no-net-rotation (NNR) condition which is directly applied using the plates as a discretization of the Earth's surface;
- GPS provides the most precise polar motion, being based on continuous observations of a dense network;
- using IGS products (orbits and clocks), GPS allows real-time or near real-time access to the ITRF;
- GPS strengthens the link between VLBI and SLR networks in the ITRF combinations.

On the other hand, considering the vital role and the requirement for a stable and reliable reference frame and its maintenance over time, we can mention the following weaknesses of the GPS technique and the IGS network as seen by the ITRF combination:

- imprecise origin and geocenter estimates mainly due to orbit mismodeling errors;
- imprecise TRF scale determination due to phase-center variations of the ground and satellite antennas;
- 50% of the IGS sites have discontinuities in the position time series due to equipment changes (antenna, receiver, radome);
- Many of the IGS reference frame stations need to improve their quality and performance, continuous operation, and stability. They should follow strict standards of installation, operation and monumentation as defined in the IGS site guidelines [IGS, 2007] in order to secure the

minimum requirements on the stability of the IGS reference frame. A set of proposed specifications for reference frame stations has been published by [Ray, 2004].

3.4 Conclusions

Wide-spread skills in such areas as atomic clock making, time scale generation, time dissemination and network synchronization are available in European national metrology institutes, space agencies, and universities. ESA should seek to make use of these resources by supporting joint research projects fostering clock development and improved time transfer methods. Galileo evolution and also other ESA projects such as its Deep Space Tracking and its Living Planet Programme would benefit thereof. Similarly, the Global Geodetic Observation System (GGOS) will rely on the availability of a common reference timescale which could be disseminated from Galileo satellites.

From the foregoing, we identify the following important research topics directly related to Galileo operations, utilization and development in the coming years:

- Definition of the role of the Galileo TSP for the period after FOC (the operations period) – what is really needed for Galileo operations, which services are needed by European users?
- Utilization of the performance of advanced ground clocks for the realization of GST – this topic calls for an ongoing close cooperation between ESA, EC and the NMIs where such devices are ready today;
- Development of compact, easy to use, high-performance (instability $1x10^{-12}\tau^{-1/2}$) atomic clocks that could be deployed in the Galileo Sensor Stations, and added in the PTFs – such developments have already been initiated by some NMIs and ESA/EC are encouraged to continue supporting them;
- Maintaining and improving the capabilities of TWSTFT – in this regard, the European NMIs and ESA/EC have very similar interests, and ESA/EC are encouraged to provide the required financial or technical support;

- Development of multi GNSS time receivers incorporating the features required for accurate time transfer in a close cooperation between ESA, NMIs, research institutes and industry.
- Optimization of the use of the various Galileo signal components – new processing strategies and signal combinations;

For the longer term, we identify the following action items:

- Develop space qualified, high-performance atomic/ion clocks - this topic deserves a stable and adequate funding by ESA and national space agencies as the optimal type of clock for this purpose is not determined yet;
- Develop new techniques for time and frequency transfer between ground and space clocks – e.g. ESA is encouraged to capitalize on the techniques used for the ACES microwave link;

Considering that performances of $1x10^{-16}$ for clock accuracy and $1x10^{-16}$ at one day averaging for frequency transfer are achieved and will be operational in the coming years, we recommend to procure for the years 2020s:

- a set of space clock accurate at the 10^{-18} level that would provide, together with Earth based clocks, the basis for the international time reference
- a time and frequency transfer technique with time transfer accuracy below 100 ps and frequency transfer accuracy of 10^{-18} at one day averaging

Such systems deployed on GNSS or dedicated platforms would provide

- a technique for worldwide frequency comparisons with the stated accuracy (10^{-18} at one day);
- a means of disseminating the international time reference with the stated accuracy;

- assuming the parallel development of Earth based clocks of similar or better accuracy, a method of estimating the gravity potential worldwide with an accuracy equivalent to 1 cm in height, so providing a reference value for the geopotential and the origin for a worldwide vertical reference system.

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4. Fundamental Physics

4.1 GNSS and Relativistic Mechanics

In this section we discuss the need to take into account special and general relativity in the framework of global navigation satellite systems. We present the different relativistic effects that must be considered and their respective orders of magnitude. Finally, we explore the possibility of testing a variety of theoretical extensions of GR and conclude with some considerations on concepts for autonomous relativistic positioning systems.

The Galileo positioning system poses a great opportunity, not only for the improvement of new applications in navigation monitoring and related topics, but also possibly for fundamental research in physics. Indeed, GNSS may be considered as one of the first practical applications where relativistic effects are taken into account, not just from the theoretical point of view, but as a regular engineering constraint on the overall design requirements [Barlier, 2008].

Why does GNSS need to take relativity corrections into account? The so-called Allan deviation for the best orbiting high-performance Cesium clocks in the GPS system is 4 nanoseconds per day. This means that after one day initializing a Cesium clock, its offset from a stable reference will deviate from its predicted value by not more than ±4 ns with 67% probability and by not more than ±8 ns with 95% probability. The effects arising from special and general relativity – gravitational blue shift, time dilation, and Sagnac effect – account for a total onboard clock advance of about 39 microseconds per day with respect to a clock located on the Earth's ground laboratory, with sub-daily quasi-periodic variations of order 100 ns. The effect of the relativistic rate is 4 orders of magnitude above the Allan deviation but could eventually be merged with the determination of the natural rate of the clock. Nevertheless, without taking into account the various relativistic effects, the system would yield unacceptably large errors in positioning and in time transfer. For this reason, in the GPS an adequate corresponding offset on the onboard clock frequency is imposed, while time-varying effects are corrected at the user level while the increased computational capabilities made available to current and future receivers of the Galileo system leave this correction to the user [Ashby, 2003], [Rovelli, 2002], [Bahder, 2003], [Pascual-Sanchez, 2007], [Páramos, 2007].

Most often, relativistic effects are referred to in terms of the deviation they introduce with respect to the classical description. Although this is usually not the most suitable way to proceed, since classical mechanics is an approximation of relativistic mechanics and not the other way around, it is nevertheless useful to present the orders of magnitude of the main relativistic effects at work.

Theoretically, as well as experimentally, it is known that absolute synchronisation of distant clocks is impossible, a direct implication of the finiteness of the speed of light. This might seem contradictory with respect to the need of current systems to define the constellation's reference time through a synchronisation procedure. This apparent contradiction is generated by the misuse of general terms like synchronisation: In reality clocks are synchronised using a standard convention, called coordinate time synchronisation, involving the components of the space-time metric. Since one wishes to evaluate the ground to orbit clock synchronisation, it is advantageous to apply this convention in the context of the geocentric frame, which is defined by all clocks located on Earth's geoid and at rest with respect to each other. Thanks to this convention, one can define the advance or delay of distant clocks with respect to each other. This is crucial not only for positioning itself, but also for applications related with time distribution. Coordinate time synchronisation is transitive, so that if clock A is synchronised with clocks B and C, then B and C will be synchronised with respect to each other. In the context of GNSS, clocks are located where the gravitational potentials differ and corrections typically of the order of 10 nanoseconds must be introduced.

Other relativistic effects must be taken into account when comparing the frequencies of distant clocks. Let us consider the case of a GNSS satellite and an observer on ground, both equipped with similar clocks. The satellite emits a signal with frequency f, measured with its on board clock. Although the observer on the ground takes into account the classical Doppler effect, a different frequency will be measured. This discrepancy results from the gravitational blue shift and the second order Doppler effect. These two effects are different for the satellite and for the observer moving with the Earth's rotation. The overall effect results in a relative frequency excess of typically 4.7×10^{-10}, which as stated above corresponds to a onboard clock advance of 41 microseconds per day. Another relevant phenomena is the so-called Sagnac effect which concerns the propagation of electromagnetic signals in rotating reference frames. For the case of the GNSS, the Sagnac effect can amount to about 100 nanoseconds, corresponding approximately to 30 meters.

Satellite positioning systems can also be used to test the current theory of relativity. GPS has already been used to test the isotropy of the speed of light with a great precision. The Galileo positioning system could be paramount in improving the bound on the violation of the Local Positioning Invariance (LPI) principle, which is one of the fundamental pillars of General Relativity. It postulates that physical laws are independent of their space-time positions. Experimental constraints on the relative frequency deviations indicate that this invariance holds down to a level of 1.4×10^{-6} [Ashby 2007] . Endowing one or more elements of the Galileo constellation with higher precision clocks and allowing for sufficiently stable communication with stations on Earth, possibly through a microwave link, could yield an improvement of up to two orders of magnitude on the LPI [Páramos, 2007]. In order to verify the precise orbit of the Galileo spacecraft, Laser Retro-Reflectors (LRR) should be installed on the Galileo satellites which would allow accurate laser ranging.

Testing extensions of General Relativity will be possible only in a future evolution of the Galileo system. Probing different theoretical models, involving an addition of the Yukawa type contribution will only be possible with a relative frequency accuracy of about 10^{-19}, close to the quantum regime [Páramos, 2007]. The same can be stated about "ungravity" type corrections [Páramos, 2009].

The effects of general relativity are today taken into account by GNSS systems as corrections over a non-relativistic description of a "flat" space-time. This is sufficient for the current objectives of Galileo but there are numerous reasons for looking beyond this approach, and explore the possibility of developing a fully general-relativistic conceptual framework for navigation. Among these reasons are: the possible advantages of a fully autonomous orbiting navigation system, that does not need to rely on Earth stations; the long-term perspective of solar-system and deep-space navigation; and, most importantly, the theoretical value of developing a conceptual framework for navigation fully consistent with our fundamental understanding of space and time: ideally, one would like to develop a conceptual framework for navigation that could work in an arbitrary time-dependent spacetime and an arbitrary gravitational field. In principle, four clocks broadcasting their respective proper time define a coordinate system in spacetime: such "GNSS-coordinates", or "emission coordinates" are generically sufficient for defining a complete reference system in an arbitrary time dependent spacetime [Rovelli 2002, Coll 2004, Coll 2006]. Research on these relativistic and auto-located positioning constellations is ongoing, and may provide important inputs for the future of navigation. In the future, one may hope to integrate Earth-based, autonomous, and -say- pulsar-based reference systems, to develop a truly global conceptual setting for general-relativistic navigation. Furthermore, research on the setting of a truly relativistic and self-referring positioning constellation, which requires at least four clocks broadcasting their respective proper times, would allow to downsize the ground segment as well as the total amount of satellites forming the constellation needed to achieve the same level of performance as systems based on a traditional architecture [Coll, 2004] [Coll, 2006].

In what follows we discuss a set of proposals that could use *a subset of the positioning constellation, through onboard scientific secondary payloads*. They address relevant issues associated to fundamental aspects of Quantum Mechanics.

4.2 Quantum Mechanics and Astronomy

4.2.1 Quantum communication experiments and time distribution

Satellites of the GNSS could host in their payloads hardware for experiments of space-to-space and ground-to-space links. These links could open new perspectives in quantum encoding techniques for secure data encryption and for tests of fundamental physics. The encoding of data on single photons is obtained by using the usual quantum communication schemes, namely phase encoding and interferometric techniques. These communication schemes have a higher capability than the classical equivalent ones, as each received photon can code many bits.

Quantum encoding can also involve the superposition of quantum states and entanglement with strong non-local correlations that are the basis for the technique of quantum teleportation. In principle, entanglement would allow for a dramatic improvement of the time distribution among different ground-based stations, up to the picosecond level. ESA has already initiated several activities, at study level, in the domain of quantum communications. As a result, the Space-QUEST experiment (QUantum Entanglement for Space ExperimenTs), to be flown on the ISS [Perdigues, 2009], may pave the way towards distribution of entangled photon pairs from orbit. Space-QUEST might turn out to be an important step towards the use of quantum entanglement as a new resource available to users of the GNSS.

Preliminary on-ground feasibility assessment of Space-QUEST has been supported by ESA through the entanglement-based quantum communication experiment over a distance of 144 km in the Canary Islands [Ursin, 2007]. This experiment demonstrated that photon entanglement is still preserved over large distances, showing that Space-QUEST presents a valid concept and needs to move on into the orbit validation phase.

4.2.2 Relativity, gravitation and entanglement

Relativistic effects, like the gravitational redshift, can be used to measure the Earth' gravitational field by comparing orbital clocks relative to clocks located on the geoid. For instance, two clocks located in the Earth gravitational field in two different points differing by an altitude of 1 meter will have frequencies differing in relative value by 10^{-16}; a space-clock located at an altitude of 400 km will be shifted with respect to the ground clock by 4.5×10^{-11}. Clock comparisons using the Atomic Clock Ensemble in Space (ACES), which is scheduled to fly onboard the ISS, linked through state of the art microwave capabilities will allow to measure differences in the Earth gravitational field corresponding to altitude differences of the order of 10 cm. This would open the door to relativistic geodesy.

Since time distribution and experiments of Quantum Mechanics do have to take into account relativistic effects, one can envisage that if in the future the GNSS constellations will be equipped with clocks accurate enough to allow measuring the Earth gravitational field with a similar accuracy, a breakthrough in geodesy can be achieved, and a possible new range of services and space applications.

4.3 GNSS evolution, secondary payloads or extended satellite features and dedicated test satellites

Understanding the local and global structure of space-time is one of the main tasks of modern physics. Progress in this domain is a major challenge in fundamental physics, as it can provide insights about the "new physics" resulting from the unification of the laws of nature — in particular, between the two pillars of current physics, namely general and quantum field theory.

Advances in space physics allow going beyond the traditional role of observer of our immediate environment. Space is becoming a laboratory for new experiments and new technologies, which with unprecedented precision explore space-time itself. Illustrative examples include missions such as MICROSCOPE, to test in orbit the Galilean principle of the universality of free fall with an accuracy of about 10^{-15}; ACES, comprising atomic clocks in space, with a number of applications in relativity and geodesy; T2L2, laser ranging being now validated on Jason 2; and LISA, a gravitational wave detector, actually a large interferometer in solar orbit.

These projects are based on the development of instruments whose improved performances may give origin to new applications. The metrology of the Earth gravity field is an example of these potentialities, and the missions like CHAMP, GRACE and GOCE show their application in Earth sciences. The presence of state of the art clocks in space opens a long-term prospect for the realisation in space of the international atomic time scale and its global dissemination. This will allow metrology to overcome the current limitations related to the fluctuations of the terrestrial environment.

These potentialities can also be turned into improved techniques of global positioning, if resolution is better than in current GNSS. Ideas for the evolution of GNSS, based on the improvement in current instruments, may allow for tests of fundamental physics in space concerning quantum technologies and general relativity. A summary of these improvements is in order:

- Improved clocks and ground-satellite links, which would result in a benefit for global positioning and navigation, as well as applications in Earth observation (geodesy, remote sensing), metrology and astronomy (reference frames and time scales);
- Onboard accelerometers, which would make it possible to monitor the surface forces in real time, thus leading not only to improved models for the orbits, but also to a better control of the effect of the time variations of these forces;
- Inter-satellite links, which would also lead to an improved control of the constellation, paving the way to the long term prospect of an autonomous space segment for the GNSS, freeing it from the current limitations associated with the ground segment.

These ideas have to be distinguished from the in-orbit validation and deployment of the GNSS constellation. They may be implemented either as secondary payloads to be embarked on some of the satellites in the constellation or as extra satellites added up to the constellation.

These additional satellites may be either on low orbits below the constellation or on geostationary orbits above it. An improved validation and/or calibration of the constellation can be performed with a single additional free flyer with high performance onboard instruments (clock, inertial sensor, radio and laser links with the space and ground segment). A first demonstration of the feasibility of an autonomous space segment requires at least four satellites with state of the art onboard instruments; intermediate configurations lead to a wide spectrum of interesting applications for fundamental physics as well as for Earth sciences.

4.3.1 References

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5. List of recommendations

The recommendations provided in this section emerge from:

- the closing round table discussion of the 2nd colloquium on the fundamental aspects and scientific applications of the Galileo satellite navigation system (Padua, 2012, October 14-16,http://www.esa.int/esaNA/SEM78M5RN1G_index_0.html)
- discussions of the GSAC at its meeting
- sections 3 Earth Sciences, 4. Space-time metrology, 5. fundamental physics of this Galileo Science Opportunity Document.

They are provided in the sequence of general recommendations (Gi) and section-specific recommendations (Si, i= 3,4,5).

Many, if not most of the section-specific requirements assume that the scientific community has free access to the observations generated in the preceding years and currently by the GIOVE satellites. This request came out very clearly at the round-table discussion of the Padua Symposium. It was meanwhile endorsed by the GSAC at its meeting on March 24, 2010.

Recommendation G1: The measurements made by GIOVE-A and by the future Galileo IOV satellites should be easily available to the scientific community.

Many of the section-specific recommendations assume that meta data associated with Galileo are openly and easily accessible and reliable. Experience shows that such information is (a) required and (b) difficult to obtain from GNSS providers.

Recommendation G2: Meta data required to analyze GIOVE and GALILEO (IOV) measurements on the highest accuracy level (ephemeredes, attitude, detailed satellite description including mass, surface properties, antenna phase centers, position of SLR markers, etc.) must be openly available and easily accessible.

The aspect should be addressed carefully by the scientific community and by the Galileo provider. The information should be sufficient to establish Galileo-specific box-wing models for radiation pressure.

Recommendation S3.1: For the analysis of GNSS data stemming from global tracking networks, as described in Section 3.2, including the combination of observations from different GNSS gathered by receivers capable of tracking the signals of all GNSS, new analysis aspects will show up with the availability of Galileo. The issues of system-specific clocks, of inter-system biases for code and/or phase, of radiation pressure models, of the resolution of ambiguities with multi-constellation and multi-carrier combinations etc. have to be studied in particular. The overall goal must be the estimation of one consistent set of parameters allowing the user to generate results based on all observations "as if they had emerged from only one GNSS".

Recommendation S3.2: Currently, GNSS analysis is based either explicitly or implicitly on a freely selectable reference clock for each observation epoch. The excellent quality of the Galileo satellite clocks will allow it for the first time to use a reference clock as a function of time in the analysis of GNSS observations. Research related to this area will lead to a fundamental review of GNSS processing strategies and should be studied with high priority. The important aspect of clock prediction (which limits the real time point positioning performance) should be considered as well in this context.

Recommendation S3.3: Galileo (and, e.g., next generation GPS) will allow the use of code and phase on more than two carriers. Algorithms for ambiguity resolution, for the elimination or the modelling of ionospheric refraction, respectively, have to be adapted to the new options.

Recommendation S3.4: LEO orbit determination (including LEO constellations) with Galileo and with a combination of GNSS (GPS, GLONASS, Galileo) will be a particularly important application in future and should be studied in all details (absolute and relative positioning and navigation) with high priority.

Recommendation S3.5: Galileo will provide an excellent opportunity for GNSS-R-based remote sensing (section 3.3). The availability of Galileo E1 and E5 signals will allow the multi-spectral analysis of the reflected signals and the development of inversion models, which will be able to account more precisely for adverse effects, such as surface roughness and vegetation canopy. An improvement of the spatial coverage will be achieved, as well, by using all available GNSS signals (including GPS and GLONASS). Research should therefore be performed to further increase the potential of the GNSS-R techniques with the advent of Galileo. A proof of concept mission should be envisaged.

Recommendation S3.6: The number of GNSS satellites, which may be observed quasi-simultaneously by a particular receiver on the Earth surface or on a Low Earth Orbiter (LEO), is the key to the accuracy and robustness of atmosphere studies. The impact of multi-GNSS to ionosphere monitoring (including models, tomograms, scintillations, space weather, etc) and to the monitoring of the neutral atmosphere (including tomographic studies of water vapour using terrestrial arrays of receivers and/or profiles gathered by LEOs) should be studied with high priority. The mutual benefit of Galileo and other GNSS should be studied in particular.

6. Acknowledgments

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