Kepler – Satellite Navigation System Description and Validation

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INTRODUCTION

Galileo launched its initial services on December 15th, 2016 with 11 active satellites. Today, there are 26 satellites in orbit of which 17 satellites are integrated in the service provisioning. The signal performance of the satellites is outstanding and the signal in-space accuracy already reaches levels similar to GPS. Galileo has ultimately developed into a success. Its earliest satellites were launched on October 21st, 2011 and have thus passed half of their lifetime. A number of additional satellites have been ordered and plans are currently made for further developing the European Global Navigation Satellite System (EGNSS) program. Kepler is one proposal, and shall be presented in this paper, in particular with respect to first ideas about its validation.

Program continuity and stability are two essential properties that must be ensured in any evolution of the operational Galileo system. In the case of Kepler this is achieved by re-using the orbital positions of Galileo and by launching the first generation of Kepler satellites as dual-mode Kepler-Galileo satellites. This allows maintaining the current services, while upgrading the capabilities. The new Kepler mode of operations shall be first initiated in the background without interference with Galileo. This allows fine-tuning the new mode before switching completely over once the constellation is sufficiently populated with Kepler-Galileo satellites.

The current Galileo signals will be maintained to ensure the backward compatibility of user equipment. Most such user equipment will benefit from the increased precision in orbit determination and time synchronization from the start. Additional targets of Kepler are to provide global real-time precise positioning, potentially using a second broadband signal near the E1/L1-frequency band. Furthermore, Kepler also aims at providing global integrity with a time to alert of 3 seconds. Signals at higher carrier frequencies, would furthermore make anti-jamming multi-antenna processing accessible to smaller form factors. Even if the focus of Kepler is on improving the civil EGNSS, Kepler would also support new signals for the Public Regulated Service (PRS).

The ground segment of Galileo currently counts 16 sensor stations, 5 up-links stations and 5 Telemetry and Tele-Command (TTC) stations and shall be further expanded. This requires a global deployment with agreements by hosting states, the protection of the systems against jamming, spoofing and other manipulations, as well as reliable communication links between these stations and the control centers. A major benefit of Kepler is the reduction of the ground segment to a single sensor and control station, which would also create the link to Universal Time Coordinate (UTC). A few more stations will be used for redundancy but are not needed from a performance perspective.

The Kepler architecture does not only support UTC time distribution but will also enable intercontinental comparisons between optical clocks of time laboratories. Even more, the system itself could host a major contributor to Universal Time Coordinated (UTC) by embarking long-term stable optical atomic clocks. This requires, however, that such clocks are made robust and small enough to fly on satellites. A small number of correspondingly equipped satellites (2-3 for redundancy) are sufficient to provide the desired stability throughout the whole system, which remains otherwise unchanged.

The remaining part of the paper is structured as follows. A first section describes the system. It is itself structured into a description of the "principles of operations," the "signals" and some key elements of "processing." A more detailed description of that part is found in [1]. The second part addresses the validation concept. The mentioned migration from Galileo to Kepler actually makes the transition and the validation an integral part of the system design. First ideas on how to realize this are provided in this second section.

SYSTEM DESCRIPTION

Principle of Operation

Kepler is a Global Navigation Satellite Systems (GNSS), in the sense that user receivers estimate their position and clock-offset using pseudorange measurements with respect to at least four satellites. The main distinction between Kepler and first generation GNSS, including GPS, GLONASS, Galileo and Beidou, is on how the infrastructure measures signals, performs time synchronization, estimates satellite orbits, and exchanges information. Optical inter-satellite links play an important role in the new Kepler system.

Kepler reuses the Medium Earth Orbital (MEO) slots of Galileo. The latter are arranged in a Walker constellation (24/3/1) with a radius of 29’601 km. Neighboring Kepler MEO satellites in the same orbital plane are connected by optical links. Additionally Kepler uses a constellation of LEO satellites. The minimum constellation originally considered was a Walker constellation (4/2/1) at a height of 1209 km. It was recently extended to a (6/2/1) constellation to ensure positive MEO satellite elevations for all LEOs [2]. The LEO satellites have optical links to MEO satellites in different orbital planes. Sometime all MEO orbital planes are connected by one LEO satellite. Two LEO satellites are always sufficient to connect all orbital planes. The LEO satellites are equipped with 3 to 4 optical terminals for this purpose, while each MEO satellite carries one additional downward pointing terminal for its potential link to a LEO satellite. The optical links are used for time transfer, ranging and communications with a data rate of up to 50 Mbps.

Time is maintained by a cavity stabilized laser (CSL) on each satellite. CSLs are the most stable oscillators available today. They are used as the flywheel in optical clocks. Without control by atomic transition, their frequency drifts over time – at a rate that depends on the quality of the thermal shields of the cavity. Figure 1 shows the performance of such a cavity as compared to an Ultra Stable Oscillator (USO) based on quartz oscillation on the one hand and to a Galileo H-maser on the other hand. The region of stability of the CSL extends to a few seconds, which is the time needed to perform two-way time comparisons between neighboring satellites and to transport the results to all other satellites (see [1] for details). The latter time comparisons, when based on optical carrier phase measurements, are only limited by the stability of the oscillators. This obviously assumes that relativistic corrections are correctly accounted for. The latter corrections create a weak dependency to orbits, which can be solved iteratively. The joint processing of all time offsets using a composite clock algorithm produces the Kepler System Time (KST) as well as the offsets of each clock with respect to KST, see [3] [4]. The level of synchronization of the optical timing systems at the short end (τ small) is very similar to the values shown in Figure 1**Error! Reference source not found.**.

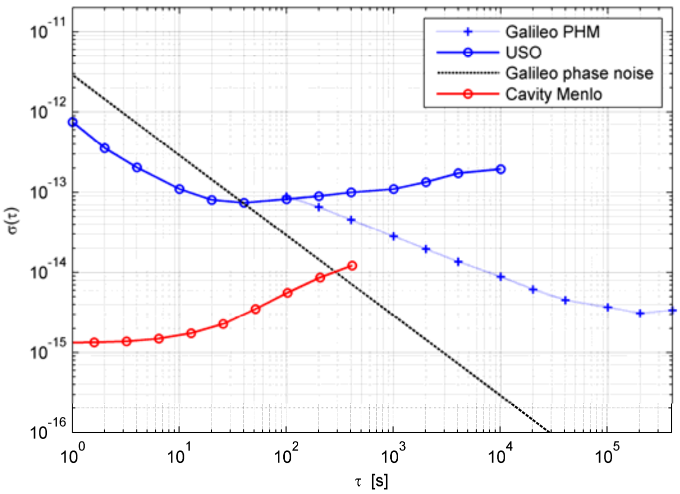

Figure 1: Allan deviation for an Ultra Stable Oscillator (USO) [11], the Galileo Passive Hydrogen Maser (PHM) [12] for reference and a Cavity Stabilized Laser (CSL) [13]. The interesting region for Kepler is at $\tau \backslash leq 10$ s. In this region, the optical CSL is much more stable than any system running a quartz oscillator.

The synchronization in the optical domain is transferred to the L-band using an optical comb on every satellite. On the MEO satellites, this comb allows to synchronize the signal generator to KST. The L-band signals are aligned to KST by an appropriate control of a Numerically Controlled Oscillator (NCO), see [1]. As a consequence, the navigation messages of Kepler satellites always show zero values for the clock offsets.

Each LEO satellite is equipped with a zenith pointing L-band navigation antenna and with a navigation receiver to observe the signals transmitted by the MEO satellites. The combs on the LEO satellites ensure the locking of the L-band receivers to the synchronized optical signals. Thus, these receivers on the LEO satellites measure ranges rather than pseudoranges. Since the plasma density of the ionosphere is concentrated at altitudes well below 1209 km, the path from the MEO to the LEO satellites is not much affected by extra delays due to atmospheric propagation. Thus, such measurements are well suited to calibrate inter-signal biases and most importantly: they provide unaltered range measurements for orbit determination. The latter measurements are exchanged amongst MEO and LEO satellites and used to compute orbits, e.g. on the LEO satellites. These results together with bias estimates are then distributed to the MEO satellites for integration in the navigation messages.

The above architecture makes Kepler independent of any extended ground infrastructure. At least one station is still needed to maintain

- the alignment of the constellation with earth rotation, and to keep
- KST synchronized to UTC.

Finally, some control, tuning, maintenance and upgrading of the system are necessary and can be performed via this light weight ground infrastructure as well. The communication between the ground and the constellation is ensured using a directional two-way C-band/L-band link to the satellite that is closest to the zenith at the location of the ground station, see [5].

Kepler Signals

The user signals of Kepler are those of Galileo and its planned evolution. The high accuracy of Kepler with respect to orbits, timing and signal biases makes the system an ideal host for more sophisticated signals, including signals at higher frequencies. They might go up to V-band frequencies for scientific space applications.

Additionally, Kepler uses an evolved C-band/L-band satellite-ground data channel with data rates up to 1 Mbps and an improved time transfer capability. This is further developed in [5].

Besides the above radio frequency (RF) signals, Kepler uses optical signals between satellites. The current assumption about the carrier frequency is that it is generated by a Nd:YAG laser with a wavelength of 1064 nm. The associated frequency is 281.7 THz. For time transfer purposes, the optical carrier is coherently modulated by a pn-sequence of length 511, which repeats every 20 ns. Thus, the modulation rate is 511×50 Mbps = 25.55 Gbps. The clock signal for the modulation is derived from the optical frequency using the same frequency comb mentioned above. The optical modulation is thus phase-locked to the optical carrier frequency. The resulting spread spectrum signal is furthermore modulated by the information that needs to be conveyed from one satellite to its neighbor. The link budget is closed with a bit error rate below 10^{-6} [5]. Such error rates can be handled using simple cyclic redundancy check (CRC) codes.

Processing

Orbit Determination and Time Synchronization (ODTS) is the central process in the infrastructure of GNSS systems. Traditional GNSS systems aim at first eliminating time by taking differences (between satellites and/or receivers) in order to estimate the orbits. These orbits then become the basis for estimating the time offsets. In Kepler the situation is mostly reversed. The synchronization is first established and then becomes the basis for determining the orbits. At a second look, the relativistic corrections couple the two processes.

The first step in Kepler processing is to perform two way measurements, e.g. twice per second. These measurements are used to determine clock offsets and ranges as well as frequency offsets and range rates between neighboring satellites. All of these computations are performed in a geocentric non-rotating coordinate system K, and involve relativistic corrections, which depend on the velocities of the satellites as well as on the gravitational field at both the location of the satellites and on the optical paths between them. The clock offsets in the coordinate system K are exchanged between all satellites. Thus, each satellite can compute a joint composite clock using the Greenhall algorithm [4]. The latter is a Kalman filter with an extra step to reduce the covariance of the time component. The result is an implicit ensemble mean, which has been found to be as stable as the most stable clock from the ensemble at any time difference τ. Furthermore, the algorithm also provides the offset of any particular clock to the implicit ensemble mean. The Kepler System Time (KST) was defined as being this implicit ensemble mean in [1]. Any representation of KST needs clocks. In the short term (small values of τ), the KST is dominated by the performance of 24 MEO CSL and 4-6 LEO CSL and is thus more stable than any of its representing clock. Thus, any representation is limited by the performance of the CSL representing the KST (and not by the KST itself). That CSL propagates KST computed using past time comparisons to the present time, see [6]. The offset of the local CSL and the KST is used to correct the timing of the L-band signal generator to ensure that all signals are and remain synchronized.

The optical intersatellite ranges between neighboring satellites, the MEO-LEO L-band ranges as well as a set of MEO to ground (GND) pseudoranges are the basis for orbit determination. Note that for any given LEO satellites, the MEO-LEO L-band ranges are measured with respect to all MEO satellites in view with an elevation of at least 5-10° [2]. The final choice of the cut-off angle is a trade-off between signal quality and the number of satellites seen. The dynamics of the satellites are mainly controlled by the gravitational field of the earth and by the solar pressure. LEO satellites are additionally subject to drag by the residual atmosphere. Models are used to reduce the impact of solar pressure and atmospheric drag to very few parameters. Similarly, earth tides and ocean loading are considered for the station. So far orbits were determined in a batch least square approach with 4 LEO satellites only and a single ground station. Even with this minimal configuration, the performance in the important radial direction is quite amazing. The MEO radial orbital error is below 1 cm. The corresponding along track and across track errors are at 5 cm [7]. This is due to the slack between the constellation and earth rotation. The lack of substantial ionospheric delay in the L-band ranges furthermore allows for a calibration of all inter-signal biases.

The 3D-uncertainty of the orbit allows to compute protection levels as commonly done in augmentation systems. The observations made by the LEO satellites can additionally be used to validate the MEO signals. In this case, it is beneficial that each MEO satellite is observable at positive elevations from at least one LEO satellite. This is possible with 6 satellites in a Walker (6/2/1) constellation. Since Kepler does not observe the ionosphere, the present approach to reliable positioning requires multi-frequency receivers at the user or an external ionospheric service. The reliable calibration of inter-signal biases in Kepler, however, supports position estimation with an ionospheric uncertainty mainly controlled by higher order corrections.

VALIDATION CONCEPT

Kepler introduces new concepts at different levels:

- system: LEO satellites, optical intersatellite links, in-orbit monitoring, in-orbit processing,
- subsystems: cavity stabilized lasers, optical combs, optical terminals, and
- processing: synchronization, bias estimation, orbit determination, integrity.

Since Galileo is an operational system used by an increasing number of receivers, potentially a billion or more at the time of introduction of a next generation, with some of these receivers being part of critical infrastructures, the continuity of precise and reliable services is a fundamental requirements. As a consequence, any evolution and in particular Kepler has to fulfil this requirement. Since service continuity cannot be retrofitted, it must be a guiding principle for the complete design cycle. The use of dual mode Kepler-Galileo satellites, employed during the transition, was already addressed. This crucial element for transition is also very useful for verification. Beyond sequential operations of Galileo and Kepler, the Kepler design shall support parallel operations. More precisely a simulated Kepler mode shall be possible in parallel to regular Galileo operations. Mixed modes are supported as well.

The hardware for implementing mixed mode operations is shown in Figure 2. The time from the local atomic clock t_{Gal}^k of satellite k and from a local representation KST^k of the distributed Kepler System Time KST are combined in a Time Combination Unit (TCU). In the initial phase, this unit has two outputs: t_{Gal}^k and $\Delta t^k = t_{Gal}^k - KST^k$. In later phase the first output might be replaced by a combination of t_{Gal}^k and KST^k, ultimately ending up in KST^k. The first output is used for the timing of the L-band signal generator. Thus, in the initial phase, there is no difference to a traditional

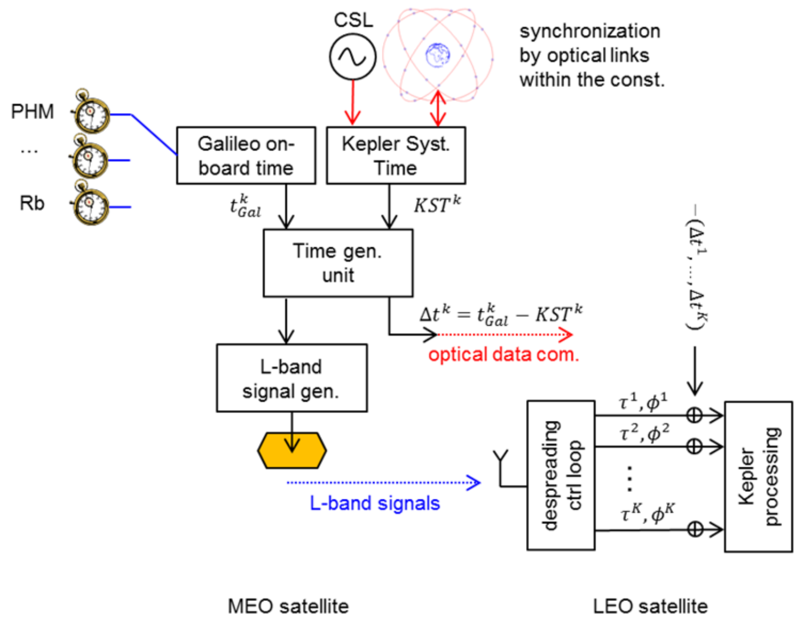

Figure 2: The dual-mode Kepler/Galileo satellites can operate as Galileo satellites, while simulation Kepler operations

Galileo satellite. The difference Δt^k is communicated to the LEO receivers via 50 Mbps optical links. The optical signals are additionally used for time transfer and ranging as foreseen in the Kepler system. The LEO L-band receivers perform a synchronized decorrelation and estimate the code and carrier phase of the received signals. These are then corrected by Δt^k before being further processed. This simulates Kepler L-band transmissions towards the LEO satellites. The quality of this simulation is dominated by the stability of the Galileo atomic clocks, which is not too far from the limitation imposed by L-band phase noise (see Figure 1). The simulated mode is thus not perfect but quite close to it. The simulated L-band measurements allow for orbits computations and bias estimations. The associated information is provided back to the MEO satellites and, at a lower rate, to the control segment via the single 1 Mbps MEO-GND link.

The satellites assemble the navigation messages on board in a Message Generation Unit (MGU). This unit uses inputs from the ground, including the ephemeris data Eph^k_{Gal}, clock offset δ^k $(t_{0c}, a_{f_0}, a_{f_1}, a_{f_2})$ and broadcast group delays BGD, and from the Kepler processing including the ephemeris data Eph^k_{Kep}, the time offset Δt^k, and a broader set of biases, which also includes phase biases. Initially, the navigation messages will only include information from the ground processing. As soon as the Kepler data will have been sufficiently validated, it will be phased into the navigation messages. Since the group delays are directly observable on the LEO satellites and are thus less perturbed than terrestrial estimates, this might be the first information to be replaced.

The parallel approach to operations and validation allows controlling the risk of introducing Kepler and at the same time may reduce the costs of validation, since the associated MEO satellites can be re-used after initial validation, during which the validation procedures control the satellites. After such an initial phase, the satellites could be transferred first into the Galileo constellation and later perhaps even into the Kepler constellation provided that the validation does not require a major redesign of Kepler functions. Taking advantage of such an option requires that the Galileo control is at most marginally affected by the Kepler validation mode and that the control of the different modes is performed from separate centers. The near complete autonomy of Kepler in terms of measurement and communication capabilities is a big asset in this respect. For validation purposes, we thus propose an in-orbit validation mission, named GIOVE-C, consisting of two Kepler/Galileo MEO satellites and one Kepler LEO satellite.

Besides the system aspects, Kepler also introduces a number of subsystems that are new in satellite navigation. Primarily, these are optical subsystems, which all have some flight heritage. This means that these systems went through thermal vacuum and vibration testing and survived a launch, which was often rougher than the type of launches envisaged for Kepler-Galileo. The requirements on the resistance to radiation are rather different, however. Fortunately, radiation testing is performed on the ground in order to achieve the desired doses in a decent time.

Subsystem	**Vacuum and vibrations**	**Radiation hardening**
Lasers 1064 nm	EDRS TRL 9	EDRS TRL 9 in GEO
Ytterbium amplifiers	EDRS TRL 9	EDRS TRL 9 in GEO
Lasers 1550 nm	LEO (in orbit demonstration)	level of testing unknown
Erbium amplifiers	LEO (in orbit demonstration)	level of testing unknown
Cavity 1064 nm	GRACE FO (in orbit test)	
Frequency comb 1550 nm	3 times on sounding rockets	
Coarse and fine pointing assembly	EDRS TRL 9	EDRS TRL 9 in GEO
Modulator and Demodulator 1064 nm	EDRS TRL 9	EDRS TRL 9 in GEO
Drive for rotation of antenna	ROKVISS on ISS (in-orbit demonstration)	e.g. ANIK and early Intelsat Satellites... TRL 9 in GEO
Bearings for antenna		e.g. ANIK and early Intelsat Satellites… TRL 9 in GEO

Table 1: Validation status of various components (EDRS=European Data Relay System, GRACE FO= Gravity Recovery and Climate Experiment – Follow-On, ROKVISS= RObotic Components Verification on the ISS)

The frequency comb plays a critical role in the Kepler concept. Its space compatible implementation drives the choice of the optical wavelength. The dispersion compensation for handling ultrashort pulses, as required for frequency comb generation, is much easier at 1550 nm than at 1064 nm. This is due to the availability of fibers with normal and anomalous dispersion at that wavelength, which are not available at 1064 nm. The latter wavelength requires more complicated mechanisms for dispersion compensation, e.g. gratings. Thus, 1550 nm is the preferred wavelength for the comb. A cavity at 1064 nm can be connected by frequency conversion in nonlinear fibers. The development of radiation hardened fibers at 1550 nm is an engineering issue and not considered as a major risk. For Erbium doped fibers at 1550 nm as well as for Ytterbium doped fibers at 1064 nm radiation hardened fibers are available showing the fundamental concepts. Those concepts still need to be applied for the specific fibers needed for frequency comb generation with higher doping levels and appropriately engineered dispersion.

Cavities are blocks of Ultra Low Expansion (ULE) glass. The main property of the glass that must be preserved under radiation is the ULE property. This needs further investigation but is a priori not considered particularly critical in view of the limitation of the stability to rather short time intervals. The coarse and fine pointing assemblies consist of mirrors and lenses and are considered uncritical. Modulators and demodulators use the same type of components at both frequencies.

Finally, the type of drives envisaged to rotate the antenna has been tested on the International Space Station (ISS) in the ROKVISS experiment. They will require further hardened electronics and some potential tuning. This is again not considered critical. Some experience on despun antennas exists from the time of spin stabilized satellites. Examples include the ANIK and early Intelsat missions. These satellites were spinning with 120 rotations per minute, while the Kepler antenna will rotate with a rate below once per 14 hours.

Besides the space qualification of equipment, the functional qualification of the Kepler system is the other crucial element. It includes, in particular, the simulation of the time generation, with initial results reported in [3], corresponding results for orbit determination reported in [7] as well as a laboratory tests of the optical time transfer, ranging and communications with a setup described in [8]. All this work is carried out in the project on Advanced technologies for Navigation and Geodesy, see [9]. Furthermore, a compact iodine optical clock that could be used as a time basis on LEO satellites is currently being qualified [10].

CONCLUSIONS

Kepler is our proposal for a next generation of satellite navigation systems. It uses optical links to tightly synchronize satellites and precisely measure inter-satellite ranges. The optical links are additionally used for inter-satellite communications, which makes the system rather self-contained. Kepler reuses the orbital slots of Galileo and complements them by small constellation of LEO satellites to observe the transmitted signals. These satellites are at 1209 km, i.e. basically outside of the ionosphere. Thus, these signals are not much subjected to atmospheric delays. This leads to very precise orbits and inter-signal bias estimates. A single terrestrial station is sufficient from a performance perspective to ensure that the constellation and earth rotation stay aligned and that Kepler time remains synchronized to UTC. Additionally, the ground system is used for reconfiguration, upgrading and the like.

Kepler will be introduced at a time, at which the European as well as the world economy heavily depends on Galileo. The present paper introduces initial ideas on how to ensure the necessary level of continuity during the transition process. The parallel operation of Kepler and Galileo is proposed as a central enabler. It allows to operate Kepler in the background without inference in an initial phase and to gradually replace Galileo functions by Kepler functions, as they reach the desired level of certification and assurance. Finally, the paper also provides a very rough idea about the level of maturity of the underlying technology.

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