# Kepler - Satellite Navigation without Clocks and Ground Infrastructure

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Dedicated to my father Alfred Günther †10.6.2018 and my friend Per Enge †22.4.2018.

**Abstract**

Global Navigation Satellite Systems receivers use pseudorange measurements for positioning and time determination. The control system uses the same measurements for estimating the satellite orbits, clock offsets and signal biases in a complex estimation process, which additionally involves the determination of atmospheric delays. In current systems, the separation of these different parameters imposes strong requirements on the stability of the satellite clocks and on the ground infrastructure. Several hundred ground monitoring stations are additionally used in high accuracy applications. The Kepler proposal follows a different approach. It re-uses the Galileo constellation of Medium Earth Orbiting (MEO) satellites, as well as its signals but complements them by a small constellation of Low Earth Orbiting (LEO) satellites and by selected optical Inter-Satellite Links (ISL). The LEO satellites are used to observe the signals transmitted by the MEO satellites from outside the atmosphere. The optical ISL connect all satellites in a multi-hop fashion. This enables a direct synchronization of the satellites at a level not achievable today and additionally does not require that the MEO satellites are equipped with clocks. The optical ISL furthermore provide ranges rather than pseudoranges for orbit determination as well as a broadband intra-system communication network. Terrestrial infrastructures become mostly obsolete with the Kepler approach. A single monitoring and control station remains necessary to maintain the alignment with earth-rotation, the synchronization to Universal Time Coordinate (UTC), and the capability of controlling the system.

## BIOGRAPHY

Christoph Günther studied theoretical physics at the Swiss Federal Institute of Technology (ETH) in Zurich. He completed his PhD in 1984 and worked in different industrial positions at Asea Brown Boveri, Ascom and Ericsson. Since 2003, he is the director of the Institute of Communications and Navigation at the German Aerospace Center (DLR), and since 2004 he is additionally holding the Chair of Communications and Navigation at Technische Universität München (TUM).

## I. INTRODUCTION

Satellite navigation has become quasi indispensable in many areas. This includes air, sea and land transportation as well as logistics; the synchronization of power grids, telecommunication networks and financial system; as well as the automation of agriculture, forestry, mining and construction. The two most important performance measures of satellite navigation are the accuracy and integrity achievable in positioning and timing. The new system described in this paper aims at improving them. We named the new system in honor of Johannes Kepler, who laid the basis for understanding planetary and satellite motion in the early seventeenth century.

Today, extensive ground infrastructures are used to improve the performance parameters mentioned. Dedicated networks for precise positioning typically count more than 100 stations for global coverage with another few hundred per region in order to achieve the desired performance in real-time. Advanced integrity systems exist for aviation with Satellite Based Augmentation Systems (SBAS) counting a few dozens of monitoring stations per region and with Ground Based Augmentation Systems (SBAS) deployed at each airport. A number of such infrastructures already exist but even then need to be maintained and renewed on a regular basis. Kepler aims at achieving a similar - and in some respect superior - performance by only using a constellation of 24 MEO satellites, a small number of LEO satellites and a single ground station. Obviously, in reality a few redundant stations will be used to increase the robustness. The most important elements of Kepler are:

- the global synchronization of all satellites by two way optical links, and
- the observation of the L-band navigation signals without atmospheric distortions by a constellation of Low Earth Orbiting (LEO) satellites.

The optical links are additionally used for ranging and communications. The high-precision optical ranges and the L-band ranges (all signal sources are synchronized) lead to very accurate orbits. At the lowest level of approximation, the Kepler system first synchronizes the satellites and then performs orbit determination. This is the inverted ordering of current GNSS systems. In a strict sense, synchronization and orbit determination are interleaved due to relativistic corrections.

The present paper introduces the Kepler System. Section II discusses the importance of synchronization and how it is achieved on a satellite-by-satellite basis. Section III describes the constellation of MEO and LEO satellites and the achievement of connectivity among all satellites. The set of measured inter-satellite time offsets are consolidated into Kepler System Time


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(KST) in Section IV. The synchronization in the optical domain is transferred to the L-band in Section V. Specifically the offsets of the local time source with respect to KST is compensated in the generation of the L-band navigation signals. Section VI shortly addresses the determination of orbits and signal biases. Integrity and other aspects are taken up in Section VII. Conclusions are finally drawn in a last section. Many of these aspects are deepened in additional papers of the same session, they include:

- initial results on precise Kepler orbits, described by Michalak et al. in [1],
- optical clock technologies, as used for Kepler, introduced by Schuldt et al. [2],
- the development of a test setup for optical inter-satellite links, described by Poliak et al. [3], and
- the generation of Kepler system time, discussed by Schmidt et al. [4].

Additional information about the technologies used in Kepler is provided in the paper by Giorgi et al. [5]. Furthermore, Glazer presents a first analysis of the impact of some properties of the Kepler system on geodetic parameters [6]. A more detailed presentation of the system is provided in a full paper [7].

## II. Basic Principle

Current Global Navigation Satellite Systems (GNSS) are based on the measurement of pseudoranges, which are jointly used to determine the receiver's position $\vec{r}$ and the offset of its clock $\delta$. The pseudorange $\rho^k$ associated with satellite $k$ is defined by

$$\begin{aligned} \rho^k &= c(t_R - t_T^k) \\ &= \|\vec{r} - \vec{r}^k\| + c(\delta - \delta^k) + \ldots + \eta^k \end{aligned} \tag{1}$$

with $t_T^k$ denoting the time of transmission by satellite $k$ measured using the satellite's clock, and with $t_R$ denoting the time of reception measured using the receiver's clock. The different clocks used at the transmitter and receiver are the origin of the clock offsets $\delta^k$ and $\delta$ in the second line of the equation. The other symbols in the equation are the satellite's position $\vec{r}^k$, the additive white Gaussian noise $\eta^k$, and unspecified atmospheric and multipath delays as well as instrumental biases, which are not of much interest in the present discussion and thus replaced by dots.

The information about the satellite's orbit and clock offset are described in a so-called navigation message broadcast by the satellite. GPS and Galileo messages have a nominal life-time of 120 and 100 minutes, respectively. As a consequence, the description of the orbit and of the clock offset must remain valid during that time interval, which requires that the clocks are stable over these times. The separation of orbits and clocks in the estimation process actually requires an even longer stability, namely over several hours.

The second line in Equation (1) depends on the clock offsets $\delta^k$ and $\delta$ but not on absolute time. Thus, it is natural to consider the possibility of directly synchronizing the transmissions of the satellites. This does not require clocks in the proper sense, just oscillators for generating the signals that remain stable during the synchronization process. The latter synchronization process consists of four steps:

- measurement of time offsets by two-way signaling,
- propagation of the measurement results to all satellites,
- computation of the clock offsets in a common reference frame,
- correction of the offsets during signal generation.

The second step is discussed in Section III and the last two steps are analyzed in Section IV. We shall presently focus on the first step, and on the selection of an appropriate reference oscillators and measurement techniques.

Two-way signaling allows to perform time transfer without interfering with the movement of the satellites. Consider for simplicity a one dimensional movement of the satellites in the absence of gravity, with Satellite 1 flying with a constant velocity $v_1$ behind Satellite 2, which moves with velocity $v_2$, see Figure 1. Both velocities are constant with respect to the coordinate system $\mathcal{K}$. Furthermore, assume that Satellite 1 sends a pulse to Satellite 2 at time $\tau_{1,T}$, which is received at Satellite 2 at time $\tau_{2,R}$, and retransmitted without delay $\tau'_{2,T} = \tau_{2,R}$ to Satellite 1. Satellite 1 receives the returned pulse at time $\tau'_{1,R}$, see Figure 1. The times $\tau$ are measured locally by the satellites, i.e. they are the proper times of the events in coordinate systems that move with the transmitting or receiving satellite, respectively. The quantities without prime relate to the initial pulse from Satellite 1 to Satellite 2, while the primed quantities relate to the return pulse from Satellite 2 to Satellite 1. All time readings are exchanged among the satellites. The consideration of a single pulse is simple. In reality a structured continuous signal is transmitted and sampled 50 millions times per second. The latter results are filtered before being exchanged. Under the stated conditions the clock offset between of Satellite 2 with respect to Satellite 1 expressed in the coordinate system $\mathcal{K}$ is:

$$\Delta t_{21} = \gamma(v_2)\tau_{2,R} - \frac{\gamma(v_1)}{2}\left[\left(1 + \frac{v_1}{c}\right)\tau'_{1,R} + \left(1 - \frac{v_1}{c}\right)\tau_{1,T}\right], \tag{2}$$

with $\gamma(v) = 1/\sqrt{1 - v^2/c^2}$. Since the time offsets $\tau_{2,R}$, $\tau'_{1,R}$, and $\tau_{1,T}$ are all measured by the satellites and exchanged, the clock offset $\Delta t_{21}$ can be determined. All clock offsets $\Delta t_{21}$ between pairs of satellites are communicated to all satellites at a rate of twice per second. The expression corresponding to Equation (2) in three space dimensions and in the presence of masses is non-linear, but the difference $\Delta t_{21}$ can again be determined by proper processing. The geocentric coordinate system

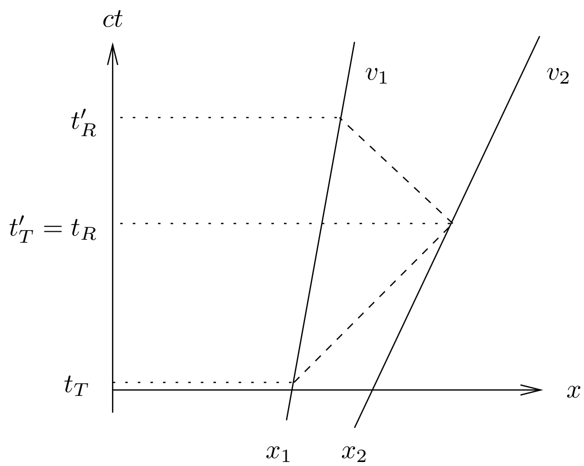


Figure 1. Two-way time transfer: a pulse is sent from Satellite 1 to 2 and then returned back to Satellite 1. The respective times of transmission and reception are measured and subsequently exchanged.

that is co-moving with the center of gravity of the earth is an option for the coordinate system $\mathcal{K}$ . The associated time is the Temps Coordonnée Géocentrique (TCG). The practical aspects of this choice are to be further consolidated. Today's GNSS

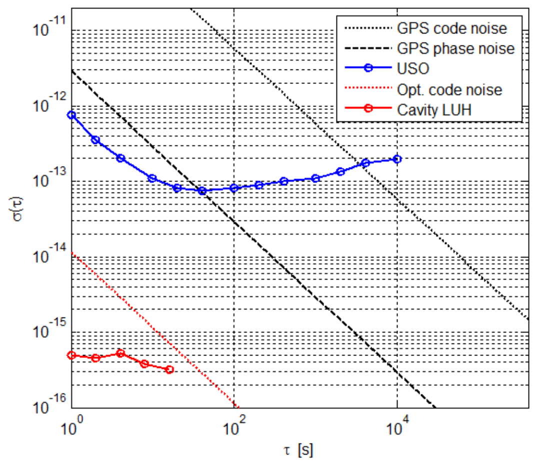


Figure 2. Allan deviation of an Ultra Stable Oscillator (USO) [8] and of a Cavity Stabilized Laser (CSL) [9]. The straight additional lines are the second term in Equation (3) and (4) for L-band measurements performed on earth (upper lines) and for optical ISL links (lowest line).

are using radio frequencies (mainly L-band) both for links and reference oscillators. Ultra Stable quartz Oscillators (USO) are the most stable oscillators at these frequencies. They are obtained by using carefully selected quartz crystals maintained at a constant temperature. The Allan deviation of such an USO is shown in Figure 2 (blue circles). If such an USO was used to generate Galileo signals, and if these signals were measured on earth (there are currently no links between satellites), these measurements would be significantly degraded by measurement noise. Since the disturbances to the oscillator and to the link are statistically independent, the associated Allan variance measured on the ground would be

$$\sigma^2_{A,\rho}(\tau) = \sigma^2_{A,Osc}(\tau) + 3\frac{T_c^2\sigma_\rho^2}{\tau^2} \tag{3}$$

for code measurements, and

$$\sigma^2_{A,\phi}(\tau) = \sigma^2_{A,Osc}(\tau) + 3\frac{\sigma_\phi^2}{(2\pi f_c\tau)^2} \tag{4}$$

for phase measurements, with $\sigma_\rho$ and $\sigma_\phi$ being the code and carrier measurement noise, respectively. This is optimistic, since it neither involves atmospheric nor multipath components. Figure 2 shows the square root of the second terms from the above equations (blue dashed and dotted lines) under the assumption that the code noise is 10 cm and the undifferenced phase noise is 0.5 mm. The size of these terms suggests that the stability of the USO becomes at best apparent using carrier phase measurements. As a consequence considering improved oscillators together with measurements in the radio frequency domain is unattractive. The situation changes totally in the optical domain. The noise of the optical inter-satellite code measurement is plotted as a dashed red line in the same plot. The associated uncertainty of the individual measurements ($5 \cdot 10^7$ per second) is roughly 20 $\mu$m. They are furthermore not impaired by atmospheric delays and multipath. The phase noise for the optical signals is several orders of magnitude smaller and not visible in the plot. A Cavity Stabilized Laser (CSL) is the oscillator of choice under these circumstances. Its performance is shown as red circles. These oscillators are orders of magnitude more stable than USOs, which are themselves much more stable than any current atomic clock at short times. Short times means values of $\tau$ of several seconds. Since the measurements are performed continuously and since they only take one second to propagate to all satellites the achieved level of synchronization is outstanding. The latter is limited either by the optical code noise if code noise measurements are used or by the stability of the CSL if optical phase measurements are evaluated. Optical carrier phase measurements are feasible since the associated ambiguities can be mapped to the clock biases, which is discussed in more detail in [7].

## III. Constellation and Optical Connectivity

Today's Galileo system uses a Walker (24/3/1) constellation. Such a constellation has three orbital planes with 8 satellites that are equally distributed in each plane. The phasing between the satellites in different planes is $2\pi/8$. Kepler uses the same constellation and the same assignment of orbital positions in order to allow for a smooth transition using dual-mode satellites. The dual-mode satellites are first operated as Galileo satellites. As soon as there are enough dual-mode satellites in one orbital plane the mode is switched to Kepler. Two-way optical links are realized between adjacent satellites in each orbital plane, with the possibility to skip one satellite in the case of a failure. This arrangement requires an ahead and a behind terminal on every satellite. They are arranges on the back side of the earth-pointing L-band navigation antenna. The attitude control of the satellite is identical to Galileo: the $z$-axis of the satellite is earth pointing and the solar panel are maintained oriented towards the sun. In Kepler, the antenna plane with its ahead and behind terminals is additionally despun with respect to the satellite rotation in order to maintain the terminals in the orbital plane. This arrangement ensures a constant geometry and allows to maintain synchronization in each orbital plane, see Sections IV and V. A constellation of four Low Earth Orbiting (LEO)

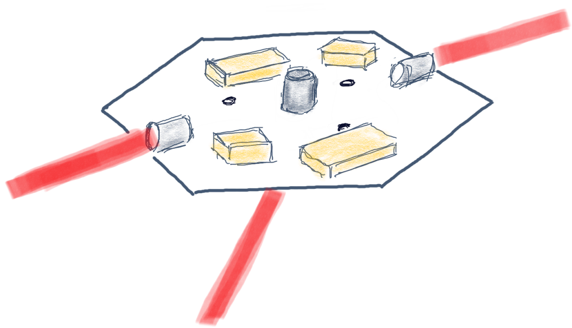

Figure 3. This drawing shows the ahead and behind as well as the downward pointing terminals mounted on the back of the L-band antenna plane.

satellites furthermore enables the inter-plane connectivity. They are equipped with the same CSL as the MEO satellites and a set of 3 to 4 optical terminals that together cover the upper hemisphere. The inter-plane connectivity is achieved by MEO-LEO links, facilitated by downward looking terminals on the MEO satellites, see Figure 3. The downward looking MEO terminals need to cover an angle of up to $14°$ as measured from the nadir direction, which can be achieved with rather simple designs. The link budget and other performance parameters are developed in the full paper [7].

The optical ISL signals are spread spectrum signals with a chip-rate of 25.55 Gcps. Sequences of 511 chips are used to perform time transfer and ranging. The range $r(t_R)$ at the time of reception of the pulse by Satellite 2 in the setup of Figure 1 is obtained in a similar manner as for Equation (1). With the same notations:

$$r(t_R) = \frac{1}{2\gamma(v_1)} c \left( \tau'_{1,R} - \tau_{1,T} \right)$$

Vibrations are thereby pre-compensated and the ranges are filtered with a bandwidth of 2 Hz, before being collected for orbit processing. The optical ISL spread spectrum signals are furthermore modulated by communication data. The raw bit error rate of the communication system is at most $10^{-6}$, which is further reduced by coding.

## IV. Synchronization and Kepler Time Scale

Under nominal conditions, all satellites receive all inter-satellite time offsets at a rate of 2 per second. Each satellite can thus compute a composite time associated with all time offsets measured in the system. Corresponding algorithms were developed by Brown [10] and Greenhall[11]. Due to the lack of long term stability of the CSL, a time scale based on CSL alone would successively drift. This must be prevented. Furthermore, the Kepler time scale should be synchronous to Universal Time Coordinated (UTC) as well. In the case of Galileo, a UTC representation by an H-maser of the Galileo Time Service Provider

(GTSP) is used for this purpose. Similarly, L-band measurements of Kepler are used to ensure long term stability. The blending of CSL and H-masers leads to an ensemble of clocks with widely varying properties. Greenhall's algorithm [11] is best suited for handling such situations. The resulting Implicit Ensemble Mean (IEM) essentially follows the most stable source at all values of $\tau$, i.e. forms a sort of lower envelope of the Allan deviations of all sources. This behavior has been observed in many simulations, also for Kepler [4]. The Greenhall algorithm computes the IEM using a Kalman filter and a renormalization of the time component of the covariance matrix. This IEM is the Kepler System Time (KST). Greenhall's algorithm also provides the offset of each oscillator from the IEM, which means that every oscillator represents the IEM.

Figure 4 shows three models of oscillators: a Menlo cavity, the iodine clock of Schuldt et al. [2] and a Kvarz H-maser. They were chosen due to the availability of data in a sufficiently large span of $\tau$ to derive two state models for them. The latter models are needed to run the composite time algorithm, which was done by Trainotti [4]. He used 24 CSL on MEO satellites, 4 CSL as well as 4 iodine clocks on LEO satellites, and one H-maser on the ground. The resulting KST is plotted in Figure 4, see Schmidt et al. for more details [4]. The result shows that KST follows the H-maser for time intervals longer than 1000 seconds in the absence of measurement noise. For L-band carrier phase measurements, this applies for values larger than 10'000 seconds. In this time domain, the KST is controlled by the H-maser, which represents UTC. Below 50 seconds, the KST follows the ensemble of 28 CSLs. In the gap between 50 and 10'000 seconds the stability of the time scale is influenced by the noise of carrier phase measurements on the ground. Since this is at the limit of observability for terrestrial users, the associated degradation is uncritical to them. However, in the Allan deviation plot, this looks like a significant degradation. The iodine clock developed by Schuldt et al. [2] ideally fills the gaps. The data shown are from a validation of the iodine clock using a CSL by Schuldt et al. [12] extended to a model for that clock. In the Kepler system the iodine clocks are placed in orbit to avoid too much dependency on ground links. Any orbit is a candidate for their placement, as long as the clock can be connected optically to the Kepler system. An interesting choice is to place them on one or several LEO satellites. These satellites can be easily replaced whenever improved clock technologies become available. Using the present proposal, the Kepler time scale is more stable than $10^{-15}$ at all times shown in the plot and most importantly: the KST follows UTC rather closely.

Operationally, all CSL and all clocks are free-running - otherwise the models for these clocks would loose their validity and the unmodified Greenhall algorithm could no more be applied for computing KST. KST is implemented by compensating the time offsets of the local CSL, as estimated by the Greenhall algorithm, during the generation of the L-band signals. This ensures that the L-band navigation signals are synchronized among each other.

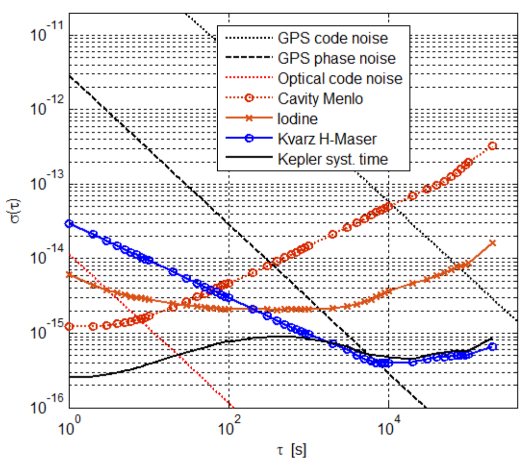


Figure 4. The Kepler time scale (black line) is controlled by the CSL and optical links (red circles) for times up to 50 seconds. Above 10'000 seconds it is the comparison with a terrestrial representative of UTC (blue circles) which dominates, and in between, it is the iodine clock (red crosses), which exerts control [Courtesy of Christian Trainotti, DLR].

## V. Signal Generation

The previous sections showed how Kepler establishes a global synchronization of all satellites in the optical domain. Although it was not mentioned, this requires that a carrier frequencies $\nu_a$ be used on MEO ISLs in the directions ahead to behind, i.e. co-rotating, and a different frequency $\nu_b$ in the direction behind to ahead, i.e. counter-rotating. The same applies to the down and up direction between MEO and LEO satellites. While $\nu_a$ is obtained from the CSL, $\nu_b$ must be derived from it. Both frequencies are rather close. For $\nu_a$ two choices: $\nu_a = c/1064$ nm or $\nu_a = c/1550$ nm are currently being considered. Beside $\nu_b$, the timing signals for the optical and for the L-band signals must also be generated. They have rates of $2.555 \times 10^{10}$ and $1.023 \times 10^7$ clock cycles, respectively. All these signals must remain locked at all times. This is achieved using a so-called frequency comb for whose invention Hall and Hänsch received the Nobel Prize in 2005. A frequency comb synchronizes the envelope and carrier of femto-second laser pulses with a repetition frequency typically in the radio frequency domain. This creates a comb of spectral lines with locked signals from which all desired signals can be synthesized, see Udem et al. [13]. Figure 5 shows a schematic for the signal generation on a Kepler satellite. It also includes the correction of the timing of the L-band signals by the time offset with respect to the IEM. This latter synchronous L-band signals are then radiated towards earth by the nadir-pointing navigation antenna with a satellite clock offset $\delta^k$ set to 0. The Kepler receiver correspondingly needs only compute and apply relativistic corrections.

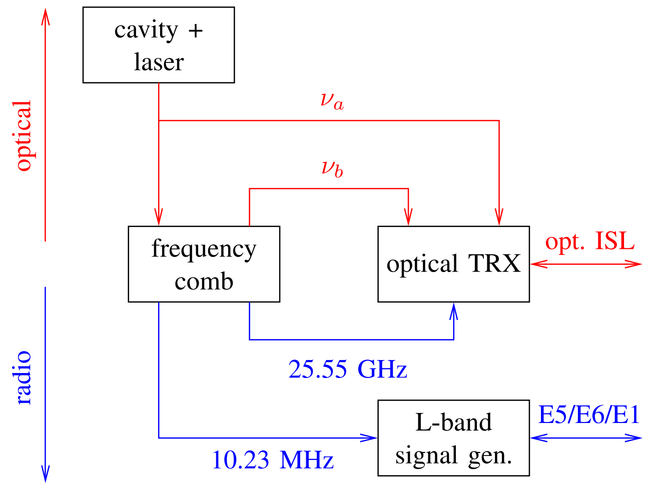


Figure 5. All signals are derived from a Cavity Stabilized Laser (CSL). The frequency comb creates the links between the optical and radio-frequency domain.

## VI. Orbits and Biases

The L-band signals transmitted by the MEO satellites are received and analyzed by the LEO satellites. Since the LEO satellites are globally synchronized with the MEO satellites, the measurements of time differences in the coordinate system $\mathcal{K}$ are ranges. Remember that the time component of the coordinate system is TCG or a similar choice. Additionally, all LEO satellites perform (two-way) range measurements to at least two MEO satellites and all MEO satellites perform similar measurements with respect to their neighbors. This creates a mesh of L-band and optical measurements, which are used for orbit determinations. Since the plasma density above 1209 km is extremely low, these measurements are not much affected by the atmosphere, Additionally, L-band pseudoranges are measured by one single ground station to maintain the alignment with earth rotation. Clearly, several ground stations may be used for robustness but are not needed to achieve the performance described below. The orbit determination capabilities were analyzed by G. Michalak et. al. [1]. They performed both simulations without any impairment beyond measurement noise, as well as simulations with a number of mismodeling assumptions. The latter included: phase center offsets, differing models in the simulation and in the estimation for solar pressure, air drag, gravity field, earth tides and ocean loading. They used a simple force model to absorb the mismodeling and estimated the associated parameters in 30 minutes intervals. The estimation was performed by least squares - which will need to be extended to a Kalman filter approach in the future. Nevertheless the quality of the estimates are indicative. The measurement noise was assumed to be 50 cm for L-band code measurements, 3 mm for L-band phase measurements and 1 mm for optical range measurements. The worst case errors in the estimation of the orbit for the MEO are 5.0 cm rms and 0.6 cm in the important radial direction with float ambiguities. The LEO orbital errors are at 1.4 cm rms. The code noise and mismodeling assumptions are very conservative. Fixing the ambiguities further improves the results. The use of least squares estimation needs to be revisited but is not expected to change the picture significantly.

Besides orbits the measurements without atmospheric delays also facilitate the direct measurement of spatial L-band biases. The latter can be calibrated using optical links and tracked by comparing the propagation delays of code and carrier signals at different frequencies among each other.

## VII. Additional Aspects

### A. Integrity and Augmentation

Receivers in LEO orbit can be used to verify the integrity of the signals and of the navigation messages. Either the Kepler LEO receivers or receivers on separate LEO satellites can in principle be used. Ensuring integrity means that all satellites must be observed at all times. Uncompensated biases are detected by analyzing code and carrier signals at different frequencies. Isolated anomalies in the signal or message generation are detected by verifying the consistency of the signals among themselves. Ideally, optical links are included since they have different failure modes. The other measurement results are all analyzed for inconsistencies. This can be performed on a LEO satellite by satellite basis and additionally by comparing measurements made by different LEO satellites.

The satellite-by-satellite procedures are executed on the basis of 10 ms intervals of signal. Whenever an anomaly is considered critical, an alarm is sent to the users. This is implemented by preempting a Galileo/Kepler half-frame, which takes at most one second, propagating the signal to the remote satellite and transmitting it to the user, which takes another second (see below) and receiving the frame at the user location, which takes again one second. This implies that users receive integrity alerts within 3 seconds, which is close to the time of 2 seconds specified for Ground Based Augmentation Systems (GBAS).

Since receivers increasingly use signals from several constellations, integrity must be provided for other GNSS systems as well. The observation by LEO satellites is thus extended to these systems. The lack of optical links will in this case lead to larger detection thresholds and thus to a somewhat increased time to alert. The absence of atmospheric disturbances still provides an improved observability of signal in space errors as compared to ground measurement. Furthermore, the short propagation time of alerts remains unchanged.

### B. *Networking*

The networking of the satellites is organized through the optical links. The comparatively high data rate of 50 Mbps keeps the queuing delays short. A first signal format is described in the full paper [7]. The furthest path between two MEO satellites is reached in three segments: a first segment in orbital plane of the source MEO satellite, a second segment to reach the orbital plane of the target MEO satellite and a third segment in the latter orbital plane. Since each MEO orbital plane counts 8 satellites, the worst number of hops is 4. Additionally, two hops a MEO-LEO and a LEO-MEO are needed to connect the orbital planes. Adding up all these delays leads to a worst case delay of 795 ms.

The connection between the ground control center and the satellite constellation is established by a bi-directional ground to MEO link with a capacity of 1 Mbps. The connection can be with any MEO satellites that is visible at a high elevation above the ground station. This anchor-MEO distributes and collects the data to/from the constellation. All control and measurement data between the ground and space-segment are exchanged through this link.

### C. *System Security*

Within the constellation all data are transported via optical links. The divergence of those links is so small that the area illuminated by the signal has a radius of around 700 m at the inter-satellite link distance! As a consequence, these optical links are essentially impossible to jam or spoof. The L-band receive antenna of the LEO is upward looking at an altitude of 1209 km, which makes jamming and spoofing difficult from the ground. The robustness of the receiver can be further increased by spatial processing. Attacks that we could think of are either space-based or of a military nature. This compares favorably with current GNSS systems.

## VIII. CONCLUSIONS

Kepler uses the most stable oscillator technology currently available - namely CSL. It synchronizes these lasers using inter-satellite links between all MEOs in one orbital plane and through the LEOs between planes. The accuracy of the synchronization is limited by the capability of compensating satellite vibrations and ultimately by the stability of the lasers. The latter have an Allan deviation of around $10^{-15}$. The synchronization of the satellites is the basis for the determination of the orbits using L-band and optical ranges (not pseudoranges). The latter are measured without atmospheric contributions, which leads to very accurate satellite orbits (below 1 cm in radial direction) even with pessimistic mismodeling assumptions. The orbit determination is still based on least squares estimation. A Kalman estimation approach is currently being prepared. The alignment of the satellite orbits with earth rotation as well as the synchronization of Kepler system time with UTC are achieved by one single ground station. This is the only ground infrastructure really needed. The maintenance of time synchronization in the case of a loss of the ground link is mitigated by a small group of long term stable clocks on LEO satellites. Replacing any of those satellites by satellites carrying newer, more stable, clocks immediately propagates the improved stability throughout the complete constellation.

The Kepler system has great operational benefits and creates potentials for the future. Besides this, we expect to provide stable Precise Point Positioning (PPP) services without external infrastructures. This expectation is based on the near perfect synchronization, the accurate orbits and the direct determination of signal biases. The capability of establishing global integrity services without further augmentation is another direct benefit of Kepler. Intercontinental optical time transfers down to very short time intervals $\tau$ are promising as well. Additional scientific benefits in geodesy have been identified by Glaser et al. [6].

Some technologies needed in Kepler are not used in current GNSS systems. Most of them have gone through thermal-vacuum testing and flown in space, however. The associated orbits range from sounding rocket flights to geostationary orbits. Obviously sounding rockets and LEO satellites are in another class with respect to radiation hardening. Selected new developments are needed in this respect. These development as well as verifying these technologies in space with the goal of creating trust in the concept are an important focus of our work in the coming time; developing a validation plan for the system is another one.

## ACKNOWLEDGMENT

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## REFERENCES

[1] G. Michalak, K.-H. Neumayer, and R. Koenig, "Precise Orbit Determination with Inter-Satllite Linsk and Ultra-Stable Time for a Future Satellite Navigation System," in *Slides from ION GNSS$^{+}$18*.

[2] T. Schuldt, M. Oswald, M. Gohlke, J. Sanjuan, K. Abich, K. Döringshoff, E. Kovalchuck, A. Peters, and C. Braxmaier, "Optical Clock Technologies for Future GNSS," in *Proc. of the ION GNSS$^{+}$18*.

[3] J. Poliak, R. Mata-Calvo, and J. Surof, "Laboratory Demonstrator of Optical Inter-Satellite Links for the Kepler System," in *Proc. of the ION GNSS$^{+}$18*.

[4] T. D. Schmidt, C. Trainotti, J. Isoard, G. Giorgi, J. Furthner, and C. Günther, "Composite Clock Approach for System Time in Global Satellite Navigation Systems," in *Proc. of the ION GNSS$^{+}$18*.

[5] G. Giorgi, T. D. Schmidt, R. Mata-Calvo, C. Fuchs, M. M. Hoque, J. Berdermann, C. Furthner, C. Günther, T. Schuldt, J. Sanjuan, M. Gohlke, M. Oswald, C. Braxmaier, K. Balidakis, G. Dick, F. Flechtner, M. Ge, S. Glaser, R. König, M. Grzegorz, M. Murböck, M. Semmling, and H. Schuh, "Advanced Technologies for Satellite Navigation and Geodesy," *submitted to Advances in Space Research*.

[6] S. Glaser, G. Michalak, M. Murböck, K. Balidakis, R. König, G. Dick, M. Semmling, M. Ge, J. Wickert, F. Flechtner, and H. Schuh, "On the Impact of Inter-Satellite Links and Ultra-Stable Clocks within Future GNSS Constellations on Geodetic Parameters," in *Proc. of the ION GNSS$^{+}$18*.

[7] C. Günther, "Kepler - A Concept for Future Satellite Navigation Systems," *submitted to Journal of the Institute of Navigation*.

[8] P. Cash, D. Emmons, and J. Welgemoed, "Ultrastable Oscillators for Space Applications," Symmetricom San Jose CA, Tech. Rep., 2008.

[9] A. Pape, "Hochstabiler Lokaloscillator für einen Optischen Magnesium-Frequenzstandard," Ph.D. dissertation, Leibniz Universität Hannover, 2012.

[10] K. R. Brown Jr, "The Theory of the GPS Composite Clock," in *ION GPS-91; Proceedings of the 4th International Technical Meeting of the Satellite Division of the Institute of Navigation*, 1991, pp. 223–241.

[11] C. A. Greenhall, "A Kalman Filter Clock Ensemble Algorithm that Admits Measurement Noise," *Metrologia*, vol. 43, no. 4, pp. 311–321, 2006.

[12] T. Schuldt, K. Döringshoff, E. V. Kovalchuk, A. Keetman, J. Pahl, A. Peters, and C. Braxmaier, "Development of a Compact Optical Absolute Frequency Reference for Space with $10^{-15}$ instability," *Applied Optics*, vol. 56, no. 4, pp. 1101–1106, 2017.

[13] T. Udem, R. Holzwarth, and T. W. Hänsch, "Optical Frequency Metrology," *Nature*, vol. 416, no. 6877, p. 233, 2002.