OPTICAL CLOCKS IN FUTURE GLOBAL NAVIGATION SATELLITES

U. Hugentobler[1], M. Plattner[2], S. Bedrich[2] , M. Heinze[1] , V. Klein[2] , D. Voithenleitner[1]

[1]Technische Universität München. Arcisstrasse 21, 80333 Munich, Germany, Email: urs.hugentobler@bv.tum.de
[2]Kayser-Threde GmbH, Wolfratshauser Strasse 48, 81379 Munich, Email: markus.plattner@kayser-threde.com

ABSTRACT

The primary payload of a navigation satellite is its clock that is indispensable to perform precise ranging measurements. Navigation and positioning performance depends, among others, on the quality of the frequency generator. The first Hydrogen maser is in orbit with GIOVE-B. With further progress of clock technology a future GNSS system could be equipped with optical clocks, thereby making available a network of frequency standards of utmost stability in space.

Today, epoch-wise synchronisation of satellite and receiver clocks is an integral part of precise carrier phase positioning. As a consequence only relative positions are obtained with high accuracy and reference sites with well-known coordinates are needed to retrieve absolute position. Synchronised space clocks, on the other hand, allow for absolute precise positioning in single receiver mode. Similarly precise orbit determination will profit from the increased stability of the observation system. Simulations for the latter are presented in the paper.

Optical clock technology can be divided into two main implementations. Single ion clocks have a higher technical maturity while a stable frequency is obtained in a shorter integration time with optical lattice clocks. A trade-off between the different types of optical clocks involves not only performance but also readiness for space qualification of the optical clock components.

1. CLOCKS AND NAVIGATION

Global Navigation Satellite Systems (GNSS) broadcast all information a user requires for autonomous navigation in real time. The basic principle of satellite positioning consists of time-of-flight measurement of transmitted signals. Clocks thus play an eminent role, stable signal generators are the primary payload of a navigation satellite. Since the signals travel only in one direction – from the satellite to the receiver – the time of flight is measured with two different clocks at both ends of the light path. Synchronisation of the receiver clock with the space clocks is thus an integral part of the positioning task.

For high precision applications based on carrier phase measurements, all involved clocks, including the satellite clocks, need to be synchronised for each measurement epoch in order to achieve maximum positioning accuracy. As a consequence only relative positions of antennas in a network are obtained with highest accuracy while the entire network may easily be shifted without degrading observation residuals. Reference sites with well-known coordinates are thus required to retrieve precise absolute site positions.

Satellite optical clocks that are stable enough in order to synchronise them at the level of a few picoseconds for hours or days would fundamentally change this picture. The high-precision user would work with a constellation consisting of *n* satellites but with a single space clock. He would thus obtain the geodetic datum of the reference system realised by the satellite constellation with carrier phase precision in real time without need for additional information from reference stations. A large variety of applications can be envisaged in such a scenario ranging from centimetre accuracy in absolute navigation without requiring of additional servicing installations and communication links to tsunami warning systems that include high precision real-time kinematic positioning sensors at remote locations.

The advantages of highly stable satellite clocks can only be materialized if error sources, e.g., in propagation delays or satellite orbits are controlled at a precision similar to the clock stability since modelling errors could not be absorbed by a large number of epoch-wise estimated clock parameters. Typically, e.g., radial orbit errors are compensated by satellite clock corrections. If no or only few satellite clock parameters need to be estimated in the orbit determination process, an improvement of the radial orbit error can be expected. If phase accuracy, i.e., mm-level accuracy is strived for, modelling of relativistic clock corrections will have to include effects caused by Earth oblateness – corrections of some 60 ps or 2 cm [1] – in addition to the classical eccentricity dependent term.

With current clocks, prediction at a precision corresponding to carrier phase measurements is not feasible even for short time periods. Orbit prediction is, however, routinely done at the sub-decimetre level. With highly stable satellite clocks this situation is inverted: Clock prediction would be straight forward and prediction errors would be dominated by orbit errors. Orbit prediction accuracy will, however, improve with refining orbit models and exploiting of clock stability for precise orbit determination.

2. OPTICAL CLOCKS

Contrary to microwave clocks, where an atomic transition in the microwave range is excited, optical clocks are based on an atomic transition in the optical domain. Using optical frequencies as clock oscillator can yield higher accuracy since the ticks of the clock have much shorter timing intervals. A typical block diagram of an optical atomic clock is shown in Figure 1.

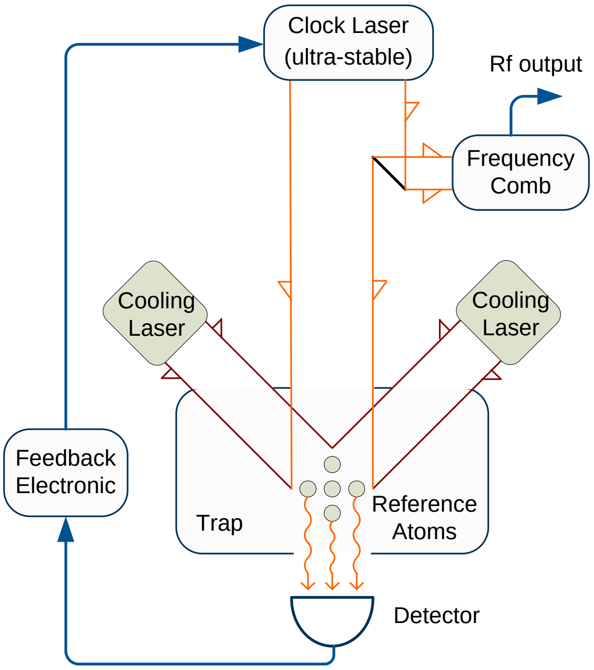

Figure 1: Block diagram of an optical clock. The main components are clock laser, atom or ion trap and feedback electronic for closed loop control of the laser frequency. The frequency comb is used for transforming optical to microwave frequencies.

Optical clock technology in principle can be divided into two main implementations: single ion or optical lattice clocks [2], [3]. Single ion clocks use a magneto-electrical trap like a Paul trap in order to confine a charged atom locally. Considering an optical lattice clock, an additional laser for generating an optical lattice wherein a bunch of neutral atoms is trapped, is needed instead of the Paul trap. Although single ion clocks benefit from their simpler and more mature setup, lattice clocks potentially will yield higher stability. This is due to the fact that in a lattice clock a high amount of atoms is used and thereby a high signal to noise ratio is achieved by averaging.

The reference atoms (or the reference ion) are locally confined in a trap. Reducing the temperature of the atoms down to micro Kelvin range by laser Doppler cooling results in atomic motion amplitudes of less than 100 ns. The natural linewidth $\Delta f = {}^{1}\!/_{(2\pi\tau)}$ of the transition depends on the lifetime τ of the upper state. Long lifetimes are desired in order to ensure narrow linewidth of the transition frequency and thereby high stability of the frequency standard.

An ultra stable clock laser is used to probe the transition of the ion or neutral atoms. To achieve the necessary sub-Hertz linewidth, the laser is locked to a reference cavity [4]. The cavity itself has to be decoupled from environmental disturbances by temperature and vibration shielding. Laser excitation of the reference atom is measured by a photo detector. A feedback electronic automatically tunes the laser frequency in order to maximize the excitation probability of the single ion or the number of excited atoms in a lattice clock. The laser frequency is then “down-converted” to radio frequency signals with an optical frequency comb. Thereby the frequency signal can be evaluated by standard electronic equipment like a frequency counter.

Selecting the technology and the reference atom which is used inside an optical clock determines the available optical transitions and thereby the wavelengths and characteristics of all necessary lasers and subsystems including the highly stable probe laser. Since different subsystems of different clock technologies all have varying complexity, a trade-off between all possible clocks has to be performed carefully. In an ongoing study we are estimating the achievable performance benefits for different optical clocks inside navigation satellites. These results will then be compared to the technical effort which is necessary to space qualify the different optical clock technologies.

Taking GIOVE satellite data as a basis, an optical clock has to cope with the expected space environmental conditions. Enhanced temperature ranges, vacuum, microgravity and radiation loads are the main concerns that need to be considered during development of a space proven optical clock. The absence of air and gravitation leads to modified heat distribution and to out-gassing of lubricants and polymers. Total ionizing doses of more than 10 krad per year have been identified by radiation monitors mounted on GIOVE [5]. This irradiation dose can lead to photo darkening in optical components like lenses or fibres. Also electronic equipment has to be rebuilt using radiation hard components. Additionally to the above mentioned space related conditions it has to be ensured, that the optical clock survives shock and vibration loads during launch.

Several projects funded by European or national space agencies have already been realised in order to bring optical clock technology into space. One study, which was led by NPL [6], compared optical clock technologies and estimated the development effort for space qualification. The most promising candidate in this study was the Strontium ion clock because of its high technical maturity. In the international project Space Optical Clocks (SOC) [7] two optical lattice clocks are currently under development based on Strontium and Ytterbium neutral atoms. The goal of this project is to develop transportable optical lattice clocks which can be shipped from one laboratory to another in order to enable comparison of clock parameters.

3. STABLE CLOCKS FOR PRECISE ORBIT DETERMINATION

As mentioned in Section 1, highly stable clocks such as optical frequency generators can support precise orbit determination. In order to investigate the potential, e.g., for the system operator, simulations were performed involving a Galileo constellation of 27 satellites tracked by eight globally distributed stations (CONZ, HRAO, MAUI, NTUS, TIDB, TSKB, UNB1, WTZR). Such a small network does hardly allow for a continuous covering of all orbit positions with two or more tracking stations (see Fig. 2). For specific tests the network was further reduced to five globally distributed sites.

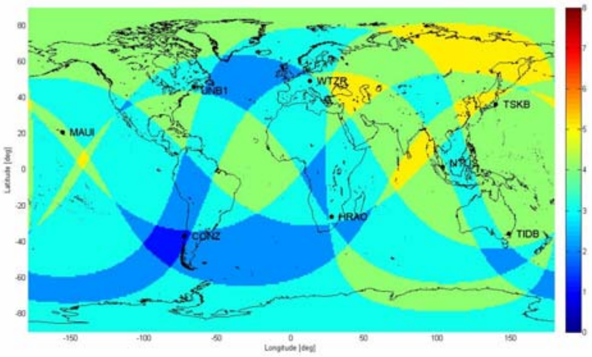

Figure 2: Depth-of-Coverage for the simulated eight stations network adopting an elevation mask of 10°.

Simulations and analysis were performed using a modified version of the Bernese GPS Software, V5.0 [8]. A different a priori radiation pressure model and more sophisticated troposphere modelling were applied for simulating the observations than for the later analysis. Pseudorange and carrier phase observations were simulated for E1 and E5a with measurement noise of 20 cm and 2 mm (1 sigma) respectively. Realistic clock performances were used for Rubidium frequency standards (RAFS), Hydrogen masers (SPHM), and optical clocks to simulate clock offset time series for satellites and ground stations (Fig. 4). Fig. 5 shows the corresponding time series.

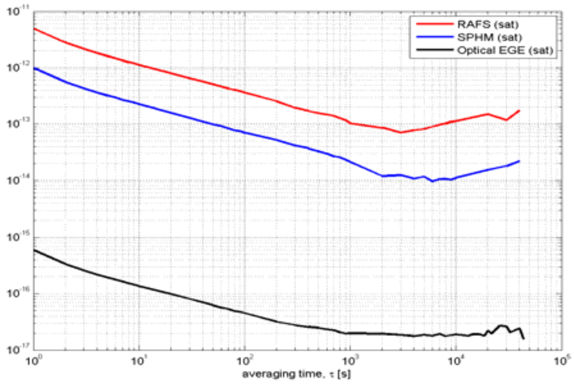

Figure 4: Modified Allan deviations for three types of simulated space clocks.

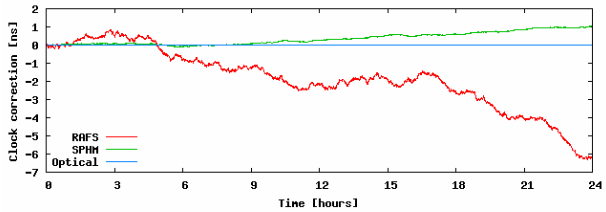

Figure 5: Time series of clock corrections.

In a first run the ionosphere-free linear combination of the simulated observations was used to estimate orbit parameters (initial conditions and nine radiation pressure parameters), differential code biases for receivers and spacecraft as well as epoch-wise receiver and satellite clock corrections. The code biases for one station were kept fixed in order to remove a corresponding singularity.

Fig. 6 (top) shows the clock corrections estimated for one satellite for the case that optical clocks are available for satellites and ground control stations. The corrections show a periodic variation with an amplitude of about 0.5 ns and a period corresponding to the orbital period. Evidently, radial orbit errors are absorbed by the space clock. In fact, the red curve in Fig.6 (bottom) shows the radial displacement of the orbit with respect to the true orbit. This result underlines the strong correlation between orbit and epoch-wise clock parameters.

The green curve in the same figure shows the radial orbit errors obtained when in a second run all clock values were fixed on their nominal values and optical clocks are used. Obviously the radial orbit error that is caused by the uncertainty in estimation of orbit parameters is no longer present. Fixing the clock values forces the least squares procedure to provide improved estimates for the orbit parameters. The remaining radial orbit differences are caused by troposphere modelling deficiencies.

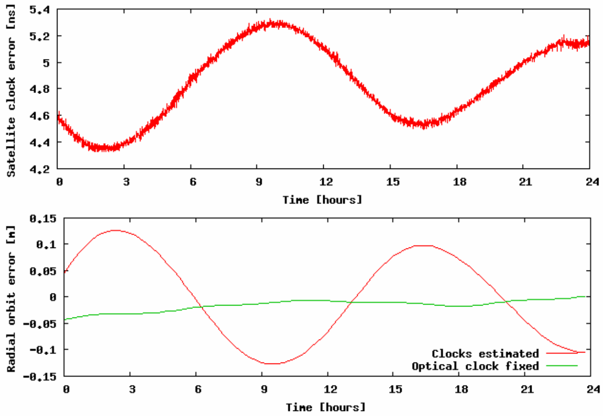

Figure 6: Estimated epoch-wise clock corrections for satellite E01 based on optical clocks (top) and corresponding radial orbit errors (bottom). The green curve (bottom) shows the radial orbit error for nominal readings of the optical clocks introduced as fixed.

Fig. 7 shows the epoch-wise clock corrections for different types of space clocks. A once-per-revolution signal indicating absorption of radial orbit errors can be found for optical clocks and for passive space Hydrogen masers. While for Hydrogen masers a small orbit improvement is possible by fixing the clock values during orbit determination (green curve), a degradation of the orbit has to be expected for Rubidium frequency standards (blue curve).

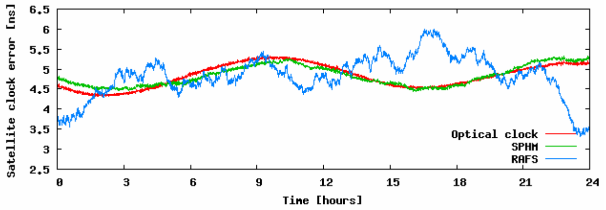

Figure 7: Epoch wise clock corrections for different frequency standards.

If a very sparse tracking network is used, orbit determination results are degraded. The reason is that observations for epochs where only a single tracking station acquires measurements do not contribute to orbit determination if epoch-wise clock parameters are estimated. If clocks can be modelled with sufficient accuracy, also single observations contribute to the estimated orbit parameters.

To verify the impact, observations for only five ground stations were generated in a second simulation. In this case the satellite orbits are covered by only single observations for significant time periods (s. Fig. 8). The radial orbit errors for the 27 simulated satellites are shown in Fig. 9. Radial orbit errors reach several metres when clock values are estimated epoch-wise (red curves) and are below 1 m if nominal clock values are kept fixed and optical clocks are used. Employing Hydrogen masers results in radial orbit errors of up to 2 m.

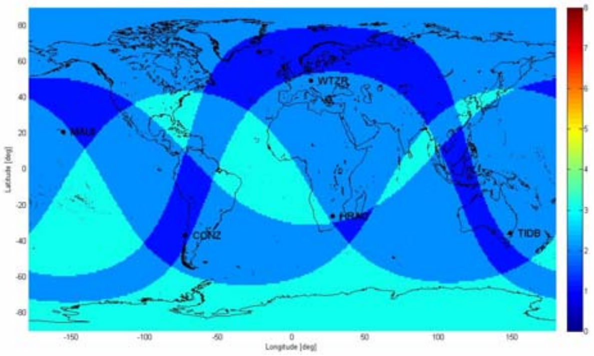

Figure 8: Depth-of-Coverage for the simulated five stations network adopting an elevation mask of 10°.

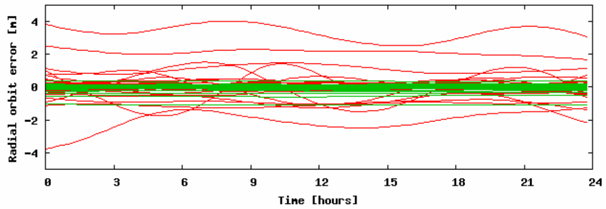

Fig. 9: Radial orbit errors for 27 satellites for a sparse tracking network and estimating epoch-wise clock corrections (red) or fixing clock corrections on nominal values when optical clocks are used (green curves).

4. CONCLUSIONS

Clocks are the main instruments required for navigation with GNSS satellites. Highly stable and accurate satellite clocks present a large potential for improvements of user positions in real-time. If clocks are stable enough such that epoch-wise clock synchronisation is no longer required for precise positioning involving carrier phase, precise point positioning in real-time becomes possible using only broadcast information from the GNSS itself, i.e., in single receiver mode. It is, however, necessary to control other error sources such as propagation delays, orbit errors or relativistic corrections at a similar quality level.

A large variety of applications could profit from such improved space infrastructure, ranging from precise navigation, e.g., for automatic navigation of ships in ports without reference station installations, tsunami warning systems with sensors at remote locations, space applications such as docking manoeuvres, and finally, distribution of atomic time and a high-precision frequency standard from space. The paper demonstrates as an example improvements expected for precise orbit determination based on optical clocks. GNSS operators would profit from a possible reduction of ground infrastructure.

Upon the result of our ongoing investigations, it can be decided whether single-ion or optical-lattice clocks shall be used for future GNSS. Therefore we review all types of optical atomic clock technologies in order to determine their current technical maturity. Dependent on the technical readiness level of the subsystems of optical clocks concerning their space qualification status and the performance requirements needed for optimized navigation, we will identify the best suited optical clocks for future GNSS.

5. ACKNOWLEDGEMENT

This work is supported by the Space Agency of the German Aerospace Center (DLR) with funds from the Federal Ministry of Economics and Technology (BMWi) based on a resolution of the German Bundestag under the code 50 NA 0904.

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