Optical Clock Technology for Optimized Satellite Navigation

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ABSTRACT

The primary payload of navigation satellites are stable clocks. Today the first navigation satellite carrying a passive hydrogen maser is in orbit. In future navigation satellites may carry ultra-stable optical atomic clocks. As part of a research project we investigate the optimization potential for GNSS by the use of ultra-stable clocks in satellite and ground segments. A primary goal is to identify optical clocks which are best suited for GNSS implementation. Not only high performance concerning stability and accuracy of the frequency standards but also the capability for space-qualification is a requirement for such clocks. Therefore we analyze different optical clock technologies developed by European metrology institutes and research facilities in terms of performance and space qualification level.

An optical frequency comb as one subsystem of an optical clock was in this context examined in detail in an ESA funded GSTP project. Two commercially available mode-locked lasers based on rare-earth doped fibers have been analyzed and tested under space relevant environmental conditions. We present test results of thermal, thermal-vacuum and radiation tests and discuss the non-linear polarization rotation mode-locking in view of the ability for space qualification. All tests indicate that mode-locking based on polarization rotation is extremely sensitive to environmental influences.

The Bernese GPS Software was used to evaluate the performance benefits of ultra-stable clocks by simulating different scenarios. Dedicated tests demonstrate that also with tracking data from sparse global tracking networks precise GNSS satellite orbits are determined when satellite and station clocks are modeled. The results are of potential interest for designing the ground segment for future global satellite navigation systems.

APPLICATIONS OF ULTRA-STABLE CLOCKS FOR SATELLITE NAVIGATION

Positioning and navigation using Global Satellite Navigation Systems (GNSS) is based on measurements of the travel time of signals from the satellites to the user receiver. Clocks play thus a fundamental role, and stable atomic clocks are the main payload of GNSS satellites. For standard positioning and navigation applications the user obtains all information from the satellite through the broadcast message. The predicted orbit and clock information allow him to navigate in real-time. For high precision applications, on the other hand, additional information is today required such as precise satellite orbits and clock corrections or tracking data from nearby reference stations. Precise orbits and clock corrections at an accuracy level of a few centimeters are available from the International GNSS Service [1] for GPS and GLONASS. While also highly accurate predicted orbits can be downloaded, this is not true for clock corrections due to limitations of modeling of the satellite onboard clocks. Tracking data from neighboring stations observing the same satellites as the rover receiver allow the elimination of the satellite clocks. High precision positioning results can be obtained in real-time using this baseline approach.

With onboard clocks that are stable enough to be predicted at the 10 ps level over a broadcast update rate (i.e., a few hours), clock prediction can compete with orbit prediction short term precision. Corresponding broadcast information would allow users to position with centimeter accuracy using phase observations without requiring additional information from reference stations. Examples out of a multitude of possible applications are remote sensors of a Tsunami warning system or autonomous docking maneuvers of low Earth orbiting spacecraft. We may have to leave the concept of baselines (differencing of observations of stations to eliminate clock parameters) but can think of point positions. It is required, however, that the broadcast information refers to a well defined reference frame. For long-term prediction the limiting factor may be the orbit prediction and no longer the clock prediction as today. Examples for applications of multi-day predictions are the display of positioning results immediately after starting the receiver (e.g.

after leaving the car several days in the garage), or indoor navigation, where decoding of navigation message is critical. In both cases previously stored orbit and clock information has to be used.

Apart from prediction also modeling is possible with stable clocks. For ultra-stable clocks only very few clock parameters may have to be estimated per clock and per day, e.g., a clock offset or a clock and a frequency offset instead of epoch-wise clock offset parameter estimation. The dramatically reduced number of parameters stabilizes the solution. On the other hand error effects, e.g., from imperfect troposphere delay modeling may no longer be absorbed in the large number of clock parameters. Improved models for observation error sources as well as for orbit perturbations have thus to be developed. In addition, modeling relativistic clock corrections has to be refined. Apart from higher realtime positioning accuracy for users and increased system autonomy more applications of ultra-stable clocks can be envisaged such as real-time distribution of TAI through navigation satellites.

OPTICAL FREQUENCY COMB ENVIRONMENTAL TESTS

In future probably optical clocks will be implemented in satellites and used for navigation. To transfer the optical clock resonance frequency down to the rf regime, an optical frequency com is used. Several different laser technologies for generation of an optical frequency comb, for example solid-state or fiber based lasers, are nowadays commercially available or in use in scientific institutes. For the utilization of optical frequency combs in space applications like space borne optical atomic clocks or interferometers, fiber based systems are promising candidates. Advantages are for example compact, robust, lightweight, small volume and alignment uncritical setup as well as power efficient operation. Therefore two fiber based mode-locked lasers have been tested in an ESA funded GSTP study [2]. The following chapter present test results of the Erbium doped mode-locked laser.

Description of Mode-Locked Lasers

The Erbium doped laser uses polarization rotation as mode-locking principle and produces pulses at a repetition rate of 100 MHz with a pulse length of 100 fs. It could directly be used as optical frequency comb generator since the laser system includes control and monitoring mechanisms that can be used for repetition rate and carrier envelope offset stabilization in a complete optical frequency comb. During our work however, only the mode-locked laser without additional components for frequency comb generation and without stabilization loops was used.

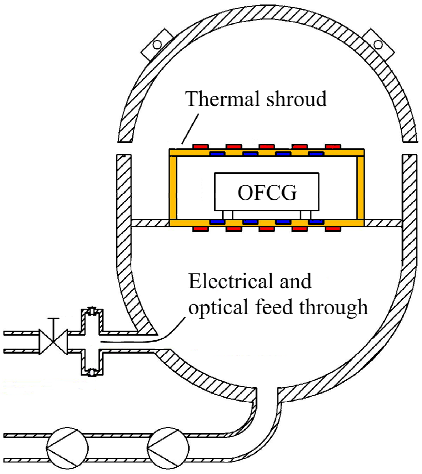
Thermal Vacuum Test

In order to determine the temporal behavior of the mode-locked laser in vacuum environment, it has been mounted inside a vacuum chamber as shown in Fig. 1. Thermal cycles in a temperature range from 10°C to 45°C have been performed, which simulate typical satellite environment.

Calculation of the fiber length s_{fiber} using the nominal repetition rate $f_{rep,0}$ and the free beam range $s_{air,0}$ = 0.140 m ± 0.001 m at a temperature of T_0 = 293 K results in:

$$s_{fiber} = \frac{c}{n_{fiber,0} \cdot f_{rep,0}} - s_{air,0} = 1.938m \pm 0.001m \quad (1)$$

The dependency of the repetition rate f_{rep} on temperature variation is caused by two superimposed effects: Firstly the length changes of optical fibers and aluminum housing that holds all free beam optics change the resonator length. Secondly the temperature dependent refractive index of the fiber also results in a change of repetition rate when the temperature changes. The combination of both effects results in an equation which reads in its linearized approximation



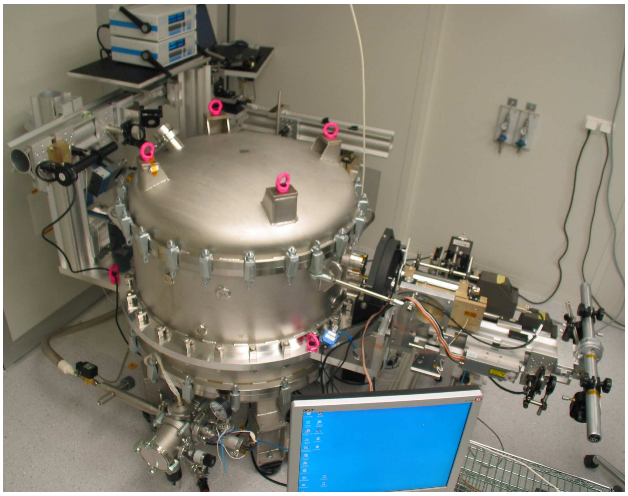


Figure 1. Overview of the thermal-vacuum test configuration. The OFCG is placed inside a thermal shroud which can be heated by electrical resistors and cooled by nitrogen. Electrical and optical feed through allows control and monitor of the OFCG behavior.

$$f_{rep}(T) = f_{rep,0} - c\frac{\left(n_{fiber,0}s_{fiber,0}\left(\alpha_{air}+\alpha_{fiber}\right)+n_{air}s_{air,0}\alpha_{alu}\right)}{\left(n_{fiber,0}s_{fiber,0}+n_{air}s_{air,0}\right)^2}\left(T-T_0\right)+\mathrm{O}\left(T^2\right) \qquad (2)$$

The nonlinear equation was approximated around T_0 = 293 K Refractive indices and thermal expansion coefficients are denoted as n and α respectively, c stands for the speed of light. The term $\mathrm{O}(T^2)$ contains the residual of the Taylor expansion and was estimated to be smaller than 100 mHz. Fig. 2 shows the measured and the calculated repetition rate as a function of temperature.

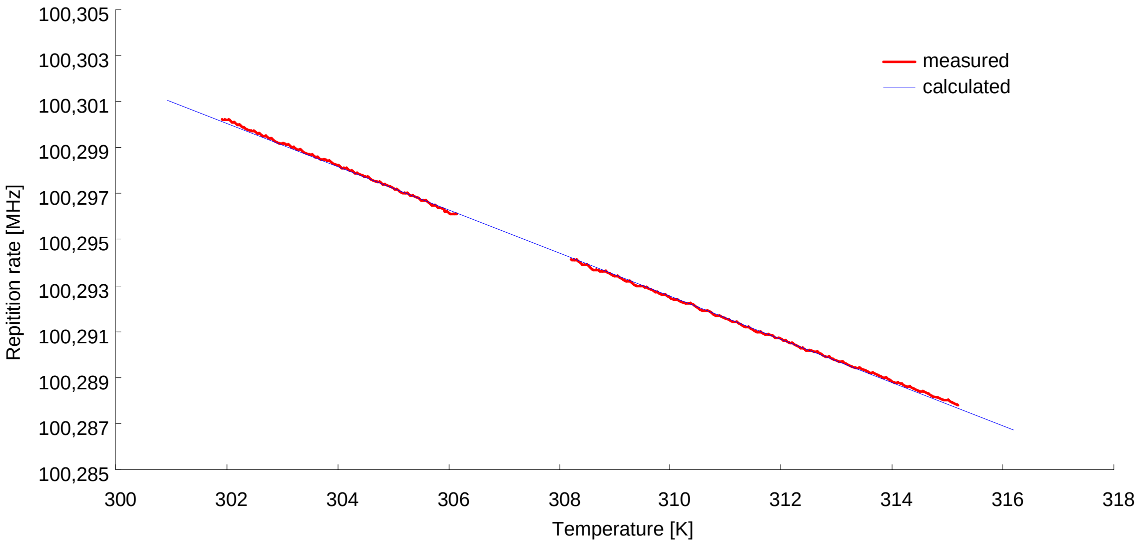


Figure 2. Repetition rate change of the Erbium doped laser due to temperature variation.

Another temperature dependent effect that was identified during thermal cycling of the OFCG is shown in Fig. 3. A continuous wave peak which is temperature dependent was observed. The mode-locking based on nonlinear polarization rotation uses free beam optics (waveplates and polarizers) in order to build up an artificial saturable absorber. Saturable absorption is based on correlations of all waveplates such that high intensity light passes and low intensity light is blocked by the configuration of waveplates. Since the suitable configuration of waveplate positions is determined by randomly rotating all waveplates, this mode-locking technique is non-deterministic. The fibers of the resonator are not polarization maintaining and this technique is therefore rather sensitive to temperature variations. Similar effects are also described by Paschotta in [4].

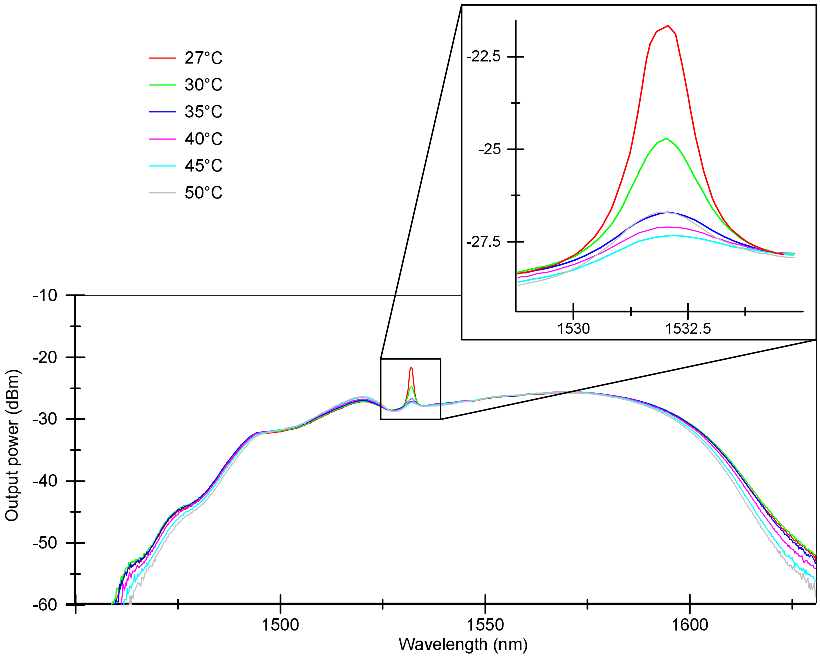


Figure 3. Output spectrum of the Erbium doped laser is dependent on temperature.

Some of the found mode-lock states only show a desired flat output spectrum at a specific temperature. Unless configuration of fibers and free space optics changes (e.g. due to vibration load), the output spectrum stays constant.

Radiation Test

Rare-earth doped fibers are well known to be rather sensitive to radiation; several studies have already been performed on various kinds of gain fibers e.g. [5], [6]. The exact effects behind transmission degradation of these fibers and the optimum doping configuration for achieving minimized radiation sensitivity are not known. Each fiber has to be tested individually in order to determine the respective sensitivity. By only irradiating one single part of the laser under test (the gain fiber in our case) and not the entire laser system, the degradation of the output signal can be ascribed to the part under test. After testing one part of the laser, the irradiated component has been exchanged by a new one and the initial performance has been checked by measurement.

Fig. 4 sketches the setup used for radiation testing of the rare-earth doped fiber of the Erbium based laser.

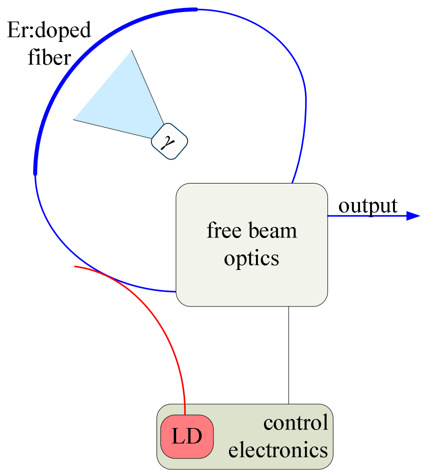


Figure 4. Radiation test setup for the Erbium doped mode-locked laser.

Fig. 5 shows the results of the Erbium fiber test. The output power decreases due to radiation induced optical attenuation. After an accumulated dose of approximately 30 krad, the laser looses its mode-locked state and immediately starts searching for a new one. This results in fluctuations of the output intensity. A new mode-locked state was not found. The optical output spectrum, displayed at the right hand side of Fig. 5, shows strong continuous wave peaks even at a total dose lower than 30 krad.

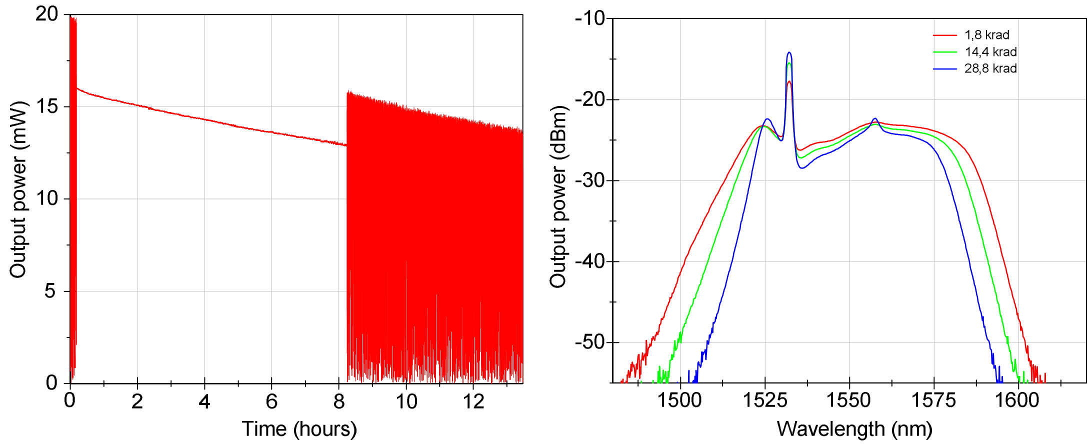


Figure 5. Radiation test results of the irradiation of the Erbium fiber. Left: The output power of the laser decreases until the laser looses its mode-locked state after approx. eight hours. Then it starts a random search algorithm. Right: The optical output spectrum becomes narrower with rising total irradiated dose.

Due to radiation, the lasing efficiency of the gain material decreases. Therefore the optical output spectrum becomes narrower when the accumulated dose increases.

Additionally to the discussed test, where the gain fiber was irradiated during laser operation, hydrogen loaded fibers have been tested. These specially treated fibers [7] were tested passively, meaning just transmission tests have been made. The test results show that the radiation induced attenuation of this kind of fiber is less than 0.2 %/krad for a total dose of 80 krad. Building an OFC on the basis of hydrogen loaded fibers could therefore result in a radiation hard system.

SIMULATION OF GNSS OPERATOR SCENARIOS AS APPLI CATION OF ULTRA-STABLE CLOCKS

Ultra-stable clocks will have a number of applications for the user in particular for real-time precise navigation. But also the system operator would profit from ultra-stable clocks in the space and in the ground segment. Modeling of clocks stabilizes the orbits determined in the ODTS process. As a consequence the system may be operated with fewer ground sensor stations. The longer clock prediction interval may reduce the communication needs for synchronization.

In order to investigate the potential for orbit improvement a simulation emulating an ODTS procedure was performed. The simulation involves two globally deployed tracking station networks, one consisting of 15 stations, the other of only 6 stations (Fig. 6) and a GPS-like constellation of 32 satellites with orbits from IGS inserted as true. Pseudorange and phase observations were simulated on two frequencies for each station with a measurement noise of 20 cm and 2 mm respectively on two frequencies and including realistic deterministic and stochastic troposphere errors. No ionosphere errors were simulated since the ionosphere-free linear combination of the two carriers were analyzed to estimate orbit parameters, station specific parameters, and phase ambiguity parameters. The quality of the determined orbits is quantified by analyzing the long-term alongtrack prediction error.

Different types of clocks with typical behavior were simulated based on specified Allan deviations, namely Rubidium Atomic Frequency Standards (RAFS), Passive Hydrogen Masers (PHM) for space clocks and Active Hydrogen Masers (AHM) for ground clocks as well as optical clocks with specifications similar as for the Einstein Gravity Explorer [8] for space clocks and optical clocks with even better performance for ground station clocks. Fig. 7 shows the Allan deviations considered to simulate the clock time series. The simulated clocks were introduced into the simulation of the observations while the clocks were fixed to nominal values in the analysis of the simulated data. This corresponds to a modeling of the clock as a constant value for an entire day. The four simulated scenarios are summarized in Table 1.

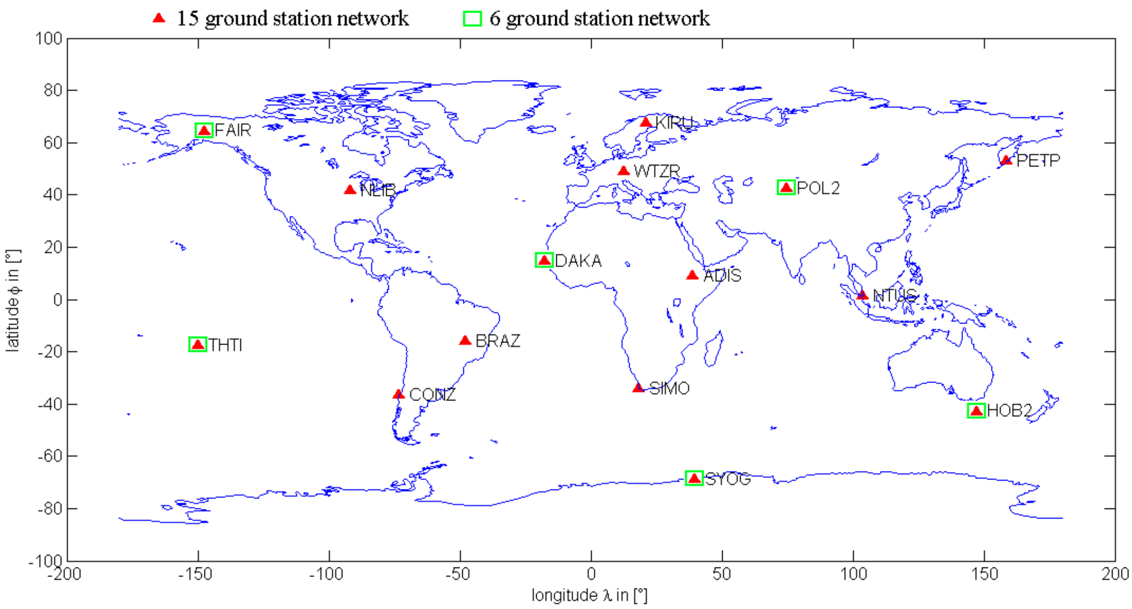


Figure 6. Two globally deployed tracking station networks that were used for simulations.

Table 1: Simulated GNSS operator scenarios

	Satellite clocks	Ground stat. clocks	Network
Scenario 1 – GPS	32 RAFS	15 RAFS	15 stations
Scenario 2 – Galileo	32 PHM	15 AHM	15 stations
Scenario 3 – Optical	32 Opt. space	15 Opt. ground	15 stations
Scenario 4 – Sparse Optical	32 Opt. space	6 Opt. ground	6 stations

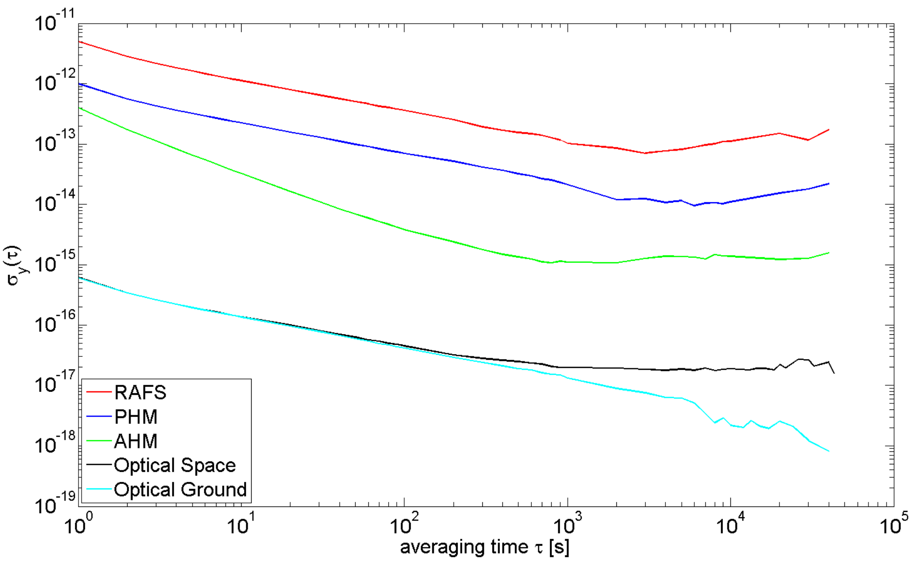


Figure 7. Allan deviations for RAFS, PHM, AHM, optical space clock, optical ground clock (sequence in order of increasing stability).

Figure 8 summarizes the resulting alongtrack orbit prediction errors for the considered satellites for a time interval of 10 days. Table 2 lists the root mean squares (RMS) of the alongtrack orbit prediction errors of all satellites after 10 days. With modeled clocks the prediction error decreases as expected for improving stability of the clocks involved in the ground and space segment. If clock corrections are estimated as epoch-wise parameters in the ODTS procedure the orbit prediction does not depend on the clock stability. Rubidium clocks are not stable enough to improve the orbit prediction compared to epoch-wise estimation of clock parameters. For hydrogen masers and optical clocks, on the other hand, an improvement by modeling the clocks can be achieved. Orbit errors with optical clocks involved are dominated by systematic modeling and stochastic measurement errors. Since typical prediction errors of hydrogen masers over 10 days are of the order of 10 m (30ns), positioning errors after 10 days are of the order of 100 m. Prediction errors of optical clocks are of the order of 1 cm within 10 days, positioning errors after a 10 days prediction interval are thus fully governed by orbit errors and are of the order of 40 m. A large improvement is achieved for a very sparse tracking network with modeled ultra-stable clocks. While epoch-wise clock estimation leads to orbit prediction errors after 10 days exceeding 1 km for a 6-station network, the prediction error is below 200 m for modeled clocks.

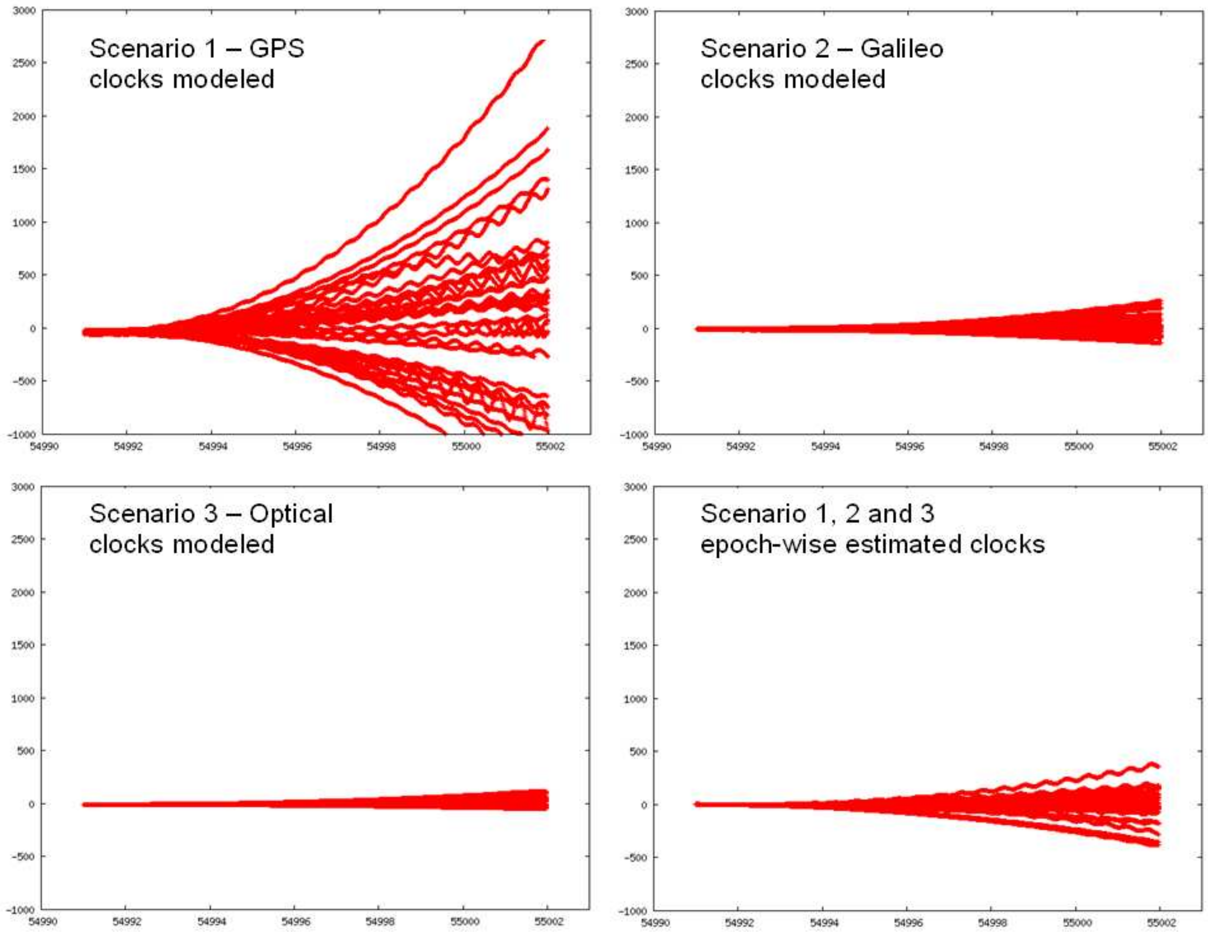


Figure 8. Alongtrack orbit prediction error in meters over 10 days based on modeled RAFS clocks (top left), modeled hydrogen masers (top right), modeled optical clocks (bottom left), epoch-wise estimated clocks (bottom right). All figures to same scale.

Table 2: RMS of alongtrack orbit prediction errors of all satellites after 10 days for scenarios with modeled clocks and with epoch-wise estimated clock corrections.

Scenario	Clocks modeled	Clocks estimated epoch-wise
1: GPS, 15 stations	780 m	110 m
2: Galileo, 15 stations	80 m	110 m
3: Optical, 15 stations	40 m	110 m
4: Sparse optical, 6 stations	170 m	1200 m

Conclusions

Environmental tests of the Erbium doped mode-locked fiber laser are a first step towards the development of a space borne optical frequency comb system. In order to identify a suitable mode-locked state, the output spectrum of the femtosecond laser has to be evaluated. Thermal-vacuum tests reveal that the output spectrum strongly depends on the temperature of the laser head. Even if the temperature of the laser is kept constant by a temperature control system, the laser output does not necessarily show the desired spectrum. This is due to the mode-locking technique of non-linear polarization rotation which is non-deterministic. During gamma radiation testing a strong continuous wave peak was observed after a total dose of less than 2 krad, which indicates that the laser changes its comb generating properties. In order to achieve optical frequency comb generation for space applications, these issues have to be eliminated.

While estimated GNSS orbits are independent on the performance of used clocks, if the clocks are synchronized epoch-wise, clock modeling improves the orbit and orbit prediction if stable clocks such as H-masers and optical clocks are involved. Results are degraded, on the other hand, if the system is operated with clocks that do not allow linear modeling over one day such as Rubidium clocks. A significant gain is achieved through clock modeling of stable clocks for a very sparse tracking network, a result that may be of interest for the design of the ground system for future satellite navigation systems.

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References

[1] Dow, J.M., Neilan, R. E., and Rizos, C. (2009): The International GNSS Service in a changing landscape of Global Navigation Satellite Systems, Journal of Geodesy 83, 191–198, DOI: 10.1007/s00190-008-0300-3.

[2] European Space Agency, Optical Frequency Combs: Critical Elements Predevelopment, Contract Number 20071/06/NL/PM.

[3] Stumpf, M. et al. (2010): First Fully Stabilized Frequency Comb from a SESAM Modelocked 1.5-µm Solid-State Oscillator, 24th European Frequency and Time Forum, given presentation.

[4] Paschotta, R.: Nonlinear Polarization Rotation, Encyclopedia of Laser Physics and Technology, http://www.rp-photonics.com/nonlinear_polarization_rotation.html.

[5] Henschel H., Köhn O., Schmidt H. U., Kirchhof J., Unger S. (1998): Radiation-Induced loss of Rare Earth doped Silica Fibres, IEEE Transactions on Nuclear Science, Vol. 45.

[6] Ott, M. (2004): Radiation Effects Expected for Fiber Laser/Amplifier Rare Earth Doped Optical Fiber, Sigma Research and Engineering / NASA GSFC, Parts, Packaging and Assembly Technology Office.

[7] Zotov, K. V. et al. (2007): Radiation-resistant Erbium-doped Fiber for Spacecraft Applications, RADECS Conference.

[8] Schiller, S. et al. (2009): Einstein Gravity Explorer – a medium-class fundamental physics mission, Exp. Astron. 23, 73-610, DOI: 10.1007/s10686-008-9126-5.