

**IAG Joint Working Group 2.1 “Relativistic Geodesy: First steps
towards a new geodetic technique”
2nd Meeting, Bureau International des Poids et Mesures, Sèvres,
October 10-11, 2018**

1. Welcome, organizational matters

Gerard Petit (co-chair) opened the meeting at 14:00 on Oct 10. Jakob Flury (chair) welcomed the group members and guests. He discussed the current membership list (no changes were suggested) and recalled the results of the 2017 meeting of the group. Petit and Flury mentioned the activities of the ISSI (International Space Science Institute) Team “Spacetime Metrology, Clocks and Relativistic Geodesy” and its first workshop (March 19-23, 2018, <http://www.issibern.ch/teams/spacetimemetrology/index.php/schedule-meetings/>). The conditions for the extension of the JWG 2.1 beyond 2019 will have to be discussed with IAG representatives.

2. Progress in optical clocks development and evaluation

Sebastien Bize presented a talk on “Progress in optical clocks Optical clocks at SYRTE”. He discussed strengths and challenges of single ion clocks and lattice clocks. He summarized available frequency comparisons between optical clocks, in particular between the Sr and Hg lattice clocks at SYRTE, and international comparisons with optical clocks at PTB, including PTB’s Yb+(E3) clock. He included an outlook towards non-destructive atomic detection in clocks to avoid dead time as a factor limiting clock stability.

3. Campaigns of optical clock comparisons

Christian Lisdat presented the talk “Transportable Sr Lattice Clock” reporting on the evaluation of the clock at PTB, and on the recent and ongoing remote frequency comparison measurement campaigns. The evaluation included tests with the transportable and stationary cavities for the clock lasers in different configurations. In a 2017 campaign, the transportable clock was at SYRTE, Paris. The remote comparison with PTB achieved a combined frequency uncertainty of 3×10^{-17} (corresponding to 30 cm height difference) for parts of the campaign. However, for other parts of the campaign, anomalies were observed that could not be resolved so far. First results of the ongoing campaign 2018 to MPQ, Munich, were reported as well.

In a break, the participants visited BIPM’s Kibble balance experiment that is involved in the new definition of the kilogram.

Davide Calonico presented, by Webex, the talk “Geodesy with fibre links: update from Italy” reporting on the setting up and characterization of the Italian Quantum Backbone optical fiber link with a length of 1800 km. The link includes INRIM, Torino, the 3 VLBI stations in Medicina, Fucino and Matera, and the connection to the Laboratory Souterrain de Modane and France. Calonico discussed perspectives to deliver a common clock such as the Yb

optical lattice clock of INRIM to the radiotelescopes for applications in radioastronomy and geodesy.

Gesine Grosche presented the talk “Frequency dissemination and remote frequency comparisons”. Grosche reviewed the status of interferometric optical fiber links with effective attenuation counteraction and 10^{-20} relative frequency accuracy. The talk summarized the recent campaigns linking PTB, SYRTE and NPL that involved a total of 9 optical clocks in June 2017, and 6 optical clocks in April/May 2018, and discussed the value of such comparisons for detecting clock errors. Grosche reported on the current setting up and characterization of the fiber link to MPQ Munich, and on methods to identify problems at intermediate frequency amplifiers. She discussed future perspectives on time dissemination at this accuracy level, on the characterization of GNSS-based frequency transfer, and on the observability of the Sagnac effect in large networks.

4. Links with the work of the CCTF towards redefinition of the second

Gerard Petit presented the talk “The SI second: present realization and path to a redefinition”. He reported on the adjustment of frequency standard values for 14 frequencies from absolute measurements and frequency ratios. The talk discussed the status of the CCTF roadmap towards the redefinition of the second. Milestones of the roadmap (e.g., 3 clocks in 10^{-18} regime, 3 clock comparisons between institutes in this regime, optical clocks contributing as secondary standards to TAI) have partially been reached and it is envisioned that they could be achieved in 2021. Currently, 2 optical clocks (at SYRTE) have contributed to TAI. The talk discussed the expected improvements in frequency transfer using GPS-IPPP, upcoming optical fiber networks, and ACES / ELT. The talk emphasized the mutual benefits of long-distance clock comparison and relativistic geodesy experiments, which will, however, be limited by the lack of intercontinental connections.

5. Progress in time and frequency transfer techniques

The second day, October 11, started with a talk by Julia Leute on “Worldwide 10^{-17} clock comparison with IPPP”. The talk discussed the GPS-IPPP analysis procedure based on the GINS software, including the determination of satellite clock phase solutions with integer ambiguity fixing and the formation of continuous links with cycle slip fixing. The comparison with optical time transfer (OTT) links, e.g., between PTB and Deutsche Telekom in Bremen or between AOS and GUM in Poland showed frequency deviations in the $1 \cdot 10^{-17}$ to $2 \cdot 10^{-17}$ regime when averaged over several weeks of measurements. Leute also showed the combination with T2L2 links between France and the UK for high-accuracy continuous time transfer.

Yi-Jiun Huang presented the talk “Long-baseline frequency comparison by a two-way microwave link”. He demonstrated that Two-way carrier phase (TWCP) measurements by way of a geostationary satellite, e.g. between NICT (Japan) and PTB, achieve a frequency stability in the lower 10^{-16} regime, significantly better than TWSTFT measurements. Systematic uncertainties of $1 \cdot 10^{-15}$ and options for improvement were discussed.

Frederic Meynadier presented the talk “ACES-PHARAO and its two-way Microwave Link”.

The talk described the ACES mission to the International Space Station (ISS) and its payload that will provide the best timescale on orbit today as well as comparisons of the best clocks on ground. The microwave link configuration was described. A validation procedure with simulated data generated at SYRTE was presented. As one of the results, it was demonstrated that ISS orbit errors do not significantly impact the time transfer.

Paul-Eric Pottie presented the talk “From fiber links to fiber network: recent progresses”. He presented concepts and activities of national metrology institutes and National Research and Education Networks towards a sustainable, layered fiber access infrastructure in Europe, e.g., in the Clonets project (such as an EU backbone). He informed about the upcoming fiber connection with the Modane mountain laboratory as possible site for chronometric geodesy, and on to INRIM. He discussed the advantages of fiber sharing. He showed the progress in industrial grade links with uptimes of 90% and higher for the links from Paris to Strasbourg and Lille.

6. Theory of relativistic geodesy

Claus Lämmerzahl presented the talk “Theoretical aspects of relativistic geodesy”. He gave an overview of GR effects affecting geodetic measurements, and in particular on the gravitational redshift. He derived that in a relativistic framework, the potential describing frequency redshift is consistent with the potential describing accelerations. The talk gave equations on the redshift for clock comparisons between ground and space, and showed computational results on the relativistic quadrupole geoid contribution.

Pacome Delva presented the talk “Relativistic Corrections for Time and Frequency Transfer in Optical Fibres” aiming at a fully relativistic description of the signal propagation in optical fibers. The talk discussed the equation for time transfer, including in particular the Sagnac effect that remains in the case of two-way time transfer. Delva showed relations for frequency comparison and for the proper time - coordinate time relation in GCRS. He discussed one-way fiber propagation with examples concerning tidal effects in the 10^{-20} frequency range.

7. Determination of geopotential with clocks

Guillaume Lion presented the talk “Determination of the geopotential at high spatial resolution with optical clocks”. The talk discussed the complementarity of chronometric observables to classical gravity observables concerning spatial resolution and sensitivity. A synthetic gravity model and synthetic measurements were used to test the quality of simulated geopotential determination, with a specific focus on coastal zones in France and offshore measurements. The talk discussed genetic algorithms for the optimization of measurement locations and for the estimation of covariance function parameters.

Jürgen Müller presented, by Webex, the talk “Using optical clocks and quantum gradiometers onboard satellites for determining the Earth’s gravity field”. The talk presented gravity recovery results from simulated potential measurements based on space clocks, assuming frequency accuracies in the 10^{-17} to 10^{-19} range, along a GOCE-type low Earth orbit. Results demonstrated relevant contributions to the recovery of very low degree spherical harmonics. Complementarily, simulated cold atom gradiometry measurements with a

precision of $5\text{mE}/\sqrt{\text{Hz}}$ would contribute to the improved recovery of spherical harmonics for degrees 50 to 250.

Hu Wu presented, by Webex, the talk “Clock networks for future height systems”. He discussed limitations of current methods to establish an International Height Reference System IHRS, and proposed the concept of hierarchical clock networks for an IHRS, including transportable clocks for densification. The talk presented a European-scale simulation to eliminate offsets and tilts in regional height systems at the decimeter-scale using several clock observations in each region.

8. Applications in geodesy and related fields

Marie-Francoise Lequentrec-Lalancette presented the talk “Relativistic geodesy and ocean challenges - what is at stake in ocean sciences?”. The talk discussed needs for accurate mapping and navigation in shallow areas, and for an accurate reference as basis for deep sea exploration. Applications include the planning and construction of energy generation in oceans, and hydrodynamic models for coastal safety. References for mapping often contain artifacts due to differences in chart datums (e.g., differences between local and global references). Merging and homogenization is critical, e.g., for the combination of airborne and terrestrial recovery of topography and bathymetry, and needs high-resolution geoid information.

The concluding talk “Integration of future clock networks into geodetic reference frames” was presented by Jakob Flury. He outlined the concept of combining pointwise geopotential data from classical geopotential determination using satellite-based gravity models and high-resolution terrestrial gravity data on one hand with relativistic potential differences between clock sites on the other. The concept could be used for establishing a geopotential reference frame with similarities to the realization of the International Terrestrial Reference Frame ITRF that is based on the combination of best available techniques. A European network linking clock measurements by way of optical fiber frequency transfer appears to be feasible, while intercontinental links will remain much more challenging.

9. Concluding discussion

In the concluding discussion, it was proposed to inform relevant entities such as EUREF about the concept of using frequency transfer networks for chronometric leveling and geodetic reference frames. It was suggested to start a Position paper outlining the concept and current status. In addition, research on free-space optical links for frequency transfer was considered as very important and promising.

The meeting was closed at 17:00.

Minutes published on Feb 18, 2019 (Jakob Flury, Gerard Petit)

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