22nd IWLR Abstract Book

Index

Invited speakers

Invited 01

United Nations working to sustain geodesy

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The Global Geodetic Reference Frame (GGRF) is the term adopted by the United Nations (UN) to describe the collection of datums, infrastructure, governance, data analysis, standards and people which together enable accurate and reliable positioning and the alignment of geospatial data. The GGRF is an important foundation for evidence-based policies, decisions and program delivery. It underpins the collection and management of nationally integrated geospatial information and is used to monitor our dynamic Earth for social, environmental and economic initiatives.

In a world increasing reliant on high accuracy measurements and location based services, the sustainability of the GGRF is more important than ever before. However, its quality, accuracy and accessibility are at risk of failure due a multitude of complex issues including a lack of geodetic infrastructure, poor accessibility in some regions, a reliance on in-kind contribution and insufficient collaboration and coordination.

Recognising the importance of the GGRF to an ever-increasing location-based society, the UN General Assembly adopted resolution 69/266 in February 2015, entitled ‘A Global Geodetic Reference Frame for Sustainable Development’. Since 2015, the UN Global Geospatial Information Management Subcommittee on Geodesy (UN-GGIM SCoG) have been working with countries to better understand what they need to sustain, and improve access to, the GGRF.

This presentation will discuss the actions the UN-GGIM SCoG are taking to sustain the GGRF. This includes a plan to achieve the long-term sustainability of the GGRF by delivering improvement in five focus areas: Governance; Geodetic Infrastructure; Policies, Standards and Conventions; Education, Training and Capacity Building; and Communication and Outreach. The presentation will also discuss the establishment of a Global Geodetic Centre of Excellence which will be established in Bonn, Germany. The Centre will assist in sustaining the GGRF by addressing critical gaps in global geodesy capacity and capability.

Invited 02

Radioastronomy at Yebes Observatory

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Radio astronomy is a field of Astronomy that is relatively young. Yebes Observatory initiated its first steps in this area in the 1970s and gathered a team of astronomers and engineers to run and exploit its first radio telescope. Currently, Yebes Observatory manages two radio telescopes and it is a technological development center for radio astronomy equipped with laboratories and workshops. The 40m radio telescope is used for astronomy studies and works as single dish and as an element of interferometric arrays. The 13 m radio telescope, part of RAEGE, is integrated in the VGOS project to determine the Earth Orientation Parameters and study relative motions on the surface of the Earth.

Invited 03

The International VLBI Service for Geodesy and Astrometry – Status and Prospects

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The International VLBI Service for Geodesy and Astrometry (IVS) is one of four services of the International Association for Geodesy (IAG) that collaborate and contribute as technique centers to the efforts of the International Earth Rotation and Reference Systems Service (IERS). Important products that arise from this cooperative work are time series of Earth orientation parameters (EOP), as well as celestial and terrestrial reference frames (CRF, TRF). The different techniques have individual advantages and complement each other. In this context, VLBI is unique in providing the basis for the International Celestial Reference Frame (ICRF) as well as celestial pole offsets. Together with Laser Ranging VLBI provides the scale of the International Terrestrial Reference Frame (ITRF). All techniques contribute to polar motion observations, while VLBI in particular contributes to observations of the earth rotation angle.

In this presentation, the principles of geodetic VLBI will be described as well as the current status of the IVS and its prospects. The IVS is currently in a renewal phase and is introducing and rolling out the next generation geodetic VLBI system, called the VLBI Global Observing System (VGOS). Several agencies worldwide have already built VGOS stations, e.g. Yebes Observatory, or are in the process of doing so. VGOS makes use of relatively small and stiff radio telescopes that allow high speed motion in azimuth and elevation and thus many observations per time unit in many different directions on the sky. The VGOS receiving systems are broadband and can cover about 2–14 GHz in two polarizations and allow high data rates. Using this approach, the expectations are that VGOS will improve the performance of geodetic VLBI by one order of magnitude compared to the legacy VLBI system that has been operated since the 80ies. The current status of the IVS network, both legacy and VGOS, as well as examples of result derived will be presented.

Space Debris - How can laser technology contribute to a sustainable solution for the further exploitation of space as a resource?

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From more than 6,250 launches about 8,800 satellites remained in space today; out of which 6,500 are operational. These are accompanied by almost 2,500 spent orbital rocket-bodies and a large number of fragmentation debris and mission related objects. This large amount of space hardware has a total mass of more than 10,000 tonnes. More than 630 fragmentation events occurred meanwhile. All non-functional, human-made objects are considered space debris. Low Earth orbit (LEO) has become the most congested region in near-Earth space, containing approximately 75% of all known objects. At typical collision speeds of 10 km/s in LEO, impacts by debris larger than about 10 cm are assumed to cause catastrophic break-ups – the destruction of the spacecraft. Collisions with debris larger than 1 cm could disable an operational satellite or could cause the break-up of a satellite or rocket body. Impacts by millimetre-sized objects could cause local damage or disable a subsystem of an operating satellite. Today's evolution of the space debris environment raises concerns on the long-term sustainability, and is a safety issue for operational spacecraft and to persons and property on Earth in cases of uncontrolled re-entry events. Protecting our space-based infrastructure is at the focus of ESA's Space Safety Programme in recognising the safety aspects of missions and the importance of sustainable utilisation of space as an integral part of society and economic growth.

In the talk we will introduce ESA's Space Safety Programme, with focus on current technology needs to track and catalogue objects. We show how such data is used for modelling the environment and also in daily operations, i.e. to detect critical conjunction events, upcoming uncontrolled re-entry events or other major space events like break-ups. The rapid progress in developing satellite laser ranging to space debris brings many new opportunities and several challenges. We will present recent achievements and ESA's perspectives for further steps. A brief look at the internationally agreed efforts to mitigate space debris, and how ESA implements these, completes the presentation.

Session 1. ILRS Contribution to the Terrestrial Reference Frame and Earth Orientation Parameters

Oral 01-01

ITRF2020 and the ILRS contribution

Zuheir Altamimi (1), Paul Rebischung (1), Xavier Collilieux (2), Laurent Métivier (1), Kristel Chanard (1)

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The ITRF2020 published on April 15, 2022 is provided in the form of an augmented reference frame so that in addition to station positions and velocities, parametric functions for both Post-Seismic Deformation (PSD) for stations subject to major earthquakes and periodic signals (expressed in the Center of Mass frame of Satellite Laser Ranging) are also delivered to the users. The presentation will summarize the main results of ITRF2020 analysis, with a special focus on the ILRS/SLR contribution. In particular, the paper will discuss the usage of the ITRF2020 kinematic model, the level of the scale agreement of the four techniques, as well as their variations and behaviour over time. We will also discuss the level of technique consistencies of nonlinear station motions at co-location sites, as well as some key performance indicators of the ITRF2020.

Oral 01-02

DTRF2020: the ITRF 2020 realization of DGFI-TUM

Bloßfeld Mathis, Seitz Manuela, Glomsda Matthias, Angermann Detlef, Rudenko Sergei, Zeitlhoefler Julian

DGFI-TUM, Munich, Germany

As one of three IERS ITRS combination centres (CC) worldwide, DGFI-TUM is in charge of the computation of an own ITRS 2020 realisation, the DTRF2020. The solution is carried out within the framework of the computation of the ITRF2020, the official ITRS realisation calculated and released by the Institut national de l'information géographique et forestière (IGN, Paris, France). A third realization, the JTRF2020, which represents a time series of terrestrial reference frames (TRF), is computed by the ITRS CC at NASA's Jet Propulsion Laboratory (JPL, Pasadena, USA). The DTRF2020 is based on the combination of constraint-free normal equation systems (NEQs) of the techniques and accounts for non-linear station motions due to all three components of the non-tidal loading signal (atmospheric, hydrological and oceanic component) as well as post-seismic deformation. Hence, it serves the validation and quality assurance of the official ITRF solution.

The input data for the ITRS realizations are long time series of weekly or session-wise solutions of the observation techniques VLBI, SLR, GNSS and DORIS, covering each entire observation history of the respective technique (e.g., more than 40 years in case of VLBI). By combining the techniques a precise and long-term stable TRF solution together with consistently estimated Earth Orientation Parameters is obtained, taking advantage of the individual strengths of each

technique. The DTRF2020 accounts for non-linear station motions due to, for the first time, the full non-tidal loading signal and post-seismic deformation. Both effects are reduced from the NEQs by applying corresponding model values.

The presentation shows the computation strategy of the DTRF2020 and its special features. Moreover, the datum stability and the quality of the TRF realization is presented. Finally, the presentation provides an overview of the DTRF2020 release dataset.

Oral 01-03

Enhanced ILRS analysis for ITRF2020

Vincenza Luceri (1), Erricos C. Pavlis (2), Antonio Basoni (1), David Sarrocco (1), Magda Kuzmicz-Cieslak (2), Keith Evans (2) and Giuseppe Bianco (3)

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The time series of station positions and EOP provided by ILRS for the realization of the ITRF2020 was obtained as the combination of loosely constrained individual solutions from the seven ILRS Analysis Centers: ASI, BKG, DGFI, ESA, GFZ, JCET and NSGF. Everyone followed strict standards agreed within the ILRS Analysis Standing Committee (ASC) and used SLR data from LAGEOS, LAGEOS-2, Etalon-1 and Etalon-2. The ILRS ASC devised an innovative approach in handling systematic errors in the network, never before utilized. A preparatory pilot project delivered a series of long-term mean bias estimates for each station, the time intervals of applicability and their statistics. They were derived from freely adjusted station position and EOP solutions for the period 1993.0 to 2020.5, using the latest satellite CoG model. The simultaneous estimation of the station heights and measurement biases resulted in a self-consistent set of weekly bias estimates for each site. Breaks and “jumps” were used to define the periods of applicability and to calculate the mean bias and its standard deviation. These mean biases were pre-applied in the re-analysis forITRF2020, limiting the remaining jitter of the bias to negligible level. This approach strengthened the estimation process without a compromise of the final results’ accuracy. As a result, the ILRS contribution to ITRF2020 minimized the scale difference between SLR and VLBI to below 2 mm (ITRF2014 ~9 mm). We present an overview of the procedures, models, and the improvement over previous ILRS products, focusing especially on the Core ILRS sites.

Oral 01-04

Some Aspects of BKG’s SLR Contribution to ITRF2020

Daniel Koenig (1), Claudia Flohrer (1), Sadegh Modiri (1), Ulrich Meyer (2), Rolf Dach (2), Daniela Thaller (1)

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BKG as one of the Analysis Centres of the ILRS participated in the ILRS contribution to ITRF2020 by submitting its series of loosely constrained weekly SLR normal equations. For evaluation purposes BKG derived from its weekly submissions a series of weekly Minimum Constraints solutions that are presented here. Mainly the ground network’s scale, range biases

of selected stations, local ties measurements at the Wettzell fundamental station as well as some statistical figures are discussed. Special focus is put on disturbing influences on the ground network's scale as well as on comparisons to ITRF2020 and BKG's VLBI solutions.

Oral 01-05

A Global SLR-only Reference Frame

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The current official ILRS products provide a time series of station positions and EOP, leaving the estimation of velocities under the umbrella of the ITRF realization.

The goal of this work is to present a global Reference Frame for the ILRS network stations obtained using only the ASI solutions contributed to the ILRS official products.

The analysis has been performed using almost 30 years of data (1993 to 2022) collected from the operational weekly loose-constrained SINEX products.

The estimates from the historical series were obtained through the Globk software, part of the Gamit/Globk software, natively built for GPS analysis but adjustable for a multi-technique analysis.

We present the approach used through the Globk, describing the workflow, the configurations, and the results of the comparison with respect to the newest ITRF2020 Reference Frame, showing a good agreement.

The quality of the results could initiate a discussion within the Analysis Standing Committee leading to the generation of an internal ILRS reference frame to be updated more frequently than the ITRF.

Oral 01-06

Multi-satellite SLR solutions including LARES/LARES-2 SLR data

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With the launch of the spherical satellite LARES-2 on July 13, 2022, there is a new target in space which can be used for SLR observations. LARES-2 has a very small area-to-mass ratio and is orbiting the Earth at an altitude of 6000 km, such that the non-gravitational disturbing forces are minimized and therefore the orbit modeling is simplified. In this study, multi-satellite SLR solutions are generated by using spherical geodetic satellites, i.e., LAGEOS-1/2 and LARES/LARES-2. The orbits are determined in 7-day arcs together with station coordinates, range biases, Earth rotation parameters and spherical harmonic coefficients of the Earth's gravity field. The quality of the solutions are validated by comparing the estimated parameters, e.g., the Earth rotation parameters and spherical harmonic coefficients, with external quality metrics and by analysing the decorrelation of the estimated parameters.

Oral 01-07

Determination and analysis of Herstmonceux geodetic heights for the period between 1984 and 2022

Andreja Susnik (1), Graham Appleby (2), José Carlos Rodríguez (3), Peter Dunn (4)

(1) British Geological Survey (BGS), Space Geodesy Facility (NSGF), Herstmonceux, United Kingdom; (2) Honorary Research Associate, BGS NSGF; (3) Yebes Observatory (IGN/CNIG), Yebes, Spain; (4) Peraton Inc.

Following the NSGF Analysis Centre 'SSEM' work towards its submission for ITRF2020, we have carried out further research using the SATAN analysis package with the main goal to improve the quality of station height time series. A particular interest is whether the ITRF2020 height time series for Herstmonceux, publicly available online, contains contamination from the historical period when Stanford interval counters were used (1990-2002) and when their known range-dependent errors were not fully compensated; such contamination has the potential to compromise long- term geophysical interpretation of the height series in this fore-bulge collapse zone.

We present results whereby potential systematic range errors are accommodated within the weekly (two-weekly for 1984-1993, LAGEOS-only) LAGEOS, LAGEOS-2 and Etalon solutions using no a-priori bias information except the measured Stanford errors. A comparison is carried out between the height series where the Stanford systematics are accommodated and where they are not.

Oral 01-08

EOP Prediction with special focus on SLR

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The Earth orientation parameters (EOP) became a significant interest in various fields of Earth sciences, astronomy, and climate change studies, as their variations are related to mass redistribution, gravitational, and geodynamic processes in the Earth system. Moreover, real-time EOP information is needed for many space geodetic techniques applications, including satellite navigation on ground and for low-Earth-Orbiters, as well as real-time tracking and navigation of interplanetary spacecraft, and climate forecasting. Currently, the EOP can be estimated at the best possible accuracies with modern high-precision space geodetic techniques like Very Long Baseline Interferometry (VLBI), Global Navigation Satellite Systems (GNSS), and Satellite Laser Ranging (SLR). However, the complexity and time-consuming data processing always lead to time delays. Consequently, predicting EOP is of great scientific and practical importance. Accordingly, several methods have been developed and applied for EOP prediction. However, the accuracy of EOP prediction is still not satisfactory even for prediction of just a few days in the future. Therefore, new methods or a combination of the existing approaches are investigated to improve the accuracy of the predicted EOP. Such in-depth investigations are currently conducted within the "EOP Prediction Comparison Campaign (EOP-PCC)" organized by IAG and IERS. We will briefly present the EOP-PCC and show our

contribution. In this study, we investigate a new prediction package (input data and method) to improve the possibility of bridging the existing gap between the observation and the final estimated product. We run our prediction algorithm with official IERS EOP series as well as with our BKG's single-technique analysis products for VLBI and SLR using the combination of a deterministic and a stochastic method. This method consists of a deterministic part estimated by SSA, whereas Copula is used for modeling the stochastic component. We will show the potential of using the SLR technique to obtain real-time EOP estimates.

Oral 01-09

Height Determination for the most Accurate SLR Stations

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Peraton Inc; Greenbelt, USA

Recent advances in SLR data analysis allow the separation of accurate height measurements from the non-geodetic signal, to complement the more easily resolved horizontal motion. However, elimination of engineering and environmental effects requires knowledge of the form of the signal. A constant range bias has the simplest, the most common and the most easily accommodated form. It can be resolved during the reference frame analysis process, given an accurate time interval over which it is expected to apply. We examine the emerging results from ITRF2020 (Pavlis et al, REFAG 2022) and prioritize the most accurate geodetic products. We will show height variations from a variety of SLR stations in different tectonic regimes. They contribute to long-term tectonic Earth models and monitor vertical variation at higher frequencies: annual, tidal, and diurnal. Data handling techniques will be outlined to enhance the isolation of the geodetic signals and enable their application to Earth and Ocean model development

Poster 01-01

Reconstructing local ties via co-location in space onboard GNSS and LEO satellites

Dariusz Strugarek, Krzysztof Sośnica, Grzegorz Bury, Radosław Zajdel

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Satellite missions incorporating more than one space geodetic technique onboard the spacecraft allow for co-location in space. All Galileo satellites are equipped with the laser retroreflector, thus allowing for the co-location between GNSS and SLR data. Low Earth Orbiting (LEO) satellites, such as SWARM, track GPS signals and are equipped with laser retroreflectors, thus, integrating two space geodetic techniques onboard.

In this study, we employ Galileo satellites as a tool for the reconstruction of local ties between SLR telescopes and GNSS receiver antennas measured on the ground. We use a time series of SLR observations to Galileo satellites and a global network of stations tracking microwave GNSS signals. SLR and GNSS solutions are combined using different approaches of range bias handling and network constraining.

We also employ double SLR telescopes at one station, such as in the Wettzell Observatory, to reconstruct the local tie using the observations of SWARM satellites and high-accuracy GPS-based orbits. We test different approaches of SLR network constraining, solutions using LEO, Galileo, and LAGEOS data, as well as the solution without introducing any constraints, the so-called SLR Precise Point Positioning. We show that LEO satellites can be used for the reconstruction of the local ties with the agreement of the mean value at the level of a few millimeters when using at least several months of SLR data.

Oral 02-01

A comparison of different ocean tides models

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Ocean tide models are an important constituent in precise orbit determination (POD) of near-Earth satellites since these effects influence both the station positions of ground-based observing stations and the satellite orbit itself. Ocean tide models express periodic variations based on amplitudes and phases of main tidal frequencies (main waves) and an interpolation of smaller tides (secondary waves). In recent years, different models were generated (e.g., EOT11a, FES2014, EOT20). We will present results regarding the performance of these models based on POD results of low Earth orbiting satellites.

Oral 02-02

Precise orbit determination of SLR and altimetry satellites using ITRS2020 realizations

Sergei Rudenko, Mathis Bloßfeld, Alexander Kehm, Denise Dettmering, Julian Zeitlhöfler, Matthias Glomsda, Detlef Angermann, Manuela Seitz

Deutsches Geodätisches Forschungsinstitut der Technischen Universität München (DGFI-TUM), Munich, Germany

In 2022, three new realizations of the International Terrestrial Reference System (ITRS), namely, ITRF2020, DTRF2020 and JTRF2020 are to be published. Compared to the 2014 realizations of the ITRS, they are based on a 6-year longer data time span (extended by 2015.0-2021.0), observations from new tracking stations, improved modelling of geophysical and other effects as well as technique-specific biases. Additionally, long-term mean satellite laser ranging (SLR) range biases were determined and applied for the 2020 realizations of the ITRS. A precise and stable reference frame realization is the basis for the computation of precise satellite orbits. In this study, we hence discuss the application of the new ITRS2020 realizations for precise orbit determination of some spherical SLR satellites at the altitude between 690 and 19135 km, as well as of four non-spherical (altimetry) satellites at the altitude of about 1300 km. We investigate the impact of the new ITRS realizations on the root-mean-square (RMS) and mean fits of SLR observations and remaining range biases. For altimetry satellites, we additionally investigate the impact on the RMS and mean of the sea surface height crossover differences as well as geographically correlated errors. We also compare the results derived with the new 2020 realizations to those derived with the previous (SLRF2014) realization of the ITRS

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Oral 02-03

COST-G gravity field models: application in SLR orbit determination

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The Combination Service for Time-variable Gravity fields (COST-G), as a product center of the International Gravity Field Service (IGFS) of the International Association of Geodesy (IAG), provides monthly GRACE, GRACE-FO and Swarm gravity fields that are combined from the contributions of the associated analysis centers and partner analysis centers worldwide. To support operational Precise Orbit Determination (POD) of Low Earth Orbiters (LEO), where the GRACE-FO monthly gravity fields cannot meet the latency requirements, COST-G is providing a Fitted Signal Model (FSM) that allows for the prediction of temporal gravity field variations. The COST-G FSM is updated quarterly with the latest GRACE-FO data and therefore is always based on the most recent gravity fields available. We will present the COST-G FSM and its application for the daily SLR routine processing of LAGEOS/ETALON, as well as LARES orbit determination.

Oral 02-04

Thermal Thrust Perturbations, Spin evolution and the long-term behavior of LAGEOS II Semi-Major axis

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Understanding the effects of Non-Gravitational Perturbations (NGPs) has characterized the study of the dynamic model of LAGEOS satellites since their launch. These passive geodetic satellites, tracked by the Satellite Laser Ranging technique, are the most extensively studied so far in the literature for the development of ad-hoc perturbative models. Besides their significant applications in geodesy and geophysics, this is related to the numerous measurements and investigations that have characterized these satellites in the field of gravitational physics and the verification of the predictions of General Relativity. Among the numerous NGPs, thermal thrust forces arise as a consequence of a non-uniform distribution of temperature across the surface of the satellite. This temperature distribution is responsible for an anisotropic emission of radiation with also significant long-term effects on the orbital elements. These effects are produced by the pressure of solar and terrestrial radiations (albedo and infrared).The different importance of these forces, strictly influenced by the rotational state of the satellites— both in orientation and in rate— seems to be the main cause of the inversion observed in the decay of the semi-major axis of LAGEOS-II starting from mid-March 2012, approximately 19 years after its launch. This behavior, apparently unexpected and far from its previous interpretation, will be described and discussed in light of the thermal thrust and spin

models of the satellite that we have developed and compared with Precise Orbit Determination results. This research is part of a broader activity in the field of fundamental physics, aiming to use geodetic satellites as proof masses to test and compare the predictions of General Relativity with those of other alternative theories of gravitation, in the context of the project SaToR-G (Satellite Test of Relativistic Gravity).

Oral 02-05

A new system-dependent SLR measurement correction function for TOPEX/Poseidon

Julian Zeitlhöfler, Mathis Bloßfeld, Sergei Rudenko, Denise Dettmering, Florian Seitz

Deutsches Geodätisches Forschungsinstitut der Technischen Universität München (DGFI-TUM), Munich, Germany

One of the first major altimetry missions synoptically mapping the global ocean topography was TOPEX/Poseidon (T/P). It was launched in 1992 and provides important information for studies on global and regional sea level trends, ocean circulation, and phenomena such as El Niño or La Niña.

A significant limiting factor for T/P precise orbit determination (POD) are phase centre variations caused by the large laser retroreflector array (LRA) mounted on the spacecraft. The LRA is the target for satellite laser ranging (SLR) measurements from crust-fixed stations. In the case of T/P, it is not optimally designed since its diameter is over 160 cm. To meet the ambitious orbit accuracy requirements of an altimetry mission, the application of an SLR measurement correction for the POD is essential. Up to now, only tabulated, non-publicly available LRA corrections exist which had been determined from pre-launch calibration measurements (before 1992).

We present a new approach to remove the LRA phase centre variations in combination with station-specific systematics. The approach is based on an empirically derived correction function using uncorrected SLR normal point observations and the observation's azimuth and incidence angles in the LRA frame. The value obtained from the correction function is added to the theoretical SLR measurement and resolves, among station-related effects like range biases or hardware and software changes, the LRA phase centre variations.

The advantages of this method are (i) the continuous functional, which is easy to implement in existing software packages, (ii) the avoidance of an interpolation between tabulated values, as well as (iii) the computation of a new correction function based on most-recent geophysical background models. To prove the benefit of using the measurement correction function, differences between orbits without and with the correction applied, as well as some results of altimetry crossover analysis will be presented.

Oral 02-06

SLR validation of IGS Galileo orbits derived in the framework of the ITRF2020 realization

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The latest realization of the International Terrestrial Reference Frame, ITRF2020, incorporates for the first time, the observations of the European Galileo satellite system. Thanks to the effort of the ILRS stations, a large number of SLR observations has been collected to Galileo In-Orbit-Validation (IOV) and Full Operational Capability (FOC) satellites, allowing for the orbit validation.

In this study, we show results from the Galileo orbit validation of different International GNSS Service (IGS) analysis centers, as well as the combined orbits from the 3rd IGS reprocessing campaign (Repro3) generated by the IGS Analysis Centre Coordinator (IGS ACC) at Geoscience Australia. We identify systematic errors related to the signature effect for IOV and FOC satellites that are equipped with different types of retroreflectors for SLR stations equipped with CSPAD, MCP, and PMT detectors. Finally, we compare the orbit quality from different IGS analysis centers, especially those that use zero-difference GNSS solutions with the clock estimation and double-differences that lead to an inferior quality of the orbit radial component. We summarize the recent progress in GNSS orbit modeling with the emphasis of the SLR contribution to the validation of GNSS orbits and the realization of the international terrestrial reference frames.

Oral 02-07

The ILRS Support to the Copernicus Sentinel-3 & -6 Missions

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The Copernicus Precise Orbit Determination (CPOD) Service, part of the ground segment of the Copernicus programme, is in charge of computing the precise orbits of Sentinel-1, -2, -3 and -6 missions. The Sentinel-3 and -6 missions, being both satellite altimetry missions, incorporate Laser Retro Reflector (LRR) to support the Precise Orbit Determination (POD) of these missions.

The ILRS has an important role within the POD calibration of these two missions by tracking them with laser and providing high-quality observations to the scientific community. The observations are used to assess the quality of the microwave-based determined orbits (i.e., computed with GNSS and/or DORIS), to investigate biases in the GNSS and DORIS sensors, or to determine orbits as well.

The CPOD Service is in charge of generating the CPF files of Sentinel-3 mission (EUMETSAT generates those files for Sentinel-6) and make use of the Satellite Laser Ranging (SLR) observations to quality control purposes, on both routine operations and in post-processing activities.

It will be presented the support provided by the ILRS to these missions through the routine tracking, and the use of the SLR data within the CPOD Service. Among other things, it will be showed the number of passes per ILRS station, the accuracy of the S-3 CPF predictions, the biases found per station, and the SLR residuals of the Sentinel´s orbits.

Poster 02-01

Precision Orbit Determination of BDS satellites using combined SLR and Inter-satellite link measurements

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The BDS satellites are equipped with the inter-satellite link (ISL) equipment, which can observe other satellites and ground monitoring stations with Ka-band measurements. The relative satellite clock and geometric distance can be separated to decouple the satellite orbit and clock difference using the dual one-way ISL ranging measurements of BDS satellites. The geometric distance is taken as the observation and is combined with the ground-based measurements to determine the precision orbit of BDS satellites. SLR has no carrier phase ambiguity and clock difference, not affected by the ionosphere, simple data and data processing, which can be used as a measurement technology independent of GNSS observation technology. This paper focuses on evaluating the precision orbit determination accuracy of 11 BDS satellites (MEO/IGSO/GEO) based on SLR and intersatellite link (ISL) measurements. The results show that the orbit accuracy of BDS satellites are 0.04m for radial components and 0.30m for 3D. The accuracy of 12h and 24h predicted orbit for MEO is about 40cm for the 3D, the accuracy of orbit for IGSO orbit is less than 60cm for 3D and the accuracy for GEO is about 1m for 3D. The results show that the high precision orbit of the navigation satellites can be achieved using combined SLR and ISL measurements.

Oral 03-01

A once in a lifetime experiment: SLR observations of the Apophis encounter Friday, April 13, 2029

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On the night of Friday, April 13, 2029 a little after 21:00 UTC, the asteroid Apophis and the Earth will have a very close encounter. Apophis will pass inside the geostationary belt. During that period Apophis's minimum range distance to the European SLR stations will be around ~32000-35000 km.

This close encounter will occur during local night-time in Europe.

The Apophis sky elevation will be in the same range as for regular SLR observations.

A general overview of Apophis visibility conditions for Europe is presented.

Given the current SLR state-of-art ranging to passive objects (space debris) mainly among the EUROLAS SLR stations. And considering the expected technological advances in the next seven years. It is the time to start a preliminary discussion about organising a European-wide SLR Apophis laser ranging campaign based on the multistatic SLR ranging mode.

This SLR data set will complement a wide array of observations planned or proposed.

Some initial ideas about how to organise such a campaign are presented.

Oral 03-02

The Galileo for Science project: Fundamental Physics and Technology development for the Constellations of Galileo satellites

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The Galileo for Science (G4S 2.0) project, funded by the Italian Space Agency (ASI), aims to perform a set of measurements about gravitation with the two Galileo satellites GSAT-0201 (E14) and GSAT-0202 (E18) exploiting the relatively high eccentricity of their orbits with respect to those of the other satellites of the Full Operational Capability (FOC) constellation. These two satellites have been already used in 2018 by both ZARM and SYRTE collaborations for a new measurement of the Gravitational Red shift that has improved the 1976 measurement of

Gravity Probe A by a factor between 4 and 6 respectively. In fact, from an accurate analysis of the orbits and clocks of these two Galileo satellites, a set of relativistic tests can be performed with the objectives of comparing the predictions of Einstein's theory of General Relativity with those of other gravitational theories concerning, mainly, the motion of a test particle along a geodesic of space-time and the time dilation of the on-board clocks. Conversely, the clocks of the full Galileo-FOC constellations will be analyzed to set possible constraints on the presence of dark matter in the Milky Way in the form of Domain Walls. Finally, a new accelerometer concept will be developed to be embarked on a next generation of Galileo satellites to measure non-gravitational accelerations. These, in fact, constitute the main source of uncertainty for a further improvement in the precise orbit determination of navigation satellites. Three Italian research institutes are involved in G4S 2.0: Center for Space Geodesy (ASI-CGS) in Matera, Istituto di Astrofisica e Planetologia Spaziali (IAPS-INAF) in Roma and Politecnico (POLITO) in Torino. The project will be presented with some of the ongoing activities at IAPS-INAF.

Oral 03-03

Relativistic Positioning as a complementary technique of LASER Ranging

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Relativistic positioning methods and techniques will be presented. Such techniques, besides incorporating general relativity from the very beginning, are based only on local accurate time measurements, allowing both for self-positioning for a receiver of signals sent by known emitters, and for the positioning of a remote emitter in the reference frame of at least four known receivers. The approach basically solves a geometric problem in four dimensions on a curved space-time manifold. In general, the accuracy of the final space-time positioning depends on the accuracy of the time measurements performed at the receivers and on the precision with which the space position of the receiving/emitting reference stations is known. The method is exemplified considering the ground based stations of the ILRS network and the Galileo satellites, especially the two actually parked on high eccentricity orbits being the object of the Italian Space Agency (ASI) Galileo for Science project. The relativistic positioning approach could be complementary to the LASER ranging technique, especially for transverse positioning. Furthermore, it would allow self-guidance for spacecraft in the solar system provided well localized beacons are available not only on earth, but possibly in the Lagrange points of the sun-earth pair (or other pairs of celestial bodies) or even considering pulsars.

Oral 03-04

Space Geodesy for the monitoring of Volcanoes and Surrounding Hills of Arequipa using the Arequipa Station as a reference

P. Yanyachi (1), K. Rodriguez (2), C. Carabajal (3), J.P. Boy (4) and others IAAPP-UNSA members

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Historically, Arequipa, which is located within the Pacific "Ring of Fire", has special seismic-tectonic conditions and the presence of the Misti Volcano adds seismic-volcanological

conditions. The objective of this project is to implement a monitoring network that allows analyzing deformations before, during and after seismic and volcanological events by applying spatial geodesy techniques, allowing possible risks to be alerted. Among the techniques used for spatial Geodesy, there are the GNSS (Global Navigation Satellite System), SLR (Satellite Laser Ranging), VLBI (Very Long Baseline Interferometry) and DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite) techniques that allow perform measurements with centimeter or millimeter precision both in planimetry and in altimetry. Regarding measurements on land, there is the EDM (Electronic Distance Meter) technique with a precision of 0.5–1.0 mm for distances between 1 to 12 km, which were used to calculate the deformation of the Long Valley Caldera east of Yosemite in 2005. in United States.

Initially, the GNSS technique was used to monitor the Misti volcano during the years 2021 and 2022 to determine the position and speed of a certain point on the volcano and relate it to the GNSS point of the Arequipa Station. For the processing of the data obtained, the software developed by MIT is used: GAMIT/GLOBK, which allows estimating the three-dimensional relative positions of terrestrial GNSS stations, satellite orbits, atmospheric zenith delays and Earth orientation parameters. GAMIT can reduce measurement error using various ionospheric, atmospheric, meteorological and oceanic correction models, with which this software allows daily measurements to be obtained, 24-hour sessions with millimetric errors. GAMIT is currently widely used by international geodetic institutions such as the "International GNSS Service" (IGS) and other institutions at regional and national levels.

For the elaboration of this project, the GNSS data of the MTPI station located in the Misti volcano were used. These data were provided by agreement between a Peruvian government institution and the National University of San Agustin (IAAPP-UNSA). Although in a later stage, GNSS stations installed by the IAAPP-UNSA that include the SLR/EDM technique will be placed.

The mathematical and theoretical foundations used for the development of the project are presented, the methodology and the steps carried out for the processing of the GNSS data of the local MTPI station with the GAMIT 10.71 software are detailed. This Section details the procedure carried out for the conversion of the binary files and the configurations made in GAMIT/GLOBK for processing, and the results obtained in the processing. Finally, the conclusions of the analysis of the baselines obtained and the possibility of volcanic risk are shown.

Poster 03-01

Time-variable Earth’s gravity field derived using SLR and GRACE data

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Observations of the time-variable Earth’s gravity field describe the redistribution of environmental masses in the Earth system, including changes in land hydrology, ice, ocean, and atmosphere. These observations provide essential insights in to the global water cycle, changes in ocean surface currents, mountain, and polar ice mass loss, large-scale underground droughts, sea-level rise, surface load displacements, as well as many other environmental processes. The variations of the Earth’s gravity field directly influence the Earth's rotation, in

particular, pole coordinates and length of the day variations from intra-annual to decadal and secular scales.

Currently, the observations of mass transport within the system Earth are mainly observed by two satellite missions, GRACE, and GRACE Follow-On. During these missions, there were problems with acquiring actual observations, especially at the end of the mission, and in some periods data gaps occurred. For there covery of the mass redistribution processes on large scales, we may employ Satellite Laser Ranging (SLR) observations to spherical geodetic satellites, such as LAGEOS-1/2, Starlette, Stella, Ajisai, and LARES-1/2.

The primary goal of this study is an analysis of monthly temporary models from different available solutions. We compare solutions from GRACE and GRACE Follow-On missions with those from SLR missions. For this comparison, we use calculated trends and amplitudes in equivalent water high (EWH) in global and specific regions with prominent changes. Trends are derived for models using their entire period, but also for shorter periods. We also calculate global empirical orthogonal functions (EOFs) for GRACE and SLR models to compare the main EOF contributors. Finally, we analyze the time series of selected zonal, tesseral and sectorial spherical harmonics of significant interest.

Session 4. Errors in SLR: Detection, Mitigation and Modelling

Oral 04-01

A tool for simulating SLR residuals - Placement of backup retroreflectors for future satellite missions

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Defunct satellites or other space debris can start to rotate related to external or internal forces acting on the body. Future removal missions rely on a profound knowledge of the orbit and attitude of space objects. Utilizing different techniques (satellite laser ranging (SLR), space debris laser ranging, radar or light curves) rotational parameters can be measured.

The design and placement of additional (backup) CCRs on side faces of satellites was studied within the ESA activity "Retroreflector-based Attitude Detection System (RADS)". The placement of small (e.g. commercial-off-the-shelf) CCRs on future satellite missions would allow accurate monitoring of such tumbling behavior e.g. within the ILRS even for stations without a space debris laser.

Using a modular approach, a simulation tool is introduced to simulate SLR residuals. Rotating satellites produce a distinct periodical residual pattern connected to the movement of the CCRs with respect to the center of mass of the satellite. Within the tool different parameters (satellite, orbit, CCR position and orientation, rotation period, rotation axis orientation, reference coordinate frame) can be arbitrarily adjusted, allowing to design and orient the CCRs according to specific needs or boundary conditions of the mission. A comparison of measured SLR datasets to satellites with known attitude was used to validate the simulation results of the tool.

Oral 04-02

Homogeneous formation of SLR Normal Point data

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Nowadays, the SLR Normal Points (NPs), i.e., compressed full-rate data, are generated by each SLR station, and are provided through the International Laser Ranging Service (ILRS) to the analysts for their SLR processing. However, in 2018, the ILRS requested the stations to provide also their full-rate data. This enables the analysts to generate the NPs homogenously for all stations to reduce systematic errors. Therefore, we designed in collaboration with the Swiss Optical Ground Station and Geodynamics Observatory (SwissOGS) in Zimmerwald a NP generator offering different screening techniques, e.g., standard filter or leading-edge filter. The newly derived NPs can then be used immediately to perform weekly SLR solutions for

LAGEOS-1/2, where the orbits are determined in 7-day arcs together with station coordinates and other geodetic parameters. The quality of different sets of NPs is evaluated by comparing, e.g., station coordinates, Earth rotation parameters or observation residuals.

Oral 04-03

Novel Data Analysis Strategy at the SwissOGS Zimmerwald (7810)

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A standard figure of merit to assess the quality of satellite laser ranging (SLR) observations, for a given station, may be a time dependent average describing the root-mean-square (RMS) after the formation of the so-called normal points. The nominal RMS per normal point depends on the station technical specifications and target characteristics, such as the so-called target depth, which describes the location of the target's reflective elements with respect to the target's centre of mass and their orientation with respect to the observing station. However, other information affecting the quality of the observations, e.g. the return rates, are presumably not analysed even though those quantities potentially provide useful information about the health, or status, of specific system components. In this work, we will use the latter as the observables from which we want to infer indicators for the status of the system, and therefore the quality of the observations.

Specifically, the questions addressed by the present work are: how can we make use of historical raw data to derive and define key performance indicators (KPIs)? To which specific system components might these KPIs relate?

Is there any benefit on using such KPIs for detecting system flaws? To answer these questions, we analysed passes to the target Lageos-1 during one year, considering the correct discrimination of the target's backscattered photons from the background noise. One outcome shows a decreasing return rate per month matching with independent in situ laser power measurements utilizing a power meter. In this case, the KPIs helped to identify health issues related to our laser source.

Oral 04-04

Satellite Orientation effects on Centre of Mass Corrections

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The current centre of mass correction values employed by ILRS analysts for the processing of SLR observations to spherical geodetic satellites are station-, satellite-, and operation-specific, and are available for most stations that have contributed significant volumes of data over their tracking history. By design, these corrections are averaged values over all possible orientations of the satellites. The underlying assumption here is that instantaneous departures from the computed mean values do not affect in significant ways the quality of the thus corrected observations, and therefore their derived products. Far from being a neglected topic, several groups have devoted in the last years substantial efforts towards improving current data reduction strategies, even if not always explicitly framing the problem as an orientation-dependent effect or a centre of mass correction issue. Here we examine the extent to which the variability present in SLR normal point data, in particular for single-photon operations, is caused by changes in the relative orientation between the satellites and ground stations, present a simple method to account for this effect, and discuss the impact on the actual geodetic products computed from the data in global solutions.

Oral 04-05

Modeling NASA/SLR Multi-Photon Receive Energies

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The worst type of SLR systematic errors are range (e.g. frequency) and/or elevation (e.g. tropospheric) dependent biases, because if unmodeled they can impact scale estimates and SLR station coordinates of the International Terrestrial Reference Frame (ITRF) [Drożdżewski, 2021]. In this paper, we will discuss a case study of modeling receive signal strength from NASA SLR multi-photon systems. We will discuss the pros and cons including the potential impact on normal point data quality. We will also try and answer a long-standing question from the data analysts. Is NASA SLR receive signal strength elevation dependent?

Oral 04-06

Modeling ILRS Barometric Accuracies using the Vienna Mapping Function (VMF)

Van Husson

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SLR tropospheric errors, in particular barometric errors, are elevation dependent and if unmodelled will negatively impact SLR station height estimates. To reduce systematic errors to less than 1 mm caused by barometer errors requires absolute barometric sensor accuracies of less than 0.15 hectopascal (hPa). Barometric errors of a few or several hPa were common in the SLR network prior to the mid 1990's.The proliferation of more accurate SLR meteorological sensors and more frequent sensor calibrations in the mid to late 1990's had a positive impact on our SLR data quality and SLR scale. In this paper we will discuss using two types of VMF data for optical wavelengths in identifying past, present, and future ILRS barometric measurement errors. We will also discuss an approach for modeling past barometric errors.

Oral 04-07

Seasonal variations in the station ranging bias and tropospheric zenith delay in SLR

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Changes of the surface mass loading deform the Earth's surface and cause a modulation of mass loading center, and also produce an additional loading potential acting on satellite. In all of studies, the SLR observations are assumed to only contain a constant or pricewise systematic station dependent bias. However, a significant seasonal signal appearing in station ranging bias was observed for most tracking stations in the global SLR network. A large part of the seasonal signal in raging bias could be produced by the degree one loading potential affecting on satellite, and a small part is due to the high degree surface mass loading induced variation. The monthly solution of geocenter parameters become comparable with the solution from the GPS based global conversion when the ranging biases are simultaneously estimated for the tracking stations. The effects of the error in the modeling of tropospheric zenith delay and gradients are negligible effect on estimating of the geocenter variations and can be separated from ranging bias.

Oral 04-08

Tropospheric delay modeling in SLR solutions based on numerical weather models and the estimation of tropospheric bias corrections

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The tropospheric delay modeling in SLR data relies on in-situ meteorological observations collected at SLR stations. However, some meteorological sensors can be affected by systematic errors and biases. Furthermore, the asymmetry of the atmosphere is not accounted for when considering in-situ meteorological data from one station because the atmosphere around the station cannot be well characterized.

In this study, we test different methods of accounting for the tropospheric delay based on numerical weather models provided in the Potsdam Mapping Function (PMF) for SLR data and the Vienna Mapping Function 3 for optical measurements (VMF3o). We can identify those stations which possibly may have issues with barometer readings from the comparison between numerical models and meteorological data from SLR stations. We also test the possibilities to separate the mapping function for the wet and hydrostatic delays as well as the horizontal gradients derived from VMP3o, PMF, and a simple parametric model of gradients. We test the models based on SLR observations to LAGEOS-1/2 satellites as well as to GPS-based SWARM-A/C/B satellite orbits with and without the estimation of corrections to the zenith delay and horizontal gradients.

Oral 04-09

Modeling of systematic effects in SLR observations to Swarm satellites for determination of global geodetic parameters

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The ESA low Earth orbit (LEO) satellites Swarm-A/B/C are equipped with Global Navigation Satellite System (GNSS) receivers and retroreflectors for Satellite Laser Ranging (SLR). Most commonly, the SLR technique is used to validate the Precise Orbit Determination (POD) products based on GNSS. The SLR observations to LEOs are currently not considered for the realization of terrestrial reference frames. The increasing accuracy of laser observations to LEOs, including Swarm satellites together with high-quality POD products allow for the utilization of SLR observations for various purposes, including identifying systematic effects in SLR data and determination of SLR station coordinates and global geodetic parameters.

We reduce systematic effects affecting the SLR residuals to LEO Swarm satellites by incorporating GPS-based POD products and special handling of SLR systematic errors emerging from tropospheric delay modeling. The Swarm POD products are based on ionosphere-free linear combinations, fixed ambiguities, and satellite macro-models used for modeling non-gravitational forces.

We test solutions incorporating the estimation of range biases, station coordinate corrections, tropospheric biases, and horizontal gradients. We propose estimating a daily correction to troposphere delay in the zenith direction w.r.t. the a priori tropospheric delays based on the Mendes and Pavlis (2004) model and meteorological observations collected at the SLR stations. Applying tropospheric bias correction in SLR allows obtaining orbit validation twice better than for solutions without modeling systematic effects. The solutions with modeling of tropospheric bias corrections show validation results better by 3 mm than solutions considering present methods of range bias handling. We use corrected SLR observations and orbits of Swarm satellites for the determination of SLR station and geocenter coordinates, the length-of-day parameter, and pole coordinates. We compare our estimates with LAGEOS-based solutions and evaluate the consistency of results based on active and passive satellites tracked by SLR.

Oral 04-10

Systematic errors in Satellite Laser Ranging validations of microwave-based low Earth orbiter solutions

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Satellite Laser Ranging (SLR) has become an invaluable core technique in numerous geodetic applications. For many applications a mm accuracy and 0.1 mm/year stability of reference frames is required or at least desired. Unavoidable SLR station biases and coordinate

uncertainties are a major error source and obstacle to reach these accuracy and stability goals when relying on SLR data. Among the stations of the International Laser Ranging Service (ILRS) there is a large diversity of biases and measurement qualities, and the calibration of these biases for all stations is key to further exploit SLR data for present and future geodetic applications.

We show that the analysis of SLR data to active Low Earth Orbit (LEO) satellites with fixed microwave-derived orbit solutions is a promising means to analyze SLR station biases and their stability. For this, a combined analysis of numerous different satellites and a high-quality modeling of gravitational and non-gravitational forces is a prerequisite. Nevertheless, different uncertainties in various dynamical models and offsets remain, potentially degrading the microwave-derived orbits and thus affecting also SLR station-related calibration parameters. In this presentation we address the question on how both station- and orbit-related correction parameters can be simultaneously derived from SLR analyses to active LEO satellites. Based on a consistently produced set of orbit solutions for 9 different LEO missions (Sentinel-3A/B, Sentinel-6A, Swarm-A/B/C, GRACE-FO C/D and Jason-3) we explore different possibilities to compute parameters that reflect corrections to individual orbit solutions, next to station calibration parameters. A special focus is on how to put constraints that are needed to decorrelate the different parameter sets, as well as their impact on the results. These investigations will help to disentangle station- from orbit-related systematic errors, allowing in particular for a better characterization of the former ones.

Poster 04-01

SLR link budget and retroreflector optical cross section evaluation

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The network of satellite laser ranging stations is expanding every year, which is partly driven by new applications such as space traffic management as well as new companies that commercialize the technology.

For the design of new ground segments, it is important to find the balance between an optimization of the link budget, e.g., through the utilization of high-power lasers, large telescopes, etc., and the mass, the volume, and the overall costs of such systems. A key uncertainty in the estimation of the link budget is the optical cross section of the satellites that are equipped with retroreflectors.

The objective of this study is the derivation of the practical “in-orbit” optical cross section from Satellite Laser Ranging (SLR) measurements with a given link budget model. In addition, theoretical values are determined from a state-of-the-art analytical approach that was proposed by Degnan. The results of both methods are compared with literature values, which were computed via diffraction theory.

The analysis is accomplished using the historical normal point data that was published by the EUROLAS Data Center (EDC) and the data that was obtained from our system, namely the miniSLR®. The data comprises a selection of satellites in various orbit altitudes and single photon operating ground segments. The optical cross sections are derived from the link budget equation under consideration of atmospheric-, system specific-, and free space losses.

The findings show that the theoretical values reflect the literature values for single retroreflectors or arrays. However, larger deviations are found for spherical satellites. The derived practical optical cross sections are in the range of two orders of magnitude to the theoretical values. Additionally, a relative constant bias between the individual stations is found. This indicates that these stations over- or underestimate their available system specifications.

Poster 04-02

A SLR Pre-Processing Algorithm Based on Satellite Signature Effect

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Satellite signature effect is the one of major SLR error sources. The reflected signal is deformed and spread with a long tail in temporal distribution due to Satellite signature effect. To reduce the satellite signature effect on the SLR precision, we recently simulated the satellite signature effect removal process for normal point algorithm. The simulation is conducted based on a revised model of satellite response, which fully considering the structural and distribution characteristics of retroreflectors. In order to eliminate both long-term and short-term satellite signature effect, a clipping method for SLR data processing is proposed by defining the clipping location as 5.6mm away from the mean value of the long-term fit residuals to select effective returns for normal points. We applied the clipping method for SLR data processing of Changchun station. The results indicate that compared to normal points algorithm, the stability of RMS is improved 53% and both the stability of skew ness and Kurtosisfor LAGEOS-1 also improved. The new method has stronger robustness and applicability, which can further minimize the influence of satellite signature effect on the SLR production. The results have been published in *Appl. Sci.*

Poster 04-03

Systematic range residuals 2021-2022

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Following our reports presented at the previous workshops (e.g. Otsubo, 2017 ILRS Technical Workshop; Otsubo, 21st International Workshop on Laser Ranging, 2018), we apply the precise investigation into the latest SLR data.

First, global SLR data to the six satellites, LAGEOS-1, 2, AJISAI, STARLETTE, STELLA and LARES, of one year span, July 2021 to June 2022, are precisely reduced in one batch by our software c5++. In addition to the orbital parameters, Earth gravity field coefficients (up to 5x5) and station positions and range biases are adjusted where the station velocity and the earth orientation parameters are fixed to ITRF2020 and EOPC04 respectively. Time-varying atmospheric loading displacement of Strasbourg EOT is applied.

Second, the post-fit residuals were related to other parameters, such as number of normal point returns, bin rms, applied system delay, meteorological data etc. Systematic trends have been detected in various “satellite x station” combinations. We hope that the latest result will be useful motivation to improve the measurement quality of each SLR station, and then to improve global geodetic parameters derived from SLR.

We plan to upload the station-by-station charts to our website that is linked from the ILRS NESC Forum (http://sgf.rgo.ac.uk/forumNESC), before or after the workshop.

Oral 05-01

Galileo mission recent results, ongoing support and future launches

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Satellite laser ranging (SLR) has proven to be a unique and powerful tool for over two decades in the calibration and validation of spacecraft dynamics. The technique's greatest strength—in contrast to microwave measurements—is its ability to provide an independent, unambiguous, and absolute observation of a satellite's orbit. In this presentation, we characterize the Galileo satellite orbit quality and its temporal evolution since 2012 using tracking data from the global SLR network including the recently operational ESA station IZN-1 at Tenerife, Spain. The current size of Galileo SLR residuals indicates unsurpassed radial orbit accuracies up to 1 cm root mean square (RMS), suggesting that the SLR station accuracy limit has been reached. This result has prompted us to take closer look at the Galileo SLR data availability, link budget and normal point accuracy. One of the most important parameters of the link budget on the satellite side is the optical cross-section of the laser retroreflector array (LRA), as the amount of available tracking data for the two type of Galileo LRAs shows a dependency to this parameter. A statistical method has been applied on the available data to validate the LRA's optical cross-section in space. The results of this method are consistent with the specifications of the LRA and corresponding values for LAGEOS and Etalon satellites could be determined. In addition, the accuracy also depends on the LRA properties. A new normal point formation method, the so-called pattern correlation method, has been introduced taking into account the distance distribution of the individual prisms of the Galileo LRA. The new normal points have comparable precision as the standard method and a mean offset of 1.5 mm. Finally, a brief overview about the evolution of the Galileo mission including the future launches will be provided.

Oral 05-02

Fundamental Physics results in testing Gravitation with Laser-Ranged satellites: the LARASE and SaToR-G experiments

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Launched into orbit in 1976 and 1992 respectively, the two satellites LAGEOS (NASA) and LAGEOS II (ASI/NASA) have up to now constituted two very precious sources of scientific results thanks to the precise laser tracking of their orbits. Space geodesy, geophysics and gravitational physics have been extensively studied with their tracking and modeling of their orbits, but also space-to-ground quantum communication has been successfully verified. Several research teams and institutions have exploited the orbits of these satellites— and more recently with the inclusion of the LARES satellite (ASI-2012)— for tests of General Relativity and other theories of gravitation. We will present the results obtained in this field of fundamental physics from two Italian projects called LARASE (2013-2019) and SaToR-G (2020-2024), funded by the National Scientific Commission II of the National Institute for Nuclear Physics (INFN).

Oral 05-03

The LARES 2 satellite for testing general relativity successfully placed in orbit with VEGA C

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The 13 July 2022, ten years after the successful LARES 1 mission, a new laser ranged satellite for testing the space time warp produced by the Earth rotation, predicted by general relativity, has been placed in the final orbit with high accuracy. VEGA C, the newest European Space Agency launch vehicle developed by ASI-ESA-Avio, an empowered version of VEGA used for the LARES 1 satellite ten years ago, passed the qualification flight with full marks. The main objective of the LARES 2 satellite, of the Italian Space Agency, is to provide tests, with unprecedented accuracy, of the phenomenon of frame-dragging predicted by general relativity, that is with accuracy improved by about one order of magnitude, or better, with respect to the LARES 1 mission. LARES 2 will also provide other tests of general relativity and gravitational physics. This will be achieved thanks to the very special orbit chosen for the LARES 2 satellite which is supplementary to that of LAGEOS 1 (launched by NASA in 1976). For that reason the orbital injection accuracy required for the LARES 2 satellite was much more stringent than the one previously chosen for LARES 1. The very preliminary orbital determination, obtained with the laser ranging data, available a few days after the first laser returns acquired by the Matera Laser

Ranging Observatory (MLRO) on the 16th of July 2022, confirms that the orbital injection accuracy is much better than what requested by the scientific team of the LARES 2 mission and very much below the 3-sigma accuracy reported by the launch vehicle user's manual. This, along with the improved Earth gravitational field obtained with the GRACE Follow-On mission, will allow to obtain a better improvement, with respect to what expected, of the measurement of the Earth frame-dragging, potentially bringing the measurement accuracy to about 0.1%. In the paper, the LARES 2 mission will be described in more detail along with the error budget of the space experiment.

Oral 05-04

A simulation study for future geodetic satellite constellations

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Satellite laser ranging (SLR) is currently one of four space geodetic techniques that provide a relevant contribution to the International Terrestrial Reference Frame (ITRF) realization as well as to the determination of global geodetic parameters or low-degree harmonics of the Earth's gravity potential. ITRF realizations are mostly based on the observations to the two LAGEOS and two Etalon satellites, however, the impact of observations to Etalon satellites is marginal when compared to LAGEOS. Currently, an extension of the ITRF solution to include the LARES and LARES 2 is under consideration. The latter was designed and developed by the Italian Space Agency ASI and launched on July 13, 2022.

This study aims at evaluating the contribution of the LARES 2 satellite to the realization of ITRF and deriving global geodetic parameters. Moreover, we consider adding subsequent satellites which supplement the existing constellation of LARES and LAGEOS satellites. Our research aims to investigate a maximized contribution to the accuracy improvement of global geodetic parameters. We also examine various approaches to estimating geodetic parameters depending on the number of determined empirical once-per-revolution parameters for satellite orbits and different approaches of parametrization for the Earth rotation parameters, including piecewise linear and piecewise constant parametrization.

We simulate satellite orbits and SLR observations to LAGEOS-1/-2 and LARES 1/2, as well as to possible pairs of LARES 3/4 and LARES 5/6. We check how the satellites at different inclination angles and heights contribute to deriving global geodetic parameters and compare the results to LAGEOS-1/-2 solutions based on simulated data. We show the improvement that can be obtained by adding observations to the LARES 2 satellite, e.g., for geocenter coordinates, whose median formal errors from weekly solutions based on simulated data are 0.8, 0.8, and 1.6 mm for X, Y, and Z coordinates, respectively when adding LARES 2.

Oral 05-05

SLR Contribution to the new Regional Navigation Satellite System of Korea

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Korea Positioning System (KPS) is the name of new regional navigation satellite system, which will provide the Positioning, Navigation and Timing (PNT) service in Korean peninsula and beyond from 2036. The development and construction program for KPS have started in last July with the conceptual design to provide6 PNT services including Open Service, Differential GNSS, Precise Point Positioning, Satellite Based Augmentation System, Public Safety, and Search and Rescue (SAR).

Space segment of KPS will consist of 5 satellites in the Inclined Geo-Synchronous Orbit (IGSO) and 3 satellites in the Geo-Stationary Orbit (GEO) which are all equipped with Laser-Reflected Array for SLR tracking. The first KPS satellite will be launched in 2027 and the other KPS satellites will be deployed during 2033~2035.The preliminary design of ground segment for KPS including the SLR system is similar to the other satellite navigation systems and the construction of new SLR system dedicated for KPS and GNSS satellite is considering.

In this presentation, we will give the brief introduction of KPS and the contribution of SLR in KPS including the conceptual design of LRA for KPS satellites.

Oral 05-06

JAXA developed SLR Reflector Mt.FUJI and Technical Demonstration on HTV-X

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In recent years, the use of space has expanded rapidly, resulting in a drastic increase in the number of orbital objects. Active debris removal (ADR) and space situational awareness (SSA) have therefore attracted much attention, and thereby, the importance of grasping the orbital and attitude motion of space debris has been increased. To observe space debris motion from the ground, radar and optical observations are commonly per- formed. However, those observation methods do not have sufficient resolutions for atti- tude estimation. Japan Aerospace eXploration Agency (JAXA) is now focusing on satellite laser ranging (SLR) as a means of accurately estimating attitude motion from the ground.

If a space object is equipped with an SLR reflector, its visibility from the ground can be ensured even after it becomes debris. However, because conventional SLR reflectors are expensive, heavy, and large, there are not many space objects with an SLR reflector. Therefore, JAXA has developed a general-purpose SLR reflector, named Mt.FUJI (MulTiplereFlector Unit from Jaxa Investigation), with the concept of small size, lightweight, and reasonable price. Three Mt.FUJIs are installed on a new unmanned spacecraft HTV-X for demonstration in orbit. The objectives of the Mt.FUJI mission are:

- to verify in-orbit performance of Mt.FUJI as an SLR reflector

- to evaluate SLR-based attitude estimation technique by using true data (telemetry of HTV-X)

In particular, the latter will enable the world's first quantitative evaluation of the effectiveness of the attitude estimation method by SLR, as it has not been evaluated with true values.

In the workshop, we will explain the detail of the Mt.FUJI mission. SLR is essential to achieve Mt.FUJI mission, and we believe that the results of this mission will provide new insights into space debris, as it will enable us high-accuracy orbit determination and attitude estimation of space debris.

Oral 05-07

Impact Analysis of Multiple LRR On-Board Future Copernicus CRISTAL Altimetry Mission

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The Copernicus Expansion CRISTAL mission is a Polar Ice and Snow Topography Altimeter that will carry a Ku/Ka bands dual-frequency radar altimeter with an interferometric capability in Ku-band and a microwave radiometer. One of the primary objectives for this CRISTAL mission is to measure and monitor sea-ice thickness and its overlying snow depth. Planned to be launched in 2027, it will nominally carry GNSS receivers and a Laser Retro Reflector (LRR) to support the Precise Orbit Determination (POD) needed by the altimetry.

It is also considered to incorporate 20 additional LRR, 4 on each side of the satellite except on the nadir pointing, where it is located the geodetic LRR, to support future active space debris removal. The idea is to allow a future space mission to approach CRISTAL making use of laser that will reflect from all sides of the satellite. It is currently foreseen that these additional LRRs would have a field of view of 50° (±25°) and will be mounted with at least 1 metre from each other. Still on-going analysis are being carried out to assess different configurations.

Taking into account the current design, it is quite possible that the routine tracking by the ILRS of this mission will be challenging, as multiple reflections from different LRRs will be received simultaneously. The support from the ILRS community will be more than needed.

The mission and its current design will be described. Then, results of simulations will be provided to show the effect of receiving multiple returns from the satellite, coming from several LRR. This presentation is provided to motivate the discussion with the ILRS on potential issues on the ILRS operations.

Oral 05-08

METRIC: a compact mission concept for upper atmosphere mapping, fundamental physics and geodesy

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We describe here a mission concept – called METRIC (Measurement of EnvironmenTal and Relativistic In-orbit preCessions) – for a compact spacecraft to be placed in a low Earth orbit, with dedicated instrumentation to provide data useful for atmospheric science, fundamental physics and geodesy. The main scientific objectives are: map the atmospheric density by in-situ acceleration measurement and by spacecraft tracking at altitudes of great interest for satellites deorbiting; perform fundamental physics tests through a precise orbit determination and verification of the equation of motion for a well-characterized test mass; provide an additional, space-based, node to improve the tie among different space geodesy techniques. These three areas being distinct but strongly interrelated in the case of Earth System science, it appears that they can benefit from the availability of a well-calibrated space-based platform such as the one being proposed. Following a discussion of the scientific objectives, the mission idea will be described with a baseline for spacecraft configuration, scientific instruments and data analysis strategies, with a discussion of current outlook.

Oral 05-09

Lunar Pathfinder Laser Retroreflector Array

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ESA's Lunar Pathfinder mission is scheduled to launch and orbit the Moon at the end of 2024 in an elliptical lunar frozen orbit. The mission will provide lunar communication services and host a Navigation In-Orbit-Demonstration payload that will use Global Navigational Satellite System (GNSS) signals from the moon for positioning. NASA is providing a laser retroreflector array (LRA) for this mission to validate the GNSS-based positioning and demonstrate two-way laser ranging in support of precision orbit determination for lunar missions. The LRA consists of 48 x 4.06 cm diameter uncoated cube corners that will provide an optical cross section around 10 times larger than LRA on the Lunar Reconnaissance Orbiter (LRO). This increased cross section

along with regular dedicated periods where the LRA is pointed towards Earth should significantly reduce the challenges encountered during laser ranging to LRO. An overview of the Lunar Pathfinder mission will be presented along with results from optical measurements of the Lunar Pathfinder LRA.

Poster 05-01

Preliminary design of a laser retroreflector payload for the MARTINLARA mission

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The MARTINLARA Program is a Research Project financed by the Government of the Community of Madrid. Its main objective is the design of a demonstration space mission in orbit, and the development of a nanosatellite platform for airborne validations as well as several technologies to be airborne validated, namely radio astronomy and earth observation instrumentation, space photonics and plasma micropropulsion. Among its five main goals, the one for the demonstration of several functional space oriented technologies includes onboard retroreflectors acting as the space segment of a SLR system.

Both the definition of the mission orbit and the platform are activities still in progress. With respect to the orbit, the current baseline is a down-dusk orbit of altitudes in the range 400-500 km. Regarding the platform concept, a 12U CubeSat nanosatellite has been chosen as baseline.

A first version of the preliminary design of this payload based on retroreflectors has been generated. Its main objective is to provide the necessary preliminary information to evaluate its integrability in the platform, mainly due to its impact on the mass budget, volume/area allocation and elimination of any physical or functional interference with the rest of the payloads. The final version of the preliminary design will be carried out at a later stage, once the platform design is closed.

Three payload concepts have been proposed, each for a different application: precise orbit determination (POD), satellite attitude determination, and space debris tracking. The possibility of overlapping some of them has also been considered. For some, development models have been manufactured and a dedicated optical test bench has been outlined to verify their performance.

The mission, platform design and preliminary design of this payload as well as its location on the platform will be described in this contribution.

Oral 06-01

SLR-System Upgrade and Experiments at Zimmerwald

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The SLR-system upgrade covers a new dome, cooling system and thermal isolation of the Coudé room. Due to aging and new state of the art, this upgrade and refurbishment was necessary. Two new lasers are available to the station and are going to be integrated into the system. One laser will replace the current laser used for geodetic applications and the other will be dedicated to space debris observations. Preliminary experiments for quantum communication were carried out and some ground and ground to space optical communication experiments were conducted by some partner research institutes. The quantum communication experiments used a drone which is sending its position to the telescope. Ground to ground optical communication campaigns, e.g. from Zimmerwald to the Jungfraujoch were using the air traffic control safety system of the station.

Oral 06-02

Validation of the ESA's IZN-1 station and overview of current station capabilities

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The ESA laser ranging station IZN-1 was deployed in Tenerife in 2021. The goals of these assets are to support future Space Traffic Management (STM) applications, to carry out precise orbit monitoring of satellites and space debris and to operate direct-to-ground satellite laser communications. The station performs routinely Satellite Laser Ranging (SLR) at 532 and 1064 nanometres and passive observations of space objects. After an initial ranging campaign and following the site acceptance testing, IZN-1 joined the ILRS as engineering station, completing the qualification process in April 2022. In parallel, two additional independent validations of the station performance were conducted by the ESA Optical and Laser Expert Centre and the ESA/ESOC Navigation Support Office, the latter being one of the ILRS Analysis Centres. Since almost one year of regular remote operations, several targets including geodetic and navigation satellites were tracked. Moreover, active and passive observations of space debris with retroreflectors could be demonstrated.

Besides laser ranging, IZN-1 serves as an advanced technology test-bed supporting also optical communications. The station was recently upgraded with additional components for the

implementation of the IZN-1 optical communication mode and a first optical downlink from a LEO satellite was successfully acquired.

This paper provides a brief overview of the station architecture including the upgrades for optical communications. The results from the different validation entities will be presented as well as SLR and passive observations and optical communication sessions, highlighting the current IZN-1 capabilities.

Oral 06-03

Current state of the contribution of ESA's Izana-1 station to the ILRS

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ESA's Izana-1 station deployed on Tenerife in 2021 serves as a testbed for new technologies, such as active and passive space debris observations as well as optical communication. It also features a geodetic piggy-back laser and detector package with a novel and efficient design. The station actively contributes to the ILRS and submitted more than 850 SLR passes at 532 and 1064 nm to the European Data Center (EDC) between end of November 2021 and September 2022. Since August 4th, the station is released from quarantine within the ILRS. The calibrations shown an RMS of 23 ps at 532 nm and 29 ps at 1064 nm thus achieving mm precision. The accuracy of the station data is at mm level based on range bias analysis. The impact of the return rate on the measured distance has been characterized for both wavelengths, in order to ensure single-photon level for the regular but also the fully autonomous operation of the station in future.

Currently mostly targets from the ILRS list (LEO to GNSS) are tracked with high productivity in terms of achievable return rates, even at low elevation, also during the day and with short NPT accumulation times given the 0.2 W power of the Passat laser at 1064 nm. Also, cooperative inactive targets such as Envisat, Topex and various rocket bodies have been tracked on a regular basis. Passive observations have been recorded to these and other targets that are used for orbit determination and attitude characterization using the high-resolution camera FLI ML 16070. This is done in preparation for a future extension of the system with more powerful laser establishing tracking of uncooperative targets on a regular and even autonomous basis. This paper will summarize the current status of the Izana-1 station as well as its contribution to the ILRS.

Oral 06-04

Development Status of JAXA’s New SLR Station in Tsukuba

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JAXA has been developing a new SLR station since 2017. Tanegashima station (GMSL) had been operated by JAXA since 2004 and had provided satellite ranging data as a part of the ILRS network. However, the operation of GMSL was terminated on 1st April 2021 due to aging and repeating system failures. The purpose of the new SLR station is to take its place and to introduce state-of-art SLR technology. The new SLR station is built in the Tsukuba Space Center (JAXA) where our office is located, and thus it is referred to as "Tsukuba station."The much better accessibility from our office than GMSL makes it easier to change the H/W configuration for experiments and investigate the cause of a system failure.

Tsukuba station is mainly developed by KDK (Japan), TOYO (Japan), and DiGOS (Germany).The design of Tsukuba station is modern and flexible which follows a standardized concept and based on the ESA’s new SLR station, Izaña (IZN-1) in Tenerife, Spain, which was also developed by DiGOS. The lasers and the detectors are mounted on the telescope directly to avoid any Coudé Path, which results in the simple and compact design. Two lasers with the wavelength of 532 nm and 1064 nm are installed and the repetition rate of the lasers is 1 kHz. Tsukuba station has the capability of ranging from LEO to GEO satellites.

Although the operation of Tsukuba station was planned to start in April 2021, the development is about 2 years behind schedule due to the coronavirus pandemic. The construction was suspended in November 2020 and restarted in June 2022.Now, Tsukuba station is undergoing an acceptance test. The laser ranging to some satellites including Galileo is already performed. JAXA plans to start the operation of Tsukuba station from April 2023.

Oral 06-05

Yebes Laser Ranging Station (YLARA), development status 2022

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Yebes Observatory (OY) has been working for years on the construction of a Fundamental Geodetic Station that fulfils the requirements of the GGOS project. Currently, the Observatory host a RAEGE/VGOS radio telescope in operation since 2016, GNSS receivers, a gravimetry laboratory (with absolute and relative superconducting gravimeters), time and frequency systems and a local tie network.

At the beginning of 2018, funds for the construction of an SLR station at Yebes, coming from the European Regional Development Fund (ERDF), were approved. Including this technique, OY will become a GGOS Core Site.

The main objective of YLARA station is to perform geodetic observations contributing to the ILRS network, but a second application is already under development. The station will be equipped with a dedicated laser system for space debris observations, since the beginning of its operation.

The design of the system is based on the SLR stations classic design including a biaxial telescope with a Coudé focus and a conditioned room fully prepared for a laser system installation. However, the design also complies with the state of art of the SLR technique and the operation of the station for SLR observations will be done using a laser package installed in a piggy back configuration. The system will use a two color laser, 532 nm and 1064 nm, with a repetition rate of 1 kHz. The detector package, with a C-SPAD and an IR-SPAD detector, will be also installed on the telescope mount.

Currently, most of the main subsystems have been completed and factory tested, just the telescope assembly is close to completion and will be tested by the end of this year.

It is planned to have every subsystem installed at Yebes in spring 2023, starting observations by summer.

Oral 06-06

Barometer Calibration at the SLR Riga 1884, current status

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The SLR station Riga has operated a Vaisala WXT510 since 2007 as a primary meteorological unit. During the period 1987-2007 the aneroid barometer Paulin VBM2 (Erickson) was used as reference. A Vaisala PTU300 unit installed at the SLR Telescope room is used as an auxiliary unit.

During 2017-2018 both Vaisala Units, WXT510 and PTU300, were calibrated against the GFZ Potsdam GE Druck141 DPI absolute barometer. Currently we are calibrating the aneroid barometers Paulin VBM2 and a 1978 Soviet model against the Vaisala units.

We present the calibration results, and discuss future steps to be done.

Oral 06-07

Automatically and Consistently Detecting and Extracting SLR Measurements for Every Satellite Pass

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After each observed satellite pass, SLR return measurements must be identified and extracted from the surrounding noise points.

This task is made more difficult with weaker return signals, intermittent data flows and greater background noise levels due to sky brightness.

At the SGF, Herstmonceux, an operator manually selects regions of a range residual plot that contain visibly recognisable returns. This selected dataset is flattened by time and radial corrections to the reference orbit, filtered for high return rate levels and clipped so that normal points can be calculated. This task takes observer time and is only performed when the observing schedule allows.

A process for reliably and automatically extracting SLR returns is under development and testing at the SGF. Range returns are first recorded by track detection in real-time and these are used for an initial orbit correction solution using the orbitNP.py software, developed at the SGF. Applying these orbital corrections to the whole dataset produces flattened SLR residuals.

Selecting areas around SLR returns is achieved by considering the relative densities of surrounding residual points. A new return rate calculation method uses the interval between successive track points and the data is filtered for high and low return rates.

A continuously running, multi-process Python program organises the necessary calibration, track, prediction, status and meteorological files for each satellite pass in preparation for automatic data reduction.

Oral 06-08

Current Status and Plans for Test and Deployment of the First NASA SGSLR System

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Over the last decade the Space Geodesy Project has been progressing toward the development and deployment of NASA's next generation network of geodetic stations (https://space-geodesy.nasa.gov). The Satellite Laser Ranging (SLR) part of this effort is called Space Geodesy Satellite Laser Ranging (SGSLR). Significant progress has been made in the development of SGSLR's nine subsystems, and many of these subsystems are completed or are nearing completion. The next major step will be the Integration and Testing (I&T) of all subsystems into the first SGSLR system which will start before the end of 2022. Verification testing (collocation) with NASA's legacy operational SLR system, MOBLAS-7, is planned for early 2024.

The first SGSLR system is being developed for Kartverket, also known as the Norwegian Mapping Authority (NMA). The system will be installed at Ny-Ålesund in Svalbard, Norway. The planned start of operations is early 2025.

This presentation will give the current status of development, the testing and deployment plans, and the future of NASA's SGSLR global network.

The authors would like to thank our colleagues from NMA (Gro Grinde, Gøril Breivik, and Ole Klingan) for their support of the SGSLR development and deployment efforts.

Oral 06-09

Ny-Ålesund: New SLR Site in the Arcticat 79°N

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Kartverket / Norwegian Mapping Authority (NMA), Hønefoss, Norway

Ny-Ålesund is a new Satellite Laser Ranging (SLR) site located in the Arctic at 79° north. The first SLR subsystems have already been installed, and the gimbal and telescope arrive in 2023. The complete SLR is planned for on-site test in late 2024, with start of SLR operations in early 2025.

Ny-Ålesund will be the first of an initial three SLR stations developed by NASA as part of the Space Geodesy Satellite Laser Ranging (SGSLR) project, and NASA plans to further develop five or more similar stations in the coming decade.

After SLR operations start, Ny-Ålesund becomes a GGOS core site that co-locates the four space geodetic measurement techniques; SLR, VLBI, GNSS and DORIS, and gives valuable contributions to the terrestrial reference frame.

We will present status and plans for the Ny-Ålesund site, with emphasis on opportunities and challenges related to SLR operations at this very remote location. Laser safety for aircrafts is considered in particular, and we give a first overview of our Aircraft Avoidance System (AAS) currently under development.

Poster 06-01

San Fernando Laser station: News and improvoments

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San Fernando laser station has been working on this geodesic technique for more than 4 decades. In 2015, a new field of work was opened, such as the monitoring of non-active collaborative objects. It marked a first step towards space debris tracking. Since then, several changes and improvements have been made on the station, such as the incorporation of two new laser benches, and a severe modification of the hardware and mainly on the software which controls the station.

The exponential increase of the number of artificial satellites has led to an even more remarkable increase in the number of inactive objects orbiting the outer space (mainly at LEO segment). This is a major issue for our society. It is a serious threat to the constellation of currently active orbiting objects, and to the future space missions. In 2016, this station joint the European Union (EU) effort on SST (Space Surveillance and Tracking) activities, as one of the sensors provides by Spain to space debris monitoring. Since then we have participated in several campaigns on a regular basis.

Currently our major limitation refers to the laser-telescope mount. Recently we have got funding to carry out its replacement and we hope it will be a reality in the next coming months. It means that San Fernando station will be out of activity temporarily for some months.

This project will be a turning-point as it will enhance our angular resolution, reaching 2 or 3 arcseconds. We hope that our observational performance will be very clearly improved, opening the possibility of daytime and blind tracking on active objects and space debris as well. In this presentation, we will show the modifications already carried out, results obtained and the perspectives of the station for the immediate future.

Poster 06-02

New opportunities of SLR service of Main Metrological Center of State Service of Time, Frequency and EOP evaluation

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Federal State Unitary Enterprise (FSUE) “National Research Institute for Physical-Technical and Radio Engineering Measurements” (VNIIFTRI) is subordinated to Federal Agency on technical regulation and metrology of Russia. It has the status of the State scientific metrological center and is one of the main centers of the State standards of Russia. The VNIIFTRI plays role of the Main Metrological Center (MMC) of State service of time, frequency and EOP evaluation (SSTF).

The satellite laser ranging (SLR) observations had been provided in VNIIFTRI from seventies of the previous centure to the now days for purpose of Earth’s orientation parameter (EOP) evaluation and maintenance of the terrestrial reference frame ITRF. The equipments, methods and metrological maintenance has been improving permanently together. Now, the two SLR instruments of the new generation of the type "Tochka" are started work in Mendeeleevo (VNIIFTRI) and Irkutsk city (East-Siberian Branch of VNIIFTRI). It has the instrumental error not exceeding units of millimeters at single measurement.

The results of the last SLR experiments are considered. It has showed that VNIIFTRI’s SLR instruments of new generation are confirming the declared high characteristics.

Poster 06-03

SLR Station Riga 1884, Status Report

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The poster covers the SLR station upgrades and results since 2018.

Among them:

A new SLR detector unit was installed, including a second channel with a new HPD photodetector.

Upgraded visual guiding channel, using the Andor iXon Ultra EMCCD camera and a computer-controlled filter wheel for photometry. We have started photometric observation (up to 10 Hz).

A new upgraded local ties network determination, replacing the 1996 solution. Redetermination of the SLR system delay using the new local ties monuments as external targets.

New computer-controlled optical channel switching system, laser beam divergence unit and receiver FOV control installed. The Telescope drive has been upgraded with COTS components.

Testing of new Event Timer models has started.

Due to the repairs, upgrades and COVID regulations, the total number of observations has been affected during the period 2020-2022.

Poster 06-04

The Impact of Cyclone Seroja at Yarragadee

Randall Carman

Geoscience Australia, Yarragadee, Australia

On the 11th of April 2021 at approximately 1430 UT, Category 3, Tropical Cyclone Seroja passed directly over the Yarragadee Geodetic Observatory. Wind speeds in excess of 160km/h were measured but thankfully the cyclone passed through very quickly, meaning structural damage was limited mainly to non-geodetic infrastructure.

Although a lot of superficial damage was caused and we were without communications for some time and commercial power for 11 days, the impact to operations was minimal, with our first SLR data obtained within 36 hours of the cyclone passing.

The Geoscience Australia survey team performed a minimized local tie survey as soon as possible post cyclone and the results are discussed in this poster.

Even though a nearby 13m satellite dish was damaged and wind speeds were very close to maximum load ratings, our 12m VLBI dish was mostly unaffected apart from needing a new pointing model, due mostly to movement in elevation. The GA survey team did not however have time to include the VLBI dish and will return later in 2022 to check for any change.

This poster will give an overview of some of the structural damage caused to our ancillary infrastructure.

Poster 06-05

Determination of the reference point of Metsähovi SLR telescope

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Metsähovi Geodetic Research Station (MGRS) of the Finnish Geospatial Research Institute (FGI) is one of the core stations of the GGOS, housing all the major space geodetic techniques. FGI has been a part of a large EMPIR (European Metrology Research Programme) funded consortium GeoMetre in which we studied the best methods for measuring and determining reliable and accurate local ties between all the geodetic infrastructure on a geodetic station. To determine the intersection of the azimuth and elevation axis of the MGRS SLR telescope and tie it to the global reference frame, we used a robotic total station to measure accurate locations of two retroreflectors attached on the telescope's optical tube assembly. Measurements were done from two concrete pillars outside the observatory dome in various telescope azimuth and elevation positions. The coordinates of the measured retroreflector reference points were used as observations in the reference point estimation. The purpose of the measurements was to get the initial accurate reference point coordinates and to learn how the process could be automated in Metsähovi in the future. Unfortunately, we couldn't fully automize the process or use independent star observations during this measurement campaign as the SLR telescope was not yet fully operational. Here we present the results of three different approaches to the reference point calculation from the measurements: antenna model with axis, sphere fitting and circle fitting.

This project 18SIB01 GeoMetre has received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme.

Poster 06-06

EUROLAS Data Center (EDC) – Status Report 2018-2022

Schwatke Christian

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Since 1991, the EUROLAS Data Center (EDC) has been one of the two global data centers of the International Laser Ranging Service (ILRS). The EDC has the task of archiving SLR data and derived products, and making them available to the ILRS community. In recent years, the new

Consolidated Laser Ranging Data Format (CRD) of version 2 has been developed with great effort by the ILRS and introduced as official SLR data format in the ILRS. Moreover, also the new Consolidated Laser Ranging Format (CPF) of version 2 has been developed and introduced as official data format for predictions.

In this poster, a status report of the EDC over the period from 2018-2022 is given. First, the development of the SLR data holding regarding normal point data and full-rate data of both CRD versions is presented in detail. These data sets are essential for the ILRS in order to derived SLR related products (e.g. EOP, etc.). The EDC also archives and provides CPF predictions which are necessary for SLR stations for tracking satellites. Here, statistics of CPF predictions of both versions are shown as well. Furthermore, the development of the SLR network regarding new stations and new satellites is presented in this poster. Finally, information about SLR products available at EDC and the maintained mailing lists (e.g. SLR-Mail, SLR-Report) is shown.

Poster 06-07

LARES-2 – initial results from NSGF Space Geodesy Facility, Herstmonceux

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An initial priority at SGF, Herstmonceux following the launch of LARES-2 was to obtain ranging data as soon as possible. The difficultly at this post-launch stage is very high due to the lack of accurate predictions that are required to aid acquisition. Nevertheless within a few days SGF was one of 5 stations that had managed to obtain precise data to the new satellite, using publicly available radar-based predictions with km-level accuracy. To enable the rest of the global network to join in making routine observations, especially during daytime, regular accurate predictions are required, based on recent data. Without this service the science benefits of the new target cannot be unlocked.

The SGF Analysis Centre has a long-term commitment to the global community to compute predictions for the geodetic spherical satellites and, using this first data obtained after the launch, provided the first very accurate predictions for LARES-2. The predictions, which are generated automatically every day, are based on fits to four days of range measurements to determine accurate orbital elements, which are then propagated a few days into the future.

In this study we present the impact of adding the new target into the observing schedule and evaluate the quality of the predictions. From the analysis point of view, we present the initial impact of adding observations from LARES-2 into our7-day orbital fits, including estimating range biases to mitigate our use of an approximate LARES-2 Centre of Mass value.

Poster 06-08

CDDIS Services to the ILRS

Justine Woo (1), Benjamin Patrick Michael (2), Sandra Blevins (1)

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The CDDIS is one of twelve NASA Earth Observing System Data and Information System (EOSDIS) Distributed Active Archive Centers (DAAC) and supports the space geodesy and geodynamics community through the International Association of Geodesy (IAG) services, which includes the International Laser Ranging Service (ILRS). As an EOSDIS DAAC, the CDDIS is required to meet best archival practices including the Findability, Accessibility, Interoperability, and Reuse (FAIR) Guiding Principles for scientific data management and stewardship which ultimately serves data and product providers and users. These best practices and artifacts built to support them are not always visible to users although utilizing them ultimately benefits the community, for example with citing with DOIs to ensure traceability and that proper credit is given to the data and product creators. To address this gap, this poster steps through the CDDIS's ingest, quality control, and archive systems that ensure data is searchable, citable, and credit is given to providers. The CDDIS will then review ESDIS tools for exploration of the CDDIS archive. Beginning next year, the CDDIS will start migrating to the cloud to support open science.

Poster 06-09

ILRS Data Centers – Overview, Current Status, and Future Work

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The ILRS Data Centers are composed of two primary data centers, the Crustal Dynamics Data Information Systems (CDDIS) and the EUROLAS Data Center (EDC) and other associate data centers. Each serves a role in accessibility by providing quality assurance, tools, and reports among other resources to the ILRS community. In recent years, there has been several updates at the data centers to provide additional quality assurance and beneficial tools to the community including the addition of the new CRD and CPF formats and new quality assurance for ITRF2020 SINEX products. The data centers are also at the starting phases of addressing community needs such as creating citations for data and products. These items, among others will be discussed in this poster along with current and future work.

Poster 06-10

Detecting Satellite Laser Ranging Station Data and Operational Anomalies with Machine Learning Isolation Forests at NASA's CDDIS

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The International Laser Ranging Service (ILRS) is currently composed of 45 active satellite laser ranging (SLR) stations with several more set to join the network over the next several years. Station changes and histories are logged to files, but not always in real time. Sometimes these details are not added until long after changes have been made to the station – on occasion, years later. This in addition to unexpected hardware errors and other system issues that are not immediately detected affects data trustworthiness and the quality of models and products generated by analysts. The ILRS Central Bureau (CB) and NASA's Crustal Dynamics Data Information System (CDDIS) have worked to provide tools for station engineers to use. This includes the creation of station plots which contain temperature and pressure information along with LAser GEOdynamic Satellite (LAGEOS) and Laser RElativity Satellite (LARES) tracking information that enable the monitoring of station performance and to determine whether the station has undergone any changes. As next steps, the CDDIS is working to enhance these station performance monitoring tools through machine learning to improve data quality and integrity. Isolation forest is an unsupervised machine learning algorithm commonly applied to anomaly detection. In this poster, the CDDIS details the steps taken to track anomalies within SLR station performance using isolation forest with LAGEOS and LARES satellite data.

Poster 06-11

The further development of the DiGOS Allsky camera

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AllSky cameras are essential for SLR station operation both manual and autonomous. They provide information about the general weather situation, cloud conditions relevant for scheduling as well as the general station condition. Requirements on the camera are a good image quality, weather resistance as well as easy maintenance and integrability into a station. The DiGOS AllSky camera is a product which is made to fulfill these requirements.

The camera is capturing images with an 8,86mm CMOS chip at a resolution of 3096x2080 pixels. It features exposure times up to multiple minutes, while automatically adjusting to day and night conditions. The lens system provides a field of view of 185° and thus images of the full sky at high quality during day and night

A Raspberry Pi based Debian Linux provides a full OS, in order to keep the software maintainability high. A developed Mosquitto-based network interface allows easy streaming of the images and controlling of the camera properties from or to multiple clients

The camera is made for low maintenance outdoor operation. It features an integrated heater in order to remove dew from the cupola and thus provide continuous visibility. Furthermore, a dry cell which can be checked and changed easily from the outside, keeps the inside of the system dry. The whole system is powered via a PoE+ interface.

With its setup, the DiGOS AllSky camera provides high quality full sky images at day and night during summer and winter, while being easy to integrate and maintain in a station network, both hardware and software wise. The system was developed and tested in cooperation by DiGOS and GFZ Potsdam.

Poster 06-12

Determination of the natural frequencies of vibration of geodetic pillars with a COST seismometer

José C. Rodríguez, José A. López-Pérez, Pablo García Carreño, Adolfo García-Marín, Elena Martínez, Beatriz Vaquero

Yebes Observatory (IGN/CNIG), Yebes, Spain

The design and construction of geodetic monumentation in an observatory is not a common event, linked to the installation of new instrumentation with working lives counted in decades. Since the performance of this instrumentation is affected by the physical behaviour of its supporting monumentation, it is worthwhile to devote sufficient efforts to ensure that the design is adequate and will not prove to be a limiting factor in the long term. Questions such as the stability, longevity, thermal behaviour, cost and practicalities of different kinds of installations have been thoroughly considered for GNSS monumentation. Owing to their much rarer deployment, the optimal properties and characteristics of pillars of big dimensions, e.g. for SLR, appear less widely known and standardised. Of special consideration in these cases are the natural frequencies of vibration of the structures, as they must provide support for mechanical mounts whose control loop might be adversely affected, or even rendered hopeless, if a sufficient stiffness were not achieved. In the design phase of the new SLR station at Yebes Observatory, a study of this issue was commissioned to an engineering firm. Concurrently, consideration of the problem led us to conduct an experiment to determine the vibrational frequencies of existing pillars in the Observatory. We performed the measurements with a seismometer developed in-house based on COTS 3-axis MEMS accelerometers, with which we determined the vibrational frequencies from the impulse response of a pillar in the VGOS radio telescope. The expected theoretical values for simplified cylindrical structures agree reasonably with the measurements. The measurement method can be applied to structures of any complexity that might need testing for their suitability, and we will employ it to measure the frequencies of the Yebes SLR pillar.

Poster 06-13

Astrometric calibration of allsky camera for aircraft spotting and meteor observations

José C. Rodríguez, Adolfo García-Marín, Beatriz Vaquero, José A. López-Pérez

Yebes Observatory (IGN/CNIG), Yebes, Spain

For the new SLR station at the Yebes Observatory, an all-sky camera was purchased to aid observers in their operations. The primary function of these instruments in SLR stations is environmental awareness, e.g. cloud presence, illumination conditions, Sun and Moon positions, and laser beam direction. Due to the limited angular resolution and often moderate sensitivity of these cameras, their use for air safety purposes is at best secondary. Still, provided that a suitable calibration is performed, they can complement other safety systems providing positional information that can be employed for validation purposes. The astrometric calibration of these optical systems has been researched for meteor astrometry, where positional measurements of the same event by geographically distributed cameras are used for orbit determination. We have implemented a calibration system for our camera following a selection of methods described in the literature, achieving subpixel positional precision (<2 arcmin RMS in Az/El). The calibration system requires no manual intervention after an initial coarse setup, and includes the steps of source extraction, selection, matching, and least squares fit of the camera model. A fully calibrated all-sky camera allows for pixel-perfect accurate overlays (e.g. in operational GUIs with predicted satellites or ADS-B relayed aircraft) as well as their use for meteor observations within dedicated networks. It also makes feasible to employ these cameras for complementary safety purposes.

Poster 06-14

The local tie at RAEGE stations

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The International Terrestrial Reference Frame (ITRF) is based on 4 Geodetic Techniques: GNSS, VLBI, SLR and DORIS. ITRFs need an accurate determination of the vector between the Invariant Referent Points (IRP) of each technique in co-location, through what is called local tie. Classical survey techniques and GNSS observations are needed to obtain the vector that connects all IRPs of the geodetic infraestructure.

In this poster it will be presented the local tie planning at two RAEGE stations: Yebes (Spain) and Santa Maria (Azores) according to the new ITRF standards. The planning will include the new SLR station at Yebes.

Laser Safety in Ny-Aalesund: Aircraft Avoidance System (AAS)

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The new SLR station in Ny-Ålesund will be different from the other SGSLR stations as it cannot use a radar for aircraft detection.

A lot of work has been put into creating a system for aircraft detection that will meet the requirements of all stakeholders (NMA, NASA, The Norwegian Civil Aviation Authority, The Governor of Svalbard, etc.).

We will present the current status of the system development, as well as showing what subsystems the AAS will consist of, how they fulfill each other to make a complete and safe aircraft detection system and how the system interfaces with the SGSLR Laser Safety Subsystem.

Oral 07-01

Space Debris Laser Ranging – Challenging and Rewarding – Update of the Izaña-1 station

Martin Ploner (1), Nils Håkansson (1), Linus Heinzl (1), André Kloth (1), Laura Aivar (2), Alberto Águeda (2), Tim Flohrer (3), Clemens Heese (3)

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The Izaña-1 station (IZN-1) is located at the Observatorio de Teide on the Spanish island of Tenerife. It is a multi-purpose optical ground station for satellite observation, position measurements and communication. The telescope carries the Satellite Laser Ranging (SLR) laser package for ranging to cooperative targets equipped with retro reflectors. Currently on the two Nasmyth foci the laser ranging detector package and the laser communication terminal is installed. Additionally on one of the 2 optical ports a space debris observation camera is installed for passive optical space debris observations.

As part of the upgrade of the IZN-1 (ESA project S2P S1-SC-06 - Laser Ranging - Evolution Towards Active Sensor Networking for Debris Observation and Remediation), it is planned to extend the functionality of the system with a space debris laser ranging transmitter for ranging during nighttime as well as daytime to uncooperative targets. The space debris laser system will be installed in a separate structure, on its own mount. Such a system can be installed adjacent to any SLR station, enabling it to perform Space Debris Laser Ranging (SDLR) without modifying the main SLR system.

In order to improve the aircraft detection of the laser safety system, an additional thermal IR camera will be installed onto the telescope.

The integration of a single-photon detector as light curve detector in the existing laser ranging detector package will enable high temporal resolution light curve recording simultaneously to the ranging measurements.

The additional stare & chase functionality will allow the ranging to targets with worse predictions. Based on passive optical observations an orbit improvement will be carried out for increasing the accuracy of the orbit predictions and assists the SDLR system.

European Expert Centre for Sapec Safety providing services andsupport for space surveillance and traffic management

Thomas Schildknecht (1), Peter Pessev (1), Palash Patole (1), Julian Rodriguez (1), Tim Flohrer (2), Beatriz Jilete (2), Emiliano Cordelli (2)

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Developed within ESA's SSA and Space Safety Programme (S2P), the Expert Centre for Space Safety provides subject matter expertise and operational services to coordinate SST data acquisition by a multitude of diverse sensors. It supports a variety of applications including tasked tracking, survey, and characterization observations by means of passive optical, satellite laser ranging (SLR), and radar techniques. A core service consists in the validation and qualification of sensors for the mentioned applications. The service includes technical support to sensor operators by experts to achieve compliance with data calibration and quality, as well as data formatting requirements. All formats and interfaces used by the Expert Centre are based on international standards and the data quality requirements are derived by the user community.

Coordinating observation campaigns for customers, in particular ESA, is another important service offered by the Centre. Such campaigns may include very heterogeneous types of sensors operated by commercial companies, academia, government, and inter-governmental institutions. The Expert Centre takes care of the sensor planning, the data quality control, calibration and reformatting of the data if necessary, as well as the monitoring of key performance indices defined in service level agreements.

In terms of object characterization, the Expert Centre focuses in particular on establishing and maintaining a catalogue of attitude information by fusing observations from different techniques, such as light curves, SLR and radar measurements.

The paper will illustrate the different services and operational capabilities with examples of sensor qualifications and extensive survey, tracking and characterization observation campaigns which involved more than a dozen optical, SLR and radar sensors.

The Expert Centre is hosted and operated by the Astronomical Institute of the University of Bern, Switzerland (AIUB) and may serve as a reference for future national expert centres and site-specific deployments within ESA.

Oral 07-03

Validation & Qualification of Space Debris Laser Systems atthe Expert Centre for Space Safety

Julian Rodríguez Villamizar and Thomas Schildknecht

Astronomical Institute University of Bern, Bern, Switzerland

To pave the way towards a sustainable use of the outer space, the Expert Centre for Space Safety (ExpCen) coordinates data acquisition and exchange for passive and active sensors operating in different spectral regions, and configurations, aiming at diverse target objects. Within the optical regime, ongoing efforts address the validation and qualification (V&Q) of passive optical and space debris laser ranging sensors, which is an integral service that comprises the interfacing and tasking of the candidate sensor, in addition to retrieving and post-processing the acquired observations to ensure the compliance with predefined quality metrics. The candidate sensor will be certified for participating in future campaigns, after successful completion of V&Q, besides being provided with technical support and system-related feedback to successfully complete the V&Q.

Regarding active optical systems, the ExpCen has does not only profit from the profound legacy from the Satellite Laser Ranging (SLR) community, but the outcome of different activities conducted within the development and establishment of the ExpCen.

In this presentation, we will describe the architecture of the ExpCen laser ranging processing engine, including algorithms, new in-house developments and future improvements. Furthermore, after the compilation of results and lessons learnt from past activities, we redefine the requirements for validation and qualification of candidate sensors. We present examples of observations including sensors operating in monostatic and bistatic configurations.

Oral 07-04

Laser ranging – Evolution towards active sensor networking for debris observation

Laura Aivar (1), Alberto Águeda (1), Martin Ploner (2), André Kloth (2), Clemens Heese (3), Tim Flohrer (3)

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Satellite Laser Ranging (SLR) of orbital targets is a well-established technology in the scientific community (geodesy, space radar/optical imagery) with precision ranging to operational satellites equipped with retroreflectors as well as to the Moon. Recently, the use of this technology was pioneered also for the tracking of defunct objects (debris), e.g. in order to identify its attitude motion from range residual analysis.

After introducing more sensitive receivers, more powerful transmission systems and improvement of track initialisation techniques, it became possible to receive and process echoes from uncooperative targets. However, in order to assure the success of these observations, an accurate a-priori pointing information is required and tight constraints on the observation's conditions must be met. These challenges are the motivation drivers for establishing a "proof-of-concept" for fully automatized SLR stations, the Distributed Laser Ranging Network (DLTN), integrating the upgraded ESA's IZN-1 station.

The activity whose main goals are the upgrade of ESA's IZN-1 to track debris and the development of an online sensor network platform for near-real time requesting, scheduling, analysing, displaying and providing space safety data products for the end users has started in summer 2022 and it will finish at the end of 2024, performing an observations validation campaign in the first semester of 2024. This presentation is provided to introduce the project to the community and describe the activities intended to be done.

Oral 07-05

Space Debris: Extraction of the Rotational State from Multistatic Light Curves

Manik Reichegger, Anja Schlicht, Urs Hugentobler

Technical University of Munich, Germany

With the rapid increase of space debris in the last decades, the risk for collisions of objects in orbit grows significantly. To avoid collisions it is important to catalog the objects and determine their orbits. In order to propagate accurate orbits, it is necessary, to know the orientation of the object, so that the perturbation forces acting on it, can be taken into account in the orbit determination. Due to the changing observation geometry during a pass, an observed object reflects sunlight with different intensities. This change in brightness over time can provide information about rotation parameters such as rotation speed and axis. These data can be used to propagate future orbits with higher accuracy.

The goal of this work is to quantify the information content of multistatic light curves, trying to investigate the sensitivity to the rotation parameters. Analyses are planned with respect to the initial orientation, the geometry change due to the motion in the orbit, as well as the optical parameters and the size of the object. The information obtained can also be used to simplify a time- and computationally-intensive simulation if the maximum resolvable step size is determined for each rotation axis. In a forward simulation, the findings from the theoretical analyses will then be used and analysed in the context of multistatic images.

Furthermore, a database is to be built up which, in addition to the light curves, also contains further information about the objects and the stations involved. Not only information about the sensitivity of the individual measuring instruments, but also about the measuring conditions will be available. This will allow a quantification of the quality of the measurements. The multistatic measurements are performed by a local measurement network, which includes the observatories in Munich, Wettzell, Graz, Uedem and Zimmerwald. But others are welcome.

Poster 07-01

Laser tracking to space debris with low power of ps laser/1 kHz based onthe 1.2-meter telescope at Mid-West China

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The high power and nano-lasers have been commonly used at SLR stations while tracking space debris. In this paper, the feasibility of picosecond pulse width laser to debris targets tracking with low power was researched at Shanghai Astronomical Observatory, cooperated with Purple Mountain Observatory. There is a 1.2-meter telescope for laser quantum communication. It is located in mid-west China with an altitude of 3200 meters with seeing about 1 arcsecond. Both Observatories have upgraded its astronomical observation terminal for SLR measurements, while a laser system with the power of 1.2W at a 1 kHz repetition rate and 532nm wavelength was installed. Firstly, the satellites with reflectors were successfully measured. Then, HQE-detector with a narrow spectral filter (2nm) was used, and the large FOV camera was also installed to acquire debris targets. Using the TLE predictions, debris laser ranging was successfully performed for this telescope. Finally, a total of more than 60 debris targets were measured in ten days. Among them, the farthest range was about 1620 km, the RCS was 2.41 m2, and the equivalent RCS at the 1000 km range was 0.35 m2. In addition, the ranging precision was 10.6cm, which was better than the nano pulse width laser. The results demonstrate the feasibility of laser tracking of space debris using a routine SLR laser system with pico-pulse width. We hope more SLR sites with such good seeing can join the activities of laser tracking space debris by using the routine SLR system with a few modifications.

Poster 07-02

Orbit determination by merging optical, radar and laser measurements

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The proliferation of space debris puts the continuity of space missions at risk and poses a serious challenge to be corrected. The number of objects classified as space debris is increasing rapidly, especially in regions of high interest for commercial or scientific exploitation (LEO and GEO). Due to the high added value of these regions, the cataloging, and more specifically, the orbit determination of space debris objects has become a topic of great importance and growing interest.

This study outlines the Initial Research Plan of the doctorate entitled "Orbit determination of space debris objects from the fusion of the information obtained by different sensors", included in the Aerospace Engineering Doctorate Program of the Carlos III University of Madrid. The main objective of this study is to analyze the benefits of merging laser distances, radar observations and angular measurements in the same orbit determination process.

During the development of the thesis, access to data from different sensors will be available for scientific exploitation: a) laser measurements from stations belonging to ILRS, b) angular measurements from the TFRM telescope and c) observations from the S3TSR radar. With the use of these real measurements, it is intended to show how the observed object-sensor geometry affects the results, as well as the precision of the sensors used, the number of observations and the observed arc length, among other factors. Likewise, it is intended to investigate the different algorithms and mathematical methods that lead to orbital determination and to explore techniques that allow real-time corrections to be applied to the analyzed orbits.

Poster 07-03

Research on laser in-sky safety early warning method for high power debris laser ranging system

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A method for judging the in-sky safety of the laser beam pointing for high-power debris laser ranging (DLR) system is proposed. It realized the real-time safety area judgment and early warning of the laser beam intersection with the transiting aircraft. We build the laser beam pointing safety warning system at Changchun Station to validate the method. Results showed the intersection time between the transiting aircraft and the laser beam accounts for 0.86% of the observation time, which does not affect the regular operation of the laser ranging system; the energy density of the aircraft outside the intersection area is between 10-14 ~ 10-25 J/cm2, which is much smaller than the laser safety threshold corresponding to the ANSI Z136 standard. Result shows the effectiveness of the laser in-sky safety warning method on the high-power debris laser ranging system.

Oral 08-01

The miniSLR®: A low-cost, high-performance laser ranging system for the ILRS

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The miniSLR® has been developed as a low-cost, high-performance alternative to conventional SLR systems. It is completely integrated into a movable container of less than 2 x 2 m^2 footprint. Using a 500 ps laser at 50 kHz repetition rate, it achieves sub-centimetre precision. Long-term stability has been considered as integral part of the design and is facilitated by a full encapsulation, air-conditioning, short cable lengths and a calibration target on the main support structure. While the focus is on LEO targets including Lageos, all targets including GNSS constellations can be ranged.

The main advantages of such a small, highly integrated system are rather obvious: Low production cost, reduced engineering effort, shorter commissioning times. The system can be constructed and validated at the factory, before it is transported to its final observation site. At the site, no civil works are required and no building permits need to be obtained. Yet the system can be connected firmly to the ground, and using an appropriate site survey, local ties can be established in the same way as for conventional systems.

At DLR in Stuttgart, tests with an improved miniSLR® prototype have commenced in March 2022. Minor modifications for improved stability and reliability are underway. In July 2022, the system has been accepted into the ILRS as engineering station. It is planned to regularly deliver data to the ILRS to validate the system performance and stability. Furthermore, DLR will use the system as a test platform for its own research, including experiments with smart retroreflectors which can be used for satellite identification.

Oral 08-02

State report of current developments for picosecond precision Time-of-Flight / Time-Tagging systems

Victors Kurtenoks

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Since 2011, the Eventech team has demonstrated high competence in event timing, producing the fully CE certified ET33 time-tagging system with 2.5 (ps) precision recognized as a standard for SLR by NASA&ESA and used in more than half of the SLR stations in the world.

Recently, we have implemented certain updates for ET33 timer, including USB3.0 interface implementation, that allowed us to implement 20 (Mevents/sec) registration speed and ever more stabilize over temperature operation. These products are commercially available.

Our current development is focused on multi-channel picosecond precise time-tagging system. Target is to develop specialized timing devices platform which allows to combine several different functional, synchronized devices (PPM modulator, laser PWM, photon counter with ability to detect both edges of a pulse) in one measurement equipment. The technology should allow multiple independent measurement channels and provide stability and binding time scales of all these channels with the required picosecond precision, as well allowing easy implementation of multiple wavelengths SLR. This can significantly increase the precision of the measurements and open new opportunities in the satellite position field.

Our technology has been accepted by ESA for space application, closest mission is the 2024 HERA asteroid mission. It includes a centimeter-resolution PALT planetary altimeter, the main electronic unit of which is a precision time interval meter. The range of measured time intervals is from 0.4 to 134(μs) with a precision of 10 (ps). The calibration system of the meter allows maintaining its parameters in difficult conditions of deep space in the temperature range -40C° ÷ +60C° and radiation level up to 100 (krad). Despite the use of the low-class generator, special compensation system keeps the accuracy value at 0.5 (ppm). Even though the mass conditions dictated severe restrictions on PCB dimensions and power consumption, the meter has a self-control system and redundancy of individual nodes.

Oral 08-03

Day- and night-time SLR at MHz repetition rate in Graz

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Ultra-high repetition (≥100 kHz) rate is one of the most promising strategies for future satellite laser ranging (SLR), and a few stations have already started such attempts. Heretofore, all of them had efficiently proved the concept and the benefits of the ultra-high repetition rate SLR during night-time. Since the year of 2019 a demo then a purchased laser version (>45 Watt @ 1064nm, ≤10 Mhz, ≤10 ps pulse width) are installed in Graz. After some integrations and developments some successful passes up to inclined geosynchronous orbit (IGSO, slant range > 380,000 km) satellites during station were tracked successfully during night time, presenting max. return ratio ≈ 53.0 % for Swarm-B, equivalent 265 k returns per second; max. 800 returns per second for Beidou IGSO5. In addition during daytime with the application of propagated MHz range gate some low and middle earth orbit satellites were also achieved. In this talk the system setup and several involved key methods or techniques will be presented, for example the timing issue of the burst mode, the propagated range gate generator, and the fast real time displaying and storing of PC software, etc. The approach of this work will significantly prompt stations who are will to go to MHz direction in the interest of superior data precision, shorter normal point acquirement time, more advanced strategy regarding target signature and attitude identification.

Oral 08-04

Degoras Project: A libre software and hardware for satellite laser ranging stations

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Degoras Project (*Debris and Geodetic Ranging System Project; DP*) is a modern libre software and hardware system, currently in development, for the control of SLR stations. The aim of this project is to have a system that can be integrated into any station without much effort. This way, stations with obsolete systems with high coupling could take a step forward. The software includes a core that acts as a service or daemon (*DP Core*)and different user-friendly GUI applications that interacts with this core. These applications cover all the functionalities, such as space objects and files management, predictions generation, tracking and control subsystem, data analysis, as well as other secondary functionalities. The different GUI applications can be accessed from the main application (*DP Station Control*). The software can be integrated into different stations by using a dynamic system of plugins and interfaces. The hardware consists of a FPGA-based Range Gate Generator (*DPRGG*), responsible for maintaining real-time control of the station. This equipment, among other functionalities, maintains the real-time clock and generates the operating frequency of the laser devices as well as the gating signals for the photon sensors and lasers. The FPGA has its own embedded control software, so the RGG can operate independently without producing coupling in other systems. Other computers can also command it through a TCP/IP interface. The software is written in C++17 and Python 3, using the Qt5 framework. On the other hand the hardware is developed in VHDL using an Intel Cyclone V SX SoC FPGA and C++14 for its internal control software. The modular design of Degoras Project allows adding new features easily in an optimal way within a collaborative development environment.

Oral 08-05

Progress of Laser Time Transfer at Chinese Space Station

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The Mengtian lab experiment module will be installed onboard the CSS (China Space Station) at the end of this year. And Shanghai Astronomical Observatory (SHAO) is responsible for the laser time transfer link, cooperated with Technology and Engineering Centre for Space Utilization, which is used to assess the stability of space-board atomic clocks and carry out tests of fundamental physics such as the gravitational red shift. The onboard hardware consists of a laser retro-reflector, a single photon detector package, and an event timer.

In addition, two new SLR stations with high stability are also included, aiming to achieve laser time transfer between CSS and the earth. To overcome lots of difficulties such as low orbit, fast range variation, and short overpass time, the payload is designed with specifications such as

high repetition rate of 10 kHz, large field of view up to 128 degrees, compact design, low noise, and high stability. A low-temperature drift detection circuit and input optical system with stable transmittance in various incident angles are applied, combined with ground laser emission energy control, to achieve low time walk in photoelectric detection. To realize all-day observation, we use two small pinholes, a super narrow-band filter, and range gate generator to reduce strong background noise. The frequency division clock signal was measured to calibrate the measurement epoch of the event timer in real-time.

The fly module of the laser time transfer payload was submitted in April of this year and its stability (TDEV) is better than 0.1ps@300s and 1ps@1day. Two SLR systems with an aperture of 40cm have been constructing. At the beginning of next year, the laser time transfer link will provide the scientific data for assessing the onboard atomic clock, and welcome your stations to participate.

Oral 08-06

Recent progress in SPAD detectors for SLR and laser time transfer

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Our group is working on the development and improvement of existing Single Photon Avalanche Detectors (SPADs) for satellite laser ranging and laser time transfer applications. The existing SPAD detector package based on a 100um diameter Si-based SPAD chip, cooled by a single-stage TE cooler, is under improvement, intending to reduce its temperature dependency of a detection delay. We modified the ultrafast comparator and related signal logic to reduce the detection delay temperature dependence from original values exciting 250 fs/K down to a nearly linear dependence with a slope well below 100 fs/K. This detector package was optimized mainly for laser time transfer ground to space.

The new version of the infrared detector package based on the InGaAs/InP detection chip was developed and tested. It is based on a commercial chip. Its active area diameter is 80 um and is dedicated for 1064 nm wavelength only. Cooling is ensured by three stages thermoelectric cooler. We developed new active gating and active quenching circuit, which in connection with this chip guarantees the fixed detection parameters (sensitivity, jitter, detection delay) within a broad gate window. The detection chip is operated at 4.2 Volts above its breakdown voltage. The timing jitter is well below 60 ps rms. The detection delay is stable and reproducible for range gates up to 10 us wide. Its timing stability computed using Time Deviation TDEV is better than 300 fs for averaging times of hours.

Oral 08-07

New Pico Event Timer for space applications

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We report on the concept, design, and tests of a New Picosecond Event Timing (NPET) device and its response to the radiation dose. These radiation tests were aimed to verify that the existing version of the NPET device may be used in space missions. The device was subjected to radiation of a total dose of 74 Gy provided by a 60Co source. This radiation dose did not affect the epoch timing part of the device. After irradiating the device with the final radiation dose, a single measurement resolution is better than 0.9 ps. The overall timing stability characterized by Time Deviation is better than 5 fs for 100 s. The completed device tests and results indicate the possibility of using the existing New Pico Event Timing device electronics version for a space mission in which the total radiation dose will not exceed 74 Gy value. Presently a new version of the NPET device is under development. The goal is to modify its mechanical design to be suitable for space application and to integrate the pulse signal input logic into the main board. The newly developed version of the device is expected to be applicable in the laser time transfer mission in the space segment.

Oral 08-08

Two Color SLR at the WLRS – Scope & Limitations

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In the middle of 2019 the WLRS has started to routinely observe at the laser primary wavelength of 1064 nm. Due to the lack of suitable detectors, this wavelength has been uncommon for SLR-systems in the past. With the availability of a new generation of InGaAs detector technology this has changed, making two color SLR feasible for high repetition rate systems with a reasonable amount of observations. Recently the WLRS was upgraded for a second detection channel at 532 nm and the support of high repetition rate SLR. From the time delay between both detection channels the atmospheric range delay can now be compared against well established models. In this talk we want to provide an overview of the system setup at the WLRS, including the basic implementation concept and the detectors in operation. We present the ranging performance for both wavelengths that we obtained so far. Finally we will outline some preliminary results.

Oral 08-09

Progress on the implementation of two-color high count rate laser ranging at Grasse

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Advancing our understanding of the dynamic Earth system in the context of global warming requires observations with millimetric accuracy. Since 2014, we are developping at the Grasse laser station (GRSM) an experiment to demonstrate two-color Satellite Laser Ranging (SLR) at high repetition rate. In the presentation, we will report the difficulties encountered in the implementation of the new instrumentation in parallel of the current setup. We will present some preliminary results on calibration, on ground link and on satellite links. We will briefly talk about the measurement campaign done in September 2022 for the Geometre Project and we will conclude with the perspective of new developments and measurements.

Oral 08-10

Preliminary results of the new Event Timer with the IECS technologies

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The new line of event timers with parameter stabilization and a new, integrated technology for simultaneous time tagging and pulse amplitude measurement is currently being developed at the Institute of Electronics and Computer Science (IECS).This paper discusses the first test results obtained at the SLR station Riga with the first prototype of the new device.

Oral 08-11

Development and validation of object detection algorithm for robust video based laser safety system

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The majority of ground based systems requires continuous tracking of satellites or objects creating a demand for moderate cost automation systems. However, working with high powered lasers requires independent measures to ensure the safety of any flying objects. Low

cost receivers such as ADS-B and FLARM 1 can provide the position of an aircraft allowing for an easy implementation of laser safety measures. However, objects such as helicopters, small aircraft, gliders, balloons or others might not carry such transponders and are therefore at risk of exposure to laser radiation. Hence, a robust video based detection system was developed to provide sensors in addition to ADS-B for an independent and thus redundant mean to establish in-sky safety, allowing for a safe autonomous operation of laser systems in the future. The system features cameras in three different spectral regions: thermal infrared (TIR) [8 - 14μm], near infrared (NIR) [0.4 - 1.7μm], and visible spectral band (VIS) [0.4 – 0.7μm], to exploit strengths of the individual camera systems under different lighting and weather conditions. An image-based object detection algorithm was developed to evaluate the real-time video feed of each camera.

A total of 150,000 images from each camera containing 200 individual objects such as aircraft, helicopters, balloons, etc. was captured during day and night time. Furthermore, the video streams of the GFZ Potsdam SLR station in the TIR and VIS wavelength were used, providing additional data for an independent comparison. The developed algorithms were tested on collected data and cross compared with each other, as well as the ADS-B data to quantify the algorithm performance. Furthermore, a detailed analysis was performed to highlight the limitation associated with individual sensors. The presented approach is promising for current and future satellite/space debris laser ranging and optical communication applications.

Oral 08-12

Laser Safety at NASA’s New Laser Ranging Stations

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Laser safety has been a critical part of the NASA’s satellite laser ranging stations for many decades. As the new Space Geodesy Satellite Laser Ranging (SGSLR) systems complete development and begin integration/testing, they have had to adapt to evolving technologies and regulation changes. NASA’s SGSLR system will be deployed in many parts of the world, each with their own local safety framework and specific concerns. We describe the status, methods, and technologies of laser safety that are being implemented for our current scheduled deployment of SGSLR stations. We pay special attention to our partnership with the Norwegian Mapping Authority, and our collaboration in deployment of SGSLR in Ny Ålesund, Svalbard.

Poster 08-01

Development of Omni-SLR System: (1) Optical subsystem

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Very compact and low cost SLR system, Omni-SLR, is now under development by the joint team of Hit-U, NAOJ, U-Tokyo, and JAXA aiming to expand SLR tracking station network. The system is designed to be controllable via web browsers, on-site or remotely, as the user interface part is constructed using Streamlit and Flask.

Laser transmission part (compact laser and beam expander telescope (TX)) and receiving part (receiving telescope (RX), bandpass filter, and photon detector) are on AXJ mount (Vixen). Green pulse laser FDSS532-Q2 (CryLas; λ=532nm, Δt=1.3 nsec.) is selected as laser source considering its repetition rate (10kHz) and averaged power (60mW). Laser output timing is controllable by the external trigger signal generated by Raspberry-Pi. Small refractor FL55SS (Vixen, D=55mm, FL=300mm) is selected for TX to get the beam spreading angle less than 10 arc sec. There are two candidates for RX; 1. Classical Cassegrain reflector cc6 (MICROTECH, D=15.3 cm, FL=1836mm) and 2. Catadioptric reflector VMC260 (Vixen, D=260mm, FL=3000mm). We aim to build the optical subsystem using cc6 telescope as the first step then develop it to the next model using VMC 260. MPPC C11202-100 (Hamamatsu Photonics) is mainly used as detector and id100-50 STD (IDQ) or SPD-100-CTC (MPD) can be optionally used.

Several optical mounts, plates and attachments of the detector and filter used for configuring total optical subsystem are now under development including self-making with 3D printer in Hitotsubashi University. Basically, the optical axes of TX and RX are collimated using a star. Then laser and TX are collimated through the laser spot position test. Concurrently, we are investigating the method and procedure how the optical alignment is established reproductively among TX, RX, and Laser.

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Poster 08-02

Development of Omni-SLR System: (2) Tracking subsystem

Toshimichi Otsubo (1), Mihoko Kobayashi (1), Hiroshi Araki (2), Yusuke Yokota (3), Takehiro Matsumoto (4) and Tetsu Takashima (5)

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The small-size, low-cost Omni-SLR system is being developed by a multi-institute group in Japan. We are testing a commercially available telescope mount Vixen AXJ for satellite/aircraft tracking purpose.

The AXJ mount is designed to work as an equatorial mount in the latitude of 0 to 70 degrees. To avoid a flip and a resultant time loss, and also to simplify the mount model, we use it as an Alt-Az system, using a specially designed fork.

We have developed tracking software engine in Julia language. It can control the motor speed of the mount at the period of 60-70 milliseconds for smooth pointing/tracking. The engine is wrapped by a Python-based handler that can be accessible via Streamlit web UI.

Plate-matching software tool "solve-field" publicly provided by astrometry.net is used to observe a pointing (RA, Dec) direction. Without a procedure to move a star in the centre of the view field, it significantly reduces time and workload.

As the mount is driven by worm and wheel gears, a periodic motion error is inevitable. The RA=Azimuth axis is compensated at the stage of product check of Vixen, and therefore we developed a "solve-field"-based scheme for the Dec=Elevation compensation. The amplitude has been 15-20 arcseconds at the period of 1.875 degrees.

The star calibration for the whole sky is also based on the "solve-field" solutions. By applying 10-15 parameters, we have got 10-25 arcseconds rms, depending on the sky conditions, etc. We are also testing a star image acquisition in daytime where the plate matching is of no use.

Although we have not tested SLR with the system yet, we have demonstrated the capability of satellite (low to high) and aircraft tracking, by communicating Raspberry PIs that provide the position or direction of the objects.

There is room for improvement and will continue the test.

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Poster 08-03

Development of Omni-SLR System: (3) Timing/software subsystem

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Omni-SLR Project is a Hit-U, NAOJ, U-Tokyo, JAXA joint project aiming to build a small SLR system. A small PC such as Raspberry-Pi is arranged for each part of the timer part that acquires time data, the laser part/detector part that is the transmission controller of the laser, the mount, and the software parts.

Omni-SLR uses Swabian Instrument's Time Tagger (TT) for the timer part. For the detector part, we conducted in situ ranging experiments for several candidates. Using this setting, the outdoor background noise was acquired with a noise rate of around MHz through an ND5 filter. We also confirmed the operation in the cold-room (-30 degrees Celsius) environment in the NIPR.

With high-frequency lasers above kHz, the amount of received data, that is, the amount of communication from the timer part to the PC, increases together with the background noise. We are experimenting with arbitrary waveform generators and receivers to see how much data can be processed in real-time.

Received data is introduced to the PC side via a USB3.0 cable in binary format. In the case of MHz rates, saving each time data acquisition and ascii conversion cause processing delays. Therefore, we are considering a design in which a virtual reception channel is set for the real reception channel of TT, and a channel that can automatically record the round-trip time is installed in TT. This virtual channel can support various uses such as conventional transmission mode with about Hz, burst mode, and operation to targets other than satellites by shifting only the timing. We are also considering GUI for real-time measurement. The system is designed to be controllable via web browsers, on-site or remotely, as the user interface part is constructed using Streamlit and Flask.

Acknowledgement: This research was supported by JSPS KAKENHI Grant Number JP20H01993.

Poster 08-04

A compact, mobile, robotic, high precision tracking platform for SLR, astrometry, photometry, and lasercom

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Cybioms'automated tracking systems, capable of sub-mm SLR normal point precision and 1 mm system accuracy on geodetic satellites, have been going through field commissioning. A scaled-down lower-cost modular version of this with a compact telescope (~300 mm) capable of reaching GNSS with sub-arcsecond precision tracking has been under development upon completion of an extensively tested laboratory prototype. This tracking platform will support target imaging, photometry, astrometry, debris tracking, laser transponder, lidar, SLR, and lasercom. Simultaneous multicolor high PRF (MHz) ranging capability is planned with multiple transmit/receive telescopes. One key consideration is the modularization and migration of certain traditional hardware functions into the software regime to reduce cost, weight, and suitability as a broad platform for applications including laser communications. To enable a mobile compact SLR platform for precision geodetics and to minimize the need for surveying, there is a built-in provision for precise and repeatable optical placement over a fiducial reference as well as internal system calibration. Currently, such a robust tracking telescope is going through development and integration in the lab in support of a US Govt project.

Poster 08-05

An automated, intelligent, LHRS (AI-LHRS) for supporting the safety of lasers in airspace

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A radar-based laser safety system, for eliminating the potential for laser radiation hazards in airspace, has gone through extensive indoor and outdoor testing. The system operations at ~600Hz and airspace monitoring are built with automated features of hardware and software. The system allows the mapping of the safety system functions and parameters throughout its operation. The coordinates of the radar beam pointing in 3-d space, target range, transmit epoch, receive epoch, and target-intercepted signal return strengths are captured every frame for interrogation and inferencing. Intelligence is built in the analysis and inferencing of various operational and system parameters to ensure situational awareness, the integrity of operations, and the avoidance of potential system problems that may interfere with the radar safety functions. Certain operational details of this system will be discussed.

Poster 08-06

SGSLR Receiver Detector Testing and the Pulse Width Calibration Technique

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The NASA Space Geodesy Satellite Laser Ranging (SGSLR) Receiver subsystem detector combines a proprietary Hexagon US Federal (Sigma Space) event timer chip and an array of SensL detectors. The receiver provides high precision event measurements along with spatial information essential to closed loop tracking and system automation. During the initial characterization testing of the prototype receiver a range dependence on the signal return rate (and inferred pulse intensity) was observed. Using the pulse width determined from the return leading and trailing time tags provided by the receiver, a technique was developed to compensate for range dependence on pulse intensity (2019 Technical Workshop, SGSLR Receiver Detector Pulse Width Calibration Technique, C. Clarke, et al). This poster will provide an update to the referenced poster. It will also describe the technique, compare test results before and after the correction, describe the method to differentiate between single and multi-photoelectron returns, and summarize the results of recent calibration stability testing and multi-cube configuration testing.

Modular setup of SLR laser and detection packages

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An increasing demand of facilities capable of doing satellite laser ranging, space debris laser ranging or optical communication pushes the demand to create accurate, cost-efficient, reliable and yet simple components to be integrated. In the framework of the development and upgrade of the new Izaña-1 SLR station located on Tenerife in Spain, IWF Graz created new concepts for modular piggyback laser and detection packages. Optical components are selected based on commercial off the shelf (COTS) components and simulated with ray tracing software.

Laser packages consist of the laser with two separate beam expansion telescopes with a collimated part in between, which can be used for imaging of e.g. the backscattered laser beam or the visualization of stars for alignment purposes. A combination of wave plates and polarizing beam splitters allow for power adjustment and measurement. One of the lenses is mounted on an electronically movable lens holder which gives the possibility of flexible variation of the beam divergence and a tip-tilt mirror enables direction control of the laser beam. Furthermore, start pulse detection is integrated.

Detection packages are mounted in one of the Nasmyth foci of COTS type astronomical telescopes. In the beam path direction the field of view iris is followed by optics to collimate the entering photons to approx. 1 cm with some flexibility to tune the field of view of telescope. Dichroic mirrors separate the incoming light w.r.t. wavelength and distribute it to various sensor modules (e.g. single photon avalanche detectors for green and infrared, single photon light detection, optical guiding cameras and beam adjustment cameras). Both sensor and detection package operate a temperature control system and the necessary interfaces to connect to e.g. event timers, power supply or control pc.

Oral 09-01

Polarimetric satellite laser ranging

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We report on concepts and laboratory experiments pioneering polarization-modulated SLR. The idea is to equip satellites with specially designed retroreflectors with different polarizing properties. These retroreflectors can be coded into arrays and act as an identifier for satellites (a "number plate" that can be read from ground), while maintaining the precise orbit determining capability of conventional SLR. [1] The intended demonstration of the technology in a space mission not only requires the design of new retroflectors with additional polarization optics, but also modifications to our SLR station (the miniSLR®) in terms of hardware and software to be able to emit and detect photons with different states of polarization.

The main focus of our development is to meet increasing demands of space object monitoring, for example of mega-constellations or during cluster launches. However, we think that polarization-modulated SLR might also have applications in space geodesy, which is one of many topics we would like to discuss with the ILRS community.

[1] Bartels, N., Allenspacher, P., Hampf, D. et al. Space object identification via polarimetric satellite laser ranging. Commun Eng 1, 5 (2022). https://doi.org/10.1038/s44172-022-00003-w

Oral 09-02

Exploiting the synergy between optical two-way and microwave one-way ranging in a GNSS constellation: A simulation study

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The progress for satellite precise orbit determination (POD) and navigation depends on the future ranging and time transfer capabilities. This leads to the need for high-precision links as well as high-precision clocks. In a simulation study, we performed scenarios using the synergy between L-band observations as well as high-precision dual one-way Optical Inter-Satellite Links (OISL) and ground-space based dual one-way links, called Optical Two-Way Links (OTWL). Having the observation technique combinations, we show the POD capabilities within a MEO+GSO constellation for the GSO and MEO satellites. While first using Passive Hydrogen Masers (PHM) on all satellites in the constellation, we compare the solutions regarding clock estimation and prediction with solutions using the ACES (Atomic Clock Ensemble in Space) clock as a high-precision clock example.

This brings us close to the concept of GETRIS (GEodesy and Time Reference In Space). This is based on the idea to have high-precision clocks carried by geosynchronous orbit (GSO) satellites. With high-precision optical links, the connection to Medium Earth Orbit (MEO) and Low Earth Orbit (LEO) satellites, but also to far Earth satellites shall be established. The goal is to achieve a GSO satellite based reference in space. The orbit accuracies should be at the same level as the ground stations accuracy – a few millimeters.

Oral 09-03

Combination of Microwave and Optical Observations for minimizing Atmospheric induced variations in Parameter Estimation

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Atomic Clock Ensemble in Space (ACES) is an ESA future space mission, with focus on fundamental physics and time transfer. The basic configuration consists of a Microwave-Link-System (MWL) in space and ground, an optical detector and reflector, as well as a new generation of atomic clocks. To use their full fractional frequency stability and accuracy, all observation errors have to be minimized before post-processing. Especially electronic delays of MWL systems in transmitting and receiving are correlated with clock estimations. For that, the hardware will be pre-calibrated on ground, but there is no guarantee that the electronic delays of the system calibration will be static. Therefore, we develop a strategy to calibrate the MWL in downlink as well as in uplink direction. Due to the fact, that the official launch date is in 2025, there is a lack of real observation data. For that, we focus in our work first on near-realistic error simulation and afterwards on the calibration process. The developed simulation software, produces MWL code and phase observations in downlink and uplink, as well as one- and two-way laser observations. For calibration, we combine MWL- and optical-data in a Least-Square-Adjustment (LSA). Our studies show, that minimizing the atmosphere induced errors, is crucial for a proper hardware calibration. Assuming a common atmosphere for simultaneous optical and microwave observations, minimizes the tropospheric delay on the MWL observations sufficiently. We tested our calibration strategy with one month of simulation data, which corresponds to about 100 passes over a specific ground station. The delays could be estimated within sufficient accuracy, but there is still some space for improvements. Our further research will be focused on common troposphere estimation, as well as the impact of different observation weights on parameter estimation in LSA.

Oral 09-04

Satellite illumination for pointing and auto-tracking at Grasse station - France Station (ID7845)

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The MeO optical ground station, located in Grasse-France, was designed at the end of 1970's in the framework of lunar laser ranging (LLR). Today, in addition to the LLR program, the station is part of the ILRS network (ID7845) and participates to various laser applications including Satellite Laser Ranging (SLR), Time Transfer by Laser Link (T2L2), high-resolution imagery, debris detection and laser/quantum communication. In order to improve the pointing & auto-tracking system of the telescope and to test new detectors (with small detection area), we have performed some experiments basing on a high power continuous laser (uplink laser - 30 W) that illuminates some geodesic satellites. The spot of the returning beam is detected by a high-speed camera that enables the auto-tracking of a steering mirror. Therefore, the returning spot is maintained in the center of camera/detectors despite of the pointing error of the telescope and prediction error of satellite orbit.

In the presentation, we will first give a global view of experiment setup with some details on the uplink laser, the auto-tracking system with the steering mirror and camera. Then, we present some preliminary results obtained when we illuminated Ajisai, Stella, Lageos and our prospective applications of this such experiments.

Oral 09-05

Downlink communication experiments with OSIRISv1 laser terminal onboard Flying Laptop satellite at Grasse SLR/LLR station

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Downlink measurement campaigns from the optical downlink terminal OSIRISv1 onboard the LEO satellite Flying Laptop were carried out at Grasse SLR/LLR station (Observatoire de la Côte d'Azur) and with two Optical Ground Stations of the German Aerospace Center. On/off keyed data at 39 Mb/s were modulated on the laser signal, and according telecom reception was performed by the ground stations. The pointing of the laser terminal was achieved by open-loop body pointing of the satellite orientation, with its star sensor as attitude control signal. We report here on the measurements and investigations of the downlink signal and the data

transmission. We also present a detailed scintillation analysis using data acquired from atmospheric turbulence monitoring instrumentation from the CATS station.

Oral 09-06

System design and concept of small-size, low-cost, multi-purpose Omni-SLR System

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We have initiated a small project for a future SLR system. Our goals are to hugely reduce the cost per SLR station and to enable the future expansion of SLR tracking network, including a possibility of operations in Antarctica. A significant increase of SLR stations will not only enhance the precision of global geodetic products (e.g. Otsubo, et al., 2016) but also change the role of SLR. In addition, a number of key technologies in SLR development can be applied to optical communications and other purposes.

As already demonstrated by DLR Stuttgart's Mini-SLR (Hampf, et al., 2019), size reduction and use of COTS products are getting a realistic option for SLR. Our system is now called "Omni-SLR" and has the following features:

- Compactness: Easy to move. Transportable by a small car. Assembled in a few hours.
- Low cost: Collection of COTS products. Total 50 thousand dollars/euros.
- Distributed system: Small tasks dispatched to Raspberry PIs. Independent and autonomous subsystems.
- Multi-purpose: Aircraft tracking capabilities for future mobile communications. Applicable to space communication, debris tracking etc.
- Green: Low energy consumption ~ 100W. Operable with a portable battery.
- Open: Most of the system setup, software source codes etc to be opened to the community.
- Challenge: Trial-and-error approach. Development without fearing failure.

Technically, the Omni-SLR configuration features a nanosecond-pulse laser, a non-Coude bistatic telescope, a range-gate-less timing, a web-browser UI etc. More details of the Omni-SLR system are presented in the three posters (optical subsystem, tracking subsystem and timing/software subsystem) submitted to this workshop.

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Oral 10-01

Recent Developments of the Apache Point Lunar Laser Ranging Station

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The Apache Point Lunar Laser Ranging Station (formerly the Apache Point Observatory Lunar Laser-ranging Operation, or “APOLLO”) became part of the NASA Space Geodesy Network at the beginning of 2021. In conjunction with the former APOLLO team, best practices were established regarding observation and processing of data into normal points. A quality control process to identify centimeter-level biases was introduced, archival procedures were adjusted to match version 2 of the Consolidated Range Data format, and a fully reduced 2021 dataset was published to the Crustal Dynamics Data Information System’s database.

The APOLLO experiment has achieved median range precision at the (1-3) millimeter level for many years, yet comparisons of measurements against models are nearly an order-of-magnitude larger. Model-measurement disagreement raises the question of whether APOLLO suffers from gross systematic inaccuracies or if models are incomplete in some manner. In 2016, the APOLLO team added an Absolute Calibration System (ACS) consisting of a high-repetition-rate (80 MHz) short-pulsed (< 10 ps) laser that is locked to a cesium clock. The ACS delivers “truth” photons to the APOLLO detector at well-known time intervals which provides an independent assessment of the accuracy of the APOLLO system and an avenue for correcting range data in-situ. ACS results suggest systematic errors are reduced to ≤ 1 mm such that both the accuracy and precision of the data are at the ~ 1 mm level.

Deep-Space Synchronous Two-way Laser Ranging Experiment Using the LIDAR on board Hayabusa2

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Altimeter (LIDAR) on board the deep-space explorer Hayabusa2 as an optical transponder, successfully establishing a 2-way link over a distance of up to 6.46 million kilometers. This demonstration experiment was conducted to explore new applications in which deep-space laser ranging is performed using LIDAR as an echo transponder. In the experiment, a laser pulse (uplink) was first emitted from a ground laser station and received by Hayabusa2's LIDAR. The LIDAR then transmitted a laser pulse (downlink) back immediately after reception. This downlink pulse was successfully detected at the Côte d'Azur Observatory in France.

The experimental conditions were difficult due to the low repetition rate of 0.5 Hz when the LIDAR functioned as an echo transponder, the large jitter from the passive Q-switch of the laser, and the large background noise due to the link time with Hayabusa2 being during the daytime. However, the high temporal coherence enabled detection of the laser on the ground. To confirm this coherent property, we measured the coherence in a preliminary experiment using the LIDAR's engineering model and distance image sensors. In this presentation we will also discuss this preliminary experiment.

We would like to thank the Koganei station of NICT, Mt. Stromlo station in Australia, the Wetzel station in Germany, the Cote d'Azur Observatory in France, the Hayabusa2 operation team, and the NASA/JPL Deep Space Network for their cooperation on the RF downlink for this experiment.

Oral 10-03

Benefit of improved Lunar Laser Ranging data for the determination of Earth orientation parameters

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The Earth-Moon distance has been measured with Lunar Laser Ranging (LLR) since 1970. In the current analysis we use more than 30000 normal points (NPs) covering the period until April 2022. In recent years, there have been improvements in both, observations and analysis. For example, the NPs now are better distributed over the lunar orbit and retro-reflectors. In addition, the measurements have achieved a higher accuracy and the number of NPs per night is higher compared to the years before 2015. Together with improvements in the LLR analysis software, such as refined modelling (e.g. of the lunar core) and changes in the analysis strategy (e.g. optimised calculation of ephemerides), the determination of various parameters in the Earth-Moon system is now possible with higher accuracy. The recent improvements in NPs and their analysis will be presented and discussed.

By analysing LLR data, Earth Orientation Parameters (EOP) such as the Earth rotation phase ΔUT1, terrestrial pole coordinates, and nutation coefficients, as corrections to the MHB2000 model of the IERS Conventions 2010, can be determined along with other parameters of the Earth-Moon system in a least-squares adjustment. FocusingonΔUT1 and terrestrial pole coordinates from different LLR constellations such as single or multi-station data and for different numbers of NPs per night, the accuracies of the estimated Earth rotation phase and pole coordinates from the new LLR data have improved significantly compared to previous results. We now achieve an accuracy of about 20 µs for ΔUT1 and about 2 mas for xp and yp from subsets of the LLR time series with 15 normal points per night. Focusing on determining corrections to the nutation coefficients to theMHB2000 model, significantly smaller correction values and higher accuracies with an order of magnitude improvement, i.e., accuracies better than 0.01 mas, are obtained now. Recent results for these parameters are presented and discussed.

Oral 10-04

Uncertainty determination of Earth Rotation Parameters from LLR by parameter variation during data analysis

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Lunar Laser Ranging (LLR) has been measuring the distance between the Earth and the Moon since 1969. The IfE LLR dataset includes more than 30,000 normal points (NPs), currently until the end of April 2022. The analysis in the IfE LLR software (LUNAR) follows an iterative adjustment process where each iteration step first calculates the ephemeris of the solar system followed by the estimation of parameters. The adjustment is performed following the

Gauß-MarkovModel (GMM). In a standard calculation, LUNAR can determine over 175 parameters, and in cases of extension, the Earth rotation parameters (ERP; terrestrial pole offsets, xp and yp, and Earth rotation phase, ΔUT1) can also be estimated. The ERPs are determined for a subset of nights selected, based on the LLR NPs. The standard deviation of all parameters determined from LUNAR (standard calculation and extensions) are determined from the adjustment following the GMM, and the uncertainty of the parameters is reported as 3-sigma values (i.e. three times standard deviation, for a more realistic representation). In this study, we determine the ERPs from LUNAR, creating different modifications to the software to address various cases (for example, by keeping all LLR parameters fixed to standard solution values or adjusting them along with ERPs) and to obtain ERPs from all these different cases. Overall, the different cases provide a range of values for the determined ERPs on each night. Preliminary results show that the range of the ΔUT1 values is in close agreement with the 3-sigma values obtained from the GMM. Recent and more sophisticated results of ERP determination (from LLR) for the different cases will be presented and the different approaches to determine the errors for the standard parameters and the ERPs will be discussed.

Oral 10-05

Combination of Lunar Laser Ranging and Differential Lunar Laser Ranging

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Lunar laser ranging (LLR), i.e., range measurements from an Earth station to a lunar reflector, is carried out for more than 53 years. LLR is important for many fields, e.g., lunar ephemeris, relativity tests and lunar interior modelling. However, due to the limited LLR accuracy related to the challenging tracking conditions, the small number of received photons, the Earth's atmosphere, etc., it is difficult to achieve real breakthroughs for a better understanding of certain parts of the Earth-Moon system, e.g., the lunar interior. In future, an upgraded station with a high-power continuous wave laser at Table Mountain Observatory of JPL will enable a new technique for lunar tracking, i.e., differential lunar laser ranging (DLLR). With a large flux of received photons, the station will realize fast switching between two or more reflectors to attain a novel kind of observation: lunar range differences. DLLR will decrease the atmospheric errors largely, resulting in a very high accuracy for the differential range at the level of ~30 µm. Furthermore, DLLR will significantly improve our knowledge of the lunar interior and benefit the relativity tests. In this study, we investigate the potential of DLLR using simulated DLLR data, where we put some focus on the combination of LLR and DLLR data. DLLR data only with a rather short time span of observations (in the beginning) are merely able to determine the lunar orbit well, which has a negative effect on the estimation of other lunar parameters. However, LLR with its long timespan has the advantage of providing an accurate orbit. By combining with LLR, even DLLR data over a rather short time span (e.g., 5 years) can remarkably enhance the parameter estimation for the lunar interior. We also studied the effects of different kinds of reflector baselines of DLLR on estimating lunar-interior parameters, proving that baselines with longer length and crossing shape are most beneficial for the investigation of the lunar interior.

Paris Observatory Lunar Analysis Center: from LLR predictions to tests of fundamental Physics

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POLAC (Paris Observatory Lunar Analysis Center) is an ILRS analysis centre founded by J. Chapront, M. Chapront-Touzé, and Gérard Francou in 1996. They developed in the 80's a semi-analytical solution of the lunar motion named ELP (Ephéméride lunaires Parisiennes). The original purpose of POLAC was the fitting of ELP to the lunar laser ranging observations (LLR) in order to improve the determination of fundamental astronomical parameters, such as the free modes of the lunar physical librations, the tidal secular acceleration of the lunar longitude, or the transformation between celestial reference systems. Since its beginning, POLAC worked in close collaboration with the laser ranging station at Grasse (MéO) by providing a posteriori validation of their LLR normal points in order to avoid calibration and format issues. Since 2010, POLAC has evolved. Firstly, it additionally provides a priori predictions for laser ranging observations – mainly for the Moon tracking but also, in an experimental mode, for two ways LRO (Lunar Reconnaissance Orbiter) tracking. Secondly, with the elaboration of a new Lunar ephemeris called ELPN (Ephémérides lunaires Parisiennes numériques), POLAC also takes part to the long legacy of testing fundamental Physics with LLR observations. Indeed, even if ELPN was built originally in the framework of general relativity, it can also be used to test alternative theories of gravity. One of particular interest is the Standard Model Extension (SME) which parametrizes Lorentz Symmetry violations, in the pure gravity sector and also in the matter sector. By fitting ELPN in the pure gravity sector (including operators of mass dimension 4 and 5) and the matter sector of the SME framework to 50 years of collected data, we have been able to provide accurate realistic estimates on possible Lorentz symmetry violations arising at the level of the weak and the strong Einstein equivalence principles.

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