THE NEXT GENERATION OF SATELLITE LASER RANGING SYSTEMS

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ORIGINAL ARTICLE

CrossMark

The next generation of satellite laser ranging systems

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Abstract

Satellite laser ranging (SLR) stations in the International Laser Ranging Service (ILRS) global tracking network come in different shapes and sizes and were built by different institutions at different times using different technologies. In addition, those stations that have upgraded their systems and equipment are often operating a complementary mix of old and new. Such variety reduces the risk of systematic errors across all ILRS stations, and an operational advantage at one station can inform the direction and choices at another station. This paper describes the evolution of the ILRS network and the emergence of a new generation of SLR station, operating at kHz repetition rates, firing ultra-short laser pulses that are timestamped by epoch timers accurate to a few picoseconds. It discusses current trends, such as increased automation, higher repetition rate SLR and the challenges of eliminating systematic biases, and highlights possibilities in new technology. In addition to meeting the growing demand for laser tracking support from an increasing number of SLR targets, including a variety of Global Navigation Satellite Systems satellites, ILRS stations are striving to: meet the millimetre range accuracy science goals of the Global Geodetic Observing System; make laser range measurements to space debris objects in the absence of high optical cross-sectional retro-reflectors; further advances in deep space laser ranging and laser communications; and demonstrate accurate laser time transfer between continents.

Keywords Satellite laser ranging · Space geodesy · ILRS network · Next generation · Automation · Laser transponders

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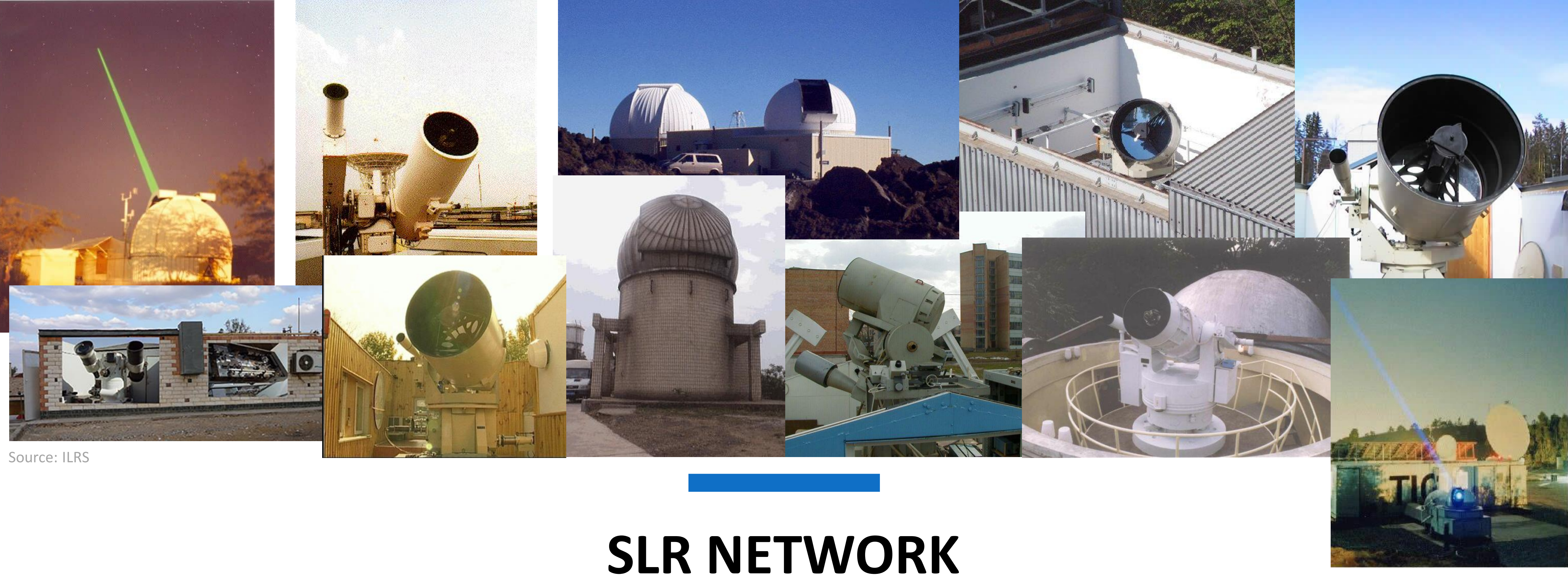


Source: ILRS

SLR NETWORK

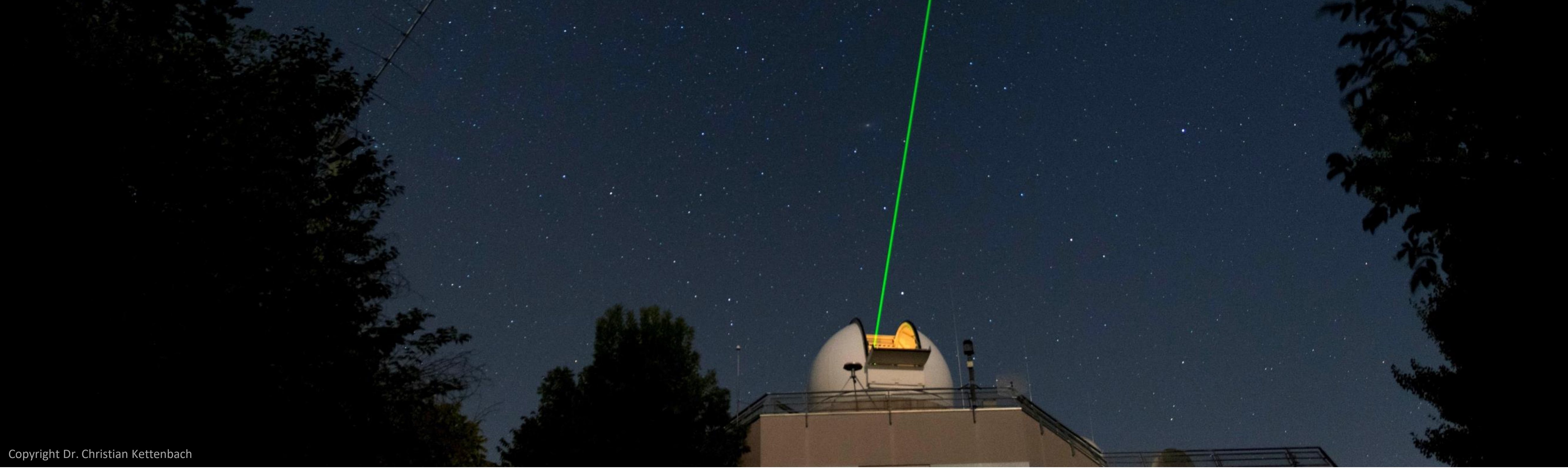
The first laser light returning from the Beacon Explorer 22 (BE-B) satellite was detected in 1964 and in the decades that followed, many satellites carrying retro-reflector targets were launched and a global network of SLR stations was established.

Source: ILRS

SLR NETWORK

There was a lot of variety in the network, but as new technologies were introduced to improve accuracy and performance, some tried and tested instruments became standard:

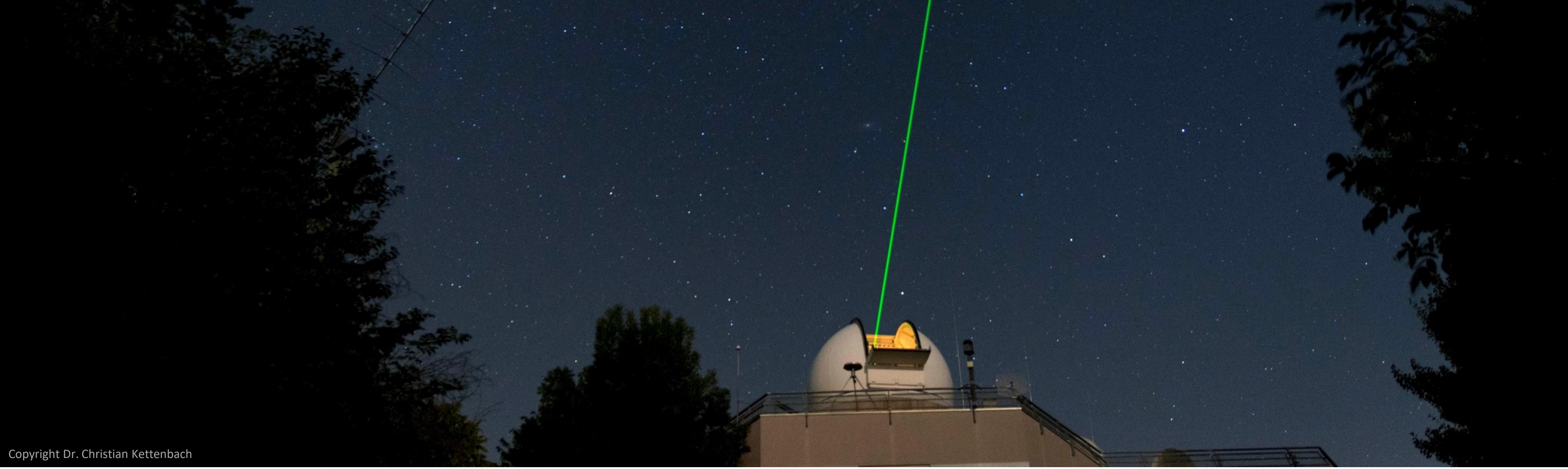
These were: frequency-doubled mode-locked **Nd:YAG lasers** that produced 20–100 mJ, 35–200 ps pulses at 10 Hz; **time interval units** and **SPAD** or **MCP-PMT** detectors.



A NEW GENERATION OF SLR SYSTEMS

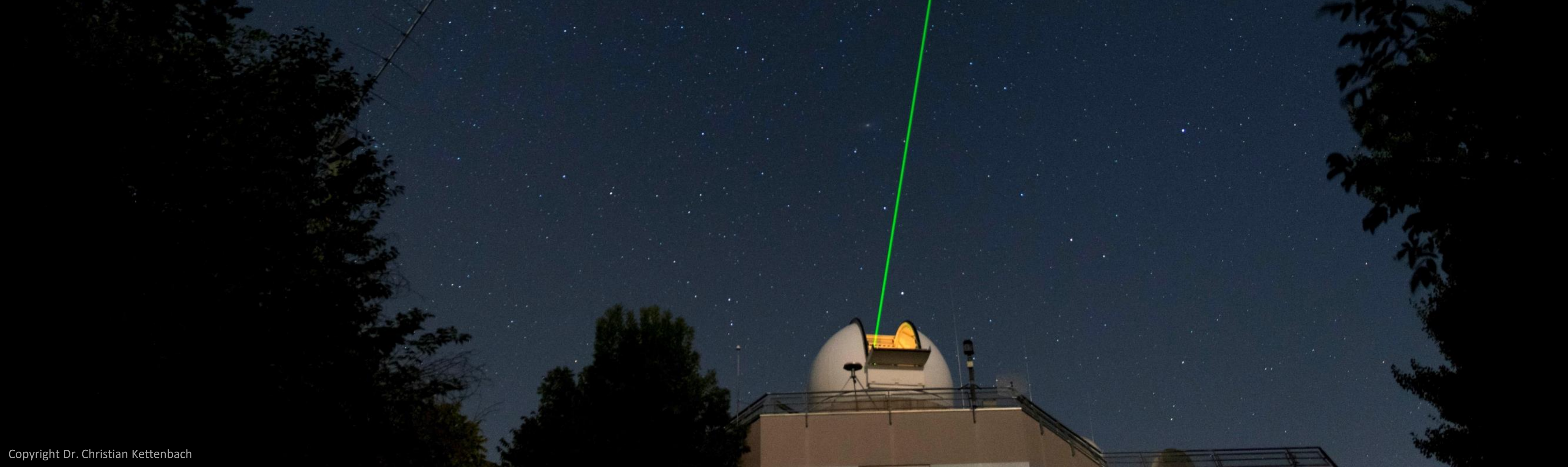
In 1994, a largely autonomous, lower cost, eye-safe, low pulse energy, high repetition rate, event timing SLR system called **SLR2000** was proposed to NASA to track LAGEOS and lower altitude satellites.

This was a radical departure from the legacy high energy, low repetition rate NASA MOBLAS systems and all the others at ILRS stations. The first successful kHz SLR returns from **NGSLR** were detected in March 2004.



A NEW GENERATION OF SLR SYSTEMS

The **Graz** SLR station, operated by the Austrian Academy of Sciences, began kHz SLR in October 2003. It did so by first upgrading its timing system from several interval timers operating in parallel to an event timer and then installing a High-Q solid-state, diode-pumped 10 ps, 0.4 mJ, 2kHz laser.

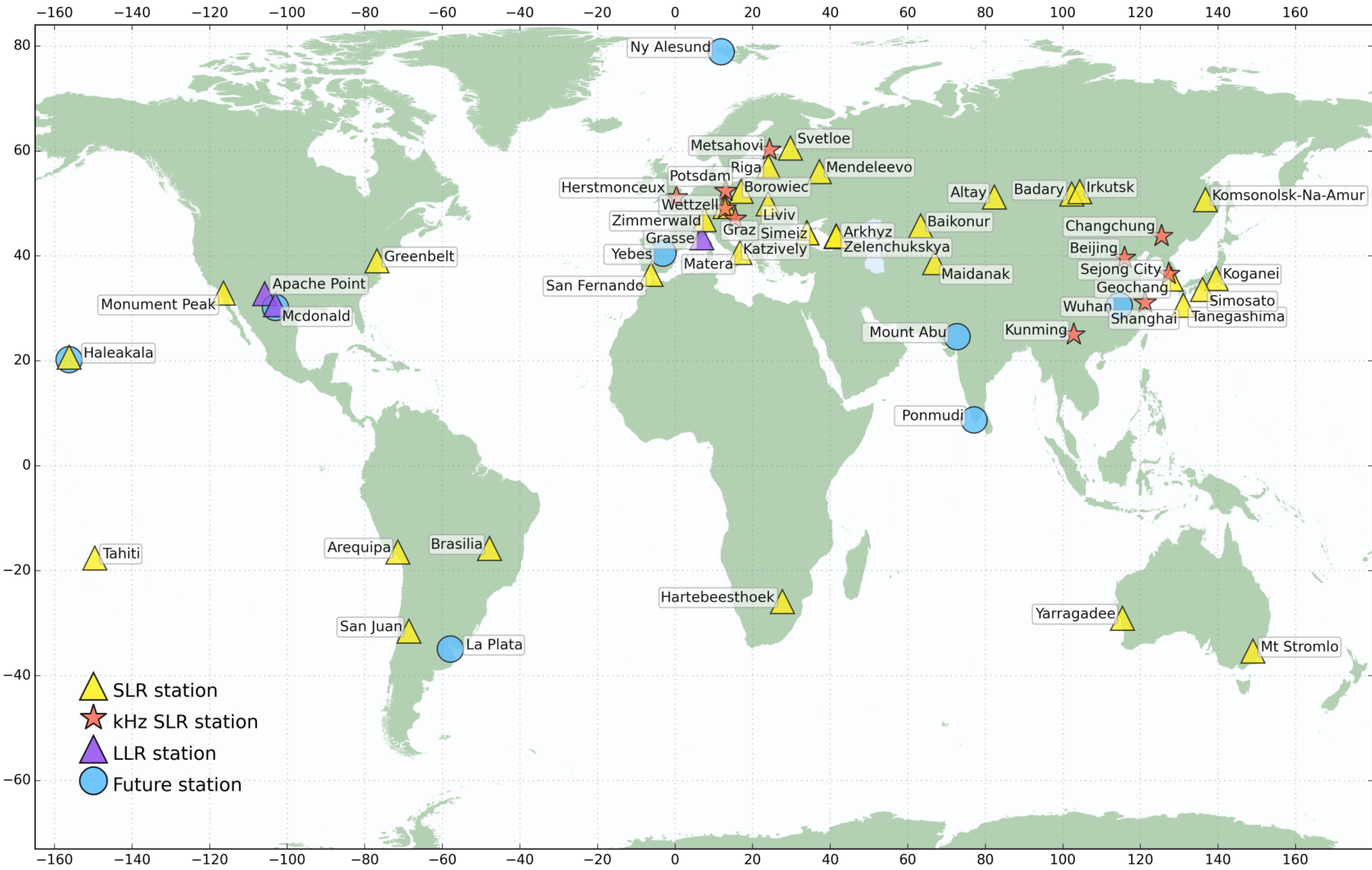


A NEW GENERATION OF SLR SYSTEMS

In 2008, **Herstmonceux**, UK, upgraded to 2 kHz SLR. The Chinese stations at **Changchun**, **Shanghai** and **Kunming** upgraded to kHz in 2009 and **Beijing** in 2010. **Potsdam** began 2kHz SLR in 2011. **Mt Stromlo**, Australia upgraded to 60Hz in 2007 and **Zimmerwald**, Switzerland switched to 110 Hz in 2008. The Russian station in **Arkhyz** began SLR in 2006 at 300 Hz, and **Altay, Badary**, **Baikonur**, **Irkutsk**, **Komsomolsk**, **Mendeleevo** and **Zelenchukskaya** were upgraded to the same. **ARG0-M**, in South Korea began 5kHz SLR in 2012.

SLR NETWORK

A significant proportion of the ILRS network now operate high repetition SLR systems.



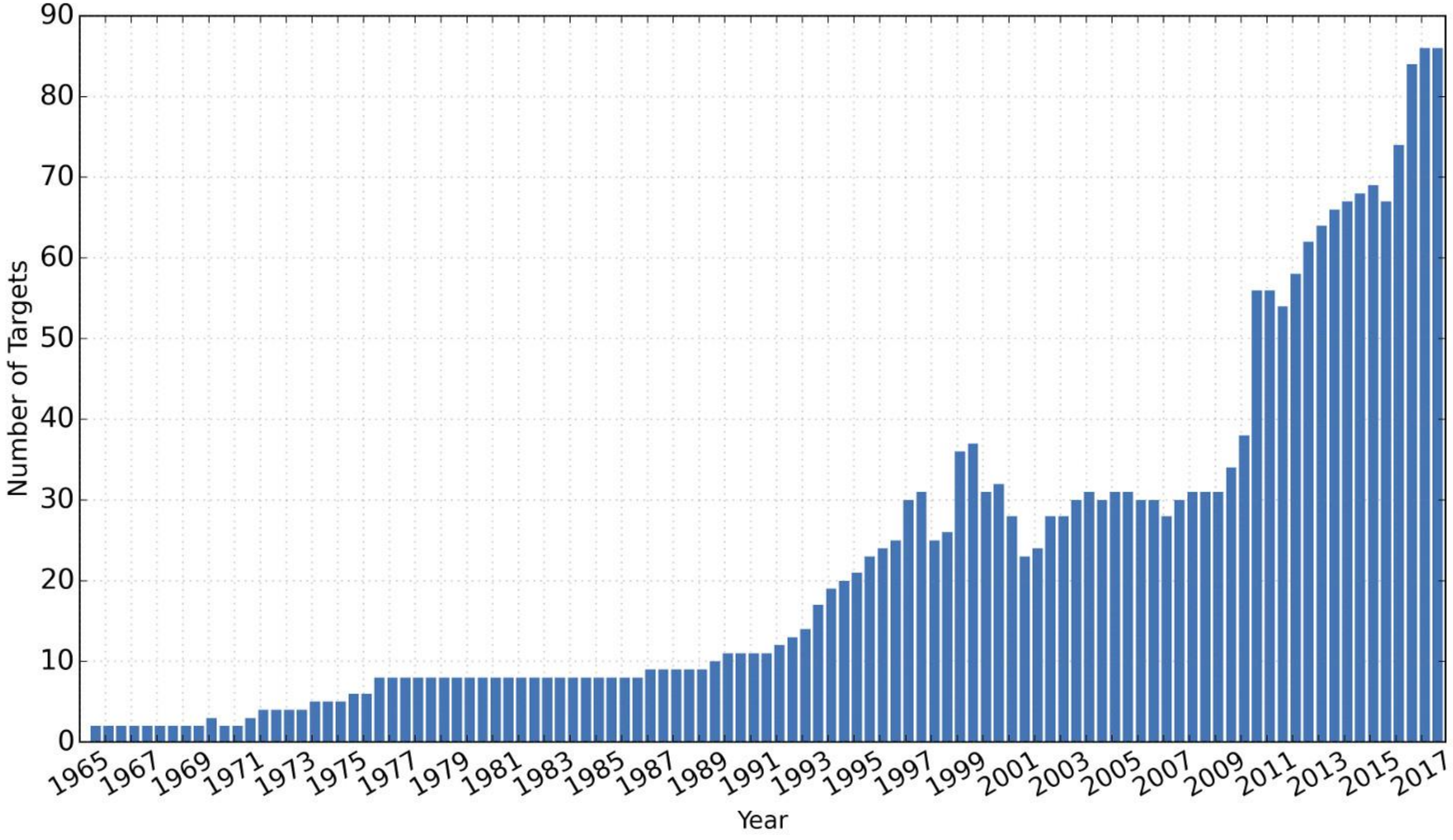
ADVANTAGES OF KHZ SLR

The demand for SLR support, as shown here, has steadily increased over time.

This will increase further if all future GNSS satellites carry retro-reflector targets.

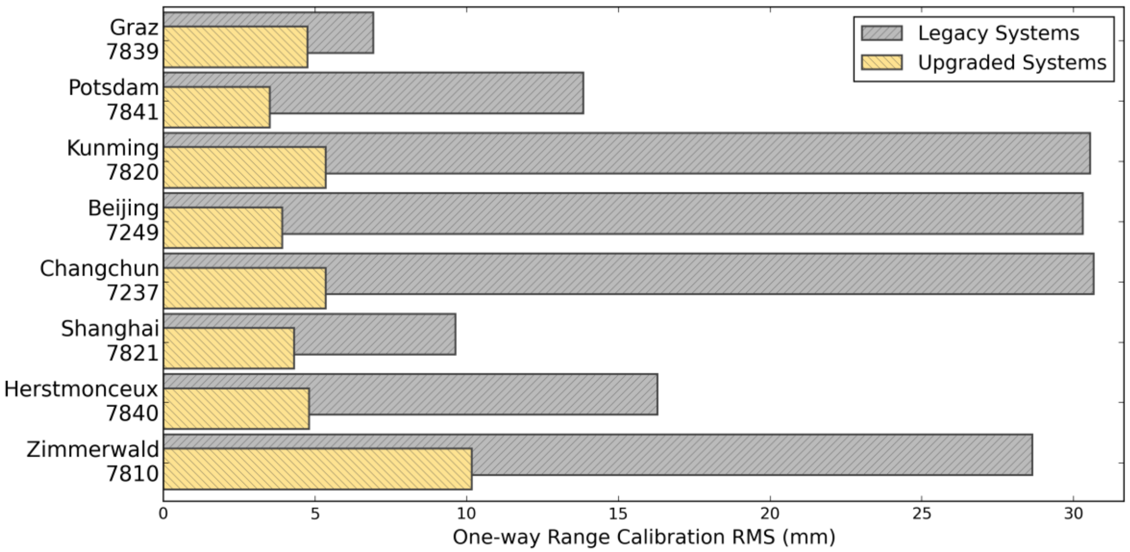
High repetition rate SLR can shorten the time for both acquisition and normal point completion. This makes them more agile and able to support more targets.

The number of satellites supported by the ILRS network throughout the history of SLR.



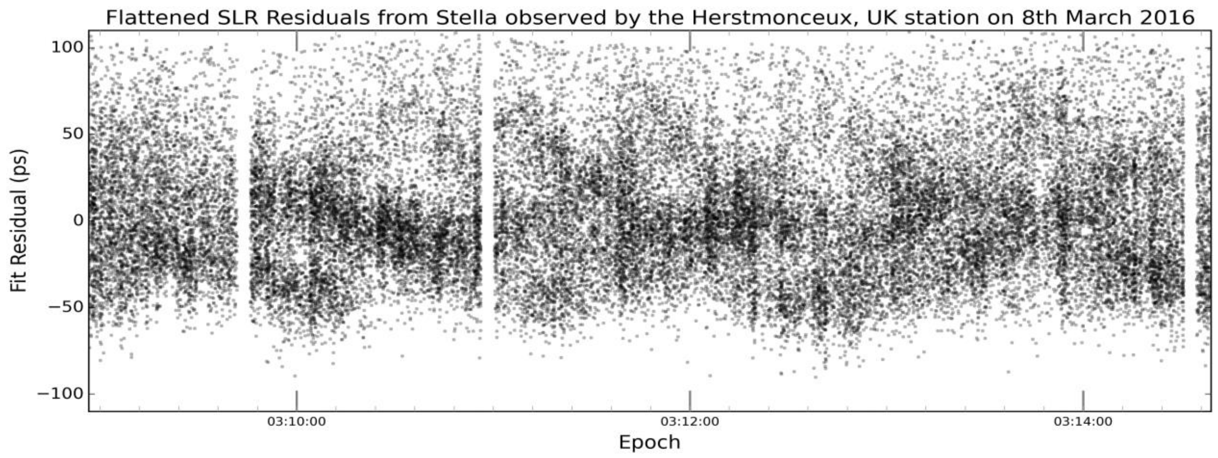
ADVANTAGES OF KHZ SLR

The one-way range precision decreases for upgraded SLR stations as estimated from the laser pulse width, detector jitter and timer precision entries in ILRS sites logs.



With ultra-short pulse lengths and the high density of data points, it is possible to distinguish individual retro-reflector cubes in range residuals.

Studies using high repetition rate data have been able to measure changing spin rates and spin axis orientation of the LAGEOS, Ajisai, Etalon and BLITS satellites.



NETWORKS

A new productive station would be able to significantly contribute to the products of the ILRS, particularly if it were to be placed in a location that would fill a gap in the network.

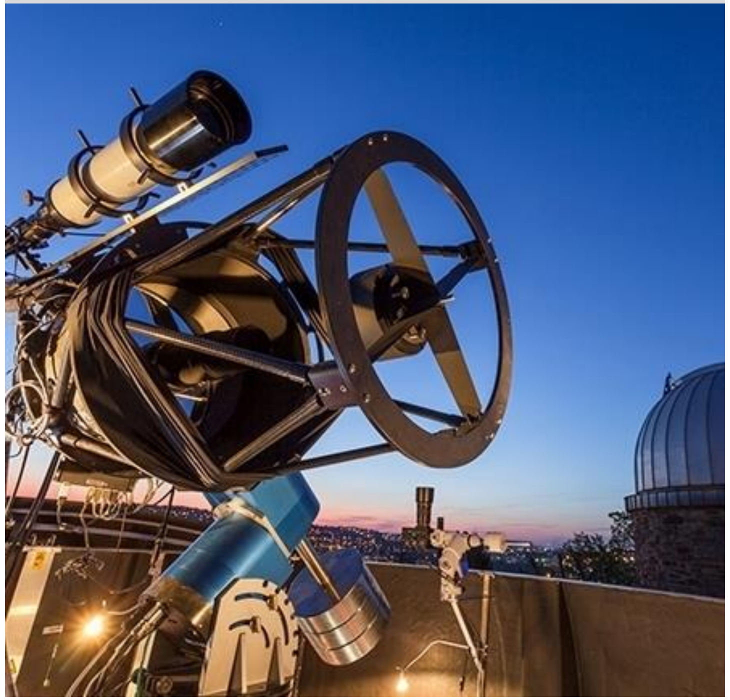
To have a greater impact on the formation of the ITRF, new SLR stations would ideally be co-located with the other geodetic techniques: GNSS, VLBI, and DORIS.

Activity in the ILRS Networks and at individual stations and institutions will result in new stations joining the network in the near future.

NETWORKS

The **Russian Network** have designed and built a ‘Tochka’ station that will conduct regular SLR and one-way laser ranging to GLONASS navigation satellites equipped with laser pulse reception modules

Tochka will be able to run in a fully automated mode that is capable of performing SLR, correcting the laser beam pointing, calibration,and conducting search routines to acquire and optimise returns from targets.

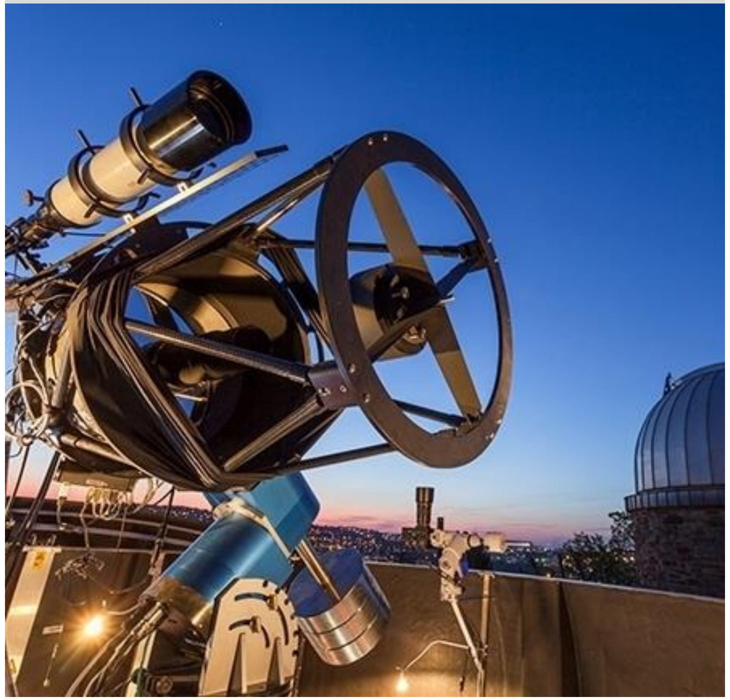


NETWORKS

The SGSLR station design for the **NASA Network** is under construction and it will be precise, stable and efficient.

It will eventually be fully automated and it will be robust enough to operate in most locations around the world.

The first stations will go to the **McDonald** Observatory in Texas, **Ny-Ålesund** in Norway, **Goddard** in Maryland and **Haleakala** in Hawaii.

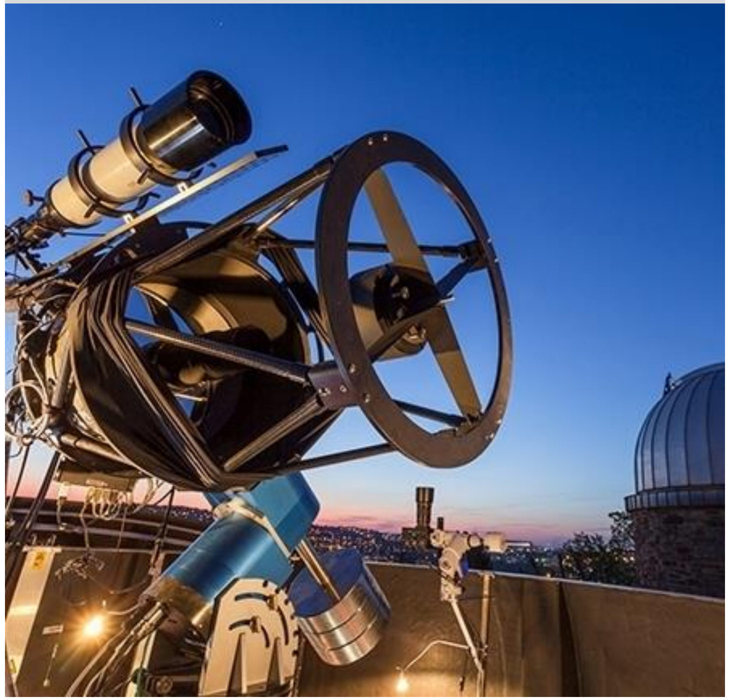


NETWORKS

A new station in **Wuhan**, **China** is operational using a 1kHz, 1mJ laser from Photonics industries, a C-SPAD and a A033-ET from EvenTech.

The Geodetic Research Station in **Metsähovi**, **Finland** will recommence SLR using a kHz laser, event timer, bi-static 50 cm telescope and a high-speed dome.

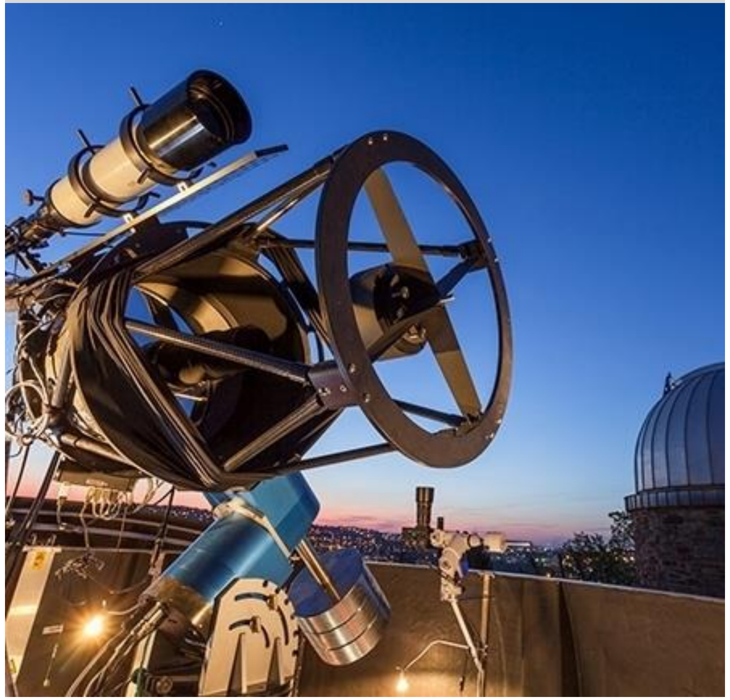
The **Yebes** Observatory in **Spain**, a SLR station is planned as a high repetition rate bi-static system with a C-SPAD, event timer and automation.



NETWORKS

The GGOS Fundamental Station in **Wettzell**, Germany build a new SLR system, SOS-W, using a Ti:SAP, 1kHz laser.

Additionally, two new stations are under construction in India, in **Mount Abu** and **Ponmundi**, operated by the Indian Space Research Organisation (ISRO) in support of the Indian Regional Navigation Satellite System (IRNSS).

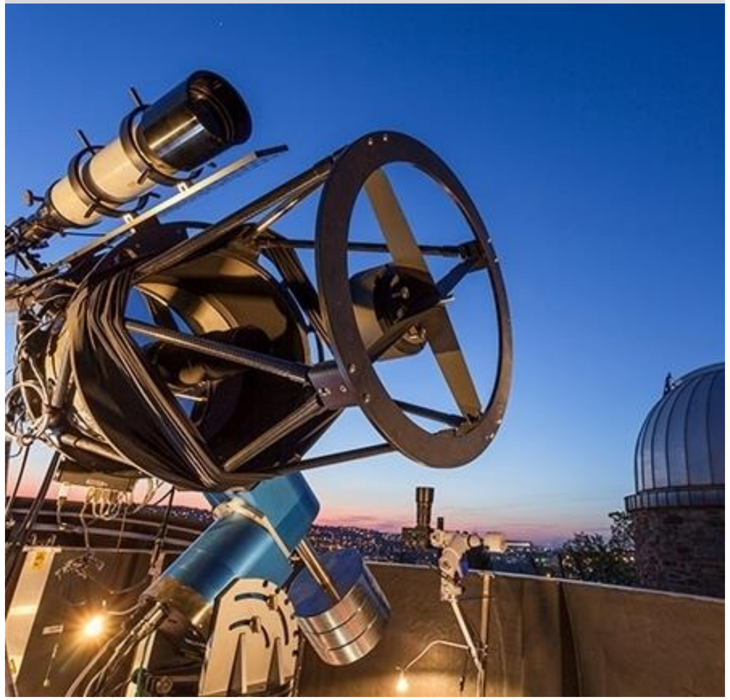


NETWORKS

A second laser telescope was installed alongside the **Graz** SLR station in Austria with a diameter of 80 cm. This telescope can potentially be equipped with multiple lasers.

The new SLR station in **Matera** is using an ‘Eskpla Atlantic 60’ laser to fire 0.1mJ, 9ps pulses at 100kHz.

A new station, ESA Laser Ranging Station (ELRS) is planned in **Tenerife, Spain** with a 400Hz picosecond laser.



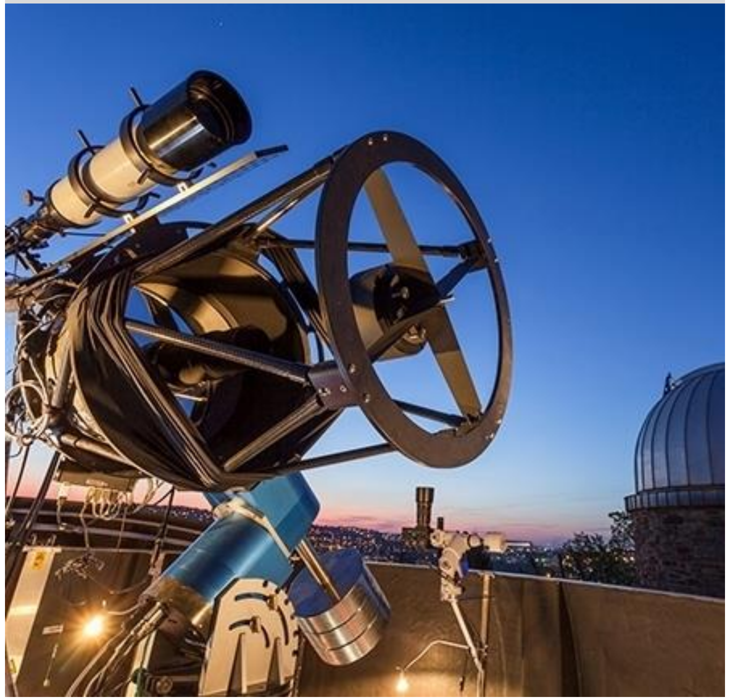
NETWORKS

And in **Stuttgart**, there is an ILRS Engineering Station which was the first to conduct SLR with a fibre optic based transmitter using an infrared 3kHz laser.

It is now using an infrared 0.12mJ, 13ns laser at 100 kHz.

It uses only commercial, off-the-shelf components and has near eye-safe operation.

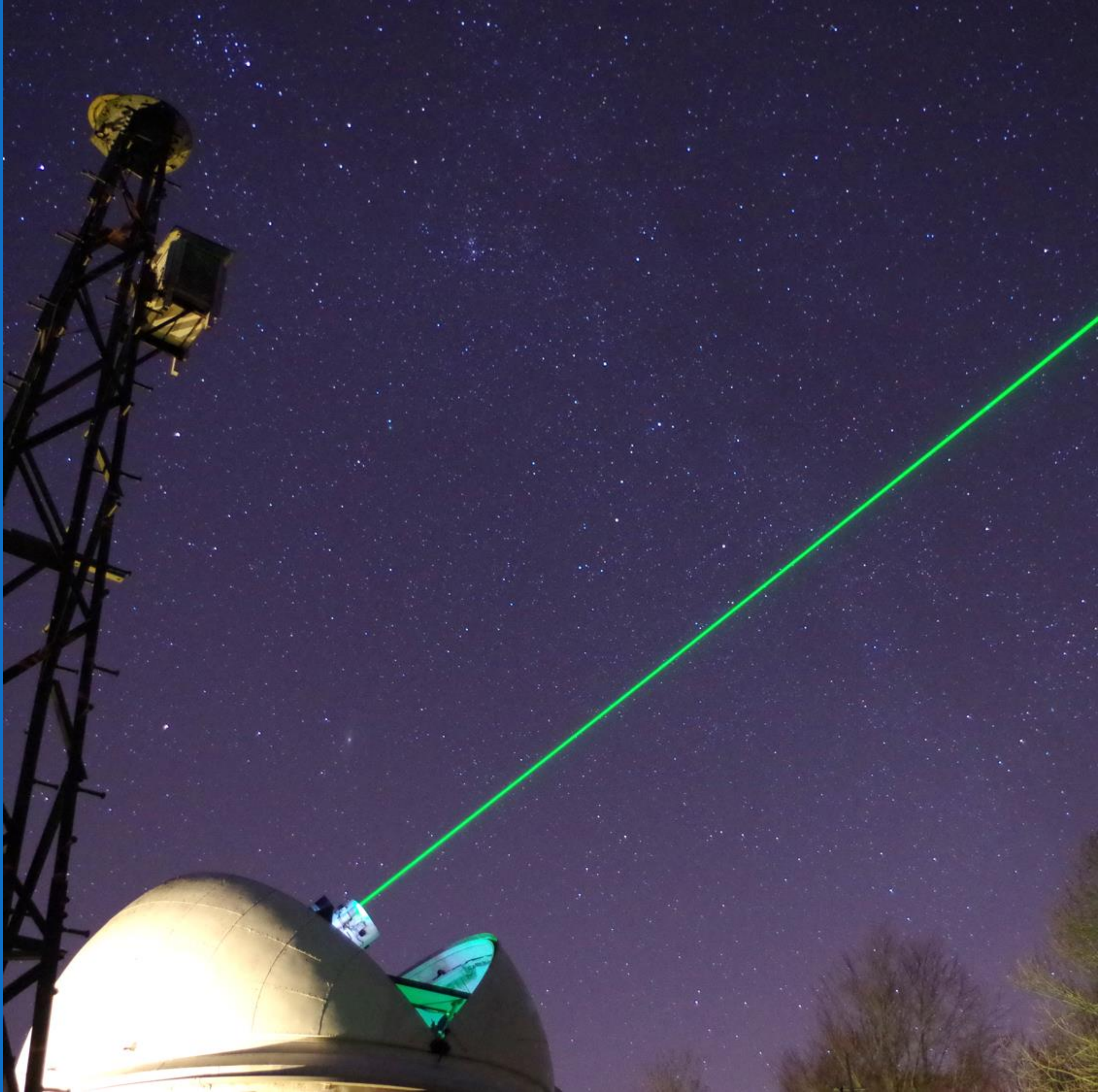
In addition, a transportable space debris system was designed and built called 'STAR-C'.



EMERGING APPLICATIONS AND DIVERSIFYING SLR STATION OPERATIONS

High precision timing; fast and accurate telescope control; laser operation and high productivity scheduling can be used in activities beyond traditional SLR.

Having additional tasks, alongside the ILRS tracking schedule, can be useful for individual SLR stations to secure funding for maintenance, development and the future.



LASER TRACKING OF SPACE DEBRIS

The large, small and minuscule objects that remain orbiting the Earth from past space missions pose a hazard to current and future satellite activity.

The ILRS network can continue to support objects that are carrying retro-reflector cubes, including satellite bodies that are no longer operational, such as ENVISAT.

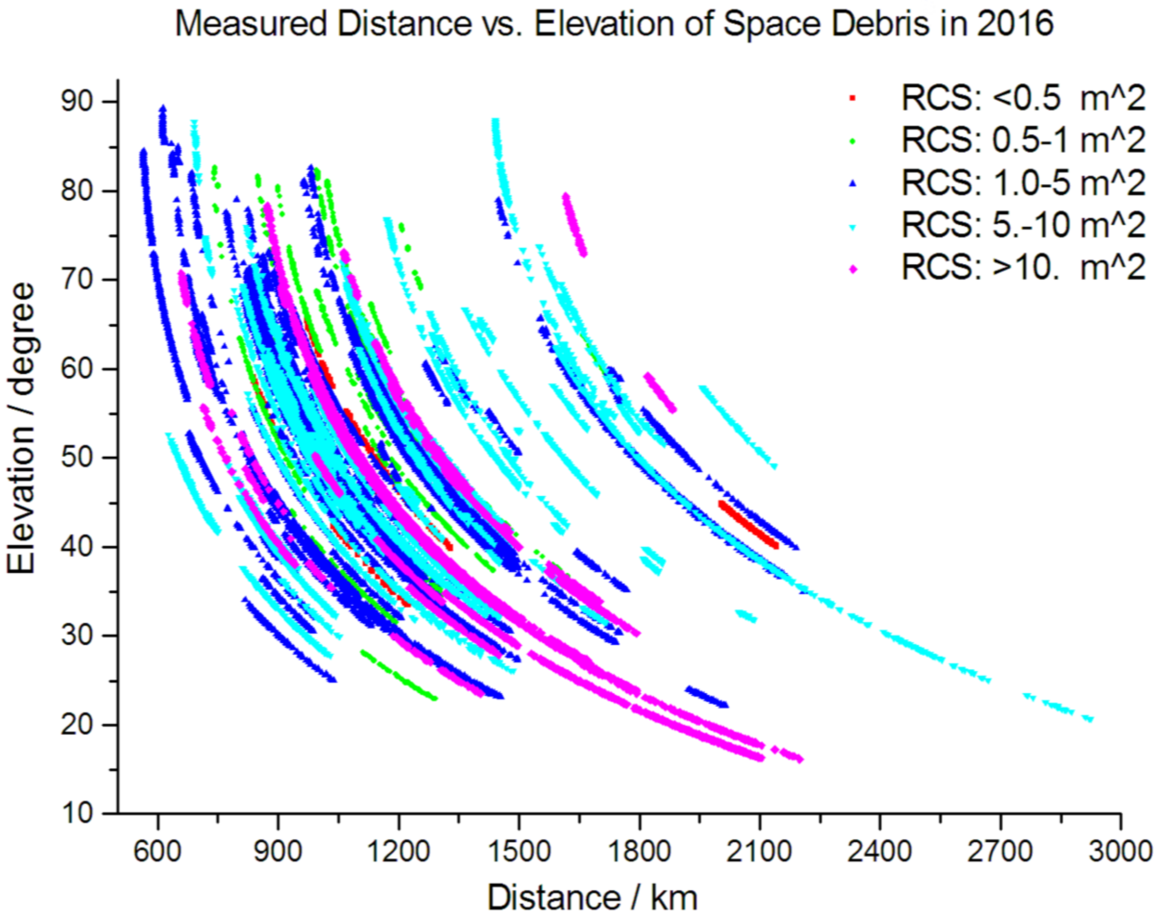
This, and tracking targets without retro-reflectors, is coordinated through the **ILRS Space Debris Study Group (SDSG)**.

LASER TRACKING OF SPACE DEBRIS

Without retro-reflectors, in order to track diffuse reflections from rocket bodies or other debris objects, a significant increase in laser energy is required.

In 2011, using a more energetic (1 kHz, 10 ns, 25 mJ) laser, the Space Research Institute of the Austrian Academy of Sciences in **Graz** detected returns from diffuse scatter from ‘uncooperative’ debris targets.

Today, a number of SLR station can track such targets by switching to more energetic lasers and detectors with high quantum efficiency.



LASER TRACKING OF SPACE DEBRIS

SLR to debris aims to improve the orbital prediction accuracy of selected objects, for example, one that could potentially collide with an active satellite.

Laser ranges to debris carried out at the **Shanghai** station using a 200 Hz, 8 ns, 60 W laser are plotted here.

The range accuracy is in the order of 0.5 m RMS and is due to the longer laser pulses and large target sizes.

Another limitation is the inaccurate orbit predictions, where the along track biases can be a few kilometres.

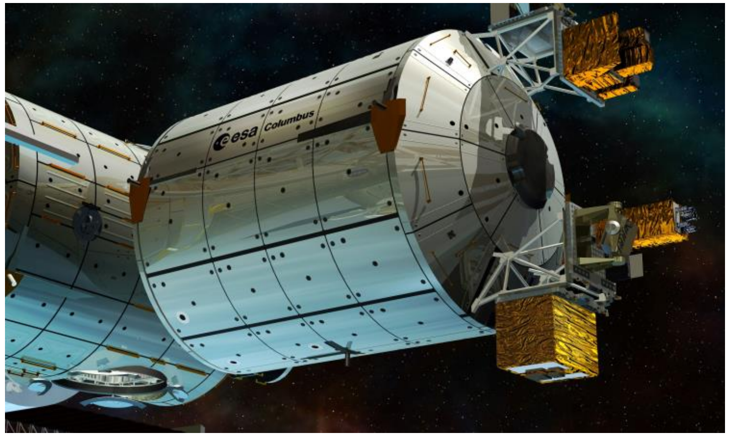
This restricts observation time slots to those where there is darkness at the SLR station, but the target is still illuminated by the Sun.

LASER TIME TRANSFER

The arrival times of laser pulses from a SLR station at a satellite can be recorded on detection. These epochs are recorded in the satellite timescale.

Using these epochs along with SLR epochs and ranges, time can be transferred and a comparison made of the onboard clock and the ground clock.

The strengths of optical time transfer are that it includes the geometrical distance between the clocks and has a small propagation delay through the troposphere and ionosphere.

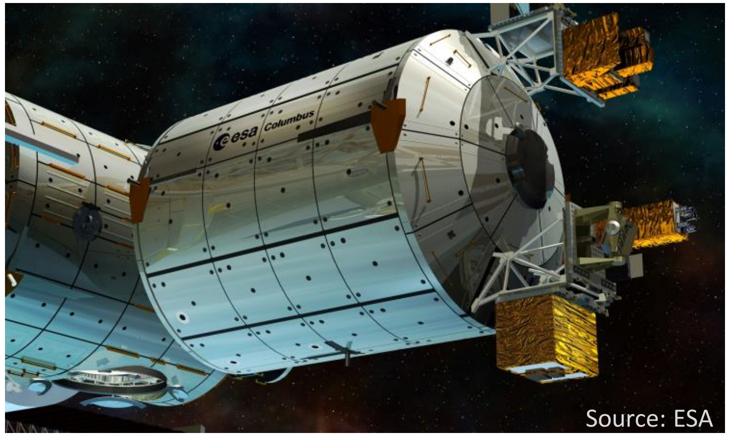


LASER TIME TRANSFER

The LAser Synchronisation from Stationary Orbit (**LASSO**) experiment was onboard the geostationary MeteoSat-P2 was first tracked by **Grasse, France** and **Graz, Austria** in 1988. Then in 1992, the Grasse and **McDonald**, USA, achieved trans-Atlantic time transfer with a precision better than 100 ps.

The **T2L2** time transfer experiment launched on Jason-2 in 2008 was tracked routinely by the whole ILRS network, enabling clock comparisons between SLR stations, including those with ultra-stable frequency sources such as active hydrogen masers.

Ground to ground synchronisation of less than 1 ns uncertainty was achieved.



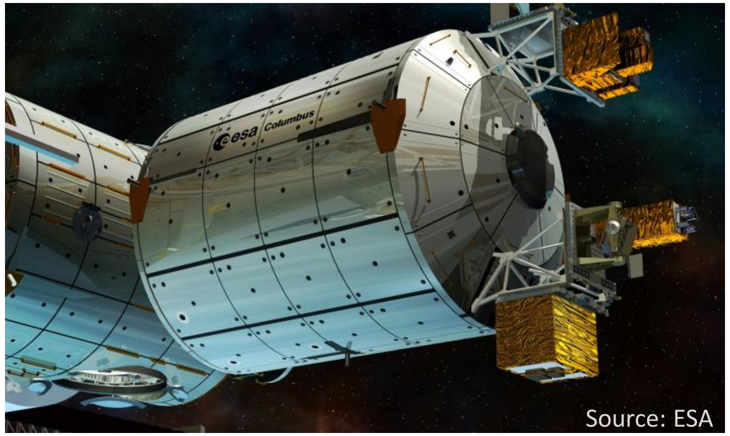
Source: ESA

LASER TIME TRANSFER

The Atomic Clock Ensemble in Space (**ACES**) mission is currently under development and is prepared for launch to the International Space Station in 2020.

It aims to make clock comparisons over a longer period of time to test gravitational redshift, a consequence of the theory of general relativity.

Time transfer to more distant satellite targets has the advantage of offering lines of sight to a larger segment of the global ILRS network for longer periods of time as has been demonstrated on Chinese **Beidou** and Russian **GLONASS** satellites.



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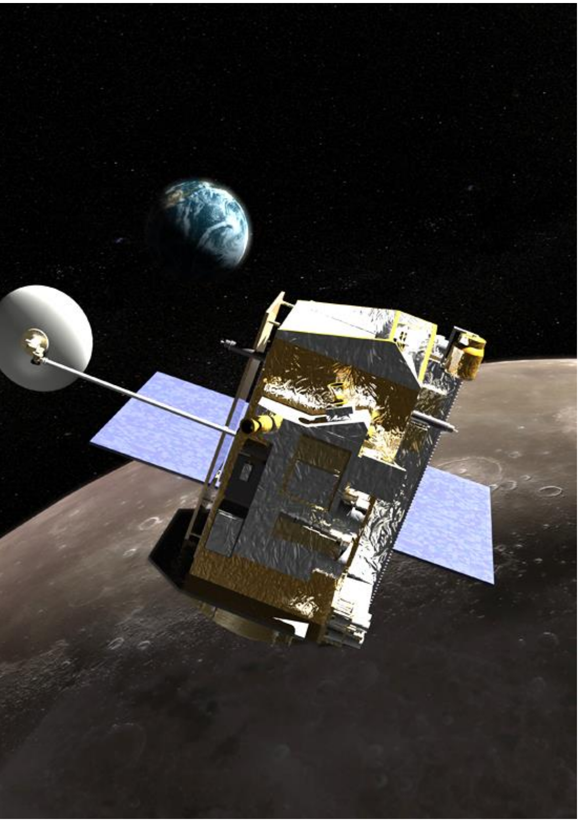
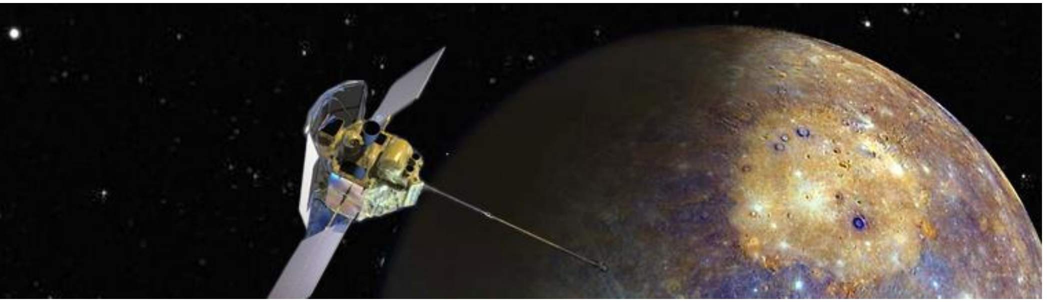


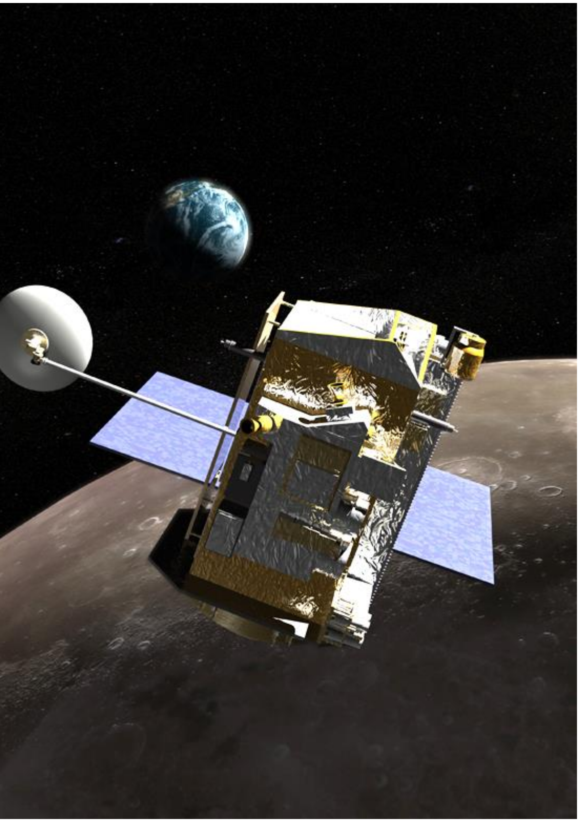
Source: NASA



DEEP SPACE LASER RANGING

Roundtrip SLR return signal strength is reduced by a factor of range to the fourth power. As a result, metre-class telescopes and high laser energies (100 s of mJ) are typically required.

However, if both ends of the link employed a laser transmitter and receiver, the signal strength in a one-way link would only be reduced by the range squared and therefore precise ranging and time transfer can be extended to much greater distances.



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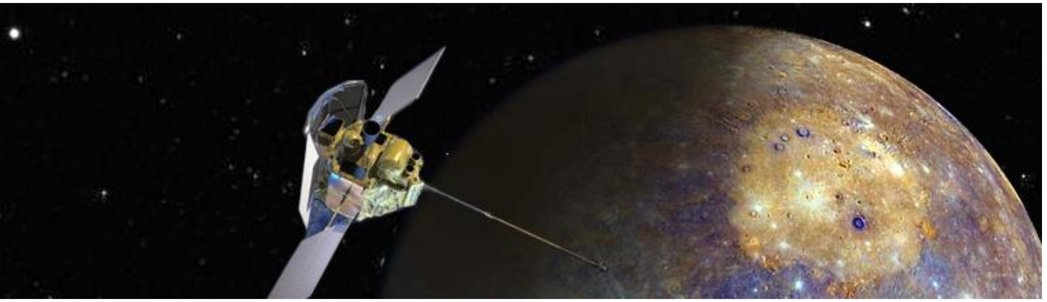
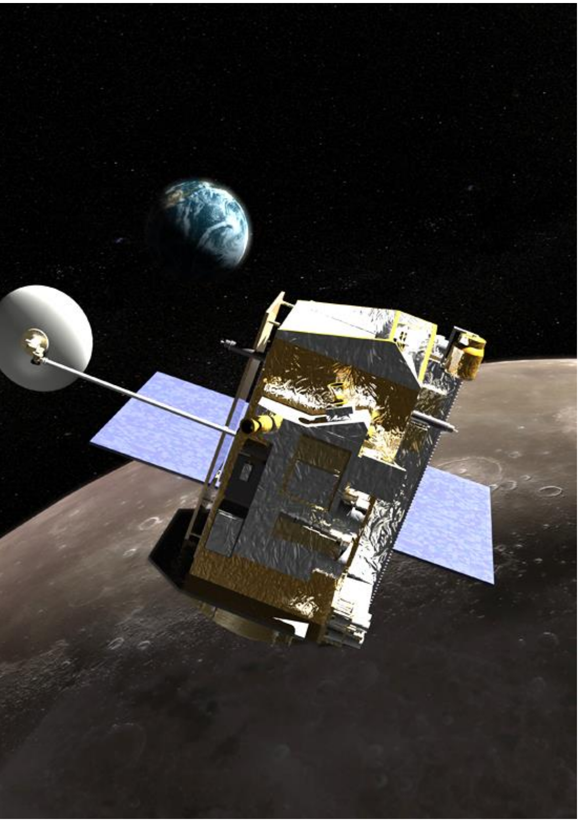


DEEP SPACE LASER RANGING

This deep space capability was first demonstrated in May 2005 between the 1.2 m telescope at the NASA Goddard Geophysical and Astronomical Observatory (**GGAO**) and the Messenger Laser Altimeter (MLA) on a spacecraft en route to Mercury, over a 24 million km link with 20 cm precision

Three months later, GGAO made a one-way 80 million km laser link to the Mars Orbiter Laser Altimeter (MOLA).

In 2015, the **Mt Stromlo** debris tracking laser station and the **Koganei** SLR station supported the Japanese explorer mission, Hayabusa2. Uplink pulses from Mt Stromlo were detected at the space craft 6.6 million km away.



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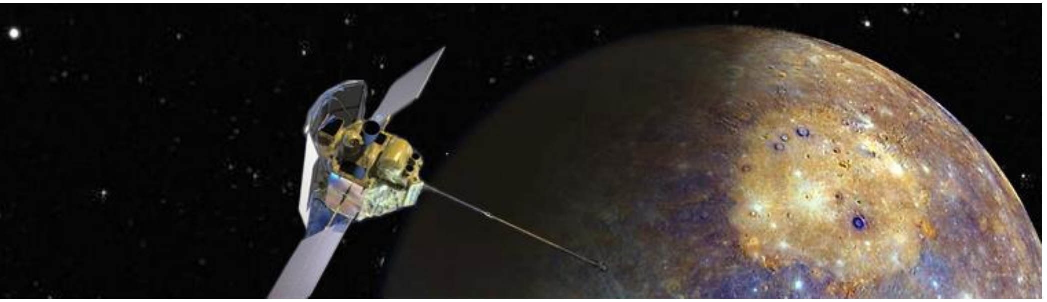


DEEP SPACE LASER RANGING

The Lunar Reconnaissance Orbiter (LRO) reached the Moon in June 2009 and was placed in a near circular, mapping orbit with an average altitude of 50 km.

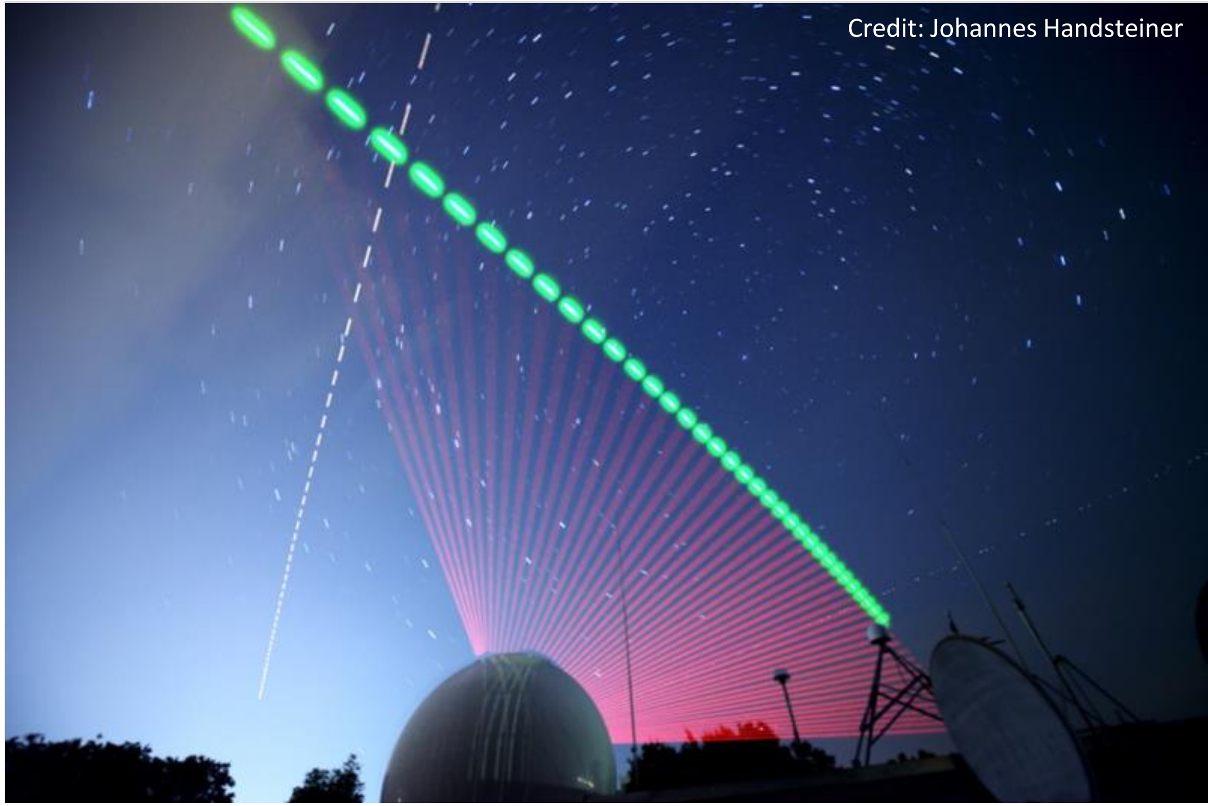
Included onboard was the Lunar Observer Laser Altimeter (LOLA) for measuring the topography of the lunar surface with 10cm resolution, which required precisely determined orbits.

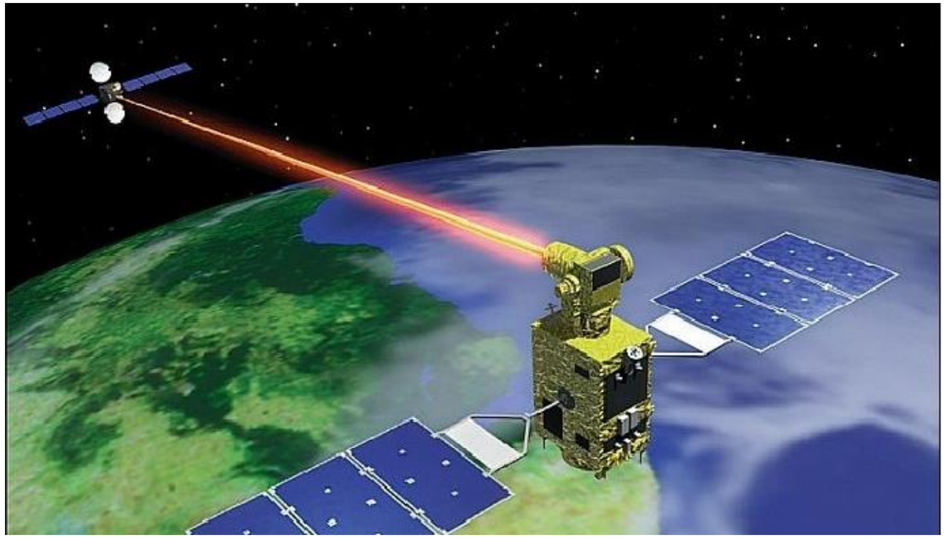
10 SLR stations performed one-way laser range measurements to LRO as part of their observing schedule.

LASER COMMUNICATIONS

The amount of data collected by Earth observation satellites and deep space missions is increasing and free-air laser communications has the potential to securely transfer greater data quantities at higher bandwidth, compared to microwave frequencies.

The space segment can be small in terms of size, weight and power consumption. Signals must, however, overcome atmospheric turbulence and cloud cover is a limiting factor.

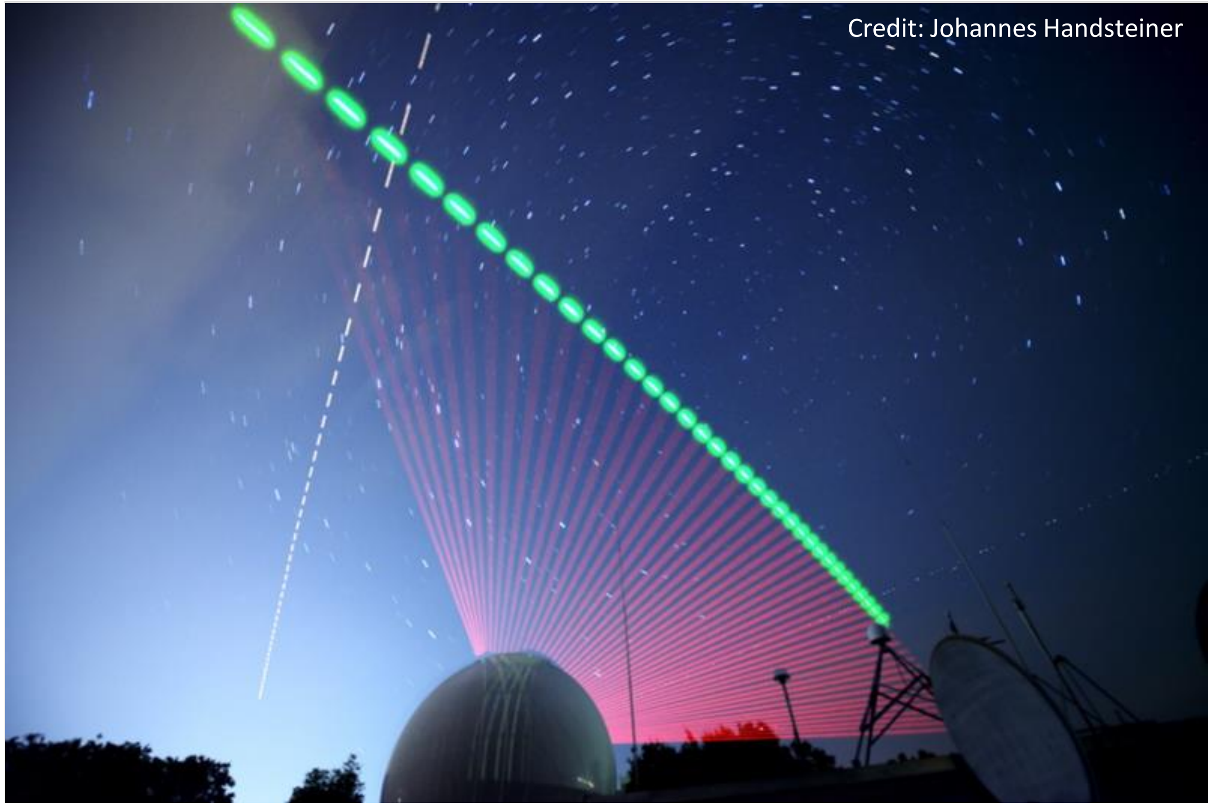

Credit: Johannes Handsteiner



LASER COMMUNICATIONS

The NICT SLR station in **Koganei**, Japan, conducted the first bidirectional optical communication demonstration to a the Japanese Optical Inter-orbit Communications Engineering Test Satellite (OICETS) in 2006,

The optical antenna on the satellite was pointed at the ground station and the downlink laser beam with a wavelength of 847 nm was positioned onto the station receiver. The uplink beacon was a continuous laser at 808 nm that enabled the satellite to locate its ground target. A second beam at 815 nm was the communications uplink.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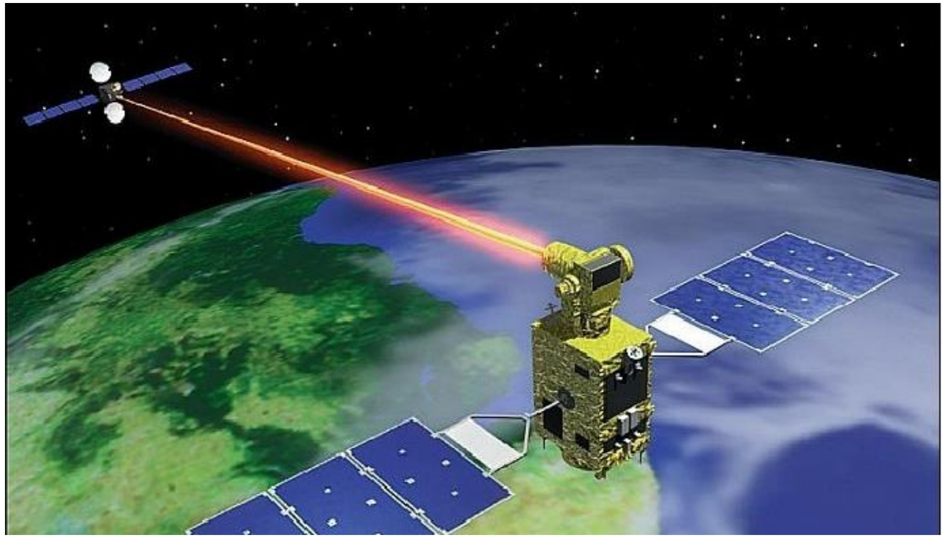
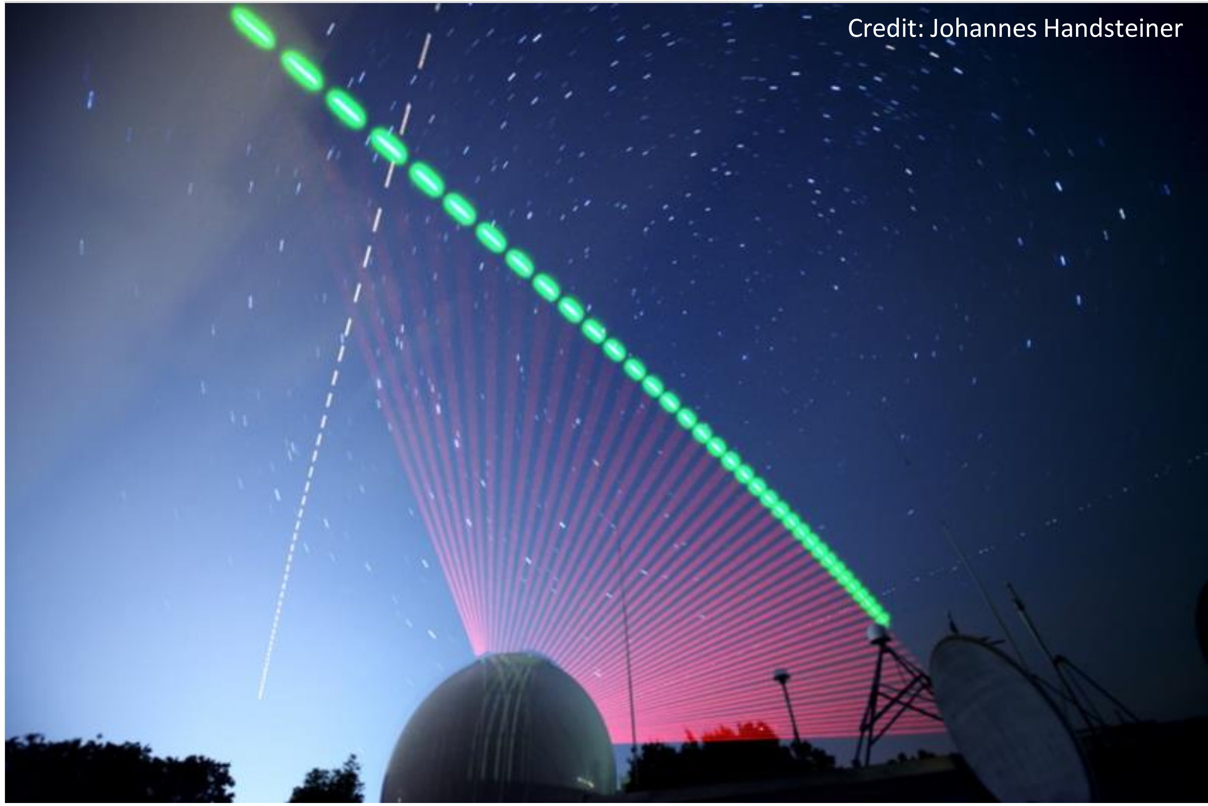


LASER COMMUNICATIONS

The LLR station in **Grasse**, France conducted free space optical communication experiments with the NICT SOTA (Small Optical TrAnsponder) instrument flying on the low-Earth orbit satellite SOCRATES. Several links at 10 Mbps were achieved at 1549 and 976 nm.

The **NGSLR** station at Goddard, USA sent an image of the Mona Lisa, to the Lunar Reconnaissance Orbiter at a rate of 300 bits/s.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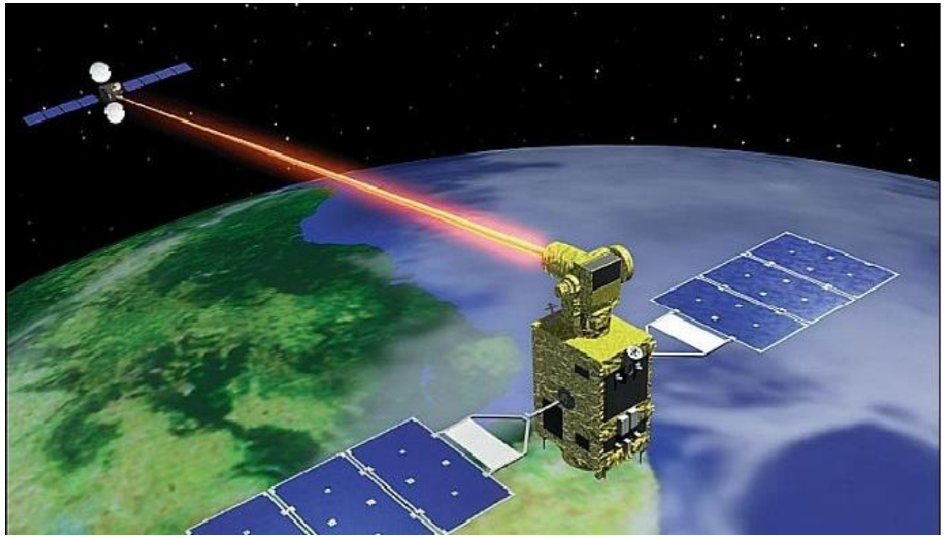
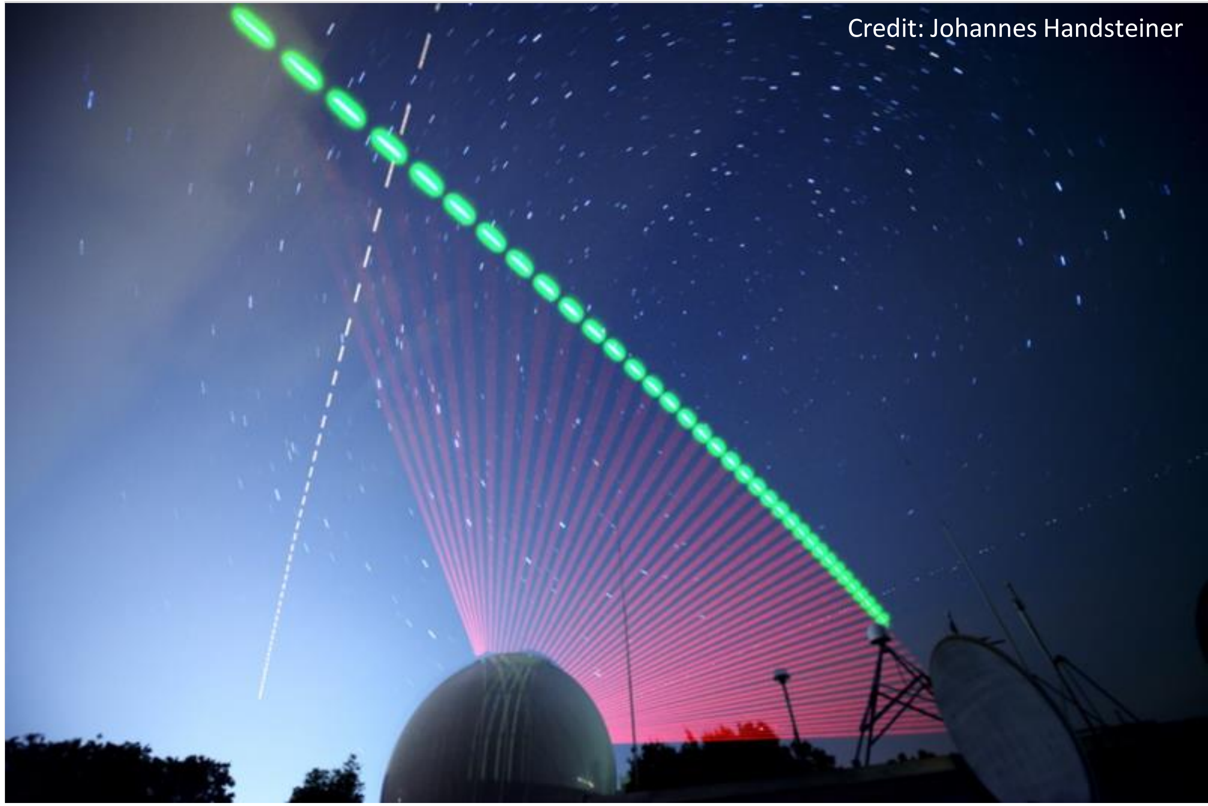


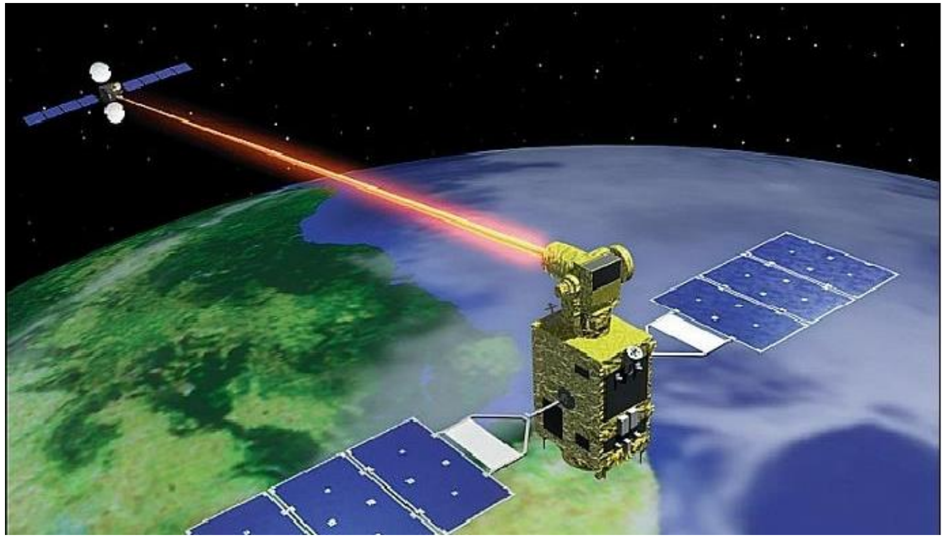
LASER COMMUNICATIONS

The **Matera**, Italy station transferred quantum information, or quantum keys, by laser link using low energy, high repetition rate qubit laser pulses during SLR tracking of low-Earth orbiting satellites.

NICT also confirmed quantum-limited communication characteristics using SOTA at the 1 m telescope in **Koganei**, Japan.

In 2017, quantum keys were created and transferred by the Chinese Micius satellite to stations in **Xinglon** and **Nanshan** in China and the **Graz** SLR station in Austria. The quantum keys were then used to transfer secure data over optical fibres.





CHALLENGES FOR THE NEXT GENERATION OF SLR STATIONS

Current limits to making further progress in laser ranging are challenging, but there would potentially be significant improvement to global SLR accuracy and productivity.

SYSTEMATIC BIAS

Systematic errors are likely to be present to varying degrees in the laser range measurements from every SLR station in the ILRS network.

The GGOS goal for a reference frame of 1 mm accuracy and 0.1 mm/year stability is demanding and so stations must continue to seek out and eliminate all potential systematic errors and particularly those indicated in analysis activities.

AUTOMATION

Automation could potentially bring improved productivity, efficiency and reliability and high standards of security and safety.

Automated SLR has been performed successfully at the **Zimmerwald** station in Switzerland and **Mt Stromlo**, Australia for some time

More recent systems, such as the German **SOS-W** in **Wettzell**, perform automatic tasks and the NASA **SGSLR** and the Russian **Tochka** are designed for full automation.

AUTOMATION

Mt Stromlo has shown that a station can operate around the clock and obtain useful data whenever there are breaks in sky cover, even in conditions that human operators would not consider worthwhile.

An unmanned, automated SLR station must be designed to meet in-sky laser safety requirements at all times, incorporating technologies such as radar, lidar, ADS-B receivers, and multiple wavelength camera systems.

TWO COLOUR SLR

One potential source of error relates to the path of the laser pulses through a highly variable atmosphere. The atmospheric delay can be modelled using local temperature, pressure and humidity readings.

Alternatively, by measuring the distance to the satellite target on two different optical frequencies simultaneously, this atmospheric correction can be obtained.

However, the range values of the two wavelengths have to be measured very accurately. Averaging over many shots with high repetition rate SLR would improve the resolution, but the correction also changes as the laser follows the satellite across the sky.

NEW TECHNOLOGY

An upgrade can advance SLR performance if it improves accuracy, precision, acquisition time, reliability, cost or safety.

Event timers have improved the accuracy and precision of SLR measurements at numerous ILRS stations. The **New Picosecond Event Timer** (NPET) achieves epoch recording with a precision of less than 700 fs using a transversal surface acoustic wave filter as a time interpolator.

NEW TECHNOLOGY

Atmospheric turbulence distorts and spreads laser beams. For example, the laser beam diameter from the MeO LLR station in **Grasse**, France can be between 2 and 10 km on the lunar surface. If there was no atmosphere, or its effects were compensated for by an adaptive optics system, this spot would be diffraction limited at approximately 200 m.

Adaptive optics systems sample light sources through the atmosphere to drive deformable mirrors at high speeds in order to correct for atmospheric wavefront distortions.

For SLR there are 2 ways to use adaptive optics systems, by correcting the downlink or the uplink.

NEW TECHNOLOGY

The **Stuttgart** station, operated by the German Aerospace Center (DLR), performs SLR in the near-infrared at 1060 nm using an InGaAs single-photon detector.

The lunar laser ranging station MeO in **Grasse**, France switched from 532nm green to 1064 nm near-infrared laser ranging in 2015. The IR LLR increased the station efficiency on all five lunar retro-reflector arrays and enabled detections on the three APOLLO targets during all lunar phases.

NEW TECHNOLOGY

Laser returns were successfully detected at the **Shanghai** , China SLR station using a superconducting nanowire, which offers an alternative single-photon detection technology from a wire of Niobium nitride.

The station in **Kunming**, China conducted SLR using a superconducting nanowire detector for the infrared.

NEW TECHNOLOGY

Existing telescopes can be modified to achieve SLR.

The need for a coudé path can be avoided either by using an optical fibre or by mounting a laser on to the telescope itself, as demonstrated by the Graz Single-Photon Detection, Alignment and Reference Tool (SP-DART) laser.

The SP-DART consists of a 1 ns, 15 μJ, 2 kHz, tilt-resistant laser, a control unit, an event timer, a GNSS time and frequency receiver and meteorological devices.

CONCLUDING REMARKS

In the future, SLR stations, and the ILRS network as a whole, will continue to be judged in terms of **productivity**, **accuracy** and **precision**.

Reducing both the time it takes for a SLR station to acquire a satellite and the time spent to achieve 1 mm precision is the key to maximising a station's capacity for SLR.

As automation takes hold, a station that is secure and has robust in-sky safety can operate continuously according to satellite availability and local weather conditions. Networks building automated stations for remote locations could strengthen the global network.

The network could also grow as a result of the lower cost and greater commercial availability of components for SLR.

CONCLUDING REMARKS

SLR stations currently set their schedules according to the ILRS geodetic, Earth observation and GNSS satellite targets passing overhead.

Included in these schedules could be:

- targets that detect the laser pulse and can conduct **time transfer** across continents.
- targets that also simultaneously perform **laser communications**.
- distant targets in the solar system that are carrying detector or **transponder** technology.

Based on the recent success in tracking **space debris**, SLR is no longer limited to targets carrying retro-reflectors, although these are required for more precise measurements.

Individual stations will continue to set their schedules to their own priorities and abilities.

CONCLUDING REMARKS

There is an enduring need for the accurate optical measurements obtained by laser ranging.

The contribution to the ITRF from laser ranging is unlikely to be replaced by other techniques and the independent validation of microwave derived orbits continues to be valuable.

But challenges in terms of individual station accuracy, the achievable precision from the global network and the increasing workload remain.

In response a **new generation** of SLR station is emerging to expand the network and continue the work towards meeting the demands for the highest accuracy.

THANK YOU

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