Section 2:

The Role of Laser Ranging

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Science from SLR

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In this section we review the science contributions of Satellite Laser Ranging (SLR) from 2016-2019. We discuss the highlights of results in different research areas from many papers that were published over this time. We have tried to synthesize the results, and provide a perspective on the most recent contributions of SLR to the terrestrial reference frame, altimeter satellite POD and the measurement of sea surface height, the measurement of mass change and time-variable gravity, GNSS, and the SLR contributions to fundamental physics.

ITRF2014

The leading science contribution of Satellite Laser Ranging (SLR) was its contribution to the different realizations of the International Terrestrial Reference Frame (ITRF) : ITRF2014 (Altamimi et al., 2016), DTRF2014 (Seitz et al., 2016 ; Bloßfeld et al., 2020), and JTRF2014 (Abbondanza et al., 2017). The SLR contribution was based on the processing of data from 1983 to 2014 (Luceri and Pavlis, 2017). Besides contribution of a time history of station positions, some from sites occupied since 1983, the SLR technique furnishes the origin of the TRF, and in combination with Very Long Baseline Interferometry (VLBI), the scale of the reference frame. The realizations of the Terrestrial Reference Frame (TRF) provide the fundamental reference for all geophysical observations of the Earth, particularly those pertaining to measurement of position, or the height of surfaces and how these positions and surfaces change with time.

The new ITRF solutions were evaluated for their performance on altimeter satellite precise orbit determination by Rudenko et al. (2017), Zelensky et al. (2018) and for their performance on SLR satellites by Rudenko et al. (2018). A general conclusion is that the impact on POD performance (measured via RMS of fit or RMS orbit differences) is smaller over the ITRF2008 data interval and larger over the ITRF2008 extrapolation period (2008-2014).

Improvements to ITRF2014

The SLR and GGOS analysis community worked intensively from 2016-2019 to improve the quality of the SLR technique and its contribution to the ITRF. The most significant result was presented by Appleby et al. (2016). The authors showed that station-dependent range errors from a variety of sources must be systematically accounted for in the weekly LAGEOS+LAGEOS-2 reference frame solutions. The authors showed that when this is done, the scale discrepancy between the SLR network and the VLBI network in ITRF2014 of about 1ppb is reduced by ~0.7 ppb. This led to detailed investigations by the ILRS Analysis Standing Committee (ASC) to systematically quantify the long-term biases on a station-by-station basis (Luceri et al., 2019). Finally, concomitant with these efforts, Rodríguez et al. (2019) developed improved Center-of-mass (CoM) corrections for the SLR geodetic satellites, derived from better modeling of the target response of these SLR targets. These improvements have been incorporated into the development of the SLR technique contribution to ITRF2020 and represent a major change from ITRF2014.

Another major improvement that will be incorporated into ITRF2020 will be the incorporation of time biases estimated from analysis of data to the Jason-2/Time Transfer by Laser Link (T2L2) experiment (Exertier et al., 2017). The T2L2 experiment showed that some stations exhibited time biases that changed with time, which for some stations reached up to several µsecs. The time biases were determined by using an orbiting clock (the DORIS Ultra-Stable Oscillator) to propagate time from a reference station (the Grasse SLR station equipped with a hydrogen maser) to the other ILRS stations that ranged to Jason-2. Ten years of these derived time bias corrections have been incorporated into the ILRS Data Handling File, which forms the basis of the data processing standards for analysis of SLR data to be included in ITRF2020 (*https://ilrs.dgfi.tum.de/fileadmin/data_handling/ILRS_Data_Handling_File.snx*). The challenge will be how to maintain time consistency with UTC for the SLR network, in the absence of an orbiting metrological reference, such as Jason-2/T2L2.

Visco and Lucchesi (2016; 2018) have worked to improve the modeling of the forces that perturb the orbits of LAGEOS, LAGEOS-2 and LARES spacecraft, with a focus on the thermal and magnetic forces. First, Visco and Lucchesi (2016) provide a critical review of the mass and moments of inertia for these satellites. The work clarifies inconsistencies and confusion that might exist in the literature regarding mass property information for the LAGEOS spacecraft. This mass property information is required in order to develop models of the evolution of the spin rate and spin axis orientation of the spacecraft. In the second paper, Visco and Lucchesi (2018) discuss the development of a new spin evolution model. While the author's motivation is to improve force modeling in order to obtain better measurements of the relativistic effects on the satellite orbits, the improved modeling could also benefit the estimation of geodetic parameters. Models of the spin axis orientation and spin rate enter into the calculations of these perturbative forces. So, in the future the work of these authors could be very useful for analysis of LAGEOS and LARES SLR data.

Hattori and Otsubo (2018) reached important conclusions concerning proper modeling of radiation forces on Ajisai. They showed that the solar radiation reflectivity coefficient, C_R, has a semiannual variation that can be attributed to the non-spherical cross-sectional area, and the low reflectivity of the surface material in the polar regions. They propose a model for analysts to use. It's important to note that Ajisai is a constituent in different solutions for the low-degree gravity field, so this effect, if unaccounted for, could alias into the time-variable gravity solutions.

In addition to the efforts to reduce systematic errors in SLR data, we note three papers that discussed simulations regarding emplacement of new stations, improvements in station performance due to better technology, and the importance of local ties.

Otsubo et al. (2016) simulated how new stations placed virtually around the globe would improve different geodetic parameters, including origin, scale, and the low degree terms of the gravity field. Based on their simulations, they find that, improvements of up to 20% are possible in the projected error for different parameters. Interestingly, stations on the Antarctic continent can reduce the error in the translation parameters, Tx and Ty, by up to 20%.

Kehm et al. (2018) in a different approach simulated improvements in performance of the current network, as well as the emplacement of up to eight SLR stations in new locations. A key point from their analysis is that the combination of increased performance (more observations) and better observation precision (improved data precision) can lead to significant improvements in the geodetic parameters. The authors find that the network performance improvement causes a decrease in the scatter of the network translation parameters of up to 24%, and up to 20% for the scale, whereas the technological improvement (improve in the quality of the observations) causes a reduction in the scatter of up to 27% for the translations and up to 49% for the scale. The results of these simulations reinforce the importance of modernizing the existing Legacy SLR network, and should encourage the operational and national agencies to pursue their efforts to update the technology of the existing stations.

Gläser et al. (2019) looked at the impact of injecting errors into site ties at key stations in a simulated GPS+SLR+VLBI TRF. The authors were able to identify which set of site ties by technique and by location had the most impact on the TRF. This study can be compared with the available library of site ties used for the ITRF (e.g., *http://itrf.ensg.ign.fr/local_surveys.php*), and inform decisions about where and when future local tie surveys can be conducted. The authors point out that the following SLR stations should have the best possible local tie standard deviations obtained from ground surveys: Fort Davis (McDonald Observatory), Monument Peak, Zimmerwald, Mount Stromlo, Graz, and Grasse.

Zajdel et al. (2019) looked at how to define the SLR datum for the reference frame. They found that some of the stations that are not included in the list of ILRS core sites could be taken into account as potential core stations in the TRF datum realization. They find that when using a robust station selection for the datum definition, the station coordinate repeatability can be improved by 4-8 % in the North, East and Up components

Altimeter Satellite Precise Orbit Determination

An important science contribution from SLR is in altimeter satellite precise orbit determination. In terms of tracking systems, the altimeter satellites fall into three categories: (1) the satellites using both SLR and DORIS: CryoSat-2, and SARAL. (2) the satellites that include SLR, DORIS, and GNSS: HY-2A, Jason-2, Jason-3, Sentinel-3A, Sentinel-3B, and (3) HY-2B, and ICESat-2 which use GNSS and SLR.

For CryoSat-2 and SARAL, the precise orbits are computed using a combination of SLR and DORIS data (e.g. Zelensky et al. (2016); Schrama (2018)). The CNES POD team uses the DORIS data as the primary data type but retains the SLR data as an external reference to evaluate precision and orbit stability (CNES, 2018). Since the altimeter orbit provides the reference for the science measurements, this means that the science results for these missions are directly traceable to the tracking data that have been used. SARAL is the first satellite to carry a Ka-Band altimeter, operating at 35.75 GHz (instead of 13.5 GHz for Jason-2). The Ka-Band altimeter provides a smaller footprint, better vertical resolution, and higher along-track sampling. The altimeter provided better observations of sea surface height over the oceans, better altimeter observations along the coasts and improved sampling of inland waters (lakes and rivers) (Verron et al., 2018). The CryoSat-2 mission has continued to gather data to support its main scientific goals: (1) to determine the regional and basin-scale trends in Arctic sea-ice thickness and mass; and (2) to determine the regional and total contributions to global sea level of the Antarctic and Greenland ice sheet (Parrinello et al., 2018). The CryoSat-2 altimeter also supplies data for oceanography and hydrology studies at global and regional scales (c.f. Bouffard et al., 2018).

SLR tracking, in combination with GNSS and DORIS has allowed the Jason-2 and Jason-3 satellites to continue the acquisition of altimeter data from the TOPEX reference ground track. The cumulative data from this series satellites (TOPEX through Jason-3) allows for the study of changes in the oceans along the same geodetic reference for up to 28 years. We can use ISI/Web of Science to gauge the scientific impact of these missions. According to ISI/Web of Science, from 2016 to 2019, 319 scientific papers were published that use Jason-2 and Jason-3 altimeter data. The most noteworthy products of these missions are the routinely updated estimate of the change in Global Mean Sea Level (GMSL) (Beckley et al., 2016), and the estimates of the acceleration in sea level rise (e.g., Nerem et al., 2018). The measurement of sea surface height to determine the change in GMSL is considered so societally important that the Ocean Surface Topography Science Team (OSTST) of the Jason-2+3 missions have determined that the missions need three independent means to track the spacecraft, which provide data at comparable levels of precision (OSTST, 2018). Only by intercomparing the GNSS vs. the SLR+DORIS orbits and showing that they agree at 6-8 mm radial RMS, and that the orbit comparisons are stable in time can we have confidence in the stability of the orbit reference for these missions and in the reliability of the measurement of sea level change.

The Sentinel-3A and Sentinel-3B missions were launched on February 16, 2016 and April 25, 2018 respectively. These missions carry multiple ocean-observing instruments, including a radar altimeter. The Sentinel satellites are sponsored jointly by the European Commission (EC) and the European Space Agency (ESA) under the aegis of the Copernicus program. For the radar altimeter, the objective is to collect altimeter data over the oceans (including coastal zones), rivers and lakes, and ice sheets (ESA, 2012). The satellites operate in high-inclination, sun-synchronous orbits, providing complementary spatial and temporal sampling to other altimeter satellite missions. The objective of the Copernicus program is to launch a series of missions for long-term environment monitoring (over more than 10 years). The requirement is for the orbits to be known at 1 cm radial RMS accuracy (Fernández et al., 2016). The POD requirement is met by using DORIS and GNSS as the primary tracking systems and using SLR data from a set of core stations of the ILRS to verify orbit performance and to rigorously intercompare the orbits produced by different analysis centers using different types of tracking data (Fernández et al., 2019).

The Haiyang-2 series of satellites (Haiyang, meaning ocean in Chinese), HY-2A, and HY-2B were launched on Aug. 16, 2011, and Oct. 25, 2018. The first SLR tracking data were acquired on Oct. 2, 2011 and Nov. 2, 2018 respectively. The satellites carry a DORIS and GNSS receiver in the case of HY-2A, and a GNSS receiver in the case of HY-2B. One of the payloads is a dual-frequency altimeter. The objective of the missions is to observe the oceans with various instruments and map the sea surface height. The spacecraft orbit the Earth at 971 and 973 km altitude from a 99.3 deg. inclination, sun-synchronous orbit. The orbit repeat periods used were 14-days during the mapping mission phase and 168-days during the geodetic mission phase. The HY-2A altimeter data are incorporated into the 25-year multi-mission sea level anomaly grids produced by the Data Unification and Altimeter Combination System (DUACS) in Toulouse, France. These multi-mission sea surface anomaly grids are distributed through the Copernicus Marine Environment Monitoring Service (CMEMS) (Taburet et al., 2019).

Time-Variable Gravity and Mass Change

It has been known for nearly 40 years that satellite laser ranging measurements of Earth orbiting satellites are sensitive to the time-variable gravity field of the Earth (e.g. Yoder et al., 1983, Guiterrez and Wilson, 1987). Over time researchers have used more satellites and better modeling to extract more time-variable coefficients and derive longer time series of data. Lemoine JM and Reinquin (2017), Cheng and Ries (2018), Meyer et al. (2019) provide recent examples of solutions obtained with SLR data alone or in combination with other data (either DORIS data from LEO satellites or GPS data from the Swarm satellites) where time series of low degree harmonics have been obtained. Using only the suite of SLR satellites, it is generally only possible to meaningfully resolve coefficients to about degree and order five on a biweekly or a monthly basis. Still the SLR-derived solutions can be used to resolve mass variations over Greenland, extending the time series of mass change to the early 1990’s as shown by Talpe et al. (2017) and earlier by Matsuo et al. (2013).

An important application for SLR is by the GRACE and GRACE Follow-On missions. Since the start of the GRACE mission, the SLR-derived values are substituted for the GRACE values in the monthly solutions of each analysis center (e.g. see Loomis et al., 2019). The GRACE-derived values of C_{20} contain a non-geophysical signal arising possibly from a temperature-dependent error in the accelerometer data (Cheng and Ries, 2017). For the size of the anomalous C_{20} signal, look at Figure 1 of Cheng and Ries (2017). A time series of low-degree harmonics is derived using the exact same background modeling as that used by the GRACE solutions, and the SLR-derived values are substituted into the monthly GRACE solutions produced by the different GRACE analysis centers (University of Texas/CSR, GFZ, and JPL) (Cheng and Ries, 2018, Loomis et al., 2019). Whereas the K Band Range-rate data can resolve mass change down to spatial scales of a few hundred km, it is essential to model properly the broad mass-change signal associated with the oblateness term, C_{20}. Without the contribution of SLR, the mass change in Greenland from GRACE could not be properly resolved.

The GRACE satellites had a long operational lifetime, from launch in 2002 to the official end of the science mission in June 2017. However, due to degradation of the batteries, active thermal control was ended in April 2011. This meant two things: (1) that every 161 days (one solar beta-prime cycle) the K Band ranging instruments were shut off for 30-50 days; (2) the accelerometers were subject to temperature variations that complicated the analysis of the data (Klinger and Mayer-Gürr, 2016). After 2011 there were increasing gaps in the mission data products. Depending on how conservative a user feels regarding the GRACE mission data in this period, there is a gap of 2-4 years in the GRACE data products from 2014 to the launch of GRACE Follow-On in May 2018. The SLR data to the geodetic and other satellites provide a tool to “bridge the gap” in mass measurements between the missions of GRACE and GRACE Follow-On, both in SLR solutions alone, and in combination with other data such as the GNSS-kinematic orbits from the Swarm constellation (e.g. Meyer et al., 2019).

The GRACE Follow-On mission brought its own set of challenges. It emerged that one of the accelerometers on the GRACE-FO spacecraft produced spurious data. So the mission decided to use a method to “transplant” the accelerometer data from one GRACE-FO spacecraft to another (Bandikova et al., 2019). This approach seemed successful, however it became apparent that on GRACE FO both the C_{20} and C_{30} terms from the GRACE gravity solutions need to be replaced with the SLR-derived values. NASA GSFC provides a replacement product designated “GRACE Technical Note 14” based on processing to the SLR geodetic satellites (*https://podaac.jpl.nasa.gov/gravity/grace-documentation*).

The C_{30} coefficient has a large impact on the measurement of mass change in Antarctica. Fortuitously, (Loomis et al., 2020) point out that LARES being a member of the SLR geodetic satellite constellation is important for being able to reliably determine the C_{30} gravity harmonic from SLR data. The SLR-derived replacement values of C_{20} and C_{30} are also used for periods near the end of the GRACE mission when the twin spacecraft had only one functional accelerometer. In conclusion, the SLR data to the geodetic satellites are a vital part of the current system to measure mass change in the Earth system, and have helped both the GRACE mission and the GRACE FO mission to meet their prime mission requirements.

Geocenter

The geocenter is used to describe the orbital center of motion for all orbiting satellites. Geocenter motion represents the motion of the center of mass of the Earth with respect to its center of figure. Geocenter motion originates due to mass transport in the Earth system, e.g. processes involving atmospheric circulation, ocean mass transport and the hydrological cycle. Processes within the solid earth such as glacial isostatic adjustment (GIA) can also contribute. The geocenter motion or the degree 1 component of mass transport is not observable from a mission such as GRACE. Geophysical models predict the magnitude of geocenter motion on an annual scale to be 2-3 mm in X and Y and 4-5 mm in the Z direction. 1 mm of geocenter motion in X, Y, Z represents -0.5 mm, -0.26 mm and -0.62 mm of mean water thickness, respectively, over the oceans. Given that the present linear global change in mean sea level is presently about 3.3 mm/yr, failure to account for the degree 1 component of mass change would mean that scientists could not isolate properly the causes of sea level rise or close the sea level budget, without accounting for the degree one component of mass change. An error of 1 mm of geocenter motion in Z also represents about 69 gigatons of mass change in Antarctica, which is a sizeable fraction of the total amount of the current annual Antarctic mass loss of about 250 gigatons/yr (Wu et al., 2012, see Table 2-1; Rignot et al., 2019).

Different techniques can be used to infer geocenter motion on the temporal scales needed for mass change studies (see Wu et al., 2017 for an extended discussion). Presently the SLR technique can supply robustly geocenter solutions on an annual basis (e.g. see Ries et al., 2016, Riddell et al., 2017) based on LAGEOS and LAGEOS-2 data, although there are issues comparing the SLR-based solutions to other techniques because they are center-of-network and not center-of-figure. The LAGEOS-based geocenter solutions can possibly be improved by also using SLR data to other satellites such as GNSS or to LEO satellites, such as Sentinel-3 (Sośnica et al., 2019; Strugarek et al., 2019), or using the approach developed in JTRF2014 (Abbondanza et al., 2017). We should note that other satellite techniques can supply solutions for geocenter, either from DORIS or from GNSS (Männel and Rothacher, 2017; Couhert et al., 2018; Kang et al., 2019). Significant improvements to geocenter estimation using SLR data require reduction in the systematic errors (e.g. in biases or range delays at the stations and in modelling of target response at the satellite (Luceri et al. (2019); Rodríguez et al. (2019)), the deployment of new SLR systems, and a more balanced global network. Thus, the knowledge of geocenter in addition to being the foundation of the Terrestrial Reference Frame (TRF), is vital for monitoring of global mass change.

GNSS and SLR

GNSS realizes the Terrestrial Reference Frame (TRF) for users with a wide variety of civil and scientific applications. SLR has a direct connection to GNSS through the SLR retroreflectors on the satellites of the GNSS constellations (currently Beidou, Galileo, GLONASS, IRNSS and QZSS). Presently the ILRS tracking roster (*https://ilrs.gsfc.nasa.gov/missions/satellite_missions/current_missions/index.html*) includes 9 Beidou satellites, 28 Galileo satellites, 23 GLONASS satellites, 7 IRNSS satellites and 4 QZSS satellites. The SLR retroreflectors and the tracking provided by the ILRS provide a direct connection between the SLR and GNSS techniques which may be exploited for the possibility of colocation in space through combined processing of both observables for contribution to the ITRF (e.g. Thaller et al., 2015) or improvement in the strength and content of the SLR reference frame by improving station positioning and LOD (Length of Day) (e.g. Sośnica et al., 2018).

We discuss first the direct benefits of SLR tracking to the GNSS constellations, and then briefly review the role of SLR with GNSS orbit determination for LEO satellites. There has been an abundance of papers in the literature on these topics from 2016-2019, and those we cite below are meant only to provide examples of applications, not to cite an exhaustive list. A recurrent theme in many of the papers is the SLR validation of ambiguity-fixed GNSS orbits. Fixing ambiguities in GNSS precise orbit determination is an important advance in GNSS processing. The methodology of finding how to fix (i.e. to resolve) the majority of GNSS ambiguity biases in the analysis of GNSS data provides a way to improve GNSS orbit determination, by converting ambiguous ranges to non-ambiguous satellite ranges. A second major theme in the GNSS use of SLR data is the validation of improvements to solar radiation pressure modelling for satellites of the different GNSS constellations. A third theme concerns validation of new GNSS antenna offset coordinates or coordinates of the center-of-mass in the spacecraft frame. Ambiguities or errors in the definition of tracking point offsets or the center of mass can occur because of miscommunications, or errors in measurement of the reference points. They can be hard to sort out or confirm without simultaneously processing additional data for example SLR data to the GNSS satellites.

Orbit Validation

SLR data to GNSS satellites have been used to characterize different aspects of GNSS orbit determination performance: (1) to provide quality assessments for different types of IGS orbit products; (2) to characterize the relative performance of the different GNSS constellations; (3) to learn how different attitude modes or eclipse regimes might affect orbit quality; (4) to test implementation of ambiguity fixing in GNSS satellite POD. Examples of some papers that present these orbit validation results are listed in Table 2-1.

Table 2-1: Examples of SLR validation of GNSS orbit products (2016-2019)

Reference	Comment
Zajdel et al. (2017)	Online tool for validation of Multi-GNSS orbits.
Guo et al. (2017)	Analysis of orbit quality for 7 IGS Analysis Centers participating in the MGEX experiment (2012-2015).
Kazimierski et al. (2018)	Evaluation of real-time orbit products for multi-GNSS orbits.
Yang et al. (2019)	Analysis of Beidou orbits as part of the MGEX performance, including assessments by satellite, attitude mode and analysis center.
Katsigianni et al. (2019)	Validation of a technique to calculate Galileo satellite orbits with ambiguity fixing.

Improvement of Solar Radiation Pressure (SRP) Models

Rebischung et al. (2016) showed that the GNSS contribution for ITRF2014 contained the (solar) draconitic signal and its sub-harmonics are present in the geodetic products. For many years now, there have been efforts to improve the radiation pressure modeling for GNSS satellites. The large Area-to-mass ratios of the spacecraft (with the solar arrays) mean that radiation pressure has a big effect on the orbits. SLR data can be used directly to evaluate if the and to what extent the SRP models are improved. The approach can be to estimate parameters of a “box-wing” model, to test an improved empirical model such as ECOM2, or test an SRP model that has been developed using techniques that involve ray tracing. Some examples of the work done from 2016-2019 in this area are listed below:

Table 2-2: Examples of SLR Validation for GNSS SRP Models (2016-2019)

Reference	Comment
Rajaiah et al. (2017)	SRP Model for IRNSS satellites.
Darugna et al. (2018)	Test improved SRP model developed via ray-tracing for QZS-1
Bury et al. (2019)	Estimation of a box-wing (macro-)model for the Galileo satellites.
Duan et al. (2019)	Estimate macromodel (box-wing)-related parameters for Galileo, Beidou 2-3, QZS1-2.

Monitoring and Estimation of GNSS Offsets

Knowing the location of an antenna phase center in the spacecraft coordinate system and with respect to the satellite center of mass is an essential aspect of precise measurement modeling. For the GNSS satellites, new Phase Center offsets (PCOs) can be estimated, but then the question arises how one can verify the new estimates. SLR data as an independent measurement in this respect are a key method of evaluation as shown by Steigenberger et al (2016) for Galileo. In another example, Dach et al. (2019) were motivated to estimate new antenna offsets for some of the GLONASS satellites after noting a dramatic increase in SLR residuals. The estimated changes in the offsets were 5-15 cm. The authors attribute one possible explanation for the “sudden changes” in antenna offsets as a failure of a portion of the GNSS transmitter on the satellites. The true cause, however, remains unknown. Incidents of this point to the value of a continual monitoring of all the satellites in the GNSS constellations by SLR in order to spot these sorts of anomalies.

Antenna Thrust Impact on GNSS Orbits

The transmission of GNSS signals causes a radial “recoil” force on the satellite orbits that depends on the transmit power and the satellite mass. Steigenberger et al. (2018) found that the orbit radius could be reduced by -1 to -27 mm by the antenna thrust. The authors found it was difficult to verify with SLR data whether the model antenna thrust improved the SLR residuals, primarily because the effect might be masked by other sources of error, such as in radiation pressure modeling. Steigenberger et al. (2019) provide an update of the GPS and GLONASS satellite transmit power values from Steigenberger et al. (2018) as a basis for the 3rd reprocessing campaign of the International GNSS Service (IGS).

Validation of GNSS Orbit Determination for LEO Satellites

We have already discussed some aspects of GNSS orbit determination for altimeter satellites. Some other examples include:

1. Montenbruck et al. (2018a) who review kinematic GNSS and reduced-dynamic GNSS orbit determination for the Swarm satellites. The SLR data validate the implementation of ambiguity fixing for the kinematic orbits, where the standard deviation of the SLR residuals are reduced from 19.5-23.0 cm to 9.4-10.5 cm for the new orbits that they have calculated.
2. Hackel et al. (2018) who derive improved orbits for TerraSAR-X and TanDEM-X where the main improvements were application of a macromodel and use of ambiguity fixing. They obtain standard deviations in the SLR residuals of 11.4 and 12.5 mm respectively, an improvement of 33% over the earlier generation of precise orbits that had been made available.
3. Montenbruck et al. (2018b) who derive improved orbits for Sentinel-3A using ambiguity fixing. A novel result from their paper is that the new ambiguity fixed orbits reveal a potential 10 mm error in the cross-track location of the center-of-mass on the spacecraft. The SLR data confirm the improvements with the new orbits and also the sense of the error in the satellite center-of-mass.

Arnold et al. (2018) present an extensive general review of GNSS orbit determination for LEO satellites. It’s worth reviewing some important conclusions from their paper which can perhaps encourage and inform improvements in SLR data quality and the deployment of new technologies to enable more precise (mm-level) SLR tracking of LEO targets.

1. SLR is a powerful tool for orbit validation.
2. To achieve the highest available orbit accuracy, models of the LRA range correction as a function of directional angles need to be applied. It is not adequate to apply a simple average value of the correction, as shown by Figure 3 in the Arnold et al. (2018) paper.
3. The SLR residuals to the GNSS orbits can be analyzed to estimate both range bias and station coordinate corrections to the a priori (SLRF2014) coordinate set. This analysis provides a method to provide quality control of station performance, and also to improve station coordinate estimation if LEO satellite SLR data from GNSS-track satellites can be incorporated into the SLR reference frame computation.
4. Since the GNSS orbits operationally achieve radial orbit accuracies of order 10 mm radial RMS, only a subset (12-15 stations) of the ILRS stations can provide fully useful information for GNSS POD orbit validation.
5. The technique of analyzing GNSS LEO satellite SLR residuals can also reveal large (µsec) level timing biases, which Arnold et al. (2018) show for Papeete (MOBLAS-8) for two epochs in 2016. This result demonstrates that processing of SLR residuals to GNSS precise orbits can identify large timing biases for SLR stations. The result also underscores the importance of SLR stations closely monitoring their equipment to make sure that they are coherent with UTC to within the prescribed ILRS requirements (+/- 100 ns).

In summary, SLR data provide a powerful tool for validation of the quality and accuracy of GNSS orbits computed for LEO satellites. This is quite an achievement, for many of these targets (e.g. Swarm, GRACE, TerraSAR-X and TanDEM-X) are at low altitudes and have very short passes. Tracking is only possible because the missions have routinely delivered accurate and timely (CPF) predictions for the stations. Nonetheless, to continue to advance, it is essential that the SLR technique continue to reduce systematic sources of error (e.g. range and timing biases). It is also essential that the ILRS community continue to deploy new SLR systems that enable mm-level satellite tracking.

Using SLR to Improve Models of GNSS Satellite Attitude

Steindorfer et al. (2019) discuss a ground and on-orbit test of ranging to a Galileo retroreflector array. The test, which was carried out with the kHz station at Graz (Austria), demonstrated it was possible to measure the orientation of the retroreflector array, and hence the orientation of the satellite, to an accuracy of 0.1° for specific station-satellite geometries. GNSS satellites mostly follow a yaw-steering algorithm, but this does depend on the satellite constellation (see Montenbruck et al., 2015). Special treatment of satellite attitude (e.g. for GLONASS, GPS and Galileo) is required during eclipse seasons and modeling the “noon” and “midnight” turns. So, this experiment demonstrates that with careful planning, campaigns of SLR measurements from kHz stations to GNSS satellites could be of tremendous value to the GNSS and geodetic community. Precise modeling of satellite orientation is required to model properly both the GNSS measurements in data analysis and to calculate properly the radiation pressure perturbations. What is not discussed in the paper, is whether solar array orientation could also be measured using kHz ranging. For the calculation of solar radiation pressure, misorienting a solar array even by a few degrees on a typical box-wing satellite (e.g. GNSS or Jason-2) can cause errors in the orbits and the geodetic products at the satellite draconitic period.

Thermospheric Mass Density

Atmospheric drag is the largest force acting on satellite orbits at low altitude. Atmospheric density at the spacecraft altitude strongly determines the magnitude of the drag force. The atmospheric density, itself varies with satellite altitude, latitude, solar time, and timing within the solar cycle. Solar indices and geomagnetic indexes are also drivers of atmospheric density (Emmert, 2015). The primary data for models of atmospheric density are : (1) density observations derived from satellite missions with precision accelerometers such as CHAMP, GRACE, and Swarm, (2) neutral mass spectrometer data ; and (3) satellite orbital ephemerides (Emmert, 2015). SLR data to geodetic satellites can sometimes be used as primary data to determine satellite orbits and then infer atmospheric density (e.g. Jeon et al., 2011), or as a tool to evaluate thermosphere density model performance (Warner and Lemm, 2016).

The geodetic or spherical satellites at low altitude are attractive targets for testing of thermosphere density models. Their spherical shape means the modeling of the nonconservative forces is simplified, compared to satellites with a complicated shape. Panzetta et al. (2018) used SLR data to the “Atmospheric Neutral Density Experiment-Pollux” (ANDE-P), developed by the Naval Research Laboratory, at 350 km altitude to evaluate four different atmospheric density models: CIRA86, NRLMSISE00, JB2008 and DTM2013. The SLR data were used to “calibrate” or adjust scale factors to the different models. Xiong et al. (2018) used SLR data to ANDE-Pollux to evaluate scale factors on another atmospheric density model, CH-Therm-2018, derived from CHAMP accelerometer measurements. In an interesting experiment with Starlette and Stella, but not using SLR data, Petit and Lemaître (2016) looked at the long-term evolution of the orbits of these satellites (1980-2012 for Starlette; 1994-2012 for Stella) determined from TLEs (two-line-elements) and compared the performance of three density models: DTM-2013, JB2008, and TD88. They were interested in how well each model “replicated” the observed satellite change in semimajor axis over several decades. Thus, SLR data and geodetic satellites are generally not a primary data source for derivation of thermospheric density models, but they play a useful role in thermospheric density model development.

Fundamental Physics

From 2016-2019, SLR also contributed to experiments that verified fundamental laws of physics, including the weak equivalence principle (Ciufoliini et al., 2019a), the Lense Thirring effect (Ciufolini et al., 2016; Lucchesi et al., 2019; Ciufolini et al., 2019b) and the measurement of the gravitational red shift (Delva et al., 2019).

The equivalence principle was first formulated by Galileo Galilei. In the context of general relativity, it means that two bodies with the same initial conditions follow the same geodesic of space time. Projected onto a spatial plane it would mean the test particles should follow the same ellipses (e.g. orbits). Tests are needed with objects with different mass properties over different distance scales to verify universality. The analysis of Ciufolini et al. (2019a) verified the weak equivalence principle to $2.0\ x\ 10^{-10} \pm 1.1\ x\ 10^{-9}$ over a range of 7890 to 12220 km using different materials (aluminum and brass for LAGEOS and LAGEOS-2, and sintered tungsten for LARES).

Einstein's General Theory of Relativity predicts that the orbital plane of a satellite is dragged by the rotation of massive body such as the Earth. J. Lense and H. Thirring derived the equations in 1918 (Lense and Thirring, 2018). We summarize the determinations from 2016-2019 in Table 2-1. The Lense-Thirring effect produces a precession of the node of 30.68 mas/yr for LAGEOS, 31.50 mas/yr for LAGEOS-2 and 118.50 mas/yr for LARES. The two most recent results verify the predictions of the Lense-Thirring effect to within two percent.

Table 2-3: Summary of Recent Tests (2016-2019) using SLR data to verify the Lense-Thirring effect.

Reference	Satellites used	Data Span	Results
Ciufolini et al. (2016)	LAGEOS, LAGEOS-2, LARES	~3.5 yrs	$\mu = 0.994 \pm 0.05$
Lucchesi et al. (2019)	LAGEOS, LAGEOS-2, LARES	L1,L2: ~25 yrs; LA: ~5.8 yrs	$\mu = 0.994 \pm 0.005$
Ciufolini et al. (2019b)	LAGEOS, LAGEOS-2, LARES	L1,L2: ~26 yrs; LA: ~7 yrs.	$\mu = 0.991 \pm 0.02$

The gravitational red shift refers to a consequence of Einstein's Theory of Relativity where clocks deeper in a gravitational field run slower than clocks further away. An opportunity arose to do a space test with two Galileo satellites (Galileo-201 and Galileo-202) that were accidentally launched into highly eccentric orbits. An elliptic orbit induces a periodic modulation of the relative frequency difference between a ground clock and the satellite clock. Using the accurate clocks (hydrogen masers) on these Galileo satellites for this "Galileo gravitational Redshift test with Eccentric sATellites" (GREAT) experiment (see *https://ilrs.gsfc.nasa.gov/missions/GREAT_exp.html* as well as Section 6 of this document), Delva et al. (2019) analyzed several years of Galileo tracking data, and were able to verify the relativistic predictions, and improve on the prior test done in 1976 with Gravity Probe A by a factor of 5.6, the first significant improvement in forty years. The SLR data played an essential role by helping to calibrate the radial orbit error for the GREAT experiment.

Science from LLR

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In 2019, Lunar Laser Ranging (LLR) celebrated its 50th anniversary. It continues the legacy of the Apollo period still enabling great science (Crease, 2019). In this section we briefly review the science contributions of LLR from 2016-2019, where normally always the full 50-year LLR dataset is analyzed. LLR has shown its strong capability to put Einstein's relativity theory to the test. In addition, lunar science and many quantities of the Earth-Moon dynamics could be studied, see Müller et al. (2019) for an overview.

Tests of General Relativity

The Earth-Moon system provides a unique laboratory to test General Relativity in the solar system. In the past years, LLR could strongly contribute to improve the limits for a number of relativistic parameters. Current improvements include, e.g., tests of the violation of Lorentz symmetry parameterized under the standard-model extension (SME) field theory framework (Bourgoin et al., 2016; Bourgoin et al., 2017). LLR analyses also provide constraints on the parametrized post-Newtonian (PPN) parameters (β and γ), and the geodetic precession of the lunar orbit (Hofmann and Müller, 2018). LLR puts the universality of free-fall to test (Viswanathan et al., 2018; Hofmann and Müller, 2018) and it was even used for recent tests of the equivalence principle for galaxy's dark matter (Zhang et al., 2020). Furthermore, LLR limits for the temporal variation of the gravitational constant (Hofmann and Müller, 2018) were used to further constrain some nominimally coupled dark energy and standard sirens (Tsujikawa, 2019). Summarizing, LLR analyses did not find any hints for a deviation from Einstein's theory of general relativity, but confirmed its validity impressively.

Lunar Science and Earth-Moon Dynamics

One further important part of LLR analyses comprises investigations of the physical properties and the interior of the Moon which can be studied via lunar tides, physical librations and the orbit (Williams and Boggs, 2015; Hofmann et al., 2018; Petrova et al., 2018; Viswanathan et al., 2019).

Discrepancies between LLR and GRAIL-derived results (Williams and Boggs, 2014; Williams et al., 2016) include, for example, elasticity parameters (Love numbers) and the degree-3 gravitational field, which leads room for further improvement, especially in the modelling of dissipation and further properties of the lunar interior.

Knowledge of the lunar fluid core's polar oblateness from LLR allows the estimation of the radius of the lunar core-mantle boundary and the lunar free-core nutation. It also helps to assess the hydrostatic nature at those depths (Viswanathan et al., 2019).

LLR analysis provides displacement Love numbers h_2 and l_2, the fluid-core/solid-mantle boundary (CMB) dissipation, and moment of inertia differences. Improved estimations of these parameters help constraining the long-term evolution of the Earth-Moon system (Williams and Boggs, 2016).

The tie between the ephemeris frame and ICRF, calculated from spacecraft VLBI (ΔDOR) data, is confirmed using the latest LLR data with an accuracy of 0.18 mas (3σ). LLR is potentially capable of tying the Earth–Moon system to ICRF (and hence, the whole ephemeris frame to ICRF) with an accuracy comparable to that of the ΔDOR-based tie (Pavlov, 2019).

Independent planetary and lunar ephemerides were generated using 50 years of LLR data at various institutions. Recent ephemeris versions are provided by Institut de mécanique céleste et de calcul des éphémérides (IMCCE) - INPOP19a (Fienga, 2019), by Jet Propulsion Laboratory (JPL) - DE430/431 (Folkner et al., 2014) and by Russian Academy of Sciences' (RAS) Institute of Applied Astronomy (IAA) - EMP2017 (Pitjeva and Pitjev, 2014; Pavlov et al., 2016). Model differences between independent solutions remain, but all solutions fit the past two decades of LLR data at the 1-2 cm (rms in one-way range) level.

Earth Rotation and Station Coordinates

LLR-based Earth orientation parameter (EOP) results contribute to combined EOP solutions, e.g., using JPL's Kalman Earth orientation filter (Ratcliff and Gross, 2018). Such combined solutions show a better fit to older LLR data than the IERS C04 series (Pavlov et al., 2016).

LLR also contributes to monitoring long-term variations of EOP (i.e., precession and nutation as well as Earth rotation and polar motion). For example, precession rate and nutation coefficients of different periods (18.6 and 9.3 years, 1 year, 182.6 and 13.6 days) have been determined and analyzed with respect to the values of the MHB2000 model of Mathews et al. (2002). Hofmann et al. (2018) obtained discrepancies to that nutation model of up to 1.46 mas.

Investigations on secular tidal changes in the lunar orbit and Earth rotation with larger data sets show improvements compared to older research (Williams and Boggs, 2016).

The coordinates of the ground observatories can be estimated with an accuracy between 0.4 and 3.6 cm and the velocities between 0.2 and 1.9 mm/yr. The comparison of the network geometry with the ITRF2014 reference solution shows 3-dimensional differences of up to 5 cm (Hofmann et al. 2018).

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