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Information resources supporting scientific research for the international laser ranging service

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Abstract

The International Laser Ranging Service (ILRS) through its permanent components (Tracking Stations, Operations Centers, Data Centers, Analysis Centers, Central Bureau, and Governing Board) distributes satellite and lunar laser ranging data and derived products to support global, multidisciplinary scientific research. The ILRS Data Centers and Central Bureau serve as the primary source for information, data, and products for this global user community. The ILRS website, <https://ilrs.gsfc.nasa.gov>, is a key tool for communication for the service, providing background information on the ILRS, its organization and operation, and detailed descriptions of ILRS components, data, and products. Links are provided to extensive information on the supported satellite missions and ILRS network stations including performance assessments and data quality evaluations. Furthermore, the website connects users to archives of laser ranging data and derived products available through the data centers. In this paper, we discuss the development of the ILRS infrastructure, its current status, website resources, description of laser ranging data and products, and plans for future enhancements.

Keywords

Laser ranging; ILRS; IAG; Space geodesy; GGOS; Reference frames; Tracking networks; Precise orbit determination; Earth orientation parameters

1 Introduction

The International Laser Ranging Service (ILRS) collects, archives, and distributes Satellite Laser Ranging (SLR), Lunar Laser Ranging (LLR), and transponder observations to a global

science community to support diverse scientific, engineering, and experimental studies as well as various operational applications (Pearlman et al. 2018). The ILRS promotes scientific research in geodesy, geophysics, and other areas contributing to the maintenance of a terrestrial reference frame, critical to monitoring global change. The ILRS Analysis Centers, as well as the user community in general, utilize ILRS datasets to advance research and produce a suite of derived operational products for the ILRS and global scientific missions. The ILRS is one of the space geodesy services established by the International Association of Geodesy (IAG) in the 1990's and is a key contributor to the IAG's Global Geodetic Observing System (GGOS). In addition, the ILRS is now a network member of the International Council for Science (ICSU) World Data System (WDS). The ILRS website, <https://ilrs.gsfc.nasa.gov>, is a fundamental resource for providing information about the service to the global user community as well as a communication tool for the ILRS membership.

The structure of the ILRS (shown in Fig. 1) consists of several levels of components that were created to efficiently handle information exchange and receipt and distribution of data and their derived products. Each of the IAG's geodetic services, the ILRS, the International GNSS Service (IGS) (Dow et al. 2009), the International VLBI Service for Geodesy and Astrometry (IVS) (Schuh and Behrend 2012), and the International DORIS Service (IDS) (Willis et al. 2010), has established a comparable, distributed organizational configuration for the transmission of data, derived products, and information files from the observing stations to the user community (Pearlman et al. 2002). A key requirement for the successful operation of these IAG services is the collaboration of all participants through the various levels of the service; this close cooperation helps to ensure timely delivery of consistent data and products to the global science community.

2 Laser ranging data and products

The ILRS Data Centers (DCs) serve as the principal source of laser ranging data, products, and information for this international scientific user community. The two ILRS DCs are:

- Crustal Dynamics Data Information System (CDDIS), located at NASA Goddard Space Flight Center (GSFC), Greenbelt MD USA, (<https://cddis.nasa.gov>) (Noll 2010)
- EUROLAS Data Center (EDC), located at Deutsches Geodätisches Forschungsinstitut, Technische Universität München, Munich Germany, (<http://edc.dgfi.tum.de/en/>)

2.1 Laser ranging data

Laser ranging data records contain the round-trip measurement of the station to satellite distance and time that results from the laser fires to an orbiting satellite (including the Moon) equipped with suitable corner cube retroreflectors (cf. Degnan 1985; Seeber 2003). Stations apply certain corrections to the range measurement, such as internal or external calibrations, before data submission. Laser stations in the ILRS network routinely transmit two types of laser ranging data for archive at the data centers: full-rate data, which include all range observations obtained during a satellite's pass, and normal point data, where range

observations are sampled or averaged over the pass, thus condensing the number of range observations reported for the pass.

In addition to ranging to orbiting artificial satellites, a few stations in the ILRS network are capable of obtaining laser ranging returns from retroreflector arrays installed by three NASA Apollo and two Russian Lunakod missions landing on the Moon during the 1969–1973-time period (e.g., Murphy 2009; Courde et al. 2017). These lunar laser ranging (LLR) data are also available from the ILRS Data Centers utilizing the same format and transmission methodology as those in place for SLR observations. Analysis of LLR data supports research in the Earth/Moon system, dynamics and structure of the Moon, its rate of rotation and orbit, gravitational physics, and general relativity (Müller et al. 2013).

All SLR data are publicly available from the ILRS Data Centers, organized as follows in subdirectories by type (i.e., normal point or full-rate), satellite, and year:

- [<<TYPE>>/<<SATNAME>>/<<YYYY>>](ftp://cddis.nasa.gov/slr/data/).
- [<<TYPE>>/<<SATNAME>>/<<YYYY>>](ftp://edc.dgfi.tum.de/slr/data/).

where <<TYPE>> is npt_crd or fr_crd (normal point or full-rate data, respectively), <<SATNAME>> is the satellite name, and <<YYYY>> is the four-digit year. These directories reflect data available in the current operational ILRS data formats; data prior to 2012 used legacy formats and are archived in other subdirectories under/slr/data at the DCs.

2.1.1 Normal point data—The main ILRS data products are laser ranging normal points. Use of normal point data reduces the amount of data to be analyzed. Following the completion of the ranging operation to one of the target satellites, the laser ranging station uses software to generate the normal points for the pass. This process compresses the full set of data (i.e., the full-rate) for the pass using sampling over time based upon a specified minimum number of data points. The altitude of the satellite primarily determines the length of this sampling interval. Satellites in lower orbits use a shorter normal point interval (i.e., 5–30 s) than higher-orbiting satellites (i.e., 120–300 s) (Sinclair 1997).

2.1.2 Full-rate data—SLR full-rate data include all valid laser returns obtained during a satellite pass. Therefore, full-rate files are larger in volume than the normal point data set; normal points are derived from these full-rate data through data sampling as described earlier. Not all ILRS stations submit full-rate data. However, these data are useful for scientific applications as well as for engineering evaluation of the laser tracking systems and satellite targets, such as investigating the performance of corner cubes and retroreflector arrays, detecting satellite signatures and calibrating corner cube targets, performing statistical analysis on satellite returns, and validating any laser systems undergoing co-location testing. In addition, full-rate data, particularly from high-repetition rate stations, have been utilized for space debris research and the determination of satellite spin-rates (e.g., Kucharski et al. 2014).

2.2 Laser ranging products

The ILRS Analysis Centers (ACs) download and utilize laser ranging data to generate a suite of official, operational ILRS products. These products include precise ephemerides for a subset of satellites tracked by the ILRS network, station positions and velocities of ILRS network stations, and Earth Orientation Parameters (EOPs, polar motion and rates, length-of-day) (Pavlis and Luceri 2018). An essential advantage of SLR is that this is the only technique, compared to VLBI, DORIS, or GNSS, which can provide a direct connection between the station network and the Earth's geocenter. SLR also helps to define, together with VLBI, the scale of the network. Therefore, the ILRS products are an important contribution to the computation of the International Terrestrial Reference Frame (ITRF) (Altamimi et al. 2007). The Earth orientation parameters from SLR are not as precise as those of the other space techniques, but they contribute on a daily basis to the series of pole coordinates and UT1-UTC differences provided by the International Earth Rotation and Reference Systems Service (IERS) (Altamimi et al. 2016).

Satellite mission support groups processing precise orbits for Earth observation missions (e.g., TanDEM-X, TerraSAR-X) or altimeter missions (e.g., Jason, SARAL, etc.) that are equipped with laser retroreflector arrays require SLR data to compute the best possible orbits, validate orbits produced by onboard GNSS receivers, and to calibrate the satellite's instruments (e.g., Lemoine et al. 2010; Cerri et al. 2010; Hackel et al. 2017; Schrama 2018).

Furthermore, the International GNSS Service (IGS) also uses SLR tracking data of GNSS satellites (GLONASS, Galileo, Beidou, etc.) to validate the IGS orbit products (e.g., Arnold et al. 2015; Guo et al. 2017; Steigenberger and Montenbruck 2017).

Users download ILRS products from the following directories at the CDDIS and EDC data centers:

- <ftp://cddis.nasa.gov/slr/products/>.
- <ftp://edc.dgfi.tum.de/slr/products/>.

General information about the ILRS ACs is available within the/slr/products/ac subdirectory; useful data concerning the ILRS products can be found in the/slr/products/resource directory.

2.2.1 Station positions, velocities, and EOPs—Official ILRS products include station positions, velocities, and EOPs, derived from routine analysis of LAGEOS and Etalon data; these products, called “pos+eop”, are available from 1983 through the present. Prior to 2012, ILRS ACs produced a weekly station position/EOP product and operationally submitted these solutions to the ILRS data centers, typically within 2–3 days following the end of the observation week. Starting in 2007, the ILRS ACs began development of daily station position and EOP solutions, with a one to 2-day delay, as a future official product of the ILRS; this daily solution became the principle ILRS product in mid-2012.

The ILRS combination centers retrieve the individual AC solution files, using them as input to produce the official, and final, ILRS combined products (Pavlis and Luceri 2007). These solutions are designated “ILRS A”, produced by the ILRS primary combination center

(Italian Space Agency/ASI, Matera, Italy), and “ILRS B”, produced by the ILRS backup combination center (NASA GSFC/University of Maryland Baltimore County (UMBC) Joint Center for Earth Systems Technology (JCET), Greenbelt MD, USA); these combination solutions are available at the data centers approximately 1 day following submission of the individual AC products. Thus, this final, combined daily product is available within 2 days following the end of the solution day. The official ILRS product files (station positions, velocities, and EOP) are available in ASCII in SINEX (Software Independent Exchange) format (Blewitt et al. 1995 and <https://www.iers.org/iers/en/organization/analysiscoordinator/sinexformat/sinex.html>). These individual ILRS AC and combination center station position and EOP solutions are stored in UNIX-compressed format within the/slr/products/pos+eop directory structure at the ILRS data centers. The solutions are available in daily subdirectories; the historic weekly products are archived in subdirectories identified by the end date of the 7-day solution interval.

2.2.2 Precise orbit solutions—ILRS precise orbit solutions for select high-priority satellites tracked by the ILRS network, LAGEOS-1, -2 and Etalon-1, -2, are now produced by the ILRS ACs as an official ILRS product. The ILRS ACs generate these orbits on a weekly basis; the ILRS Combination Centers produce the official ILRS orbit products within several days following the AC submissions. Users can download these orbits from the/slr/products/orbits directory structure in the ILRS data center archives; the solutions are archived by satellite and week. The orbits are available in UNIX-compressed ASCII format using the Extended Standard Product 3 Orbit Format (SP3c) (Hilla 2010); the SP3 format is a community standard and also utilized within the IGS and IDS for their orbit products.

2.2.3 Satellite orbit predictions—In order to acquire the orbital position of retroreflector-equipped satellites listed on the ILRS tracking roster for authorized laser ranging operations, laser ranging stations need data in a consistent format, accurately predicting the near-term orbit of the satellite. Mission operations centers, or designated prediction generation groups, construct these projected orbits and transmit the files to the stations through e-mail or by making them available for ftp download from the data center archives. Predicted orbit information is generated on a daily basis (at a minimum) and contain orbital parameters for multiple days in the future. The predicts are made available in directories by year and satellite within the ILRS data center SLR archives (i.e., directory/slr/cpf_predicts/). The Consolidated Prediction Format (CPF) (Ricklefs 2008) has been used by the ILRS for satellite predictions since its adoption in 2007. Orbit prediction files for lower orbiting satellites (e.g., 300–500 km) can be transmitted several times per day for greater resolution and pointing accuracy.

2.3 ILRS format developments

Starting in the mid-2000's, the ILRS, through its Data Formats and Procedures Standing Committee (DFPSC), went through a process of replacing its two most important formats in order to facilitate changes in the mix of tracking targets and provide for increased accuracy and data transparency (Ricklefs 2008). Redesign of and revisions to the ILRS tracking prediction and data distribution formats were formulated, developed, tested, and adopted. The old tuned inter-range-vector (TIRV) predictions format and the legacy full-rate and

normal point data formats were created when disk drives were small or non-existent and data transmission was by tape (paper or magnetic). Much has happened since those days, including electronic transmission capabilities and more sophisticated tracking stations and targets. Both of these format transitions and their motivations are discussed in more detail below.

2.3.1 Prediction formats—In 2000, it became clear that the existing ranging target predictions formats were not succeeding on several levels. First, the existing Tuned Inter-range Vector (TIV) format, used by the SLR community for decades, consisted of one prediction state vector per day with time, and body-fixed position and velocity tuned for use with specific gravity field and integrator. This format was in principle not accurate enough to properly handle the drag effects on low satellites. Second, each LLR station generally started with a lunar and planetary ephemeris good for several years and created their own unique software and tracking formats, meaning dual-function stations were required to support two sets of software and procedures. Third, plans had begun for satellites with one- or two-way transponders, and these targets would require additional prediction parameters not included in the existing formats.

Thus, the ILRS Predictions Format Study Group was formed to develop a unified format that would permit stations to use one format to track any one of the existing or envisioned target types and would be flexible enough to expand to handle target types not yet conceived of. The format had to allow a station to range to any of these targets without special software not provided with the to-be-developed sample software. The need for special drag function and time bias files had to be eliminated as was tuning of the predictions to a specific gravity model. Drag and time bias would be folded into the state vectors themselves, with the predictions being replaced as many times per day as needed for the desired level of accuracy on low satellites. What developed was a tabular format containing (usually) body-fixed position vectors at a time interval just small enough to reproduce the target's orbit to the nanosecond level of accuracy using a 10-point integrator (code supplied, but not required). The new format was designated the Consolidated Predictions Format (CPF for short, https://ilrs.gsfc.nasa.gov/data_and_products/formats/cpf.html).

The CPF format consists of a fixed-format header section followed by a free format prediction section. The header section provides satellite IDs and description, the source of the predictions, time of production and time span of the data included in the file, as well as other fields describing reference frame, etc. There is also provision for transponder information and expected prediction accuracy. The prediction section contains records with time and position vector. Records containing velocity vectors, Earth orientation, offset and rotation angles of objects about a main body, and corrections for relativity and aberration are available for use with specialized targets. The format also contains a comment record, which allows additional information to be provided with the predictions. The format is meant to be expandable through creation of additional record types as circumstances demand.

Tests confirmed that the prediction accuracy using the CPFs as seen at the laser ranging stations was far superior for all satellites to the earlier format, and resulted in abandonment

of time bias and drag function generation. The transition to the CPF was completed by early 2007.

2.3.2 Data distribution formats—In the same way that the CPF was needed to replace the older predictions formats, it became clear that a similar transformation of ILRS data distribution formats was due, and for some of the same reasons. The SLR and LLR communities had the same normal point (compressed data) format, after a modification to the SLR CSTG normal point format, but they used different full-rate data formats. Transponders (such as the Lunar Reconnaissance Orbiter, then in planning) would require more serious modifications to both format types. Different generations of station hardware, as well as different data end uses, required different data precisions (e.g., for epoch and time of flight), which was not easy to accommodate with the old formats. Add to this the desire for more real-time configuration information, and the need for a revamped format became clear.

Similar to the CPF, the Consolidation laser Range Data (CRD) format has a header section with records containing all the information needed for a specific station, satellite, and pass. It also has a data section including the epoch and time of flight of each successful return (full-rate data), a sample of such returns for rapid engineering assessment (quick-look data), or the modeled ranges at a set of averaged times across the pass (normal point data). In addition, statistical data on the normal points and calibrations are featured, including the RMS, and new to this format, the skew, kurtosis, and peak-mean. More complete meteorological and angular data are also included. In addition, the CRD format features a configuration section which gives system configuration information on a pass-by-pass basis, including laser, detector, timing, and, for transponders and time transfer experiments, a spacecraft timing record.

Adopting the CPF building-block structure allows including or excluding records depending on the target being tracked or the data type (normal point or full-rate) being represented. Multiple ranging modes (one-way or two-way ranging) and multiple-color data can be represented in a single data file, making archival and user bookkeeping much simpler. Data from multiple stations or passes from a single station can be combined into one file without duplicating all the headers. The format is also extensible in that new records (e.g., additional configuration types) can be added as needed when new requirements arise.

The ILRS performed an extensive test of the CRD format throughout its infrastructure, which unfortunately took much more time than anticipated, delaying operational use of the format. However, in May 2012 the CRD became the prime format for laser ranging data exchange and archive within the ILRS. At that time, transmission and archive of data in older formats was discontinued. Historic data continues to be available in the old formats; there are no plans for the data centers to convert these older data sets to the new CRD format. An extensive description and format document are available at the ILRS website (https://ilrs.gsfc.nasa.gov/data_and_products/formats/crd.html).

2.3.3 Sample code—Each format has its own sample code with which users can read, write, and check the files. In addition, the CPF code contains an interpolator and related

software to use for SLR and LLR targets, and software to split daily files into pass-by-pass predictions at a given station. Most software is supplied in both FORTRAN and C implementations. The software, manuals, and errata files are available on the ILRS website.

3 Flow of laser ranging data and products

As presented in Sect. 1, the procedures for transmission of laser ranging data, derived products, and related information within the ILRS provides for a dissemination of files from the network stations, to the data centers that handle validation, archive, and distribution, to the analysis groups who generate official products that are then submitted to data centers for archive and public distribution to users.

3.1 Transmission of laser ranging data

The flow of laser ranging data begins at the stations, which send normal point and full-rate data sets to one of the ILRS Operations Centers (OCs) located at EDC and NASA. The OCs validate all incoming SLR observations; more rigorous testing is performed on normal point data, the ILRS operational data product. All valid normal point data sets are exchanged on an hourly basis between the OCs. Additionally, a file containing all data received at each OC during the previous 24 h is exchanged. The NASA OC forwards the hourly files to the CDDIS for archive; the center also produces a single daily file that contains all data submitted to both the NASA and EDC OCs within the previous 24 h. This file may contain data that are several days old. Similarly, the EDC sends data submitted to their OC to the NASA OC (and the CDDIS). The CDDIS and EDC data centers merge data forwarded by each OC into their SLR data archive on a daily basis (at a minimum). This hourly and daily exchange of data files between the OCs ensures redundant data flow paths and the availability of data at both ILRS Data Centers. The CDDIS and EDC use these hourly and daily files to update their respective archives with the latest observations for use by the ILRS Analysis Centers and user community in general.

The CDDIS and EDC data centers provide SLR data files in three forms: hourly, daily, and monthly. Hourly files contain all passes from all satellites received by the operations centers in the previous one-hour time span. Similarly, daily files contain all passes received in the previous 24-h time span. In addition to these daily files of SLR data for each satellite, the CDDIS data center provides a single file (called “allsat”) containing data from all satellites. The third type of normal point data file is a monthly, satellite-specific file that contains data for the particular month. Thus, users have alternate ways for downloading data, all data received during an hour or day-time span, or all data with timestamps for a particular month. Although the two ILRS DCs (CDDIS and EDC) archive the same laser ranging data, the method in which they archive the “daily” files is slightly different. Daily files at CDDIS contain data received in the previous 24 h; daily files at EDC contain data acquired on the given day. Monthly satellite-specific files are created and archived at each data center and are, in principal, identical; these monthly data files are updated on a daily basis (at a minimum) and contain data for a specific satellite and monthly time span.

3.2 Submission of ILRS products

The ILRS ACs submit their ILRS product solutions (precise satellite orbits and station positions, velocities, and EOP) to the ILRS data centers on pre-determined schedules (e.g., weekly for orbits and daily for the pos+eop product). The ILRS Combination Centers retrieve and combine the AC solutions to generate the official ILRS products, which are in turn submitted the DCs for distribution to the global user community.

3.3 Submission and distribution of satellite orbit predictions

As discussed in a previous section, SLR stations must use predicted satellite ephemerides in order to perform laser tracking operations. Laser ranging to satellites supported by the ILRS network falls into two major categories: non-restricted, or “normal” tracking, and restricted tracking. Missions and/or their prediction providers generate the predicted orbit files at least daily.

3.3.1 Orbit predictions for non-restricted tracking of satellite missions—

The majority of satellites supported by SLR fall into the non-restricted tracking category. Stations can obtain the orbit prediction files for these satellites through e-mail or they can access the files at the ILRS data centers. Stations wishing to receive satellite predictions via e-mail can use the EDC’s CPF-Mailer tool which enables station contacts to select the satellites or prediction providers they are interested in. The SLR station’s staff will then receive the latest predictions for these satellites after they are submitted to the EDC.

3.3.2 Orbit predictions for restricted tracking of satellite missions—

A small subset of satellites supported by the ILRS must (or can) only be tracked by laser ranging under certain restrictions or conditions. Therefore, the ILRS has established a set of procedures for restricting laser ranging tracking in order to address concerns with the safety of detectors on certain more-vulnerable satellite missions or geometric conditions where corner cubes are not visible to stations. These restrictions fall into several categories:

- **Go/NoGo restrictions.** Situations when a satellite’s onboard instruments are vulnerable to damage by laser irradiation require that stations disable any ranging to the satellite under certain conditions/satellite configurations. Stations permitted to range to a restricted satellite must access a file containing the Go/NoGo flag indicator before and during ranging to determine whether tracking is permitted. Since ultimate responsibility for safely ranging to a restricted satellite lies with the mission/satellite prediction center, the mission hosts the Go/NoGo flag file.
- **Elevation restrictions.** A satellite may have a risk of possible damage when ranged near the zenith. Therefore, the mission may set an elevation value above which a station may not range to the satellite. ICESat-1 is an example of a mission that operated with both Go/NoGo and elevation restrictions (Schutz et al. 2005).
- **Segment restrictions.** Missions can allow ranging only during certain parts of the pass as seen from the ground. For some satellites, the reflector array is not

pointed toward the Earth during predictable parts of a pass, making ranging to the satellite during those times pointless. Station-dependent files list the start and stop times for ranging during each pass.

- Schedule segmentation restrictions. Another type of pass segment restriction is more of a schedule segmentation restriction; LRO/LR and Radioastron are two examples of missions where this type of restriction has applied. At certain times during long passes, the satellite may not be visible or their array is tilted away from the station. For example, with LRO/LR support, part of each pass where the satellite was behind the Moon was omitted; for Radioastron, only segments spanning a few hours from certain passes were allowed (or possible). In these cases, the mission will provide a file used at prediction processing time rather than at tracking time to remove un-wanted pass segments from the tracking schedule.
- Power limits. Missions restrict the laser transmit power to prevent detector damage; stations must set their laser power and beam divergence before and after each pass. Sentinel-3A and -3B (Donlon et al. 2012) are examples of missions with laser ranging power restrictions because of onboard instrumentation.

As discussed in the previous section, the ILRS data centers provide access to orbit prediction files for satellites tracked by stations in the network. However, for satellites requiring restricted SLR tracking, a designated mission operations group maintains, and controls access to, the orbit prediction files as well as any supporting files (e.g., the Go/NoGo key file) for controlling laser ranging. Missions must clarify any SLR tracking restrictions within the Mission Support Request Form submitted to the ILRS CB as well as make arrangements to evaluate and approve candidate ILRS stations for compliance with the restrictions before tracking operations begin.

4 ILRS website resources

The ILRS website provides information on the organization and operation of the ILRS and descriptions of ILRS science, applications, components, data, and products. Furthermore, the website provides descriptions of and links to SLR data and products available through the data centers located at the CDDIS and EDC. Although the website is a comprehensive source of information about the ILRS, the network and mission sections are the most useful and most accessed segments of the site. Through these sections, users can view extensive information on stations in the ILRS network, including their characteristics, performance assessments, and data quality evaluations by ILRS Associate Analysis Centers. Links to general mission facts and important parameters and configuration data provide essential information for effective laser ranging tracking of approved missions.

4.1 General information

The ILRS website is supported through the CDDIS computer facilities located at NASA GSFC. The website is divided into six main sections (About ILRS, Network, Missions, Science, Data and Products, and Technology), accessible through the top horizontal navigation bar on all webpages. The top banner of all webpages contains a search box for

quick browsing of the website. Each webpage's content section presents the primary material for the page, as well as the site/section navigation (both top and left side).

Content pages in the ILRS website use a vertical, multi-column layout as shown in Fig. 2. Both horizontal (persistent on all pages) and vertical (on lower level pages) menus are used for navigation through the site. This page layout style provides an organized view of the extensive information available, allowing the user to easily find main topics of interest. Drop-down menus from the horizontal navigation bar allow for quick navigation to these level 1 pages. Navigation within the level 1 sections to lower level pages is accomplished through links on the left vertical navigation column. A navigation "breadcrumb" is included within the section's banner to provide contextual information for the user as well as further assist in site navigation. Each page also includes a set of "quick-links" providing access to popular and section-related pages.

Standing Committee pages can be found within their respective topic area (e.g., Analysis Standing Committee available under Science, Network and Engineering Standing Committee under Network, etc.). The About section of the ILRS website describes the service and provides links to its organization, important meetings, and publications. The Science pages discuss laser ranging research and analysis, ILRS products, and provide links to resources for analysts and the Analysis Standing Committee material. The Data and Products section links to general data center information and access instructions, data and product descriptions and format documentation, and related standing committee/study group information. The Technology portion of the website provides background information on laser ranging, the ground and space segments of the technique, modeling and software information, as well as access to related standing committee pages. The Network and Mission sections of the website are discussed in more detail below.

4.2 ILRS network information

The station information included in the network section (<https://ilrs.gsfc.nasa.gov/network>) of the ILRS website provides details about all stations in the ILRS network, including stations that ceased operation after the start of the service. This section of the website is designed to not only provide general information to users about ILRS stations but also to provide policy, operating requirements, standards, and other useful information to station operators. Information about each station consists of a general information page with coordinates and contact data, a clickable site log that describes station configuration parameters, meteorological data graphs (temperature, pressure, and humidity), LAGEOS performance graphs (RMS, calibration RMS, system delay, observations per normal point, full-rate observations per pass) for the past year and since 2000, and satellite-specific data performance graphs (normal point RMS and number of observations per normal point in local time and as a function of range) for all satellites over the past year.

4.2.1 Station performance assessment—The ILRS Central Bureau (CB) issues monthly (formerly quarterly) station performance summaries, called "report cards", accessible within the network section of the ILRS website (https://ilrs.gsfc.nasa.gov/network/system_performance/global_report_cards/index.html). The report card data tables

and graphs are generated by ingesting the SLR data; they provide a summary, by station, of data quality and data quantity for the previous twelve-month time period. These report cards can be used by the ILRS CB to assess the compliance of the stations with minimal, ILRS-specified operational performance standards. The network summary statistics are arranged in two tables (artificial satellites in Table 1 and lunar reflectors in Table 1L) and sorted by total passes observed during the reporting period in descending order. Plots summarizing station data volume (in passes and normal points by satellite type and minutes of data) and RMS (for LAGEOS, Starlette, and system calibration) are created from this information and linked to the corresponding headings of each month's Table 1 columns. An excerpt from a recent report card is shown in Fig. 3; examples of the associated data plots, linked to the report card tables, are shown in Fig. 4.

Table 2 in each ILRS report card assembles the results from an orbital analysis of the data as processed by five ILRS ACs or Associate Analysis Centers (AACs): Deutsches Geodätisches Forschungsinstitut (DGFI), Hitotsubashi University, Joint Center for Earth System Technology (JCET), Russia's Mission Control Center (MCC), and the Shanghai Astronomical Observatory (SHAO). The table links to the corresponding AC/AAC reports for further user investigation.

The ILRS CB reviews these report cards on a regular basis to generate an assessment of how the network stations are operating, their data quality, etc. Performance guidelines, defined on the ILRS website with the "baseline" values as shown in Table 1 of the report card, pertain to the data quantity (number of passes obtained in the last 12 months), data quality (normal point precision and short and long-term bias stability over that period), and compliance factors (timely data delivery, correct data formatting, required station documentation).

4.2.2 Station-specific performance charts—The ILRS Central Bureau also generates data plots of station performance and environmental parameters for each active station in the network; the plots are cross-linked through the network and mission sections of the ILRS website. These plots can provide valuable insight to not only users, but the SLR station staff to show long-term trends and highlight anomalies and possible problems. Within the network section of the website, users can select a station from the map or one of the station lists (i.e., current, engineering, or closed/inactive stations). The resulting station-specific page then displays several navigation buttons: station overview, detailed site log, and three performance/data analysis related pages. The first of the data analysis sections, the "Meteorological Data" tab, links to plots of the station's environmental parameters, extracted from the SLR data: temperature, humidity, and pressure. For each parameter, two plots are generated, one covering the last year (for detailed analysis) and a second showing the station's data from 2000 through the present (for identifying possible long-term trends).

The station's "LAGEOS Performance" menu item displays a webpage of charts that summarize the station's data obtained from the LAGEOS satellite observations. The data analysis includes satellite RMS, calibration RMS, system delay, observations per normal point, and full-rate observations per pass. Plots spanning the last year and since 2000 are also created for the LAGEOS Performance page. SLR data from the LAGEOS satellites are the primary input for the official ILRS products. Therefore, it is critical that each station's

staff have the means to easily monitor their system's performance over time. In addition, ILRS ACs can review data quality to identify any anomalies that could affect the quality of the derived products. Figure 5 shows example plots of LAGEOS observations for the ILRS station located at Herstmonceux UK.

The “Satellite Data Info” tab displays a page of charts plotting statistics for each satellite currently tracked by the station. Four graphs are shown for each of these satellites: normal point data RMS as a function of local time and satellite range and number of full-rate data points per normal point also shown as a function of local time and satellite range. For ease of use when browsing mission-related information, these plots are cross-linked to the Missions section of the ILRS website (organized by mission with a matrix of all stations tracking the selected satellite).

4.2.3 Data center holdings reports—The ILRS Analysis Centers, and user community in general, require information about the current status of the network. To that end, both the CDDIS and EDC provide summaries of current and past data holdings. For example, the EDC website <http://edc.dgfi.tum.de/en/statistics/> lists several categories of reports that summarize data holdings. Similarly, the CDDIS provides access to reports spanning varying time periods at: <ftp://cddis.gsfc.nasa.gov/slr/data/reports/>; these reports are static and generated on a regular (e.g., daily, weekly) basis.

4.2.4 Real-time daily station status reporting—Information summarizing the current status of tracking stations can be viewed through the “EUROSTAT” utility (https://ilrs.gsfc.nasa.gov/technology/software/Eurostat_station_status_software.html), a cooperative service originally developed to provide daily and near real-time satellite acquisition information on station operations in Europe; the service has expanded and all stations in the global ILRS network are now encouraged to regularly contribute. Any ILRS station can automatically upload status information to EUROSTAT (maintained by the Astronomical Institute of the University of Berne, AIUB); the system then regularly generates an overview of the current activities of the tracking stations. The real-time report (example shown in Fig. 6) shows actual station operations at a point in time. Time bias information for the prediction file used and reported in the station's entry can aid other stations in acquiring the satellite. A second, daily report provides a one-line entry per day showing if stations are currently staffed, operational, off-shift, off-line because of system problems, etc. Thus, the ILRS community can quickly view the status of the stations in the tracking network.

4.3 Mission information

Another major section of the ILRS website describes the suite of missions that are supported by the network tracking stations. These pages describe the missions in general but also provide detailed information about the retroreflector array, the satellite center of mass, and orbital parameters, which are necessary for effective laser tracking and data analysis. A consistent set of five sections is presented for each mission currently on the roster of tracked satellites. A similar collection of pages is available for the pages devoted to many of the satellites the ILRS has supported in the past; selected sub-sections are presented for missions that have been approved by the ILRS for future support. General information and

background material provide a context for the mission and its relationship to the ILRS. The second section includes a summary of the ILRS Mission Support Request and a link to the submitted form. For current missions, a table, updated daily, provides tracking statistics by station. The next portion of the mission information provides detailed characteristics of the onboard retroreflector array, such as number of cubes, dimension, construction materials, and cube coating. The fourth mission section tab details the satellite center-of-mass (CoM) data, which includes parameters required to correct the position of the reflector to the satellite's center of mass. Finally, tracking statistics are graphically represented in the fifth section of the satellite's information; these same plots are available sorted by station within the network section of the ILRS website and discussed in Sect. 4.2.2. An example of a plot for Herstmonceux tracking of LAGEOS-1 was shown in Fig. 5. As stated in Sect. 4.2.1, these performance plots are cross-linked to the corresponding station webpages.

In addition to webpages devoted to descriptions of all missions supported by the service, the ILRS maintains information useful to both network stations and satellite contacts. The stations regularly consult the ILRS Mission Priorities webpage in order to develop their satellite tracking schedules conforming to ILRS policy. The ILRS CB sets priorities for satellite tracking in order to maximize data yield and satisfy mission requirements. The tracking priority list is typically ordered by satellite orbit parameters (satellites in lower orbits have shorter station availability and therefore have a higher priority) and to accommodate special project needs (e.g., intensive tracking campaigns). Other information available in the mission section of the website includes links to request forms for new mission support and procedures and requirements for this support.

4.4 ILRS communication services

The ILRS Central Bureau and the EDC maintain several e-mail lists to promote communication within the service; an archive of these messages is available on the EDC website at https://edc.dgfi.tum.de/en/mailling_lists/. The SLRMail list, administered at EDC, is used to distribute SLR and ILRS-related information of general interest to the scientific community. Routine reports, e.g., weekly SLR tracking reports by station or mission, are distributed through the SLReport list. Mission contacts and prediction centers can use the "urgent" e-mail distribution list to inform stations about time critical events concerning the tracking of their respective satellites, such as modification of tracking priorities, reports of unusually large time biases, satellite attitude problems, upcoming maneuvers, and post-launch satellite information. In addition, the CB maintains several e-mail distribution lists dedicated to the major components within the ILRS, e.g., stations, analysis centers, data centers, study groups, the CB, etc.

5 Using ILRS data, products, and information

As presented in Sect. 2, the main users of the ILRS data, products, and information are the network stations and the analysis centers, who use the tracking data to compute the official ILRS products. Prediction providers also download ILRS data to generate predicted satellite orbits which are essential for the stations in the ILRS network to obtain returns from orbiting

satellites. General, ancillary information available at the ILRS Data Centers at CDDIS and EDC help the ACs compute a reliable and stable product.

The ILRS Data Centers continue to see increased usage of ILRS data, products, and information each year. As an example, in 2017, over 267 K unique hosts downloaded a total of 180 Tbytes (1.6B files) of data, product, and information files from the CDDIS. Although approximately 90% of all downloads from the CDDIS are GNSS-related files, the download of SLR data, products, and information accounts for approximately 5% of the total. Data and prediction files make up the majority of SLR-related files (36 and 56%, respectively) retrieved from the CDDIS in 2017. Figure 7 shows the distribution of the CDDIS downloads to the international SLR user community in 2017.

6 Recent developments and future activities

6.1 WDS membership

With encouragement from the IAG, the ILRS submitted an application to join the International Council for Science (ICSU) World Data System (WDS). In April 2013, the WDS accepted the ILRS application to become a network member of the WDS. The WDS advocates for open and long-term access to scientific data, derived products, data services, and information about these components (World Data System, 2018). The WDS also promotes effective stewardship of data for the global research community. The WDS helps the broaden the reach of its members in the scientific user community, including the ILRS and its SLR data and derived products. Network members of the WDS represent other data centers (such as the CDDIS, a regular member of the WDS) or data analysis groups and coordinate data archiving/stewardship activities across common disciplines. The ILRS cooperates in WDS activities and participates in membership forums as personnel schedules and travel funding permit.

6.2 Data format improvements

In 2017, the Data Formats and Procedures Standing Committee (DFPSC) developed a proposal to fine-tune the CRD and CPF formats to accommodate developments in laser ranging since the original introduction of these formats over a decade ago. These modifications include time-critical changes required for time transfer activities such as the European Laser Timing (ELT) experiment, part of the Atomic Clock Ensemble in Space (ACES) onboard the International Space Station (ISS) (Schreiber et al. 2009). In addition, the updates include changes for debris and other potential tracking types to eliminate the need for separate formats for these applications. Additional modifications were required to capture more information in the CRD format and to correct other issues that have been identified since the implementation of the format in 2012. All records will now be free format. The CPF manual was rewritten to eliminate many of the references to the TIV format which were important in version 1. The formats study group and the DFPSC are reviewing the changes and plan to finalize the format updates in 2018.

6.3 SLR site log format improvements

The ILRS site logs contain critical information about the configuration of SLR stations, e.g., contact, location, equipment (telescope, laser, receiver), etc. In 2017, the DFPSC, the Networks and Engineering Standing Committee (NESC), and the ILRS CB developed an updated site log format (version 2) which includes much-needed content revisions and extensions. In conjunction with the site log format revision, the submission/update procedure will change from an e-mail submission to an online site log management system through the EDC website. The new system contains an immediate format check for station managers when updating their site logs online. Approved site logs will then be released into the EDC archive and sent to CDDIS for availability there and incorporation into the ILRS website. The EDC and the ILRS CB plan to finalize and complete the transition to the new site log procedure in the 2018 timeframe.

6.4 Routine SLR full-rate data transmission

Since SLR normal points have been considered the primary ILRS data product, network stations were not required to transmit full-rate data to the ILRS OCs/DCs due to data volume and sometimes inadequate communication capabilities. Today, communication links from the global SLR stations have adequate capacity to transmit the data on a routine basis and both the EDC and CDDIS data centers are easily able to archive these data. As the ILRS strives to achieve mm accuracy data, the details available in SLR full-rate data become more revealing. Using full-rate data, SLR engineers and analysts have been able to diagnose and address issues in both range bias and epoch timing. These investigations are a long-term activity; the ILRS analysts would like to derive as much information as possible from the data and therefore, recently recommended renewal of the routine archive of SLR full-rate data archive. In early 2018, the ILRS CB requested all stations to routinely submit full-rate data through their “normal” data transmission channels.

6.5 Station performance assessment

As discussed earlier, the ILRS CB utilizes the monthly global “report cards” to review and evaluate the performance of the stations in the ILRS network. In the past, the CB has classified stations as “operational” or “associate”, according to the results tabulated in these performance charts. Stations were nominally considered as “operational” if they met the data accuracy, data quantity, data delivery and GNSS co-location requirements. Stations not yet satisfying these criteria were categorized in “associate” status. To more accurately assess station performance, the ILRS CB is reviewing the use of additional criteria, such as interleaved tracking (e.g., alternate ranging to satellites B and C during a pass for satellite A, such as a tracking sequence: A, B, A, C, A), adherence to the ILRS tracking priorities, among other factors.

6.6 QC harmonization

While both the NASA and EDC OCs have performed some tests on the incoming SLR data to ensure data with format errors do not find their way into the archived data sets, the tests were not extensive, and the checks performed at the two OCs were not the same. In the last few years, the OCs have made a concerted effort to harmonize the checks of the data. This

process has included identifying the allowable values or range of values for every field in the CRD format. The QC activity is an ongoing project, with software development and implementation underway at both OCs to properly evaluate all incoming CRD data and to react appropriately to errors of varying severity, e.g., either rejecting the data or sending warnings to the originating station. It is envisioned that once the new vetting protocols are implemented, another level of tests will be developed to incorporate station dependencies. These tests could include evaluating such quantities as barometric pressure, which has a range of values dependent on station height. It is hoped that the harmonization endeavor will allow analysts to have more confidence in the data and be less distracted investigating issues that could easily be detected and corrected earlier in the data chain.

6.7 DOIs and metadata

The CDDIS, one of the two ILRS Data Centers, is currently developing improved collection-level metadata to describe its holdings of GNSS, SLR, VLBI, and DORIS data and derived products. “Collections” are groups of data/products with common information across all granules (or files), e.g., SLR normal point data or ILRS derived satellite orbit products. As part of this process, the CDDIS has registered DOIs that link to laser ranging data and product collections. DOIs are standard, “persistent” identifiers, assigned by authorized agencies and managed for long-term access. DOIs uniquely identify data sets and other published items. The use of DOIs permits easier access to research data and allows for citing these data in publications. Therefore, users retrieving ILRS-related files from the CDDIS can use these assigned DOIs to cite actual downloaded data and derived products that contributed to their published scientific research and results. Each DOI resolves to a dedicated “landing page” on the CDDIS website that summarizes the data set, including temporal and spatial parameters, format, publication and data center citations, and access information.

7 Concluding remarks

In the early days of SLR observations, coordination of activities performed by individual operation, data, and analysis centers was non-existent. Users of SLR data and products needed to directly contact the stations or agencies such as NASA to obtain the data and information required for scientific research. Even then, not all the essential information was readily available and data exchange was difficult and time consuming. Although initial cooperation in Europe through the EUROLAS, a collaborative effort between stations and the EDC, provided a data center acting as a common interface between stations and analysts, it wasn't until the establishment of the ILRS a short time later that a truly global service could fully make use of a robust set of SLR data for scientific research and satellite operations. Today, analysts, stations, and the international user community have a common platform to exchange data, products, and information. This service has made the consistent generation and improvement of the highest-quality SLR derived products and, due to the increasing transmission reliability of the global networks, the ready availability of SLR data, which has decreased to a few-hour delay for most stations. The daily, and even weekly, products could not be efficiently produced without the support given by the operations and data centers of the ILRS. These products are now key contributions to GGOS, to the

continued improvements of the International Terrestrial Reference Frame, and to general research in the Earth's gravity field, and global change studies in general.

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Fig. 1. The data flow paths established by the ILRS for transmission of data, products, and satellite predictions

Fig. 2. Home page for the International Laser Ranging Service (<https://ilrs.gsfc.nasa.gov>). The layout provides ready access to popular pages (e.g., news, meetings, publications) and sections of the website

Site Information		Data Volume									Data Quality		
Column 1	2	3	4	5	6	7	8	9	10	11	12	13	14
Location	Station Number	LEO pass Tot	LAGEOS pass Tot	High pass Tot	Total passes	LEO NP Total	LAGEOS NP Total	High NP Total	Total NP	Minutes of Data	Cal. RMS	Star RMS	LAG RMS
Baseline		2300	600	3000	3500								
Yarragadee	7090	15674	2775	10116	28565	288703	26492	38707	353902	196148	2.8	5.0	4.9
Changchun	7237	9199	1012	6254	16465	75495	6102	17703	99300	50580	6.0	7.7	10.3
Mount_Stromlo_2	7825	6614	1263	3890	11767	97723	10601	13761	122085	81436	3.3	4.5	7.4
Zimmerwald_532	7810	6590	1024	3424	11038	115396	14929	11380	141705	97086	6.7	9.2	11.6
Matera_MLRO	7941	4213	1636	2814	8663	49847	14260	12788	76895	69857	.8	2.5	3.5
Herstmonceux	7840	4195	736	3331	8262	58321	8314	10434	77069	50146	3.3	9.1	12.9
Graz	7839	3649	529	2762	6940	75227	3880	14009	93116	47162	2.3	3.7	5.1
Greenbelt	7105	5204	837	882	6923	99883	8435	3833	112151	66492	1.9	5.4	8.5
Wettzell	8834	3772	546	2568	6886	33935	3433	9718	47086	28657	6.8	8.6	12.1

Fig. 3.

Table 1 of an example ILRS report card for the December 2017 and summarizing data from January 01 through December 31, 2017)

Fig. 4.

Example plots from the December 2017 ILRS report card; total number of passes (left) and LAGEOS RMS (right) are plotted for each station observing during the reporting period (January 01–December 31, 2017)

Fig. 5.
Station performance chart for LAGEOS observations (number of observations per normal point and as a function of local time and satellite range) for Herstmonceux UK

Station	Date	Time	Target	Status	Returns	Ephemeris	Time Bias
Concepcion	2013-01-07	15:34:11		OUT			
Graz	2013-01-07	15:35:52		OUT			
Herstmonceux	2013-01-07	15:36:14		OUT			
MLRO-Matera	2013-01-07	15:34:10	Calibrate	CUR			
McDonald	2013-01-07	15:36:01		OUT			
San_Fernando	2013-01-07	15:36:07		OUT			
Wettzell	2013-01-07	15:36:06	Galileo102	LST	34	ESA5061	0.000
Yarragadee	2013-01-07	15:36:24	Jason1	CUR	1888	CNE5051	0.020
Zimmerwald	2013-01-07	15:30:03		DWN			

Fig. 6.

Example real-time EUROSTAT report. Columns (left to right) are: station, date, time, target, station status, number of returns, ephemeris used (source and number), and time bias

Fig. 7.
The majority of users of SLR data, product, and information available through the CDDIS are from North America and Europe. Furthermore, the type of file most downloaded from the CDDIS are SLR prediction files