

Contributions of SLR to the Success of Satellite Altimeter Missions

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Abstract

Satellite Laser Ranging has contributed and still contributes tremendously to many of the satellite altimeter missions. Laser ranging provides independent tracking data to those satellites that are also tracked by other tracking systems like DORIS, GPS and PRARE, but has also saved several altimeter missions when the primary radio-frequency tracking systems failed to provide data in due time, or failed altogether. The entire altimeter community, as well as the interferometric SAR community, is indebted to the relentless efforts of the SLR community to provide adequate tracking for so many scientific satellite missions.

Altimeter Satellites and Laser Tracking

Since the early 1990's several altimeter satellites have flown consecutively, without intermission (see Table 1). The continuous record of measurements of the sea surface height is extremely important to the assessment of trends in global sea level associated with global warming. All these altimeter satellites had laser retroreflectors mounted on their Earth-facing side, as a backup to their primary radio-frequency tracking systems like PRARE, DORIS and GPS. In all cases, the tracking systems' main goal is to provide accurate determination of the satellite's altitude over a reference ellipsoid. As shown in Figure 1, the sea surface height can be determined by subtracting the altimeter range between the satellite and the sea surface from the computed satellite altitude. Every second, the height of the sea surface under the satellite can be determined to within 5 cm accuracy. This number dropped by more than an order of magnitude over the last decade, not in the last place due to the contribution of Satellite Laser Ranging (SLR) to the determination of the satellite orbit, and in particular its altitude.

SLR plays a particularly important role during the calibration of the radar altimeters. While flying over an area of ocean equipped with tide gauges and other instruments to determine sea level independently from the altimeter satellite, an attempt is made to determine the altitude of the satellite independently of satellite dynamics (gravity, drag, etc.). This can be achieved when the satellite is tracked simultaneously by four or more SLR stations. The Mediterranean Sea, in close proximity to an abundance of laser tracking sites, has been chosen for this purpose during the ERS-1, TOPEX/Poseidon, ERS-2, Jason-1 and Envisat missions.

Table 1. Recent Altimeter Satellites and Their Tracking Systems.

Satellite	Agency	Period	Tracking Systems
ERS-1	ESA	1991-2000	PRARE (failed), SLR
TOPEX/Poseidon	NASA/CNES	1992-	DORIS, GPS, SLR
ERS-2	ESA	1995-	PRARE (sub-operational), SLR
GFO	U.S. Navy	1998-	GPS (failed), SLR
Jason-1	NASA/CNES	2001-	DORIS (problems), GPS, SLR
Envisat	ESA	2002-	DORIS, SLR

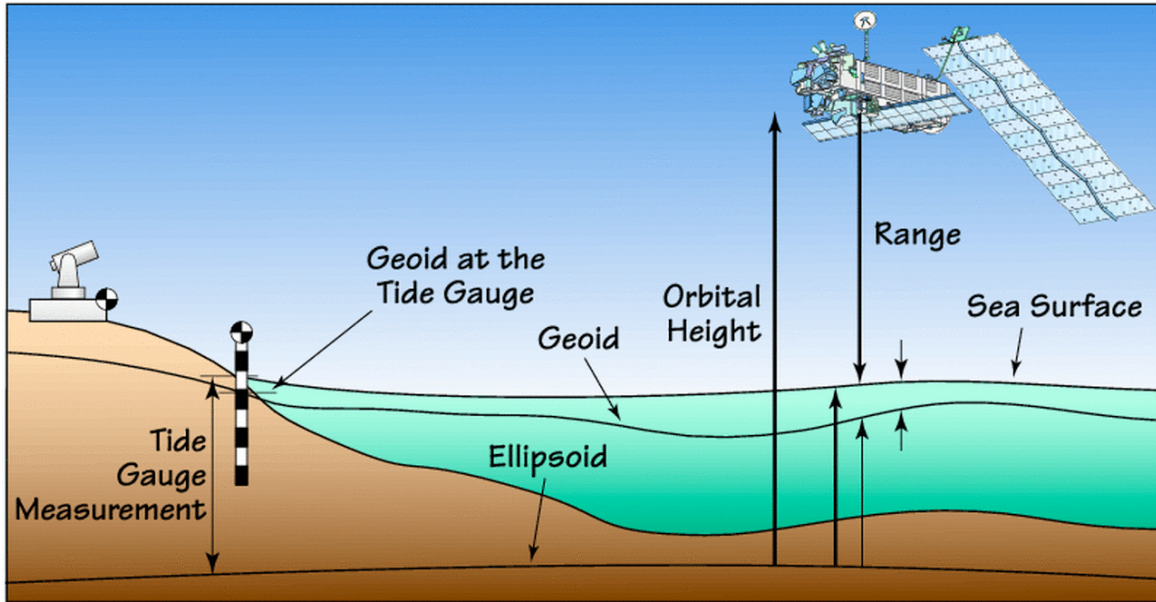


Figure 1. The principle of satellite altimetry.

The measurements of the sea surface height as provided by satellite altimetry are being used for a variety of applications. The assessment of global sea level rise is currently one of the most challenging topics in which satellite altimetry (and hence orbit determination) plays a crucial role. Historically, satellite altimetry was mainly used for studies of meso-scale ocean circulation (monitoring eddies and current meanders) and short-wavelength gravity field improvement. With the current state of orbit determination, large-scale ocean circulation and gravity field validation have been added to the list of applications. The altimeters of ERS-1, ERS-2, and Envisat also contribute to the mapping of the topography of the ice sheets of Antarctica and Greenland, as well as to the monitoring of their changes.

In the following sections, the altimeter satellites and the contributions by SLR to their missions are further identified.

ERS-1

The first European Remote-Sensing Satellite (ERS-1) marked the start of a series of multi-disciplinary environmental satellites developed and launched by the European Space Agency (ESA). ERS-1's equipment includes:

- a radar altimeter, which measures, apart from sea height, wave height and wind speed;
- a microwave radiometer, which assists the altimeter by measuring the wet tropospheric content, responsible for a lengthening in the radar altimeter range;
- a Synthetic Aperture Radar (SAR), which maps land use, land displacements, and wave spectrum;
- a wind scatterometer, designed to map the wind field over ocean surfaces;
- an Along-Track Scanning Radiometer, to map the temperature of ocean and land surfaces;
- the Precise Range And Range-rate Equipment (PRARE), a radio-frequency tracking instrument for the orbit determination of the satellite.

Soon after the launch of ERS-1 from Kiruna on 17 July 1991, the PRARE tracking system failed; high-energetic ions had toasted PRARE's computer chips. Both the altimeter mission and the capability of SAR interferometry would have been lost if it were not for the fact that a laser retroreflector had been placed on the satellite. Due to the diligent support from the SLR community, the mission was saved. By the time that ERS-1 was put into hibernation

in June 1996, the orbit determination had improved from the level of about 1.2 meters to about 4-5 cm in radial direction. The mission ended when the satellite spun out of the proper attitude and the batteries froze before the satellite was put into its proper orientation.

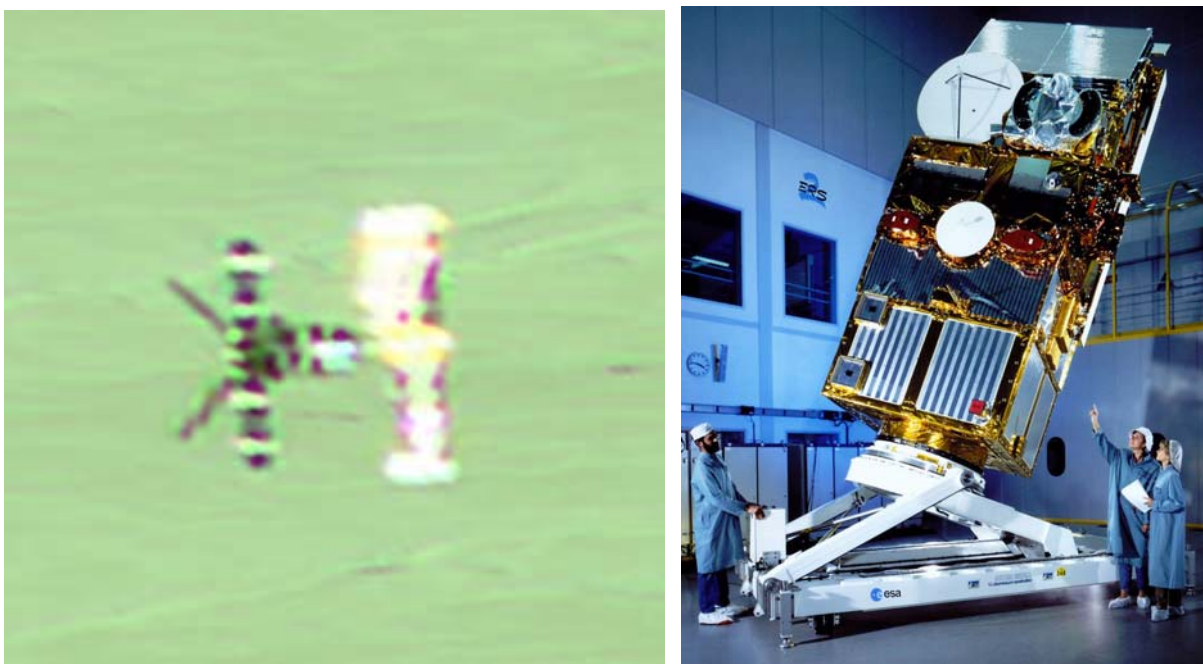


Figure 2. ERS-1 as seen by the SPOT-4 satellite (*left*) and ERS-2 at ESTEC, Noordwijk, The Netherlands (*right*).

ERS-2

The successor of ERS-1, ERS-2 (Figure 2), has proven even more successful than its predecessor. Now, more than eight years since its launch on 21 April 1995, the satellite is still fully operational. Added to the ERS-1 suite of equipment is the Global Ozone Monitoring Experiment, designed to monitor the global distribution of ozone in the upper atmosphere. A further enhancement is the implementation of a fully redundant design of the PRARE tracking system. Although PRARE is still operating, the ground segment has seriously degraded: many of the ground transponders have been rendered inoperative and no further PRARE mission is expected. Due to the delay of a month or more in the delivery of the PRARE data to the orbit determination community, the data was never seriously used in an operational way. Again, SLR provided, and still provides today, the most useful tracking data for ERS-2's operational and precise orbit determination.

Not only the altimeter community benefits from the precise orbits; SAR interferometry now also demands accurate orbits, primarily in the cross-track direction. By overlapping and differencing SAR observations of ERS-1 and ERS-2 striking images could be created that show the land displacements after earthquakes such as those in Izmit, Turkey, on 17 August 1999 (Figure 3).

Another topic in which ERS-1 and ERS-2 have excelled is the assessment of change in the elevation of the Antarctic ice sheet. Until the late 1990's the heating of the atmosphere and the associated melting of the Greenland and Antarctic ice sheets were thought to be the major contributors to sea level change. Because of the high inclination of the ERS satellites, their ability to measure the height of ice sheets as well as that of the ocean surface, and the precise orbit determination made possible by the global SLR tracking, the change of the Antarctic elevation could be measured during several years. Figure 4 shows that, except for the Western Antarctic, the elevation change is marginal and certainly not large enough to play even a secondary role in global sea level change.

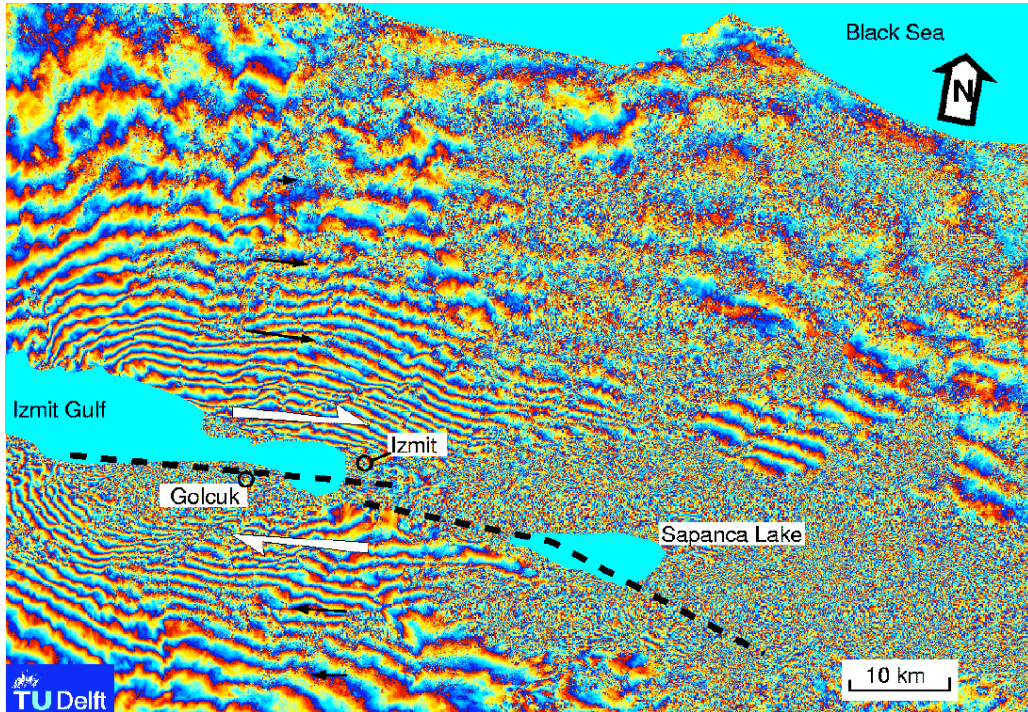


Figure 3. Interferogram created from SAR images before and after the 17 August 1999 earthquake in the neighborhood of Izmit, Turkey. The rainbow colors indicate displacements in the viewing direction of the SAR instrument.

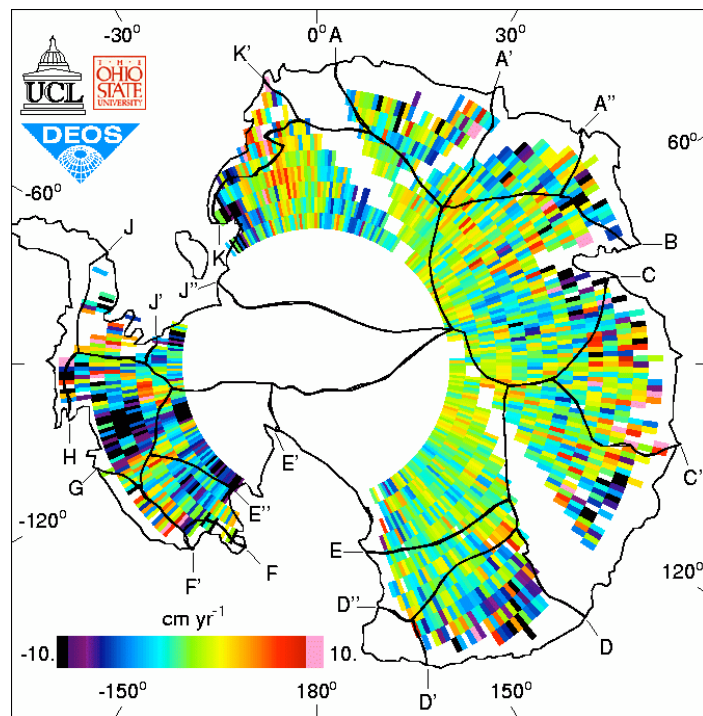


Figure 4. Antarctic elevation change determined from ERS-1 and ERS-2 altimeter observations during the period of 1992 until 1996.

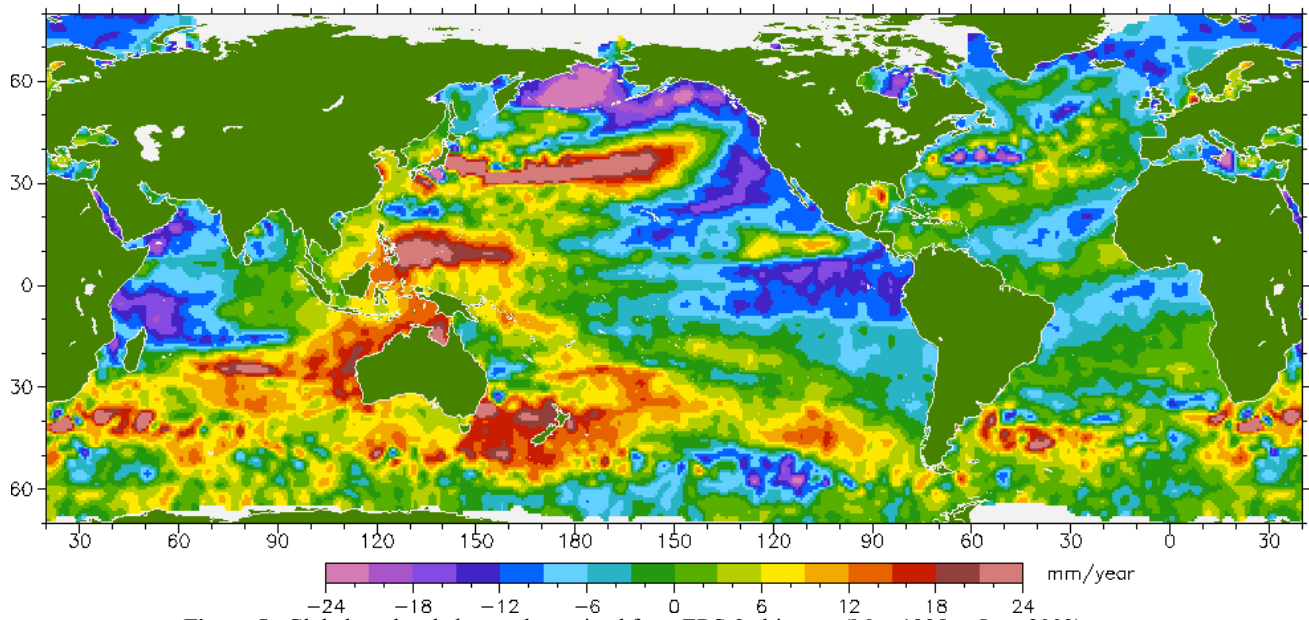


Figure 5. Global sea level change determined from ERS-2 altimetry (May 1995 to June 2002).

Sea level change itself, meanwhile, has also become better understood due to the contribution of various altimeter satellites. Now that orbit determination has so much improved and is basically similar in precision for the different satellites, the global maps of sea level rise (Figure 5) have also become similar for the different missions. Not well understood is now why different periods can show completely different rates of sea level change.

TOPEX/Poseidon

In contrast to the ERS missions, the TOPEX/Poseidon mission is dedicated to satellite altimetry. With its higher altitude, superior tracking (GPS, DORIS and SLR) and dual-frequency altimeter, it is especially suitable for studies of tide modeling and global and basin-wide ocean circulation (Figure 6). Unfortunately, the design of the SLR array mounted on the satellite – a ring of corner cubes around the rim of the altimeter – appeared to be a bad choice. Despite that, the TOPEX/Poseidon spacecraft receives more SLR tracking than any other altimeter satellite, even though it doesn't really need it with the DORIS and GPS tracking still fully operational. The combined use of DORIS and SLR tracking data currently provides an unprecedented radial orbit precision of about 1-2 cm. With its launch on 10 August 1992, it is the longest flying altimeter mission ever, which far exceeds the estimated lifetime of 4 to 5 years.

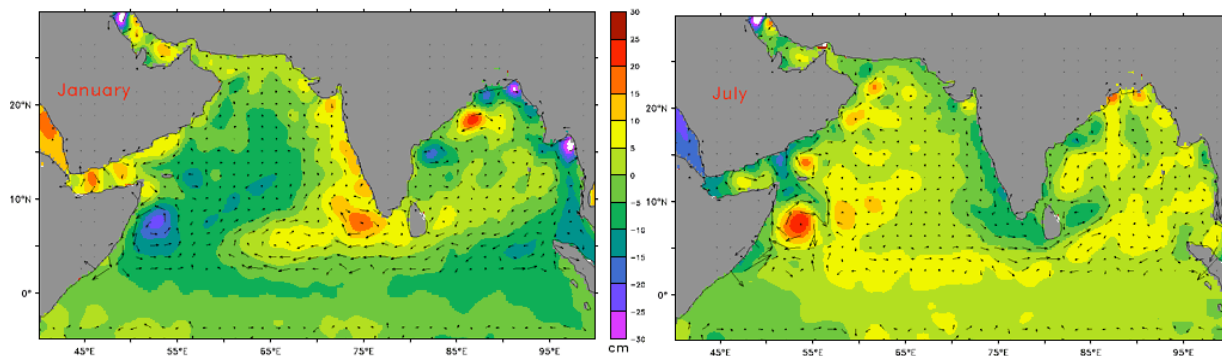


Figure 6. Currents related to the monsoon in the Indian Ocean as mapped by the TOPEX altimeter.

GFO

The altimeter satellite Geosat Follow-On (GFO) is particularly aimed at the operational use of altimeter measurements by the U.S. Navy. The satellite is equipped with various GPS receivers, of which all but one failed, while the remaining one performs badly and interferes with the operation of the main instrument, the satellite altimeter. It is fortuitous that the satellite also carries a laser retroreflector array (Figure 7); even more so since it was added to the design only at the eleventh hour. After many failed attempts to revive the GPS receivers and with the support of the SLR community, the satellite was declared operational on 29 November 2000, almost 3 years after its launch on 10 February 1998.

Although the U.S. Navy operators appear satisfied with S-band tracking as the basis for orbit determination, the SLR community has salvaged the science mission of the GFO satellite. After significant tuning of the gravity field model to this satellite with an inclination of 108° , and with the help of sufficient SLR tracking, the radial orbit precision has now come down to 5-7 cm.

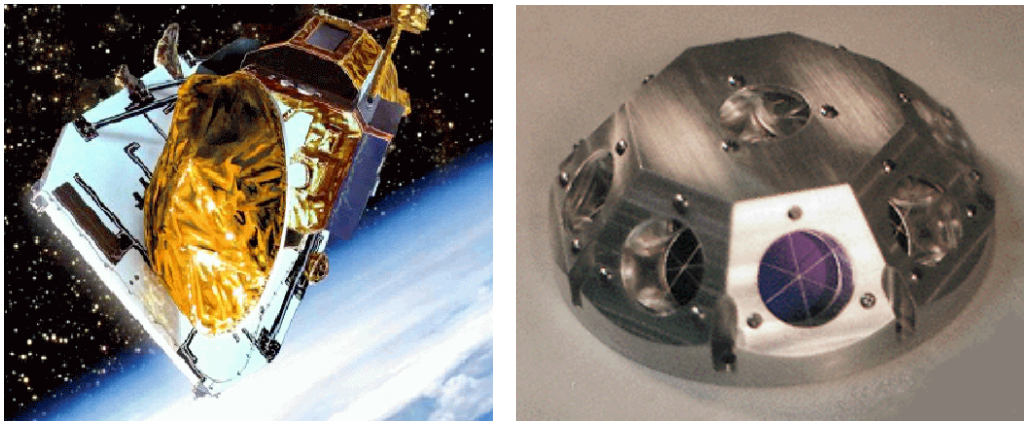


Figure 7. Artist impression of GFO (*left*), and the laser retroreflector that saved the mission (*right*).

Jason-1

Launched on 7 December 2001, the Jason-1 altimeter satellite (Figure 8) is, like its predecessor TOPEX/Poseidon, a mission solely dedicated to satellite altimetry. It carries again the combination of GPS and DORIS plus a laser retroreflector array. This time, a more optimal design of the laser retroreflector was chosen: the same one as for GFO. However, the DORIS instrument, a next generation version with more capabilities and of a significantly smaller size and mass than its predecessor on TOPEX/Poseidon, experiences some problems. The tracking system seems to suffer from the high radiation associated with the South Atlantic Anomaly, which is evident in the residuals of DORIS measurements from beacons at Southern latitudes. Is this yet another mission that has to be saved by the SLR community?

Envisat

Envisat (Figure 8) succeeds the ERS-1 and ERS-2 missions. Like its predecessors, it is a multi-disciplinary mission of which both the radar altimeter and the SAR instrument are most needy of precise orbits. Envisat has forsaken the PRARE tracking system and replaced it with the DORIS tracking system. Ever since its launch on 1 February 2002, the DORIS system has been performing well and can sustain precise radial orbit determination at the level of 2-3 cm. This system, a slightly older and less miniaturized version than Jason-1's, is not hampered by the problems we see for that satellite. With a DORIS tracking coverage far better than what SLR can provide (Figure 9), the role of SLR for this satellite is limited to short-arc orbit determination in support of the calibration activities in

the Mediterranean Sea, and to aid the establishment of a global SLR/DORIS combined reference system. Both issues are extremely important to maintain a global sea level record to within a few millimeters throughout the altimeter missions.

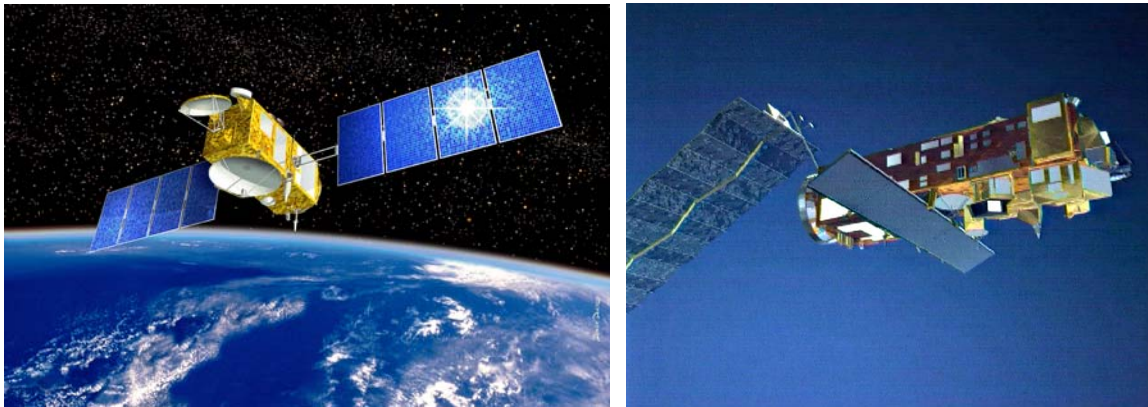


Figure 8. Artist impressions of Jason-1 (*left*) and Envisat (*right*).

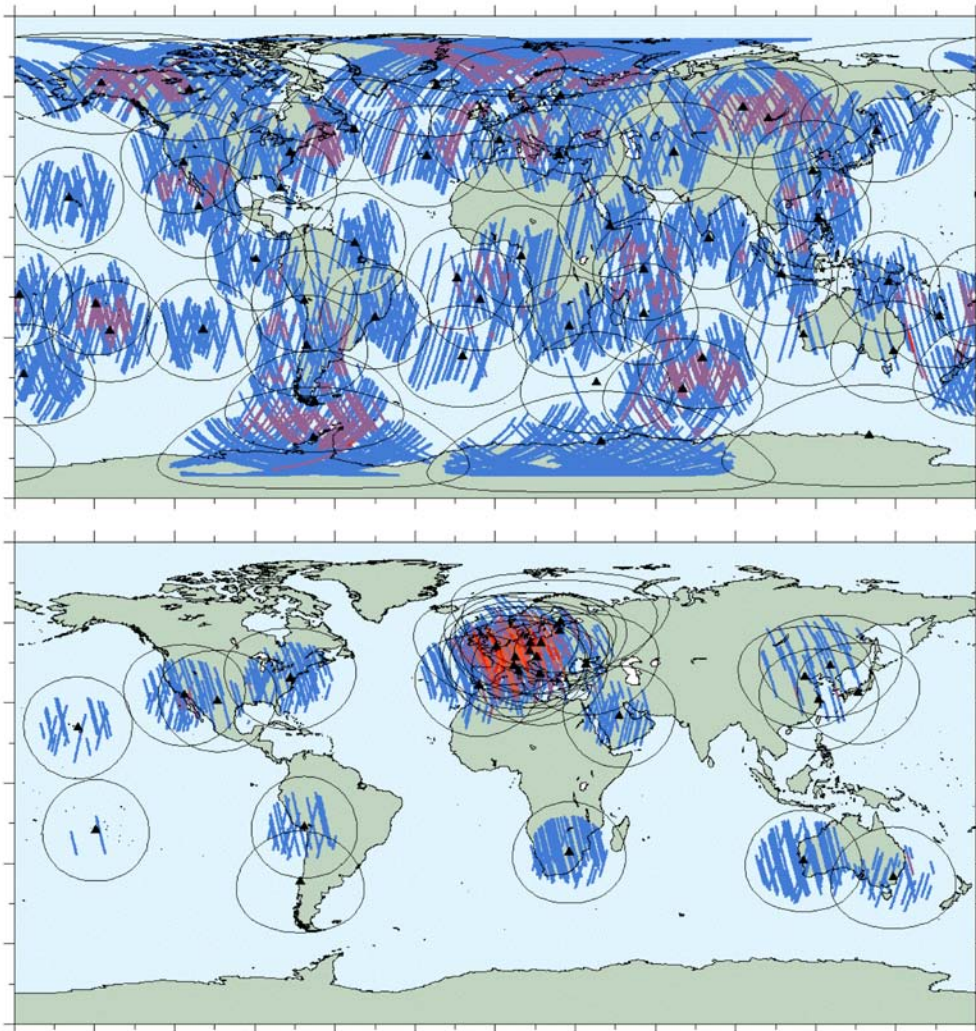


Figure 9. Envisat tracking coverage by the DORIS beacons (*top*) and SLR stations (*bottom*). The purple and red colors indicate tracking by two or more stations simultaneously.

Tracking Coverage Throughout the Years

As Figure 10 shows, despite the increasing number of altimeter satellites, the tracking coverage of each of the satellites has basically remained the same. During the first year (mid-1991 until mid-1992) there was only ERS-1. This satellite received at the time some 150 passes per month from about 20 stations. More or less the moment when ERS-1 became operational and TOPEX/Poseidon was launched, tracking altimeter satellites became more popular; the number of contributing tracking stations soared to thirty and both ERS-1 and TOPEX/Poseidon started to receive between 400 and 700 passes per month. Even when ERS-2 was launched the laser tracking of the other two altimeter satellites remained basically stable, with only the Northern Hemisphere winter showing a decline in tracking coverage (due to the generally worse weather conditions over the majority of SLR stations).

Although the altimeter of ERS-1 remained switched off ever since the satellite went into hibernation in June 1996, the SAR was revived occasionally later on. Since the technique of SAR interferometry for the mapping of land displacements relies on the availability of precise orbits, the additional tracking ERS-1 received during the years 1998 and 1999 was extremely valuable.

GFO, crippled by the failure of its GPS receivers, is currently receiving some 200 passes per month, enough to determine orbits to the level suitable for its application in meso-scale and global ocean circulation studies.

Furthermore, both Jason-1 and Envisat are relying on SLR to tracking independent of the DORIS (and GPS) receivers. The 400 to 500 passes per month are used to evaluate differences in orbits based on SLR and DORIS tracking, to assess reference frame differences, and to study the impact of the degraded DORIS tracking of Jason-1 in the Southern Hemisphere. In addition, SLR is the only tracking type that can provide highly precise short-arc orbits to be used for the purpose of the calibration of the altimeters over the Mediterranean Sea.

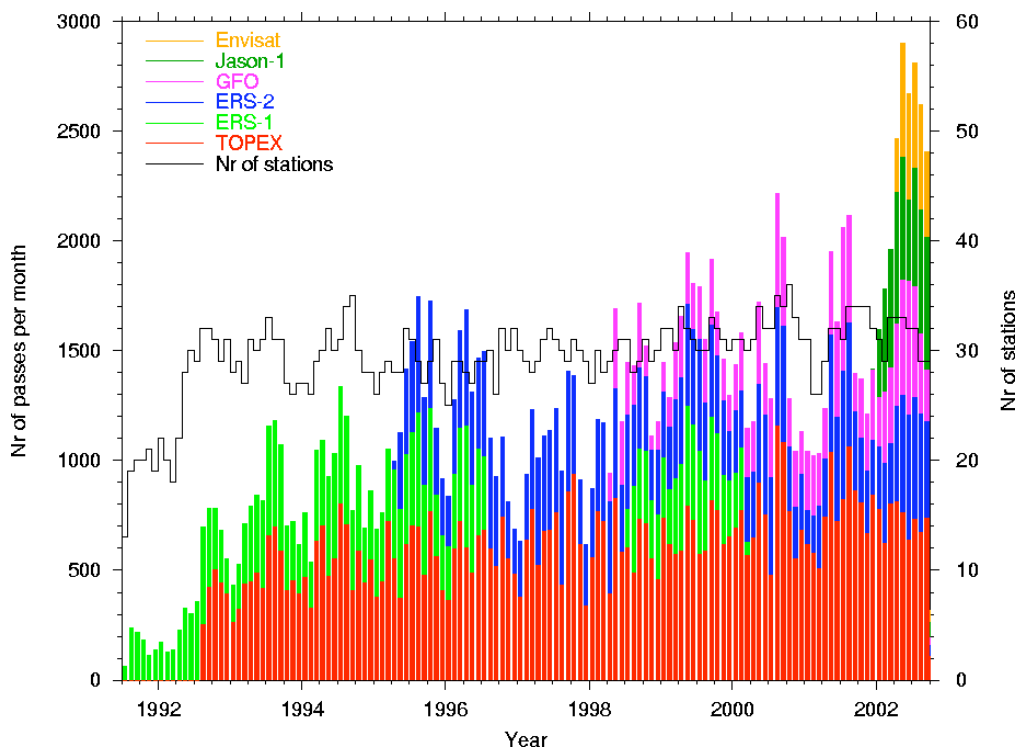


Figure 10. SLR tracking for the years 1991 through 2002. The differently colored bars indicate the cumulative number of SLR tracking passes per month dedicated to altimeter satellites. The black line indicates the number of SLR stations contributing tracking to altimeter satellites.

The amount of tracking passes is not equally distributed among the tracking stations (Figure 11); some stations have an extremely high track record. In general, the majority of the tracking comes from the ten most active stations.

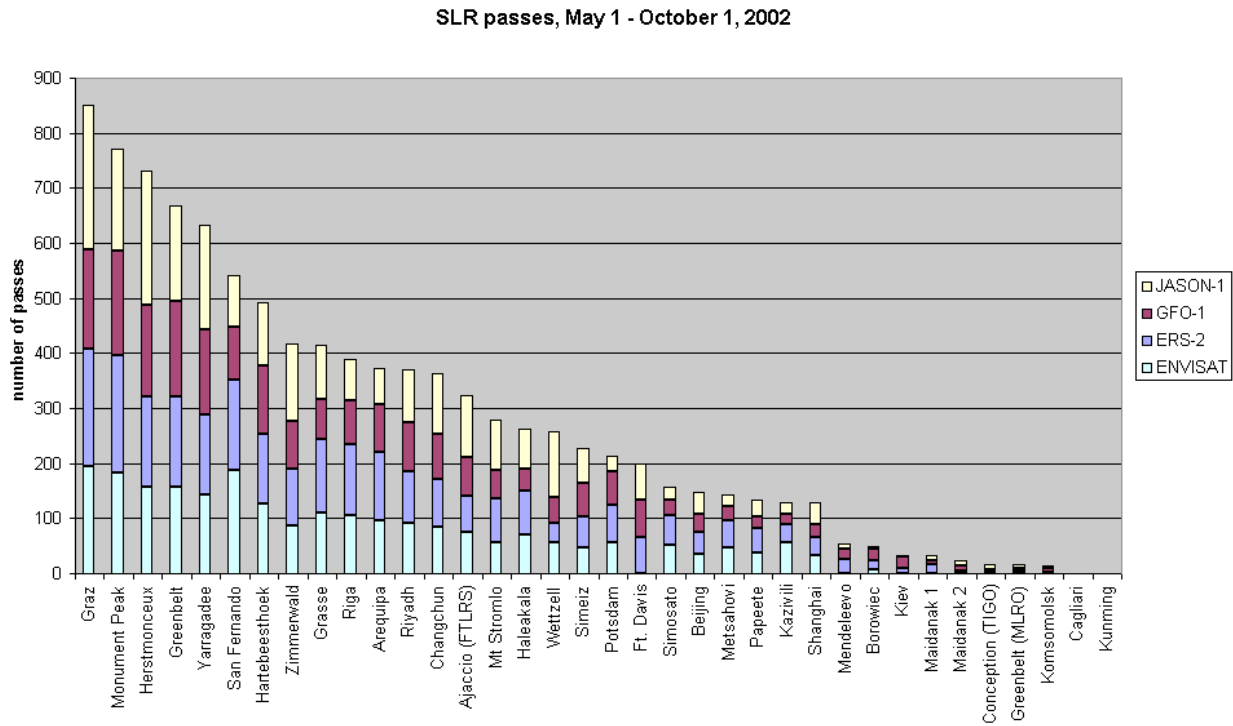


Figure 11. Number of SLR passes of altimeter satellites tracked by individual laser stations during the period 1 May until 1 October 2002 (in order of their number).

Table 2. SLR tracking awards for the period 1 July 1991 to 1 October 2002.

Most passes of altimeter satellites			
Monument Peak	12980		
Yarragadee	12537		
Herstmonceux	11540		
Most passes of altimeter satellites on a single day			
Graz	27	1 Oct 2002	
Zimmerwald	21	28 Jul 2002	
Orroral Valley	19	7 Sep 1998	
First to track altimeter satellites			
ERS-1	Grasse	17 Jul 1991 20:29	Launch + 18:35
TOPEX	Herstmonceux	10 Aug 1992 23:36	Launch + 00:28
ERS-2	Riga	24 Apr 1995 18:50	Launch + 17:04
GFO	Fort Davis	22 Apr 1998 02:56	Launch + 43 days
Jason-1	Greenbelt	19 Dec 2001 09:30	Launch + 2 days
Envisat	Riga	10 Apr 2002 19:28	Launch + 41 days

If the gratitude of the altimeter community to the SLR community can be expressed in terms of awards, certainly some should be awarded to the stations that provided most of the tracking (Monument Peak, Yarragadee, and Herstmonceux), to those that tracked most altimeter satellites on a single day (Graz, Zimmerwald and Orroral Valley), and to those that were first to track any of the altimeter satellites since launch (Grasse, Herstmonceux, Riga (twice), Fort Davis, and Greenbelt). See Table 2 for a list of their accomplishments. But evidently, the gratitude goes out to all stations that ever tracked any of the altimeter satellites during the years since 1991.

Conclusions

SLR has provided significant support to a large number of altimeter missions. In the case of ERS-1 and GFO, laser ranging saved the science mission, because without laser tracking precise orbit determination would be impossible. For ERS-2, laser ranging also continues to be the only operationally available and reliable source of tracking. The current missions of Jason-1 and Envisat benefit from laser tracking during the calibration campaigns as well as to establish a common DORIS/SLR reference frame.

The valuable contribution of SLR to all altimeter missions is mirrored in nearly every contribution that satellite altimetry makes to Earth sciences.