SLR: A point of view on scientific achievements and future requirements

P. Exertier, J. Nicolas, and F. Barlier
OCA/CERGA, av. N. Copernic, F-06130 Grasse

12th International Workshop Laser Ranging, Nov. 2000, Matera, Italy
Session: Scientific Achievements, Applications, and Future Requirements

Abstract

In Space Geodesy, scientific achievements and applications using Satellite Laser Ranging (SLR) data have been obtained and developed in many fields: orbitography, Earth rotation and geocentric reference frame, geodynamics, determination of long wave lengths of the gravity field and of the geocentric gravitational constant (GM), calibration/validation of products in space oceanography, time transfer, space debris control,….
But, in parallel, the radioelectric techniques (GPS, DORIS, PRARE) made so important progress in efficiency and precision that the role of SLR technique has to be repositioned and specified. In fact we would like to recall that in many fields the role of SLR appears to be irreplaceable, such as for the determination of the first spherical harmonics and of the geocentric gravitational constant, the long term sea level monitoring through actions of calibration and validation of the oceanographic satellite,…. Stopping the SLR technique would be a disaster in fundamental metrology of the Space Geodesy.
However SLR has to be competitive in terms of accuracy, efficiency, and cost. This technique has to be maintained at its highest level and to be improved continuously as carried out by the ILRS (for example permanent and fast quality control with feedback to the stations). Other improvements are to be considered : laser systems with high frequency rate and very small energy, automation of stations, development of two–color laser systems,…. General comments are given.

1. Introduction

The quality of space geodesy and Earth science research depends to a large extent on our ability to obtain numerous, and accurate measurements covering a wide spatial and temporal spectrum. Over the last 30 years, we have developed techniques to measure the position, the velocity, and the acceleration of objects orbiting the Earth, techniques that offer today high levels of accuracy. In this context, space geodesy research has defined innovative measurement techniques, including laser ranging, Doppler tracking, and radar altimetry, which have been implemented by major space projects such as space oceanography missions (TOPEX/Poseidon (T/P), ERS, GFO).

These achievements are the result of a long-term strategy. Over a 20-years period — from the 1970’s to the 1990’s — satellite tracking techniques were all improved by several orders of magnitude, both in terms of quality (measurement precision and accuracy) and quantity (number and rapid availability of data, and spatial and temporal coverage). During the 1990’s, applications of radioelectric systems such as DORIS (Doppler Orbitography and Radio-positioning Integrated by Satellite) and GPS (Global Positioning System) progressed to a point where they are now operating within a global network and have attained the same level of performance as the satellite laser ranging technique (SLR). At the same time, SLR has benefited notably from the emergence of new technologies, in chief among them being avalanche photodiodes in Europe and micro-channel photomultipliers (MCP) in the United States. These new technologies have enabled us to achieve subcentimeter measurement accuracy for about 30% of laser ranging instruments operated around the world (ILRS Annual Report, 1999).

While all space-based measuring techniques have become more accurate over time, they have also found their own special applications in geodesy, geophysics, and oceanography. Techniques like DORIS and SLR give an essential contribution to the Earth gravity field determination. In the domain of positioning, SLR has also a contribution in the ITRF (International Terrestrial Reference Frame) realization but this technique does not necessarily offer the highest precision and the best temporal resolution (comparing to GPS). However it is the most accurate in the long term (for geodynamics), because its performances can be permanently controlled and improved by specialist personnel on the ground. In addition, the properties of laser targets appear to have a perfect stability in space with an unlimited lifetime at the human scale. This is not the case with the other techniques. This makes the laser technique an unrivaled tool for observing slowly-varying geodynamic phenomena and for establishing an accurate global terrestrial reference system (Tapley et al., 1993). Moreover, SLR provides an absolute scale factor for orbit determination, by determining the gravitational constant (GM) from data acquired by LAGEOS (Dunn et al., 1999; Smith et al., 2000), and for space oceanography, particularly by calibrating radar altimeters (Francis, 1992; Ménard et al., 1994; Bonnefond et al., 1995).

In this paper, we highlight the advantages and drawbacks of SLR in an attempt to chart the future of this technique. In addition, we discuss the possible improvements and evolutions that will be necessary to the technique in order to permit a wide range of future applications in the Solar System.

2. SLR as Technique

The advantage of SLR lies in its simplicity—the concept is based on measuring the round-trip time of a very short laser pulse—and its accuracy. It relies on relatively low-cost retroreflectors onboard satellites or stationed on the Moon by the American and Soviet missions between 1969 and 1973. Its main drawbacks are its dependence on favorable weather conditions and the need for specialist personnel on the ground. In this sense, SLR is in many ways the opposite of radioelectric techniques such as DORIS, GPS, and GLONASS, which provide an all-weather capability, are very easy to set up and use in the field, and for which the spaceborne segments used are very costly.

New SLR technologies developed to meet the evolving needs of the space geodesy community have improved internal instrument precision by several orders of magnitude in the last decades (Degnan, 1993): from few centimeters at the end of the 1980s to few millimeters today, in terms of normal point residuals (rms). In recent years, efforts have focused on using new detectors: in Europe, with avalanche photodiodes and electronic systems to control response times in accordance with the power of the return signal (C-SPAD) (Kirchner and Koidl, 1996) while MCP are used in the United States (Degnan, 1993).

At the same time, the laser community has worked to establish precise error budgets through a rigorous study of the main technological sub-systems limiting precision and accuracy (Samain et al. 1998), i.e. station calibration, variable detector response times, timing, variable light propagation times in the troposphere, satellite signature effect, and so on. Analysis of these sub-systems in addition to analysis of many SLR data of different sites in view of geodetic/geodynamic purposes has yielded the error budget shown in Table 1.

Table 1: Laser ranging error budget for the French stations (units in mm) from (Schwartz, 1990; Samain et al., 1998; F. Pierron and J.F. Mangin, private communication, 1999; Nicolas, 2000a).

Origin	precision	accuracy
Laser	4-5	
(pulse)	(1)	
(width)	(4-5)	
Detector	3-6	
(start)	(1-3)	
(return)	(3-5)	
Timer	2-3	
Clock	1-2	
Calibration	1	2-6
(geometry)		(1-2)
(electronic)		(1-4)
Depend. (Az, El)	1-3	
Instrument	6-9	2-6
Atmosphere	3-5	5-8
(pressure)		(1-2)
(temperature)		(1)
(humidity)		(4-5)
Target signature		
T/P	4-5	1-4
LAGEOS	1-3	1-3
(Moon)	(1-50)	
Single shot	7-12	
Normal Point	1-3	8-18

Broadly speaking, these results show that the French laser stations which are among good quality laser instruments offer:

- an average precision of 6 to 9 mm with a single reflector,
- an average precision of 7 to12 mm (single shot) with a geodetic satellite (up to 30 mm for reflector panels having a complex shape or for which the orientation is not well known), i.e. a precision of 1 to 3 mm for a computed normal point,
- an overall accuracy of the order of 8 to 18 mm. However, the overall accuracy of SLR is very difficult to evaluate and to maintain near 5 mm due to instrument instabilities, and atmospheric and local effects.

Bias stability (or unstability) is the part due to uncontrolled variations of different sub-systems, variations that affect instrument precision and accuracy. The instrumental bias stability over 3 months is of about 5-20 mm and the normal point stability varies from 6 to 25 mm depending on the considered station and satellite.

3. SLR for Space Sciences

Geodynamics

Improved precision and accuracy of space-based ranging techniques have driven development of recent models of the Earth's gravity field, i.e. JGM-2, JGM-3, GRIM4-S4, EGM96 and GRIM5-S1 (Nerem et al., 1994, Tapley et al., 1996; Schwintzer et al., 1997; Lemoine et al., 1998; Biancale et al., 2000).

In addition to the three satellites currently having onboard the DORIS instrument, there are about 20 laser targets on satellites covering a wide range of inclinations and altitudes (from

350 km - GFZ-1, to 20,000 km - Etalon), and with very long operating lifetimes, such as Starlette, Stella, Ajisai, LAGEOS and LAGEOS-2. These systems, combined with long time series of centimeter-precision laser observations available over the last 10 to 15 years, have significantly enhanced measurements of the geoid long wavelengths and ocean tide terms. They have also improved our knowledge of the gravity field temporal variations (Cazenave et al., 1996; Cheng et al., 1997; Exertier et al., 1999).

Furthering our understanding of the gravity field and its temporal variations — the long wavelength terms, including the value of GM — is vitally important for orbit determination and, therefore, for positioning and space oceanography (Degnan, 1997; Dunn et al., 1999; Smith et al., 2000). On the other hand, the higher harmonics (greater than degree 20) requiring a very good coverage have been improved thanks to radiotracking data as well as gravity and altimetry data (Exertier, 1993).

All this effort enables a better gravity field and finally a better only based laser data orbit, as for ERS-1 and GFO.

Time transfer

The Satellite Laser Ranging appears to be the most accurate technique for the time transfer. Time transfer experiments consist in synchronizing space and ground atomic clocks distant from thousands of kilometers. Very short laser pulses (few tens of picoseconds) can be used. The space segment is composed of a laser pulse detection and timing system, a clock and laser retroreflectors. A laser ground station connected to a terrestrial laboratory clock is also needed. SLR measurements allow to know the time-lag between the space and the laboratory clocks.

The ultra precise clock PHARAO would be placed on the International Space Station in 2004 (ACES and Time Transfer by Laser Link T2L2 experiments). The objective is to realize this time transfer with an accuracy of about 50 ps and a temporal stability better than 1 ps over 1000 s of integration, which represents an improvement of more than 1 order of magnitude with respect to present techniques.

SLR as Service

Recently, the International Laser Ranging Service (ILRS) was set up in 1998, based on the model successfully applied for GPS (IGS). This service enables structured international cooperation on SLR issues in the future. The ILRS now aims to defining priority programs, organizing campaigns, and evaluating measurement and even product quality (i.e. results obtained in global geodesy) on an almost daily basis. Regular publications of comparative instrument bias data at different timescales and of normal point precision have created a competitive spirit that is driving stations to do even more to meet quality and performance requirements. The result is that stations can now detect significant biases without delay, thus making a much more effective contribution to improving range measurement accuracy, and above all ensuring better stability at scales such as several months, one year or more (see e.g. ILRS reports; Nicolas et al., 1999).

Orbitography

Real progress has been made through increasingly accurate determination of the T/P orbit between 1992 and 1996, to within 2 to 3 cm today (Lemoine et al., 1998). These results have been achieved largely thanks to the very good coverage of altimetry satellite orbits by the DORIS and SLR complementary systems on T/P (Nouël et al., 1994), not forgetting PRARE and SLR on ERS-2 (Andersen et al., 1998).

Actually, laser ranging stations are geographically less well distributed than the DORIS and GPS networks. Moreover, changing weather conditions mean that the laser network is never exactly the same over time. Consequently, the laser network is sometimes limited in spatial and temporal coverage leading to orbit determination difficulties at the start of missions, such as ERS-1 and GFO. But it has to be emphasized that better gravity field models and orbitographic methods, in addition to a better quality of the ITRF solution, have allowed to determine only laser-based data orbits at a much better precision level than in the past with Seasat or Geosat (Scharroo et al., 1992; Scharroo and Visser, 1998).

But the main contribution of laser ranging to orbit dynamics during the 1990's has been to achieve ever more accurate range measurements, particularly at high elevations where the uncertainty related to atmospheric propagation corrections is lowest. These absolute data have enabled us to calculate the radial error budget for altimeter satellite orbits with a high degree of confidence (Tapley et al., 1994; Bonnefond et al., 1995; Scharroo and Visser, 1998). In addition to this major contribution of SLR to altimetry, absolute range measurements obtained during the IGEX-98 campaign — for GLONASS, and GPS-35 and -36 satellites — have allowed us to establish local and regional control points to calculate orbit errors at an accuracy level of 1 to 2 cm maximum (Barlier et al., 2000).

We could call these contributions of SLR the orbit *scale factor*, since (i) radioelectric systems only yield differential tracking measurements (Doppler and GPS), and (ii) such radioelectric measurements are a lot more sensitive than laser measurements to atmospheric water vapor content, a parameter that is still poorly known.

Oceanography

The space oceanography is based on altimeter data which can be efficiently used only if very precise orbitography and accurate radar altimeter calibration are available.

With uncertainties currently running at around a few millimeters per year it is difficult to identify signatures of small oceanographic phenomena and at the same time, drift and/or inherent errors (biases) in a complete space system including terrestrial reference frames, orbit models, and measuring instruments (altimeters and associated devices as water vapor radiometers with tide gauge measurements combined with geodetic surveying and positioning systems).

The SLR role during calibration campaigns is to achieve centimeter accuracy locally for the altimetry satellite orbit (Bonnefond et al., 1995). For radar altimeter calibration to be successful, campaigns must be performed if possible under the satellite track in zones where the slope of the geoid is smooth, away from the coast (on an island or an offshore platform) and in a region where the logistics involved are not prohibitively expensive. With these aims and future space oceanography missions such as Jason-1 and EnviSat in mind, we have set up a semi-permanent site in Corsica with the lowest possible installation and monitoring costs (Bonnefond et al., 1997; Nicolas et al., 1998). The ultra mobile FTLRS system (French Transportable Laser Ranging Station) which is at the end of an improving phase in order to achieve a 1 cm accuracy (Nicolas et al, 2000b and 2001), will be deployed here in 2001 first for the Jason-1 calibration and validation phase. This kind of experiment is planned to last over several years in order to detect any drift in the spaceborne instruments. However, many absolute worldwide calibration sites are necessary, because each site brings its own systematic errors. In addition to Corsica, other sites are today into consideration: near Barcelona, Spain, or on the Crete island (Gavdos project).

Earth rotation and reference frame

A global reference frame, stable to within better than 1 mm per year and geographically well distributed, is a crucial goal that must be pursued, with strong consequences for global geophysics and oceanography.

SLR, chiefly through LAGEOS, can contribute to reference frame stability in the very long term, i.e. over several decades or so (Tapley et al., 1993).

Accuracy of 3-D laser positioning is estimated to be 12 to 14 millimeters with respect to the ITRF, and has evolved not as much as expected since ITRF94 (Boucher et al., 1999, Sillard et al., 1998). Indeed, determination of the altitude and vertical velocity of laser ranging stations has been made harder until recently due to instrument bias instabilities. This fact has been confirmed with different laser reference frames, including ITRF94 and ITRF96, in the analysis put forward by Bonnefond et al. (1999).

We must therefore continue efforts to improve the accuracy of vertical velocity fields of tracking stations, particularly laser ranging stations because they have, in addition to VLBI ones, the potentiality of driving scale and rate factors of the entire ITRF (Altamimi and Boucher, private discussion, 2001). Today, ten years of accurate SLR data are required to get an expected stability of less than 1 mm/year. In this respect, the work of the ILRS to evaluate the quality of data and information intended for stations is also important and must be pursued.

Finally, SLR appears to be the most accurate space-based technique to estimate the geocenter motion (motion of the center-of-figure with respect to the center-of-mass due to surface mass redistribution). The precise knowledge of redistribution of fluids and atmospheric masses (via in situ measurements and global models) over time-period of several years is then a crucial point to be emphasized in the years to come (Cazenave et al., 1999).

Of course, SLR data as well as other space techniques like GPS and DORIS are not very well suited to link the terrestrial reference frame to very far extra-galactic radio-sources. Thus, it is possible to determine accurately the universal time and the length of day variations over long periods of time. For doing that, the Very Long Base Interferometry technique (VLBI) has a specific and unique role.

5. Discussion about SLR short and medium terms

In the next future, the role of the ILRS will be extremely important to ensure the bias stability and the feedback from the analysis centers to the SLR stations. It is hoped that most of the stations will be equipped with metrology of highest level so that an accuracy at the level of 1.0 or 1.5 cm should be achievable and of course much better, if possible. A significant limiting factor is the laser beam propagation in the troposphere (at the level of a few millimeters up to 10 mm or even more). So the modeling of the troposphere correction should be improved, based on meteorological data including the water vapor content for instance thanks to radiometer measurements (Reipl, 2000). However, the real challenge could be to develop an operational mode two-color laser ranging stations but it is not an easy problem as it is well known by the experts (Gaignebet et al., 2000). The problem is open and has to be studied.

Another limiting factor is also the satellite signature effect, generating systematic effects even for satellite like LAGEOS at the level of few millimeters.
The number of targets to be tracked increase from year to year. Thus, the role of ILRS increases notably to define the observation priorities. But, concerning the stations, it becomes very important to have the capability to track in a quasi-simultaneous mode several satellites.
Another question is the worldwide distribution of the SLR stations. Fortunately positive decisions have been taken to install new stations in South Africa, Argentina and Chili by Americans and German colleagues (ILRS, 2000).
Finally the problem of manpower cost cannot be forgotten. Partial or fully automation has to be considered. Very encouraging experiments have been already tested for example in Australia and other experiments are ongoing as in Italy in Matera, in other Europeans countries and also in the USA (automated and eyesafe SLR2000 system). It is a very important question for SLR to be competitive with the other techniques.

New applications with the development of new generation of very precise and stable atomic clocks onboard space probes can be envisioned. New prospects for using one way laser ranging exist in the Solar System. It could be interesting not only for improving some general relativity tests by several orders of magnitude, but also for instance in positioning space probe or orbiter around planets like Mars.

References

Andersen, P.H., K. Aksnes, H. Skonnord: 1998, Precise ERS-2 orbit determination using SLR, PRARE, and RA observations, *J. of Geodesy*, 72, 421-429

Barlier, F., Ch. Berger, P. Bonnefond, P. Exertier, O. Laurain, J.F. Mangin, J.M. Torre (2000) Laser-based validation of GLONASS orbits by short-arc technique, *Journal of Geodesy*, Special Issue IGEX-98, in press

Biancale, R., G. Balmino, J.M. Lemoine, J.C. Marty, B. Moynot, F. Barlier, P. Exertier, O. Laurain, P. Gegout, P. Schwintzer, Ch. Reigber, A. Bode, R. Koenig, F.-H. Massmann, J.C. Raimondo, R. Schmidt, S.Y. Zhu, (2000) A new global Earth gravity field model from satellite orbit perturbations : GRIM5-S1, *Geophys. Res. Lett.*, 27(22), 3611-36

Bonnefond, P., P. Exertier, P. Schaeffer, S. Bruinsma, and F. Barlier: 1995, Satellite altimetry from a short-arc orbit technique : Application to the Mediterranean, *J. of Geophys. Res.*, 100(C12), 25365-25382

Bonnefond, P., P. Exertier, Y. Ménard, E. Jeansou, G. Manzella, S. Sparnocchia, and F. Barlier: 1997, Calibration of radar altimeters and validation of orbit determination in the Corsica-Capraia Area, in Proceedings of the 3rd ERS Symposium, Florence, Italy, Vol. 3, pp. 1525-1528

Bonnefond, P., P. Exertier, F. Barlier: 1999, Geographically Correlated Errors Observed from a Laser-based Short-Arc Technique, *J. Geophys. Res.*, 104(C7), 15885-15893

Boucher, C., Z. Altamimi, P. Sillard: 1999, The ITRF97, in *IERS Technical Note*, 27, Central Bureau of IERS, Observatoire de Paris, France, May 1999

Cazenave, A., P. Gegout, G. Ferhat and R. Biancale: 1996, Temporal variations of the gravity field from LAGEOS 1 and LAGEOS 2 observations, in "Global Gravity Field and its Temporal Variations", *Proceed. of IAG Symp. G3*, Springer-Verlag, New York, Vol. 116, pp. 141-151

Cazenave, A., K. Dominh, L. Soudarin, F. Ponchaud, Ch. Le Provost: 1999, Sea level changes from TOPEX/Poseidon altimetry and tide gauges, and vertical crustal motions from DORIS, *Geophys. Res. Lett.*, 26(14), 2077-2080

Cheng, M.K., Shum C.K., and B.D. Tapley: 1997, Determination of long-term changes in the Earth's gravity field from satellite laser ranging observations, *J. of Geophys. Res.*, 102(B10), 22377-22390

Degnan, J.J.: 1997, Satellite laser ranging : scientific and technological challenges for the new millenium, in *Proceed. of SPIE Symp. on Laser Radar Ranging and Atmospheric Lidar Techniques*, London, UK, Europto Ser., vol. 3218, pp. 80-91

Degnan, J.J.: 1993, Millimeter accuracy Satellite Laser Ranging: A review, in *Contributions of Space Geodesy to Geodynamics: Technology, Geodyn. Ser.*, 25, pp. 133-162

Dunn, P., M. Torrence, R. Kolenkiewicz, and D. Smith: 1999, Earth Scale defined by Modern Satellite Ranging Observations, *Geophys. Res. Lett.*, 26(10), 1489-1492

Exertier, P., S. Bruinsma, G. Métris, Y. Boudon and F. Barlier: 1999, Geodynamics from the analysis of the mean orbital motion of geodetic satellites, in *IAG Symposia - Geodesy beyond 2000 - The challenges of the first decade*, Schwartz Ed., Springer, Vol. 121, pp. 262-270

Exertier, P.: 1993, Geopotential from space techniques, *Celest. Mechanics*, 57, 137-153

Francis, C.R.: 1992, The height calibration of the ERS-1 radar altimeter, in *Proceed. of the first ERS-1 Symp. - Space at the Service of our Environment*, ESA Spec. Pub., ESA SP-359(1), pp. 381-393

Gaignebet J., J.L. Hatat and J.L. Oneto: 2000, Last developments and results in 2-color laser ranging at OCA/CERGA, in *Proceed. of the 12th Workshop on Laser Ranging Instrum.*, Matera, Italy, Nov. 2000, this issue.

ILRS: 1999, Report of the Third General Assembly of the International Laser Ranging Service (ILRS), Florence, Italy, Sept. 20, 1999

ILRS: 2000, 1999 Annual Report, Ed. by M. Pearlman and L. Taggart, NASA/TP-2000-209969, May 2000

Kirchner, G. and F. Koidl: 1996, Automatic SPAD time walk compensation, in *Proceed. of the 10th Workshop on Laser Ranging Instrum.*, Shanghai, China, Y. Fumin and C. Wanzhen Ed., pp. 293-296

Lemoine, F.G., S.C. Kenyon, J.K. Factor, R.G. Trimmer, N.K. Pavlis, D.S. Chinn, C.M. Cox, S.M. Klosko, S.B. Luthcke, M.H. Torrence, Y.M. Wang, R.G. Williamson, E.C. Pavlis, R.H. Rapp,T.R. Olson: 1998, The Development of the Joint NASA GSFC and the National Imagery and Mapping Agency (NIMA) Geopotential Model EGM96, *NASA/TP--1998-206861, GSFC*, Greenbelt, Maryland, July 1998

Ménard, Y., et al.: 1994, Calibration of the TOPEX/POSEIDON altimeters at Lampedusa : Additional results at Harvest, *J. Geophys. Res.*, 99(C12), 24487--24504

Nerem, R.S. et al.: 1994, Gravity model development for TOPEX/Poseidon: Joint Gravity Models 1 and 2, *J. of Geophys. Res.*, 99(C12), 24421-24447

Nicolas, J.: 2000a, La Station Laser Ultra Mobile – De l'obtention d'une exactitude centimétrique des mesures à des applications en océanographie et géodésie spatiales, PhD thesis, Nice-Sophia Antipolis University, Dec. 2000

Nicolas, J., F. Pierron, M. Kasser, P. Exertier, P. Bonnefond, F. Barlier, and J. Haase: 2000b, French Transportable Laser Ranging Station : Scientific objectives, technical features, and performance, *Applied Optics*, 39(3), 402-410

Nicolas J., F. Pierron, E. Samain, M. Kasser, F. Barlier, and J. Haase: 2001, Centimeter accuracy for the French Transportable Laser Ranging Station (FTLRS) through sub-system controls, *Surveys in geophysics*, in press.

Nicolas, J., P. Exertier, P. Bonnefond, F. Pierron, Y. Boudon, J.F. Mangin, F. Barlier, M. Kasser and J. Haase: 1999, Stability control of range biases on the French laser ranging stations, in *Proceed. of the EOS/SPIE Symp. on Remote Sensing*, Florence, Italy, Europto Ser., Vol. 3865, pp. 27-32

Nicolas, J., P. Exertier, P. Bonnefond, F. Pierron, and J. Haase: 1998, First results with the French Transportable Laser Ranging Station, in Proceedings of the 11th International Workshop on Laser Ranging, Deggendorf, Germany, published by the Bundesamt für Kartographie und Geodäsie, Frankfurt am Main **1**, Ed. Schlüter W., Schreiber U. and Dassing R., pp. 113-120

Nouël, F., J.P. Berthias, M. Delouze, A. Guitart, P. Laudet, A. Piuzzi, D. Pralines, C. Valorge, C. Dejoie, M.F. Susini, and D. Taburiau: 1994, Precise Centre National d'Etudes Spatiales orbits for TOPEX/Poseidon : Is reaching 2 cm still a Challenge ?, *J. Geophys. Res.*, 99(C12), 24405—24419

Reipl S.: 2000, Report on activities of the refraction study group, *12th International Workshop on Laser Ranging, Matera*, Italy, Nov. 2000.

Samain, E. et al.: 1998, Millimetric lunar ranging at OCA, *Astron. Astrophys. Suppl. Series*, 130, 235-244

Scharroo, R. and P. Visser: 1998, Precise orbit determination and gravity field improvment for the ERS satellites, *J. of Geophys. Res.*, 103(C4), 8113-8127

Scharroo, R. et al.: 1992, ERS-1 Precise Orbit Determination, in *Proceed. of the first ERS-1 Symp. - Space at the Service of our Environment*, ESA Spec. Pub., ESA SP-359(1), pp. 477-482

Schwartz, J.A.: 1990, Laser ranging error budget for the TOPEX/POSEIDON satellite, *Applied Opt.*, 29(25), 3590--3596

Schwintzer, P., et al.: 1997, Long-wavelength global gravity field models : GRIM4-S4, GRIM4-C4, *J. of Geodesy*, 71, 189-208

Sillard, P., Z. Altamimi, C. Boucher: 1998, The ITRF96 realization and its associated Velocity field, *Geophys. Res. Lett.*, 25(17), 3223-3226

Smith D.E., R. Kolenkiewicz, P.J. Dunn et M.H. Torrence: 2000, Earth scale below a part per billion from Satellite Laser Ranging, *International Association of Geodesy Symposia, Geodesy beyond 2000 - The challenges of the first decade*, 121, Ed. Springer-Verlag, pp. 3-12

Tapley, B.D., M.M. Watkins, J.C. Ries, G.W. Davis, R.J. Eanes, S.R. Poole, H.J. Rim, B.E. Schutz and C.K. Shum: 1996, The joint Gravity Model 3, *J. Geophys. Res.*, 101(B12), 28029-28049

Tapley, B.D. et al.: 1994, Precise orbit determination for TOPEX/Poseidon, *J. of Geophys. Res.*, 99(C12), 24383-24404

Tapley, B.D., B.E. Schutz, R.J. Eanes, J.C. Ries, M.M. Watkins: 1993, Lageos laser ranging contributions to geodynamics, geodesy, and orbital dynamics, in *Contributions of Space Geodesy to Geodynamics: Earth Dynamics, Geodyn. Ser.*, 24, pp. 147-174