Triple laser ranging collocation experiment at the Grasse observatory, France
September - November 2001

Joëlle NICOLAS, Pascal BONNEFOND, Olivier LAURAIN, Francis PIERRON, Pierre EXERTIER, and François BARLIER

Observatoire de la Côte d'Azur, Avenue Nicolas Copernic, F-06130 Grasse
Contact: Joelle.Nicolas@obs-azur.fr, tel.: 33.493405381, fax: 33.493405333.

Abstract

At the Grasse observatory, France, we have the opportunity to have 3 independent laser ranging stations very close one to each other (about 20 m): a Satellite Laser Ranging (SLR) station, a Lunar Laser Ranging (LLR) station, and the French Transportable Laser Ranging Station (FTLRS). We used this unique configuration to perform a collocation experiment between these 3 stations from September to November 2001. This experiment was first performed to qualify the new performances of the FTLRS after a long phase of great improvements and before its departure to Corsica for the oceanographic satellite JASON-1 (2001) calibration and validation campaign during the first six-month of 2002. But furthermore, we used this unique configuration to estimate and compare instrumental bias for each station. Herein, we present the main results on the SLR, the LLR and the FTLRS stations obtained with the analysis of this collocation experiment. One of the main results is the validation at the millimeter level for the performance of the FTLRS in its new configuration. Moreover, our analysis shows the consistency at the level of few millimeters between the 3 laser stations of the OCA, result which demonstrates the strength of the SLR technique. Another important result is the confirmation of a systematical error of 2 cm based on the mean of TOPEX/POSEIDON laser residuals for some European stations such as Grasse and Herstmonceux stations.

1. Introduction

In space geodesy, collocation experiments permit to check the accuracy of different instruments and to find relative biases between different techniques or different instruments based on the same technique. The OCA (Observatoire de la Côte d'Azur) at Grasse (France) is a good example of such a collocated site. Indeed, the OCA is one of the few fundamental geodetic observatories where several continuously operating space geodetic techniques (mainly laser ranging and GPS) and repeated absolute gravity measurements are carried out.

The OCA has 30 years of progressive experience in SLR/LLR and participated to the French Transportable Laser Ranging Station (FTLRS) development. The FTLRS (see Figure 1) is a very compact and highly transportable laser ranging system (Nicolas et al., 1999), (Nicolas et al., 2000). The system capabilities has been greatly enhanced between 1997 and 2001 to meet at least the 1 cm accuracy level, and to track LAGEOS –1 and –2 satellites at an altitude of 6000 km. This accuracy level is mandatory for the JASON-1 validation phase. High satellite tracking capability is a key requirement, especially for a mobile station, since LAGEOS data analysis is the basis of the very accurate laser station positioning.

Prior to this collocation experiment, the first results obtained with the FTLRS in its new configuration were quite encouraging (Nicolas et al., 2001). Indeed, the FTLRS successfully demonstrated the following:

- LAGEOS –1 and –2 tracking new capability,
- millimeter level calibration stability on ground targets,
- ranging capability with an accuracy exceeding 1 cm from on laboratory tests.

In order to validate the new performance of the FTLRS on artificial satellites, we took advantage of the triple laser ranging collocation experiment performed between September and November 2001 (see Figure 2). This validation was essential prior to its departure to Corsica in 2002 in support of the JASON-1 altimeter calibration and orbit validation phase (Ménard et al., 1994), (Exertier et al., 2001), (Ménard et al., 2001). But we also took advantage from this unique configuration to perform an inter-comparison between the 3 OCA laser ranging stations estimating the instrumental bias for each system.

Figure 1: The French Transportable Laser Ranging Station (FTLRS).

Herein we present the results of this triple collocation experiment concerning the FTLRS validation. This paper first presents the data set and the analysis method used. Then the main results are summarized and discussed.

Figure 2: The 3 OCA laser ranging station during the collocation campaign simultaneously tracking the LAGEOS satellites. From the left to the right: the French Transportable Laser Ranging Station (FTLRS), the Satellite Laser Ranging (SLR) station, and the Lunar Laser Ranging (LLR) station.

2. Data and method of computation

2.1. Data set

For this collocation experiment, we used the common observations of the 3 Grasse laser ranging stations on LAGEOS –1 and –2 satellites between September and November 2001. We focused our analysis on LAGEOS data since these satellites are the only common targets reachable for the 3 OCA instruments. We analyzed the common normal points of 12 LAGEOS –1 passes and of 15 LAGEOS –2 passes. We also completed this analysis with the study of all the LAGEOS –1 and -2 data of the 3 Grasse stations, the Graz (Austria), and the Herstmonceux (UK) laser systems acquired during the entire considered period. Then, we also benefit of this collocation experiment to analyze the common passes between the FTLRS and the SLR station of TOPEX/POSEIDON (T/P) at an altitude of about 1300 km. This last part of the study was performed to check the capability of the FTLRS to track JASON-1 before its launch (7th December 2001) since, for its phase of validation, JASON-1 was on the same orbit as the T/P one. But this study was not used to validate the accuracy of the FTLRS.

2.2. LAGEOS –1 and –2 analysis method

The first analysis we performed, specifically for the Grasse stations, was based only on the common normal points between the 3 OCA laser systems. In a second part, we used all the data of all the passes of the entire period from Grasse stations as well as from other European instruments of recognized great quality.

For these analyses, we used the following method. First, we computed 10-day arcs of LAGEOS reference orbits using the GINS software with the ITRF2000 terrestrial reference frame (Altamimi et al., 2002), the GRIM5-S1 gravity field (Biancale et al., 2000), and the standards IERS96 conventions (Mccarthy, 1996). We performed this orbit computation with the data of

about 10 SLR stations, but without the data of the Grasse laser ranging stations. We have chosen to use only the data from stations performing a large number of great quality observations based on the ILRS (International Laser ranging Service) criteria. We also took care of the geographical distribution of this sub-network on the Earth surface. We didn't used the data of the Grasse stations to ensure the independence of our collocation analysis results from the orbit computation. These orbits had a mean 1-σ rms of about 2 cm (laser residuals from 1 cm to 3 cm for bothe LAGEOS satellites). Then, we used these reference orbits to compute laser residuals for each arc of each LAGEOS satellite and for each one of the 3 French laser stations. For this computation, we used the ITRF2000 coordinates for the SLR system, the ITRF2000 tie for the LLR station. For the FTLRS, we used the local tie performed very accurately at the level of few millimeters by the IGN in 1999 (Germain, 1999). For the SLR-LLR eccentricity value, the agreement between the ITRF2000 and the IGN local survey is at the level of a few millimeters.
In our analysis based on the common normal points between the 3 OCA stations, we estimated the mean laser residual over the 3 months for each stations with a LAGEOS –1 and –2 combined solution weighted by the normal point number. There are about 150 common normal points for the both LAGEOS satellites. The mean laser residual differences correspond to the difference between the instrumental biases of the stations. We finally computed the differences of the instrumental biases of the 3 Grasse stations. Since this analysis was based on data acquired at the same time with the 3 stations (to within 120 s), the differences would essentially be due to technical reasons and this analysis allowed us to compare directly the instrumental performances of each considered station, and especially to validate the new performances of the FTLRS. Indeed, the analysis of the common normal points allows to minimize the orbit and the atmospheric correction errors since simultaneous observations (to within 120s) have identical orbit error and should have the same tropospheric delay. Then the differences in the station-satellite ranges are only due to instrumental differences (laser, tracking, timing, detection, calibration…) and to station coordinate eccentricities.

To enlarge this FTLRS validation, we compared the mobile station in its new configuration and some good European stations using the same method and the same reference orbits. But we used all the normal points acquired during the collocation experiment. The LAGEOS –1 and –2 normal points used are of about 350 for the FTLRS and more than about 2500 for the other systems. For this comparison analysis, we computed laser residuals for each laser station. This analysis gave us only the station quality comparison since it was no longer the context of a collocation experiment.

3. Results on LAGEOS –1 and –2 analysis and discussion

The analysis of the common observations was based on 57 common normal points on LAGEOS -1 and on 93 common normal points on LAGEOS –2 acquired between September and November 2001 between the 3 OCA laser instruments.
Pass-by-pass laser residuals were analyzed. Figure 3 gives an example for a LAGEOS –1 pass of the 12th September 2001. Generally, the LLR residuals are positive and of about 1-2 cm, whereas the FTLRS residuals are around zero. The SLR residuals are often between the LLR and the FTLRS ones, but closer to the FTLRS values. The stability of the laser residual differences is of about 6 mm for LAGEOS –1 and of about 4 mm for LAGEOS –2. Nevertheless, the laser residual differences between the three OCA laser systems are more stable than the individual laser residuals of each station pass-by-pass. Indeed, the absolute value of the residuals shows a

2-3 cm level of variability. It would mainly correspond to the orbit errors and to coordinate variations due to effects which were not taken into account in our computations such as the atmospheric loading.

Table 1 summarizes the results of the mean residuals for the Grasse instruments. The analysis of the common LAGEOS normal points gave the following instrumental bias differences between the 3 OCA laser systems for a combined LAGEOS –1 and –2 solution weighted by the normal point numbers:

- a bias difference of (5 ± 1) mm between the SLR and the FTLRS,
- a bias difference of (18 ± 1) mm between the LLR and the FTLRS, and
- a bias difference of (13 ± 1) mm between the LLR and the SLR.

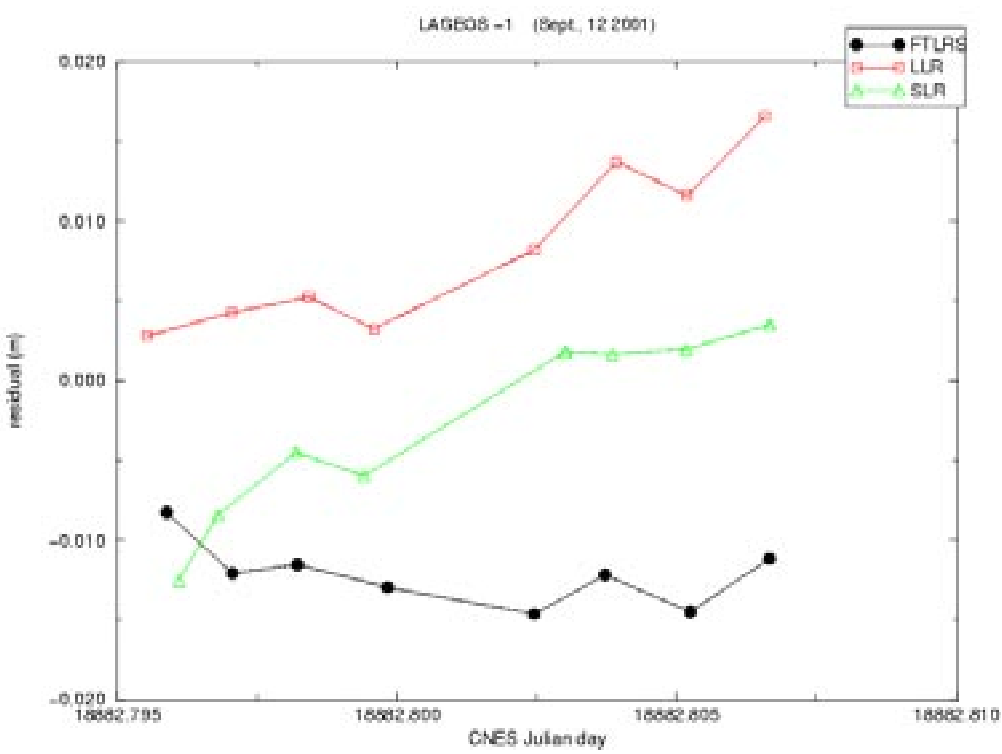

Figure 3: Laser residuals (in meters) of the common normal points of the three OCA laser ranging systems for a LAGEOS –1 pass of the 12th September 2001 (CNES Julian Day 18881).

Table 1: Mean residual from a reference orbit over 3 months (Sept. – Nov. 2001) for the 3 Grasse laser ranging stations: the fixed Satellite Laser Ranging station (SLR), the French transportable Laser Ranging Station (FTLRS), and the Lunar Laser Ranging station (LLR) based on the common normal points analysis. The values are given in millimeters.

Station	LAGEOS -1	LAGEOS -2
FTLRS	4 ± 2	1 ± 1
SLR	9 ± 2	7 ± 1
LLR	23 ± 1	20 ± 1

Then we performed a global analysis based on all the data available for the considered period. This global analysis allowed to have a better statistics (more data). For the comparison over the entire collocation experiment duration, we first studied the stability of the mean laser residuals computed each 10-day arc for each LAGEOS satellite and for each laser system. As an illustration, we compared the FTLRS with the Graz and the Herstmonceux laser systems. Figure 4 illustrates the number of normal points of each LAGEOS –2 arc and the mean laser residuals for each station. Table 2 summarizes the results of the comparison over the entire considered period between the OCA laser stations, the Graz, and the Herstmonceux laser systems. We defined the stability as the standards deviation of the mean of laser residuals computed arc-by-arc on the 10-day LAGEOS orbits over the entire collocation experiment duration, with respect to the mean of residuals over the 3-month experiment which we called bias. For the mobile station, we found the following bias differences:

- a bias difference of (0 ± 1) mm between the FTLRS and the Graz station, and
- a bias difference of (3 ± 1) mm between the FTLRS and the Herstmonceux station.

Table 2: Stability and mean residuals for the entire period (Sept. – Nov. 2001) for LAGEOS -1 and -2 satellites for the different laser stations. The LAGEOS -1 and -2 combined residuals were computed from a weighted solution with the normal point number. The values are indicated in millimeters.

	LAGEOS -1		LAGEOS -2		Combination
Station	Stability (mm)	Mean residual (mm)	Stability (mm)	Mean residual (mm)	Mean residual (mm)
FTLRS	11	6 ± 1	7	3 ± 1	4 ± 1
SLR	7	9 ± 1	5	7 ± 1	8 ± 1
LLR	7	16 ± 1	6	17 ± 1	16 ± 1
Graz	7	4 ± 1	4	4 ± 1	4 ± 1
Herstmonceux	14	2 ± 1	5	2 ± 1	2 ± 1

The comparison between the FTLRS results with other European reference laser stations gave a bias of a few millimeters between the FTLRS and the Graz and the Herstmonceux SLR stations, which is a good result.
These results confirm that this global analysis does not change the bias difference values between the three OCA laser systems. It is mainly due to the high orbit quality, to the high station positioning quality, and to the mean consistency of the atmospheric perturbations at the European scale over a 3-month period.
There are instrumental explanations for the differences found between the OCA laser systems.
First of all, the range measurement differences can be linked to the fact that the array laser satellite signature, and particularly the satellite center of mass correction, depends on the detection level of the laser returns. We estimated a difference of about 3 mm between the SLR and the LLR stations caused by this effect. Moreover, we used the standard value of the center of mass correction (251 mm), whereas concerning this value some differences exist between the SLR (247 mm) and the LLR (244 mm) stations (see Nicolas et al. paper in the session "target design, signature, and biases" of this workshop). There exists another important difference between the LLR and the 2 other OCA Grasse stations. Indeed, for the LLR station measurements, there is a well identified center edge effect (Schreiber et Haufe, 1998) on the photodiode delay of about 9 mm linked to the velocity aberration of LAGEOS satellites. Indeed, the tunings of the LLR instrument for the Moon tracking induce that the photons are always detected at the edge of the photodiode. The measured ranges are too long for the LLR station. This center edge effect would be at the level of 1 mm for the FTLRS and at the level of 5 mm for the SLR station.
Other sources of inaccuracy such as ground calibration value measurement and the local survey tie measurement accuracy would also contribute in the computed range biases between the three Grasse laser ranging stations, but at a level less than a few millimeters and less than the two first causes previously given. For instance, with the 3 mm bias due to the LAGEOS center of mass correction and with the 4 mm difference due to the center edge effects, we obtain a difference of 7 mm between the SLR and the LLR systems, whereas we found a difference of 13 mm with the collocation analysis. Thus, assuming an error of 2-3 mm for the calibration and as well as for the coordinate determination of each station, we can finally explain at the level of about 1 mm the mean laser residual differences between the 3 OCA laser stations computed from the common normal points. All these results are very encouraging to ensure an accuracy at the level of few millimeters for these stations.

4. Comments on the particular case of TOPEX/Poseidon

We got a by-product of this collocation study with the analysis of the TOPEX/Poseidon (T/P) common passes between the FTLRS and the SLR fixed station. The purpose of this analysis was to validate the FTLRS capability for the oceanographic missions such as T/P. The idea was to check if we could use the FTLRS consistently with the OCA SLR system on this kind of satellite. For this analysis, we used the 957 common normal points between the FTLRS and the OCA SLR system. We used the same method as before, but with the reference orbits regularly computed by CNES (Nouël et al., 1994), (Barotto et Berthias, 1996). We computed mean laser residuals over the entire considered period common normal points. We could only perform this analysis with the FTLRS and the fixed SLR data since the LLR station is unable to track satellites lower than 6000 km high. From many years a problem seemed to exist, especially for the European stations, a problem until now possibly interpreted as geographically correlated errors (Bonnefond et al., 1999). This analysis allowed us to conclude concerning the part of the instrumental bias coming from the station and the one coming from the satellite itself.

Figure 4 shows laser residuals from a reference CNES orbit on a T/P pass observed by different European stations. It illustrates the good consistency between the T/P observations of these 4 stations.

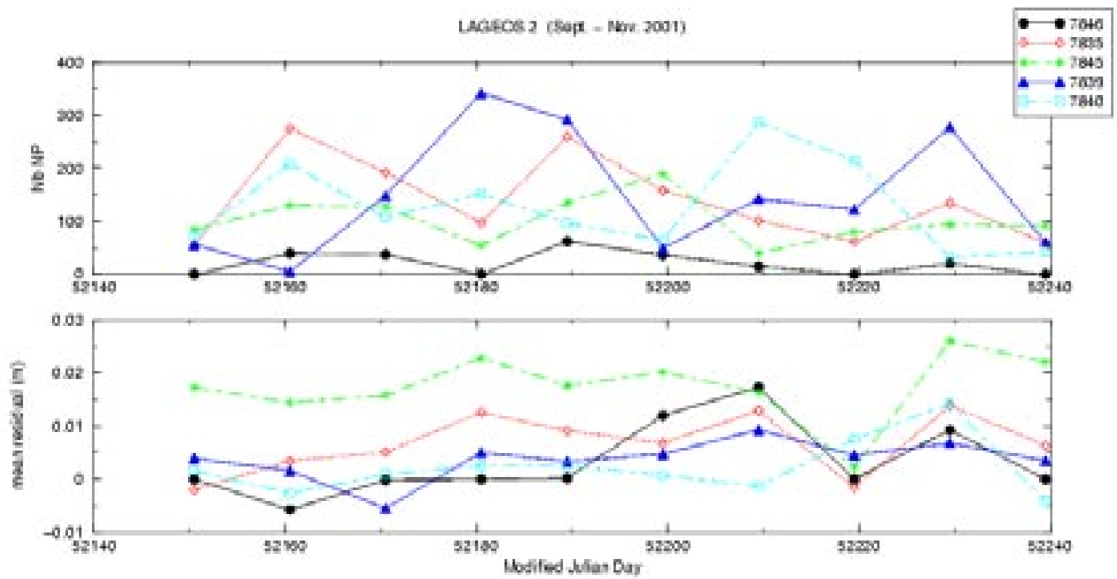

Figure 4: Number of normal points and mean laser residuals (in meters) for each LAGEOS –2 10-day arc and each laser system with respect to the date (in Modified Julian Day) during the 3-month collocation experiment (Sept. To Nov. 2001). 7846 stands for the FTLRS at Grasse, 7835 for the OCA SLR system, 7845 for the OCA LLR system, 7839 for the Graz station, and 7840 for the Herstmonceux system.

Our analysis over the 3 months gives a mean laser residual weighted by the normal point number of (2.3 ± 0.1) cm for the FTLRS and of (2.8 ± 0.1) cm for the Grasse SLR station for the common normal points. For comparison, the mean laser residuals from a combined LAGEOS -1 and -2 solution are of (4 ± 1) mm for the FTLRS and of (8 ± 1) mm for the SLR station (see Table 2). The T/P and LAGEOS analysis comparison indicates a systematic difference of about 5 mm between the FTLRS and the SLR stations which confirms the agreement between these two stations at this level. It also shows the stability of the quality of the FTLRS whatever the altitude of the observed satellites. Thus, we can say that the FTLRS has now the same level of quality as the OCA SLR station which confirms the success of the FTLRS improvements.
This analysis also indicates a systematic difference of about 2 cm between T/P and LAGEOS mean residuals, which is a significant result. This difference is properly linked to the T/P satellite itself, and not to the laser stations. T/P is a very particular target for satellite laser ranging because of its ring retroreflector array of about 85 cm diameter (see Fig. 5) placed around the altimeter antenna (Schwartz, 1990); (Neubert, 1995). Moreover, this difference is observed for the Herstmonceux station and for the Graz one at different levels, but not for the American laser ranging stations. The 2 cm bias may be due to the T/P retroreflector array model which seems to

be incorrect in the case of some European stations. This point, actually under investigation, is crucial for the T/P calibration data analysis.
Finally, these results indicate that the T/P satellite signature is the same for the OCA SLR system and the FTLRS. It shows that these two stations deliver consistent data at a sub-centimeter level. Thus, it confirms that the FTLRS performance meet the requirements of the CAL/VAL experiment of the T/P – JASON-1 in Corsica in 2002.

5. Conclusion and prospects

Finally, this triple collocation experiment validated the new performance of the FTLRS at the level of few mm, according to the mean laser residuals based on LAGEOS data analysis. This result, which is very good in terms of SLR standards, indicates the success of the improvements of this instrument. It also confirms that this mobile system now meets the conditions required for the Jason-1 calibration and validation experiment, that is to say the 1-cm accuracy level. This result can be also extended to the ENVISAT calibration phase.
Our study shows also the importance of different parameters to obtain such a few mm accuracy level:

- the dependence of the satellite signature on the detection level,
- the center edge effect of the photo-detector,
- the geodetic local survey for coordinates determination and the ground calibration value measurement.

Our results indicate that the FTLRS in its new configuration reaches the quality level of the best European stations, and thus that the mobile station can have a good place in the ILRS network.
Another important by-product is the difference of 2 cm between LAGEOS and T/P mean laser residuals for both the FLTRS and the Grasse fixed SLR station, bias which is specific to the T/P satellite and which is probably linked to a non-correct retroreflector array correction model for some European laser systems. So we confirm the T/P retroreflector array correction problem for the European stations, a problem which was already suspected, but never proved.

Since the validation of the FTLRS new performance, this system can be routinely used. The FTLRS was used with a great success in Corsica between January and September 2002 in support of the Jason-1 and ENVISAT CAL/VAL experiments. Future campaigns are already planned, such as a campaign in Gavdos island (Crete) in 2003 for Jason-1 and ENVISAT calibration and validation experiment (Mertikas et al., 2002) and a campaign in Normandy in France for ocean loading effect measurements in 2004.

Acknowledgements
We are grateful to F. Pierron, in charge of the SLR and FTLRS instruments, and to J.-F. Mangin, in charge of the LLR station. Special recognition is given to all the observers who contributed to the data acquisition during this collocation experiment which considerably increased the tracking observation planning. The authors whish to acknowledge helpful discussions with E. Samain. We also thank J.-L. Hatat for his help and for his beautiful picture of the 3 stations simultaneously tracking a LAGEOS satellite.
The FTLRS experiment is supported by CNES, IGN, INSU, CNRS, and OCA. The SLR and the LLR stations are respectively supported by CNES and INSU. This work was supported by CNES, CNRS, INSU and the French Ministry of Research.

References

Altamimi Z., P. Sillard, and C. Boucher, *ITRF2000: a new release of the International Terrestrial Reference Frame for Earth science applications*, Journal of Geophysical Research, **107**, **B8**, 2002.

Barotto B. and J.P. Berthias, *First results of reduced dynamics with DORIS on T/P and SPOT*, Journal of guidance, control, and dynamics, **Vol. 19**, **N° 6**, pp. 1296 - 1302, 1996.

Biancale R., et al., *A new global Earth's gravity field model from satellite orbit perturbations: GRIM5-S1*, Geophys. Res. Lett., **27**, **N° 22**, pp. 3611-3614, 2000.

Bonnefond P., P. Exertier, and F. Barlier, *Geographically correlated errors observed from a laser-based short-arc technique*, J. G. R., **104 (7)**, pp. 15885-15893, 1999.

Exertier P., P. Bonnefond, J. Nicolas, and F. Barlier, *Contributions of Stallite Laser ranging to past and future radar altimetry missions*, Surveys in geophysics, **Vol. 22**, **Nos. 5-6**, pp. 491-507, 2001.

Germain Thierry, *Rattachement métrologique des axes Laser Lune, Laser satellite et laser satellite mobile, Rattachement altimétrique de dalles proches du réfectoire, Rattachement altimétrique de points de gravimétrie*, Rapport IGN, Octobre 1999.

Mccarthy D., *IERS Conventions (1996)*, IERS Technical Note, Paris, July 1996, **21**, Ed. Paris Observatoire De, 1996.

Ménard Y., E. Jeansou, and P. Vincent, *Calibration of TOPEX/Poseidon altimeters at Lampedusa : Additional results at Harvest,*, J. Geophys. Res., **99 (C12)**, pp. 24487-24504, 1994.

Ménard Yves, Bruce Haines, and With Contributions from the Jason-1 Calval Team, *Jason-1 CALVAL Plan*, CNES, NASA, and JPL, April 2, 2001.

Mertikas S., E. Pavlis, Tziavos, Drakopoulos, Pesec, Forsberg, Kahle, and P. Exertier, *Establishment of a European radar altimeter calibration and sea-level monitoring site for Jason, Envisat and EURO-GLOSS*, 2002.

Neubert R., *Satellite signature model, application to LAGEOS and TOPEX*, EUROLAS Meeting, Munich-Germany, March 20-21, 1995, Ed. 1995.

Nicolas J., P. Exertier, P. Bonnefond, F. Pierron, Y. Boudon, J.F. Mangin, F. Barlier, M. Kasser, and J. Haase, *Stability control and range biases on the French laser ranging stations*, Proceedings of EUROPTO - SPIE Laser Radar Ranging and Atmospheric Lidar Technique II, Florence - Italy, **Vol. 3865**, Ed. Werner Ed. U. Schreiber and Ch., pp. 27-32, 1999.

Nicolas J., F. Pierron, M. Kasser, P. Exertier, P. Bonnefond, F. Barlier, and J. Haase, *French transportable Laser Ranging Station : scientific objectives, technical features, and performance*, Applied Optics, **Vol. 39**, **No. 3**, pp. 402-410, 2000.

Nicolas J., F. Pierron, E. Samain, and F. Barlier, *Centimetre accuracy for the French Transportable Laser Ranging Station (FTLRS) through sub-system controls*, Surveys in Geophysics, Special Issue on Evolving Geodesy, **Vol. 22**, **Nos. 5-6**, pp. 449-464, 2001.

Nouël F., et al., *Precise Centre National d'Etudes Spatiales orbits for TOPEX/Poseidon : is reaching 2 cm still a challenge ?*, J. Geophys. Res., **99 (C12)**, pp. 24405-24419, 1994.

Schreiber U. and K. H. Haufe, *Timewalk in Avalanche Photodiode*, Proceedings of the 11th International Workshop on Laser Ranging, Deggendorf - Germany, published by the Bundesamt für Kartographie und Geodäsie, Frankfurt am Main **2**, Ed. Schlüter W., Schreiber U. and Dassing R., pp. 445-451, 1998.

Schwartz J., *Pulse spreading and range correction analysis for satellite laser ranging*, Applied Optics, **Vol. 29**, **N° 25**, pp. 3597-3602, 1990.