# New technological developments for future French Satellite Laser Ranging stations

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***Abstract***
*The development of Global Geodetic Observing System and of multi-technic satellites need a new generation of Satellite Laser Ranging (SLR) stations with metrological performances which exceed the possibilities of current state of the art systems. In this paper, we presented our reflections on the development of a SLR station able to automatically observe all the satellites whatever their culminations and to provide data with millimetric accuracy. Despite three-axis gimbal is not widespread in the SLR community, this solution would enable to increase significantly the quantity and the quality of data recorded at high elevation, compared to classical Altitude-Azimuth (Alt-Az) telescope mounts. Image processing of a camera fixed on the telescope could be a solution to prevent automatically the risk of illumination of small flying objects like gliders. Finally, two-color SLR at high repetition rate can be considered thanks to the recent progress on picosecond laser. Investigations on this technic could help to improve the current SLR metrology.*

## Introduction

The Observatoire de la Côte d'Azur (OCA) developed and then exploited the French Transportable Laser Ranging Station since 1986 [1]. Coming from a collaboration between CNES / IGN / INSU, this SLR station was the smallest in the world. It gave a great support to colocation campaign, calibration mission of oceanographic satellite and time transfer by laser link project. But after seventeen years of operation, the performances of the instrument do not answer anymore to the new scientific objectives. We decided to stop the FTLRS and with the CNES support, to begin a new project in 2014. Before starting the design of a new instrument, we have revised the needs in oceanography, in geodesy and in time transfer to determine what should be improved on SLR stations. Three main points have been studied.

The development of Global Geodetic Observing System (GGOS) and of multi-technic satellites need a SLR metrology with millimetric accuracy and long term stability [2]. However, most current SLR stations have centimetric accuracy. An improvement of a ten factor has to be reached.

The choice in the implementation of a measuring instrument also lies in the cost of its operation. As compared to the GNSS positioning system, SLR suffers from excessive operating costs. To be more attractive and cheap, SLR measurements must be automated while ensuring the risk of laser illumination. Finally, compared to the other positioning technics, the contribution of SLR data is very important for observation at high elevation. Nonetheless, most of the SLR stations use two-axis Alt-Az mount which is not the ideal solution for tracking near zenith. For few satellites, a lack of observations is observed at high elevation. A new station must be able to track all satellites whatever their culminations in order to obtain the most pertinent SLR data. This paper explains our ideas of new technological developments that could improve the metrological performances and the data acquisition efficiency.

## I. Improve the metrological performances

Currently, most SLR stations use optical pulses at one wavelength for the distance measurement. The meteorological parameters are monitored at the ground near the station and allow the time of flight conversion in distance. The accuracy of the range measurement is impacted by different sources of errors. For example, it is difficult to measure the outside temperature with an accuracy better than +/- 0.5°C. The errors in the measurements of the meteorological parameters limit the accuracy of atmospheric correction model. Moreover the models do not consider local and seasonal effects, neither the transverse gradient in the vertical profiles. So, the ultimate accuracy is usually limited by the correction of the atmospheric propagation effects to around one centimeter.

An alternative technic to the use of an atmospheric model consists of measuring the dispersion effects on the optical signals. To reach the millimetric accuracy as recommended for the development of GGOS, one solution is to realize two-color SLR measurements combined with water vapour measurements as proposed by D. Wijaya [4]. The two-color technic [5] allows to compute the dispersion effects directly. Two optical pulses at two different wavelengths are sent in the same time. Along the optical path, we can consider that the two pulses see the same meteorological conditions. The difference of time of flight between the two colors reflects only the dependence in wavelength of the atmosphere integrated along the optical path. Two-color SLR measurements allow to correct 99% of the atmospheric effects. This largest part is associated with the dry atmospheric density. The magnitude of the correction is in the range of 2m to 40 m for elevation angles of 90° and 3° [4]. Water vapor density introduces errors in the range of few millimetres. The magnitude of the correction due to moist air is in the range of 2 mm to 4cm for elevation angles of 90° and 3° respectively. Such 99% correction requires a very precise time of flight measured at each wavelength. For example, for a station which exploit the fundamental (1064 nm) and the second harmonic (532 nm) of Nd:YAG laser with two independent detection channels, millimetric accuracy requires a 50 µm precision in each channel [4]. Unfortunately no station of the current ILRS network is able to obtain this level.

As reported in 2011 by I. Prochazka [6], the modern kHz SLR stations like the Graz station, obtain typically 0.7 mm precision for averaging time below 5 seconds, for all satellites. For the satellite ERS2, with just one corner cube, the precision goes down to 150 µm.

So, to obtain millimetric accuracy, we have to improve the precision by at least a factor 10 with measurements realized at two wavelengths. For satellites with very small signatures and for white noise, it could be obtained with a repetition rate multiplied by 100.

Until recently, the mean power of pulsed laser was around 1 W. It corresponds to an energy per pulse of 1 milli-joule for laser with kilo-Hertz repetition rate. Multiplying the repetition rate by 100 was not feasible due to considerations on the link budget. But now, two laser technologies have exceeded this level. Slab laser [7] and thin disk laser [8] reach mean power of 100 W. 1 mJ per pulse is produced with repetition rate of 100 kHz. It shows that a ten factor improvement in precision becomes accessible.

SLR stations have to be modified to use these new lasers. Indeed, there is an overlap between receive/transmit pulses due to atmosphere backscatter for repetition rate above 10 kHz [9]. As proposed in 2011 by G. Kirchner [9], we can use 2 telescopes separated by tens of meter. By this way, the field of view of the receiving telescope prevents from backscattered light. The difficulty will be the local tie with millimetric accuracy between the two telescopes. Another solution is to work with a high repetition rate laser in burst mode. The output of the high repetition rate laser is modulated to generate trains of pulses, each train repeated at kHz level. However we will not exploit directly the 100 kHz rate. The measurement rate will be necessarily lower.

A future measurement campaign on a distant ground corner cube is scheduled for the development of high-speed two-color detection channels, with the characterization of the different sources of bias and instabilities.

## II. Improve the data acquisition efficiency

### a. Improve the satellite tracking at high elevation

The best metrological quality of SLR data should be obtained for observations at high elevation. In this case, the thickness of crossed atmosphere is lesser. Observations are less dispersed and the accuracy of atmospheric correction models is better. Data acquired at zenith are the most pertinent to study the mass center and the gravity field of the earth but also to calibrate the altimeters of oceanographic missions.
However, most SLR stations are unable to observe low altitude satellite near the zenith. Indeed, the two-axis Alt-Az tracking mount which is the most common in the community, has kinematic difficulties at high elevation angle. In this position, the line of sight is no more perpendicular to the azimuth axis. This prevents to move the line-of-sight of the telescope orthogonally to the elevation axis and to provide a smooth control. The speed of the azimuth axis has to increase quickly which needs high torque and strong acceleration. The position range of dynamic difficulties is called keyhole [3].
The Figure 1 shows the passes of the Satellite Grace A & B tracked by the MéO telescope. The green circle represents the elevation angle. As showed on the graph, the keyhole region is highlighted by a lack of data above 70° of elevation. The speed required on the azimuth axis at higher elevation exceeds the 5°/s rotation limit of our Lunar Laser Ranging station.

For a given performance, the more the satellite orbits at low altitude, the more the keyhole region is large.

The two axis Altitude-Altitude (Alt-Alt) mount allows to move the keyhole region on one horizontal axis. Such configuration optimises the zenithal tracking. However the problem is not completely eliminated. If we want to be able to track all the satellites whatever their heights, a radical solution would be to use a three axis mount like the Altitude-Altitude-Azimuth. As this configuration leads to an infinity of available pointing control laws, we propose to fix one of those three rotation axis for each satellite pass: if the pass does not rise up to 70°, we intend to use the mount in Alt-Az configuration ; for the other cases, the Alt-Alt configuration will be preferred. Industrial solutions are available. But compared to the two axis gimbal, the three axis solution suffers from higher costs, higher size and weight and lower maturity. Simulation of the impact of more data acquired at high elevation on the SLR products should help to know if this hardware solution gives a real gain.

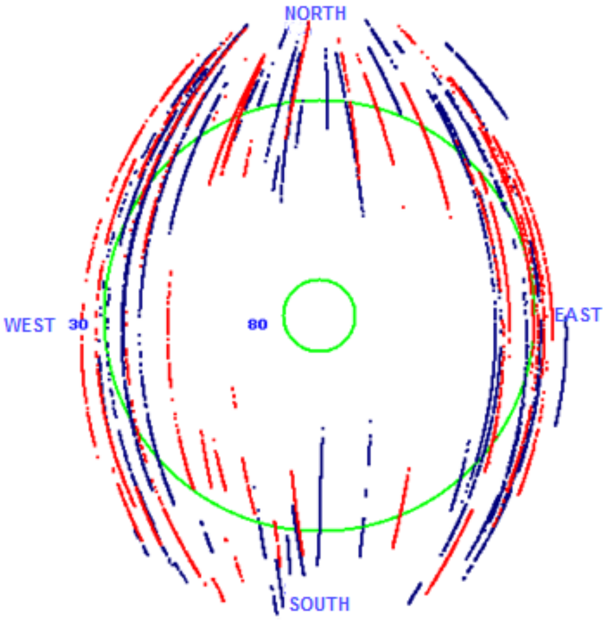

Fig 1. : Grace A (in blue) & Grace B (in red) observations with our Lunar Laser Ranging station “MéO”. Green circles represent the elevation angle.

Another possible solution is to use a classical Alt-Az gimbal designed with a very high speed motorization. Azimuthal speeds of up to 60°/s can easily be obtained with a telescope having an aperture in the range of 50 centimeters. With such a speed, the blind zone can be dramatically reduced: for example, for the TandemX satellite orbiting at 514 km of altitude, the blind zone changes from [80.6°; 90°] at a maximum of 5°/s to [89.85°; 90°] at a maximum of 60°/s.

### b. Automate and ensure the sky safety

Two techniques are currently used on the MéO telescope to ensure the sky safety. The main part of the air traffic is followed with a radar ADS-B. This hardware system allows to know the position of any aircraft equipped with transponder. Other flying objects like gliders, helicopters and small airplanes are monitored by the operator thanks to a ca camera fixed on the telescope. If we want to automate the station, we have to develop a software able to replace the human monitoring.

To design the optical system required, we have considered the altitude of travel of the objects previously mentioned to determine the visible minimum size and the apparent speed. We concluded that it was impossible to detect all the flying objects with just one imaging system because we need in same time a high field of view and a very good resolution. So, for first tests we have used only one camera (1920X1080 pixels) and a good optical focuser to image a field of view of 7° with 10 pixels for 0.5 milli-radians. This resolution enables us to detect any glider which takes off at roughly 5 km from the MéO telescope, and having a maximal angular speed of 1.75 °/s relatively to the telescope pointing. Such speed limit is sufficient to assure the security of

the glider pilot because the telescope is systematically moving at a much lower speed during low elevation satellites tracking. The software has been developed in C++ and combine shape and color detection to be suitable for different kind of skies.
The first tests on blue sky work well. Second tests in cloudy days are also encouraging: objects flying in front of clouds are detected. However we have few false alarms generated by pieces of clouds which slow the processing.
We know that this system cannot prevent all the risks. But combined with the Radar ADS-B and another system for the night, we believe that the whole can ensure the sky safety.

## Conclusion

Colocation mission with ultra-mobile SLR station is very expensive compared to a multi-technic local tie. The altimeter calibration for oceanographic mission does not need to use a mobile SLR station placed under the satellite trace. The combination of GNSS data and SLR observations done by very stable fixed SLR stations of the ILRS network produce the same results for a lower cost. And in a near future, we can expect to receive by the fiber telecom network very stable time and frequency signals, thus bringing closer reference clocks to the telescope. Taking these considerations into account, along with the fact that numerous important upgrades were necessary, we decided to stop the FTLRS station.
That is why we have preferred to work on the three main points described before instead of ultra-mobility concepts. In this paper, we have showed that the Alt-Az mount is not well suited to track low altitude satellite at high elevation. This results in a lack of data, having moreover the best metrological quality. Three axis gimbals could solve the problem. Simulations of the impact of more data acquired at high elevation on the SLR products should complete this study.
To reduce operation costs, a new SLR station must be automated. It implies to develop system able to ensure the sky safety against laser hazards. First tests show very interesting results to protect cheaply small flying objects with a simple camera, a good optic and a software combining shape and color detection. Future works will consist in combining this tool with other survey systems like Radar-ADSB to obtain a more protective system. The objective of millimetric accuracy requires new developments on the SLR metrology. Slab or thin disk laser gives the opportunity to increase the repetition rate of the measurements. Future tests on a corner cube at ground would help to conclude on precision gain of those future measurements.

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