PROPOSITION FOR A NEW SLR METHODOLOGY USING CW OR LONG PULSE LASERS

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INTRODUCTION

The main goals of SLR, as an operational orbitographic tool or as a scientific one, derive from its capability to determine artificial satellite orbits with a centimetric accuracy. From the orbit one may deduce information of very high importance concerning earth rotation parameters, earth gravity field and its temporal variations, and a very high quality absolute positioning. In this area, SLR could be a very good candidate, if not the best on a long term basis, to provide millimetric absolute altimetry for studies concerning minute altitude variations (mountains formation, tectonic subsidences and surrexions, post-glacial rebound, oceanic loading over continental margins, etc...).

The main limitations of SLR in terms of accuracy, by descending order of importance, are probably : (i) the quite inhomogeneous repartition of SLR stations in the world, (ii) the technology of SLR that lets some important biases uncorrected, (iii) target temporal signatures, and (iv) tropospheric delay uncertainties.

Concerning (i), we observe regular improvements, but there will always be some basic limitations (due to semi-permanent cloud coverage in some parts of the world, for example). Concerning (iii), the models have considerably improved and some technological possibilities not yet used exist (Kasser & Lund 1994). And concerning (iv), the correction to look for is quite low if the pressure is correctly measured at the station (Kasser 1992), and in any case it is expected soon that two-colour ranging (Prilepin 1957) will achieve automatic corrections at the millimetre level. Thus we have worked on the point (ii), i. e. how to remove any sort of instrumental bias.

To achieve this goal we have looked for the solutions used by early geodesists with electronic distance measurements (EDM). These type of instruments have been explored through a wide range of different technologies, with only a small number of scientific publications as most of the knowledge in this domain is industrial and thus not disclosed. Nevertheless we know, from the publication of patents, what technologies are used :

- Use of pulsed diode lasers (long pulses, typically 200 ns), with the same detection for the start and return pulses, and a statistical reduction of the decimetric single shot r.m.s. up to one millimetre,

- Continuous modulation of light beams (often not coherent ones), with an efficient phase measurement over periods up to a few seconds, and a systematic internal calibration removing the biasses due to ageing of components and thermal effects,

- For the highest precision EDM (Mekometer, Geomensor, Terrameter), an electro-optical device is used to modulate twice the laser beam, one before and the other after the free space propagation, and then the accuracy may be below one tenth of millimetre, due to a totally bias-free operation.

This last solution has been explored in order to check its transposability to SLR. In some way it is complicated, but it has been found that it could be used with only minor modifications of existing stations.

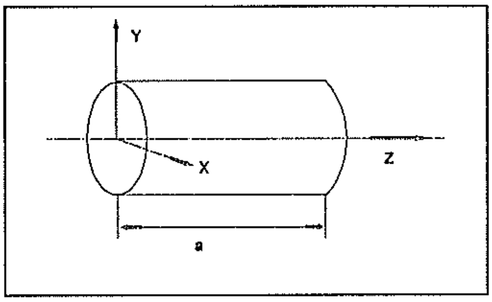
PRINCIPLE OF THE METHODOLOGY PROPOSED

Today the highest precision EDM is a laser one, named Mekometer after its invention by MM. Froome and Bradsell (NPL, Teddington, UK) and now produced by LEICA (Switzerland) as Mekometer ME 5000 and by COM-RAD as the Geomensor. This type of instrument uses an extremely interesting laser modulation method, invented by Dr. Froome in the sixties, which allows to avoid completely any systematic errors. It relies upon the use of a Potassium Di Hydrogen Phosphate crystal, called KDP for ease. The KDP is optically an anisotropic crystal.

From one point, let us draw for each direction of the space a vector whose length is equal to the refraction index experienced by the electric field of the electromagnetic wave (called *polarisation* vector). If the medium is isotropic, the end of this vector is on a sphere. For the KDP, without any electric field applied, it is on a revolution ellipsoid. This sort of crystal is said *uniaxe*, the large axis is called **z**, and **x** and **y** are chosen parallel to the crystallographic axes. The electro-optic effect in such a crystal is the following : if we apply an electric field along **z** axis, the indexes along **x** and **y** are modified with the law :

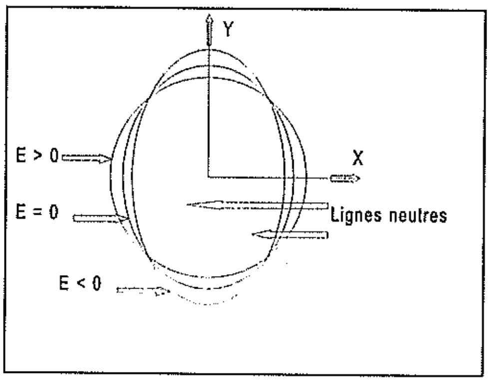
$$n_y = n_0 - n_0^3 \, r_{63} \, E$$
$$n_x = n_0 + n_0^3 \, r_{63} \, E$$

where $\mathbf{r_{63}}$ means an electro-optical constant of the crystal and $\mathbf{n_z}$, that represents the index of refraction along **z** axis, is different from $\mathbf{n_x}$ and $\mathbf{n_y}$, and is independent from **E**. The modulator of the Mekometer uses such a "longitudinal" modulation, **E** being parallel to **z** axis.



The section of the ellipsoid of refraction index in the **xOy** plane, that is a circle for **E** = 0, becomes :

With **E** ≠ 0, if we enter the crystal along **z** axis, with the polarisation **P** at 45° of **Ox** and **Oy** directions (directions called neutral axes of the crystal because an incoming polarisation along one of these planes is not modified during the propagation), we decompose **P** into $\mathbf{P}_x$ and $\mathbf{P}_y$ that do not travel at the same speed (refraction indexes along **x** and **y** are different as soon as **E** is different from zero). The difference of phase R between the components of the electromagnetic wave $\mathbf{P}_x$ and $\mathbf{P}_y$ is at the exit of the crystal expressed by : $\mathbf{R = 4\pi n_0^3 r_{63} E.a/\lambda}$, λ being the wavelength of **P**.



That way, with **R** = π/2 , the resulting polarisation from $\mathbf{P}_x$ and $\mathbf{P}_y$ at the end of the crystal is perpendicular to the initial orientation of **P** (for **R** = π/4, **P** describes a circle at an angular speed of 2πc/λ rd/s). Thus generally, we note that the emitted light has an elliptic polarisation changing at the frequency **f** of modulation of the electric field **E**.

When the modulated laser light comes back from the reflector located at the far end of the line, it is sent back through the same crystal, experiencing the same alternative high frequency electric field **E**. Let us suppose that the total optical path **L** between the output of the crystal and its second input (close to half the distance to be measured) is equal to an integer number of modulation wavelengths plus half a wavelength. The laser light will see at the first passage in the crystal indexes $\mathbf{n}_1$ and $\mathbf{n}_2$ along the **x** and **y** projections of **P**. But when it will cross the crystal for the second time, the value of **E** will be the opposite of that during the first passage, so that the crystal indexes will now be $\mathbf{n}_2$ and $\mathbf{n}_1$ along **x** and **y** axes. And if we compute the total optical paths for polarisation along **x** and **y** axes, we find that they are exactly equal. It means that the outcoming polarisation is perfectly parallel to the initial incoming one : If at the output we observe the polarisation orthogonal to the input direction, in this very precise situation where $\mathbf{L = (K + 1/2).\ c/f}$ (K integer), the output signal intensity is null. And it is easy to see that for any other value of **L**, this intensity has a value following a cycle, whose shape is close to a sinusoid when **E** does not reach too high figures, and still cyclic but more complicated beyond e. g. one kilovolt.

General description of the "Mekometer" Geodetic EDM

The ME 5000 is working so as to detect the values of **f** for which the null return intensity occurs, then with such a set of measured values, it computes the integer **K** and then **L**. And if the value of **K** is provided to the instrument before the measure, the sequence is much faster. The light source employed is a He-Ne laser ; It allows to reach ranges up to 10 km if necessary, although for such distances, the excellent precision of the instrument is limited by the atmospheric index uncertainty.

The input end of the crystal is mechanically disposed at the exact intersection of the two axes of the instrument : that way, the zero error, to be added to the measurement to get the distance, is constant and depends only of the geometrical centring device employed for the reflector.

The accuracy is excellent (the instrumental standard deviation is close to 0.1 mm + 0.1 mm/km), due to the fact that this is a null measurement, for which no electronic drift of any type will influence the result. The 0.1 mm/km is only due to the frequency standard, and may be considerably improved if necessary, but this would be useless for terrestrial measurements where the refraction index is hardly known to the 1 mm/km level.

HOW COULD SUCH A TECHNOLOGY BE USED FOR SLR ?

The main differences between SLR and an EDM are :

- A link budget that is fairly low (10^{-15} for example), which requires the use of powerful lasers (which in turn implies pulsed lasers, like YAG),

- A distances that varies all the time long during the flight of the satellite over the station.. If **Z** is the zenith angle of the satellite, the apparent speed from the station is **k.sin Z**, and the value for **k** is for example 2.6 km/s for Lageos, and 6.7 km/s for Starlette.

- Very long distances, which requires a very high quality oscillator (typically 10^{-11}), but that is now quite easy to obtain.

- A return signal that is frequency shifted due to the Doppler effect, because of the radial component of the relative speed of the satellite.

- The polarisation signature of the cube-corner retroreflectors which is quite complicated, and generally close to a quarter-wave plate (Kasser & Goupil 1996).

We have evaluated two different solutions in terms of modulation :

1/ A variable frequency, synthesised accurately from the ephemeris of the satellite and allowing a "fringe" movement (i.e. the passage to 0 of the intensity detected after the second passage in the crystal) quite steady, allowing for a very comfortable detection (e. g. at 100 Hz).

2/ On another hand, a fixed frequency and a measurement of the "fringe" movement in a much larger range. The elements we have used to perform simulations have been the following :

- Use of a YAG laser at 1.06 :m, 5 ns pulses at 10 Hz

- Atmospheric scintillation giving a random modulation of the return signal from 0 to 100 %.

- Intensity varying in $\mathbf{D}^{-4}$.

- A satellite like Lageos, with a tracking since **Z < 45°**

- An overall modulation efficiency of 90 %

- A mean value of measurements for normal points each 15 s

The measuring equipment is composed of the following instruments :

- The YAG laser that receives the polarisation modulation at a fixed frequency. The KDP is in a tuned cavity, modulated with a peak voltage close to $V_{8/2}$, with its entrance as close as possible to the intersection of the axes of the telescope.

- The return signal is driven through the modulator once again and a polarizer to an avalanche photodiode optimal for YAG. The signal observed is a series of pulses, slightly widened by the detection (e. g. 10 ns), and is amplified up to 0.5 V peak.

- The signal is then sampled by a 1 Gech/s oscilloscope, and the data and the related timing are transferred to a computer.

- The processing consists, for each period of integration used for one "normal point", in a correlation between received signals and theoretical curves corresponding to the a priori orbits provided by ephemeris.

The simulations performed show that the measurement noise is below the millimetre level, and on another hand no measuring bias is possible. Since the two-pass modulation process provides a curve that, although periodical is not purely sinusoidal and thus has a significant amount of 3rd harmonic, it is necessary to perform a correlation on the mean frequency and another on the third harmonic. In parallel an absolute chronometry is performed on the sampled pulses (with a modest precision, close to 0.1 m) in order to measure the integer number of half-wavelength of the frequency of modulation at a given moment.

If we compare with a classical SLR station, this new technology requires only a few modifications :

- On the laser, neutralisation of the mode-locking to go back to nanosecond pulses as energetic as possible.

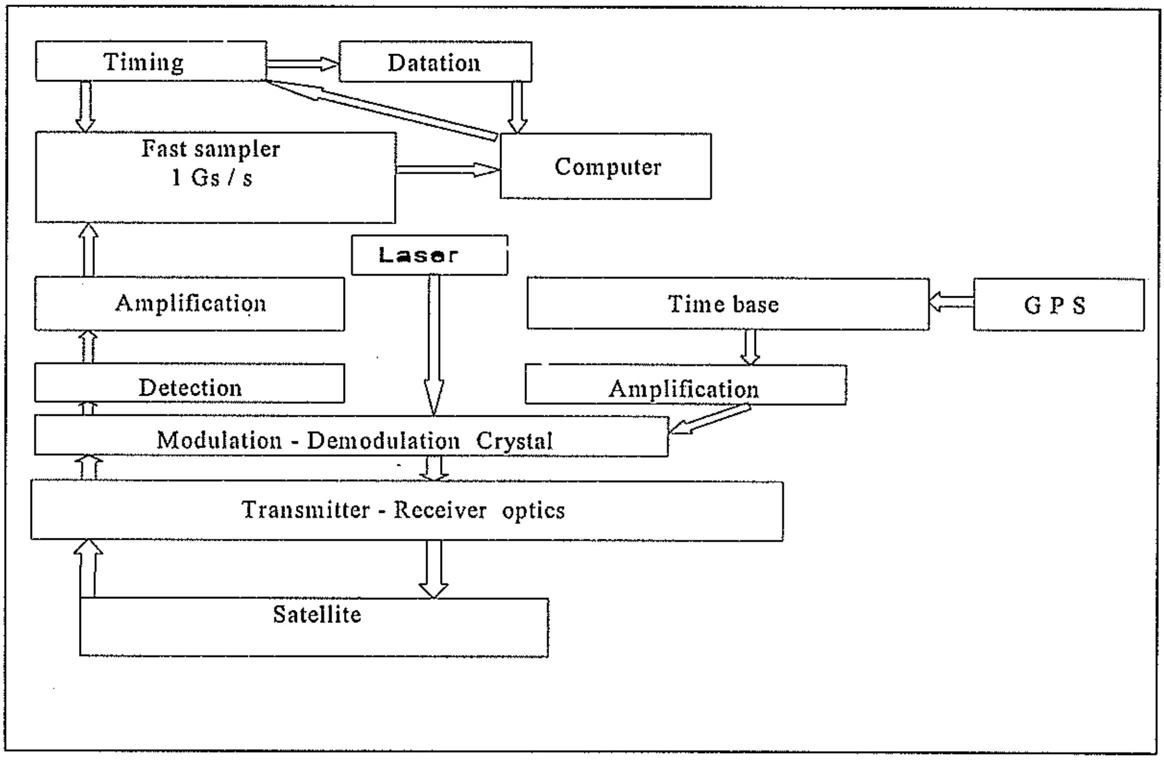
- Installation of a modulator, fed by a synthesiser driven by an atomic oscillator, with a power amplification allowing to reach in a cavity a voltage close to $V_{\lambda/2}$. This crystal must be located as close as possible to the intersection of the mechanical axes of the telescope. The same crystal will be used to modulate the return signal.

- After the detection and the amplification, use of a fast sampling digital oscilloscope, linked to the computer.

The optimal frequency to be used in an exploratory configuration could be 500 MHz, frequency where power amplification is not too difficult, and where $\lambda/2 = 30$ cm allowing for an easy determination of the ambiguity figure in the measured distance. The following drawing provides a general scheme of a SLR station using this technology.

Interesting alternatives would be to use either a powerful CW laser (e. g. an Argon one), or a very different type of pulsed laser, optimised for very energetic but long pulses (relaxed injected YAG for example), or on another hand with short pulses at a high pulse rate (e. g. Cu vapour). The main technological problem to solve will be the modulator. KDP is not suitable for high peak optical power, and it is not able to bear an important HF power during a semi-CW duty cycle. Thus some possibilities must be explored :

- Lithium tantalate or lithium niobate instead of KDP, for their behaviour at high energy levels and their mechanical strength. But in large size such crystals are quite expensive. This type of crystal would have to be used in a cavity tuned on the central frequency of the synthesiser, used as an impedance transformer.



- Considering the uncertainties about the depolarisation due to the cube corner retroreflectors used on satellites, another situation must be explored, using two successive intensity modulations of the beam, as if in the previous situation presented here we would have used an intermediate polarising plate just after the first modulation and thus before the second one. The signal-to-noise ratio will be lower, but the first modulation could be obtained directly in the YAG laser, between the pilot and the amplifiers, at a low energy level. The only other drawback of such a configuration seems to be the geometric separation between the first and the second modulators, probably not very difficult to keep stable at the 0.1 mm level.

CONCLUSION

The methodology we present here is not new at all, and its main advantage relies on the fact that the detection has no requirement at all in terms of temporal jitters, it works at a very low speed so as to perform - more or less - just photometry measurements, and not timing measurements. Its use in geodesy since late sixties has been constant for very high precision distances, and excepted for the high power HF aspects, it is very simple to get operational.

We expect to have the possibility to test as soon as possible the instrumentation described here as a temporary modification of an existing SLR station (it would be advisable to start with a station benefiting of a large collecting area in order to work with a strong link budget). The problem of the elimination of the calibration and of any measuring bias seems possible, using a technical solution that has been proved as very efficient for EDMs for more than 20 years. Nevertheless, the question of the modulator has to be solved, and our first tests have shown that it was not a minor point. We hope that this new possibility will be evaluated by other teams and at least that a good solution (this one or any other one) will be found to remove any biases in SLR. Major scientific goals will then be accessible, and especially we expect a significant improvement on the vertical component precision of the SLR stations co-ordinates.

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