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LARES/WEBER-SAT, FRAME-DRAGGING AND FUNDAMENTAL PHYSICS

IGNAZIO CIUFOLINI [a], ANTONIO PAOLOZZI [b] DOUGLAS G. CURRIE [c]
ERRICOS C. PAVLIS [d]

[a] *Dipartimento di Ingegneria dell'Innovazione, Università di Lecce,*
via Monteroni, 73100 Lecce, Italy

[b] *Dipartimento di Ingegneria Aerospaziale e Astronautica Università "La Sapienza",*
Via Eudossiana 18, 00184 Roma, Italy,

[c] *Department of Physics, University of Maryland, College Park, MD, USA*

[d] *Joint Center for Earth Systems Technology University of Maryland*
Baltimore County and NASA Goddard/926 1000 Hilltop Circle, Baltimore, MD
21250, USA

Abstract

After a brief introduction on the scientific objectives of the LARES/WEBER-SAT satellite we present the recent measurement of the Lense-Thirring effect using the nodes of the LAGEOS and LAGEOS 2 satellites and using the Earth gravity model EIGENGRACE02S obtained by the GRACE space mission. Finally, we describe an interesting possibility of testing the Brane-World unified theory of fundamental interactions by the use of a specially designed LARES/WEBER-SAT satellite.

1 Introduction

The scientific objectives of the LARES mission are:

(1) High precision tests of Einstein's theory of general relativity, in particular, (1a) a $\sim 1\%$ measurement of the frame-dragging effect due to the angular momentum of a body, i.e., the Lense-Thirring effect, and test of the Earth's gravitomagnetic field. The Lense-Thirring effect [1, 2] is a tiny shift of the orbit of a test-particle. Frame-dragging, gravitomagnetic field and Lense-Thirring effect are theoretical predictions of Einstein's theory of general relativity (see, e.g., ref. [3]). (1b) A High precision test [4] of large distance infrared modification of gravity recently proposed by Dvali [5] to explain the dark-energy problem (a study will be required to precisely assess the achievable level of accuracy), see below. An improved high precision test of the inverse square law for very weak-field gravity and improved test of the equivalence principle (see the Italian Space Agency LARES phase A study [6]). A $\sim 10^{-3}$ measurement of the gravito-electric general relativistic perigee precession of the WEBER-SAT and a high precision measurement of the corresponding combination of the PPN (Parametrized-Post-Newtonian) parameters β and γ [10, 11]. This test will be achieved in the field of Earth with a range of about 10000 km, more accurate tests of β and γ are achieved in the field of Sun but with a much longer range. The PPN parameters β and γ test Einstein's theory of gravitation versus other metric theories of gravitation. (1d) Other tests of general relativity and gravitation (see LARES phase A study [6]).

(2) Measurements and improved determinations in geodesy and geodynamics. Cannonball type satellites have been used in Geodesy ever since the dawn of the space age, being nearly perfect targets for precise distance measurements from stations located on Earth's surface. Initially the accuracy was very low, only at the meter level, but with the current state-of-the-art laser systems, we can measure these distances to better than one centimeter with a single shot, and well below the one millimeter for a "normal point" average of several hundreds or even thousands of rapid firings (2 kHz systems are now already deployed and operational). This increased accuracy allows us to determine the origin, scale and orientation of the Terrestrial Reference Frame with very high accuracy [7], [8], a fundamental requirement for future climate change research, and contribute significantly in fundamental physics research [9].

The launch of an additional cannonball target will be a great addition to the relatively small and aging "constellation" of such targets already in orbit. It is however a very much needed addition because it enables the increase of tracking opportunities by a weather-dependent system such as the laser ranging network. The new target will also allow for a better temporal distribution of the tracking data making possible a more robust observation of the minute rotational (orientation) variations of Earth under the quasi-inertial frame realized by the satellite orbits. Finally, the temporal variations of the long-wavelength harmonics, especially the zonals, of the gravitational field of Earth, are proxies of global change and interactions between the solid part of Earth, its atmosphere, hydrosphere and ice sheets [22]. The secular and long period variations in these terms are almost uniquely determined from laser ranging observations to these cannonball targets. The more targets available, the more accurate, robust are the corresponding estimates. Furthermore, we can observe more harmonics with more targets placed in differently inclined orbits.

Frame-dragging may be thought of as an aspect of the Einstein's principle of equivalence stating that, in a sufficiently small neighbourhood of a spacetime point, the effects of gravitation are not observable inside a freely falling frame, i.e. inside the so-called "Einstein elevator" [3]. The basic aspect of the equivalence principle is the equality of inertial and gravitational mass, which is one of the best tested principles of physics, measured to date with an accuracy of about 10^{-13}. However, the axes of a freely falling frame, where the equivalence principle holds, are not fixed relative to "distant inertial space", i.e. with respect to "distant fixed stars", but they are "dragged" by any moving mass. For example, they are dragged by a rotating mass; this is the "dragging of inertial frames" or "frame-dragging" as Einstein called it in 1913. In the near future the Gravity Probe B (GP-B) mission will try to measure frame-dragging, with unprecedent accuracy, on small super-conducting gyroscopes (the axes of the frames where the equivalence principle holds) orbiting around the Earth. GP-B will collect data, over a period of about one year only, that will then be analyzed to measure frame-dragging. However, the WEBER-SAT will collect data for a period of virtually hundreds of years (being a totally passive satellite with a very small orbital decay). These data could then be analyzed again in the future using the future improved gravitational models, in order to obtain much improved tests of frame-dragging and of other gravitational effects.

The orbit of a test-particle, such as a small satellite, is also a kind of gyroscope. Indeed, two of the orbital elements of a test-particle behave as "gyroscopes": the node and the pericenter (neglecting all the other perturbations).

Frame-dragging, gravitomagnetic field and Lense-Thirring effect have been described in several papers and studies, see for example ref. [3] and the ASI LARES phase A study [6].

Here we just point out that the Gravity Probe B experiment will try to measure the gravitomagnetic effect generated by the angular momentum of the Earth on a *gyroscope*, whereas the WEBER-SAT should measure the Earth's angular momentum effect on the orbit of a test particle. In some alternative theories the two effects may be different as in the case of a non-metric theory with asymmetric connection, such as the Cartan theory with torsion, that may affect in a different way the orbit of a test-particle and of a gyroscope (see ref. [3]).

2 A recent measurement of the Lense-Thirring effect using the LAGEOS satellites

Let us briefly report a recent measurement of the Lense-Thirring effect on the two Earth satellites LAGEOS and LAGEOS 2 [12]. We measured the Earth frame-dragging to be 99 % of the value predicted by general relativity; the uncertainty of this measurement was ±5 % including all the known errors and ±10 % allowing for underestimated and unknown error sources.

Recently, by analysing the uncertainties in the spherical harmonic coefficients of the recent Earth gravity model EIGEN-GRACE02S obtained by the NASA space mission GRACE [13, 14], we found that the only relevant uncertainty in the orbit of the LAGEOS satellites [15], comparing it with the magnitude of the Lense-Thirring effect, is the one, δJ_2, in the Earth quadrupole moment, J_2, which describes the Earth oblateness. In the EIGEN-GRACE02S model, the relative uncertainty $\delta J_2/J_2$ is about 10^{-7}. This uncertainty corresponds on the orbits of the LAGEOS satellites to a shift of the node larger than a few times the Lense-Thirring effect. However, the orbital uncertainty due to all the other harmonics is only a few percent of the general relativity shift. Therefore, in order to eliminate the orbital uncertainty due to δJ_2 and in order to solve for the Lense-Thirring effect, it is necessary and sufficient to use only two observables. The two orbital observables we have analyzed are the two nodes of the LAGEOS satellites [16, 17, 18]. After modelling all the orbital perturbations, apart from the Lense-Thirring effect, we are able to predict the LAGEOS satellites' orbit with an error (root-mean-square of the residuals) of about 3 cm for a 15 day arc, corresponding to about fraction of a half millisecond of arc at the LAGEOS satellites altitude. The Lense-Thirring effect is in contrast 31 milliarcsec/yr on the LAGEOS node and 31.5 milliarcsec/yr on the LAGEOS 2 node, as calculated by the Lense-Thirring formula. The residual (calculated minus observed) nodal rate of the LAGEOS satellites, $\dot{\Omega}_{residual}$, is therefore: (residual nodal rate) = (nodal rate from δJ_2 error) + (nodal rate from other δJ_{2n} errors) + (Lense-Thirring effect) + (other smaller modelling errors), where the δJ_{2n} are the errors in the Earth even zonal harmonic coefficients, J_{2n}, of degree $2n$. We can then solve for the Lense-Thirring effect the system of the two observed residual nodal rates for the Lense-Thirring effect and simultaneously eliminate the error due to the δJ_{2n} uncertainty. The maximum error in the combination of the residuals due to the δJ_{2n} is 4 % of the Lense-Thirring effect.

In Ref. [12] is reported the analysis (using the orbital estimator GEODYN

[19]) of nearly eleven years of laser-ranging data, from January 1993 to December 2003, corresponding to about one million of normal points, i.e., to about 100 million laser ranging observations from more than 50 ILRS stations distributed all over the world [20].

In Fig. 1 we show the observed residuals of the nodal longitudes of the LAGEOS satellites, combined according to the formula to cancel the δJ_2 uncertainty [12]. The best fit line through the raw residuals in Fig. 1a (one-parameter fit) has a slope of 47.4 milliarcsec/yr; the root-mean-square of these post-fit residuals is 15 milliarcsec. In Fig. 1b are the residuals after removal of six main frequencies, corresponding to a thirteen-parameter fit with a secular trend plus phase and amplitude of six main signals with periods of 1044, 905, 281, 569, 111 and (see Method) 284.5 days. In this case the secular trend is 47.9 milliarcsec/yr, however the root-mean-square of these post-fit residuals is 6 milliarcsec only. In Fig. 1c is the Lense-Thirring effect predicted by general relativity for the combination of the LAGEOS nodal longitudes, which amounts to 48.2 milliarcsec/yr. Therefore, corresponding to the thirteen parameter fit of Fig. 1b, the observed Lense-Thirring effect is 47.9 milliarcsec/yr, corresponding to 99 % of the general relativistic prediction. In conclusion, this analysis confirms the Einstein's theory predictions of frame-dragging and Lense-Thirring effect [12]. The total uncertainty of our measurement is, including systematic errors, ±5% of the Lense-Thirring effect and ±10% allowing for underestimated and unknown error sources. For example, if we consider the time-independent gravitational error (root-sum-square) to be three times larger we get a corresponding error of 9 % and a total uncertainty of less than 10 %.

3 Some geodetic results using the LAGEOS satellites and the EIGENGRACE02S model

Using the method of analysis of about 11 years of satellite ranging observations reported in the previous section, in addition to the accurate determination of the Lense-Thirring effect, an anomalous variation in the Earth gravity field since 1998 was observed [21] that was clearly identified as an anomalous increase in the Earth quadrupole moment. The trend in the nodal longitudes of both satellites distinctly showed a variation in the Earth gravity field since 1998. This effect was proved [21] to be due to an increase in the J_2 coefficient, indeed, combining the node residuals according to the formula to eliminate the J_2 perturbation only, the effect disappeared. The anomalous trend observed using EIGEN-GRACE02S was also accurately reproduced using the previous EGM96 Earth gravity model and the recent EIGEN-2 model due to the CHAMP satellite. This result confirms the measured relative increase of J_2 of the order of 10^{-11} that was recently reported [22]. The Earth mass redistribution associated with this phenomenon is so far not clearly understood.

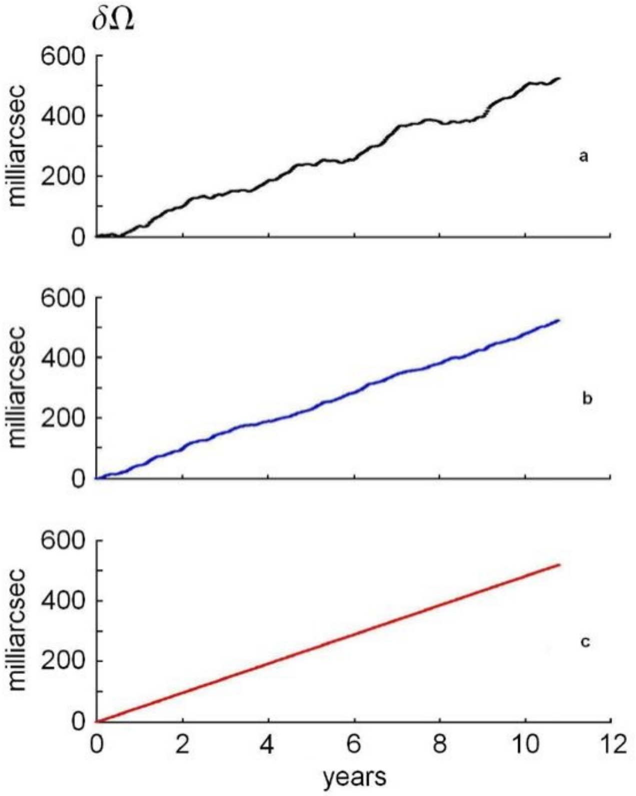

Figure 1: Observed orbital residuals of the LAGEOS satellites. The residual nodal longitudes of the LAGEOS satellites were combined according to the equation to cancel the δJ_2 uncertainty. In Fig. 1a is the raw, observed, residual nodal longitude of the LAGEOS satellites without removal of any signal, whereas in Fig. 1b is the observed residual nodal longitude after removal of six periodic signals. The best-fit line (thirteen parameter fit) through these observed residuals has a slope of 47.9 milliarcsec/yr. In Fig. 1c is the theoretical Lense-Thirring prediction of Einstein's general relativity for the combination [6] of the nodal longitudes of the LAGEOS satellites, its slope is 48.2 milliarcsec/yr.

It is important to stress that together with the measurement of the Lense-Thirring effect, it was also measured the effect of the variations of J_2, J_4 and J_6 on the nodes of the LAGEOS satellites. In [23] it is indeed reported an effective (i.e. including the effect of the higher even zonal harmonics) value of $\dot{J}_4^{Effective} \cong 1.5 \cdot 10^{-11}$. In the EIGENGRACE02S model, obtained by the GRACE mission only, the Earth gravity field was measured during the period 2002-2003. Corrections due to $\dot{J}_2$ and $\dot{J}_4$ were then applied to this 2002-2003 measurement in order to obtain a gravity field model antecedent to 2002-2003. These values of $\dot{J}_2$ and $\dot{J}_4$ used by the GFZ team are $\dot{J}_2 = 2.6 \cdot 10^{-11}$ and $\dot{J}_4 = 1.41 \cdot 10^{-11}$ and they were measured on the basis of completely independent 30-year observations before 2002. In ref. [23] are reported the orbital analyses using the orbital estimator GEODYN with and without a contribution of $\dot{J}_4 = 1.41 \cdot 10^{-11}$. First, it is important to stress that in the case of *not* applying this $\dot{J}_4$ correction to the orbital analysis, it can be clearly seen, by visual inspection, a hump in the combined residuals. Indeed, the effect of the time variation $\dot{J}_4$ shows up as a quadratic effect in the cumulative nodal longitude of the LAGEOS satellites, therefore the combined residuals of LAGEOS and LAGEOS 2 were fitted with a parabola, together with a straight line and with the main periodic terms. Then, by fitting the raw residuals obtained *without* any $\dot{J}_4$, it was measured a $\dot{J}_4^{Effective} \cong 1.5 \cdot 10^{-11}$, which includes the effect of $\dot{J}_6$ and of higher even zonal harmonics. On other hand, in the analysis of the combined residuals obtained with the EIGENGRACE02S correction of $\dot{J}_4 = 1.41 \cdot 10^{-11}$, it was measured a $\dot{J}_4^{Effective}$ of less than $0.1 \cdot 10^{-11}$, in complete agreement with the previous case. It is finally important to stress that this small value of the unmodelled quadratic effects in our nodal combination due to the unmodelled $\dot{J}_{2n}$ effects (with $2n \geq 4$) corresponds to a change in the measured value of the Lense-Thirring effect of about 1 %. In other words using the value of $\dot{J}_4^{Effective} = 1.5 \cdot 10^{-11}$ that we obtained from fitting the combined residuals (which is about 6 % larger than the value $\dot{J}_4 = 1.41 \cdot 10^{-11}$ given in the EIGENGRACE02S model) resulted in a change of the measured value of frame-dragging by about 1 % only with respect to the case of using $\dot{J}_4 = 1.41 \cdot 10^{-11}$; in conclusion this 1 % variation fully agrees with the error analysis given in [12].

4 On the possibility of testing Brane-World theories with WEBER-SAT/LARES

Let us now briefly describe the possibility of probing some recently proposed modifications of gravity using the Runge-Lenz vector, i.e., the perigee of WEBER-SAT [4].

In Newtonian mechanics, the orbital angular momentum of a satellite and its nodal line, the intersection of its orbital plane with the equatorial plane of the central body, maintain a constant direction relative to "distant inertial space" for a motion under a central force. The Runge-Lenz vector, joining the focus and the pericenter of the orbit of a satellite, has also a constant direction relative to "distant inertial space" for a motion under a central force dependent on the inverse of the squared distance from the central body. Using the technique of laser-ranging with retro-reflectors to send back the short laser pulses, to this date we are able to measure distances with a precision of a few cm to a point on the Moon and of a few millimeters to a small artificial satellite. The instantaneous position of the LAGEOS satellites can be measured with an uncertainty of a few millimeters and their orbits, with semi-major axes $a_{LAGEOS} \cong 12270$ km and $a_{LAGEOS\ II} \cong 12210$ km, can be predicted, over 15 day periods, with a root-mean-square of the range residuals of a few cm. This uncertainty in the calculated orbits of the LAGEOS satellites is due to errors in modelling their orbital perturbations and, in particular, in modelling the deviations from spherical symmetry of the Earth's gravity field, described by a spherical harmonics expansion of the Earth's potential. However, to date, the terrestrial gravity field is determined with impressive accuracy, in particular with the dedicated satellites CHAMP and especially GRACE [13]. Regarding the perigee, the observable quantity is $ea\dot{\omega}$, where e is the orbital eccentricity of the satellite and, ω, the argument of perigee, that is the angle on its orbital plane measuring the departure of the satellite perigee from the equatorial plane of Earth. Therefore, we can increase the measurement precision by considering orbits with larger eccentricities.

Motivated by the cosmological dark energy problem, Dvali recently proposed string theories leading, among other things, to weak field modifications of gravity [5]. One of the interesting observational consequences of the large distance infrared modification of gravity pointed out by Dvali is the anomalous shift of the pericenter of a test particle. The anomalous perihelion precession predicted by this gravity modification for the Moon perigee is:

$$\delta\phi = -[(3\pi\sqrt{2}/4)r^{3/2}]/(r_c {r_g}^{1/2})\ rad/orbit \tag{1}$$

Where, $r_g = 0.886cm$ is the gravitational radius of the Earth, r is the Earth-satellite distance and $r_c = 6Gpc$ is the gravity modification parameter that gives the observed galaxies acceleration without dark energy [5]. $\delta\phi = 1.4 \cdot 10^{-12}$ rad/orbit for the Moon.

Therefore in the case of the WEBER-SAT satellite with a semimajor axis of about 12270 km this effect would amount to 0.004 milliarcsec/yr only.

Since this effect of infrared gravity modification is proportional to the 3/2 power of the semi-major axis and however the number of orbits per year goes as the -3/2 power of the semi-major axis, in terms of radians per year the perigee shift is the same for both the Moon and WEBER-SAT, i.e. $1.9 \cdot 10^{-11}$ rad/yr. Therefore, we [4] simply need to consider what can be gained, or lost, with the use of WEBER-SAT versus the Moon. In regard to the measurement precision, the ranging precision is very roughly proportional to the range distance, i.e. is a few cm for the Moon and a few millimeters for the WEBER-SAT, then since the shift of the perigee at the satellite altitude is $1.9 \cdot 10^{-11}$ rad/yr times the semi-major axis, the ratio of ranging precision to the effect to be measured is roughly the same for both the Moon and WEBER-SAT, even though slightly more favorable for the Moon. However, since the recovery of the perigee shift is proportional to the eccentricity of the satellite, we could orbit the WEBER-SAT satellite with a much larger eccentricity than the one of the Moon and therefore we could make the measurement of the perigee shift of the WEBER-SAT more *precise* than the one of the Moon.

However, critical are the *systematic errors* acting on the WEBER-SAT:

(a) the impact of the modelling uncertainties in the gravitational perturbations is critical for the WEBER-SAT satellite indeed the zonal harmonics of the Earth gravity field produce a perigee shift that is a function of the inverse powers of the semi-major axis, a: $1/a^{(2n+3/2)}$, for each even zonal harmonic coefficient J_{2n} with n integer. However, considering the improvements in the future Earth gravity models from the mission CHAMP, GRACE and GOCE, the future uncertainty in the perigee shift due to gravitational perturbations should drastically decrease.

There is also an interesting possibility to choose a different orbit for WEBER-SAT, not at 70 degrees of inclination, but for example with the special inclination of about 63.4 degrees, (of the type of the Molniya orbits) at which a satellite would have a null perigee shift due to the Earth's quadrupole moment J_2. In this way we would be able to cancel the major part of the J_{2n} uncertainties to measure the perigee, but we will lose some accuracy in the measurement of the Lense-Thirring effect on the node, even though the use of LAGEOS and LAGEOS II, together with WEBER-SAT, and the future improvements in the accuracy of the Earth's gravity models should not make this Lense-Thirring measurement much worst than a 1 % measurement (this possibility has to be further investigated) and furthermore, in this case, the Lense-Thirring effect could be measured using the WEBER-SAT perigee.

The impact of the modelling uncertainties in the non-gravitational perturbations is also critical for the WEBER-SAT satellite indeed the crucial factor is the cross-sectional area to mass ratio. In other words the acceleration produced by a non-gravitational force (such as radiation pressure) acting on a satellite is proportional to its cross sectional area and inversely proportional to its mass. Then this ratio is roughly proportional to the inverse of the radius of the considered satellites. Then for the Moon is very small whereas for WEBER-SAT may be a critical source of error.

These forces could be reduced by (a) a much denser and larger satellite than the one of the original proposal (although by increasing the cost of the mission);

(b) the non-gravitational perturbations of the perigee could also be reduced through the use of a much more eccentric orbit and (c) the mismodelling of the radiation pressure perturbations could be reduced by special optical and thermal tests performed on the WEBER-SAT satellite and through the measurement of its spin axis and rotational rate, once in orbit. Finally, we also mention the possibility of a drag free system, that implies acceleration sensors and propulsion systems on board, or of a spherical satellite made of a material transparent to most of the radiation; similar spherical retro-reflectors have been tested by the Russian space agency.

5 The WEBERSAT satellite

WEBERSAT satellite is a very simple satellite. In fact it is passive and does not require telemetry, attitude control, power, downlink, etc... On the other hand it has very demanding requirements. As mentioned earlier, the surface-to-mass ratio should be the lowest possible but also the satellite size must be maintained small to keep launch cost reasonable. Unfortunately the two requirements play opposite roles, in fact the abovementioned ratio is roughly inversely proportional to the radius. Another important aspect to be considered is the visibility of the satellite. There are more than 40 laser ranging stations in the world with different ranging capabilities. From some stations such as the one in Matera, in Italy, one can reach the Cube Corner Reflectors (CCRs) deployed on the Moon by the astronauts of the Apollo missions and get the signal back. Other stations are instead more limited. The amount of light reflected by the CCR is a function of the satellite altitude as well as of the satellite radius. In fact for a satellite the size of LAGEOS (60 cm in diameter) there are in average about 7 CCRs capable of reflecting the light, while for a satellite the size of LARES (30 cm in diameter) we have only 2 CCRs in "active" condition. Presently we reached a good compromise between surface-to-mass ratio, visibility and weight, by choosing a diameter of about 30 cm for the satellite.

In order to optimize the orbit for testing Brane-World theories, it is recommended, as mentioned earlier, a very eccentric orbit. The most economical one might be a Geostationary Transfer Orbit (GTO) typically used for commercial satellites, being a secondary payload for a commercial launch a convenient solution. Most commercial satellites are in a geostationary orbit, with low eccentricity. Our release would have to be during the transfer trajectory so that it has a high eccentricity. However the perigee should perhaps be raised from 600 km to at least 2000 km to reduce the inhomogeneous drag effects on the motion of the perigee (this problem has to be further studied). Part of the GTO orbit has an altitude of 36.000 km which is far beyond the capability of many laser ranging stations. In case this orbit will be considered,

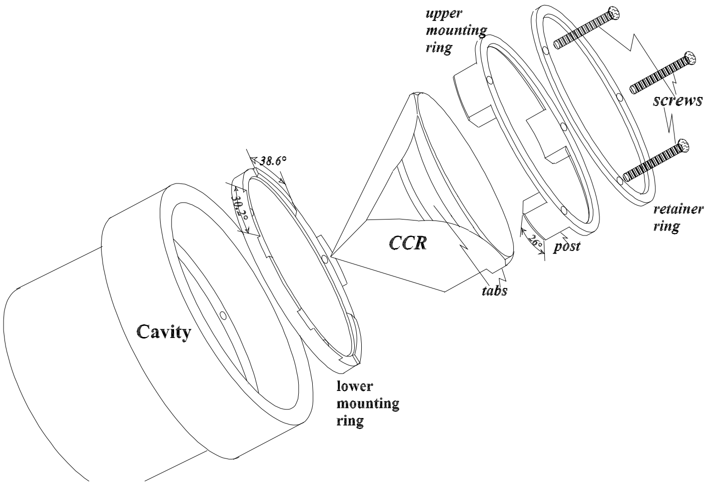

Figure 2: CCR mounting system.

one has to evaluate if a scarcity of data in the higher part of the orbit itself will be acceptable. Also the eccentricity enters in the equations, but the very accurate determination of this parameter is probably not as critical and fewer data points on the higher part of the orbit may suffice. A GTO orbit may therefore be a convenient choice to reduce the errors in the measurement of the perigee rate.

Another mitigation measure can be taken on another important source of error: the thermal thrust. The effect of thermal thrust on the node of a laser ranged satellite is relatively small, considering that this perturbation is also well modelled. The unmodelled effect on the perigee is much larger and probably bigger than the drift expected from Brane-World theories. In this last case improved modeling of thermal thrust is not enough, it is in fact required also an improved design of the satellite or even a dramatic change of it. Since thermal thrust is induced by thermal gradients on the satellite surface, thermal exchange between the several components of the satellite has to be increased. In Fig. 2 are reported the main components of the satellite (conventional design) which are: satellite cavity, CCR, plastic mounting rings, aluminum retainer ring and three screws. In [24] one can see that the estimated temperatures are quite different for the several components. In Table 1 are reported the approximate values of the component temperatures in two extreme conditions in the case of spin axis toward the Sun.

The major differences can be observed between the aluminum retainer ring and the CCRs. Also significant is the temperature difference between

	Sunlit pole	Dark pole
Satellite structure	300 K	300 K
Lower plastic mounting ring	307 K	290 K
Upper plastic mounting ring	343 K	280 K
Aluminum retainer ring	355 K	280 K
CCR	290 K	250 K

Table 1: Temperature distrubution on LAGEOS components

CCRs and satellite. Now this is certainly due to the absence of direct contact between the CCR and the metallic structure of the satellite. As suggested in [6] an improvement of thermal exchange between CCRs and satellite may be obtained by optimizing the emissivity and absorptivity of the CCR cavity and the three back surfaces of the CCR. That can be obtained by a proper choice of thin film to be deposited on the mentioned surfaces. This process will increase the heat exchange through radiation. Other mitigating measures have to be taken to reduce all the thermal conductances present in the satellite such as those between retainer aluminum rings and satellite. A further source of error is due to the satellite eclipses. Increasing the thermal capacity of the aluminum retainer rings by making them thicker for instance, one can reduce temperature variations during the eclipse [6]. A careful evaluation of temperature distribution through heat transfer analysis and dedicated tests need to be performed. A radical change in the design of WEBERSAT is being evaluated to reduce drastically temperature gradients on the satellite. The idea is that of eliminating the major cause of those temperature gradients i.e., thermal contact resistance and gaps between satellite components. This last aspect is very difficult to eliminate when one of the components is made of glass and the other of metal. Putting these two materials, with different thermal expansion coefficient, in intimate contact may jeopardize the integrity of the CCR. The more direct way to cope with this aspect is considering a full metal solution for the satellite. This means that the CCR should be carved directly on the spherical surface of a single piece satellite. Having a small satellite (a little bigger than a basket ball) made of high thermal conductivity material will drastically reduce the problems concerning thermal thrust. Temperature gradients will be reduced by about one to two orders of magnitudes. On the other hand with the full metal solution eddy currents will flow more easily and by interacting with the Earth magnetic field will cause the spin down torque to be more severe than in the LAGEOS satellites. By using a special tungsten alloy, characterized by a sufficiently low electrical conductivity (but still high thermal conductivity), the spin down torque can be mitigated. This is an advantage since modeling of thermal thrust in the rapid spin case for the satellite is more accurate. The baseline density for the satellite is at least

15.000 kg/m^3. Since with such a high density the spin down rate will be lower, the rapid spin case for WEBERSAT/LARES will last anyway many years after orbital injection. Another problem with this solution is the difficulty of getting the satellite attitude from ground observation of solar glints. These are solar reflections that can be obtained from the front surface of the silica glass CCRs. In order to reach the Brane world sensitivity it may be required to have anyway attitude information. For sure from some stations (MLRO for instance) by simply looking at the shape of the return laser beam it is possible to obtain the rotation rate. Furthermore by improving the photometric measurements it will be possible to recover spin axis orientation, and consequently thermal force direction, also in the case of full metal solution. But the big problem is the difficulty of machining the hollow CCRs on the spherical surface. The main reason is that the surface is concave and the requirements very strict: back surface angles with a tolerance of only 0.5 arcsec [25] and metallic surface polished to optical quality. It is obvious that special optical set up has to be arranged, possibly in the vicinity of the tooling machine, in order to check, in almost real time, the fulfillment of the requirements. There is also an issue concerning the retroreflecting efficiency of the hollow CCR. The conventional CCR has a reflection optical performance that decays with the cosine of the impinging angle from the normal. This is partly due to total internal reflection condition partly failing at larger angles. The hollow CCR also decays with cosine of the impinging angle. However, at large angles, there will be no failure of the total internal reflection. On the other hand, there will be absorption due to the metallic surface. For alumimun, this will be about 30% loss. However special coatings may help this.

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