Galactically inertial space probes for the direct measurement of the metric expansion of the universe

Ivan Cagnani
Physics student, University of Bologna, Istituto di Fisica, via Irnerio 46, 40126, Bologna, Italy
Email: ivan@omgl.org

Abstract. Astrometric data from the future GAIA and OBSS missions will allow a more precise calculation of the local galactic circular speed, and better measurements of galactic movements relative to the CMB will be obtained by post-WMAP missions (ie Planck). Contemporary development of high specific impulse electric propulsion systems (ie VASIMIR) will enable the development of space probes able to properly compensate the galactic circular speed as well as the resulting attraction to the centre of our galaxy. The probes would appear immobile to an ideal observer fixed at the centre of the galaxy, in contrast of every other galactic object, which would appear moving according to their local galactic circular speed and their proper motions. Arranging at least three of these galactically static probes in an extended formation and measuring reciprocal distances of the probes over time with large angle laser ranges could allow a direct measurement of the metric expansion of the universe. Free-drifting laser-ranged targets released by the spacecrafts could also be used to measure and compensate solar system's induced local perturbations. For further reducing local effects and increase the accuracy of the results, the distance between the probes should be maximized and the location of the probes should be as far as possible from the Sun and any massive object (ie Jupiter, Saturn). Gravitational waves could also induce random errors but data from GW observatories like the planned LISA could be used to correct them.

1. Introduction
The interpretation of cosmic expansion depends on the interpretation of space. Do galaxies actually move physically as Mach would say[1], distancing themselves from each other at ever increasing speed, or rather, are they to be seen as pretty stationary objects embedded in a space whose metric is expanding at an accelerating pace?

Current astronomical observations cannot rule out either hypothesis and are used by proponents of both views to proof their hypothesis. New cosmological measurements are required to discriminate between these two views, and for determining the best cosmological description of the observable universe at all astronomical length scales. Particularly interesting, among the new experimental cosmology projects, are the space missions to measure directly, although necessarily locally, several cosmological parameters. Notable in this category are the LATOR[4], STEP[5], ASTROD I and Super-ASTROD[6] and SAGAS[16] missions. A common characteristic of most of these missions is the use of a triangular formation of deep space probes, often provided with powerful lasers and ion-optical clocks, and using, whenever possible, interferometric techniques, which cannot be applied to measurement of absolute proper distances but are very performing in measuring relative velocities between the probes. A similar experimental setup is applied to several gravitational wave detection
projects, like LISA[33], DECIGO[34] and the Big Bang Observer[35]. All of these missions can provide direct cosmological measurements[36][37][39], and a possible dedicated future mission using the same technique and GW bandwidth (0.1Hz) could be able to measure the acceleration of expansion [38].

There have been attempts in recent years to recognize local effects of cosmological expansion in several high precision measurements within the solar system, in particular analyzing Lunar Laser Ranging data [3][7] and the Doppler radar tracking of several deep space probes, especially the Pioneer 11 probe [8][9][10][11][21]. Those conclusions have been contested by several authors, as there could be less exotic, non-cosmological explanations for both local phenomena [15][12][13][14]. In the case of the Earth-Moon system, the lunar recession rate is conventionally completely attributed to the energy released by tidal friction on both bodies. Tidal friction is difficult to measure accurately on Earth, but it is believed by most geophysicists to cause heating at the bottom of the oceans and in such way to contribute substantially to the energy budget of oceanic thermohaline circulation, also called Meridional Overturning Circulation. According to us, nothing should prevent the hypothesis that both cosmic expansion and tidal dissipation contribute to the recession motion of the Moon. According to [24], a lunar recession rate of 3.82 cm/year would implicate a total energy released by tidal friction of 2.5TW, assuming tidal friction as the only cause of lunar recession; anyway, the power dissipated by oceans as calculated from the surface is only 1.8TW. This energy difference should allow us to hypothesize that cosmic expansion could be a concurrent cause of lunar recession. A very interesting application of laser interferometric techniques has been proposed [3] as an enhancement of the current lunar laser ranging (LLR) project, in the prospective of placing active laser transponders on the Moon surface in addition to the current passive retroreflectors placed in the 1970s and used by LLR systems. The proposed active interferometric system would allow a direct very high precision determination of several cosmological parameters in the Moon-Earth-Sun system, including cosmic expansion and dark energy. According to us anyway the accuracy of such measurements could be debatable due to the complexity of Moon-Earth-Sun system. Current models contain already more than 170 parameters and still cannot fully explain millimeter-precision data currently obtained by the APOLLO LLR project [40][41]. For distances much greater than the Earth-Moon separation, laser interferometry cannot be applied because laser radiation would lose coherence before arriving to destination. Since the coherence length of the laser source is

\[
L = \frac{2 \ln(2) \lambda^2}{\pi n \Delta \lambda}
\] (1.1)

regardless the choice of wavelength, \(\lambda\) and the spectral bandwidth \(\Delta \lambda\) obtainable from instrumentation, a different type of tracking must be used. While radio frequencies Doppler radar tracking was the technique of choice in the last century for deep space probes, this technique is impractical for probe to probe tacking at distances of 10AU or more. For example, the antenna installed on the probe cannot match a large radio-telescope on Earth. This leaves mission designers with the need of using a system more similar to current LLR, but using active laser transponders instead of retroreflectors. For very long distances, like Earth-Mars or more, it is convenient to use transponders in asynchronous mode.

As illustrated in figure 1, Asynchronous Laser Transponders works emitting signals at a regular frequency instead of waiting for an answer signal to the original communication. This is justified by the time it takes light to cover distances of several AU or more.

The main requirements of this ranging and communication technique are sufficient laser power, a reflecting telescope with an aperture proportional to the distance to be ranged but never impractically large, and most importantly a very accurate clock for keeping the pulsing extremely regular in time.
Asynchronous laser transponders emit periodic pulses. The emission time of the pulse from probe A is independent of the reception of a signal from probe B. The pulses can contain digital information so the transponders are both ranging and communication devices.

The telescope is used both for emission and reception of signals and is fundamental in transmission for collimating and directing the laser signal. Asynchronous Laser Transponders are the ranging and communication system adopted in our proposed mission.

Our proposed mission, a direct measurement of metric expansion by measuring the time variation of the area covered by 3 probes in a special dynamical state, would help to understand the fabric of spacetime in our solar system in a novel way, and could be determinant to falsify or verify Mach's hypothesis about the nature of space ad its relationship to matter and inertia.

The simple physics which describes the problem of the local expansion between two objects originally disconnected from the Hubble flow, called the problem of the "tethered galaxy", has been very well illustrated in [15], and we highly recommend the reading of that thesis as the best theoretical introduction to the issue. Another very detailed study of the problem [2], emphasizes the difference between dynamical and kinematic effects of cosmic expansion on a satellite or a probe in the solar system, and contains very noteworthy considerations about the Pioneer Anomaly and similar Doppler tracking revealed effects.

Theoretical work on the subject is far from being exhaustive anyway, and there are still disagreements, especially about the amount of possible effects on objects within the solar system.

In the case of Pioneer 11, the numerical similitude between the anomalous Sun-ward acceleration of the probe and the product of the Hubble constant with the speed of light got many people thinking:

\[ 8.6 \pm 1.34 \cdot 10^{-10} \, m \, s^{-2} \approx 7 \cdot 10^{-10} \, m \, s^{-2} \]  

anyway the method itself used to determine the kinematics of the probe makes problematic the analysis of the violet-shift anomaly [2]. Nonetheless the Pioneer effect is interesting enough to warrant a space mission to study it. Several proposals have been made to space agencies, from dedicated missions [43][44] to the adaptation of planetary missions using the probe itself or a small dedicated probe released by the main probe [42].

Laser ranging is the best methodology for long range distance determination for general relativity tests and gravitational measurements, anyway a few authors expressed theoretical doubts about the invariance of the speed of light (for recent examples [25] [26] [27]). Any directional or temporal variation in the speed of light would be really complicate space experiments using lasers at long distances so any new investigation in that area would be welcome to remove any minor doubt before attempting very ambitious deep space laser measuring missions.

2. The mission proposal
After launch in a hyperbolic solar orbit, each probe's nuclear reactor is activated and the propulsion system powered up. The probes will reach a distance of 25AU from the Sun. They will create an equilateral triangle formation on a plane parallel to the mean ecliptic plane distanced by 7AU in the solar zenith direction and the center of the triangle will be vertically above the Sun. The projected Sun-probe distance on the mean ecliptic plane is 24AU. After this initial configuration has been
achieved, a galactic stabilization procedure will start. The aim of the procedure is to cancel any
galactic movement inherited by the probes as parts of the solar system. The stabilized probes will then
vary their galactic position and their reciprocal distances only because of metric expansion
(gravitational perturbations will still be possible from the Sun, the gaseous planets, comets passing
nearby, as well as mechanical perturbations from solar wind, radiation pressure, but they will be
assessed by releasing small laser retroreflecting test masses periodically from the from the main
probes, and minor position corrections will be performed by specialized high accuracy ion thrusters).
The probe constellation ready for the data collection phase would appear like in figure 2:

![Figure 2: Not-to-scale illustration of the constellation of the three probes at the beginning of their scientific data acquisition phase. The Sun will not keep its position at the center of the triangle during the experiment as the probes are galactically stabilized but not stabilized with the Sun.]

The reciprocal distance of each couple of probes is measured by the laser ranging system using
asynchronous laser transponders repeating a 12s optical signals sequence transmitted continuously by
each probe to the other.

| Repeating Laser Sequence |
|---------------------------|
| Trigger | Timestamp, pulsar synch, other... |
| 2s | 8s, bits of 1ms, 1KB |

![Figure 3: Sequence transmitted from each probe to the other two probes using its own asynchronous active laser transponders. The duration of the trigger must be as close to exactly 2s as feasible.]

As illustrated in figure 3, the signal sequence is actually a mixed digital transmission containing a
2s continuous trigger and a 8s digital 1KB string (bits having a period of 1ms each) with the function
of a timestamp. Both the trigger and the timestamp are followed by a 1s interval making the total
duration of the sequence 12s. The trigger duration must be as close to exactly 2s as the probe clock
and system allows, which ideally should mean a max error of $2 \times 10^{-18}$ s. The digital string following by
1s the trigger must contain the reading of the emitting probe's clock at the end of the trigger pulse. For
redundancy the value of the clock reading is repeated 3 times in the 1KB string, and of course it is
followed each time by an error correction code. Finally the string contains information about the
pulsar used for clock synchronization by the emitter probe and the particular feature of the pulsar
signal used for resetting the clock. The clock of each probe is reset and pulsar synchronized every $10^7$
seconds. Of course the new synchronization information is immediately shared in the following pulse.

The measurement of the reciprocal speed between two probes is based on the difference from the
expected time of arrival of the end of the next trigger pulse using the onboard clock to measure 12s
with $2 \times 10^{-18}$ precision from the reception of the end of the last trigger. Any displacement between the
two probes in the 12s separating two trigger emissions will generate a small delay (supposing metric
expansion dominates) or a really minimal advance (supposing the Pioneer Anomaly dominates). Each
probe's computer is aware that its clock can be affected by gravitational and mechanical perturbations
slightly different than those affecting the clock of the emitting probe. Anyway, analyzing the
timestamps, and arrival times of the end of the triggers, the receiver's computer can easily distinguish
effects induced on the emitter's clock from the effect due to the variation of the reciprocal distances. In
other words, it can distinguish a variation of the comoving positions or a perturbation of the spacetime
fabric close to the emitter, from the effect that it must closely observe: the variation of the proper distance between the probes given unvarying comoving distance and no gravitational perturbations. It is possible to conceive the transmission of “I think you are under this disturbing effect...” messages from a probe to the other instead of the third redundant repetition of the trigger end emission time in the exchanged digital string. Of course, for error correction all internal delay times must be monitored by the emitter and their eventual variation must be communicated to the receiver too.

Given the standing lack of certain knowledge about the causes of the Pioneer Anomaly, the local effect of expansions, the nature of dark energy and its local effects too, a realistic simulation of the experiment at the high precision level of the measurement is not possible at the moment. Even if a perfect mathematical model considering all possible effects and their causes were developed, the uncertainty in cosmological and astrophysical parameters as actually known would make the model unable to simulate realistic results. This situation could change in the following years, as the precision in cosmological parameters determination is certainly going to increase significantly.

In an ideal universe with $H_0 = 70\,\text{Km/s/Mpc}$ the expected recession speed between the probes at fixed comoving distance of $42\,\text{AU}$ should be $1 \times 10^{-5}\,\text{m/s}$, this means that the proper inter-probe distance will increase of $0.12 \times 10^{-3}\,\text{mm}$ between two successive laser ranging pulse emissions (each transmission cycle lasting exactly $12s$). A distance of $0.12 \,\text{mm}$ is covered in $4 \times 10^{-13}\,\text{s}$ at the speed of light in vacuum. With a nominal clock accuracy of $1 \times 10^{-18}$ and ideal measurement uncertainty of $2 \times 10^{-18}$, which could mean a real world measurement uncertainty of $1 \times 10^{-17}$ it seems realistic to be able to measure the $0.12 \,\text{mm}$ variation in length, and extract this simple displacement from the inevitable noise of unwanted effects.

Apart from the increase of the proper distance between the probes, and the following measurable increase in the timing of successive pulses, it must be considered the possibility of an effect of frequency shift in the laser signal. The Pioneer Anomaly has been measured, in the radio spectrum, as a $(5.99 \pm 0.01) \times 10^{-9}\,\text{Hz s}^{-1}$ effect. To avoid unnecessary complexity, let's suppose the probes are on the mean ecliptic plane. Since it takes the laser signal almost $2.1 \times 10^4\,\text{s}$ of time to cross the $42\,\text{AU}$ of distance between two probes, a frequency shift of $1.255 \times 10^{-4}\,\text{Hz}$ can be expected. Unfortunately a tenth of millihertz frequency shift in a laser is impossible to detect without an interferometric setup, and the coherence time of existing and conceivable lasers makes it impossible to use interferometry for distances of tens of AU. If such finely tunable laser could be built, the Pioneer effect could be measured directly in the proposed setup by recording the exact frequency of the trigger pulse at emission and communicating it to the receiver by adding it to the digital message following the trigger pulse, along with the timestamp and pulsar calibration information.

If the Pioneer Anomaly is a real acceleration and has a real effect on the probes, it should act very differently than the expansion. For two reasons: firstly expansion is not a force [15]. Unbound objects tend to follow naturally the Hubble flow, and previously tethered object getting untethered perceive no acceleration when joining the flow. Small acceleration effects may indeed be perceived but only because cosmic expansion is accelerating, possibly due to the presence dark energy. The Pioneer Anomaly appears instead to be a force but of course there is a need for more experimental data to be certain about that. The second difference is the direction, which is almost opposite in our setup. The Pioneer Anomaly appears an acceleration directed toward the Sun, the metric expansion should move the probes away from the an ideal object placed at the centre of the triangle and $7\,\text{AU}$ above the Sun, so while the two effects are not completely opposing each other, they can interact negatively. In this case, the proposed experimental setup should be able to separate the effects and measure them, anyway, as previously demonstrated, if the Pioneer Anomaly is not a real acceleration but only a cause of frequency shift of electromagnetic radiation, this will not be recorded by the proposed experimental setup and there will be not be a negative interaction to the proper recession measurement.

2.1. Galactic stabilization
Cosmic expansion should induce a subtle effect to the probes formation, so subtle it could be impossible to recognize in an environment full of disturbing interactions like that of an Earth orbit for example. As we can see from maps of the Cosmic Microwave Background radiation, the Earth motion with respect to the CMB rest frame (the closest we can have to an universal reference frame) is a combination of its rotation, its solar orbital motion, the solar motion in the galaxy (the Local Standard of Rest and the Sun's peculiar motion with respect to the LSR), then of course there are proper motions of the Milky Way in the local group and of motions of the local group.

The best kind of stabilization for each probe would be with respect to the CMB rest frame, as that would eliminate all disturbing motions and would put the probes in the same inertial system. There are several technological difficulties with this approach anyway (discussed later), which makes a less extreme stabilization worthy of consideration. In particular, galactic stabilization is the highest stabilization level that we are able to reach with technology already in development for other purposes.

Galactic stabilization means stabilization with respect to an ideal observer at the centre of the galaxy, non-corotating with the galaxy. This observer would see the constellation of 3 probes as stationary objects (shown in figure 4) in contrast of any another galactic object all orbiting around the galactic centre (including the hypervelocity stars, which while gravitationally unbounded to the Galaxy due to speeds largely greater than their local galactic escape speed, are still heavily gravitationally influenced by the Galaxy: they just follow hyperbolic orbits).

Figure 4 (up): Galactically stabilized probes are seen from an observer non-corotating with the galaxy as the only “fixed” points with respect to the galactic center, all other objects would be moving according to their peculiar and radial velocity.

Figure 5 (right): The galactic stabilization maneuver is a 4 phase process. The first and 3rd phases use mostly the navigation sensors, the 2nd phase use high-thrust impulsive propulsion, the 4rd phase uses continuous propulsion.

Given the complexity of the Galaxy stellar orbits are not really circular, but the idealized circular orbit of the Sun, the Local Standard of Rest, is fundamental for any measurement in galactic coordinates, including those necessary to calculate the galactic stabilization manoeuvre. Knowing the
deviations of the peculiar motion of the Sun from this ideal orbit is equally important. Any probe launched from the Earth is already orbiting the centre of the Galaxy as any other solar system object, and a probe launched at escape speed from the solar system will continue to follow this motion unless it can reach the same linear speed of the instantaneous tangential velocity of the Sun in its galactic orbit (estimated between 220Km/s and 260Km/s [47]) but in the exactly opposite direction. In that case the probe would find itself at zero speed in its own galactic orbit. The result of this manoeuvre of course would be the beginning of an accelerated motion towards the centre of the Galaxy (freefalling to it).

To keep the probe immobile with respect to the non-corotating galactic reference frame instead, a continuous equal and opposite acceleration would be required. This would require a very finely tunable continuous propulsion system. The galactic stabilization duration would then be limited by the amount of propellant in the engine, among other factors. After propellant depletion, the probes could attempt to continue measurements as long as possible to measure destabilized behavior and compare with stabilized data.

Both propulsion phases of the galactic stabilization maneuver (see figure 5) can be performed by a high power, variable specific impulse, electric ion engine like VASIMR [46], or better, an array of VASIMRs. Since the maximum velocity that a space vehicle can reach is bounded (although not limited) by the maximum exhaust speed of propellant, an engine like VASIMR, able to reach exhaust speeds of 300Km/s, is an ideal choice for this proposed application. Of course, using VASIMR at max power and max specific impulse mode requires a huge amount of electric power that only a space-rated nuclear generator is able to provide.

Our best LSR determinations so far come from elaborations with new methods of the Hipparcos database [19] and from the ongoing RAVE project [20] but they have uncertainties that would not allow the design of a galactic stabilization maneuver at this moment. High precision data about the Local Standard of Rest will probably only become available after the GAIA [48] astrometric mission has been launched, completed, and its results properly elaborated.

Each probe will also use its own pulsar positioning and navigational capability to test the level of galactic stabilization achieved before starting the cosmic expansion measurement along with the other probes. In particular, a precise determination of a probe's position and momentum relative to distant X-ray pulsars, to the Sun, and to a laser transponder satellite in Earth orbit (used for communication) will be required before and after the galactic circular velocity annulment maneuver, for calibration and correction.

2.2. Technology of the probes

The probes will be able to measure reciprocal distances with the maximum possible precision and accuracy. This will require extremely good clocks onboard the probes, like quantum-logic optical clocks, currently still in advanced development [17] but already used to detect subtle GR effects [18]. The clocks must be redundant. Each transponder in a probe should have 1 active optical clock and 2 inactive backup clocks, so at least 9 clocks are required in a probe. The clocks will be synchronized simultaneously to the same pulsar. Particular features of the pulsar signal will be used for synchronization as they can be recognized by all probes. These minor pulsar events will act as a trigger and all clocks in all probes will be synchronized at detection. The regular pulsar frequencies instead will be used by clocks to check internal accuracy and eventual delays.

Each transponder will use its own clock because calculating and measuring the internal delay of a circuit is crucial, so each circuit must be as simple as possible. Optical fibers should replace wires as much as possible in the circuits to reduce risks of interference and because light signals are faster. Synchronization with pulsars is common among all clocks but each transponder will compare its own active clock to the other transponders’ active clocks, and if differences are significant, the clock will get substituted by a backup unit within the transponder's circuit.

The first two transponders must be pointed at all times to the other probes and this prevents them to be used for communication with Earth. The third transponder, whose main function is laser tracking of
the retroreflecting test masses released by each probe at regular intervals during the long measurement phase, will be charged if possible to look at Earth every fixed interval of time (for example every 24 Earth-hours) to send the latest measurement data to a satellite in Earth orbit and eventually receive laser messages. It could be reasonable to install a radio antenna as backup for data downloading, and for reception of emergency transmissions from Earth when the tracking transponder is not pointed to Earth. The probes anyway would be largely autonomous and regular communication with Earth will be important for the downloading of experimental data but never critical for the survival of the probes.

Position and momentum data will be determined by each probe using multiple sensors. The main instrument will be composed by redundant X-ray pulsar sensors (as in figure 6) combined with traditional startrackers and UV sensors. Pulsar sensors will also be fundamental for calibration and synchronization of the clocks of the probes, using asynchronous common view synchronization [17] between the probes.

The accuracy of current clocks has reached $8.6 \times 10^{-18}$ in the case of the quantum-logic ion clocks [18] but they need large improvements in reliability and autonomous operation. So while an improvement of accuracy to $1 \times 10^{-18}$ in the next few years should be expected, more years will be required to have very reliable test equipment in small space-rated packages.

The Variable Specific Impulse Magnetoplasma Rocket (VASIMR) [14] is currently the only existing electrical propulsion system which, coupled with developing space-rated nuclear power generators, is able to perform the impulsive and continuous phases of the galactic stabilization manoeuvre. A 200kW version of the engine is going to be installed soon at the International Space Station. More powerful versions and arrays of them are supposed to be used for fast human interplanetary travel. An unmanned mission like the one proposed here could be the best test of their most extreme performance and of their reliability and safety in a very demanding long duration mission.

Another important consideration is that while the propulsion system must be able to accelerate the probe to about 250Km/s it must also be able to be very accurate in doing so. Feedback from inertial accelerometers will certainly help the probe's computer to build a sophisticated model anticipating the engine behaviour and predicting its performance in many different situations and requirements. The models generated from the probes would be very valuable to designers working on VASIMR spacecrafts on Earth.
Each probe contains two main telescopes (transponders) at an angle of 60 degrees but with a modest freedom of pointing in all axes. The third telescope will necessarily be able to point laser retroreflecting targets in almost all directions.

All telescopes are collimating reflecting telescopes working in assembly with a laser, a fast specialized photosensor and a clock (the main components of an Asynchronous Laser Transponder). The required diameter for the telescopes is dependent on the power and characteristics of the laser emitter chosen (probably a fiber laser in the visible band) and of the photosensor but a diameter of 0.5 m should be considered the upper limit.

The navigation system will use X-ray pulsar based techniques that have been studied for decades. Their implementation has been anyway delayed by many difficulties, more conceptual than technical anyway. In particular, many problems in their implementation are associated with the need to add special and general relativistic corrections to a classical (Newtonian) reference frame. A new coordinate system called Coll relativistic positioning system has been recently proposed for this navigation technology with the aim of eliminating the need of complicated post-Newtonian and post-post-Newtonian corrections in a Newtonian reference frame [15].

For error correction of the galactic stabilization manoeuvre, several spherical, spin-stabilized retroreflecting test masses similar to the ones already tested in space by a Russia-NASA collaboration [45] will be released by the probe at a rate of 1 every three Earth-months. They will be followed by the dedicated third transponder, and their tracking will allow the onboard probe a mapping of the local gravitational perturbations. They will be released with a really small and well controlled acceleration and a spin of 50 to 100 Hz.

About the reactor, the only discriminating quality for a reactor in space is the power to mass ratio. Research on new reactors for human space travel applications has already started in America and Russia and important advancements should be expected in field in the next ten years.

2.3. Sources of errors
There are many possible sources of error, mostly related to the fact the Galaxy is so complex that we still do not have a model describing it (or any galaxy) with the necessary accuracy. The real Galaxy is not a disk, so all features (arms, bulge, satellite galaxies...) must be considered. Even considering an idealized circular model of the solar motion, recent literature still shows too much disagreement over the correct values of the solar circular speed.

Another error source is certainly the impossibility to predict exactly the local environment of the probe for simulating sufficiently well perturbations on its motion in the mission design phase. Gravitational waves must also be considered as a source of possible errors, but they will be better known and their induced errors eliminated thanks to the future space antennas for gravitational waves like LISA.

As already mentioned, the propulsion system itself, if not extremely well monitored and finely adjusted in an interactive way, can be a major source of error. The same consideration applies to the power generation and thermal control system. The high energy requirement of the engines can be covered only by an onboard nuclear reactor which can produce unwanted disturbances due to thermal emissions and its radiation pressure, but this induced disturbance can be calculated and greatly reduced adopting a counterbalancing symmetrical geometry for radiators, and actively balancing thermal loads of said radiators.

3. Enhanced mission with CMB rest frame stabilization and dark energy measurement
Galactic stabilization is not the finest imaginable simplification of the physical system with 3 laser ranging probes considered. It was just proposed because realizable with already existing, although not mature, technologies (like the VASIMR engines for propulsion and solid core fission reactors for power production).
In 1977 a dipole in the CMB measurement from a plane was discovered. This led to a wonderful hypothesis: the universe does have a sort of absolute reference frame and the velocity of any object in the universe is measurable with respect to that frame.

The galactocentric reference frame has a peculiar velocity with respect to the CMB, so that any cosmological measurement in galactocentric coordinates needs to be corrected using the best estimates available of that peculiar velocity. Unfortunately this adds further uncertainties to the uncertainties due to galactic stabilization accuracy. If a direct measurement of the deceleration parameter is to be attempted, an extremely high level of accuracy is required which simply cannot be achieved using galactic stabilization due to the intrinsic uncertainties.

The CMB rest frame is the ideal reference frame for direct cosmological measurement, anyway deciding to employ it for 3 laser ranging probes in deep space requires a deep modification to the hardware of the probes, adding CMB sensors and preferably a more powerful nuclear propulsion system, like a fission-fragment rocket [29]. To reach 0 m s\(^{-1}\) of relative motion with respect to the CMB frame, probes need a speed of 369.0 ± 0.9 km s\(^{-1}\) relative to LSR according to the 5-years WMAP CMB dipole measurement [49]. This latter delta-V requirement makes the mission challenging for a VASIMR propelled spacecraft but rather easy for a probe propelled by a fission-fragment rocket, a technology object of study for extreme high speed unmanned exploration missions.

3.1. CMB rest frame stabilized probes
If a probe velocity is such that the cosmic background radiation shows no dipole, it means the probe is immobile in the CMB rest frame, the only universal reference frame. This would ensure that 3 CMB stabilized probes are exactly in the same reference frame independently of their galactocentric position, and that they are immobile (as comoving distances) in that frame. Such configuration would make the distance measurement between the probes a simple to interpret and very significant measurement. It would be the most epistemologically correct way of performing the experiment. If all proper movements of each probe with respect to the CMB rest frame could be stabilized only local perturbations (measured with the free drifting retroreflecting targets) and expansion could move them. While it is possible since 1977 to use the cosmic microwave radiation as a reference frame for astrophysical calculations, it’s still impossible to measure the CMB dipole and anisotropies rapidly enough and precisely enough for real-time navigational purposes. Furthermore, a highly sensitive CMB sensor needs to be helium cooled. This would put another limit on the duration of the necessarily long measurement mission. Maybe, if only a crude dipole measurement can be sufficient (to check the continuous absence of a dipole in the CMB thanks to the work of the propulsion system) it could be possible to avoid using helium-cooling.

4. Conclusion
Studying local manifestations of expansion is studying the nature of space itself. Due to the uncertainties in the determination of the Hubble's constant value for this epoch (very recent results fluctuate from 70 to 74 Km/s/Mpc), a local, high precision determination could contribute to improvements in cosmological models too. The most interesting contemporary experimentation proposal is the use of Celestial Optical Interferometry to increase the relative uncertainty in determination of the Earth-Moon distance to \(10^{-16}\). Anyway, the Earth-Moon-Sun system is far too complex to obtain a clear and indisputable measurement of cosmological expansion on local scale. A much more simplified system is required, and the first requirement of this system is isolation. While a very high speed object within the Galaxy can be gravitationally unbounded (like hypervelocity stars) no physical system can be completely isolated from the galactic environment. A comparison with the CMB rest frame can give us an idea of its dynamical state. Galactic stabilization is a partial isolation condition that can be quite useful (if the stabilization manoeuvre is correctly calculated and performed), anyway the ultimate direct measurement of cosmic expansion and dark energy should involve a stabilization of the comoving coordinates of the probes with respect to the CMB rest frame.
References

[1] Rindler W, *Essential Relativity. Special, General and Cosmological*, Second Edition, Springer (1977). See in particular section 1.15

[2] Carrera, Giulini, Influence of global cosmological expansion on local dynamics and kinematics, *Rev. Mod. Phys.* **82**, 169–208 (2010)

[3] Unnikrishnan C S, Gillies G T, Celestial optical interferometry: a new tool for ultrahigh precision studies in gravity, *Int. J. Mod. Phys. D*, Vol. **17**, Nos. 3 & 4 (2008) 617–626

[4] Turyshhev S G et al., The Laser Astrometric Test of Relativity Mission, *Class. Quantum Grav.* **21** 2773 (2004)

[5] Sumner T J, The STEP and GAUGE Missions, *Space Science Reviews* Vol. **148**, Num. 1-4, 475-487 (2009), Springer

[6] Ni W, Super-ASTROD: Probing primordial gravitational waves and mapping the outer solar system, *Class. Quantum Grav.* **26** 075021 (2009)

[7] Dumin Y V, On a probable manifestation of Hubble expansion at the local scales, as inferred from LLR data, *Preprint* astro-ph/0203151

[8] Rosales J, Sanchez-Gomez J, The "Pioneer effect" as a manifestation of the cosmic expansion in the solar system, *Preprint* gr-qc/9810085v3

[9] Nottale L, The Pioneer anomalous acceleration: a measurement of the cosmological constant at the scale of the solar system, *Preprint* gr-qc/0307042v1

[10] Fahr H, Siebert M, Does PIONEER measure local spacetime expansion?, *Preprint* gr-qc/0610034v2

[11] Oliveira F J 2006, Hubble law may explain the anomalous acceleration of the pioneer 10 & 11 spacecraft, *Preprint* gr-qc/0610029

[12] Williams J G, Turyshhev S G et al. Reply to the Comment by Dumin on “Progress in Lunar Laser Ranging Tests of Relativistic Gravity”, *Preprint* gr-qc/0612171

[13] Chodorowski M J, A direct consequence of the expansion of space?, *Monthly Notices of the Royal Astronomical Society*, **378**: 239–244

[14] Turyshhev S G, Toth V T, The Pioneer Anomaly, *Living Rev. Relativity* **13**, 4 (2010)

[15] Davis T M, Fundamental Aspects of the Expansion of the Universe and Cosmic Horizons, *Preprint* astro-ph/0402278v1

[16] Wolf P et al., Quantum physics exploring gravity in the outer solar system: the SAGAS project, *Experimental Astronomy* Volume **23**, Number 2, 651-687

[17] Chou C W et al., Frequency Comparison of Two High-Accuracy Al+ Optical Clocks, *Phys. Rev. Lett.* **104**, 070802 (2010)

[18] Chou C W et al., Optical Clocks and Relativity, *Science* 24 September 2010, Vol. **329**, no. 5999, pp. 1630 – 1633

[19] Schönrich R, Binney J, Dehnen W, Local Kinematics and the Local Standard of Rest (2010), Local kinematics and the local standard of rest. *Monthly Notices of the Royal Astronomical Society*, **403**: 1829–1833. doi: 10.1111/j.1365-2966.2010.16253.x

[20] Coskunoglu B et al., Local Stellar Kinematics from RAVE Data: I. Local Standard of Rest, *Preprint* 1011.1188v1 [astro-ph.GA]

[21] Nieto M M, Turyshhev S G, Anderson J D, 2005, “Directly measured limit on the interplanetary matter density from Pioneer 10 and 11,” *Physics Letters B* **613**, 11–19.

[22] Seto N et al., Possibility of Direct Measurement of the Acceleration of the Universe using 0.1Hz Band Laser Interferometer Gravitational Wave Antenna in Space, *Phys. Rev. Lett.* **87**, 221103 (2001)

[23] Clark R, Sheldon R, Dusty Plasma Based Fission Fragment Nuclear Reactor, American Institute of Aeronautics and Astronautics 15 April 2007

[24] Chan I, Parametric Subharmonic Instability and the β-effect, University of British Columbia, http://www.iam.ubc.ca/theses/IanChan/IanChan_MSc_Thesis.pdf
[25] Riofrío L, GM=tc3 Cosmology and the Moon, abstract: BAPS.2010.TSF.FA2.9, http://meetings.aps.org/link/BAPS.2010.TSF.FA2.9

[26] Cahill R T, Lunar Laser-Ranging Detection of Light-Speed Anisotropy and Gravitational Waves, Progress in Physics 2010:2.31-2.35, Preprint gen-ph/1001.2358v2 [physics.gen-ph]

[27] Bruchholz U E, Lunar Laser Ranging Test of the Invariance of c: a Correction, Progress in Physics 2010:4.30-4.31

[28] Clark R, Sheldon R, Dusty Plasma Based Fission Fragment Nuclear Reactor, American Institute of Aeronautics and Astronautics, 15 April 2007.

[29] Markwardt C B, 2002, “Independent Confirmation of the Pioneer 10 Anomalous Acceleration,” Preprint gr-qc/0208046.

[30] Naoki et al., Possibility of Direct Measurement of the Acceleration of the Universe Using 0.1 Hz Band Laser Interferometer Gravitational Wave Antenna in Space, Phys. Rev. Lett. 87, 221103 (2001)

[31] Lämmerzahl C et al., OPTIS: a satellite-based test of special and general relativity, 2001 Class. Quantum Grav. 18 2499

[32] Lämmerzahl et al., Is the Physics Within the Solar System Really Understood?, Lasers, Clocks and Drag-Free Control, Astrophysics and Space Science Library, 2008, Volume 349, 1, 75-101, DOI: 10.1007/978-3-540-34377-6_3

[33] Danzmann K, Rüdiger A, LISA technology—concept, status, prospects, Classical and Quantum Gravity, 2003, 20 S1. DOI: 10.1088/0264-9381/20/10/301

[34] Sato S et al., DECIGO: The Japanese space gravitational wave antenna, 2009 J. Phys.: Conf. Ser. 154 012040. doi: 10.1088/1742-6596/154/1/012040

[35] Harry G M et al., Laser interferometry for the Big Bang Observer, Class. Quantum Grav. 23 4887, doi: 10.1088/0264-9381/23/15/008

[36] Nakayama K et al., Space laser interferometers can determine the thermal history of the early Universe, Phys. Rev. D 77, 2008, DOI: 10.1103/PhysRevD.77.124001

[37] Krauss L M et al., Primordial Gravitational Waves and Cosmology, Science 21 May 2010: Vol. 328 no. 5981 pp. 989-992 DOI: 10.1126/science.1179541

[38] Seto N et al., Possibility of Direct Measurement of the Acceleration of the Universe Using 0.1 Hz Band Laser Interferometer Gravitational Wave Antenna in Space, Phys. Rev. Lett. 87, 221103 (2001), DOI: 10.1103/PhysRevLett.87.221103

[39] Takahashi R, Nakamura T. Determination of the equation of the state of the Universe using ~0.1 Hz Gravitational Wave Detectors, Prog. Theor. Phys. 113 (2005) 63-71, DOI: 10.1143/PTP.113.63, arXiv:astro-ph/0408547v2

[40] Merkowitz S M, Tests of Gravity Using Lunar Laser Ranging, Living Rev. Relativity, 13, (2010), 7

[41] Williams J G, Turyshchev S G and Murphy Jr T W, “Improving LLR Tests Of Gravitational Theory”, Int. J. Mod. Phys. D, 13, 567–582, (2004)

[42] Rathke A, Izzo D, Options for a Nondedicated Mission to Test the Pioneer Anomaly, Journal of Spacecraft and Rockets, Vol. 43, No. 4, July-August 2006

[43] Bertolami O, Páramos J, A mission to test the Pioneer anomaly: estimating the main scientific effects, Int.J.Mod.Phys.D 16:1611-1623,2007, DOI: 10.1142/S0218271807011000, arXiv:gr-qc/0702149v2

[44] Dittus H, A mission to explore the Pioneer anomaly, ESA Spec.Publ. 588 (2005) 3-10, LA-UR-05-4907, Preprint gr-qc/0506139v1

[45] Burmistrov VB et al., Spherical Retroreflector with an Extremely Small Target Error: International Experiment in Space, http://cdsads.nasa.gov/lw13/docs/papers/target_vasiliev_1m.pdf

[46] Diaz FRC, An overview of the VASIMR engine: High power space propulsion with RF plasma generation and heating, AIP Conference Proceedings, 2001

[47] McMillan P J, Binney J J, The uncertainty in Galactic parameters, MNRAS, 402, 934, 2010,
[48] Brown A G A, Learning about Galactic structure with Gaia astrometry, *Preprint* astro-ph.GA/0810.5437, 2008

[49] Hinshaw G et al., Five-Year Wilkinson Microwave Anisotropy Probe (WMAP1) Observations: Data Processing, Sky Maps, & Basic Results, *Astrophysical Journal Supplement Series*, 180, 225-245 (*Preprint* astro-ph/0803.0570v2)