# Requirements and Options for a Stable Inertial Reference Frame for a 100 μarcsecond Imaging Telescope

K. C. Gendreau*[a], J. Leitner [a], L. Markley [a], W.C. Cash [b], and A. F. Shipley[b]
[a]NASA/Goddard Space Flight Center; [b]University of Colorado

## Abstract

The MAXIM Pathfinder (MP) and Stellar Imager (SI) missions are under study to do 100 microarcsecond resolution imaging for a number of different targets using interferometers divided over formation flying spacecrafts. One of the most challenging technical hurdles for these missions is to have an independent directional reference in the sky to use for target acquisition and tracking. This directional reference will guide the placement of separate free flying elements of the interferometers to have ~<30 microarcseconds of alignment with the target. This paper will discuss some of the specific challenges as well as some possible options to explore for achieving this alignment.

## 1. INTRODUCTION

The future of astronomy will include high resolution imaging. In the next two decades, we expect to see a jump of angular resolution comparable to what has been made in the last ~400 years. Galileo could get by using his eyes, a steady hand, and a simple stand to point his ~10 arcsecond resolution telescope at Jupiter and see the Jovian moons. Today, the Hubble Space Telescope (HST) needs an interferometric Fine Guidance Sensor (FGS) to point to within 10 milliarcseconds a ~0.1 arcseconds resolution telescope at distant galaxies. What will future observatories with resolutions of better than 100 microarcseconds use?

NASA is considering several missions that will have angular resolutions greatly surpassing that of HST. The most ambitious will be the MicroArcsecond Imaging Mission (MAXIM), which will have sub-microarcsecond resolution to resolve the event horizon of a blackhole[1,2]. Along the way to MAXIM, MAXIM Pathfinder (MP) will test the technical and scientific waters with a ~100 microarcsecond X-ray interferometer[3]. MP will resolve the coronae of stars, Super Nova Remnants in other galaxies, the outer accretion disks of AGN, and more at x-ray wavelengths (4 to 0.1 nm). The Stellar Interferometer (SI) mission is another proposed 100 microarcsecond resolution imaging mission that will look in the UV band (>1000 angstroms) at nearby stars to study their solar cycles. These missions achieve their high angular resolution by distributing their optics over large distances to become sparse aperture telescopes. Other missions such as Planet Imager (PI) and Terrestrial Planet Finder (TPF) will also do science on small angular scales. Each of these missions will need some stable reference direction good to a fraction of their angular resolution in order to preserve their angular resolution.

The FGS on HST is the highest resolution attitude guidance system ever flown. It points the HST to about 10 mas. Post processing of the FGS data can be used to go to 1 mas in astrometric precision. At this level, HST deals with effects such as differential aberration of light across the field of view (FOV) and thermal mechanical jitter.
As we go to finer resolving power, these issues become more important and other concerns come up. For example, the aberration of light can be as large as 40 μas/minute depending on where we are looking based on our orbital

* Keith.Gendreau@gsfc.nasa.gov, Tel: (301) 286-6188, Fax: (301) 286-0677, Laboratory for High Energy Astrophysics, NASA-Goddard Space Flight Center, Greenbelt, MD 20771.

velocity around the sun. Similarly, parallax from stars 500 pc away can be as large as 40 μas/day. At the microarcsecond level, stars will appear to wobble as their planets orbit. For an earth size planet around a solar like star 10 pc away, this is of order 1 μas. Larger planets will contribute larger wobbles. Gravitational bending of light also becomes noticeable: a star 15 degrees from Jupiter will appear to shift by more than 50 microarcseconds. While we can trend these motions (if not predict), we will need to accommodate our guidance system for them. Gimbals with unprecedented readouts and/or large fields of view can play a role at the cost of complexity.

Thermal mechanical stability become crucial. The angle subtended by a meter stick lying on a table with 3 hydrogen atoms under one edge is about 30 microarcseconds. Materials with coefficients of thermal expansion (CTEs) of $10^{-7}$/ degree would need to be kept isothermal at the level of $10^{-3}$ degrees for structures of order 1 meter across.

For MP and SI, while absolute astrometry would be nice, it is not necessary (if at all possible). Even if the Space Interferometry Mission (SIM) comes on line, there is no guarantee that the x-ray or UV positions will be consistent with the optical positions. Given a target position to within 1 arcsecond, we can follow a target acquisition scheme (outlined in section 4). Once we have acquired the target, we need a stable reference for time scales of hours to a day. Notice that for these missions, we cannot rely on the target itself. This is because of several reasons.

First, we are expecting a fairly low counting rate- maybe at most 100 photons/sec for MP. If we want to look at a fainter, much more common target, we will have to integrate for timescales that are uncomfortably long compared to thermal mechanical and orbital disturbance timescales.

Second, these targets are variable. For example, we can often see the x-ray flux of a star vary by over an order of magnitude within an hour. In this case, the order of magnitude flux increase is almost certainly due to a highly localized flare. If we were to align by centroiding on the x-ray flux, we would have blurry vision. It is surely possible that by analysis, we could use the target data itself- but it could lead to confusion from misguided assumptions.

It is much more preferable to use an independent means to determine the stability of our pointing. There are two general classifications of ways to do this. One option is to make use of guide stars. The other is to get a stable inertial reference without stars. In the following sections, we will discuss in more detail the pros and cons of both these general options. We will describe specific implementations of both options. Finally, we will show how we would use what we consider our most cost effective option for MP.

## 2. OPTIONS THAT USE GUIDE STARS

Conceptually, using guide stars to track on a target seems very easy. It is how virtually all of observational astronomy is done. For our distributed spacecraft telescopes, we have the additional task of keeping track of where the different satellites are with respect to the guide stars. Consider figure 1 where we have two spacecraft, our target, and guide stars- this is the basic problem. Once we have aligned this simple system, we can extend to more than two spacecraft using a variety of methods. In this figure, we have put a star tracker telescope on the detector spacecraft. It looks out toward the target and the optics spacecraft. The optics spacecraft has a beacon-a wide divergence laser- which gives the optics spacecraft the appearance of being an unusual star within the star tracker telescope FOV. In the simplest situation, we will also see guide stars in the same FOV. The optics spacecraft blocks the target and directs its light onto the detector on the detector spacecraft. The Line-Of-Sight (LOS) problem is to track the relative displacement of the beacon with respect to the guide stars. This displacement needs to be measured to about 30 microarcseconds for our 100 microarcsecond imaging telescopes. It is for this reason that we have called the star tracker a “super star tracker„. For MP, the optics and the detector can pitch considerably before the interferometer performance is affected- they behave as thin lenses. Thus the real problem is to determine the lateral displacement of the optics spacecraft with respect to a line between the target and a fiducial point on the detector spacecraft. In this figure, we only want “dX„- independent of the rotation angles of either the detector or the optics. Another way to say this, is we have three points (the target, the optics, and the detector) that over constrain a line- how crooked is that line.

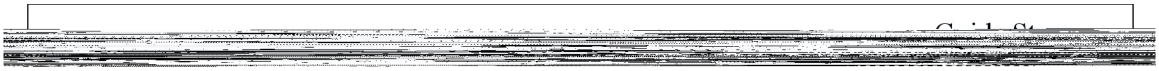

**Figure 1: The Line-Of-Sight Alignment Problem**

The first thing to consider is which bandpass would be acceptable for the guide stars. Here, we consider the optical/UV band and the x-ray band.

### 2.1 Big Optical Star Trackers

The simplest thing to consider is to make a regular optical star tracker bigger. Assuming we can make the optics diffraction limited, we expect that the point spread function should go as:

$$\theta_{psf} \sim \lambda/D$$

where, “$\lambda$„ is the wavelength of the light and “D„ is the telescope aperture diameter. If we collect N photons, then we can centroid to a position resolution:

$$\theta_{centroid} \sim \lambda/(D\sqrt{N})$$

The number of photons per second that a telescope with an aperture of diameter D would collect from a star of magnitude m is

$$N \sim 10^{7}\pi D^{2} 10^{-m/5}$$

Therefore, in “t„ seconds we would be able to centroid an “m„ magnitude star at a wavelength “$\lambda$„ with a telescope with aperture diameter D to:

$$\theta_{centroid} \sim 10^{-4}\ \lambda/D^{2}\ 10^{m/5}/\sqrt{t} \text{ radians}$$

If we want to centroid to 30 microarcseconds, then consider figure 2, which shows the required integration time as a function of telescope aperture size for various magnitude stars at 600 nanometers.

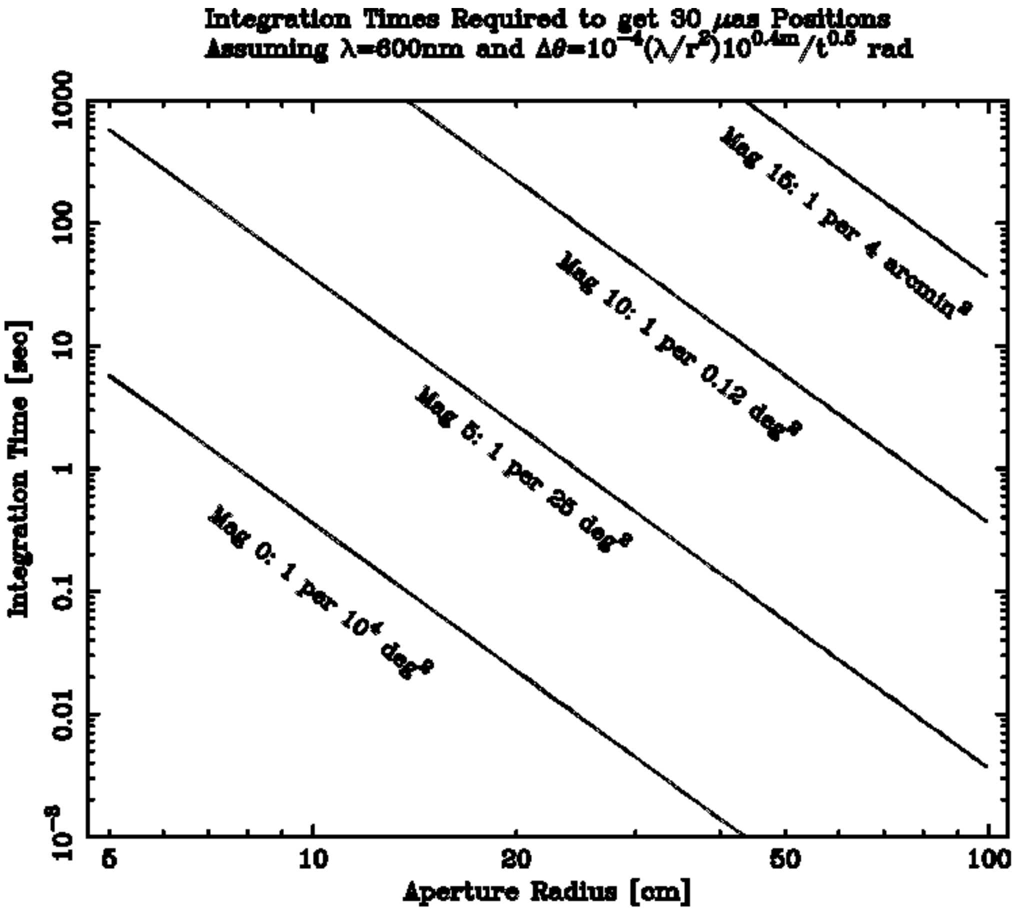


**Figure 2: Integration times required to centroid various magnitude stars to 30 microarcseconds with a telescope of given aperture size.**

We have also indicated the approximate number density of stars at each magnitude. While brighter stars will require less integration time to get to our required resolution, there are fewer of them. If we really want a situation as indicated in figure 1, then we would have to rely on 15$^{th}$ magnitude and fainter stars. But in this case, we would need a telescope similar in size to HST with exposure times of minutes- clearly unacceptable. That is too bad, since in the simple case of figure 1, differential aberration of light between the guide stars and the target is minimal. If we want shorter exposure times (eg ~< 1 second) and reasonable size telescopes (eg less than 1 m diameter), then we will need to work with brighter stars.

To work with brighter stars, we will either need an extremely large FOV or gimbals with extremely fine readout. The large FOV is difficult for a number of reasons- the optical design is difficult, and the required detector would have a tremendous number of pixels. The approach with gimbals is necessary to address the large differential aberration of light between our target and the nearest bright star (never mind corrections for other motions such as parallax and proper motion). These gimbals would require readouts and possibly controls good to 30 microarcseconds. The thermal mechanical difficulties in assembling these could be astronomical.

An other difficulty of using stars is that they will have microarcsecond and even milliarcsecond structure which could vary with time. This would be on top of proper motion, parallax, and wobble from companions.

The detectors for these star trackers would also be troublesome. If we had a PSF of 0.1 arcseconds (eg HST), then we would need to collect of order 10 million photons. A CCD pixel has a full well capacity of less than 250,000 electrons- so we would need very small pixels and very large f-numbers for the optics to get plate scales more appropriate to the angular measurements we are trying to make. As we move toward these large f-numbers and smaller pixels, then the required number of pixels to capture a reasonable FOV- even an arcminute or two across becomes tremendous.

### 2.2 X-ray star trackers

What if we went to the x-ray band? For the case of MP, we could consider making 2 x-ray interferometers that have detectors on a common spacecraft. We must then choose stable x-ray point sources which are bright enough and conveniently located in the sky. There is some possibility that blazers and other AGN might be adequate, but time variability, superluminal motion, as well as sub-milliarcsecond structure may complicate things. But once we have found suitable reference x-ray sources, then the short wavelengths of x-rays may offer more reasonably scaled alignment instruments.

Diffraction limited x-ray optics with modest baselines of meters or so would yield point spread functions at the level of 100 microarcseconds. To centroid to 30 microarcseconds would only require a handful of photons from our guide sources. With ~100 $cm^2$ of effective area over the 0.5-10 keV band, there will be at least a few candidate guide targets that could introduce at least a few photons per second onto the guiders focal plane instrument.

Two possible architectures for the x-ray star tracker are: 1) make a duplicate of the MP, 2) use normal incidence diffraction limited soft x-ray optics[13]. The first option may benefit from the case that making two of something costs less than twice the cost of one- but this is still a large cost. The second option is actually also a possible alternative for MP. It has the disadvantage that it works in narrow ~few eV band passes and therefore will get even fewer photons to centroid on. A more complete discussion of option two is given elsewhere.

X-ray star trackers may have other limitations as well. For instance, the scarcity of bright guide targets will necessitate high resolution gimbals as we discussed for the optical star tracker. These gimbals will need to have enough resolution and range to deal with differential aberration of light between the science target direction and the guide source direction.

Even if we could make an x-ray star tracker, it may not be scalable to the sub microarcsecond range where we will eventually need a guidance system for missions like full MAXIM. For instance, imagine a 100 microarcsecond x-ray star tracker with 1000 $cm^2$ of area (eg about the area of Chandra, but with optics a 1000 times better). In this case to centroid a point source down to 0.1 microarcseconds would require 1 million photons. There are very few x-ray sources in the sky that could provide this number of photons in reasonable times (~< 1 sec). The crab nebula may be able to do this in a few minutes- but it has arc minute structure that would push us to require even more photons.

### 2.3 SIM

In a previous study of MP[2], we have considered making use of an optical interferometer like SIM as the star tracker. But we have recently re-considered this due to cost. At present, SIM is expected to cost nearly $1B. Even if the costs go down a factor of 2, this is too expensive for a subsystem on MP or SI. Furthermore, SIM offers more than we need by providing an absolute astrometric solution. For now, we are looking for other options. Perhaps we will eventually find that SIM fits the bill.

## 3. INERTIAL REFERENCE OPTIONS

Gyroscopes offer an attractive alternative to using guide stars. The biggest advantage is that we do not need to find a guide star. We will still need a telescope on one spacecraft to determine if the other spacecraft has moved. Once we have acquired the target, we simply readout the gyroscope and compare it to a telescopes measurement of the position of the other spacecraft. The comparison of the two measurements will allow us to distinguish between a loss of Line-of-Sight alignment by translation of the detector from a line drawn from the target through the optics spacecraft and a simple rotation of the detector spacecraft.

The telescope on the detector spacecraft will need to be good enough to track a beacon shining on the optics spacecraft to a level of 30 microarcseconds in the case of MP. The telescope will not need to track stars to this precision and therefore benefits from some simplicities. If we make the telescope ~12cm in diameter, for optical tracking, we would need ~1 billion photons to centroid motions to the 30 microarcsecond level. We can place a quad-cell detector at the focal plane that's sole purpose is to track displacements of 1 target. Using fast photomultipliers, we can get past limitations such as shallow full well capacities of CCD pixels. The telescope would have a narrow band filter so that all it saw was the beacon from the detector spacecraft. For distances of hundreds of kilometers, a ~630 nm laser with 1 mW of output power and ~1mrad of divergence could easily provide a billion photons through the telescope aperture.

The challenge is to get a good enough gyroscope with low drift rates and reasonable readout resolution.
There are several possibilities. Standard mechanical gyroscopes may not be adequate, but slight variations may be possible. Standard laser ring gyroscopes have too high a drift. Below, we list a few unusual gyroscope options which could hold promise for the future.

### 3.1 KOG

The *Starlight* mission (a.k.a ST3) would have been the first space based stellar interferometer with a launch in 2005 as part of NASA's "New Millenium„ technology development program- but it has been recently canceled. *Starlight* would have aligned two formation flying space craft toward a star to produce fringes in 1 dimension to measure stellar diameters and test formation flying technologies for space based interferometers. One of the early methods considered to provide a stable directional reference was a novel concept called the Kilometric Optical Gyroscope (KOG). The KOG is a free space laser ring gyroscope which works on the Sagnac Effect by beating together two lasers sent in opposite directions around a perimeter defined by the spacecrafts we are trying to align. Here, the expected resolution would go like:

$$\theta \propto \frac{\lambda}{Area/Perimeter}$$

Where $\lambda$ is the laser wavelength, the area is that of the region bounded by the laser path, and the perimeter is the total length of the path. By making the area very large compared to the perimeter- possible if you have more than 2 spacecraft, one could achieve very fine resolution in the orientation of the array of space craft. Consider 3 spacecraft forming an equilateral triangle with sides of 10 km and a laser of wavelength 630nm, then this would yield a resolution of about 36 microarcseconds.

There are several difficulties with these gyroscopes including phase locking for low rotation rates. ST3 eventually dropped the KOG as an option due to these, other technical reasons, and cost.

### 3.2 Atomic Interferometers

Another type of gyroscope also based on the Sagnac Effect is the atomic interferometer gyroscope[6,7]. These type of interferometers would make use of matter waves as opposed to photon waves and therefore should have resolutions a factor of $10^{11}$ times finer. In practice, laboratory atomic interferometers have achieved results comparable to those of above average laser ring gyroscopes (short term stabilities of ~.1 mas/sec/√Hz). ESA is considering the *Hyper*[8] mission to test General Relativity's frame dragging predictions for the rotating Earth using atomic interferometers with rotation sensitivities of 0.2 microarcseconds/sec at 1 Hz. There is tremendous potential here, but more development is needed.

### 3.3 GP-B Gyroscopes

The Gravity Probe B (GP-B) mission is expected to launch within the next year to detect and measure the frame dragging of space-time by the earths rotation. In particular, a gyroscope in a 400 mile high polar orbit should rotate by about 42 milliarcseconds in one year. GP-B is aiming to measure this rotation to about 1%. To do this, GP-B has developed the world's most precise gyroscopes. The GP-B gyroscopes will provide a stable inertial reference with a drift of less than 1/3 microarcsecond/day. The readout of the gyroscopes is adequate to determine the spin axis to better than 100 microarcseconds after a few days of integration. GP-B will also have a telescope dedicated to providing a fix on a larger scale reference frame by centroiding on a $5^{th}$ magnitude star in the Pegasus constellation to a level better than 100 microarcseconds over a timescale of days. The frame dragging effect is measured as a deviation between the gyroscope measurements and the telescopes measurements.

The gyroscopes are spinning spheres with a superconducting Niobium coating. The readout scheme works by using sensitive SQUIDS readout quantized magnetic moments produced by the spinning superconductors via the "London Effect„. These spheres float in a drag free environment within the satellite. The gyros are coupled to a quartz telescope in a cryogenic insert kept below 2K. The low temperatures are necessary to make the spheres superconducting. The low temperatures also help the thermal mechanical stability of the entire structure.

A substantial development of technology has lead GP-B to near flight readiness. Coincidentially, it has properties very similar to what MP or SI would need to maintain our tough line of sight alignment. The telescope could be used to look at a beacon on another spacecraft, while the gyro package will help to disentangle rotational and translational ambiguity. Slight modifications would make the GP-B insert the perfect LOS alignment instrument.

### 3.4 Superfluid Gyroscopes

Recently[10,11,12], a new type of gyroscope has been demonstrated that makes use of superfluids such as $^3He$ and $^4He$. To see how these work, consider a superfluid inside of a torus vessel- everything initially at rest. Since a superfluid has no viscosity, as you rotate the vessel about the normal axis, the fluid will stay stationary. If there were someway to see this difference between the stationary fluid and the rotating vessel, one could make an absolute rotation measurement. Two basic methods have been used to see this difference. One involved measuring quantized phase slippage- quantized vortices- near regions of high flow in the vessel. The second method is to make the mechanical analog to an RF-SQUID (Super conducting quantum interference device) by introducing bottle necks which behave like the insulator barriers of a Josephson junction. These types of devices have been used to measure the earth rotation, but much more development is needed to meet our requirements. In principle, they should outperform the GP-B gyros by many orders of magnitude.

## 4. ACQUIRING A TARGET USING THE GP-B INSERT

Our current plan for MAXIM and MAXIM Pathfinder is to use something like the Gravity-Probe-B (GP-B) gyroscope/quartz telescope insert to lock onto astronomical targets at the microarcsecond level in the following innovative way:

1) Use conventional star trackers to point both the hub and the detector spacecraft to within 1 arcsecond of the target.
2) Position the detector spacecraft behind the optics spacecraft. Put a ~ milliwatt laser with ~ mradian divergence on the back end of the optics hub pointing toward the detector spacecraft. With the conventional star tracker on the detector spacecraft, this laser will appear as a very bright star. The detector spacecraft will position itself so that this artificial star or beacon appears to be within 1 arcsecond of where

we expect to see the target. Radio ranging will provide enough information to put the detector spacecraft at the correct distance (at focus) behind the optics spacecraft.

3) The size of our CCD focal plane is very large- nearly one arcsecond across at the detectors position behind the optics hub. We can relatively quickly scan through all the individual CCDs of this focal plane looking for the image from the periscopes. If we do not see this image, we shift the detector spacecraft laterally until we do. Once we find the target, we readout just the region of interest with high speed.
4) At this point, we make use of the GP-B insert, which sits on the detector spacecraft.. First we fine point the detector spacecraft so that the optics hub beacon is centered on the quartz telescope. This telescope will be approximately f-40 with a ~120 mm aperture. At its focal plane will be a quad cell detector consisting of roof prisms, beam splitters and high speed photomultipliers. The telescope will be able to detect if the beacon moves at the 30 microarcsecond level with $10^9$ photons- easily achievable with 1 second of integration and a milliwat/ milliradian laser several hundred kilometers away. To extend this to microarcseconds of precision, we will use a more powerful and better collimated laser such as described for LISA to achieve the required $10^{15}$ photons per control cycle.
5) There are several ways that the beacon will appear to move in the GP-B telescope. First, the detector spacecraft might pitch and yaw. Second, the detector spacecraft could move laterally off the line of sight determined by the target and the optics hub. Third, it could do both. We are only concerned about the lateral motion components since our detector behaves like a thin lens- it can pitch and yaw without loss of performance as an imager of the interferometer. To break the symmetry, we make use of the GP-B gyroscope. The GP-B gyroscope will probably be the most stable gyroscope made by man in the next decade. Its drift will be less than 1/3 of a microarcsecond a day. Some improvements in the readout scheme of GP-B's gyroscope could allow us to measure pure rotation- this would break the symmetry of the telescope readout. Dependent on the readouts of both the gyroscope and telescope the detector spacecraft will either translate or rotate to maintain the alignment of the LOS. Figures 4 and 5 show two possible control loops we could use to maintain the line of sight alignment.

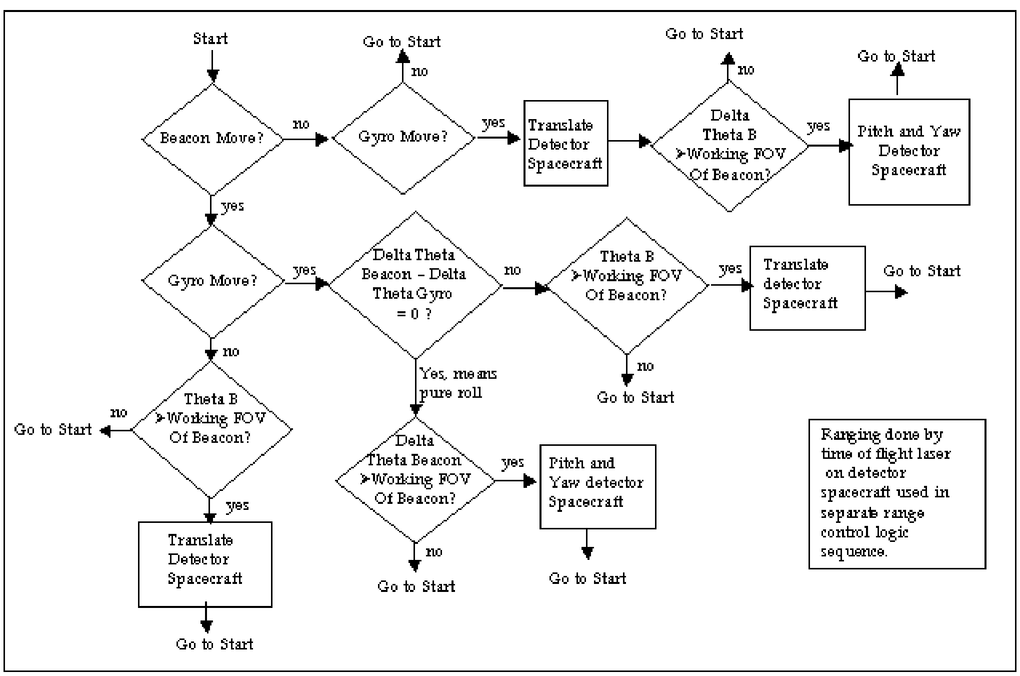


**Figure 3: A control loop for maintaining line of sight alignment between the MP detector spacecraft, the MP optics spacecraft, and the target.** The "Gyro move?" decision boxes indicate when the gyroscope has indicated a rotation. The "Beacon move?" boxes indicate that the beacon tracker on the detector has measured that the apparent

position of the optics spacecraft shifted.  The control loop works to keep the beacon within the working FOV of the telescope- about 15 arcseconds.

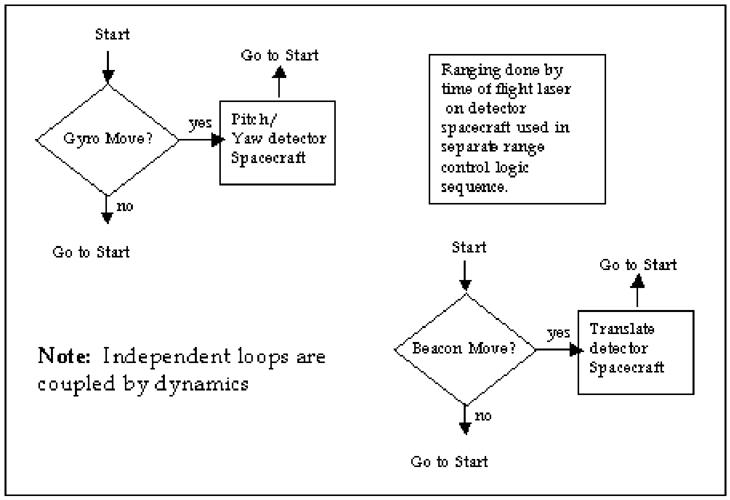


**Figure 4: A simpler set of coupled control loops to maintain the line of sight alignment.**

At this point, this is what we consider to be the most viable method for MP alignment. Of all the possible options we have discussed, this is the only one which has had some sort of a critical design review- infact GP-B hardware exists. We have made a very crude estimate that it would cost $100M or less to reproduce a GP-B like insert. A few modifications would optimize the insert for our application:

1) We would make significant savings by using cryocoolers developed for Constellation-X and NGST instead of the cryogenic dewars as on GP-B. In addition to cost savings, there are other advantages to ignoring the dewar. This allows for a room temperature launch so that earth magnetic fields will not get pinned within the superconductors. The lifetime would be longer- in excess of 5 years. Risk is reduced. We need not worry about thrust corrections to venting cryogens.
2) The gyroscope readout needs to be of finer resolution over shorter integration times. GP-B also slowly rotates so as to get a better measurement of the rotation axis of the rotors. While we may be able to accommodate a slow rolling of the detector spacecraft, an alternate scheme may work out better. Perhaps putting multiple SQUID loops around the rotors to get more measurements will help.
3) GP-B tries to keep the rotors spinning uninterrupted for the mission life (2 years). For our purposes, we will observer targets for periods of days. In this case, we may be able to modify the shape of the rotors so that they will give a larger magnetic moment when spinning. This would improve the readout sensitivity.

## 5. SUMMARY

We have summarized some of the unique difficulties with pointing a constellation of spacecrafts toward a target with sub milliarcsecond stability. The solution is not simply making a bigger star tracker. We have started to explore the novel concept of using gyroscopes to point interferometers and telescopes. We have shown some of the newer and more exotic gyroscopes that may be able to do the job we want. But, there is some significant development along the way.


## ACKNOWLEDGEMENTS

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