The MAXIM Pathfinder X-ray Interferometry Mission

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Abstract

The MAXIM Pathfinder (MP) mission is under study as a scientific and technical stepping stone for the full MAXIM X-ray interferometry mission. While full MAXIM will resolve the event horizons of black holes with 0.1 microarcsecond imaging, MP will address scientific and technical issues as a 100 microarcsecond imager with some capabilities to resolve microarcsecond structure. We will present the primary science goals of MP. These include resolving stellar coronae, distinguishing between jets and accretion disks in AGN. This paper will also present the baseline design of MP. We will overview the challenging technical requirements and solutions for formation flying, target acquisition, and metrology.

1. INTRODUCTION

We are now in a golden age for X-ray astronomy with several great observatories such as XMM-Newton and Chandra in orbit giving us high quality spectra as well as images comparable to those optical astronomers have enjoyed for many years. Chandra, in particular, has provided images as crisp as Hubble Space Telescope (HST). It is important to note that while HST is diffraction limited at ~0.1 arcseconds, Chandra is not. The diffraction limit for a telescope of aperture, D, working at a wavelength, λ, is approximately λ/D. A diffraction limited x-ray ($\lambda\sim$ 0.1-4 nm) telescope with an aperture approximately that of Chandra or HST (2 m) would be able to resolve features sharper than 100 μas- nearly 1000 times finer than HST. As the apertures approach a few 100 meters, diffraction limited x-ray telescopes will have angular resolutions a nearly a million times sharper than HST. The MircoArcsecond Imaging Mission (MAXIM) is currently in the NASA Structure and Evolution of the Universe (SEU) themes strategic plan to be such a telescope with a sparsely filled aperture[1].

With a sparse aperture of several hundred meters across, MAXIM will have better than microarcsecond angular resolution. This capability allows MAXIM to resolve the event horizon of some of the more interesting black holes. Along the way to MAXIM, we are now looking at scientific and technological stepping stones.

The MAXIM Pathfinder (MP) mission will provide 2 intermediate steps from where we are now to where MAXIM will take us. In its first phase, MP will do 100 microarcsecond science that will bridge the huge jump from Chandra's broader view of the x-ray sky to the very fine perspective of MAXIM. In phase 1, MP will image with a modest area of about 75 cm^2. In its second phase, MP will extend its baseline to several hundred meters to have some limited capabilities to catch a peek at the event horizon of a black hole with a limited effective area and an angular resolution as fine as 1 microarcsecond. MP has evolved from an earlier concept[2] to this new two phase design. It now provides more technological and scientific context.

In the next section, we will discuss some of the science targets available to a mission like MAXIM Pathfinder. As we will discuss later in the paper, MAXIM Pathfinder will have some capability to catch a glimpse of a black hole.

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In the 3rd section of this paper, we will describe the baseline design and point out the largest technical hurdles before us. We will also describe the results of an end-to-end integrated mission design study.

2. SCIENCE GOALS

With observatories we have available today, we can directly resolve objects which have interstellar and larger size scales. Timing and spectroscopic data allow us to study smaller objects through modeling. As we produce observatories with higher angular resolution, we will be able to have a fundamentally different view of the unresolved universe. We will be able to study in a model independent way, some of the most interesting objects in the sky. Figure 1 shows you the power of going beyond arc second imaging. MP will have the resolving power necessary to study the structure of AGN jets, stellar coronae, interacting binary stars, and more with in its first (100 microarcsecond) phase. As MP extends its angular resolution toward that of the full MAXIM mission, we will have the capability to catch a glimpse of the final orbits around a black hole.

In phase 1, MP's 100 microarcsecond angular resolution will address questions about stellar astrophysics by directly resolving many of the most famous stars in the night sky. We will see if coronae of other stars are like our sun- and then perhaps learn more about our own star. We will see exactly what the temperature distribution is for these coronae. Do planets affect these plasmas? What are the sizes and shapes of flare emission regions. We already know from existing x-ray data that binary stars will be bright targets for MP. With MP, we will be able to directly study the dynamo action that creates the plasmas in these systems. In this way MP will use binaries as laboratories for studying the generation of stellar coronae and winds. MP's phase 1 will have a resolution of 1 AU at the distance of Orion. This type of resolution will enable a unique study of pre main sequence (PMS) stars. We may get the

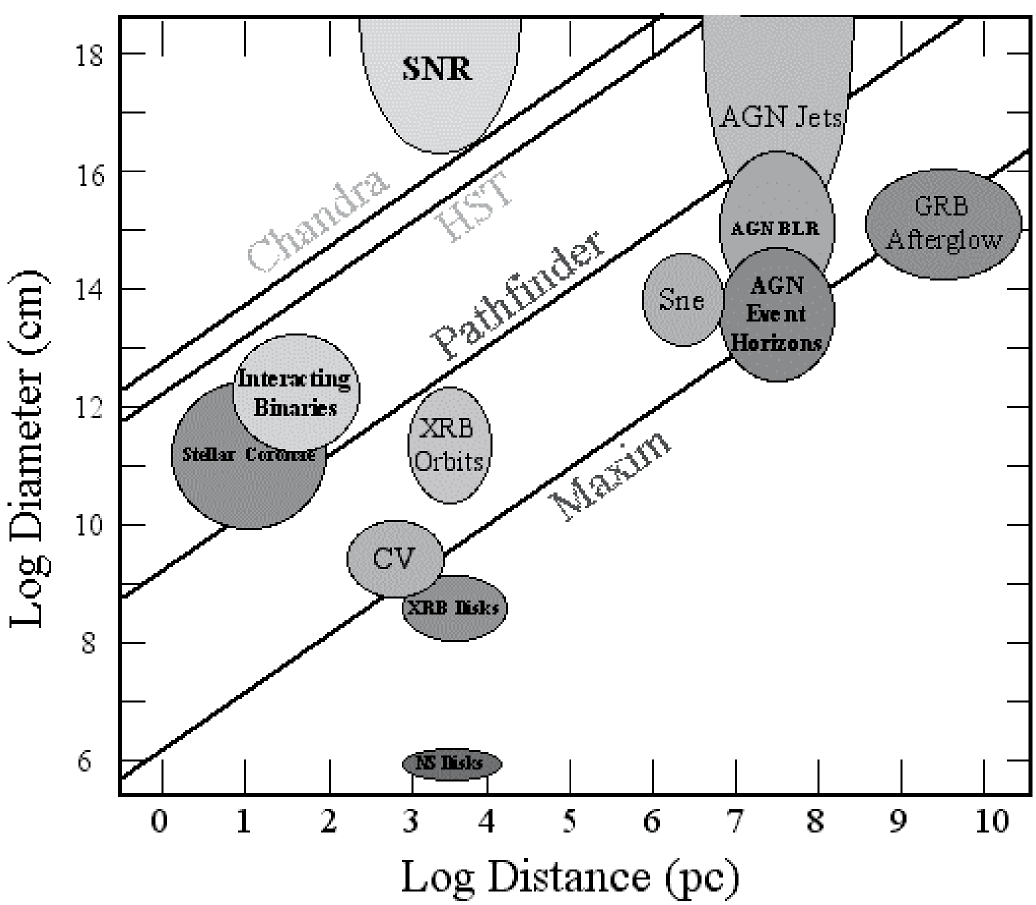

Figure 1: Dimensions and distances of astrophysical targets with angular resolutions of various observatories.

chance to see forming planets basking in the x-ray glow of bright PMS stars.

MP's phase 1 resolution will allow us to study supernova remnants in the Magellanic Clouds and our galaxy in a very unique way. We will be able to make movies of shock waves going through the ISM with frame times of days. We will watch as the shock wave goes through different density and chemistry variations in the ISM.

MP will allow us to study objects in the Andromeda galaxy as we currently do within our own galaxy- or better. At M31, our spatial resolution will be 60 AU- clear enough to separate individual stars. It will provide a unique vantage on galaxies, and help us to understand our own Milky Way.

MP's phase 1 resolution will also advance our knowledge of Active Galactic Nuclei (AGN). In particular we will be able to better resolve jets and maybe learn about where they begin to form. We will learn more about how jets interact with their environment by direct imaging. For NGC4151, 100 microarcseconds equates to 2000 AU. This will allow us to clearly distinguish broad line regions from narrow line regions.

This resolution will provide scientific context for understanding the images of full MAXIM. In fact, MP will have the capability to get an advanced glimpse of the microarcsecond universe by extending its baseline to 100s of meters in its phase 2. With 75 cm^2 of area, MP phase 2 will need longer exposure times to get enough signal in its pixels. But we will have something. In particular, we may see the shadow if the event horizon around a super massive black hole. We will also explore how jets relate to black hole spin and the strong magnetic fields approaching the event horizon.

This is only a partial list of the discovery space awaiting MAXIM Pathfinder– as other leaps in capability have shown us we should "expect the unexpected„. From Galileo's first telescope to HST, imaging made a jump of only 2 or 3 orders of magnitude over about 4 centuries. With that jump, our understanding of the universe exploded. MP will provide a similar magnitude jump- but in less than 2 decades. We are bound to have surprises.

3. THE BASELINE DESIGN

The University of Colorado at Boulder (CU) has designed and tested a very simple X-ray interferometer[3] as shown in figure 2. We call this the "x configuration„. The optical components are simple flats. For a given channel of the interferometer, a primary mirror collects x-rays from the target and directs them to a secondary mirror. The secondary mirror acts as a combiner by steering the x-rays to a common focal plane. At the focal plane, the different channels interfere and fringes appear. CU built such an interferometer and successfully tested it at NASA/Marshall Space Flight Center with ~1 nm wavelength light[3,4]. This very simple design is the core concept for MAXIM and MP.

This type of interferometer works for a number of reasons. First, the individual optical flats are diffraction limited in the way they are being used[3]. This means that mirror position stability and mirror figure errors contribute only a fraction of an x-ray wavelength worth of path length error. For optics used at normal incidence with more conventional wavelengths (e.g. $\lambda > 1000$ angstroms), this would mean that the surface figure and placement is good to a fraction of the wavelength (e.g., 100s of angstroms @ optical wavelengths). However, at a grazing incidence angle, θ, the required surface quality is loosened by a factor of $1/(2\sin\theta)$ (see figure 3). Our x-ray optics work at incidence angles less than 2 degrees which makes this surface quality easing factor nearly 2 orders of magnitude. Thus optics which are diffraction limited for normal incidence UV applications are diffraction limited for grazing incidence x-ray applications. In the CU/MSFC demonstration, they used "$\lambda/20$„ (λ=633 nm) optics at 0.25 degree graze angles. For MP, we will want to work at ~ 2 degree graze angles, thus we will need somewhat better optics (better than "$\lambda/200$„ for λ=633 nm), but it is within our technological grasp now.
Second, since the optics are flat with infinite focal lengths, they are easy to position. Similarly, the depth of focus of the interferometer is very deep. For the CU/MSFC demonstration, the depth of focus was 10s of centimeters. For MAXIM and MP, it will be 10s of meters.

A disadvantage of the flats is that the magnification is not very great. For this basic design, the magnification is given by the ratio of the spacing of the primary mirrors to the spacing of the secondary mirrors. If the secondaries were a meter apart, then fringes from 1 nm light would be only 10 nm apart from each other on a detector 10 meters away. Simple detectors not relying on spatial heterodyne methods have a spatial resolution limit of about 1 micron. In order to expand the fringes to be bigger than a few microns or so, the detector must be kilometers away. Practically speaking, 10s to 100s of kilometers of detector to optics distances are necessary in order to get a good matching of detector pixel sizes to fringe spacing.

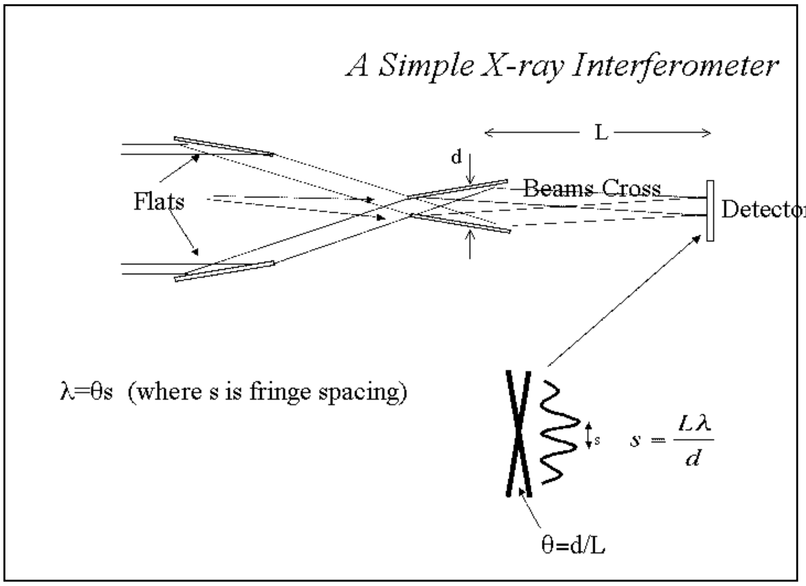

Figure 2: The core concept behind the MAXIM interferometer design.

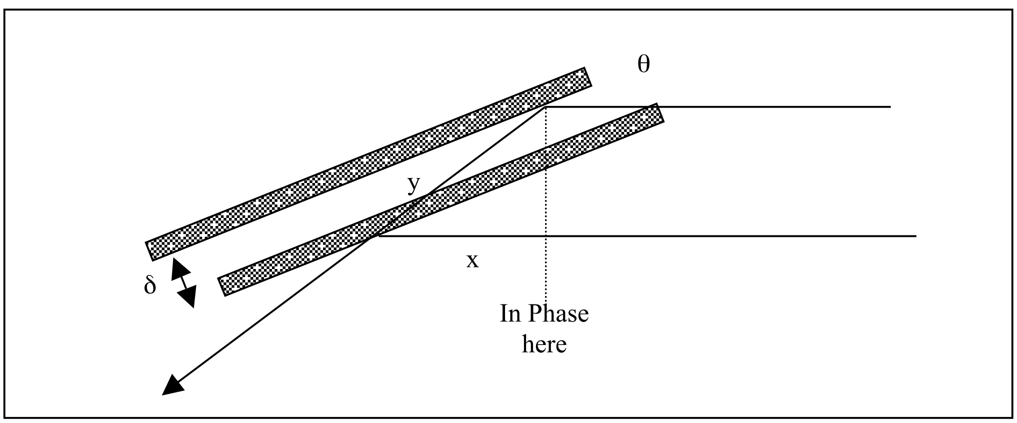

Figure 3: Grazing Incidence Loosens Tolerances: If a flat mirror surface displaces by a distance δ, then the optical path length difference induced by this for rays coming from the right and reflecting off the mirror will be: OPD=y-x. For a grazing angle of θ, then OPD=$2\delta\sin(\theta)$. Since it is the OPD which must be kept less than a fraction of the wavelength, we find that the sensitivity of the mirror motion is reduced by $2\sin(\theta)$.

For this reason and also to allow for larger baselines and sharper angular resolution, it is necessary to break up our interferometer into separate formation flying spacecraft. The details of how we implement our core concept shown in figure 2 determine the formation flying tolerances. As we will show below, the precision formation flying requirements are on the order of microns using our baseline implementation. This is loose compared to some other proposed formation flying missions- but still beyond our current technological grasp.

In the following sections, we describe how we will implement our core concept into a x-ray imaging mission. We start by describing how a good grouping of the optics makes our tolerances bearable. We then discuss the detector requirements. We overview the internal metrology requirements. We briefly describe how we point this interferometer to acquire and hold a target. Finally, we present an integrated mission design concept.

3.1 Periscopes

Given our basic concept of using flats as shown in figure 2, we have some latitude in choosing how we group the mirrors physically. For example, we could fly the primary mirrors in separate spacecraft from the secondary mirrors. This was one of our original implementations considered for MAXIM. However, this choice forces us to have a very difficult attitude control system (ACS) since the mirrors- and there for the spacecraft- need to be pointed to the x-ray diffraction limit of the individual optics. For practical designs, this limit is of the order milliarcseconds. Further more, it works out that a very sensitive component of our optical path length control is the distance between the primary and secondary mirror. By our grazing incidence advantage, this tolerance is of order nanometers- which forces our formation flying tolerance to be nanometers. Other disadvantages creep up in terms of non-optimal UV plane coverage.

A more practical choice of the mirror grouping is to put the primary and secondary mirrors within the same spacecraft. The pair of mirrors behaves like a thin lens- the pair can tip and tilt, but a ray passing through the system does not change its direction. There are limits to the thinness of these optical systems. First, x-rays reflect at grazing angles of less than 2 degrees. Second, there is some optical path length change induced by rotations. To keep the OPD due to a rotation less than about 1 angstrom, our periscopes must pitch no more than 2 mas- similar to the diffraction limit. Original designs for MP had the mirrors grouped this way, but we have recently generalized the grouping into "periscopes„. Shipley et al discusses periscopes in much more detail[5].

For MP, we are considering fabricating mirror pairs as periscope modules. Each module would have two flat mirrors. The reflecting surface of each mirror would be about 30 cm long by 1 cm across. When tilted at a graze angle of 2 degrees, this would make the geometric effective area of a single module, $A_{mod}=r^2$ cm^2, where "r„ is the reflectivity off a single mirror at 2 degrees of graze. These modules will be approximately the size of a fat rose box. Each ~5 kg module will consume 1-2 watts of power to maintain isothermal conditions necessary (fractions of a degree) to minimize thermal mechanical distortions of the mirror figure and primary to secondary mirror positioning. We have estimated that each module would cost ~$292k, which yields a cost per cm^2 of effective area similar to that of Chandra. There may be some cost savings from mass producing modules.

There are other advantages to using periscope modules as our grouping of mirrors. These include a reduction in risk. The loss of a single module will only result in slightly degraded science, while to loss of a spacecraft containing all the secondary mirrors would be the end of the mission. Also, we have some more practical control of path lengths within a module. By changing the primary to secondary mirror spacing with something like a piezo stage, we have effectively made an x-ray delay line. Periscopes also afford us a more optimal sampling of baselines. By getting a better sampling of baselines, we can squeeze power from outlier fringes into the central most fringes. This reduces the energy resolution requirements on the detector.

The most tantalizing advantage of the periscope implementation is how it loosens our formation flying tolerances. As discussed in Shipley, et al[5], we only have to hold periscopes in position with a stability of 15 microns. While difficult, this is much easier than maintaining nanometer positions- particularly in the case of formation flying.

3.2 Detector

The detector requirements for MP are modest given our use of periscope mirror modules. However, there are some limitations that detectors make on our mission.

To minimize the distance between the detector and the optics, we want the smallest pixels possible. X-ray microcalorimeters offer high energy resolution, but it is difficult to get the individual pixel sizes below 100 microns. The best hope for small pixel microcalorimeters may be the PoST position sensitive transition edge sensors of Figuerora-Feliciano which will be able to 10s of microns at the expense of some energy resolution. X-ray CCDs have been made with pixel dimensions as small as 4 microns and do not require the complicated cooling systems which calorimeters need. Physical processes within CCDs such as the range of the photoelectron and diffusion after the photoelectric interaction limit the spatial resolution of these devices for X-ray work to a couple microns. Furthermore, CCD focal planes can be made with dimensions the size of dinner plates. For these reasons and others, MP has CCDs as the baseline detector.

For MP, we are baselining CCDs with 15 micron pixels to oversample fringes from our interferometer by a factor of 5-10. For 100 microarcsecond imaging, this puts our detector about 200 km away from the optics. To get to 1 microarcsecond, our detector needs to be about 20,000 km away. We want to minimize this distance as slewing costs grow somewhat more than linearly with spacecraft distance. This same dimension also defines the formation flying tolerances on the positioning of the periscope modules. Thus, we see that the choice of the CCD pixel size has important ramifications on the formation flying. We have made our choice to both minimize the distance between optics and detector spacecrafts and also to minimize the tolerance on formation flying control. These reasons lead to contradictory requirements on the pixel size- but at this point, 15 microns seems optimal.

CCDs can be assembled into large focal planes. Several ground based telescopes have CCD cameras with focal planes nearly a foot across. The SNAP mission is looking at using a CCD array nearly 30 cm across[8]. We will use a similarly large focal plane- even though we expect our targets to fill up FOVs of only a centimeter or two across (10 mas @ 200 km, 100 microarcseconds @ 20,000 km). The larger focal plane will help us in 3 different ways: 1) it will help in acquisition of the target (to be discussed below), 2) it loosens the formation flying control requirements for the detector spacecraft , 3) it reduces risk if a CCD fails. During acquisition, we would quickly readout each part of our large focal plane to find out where the target is landing. Once we have centered on the target, we will only readout the region of interest- reducing power and readout times. A 30 cm focal plane gives is a detector limited FOV of nearly half an arcsecond which matches with the angular resolution of Chandra.
The CCD readout of the target region will be accomplished in less than 100 milliseconds which also has implications on the formation flying control. With these fast readouts, control can be replaced with knowledge for the formation flying situation. We will discuss this in the “Line of Sight„ section below.

If the periscopes are placed to minimize redundancies in baselines, then we need less energy resolution in the detector to distinguish power in our core image from power in outside ghost fringes. Blurring due to differing plate scales from different wavelength light is also small. A CCD with 2% energy resolution will produce energy resolved images with negligible plate scale smearing across our targets of interest..

3.3 Internal Metrology

There are several levels of metrology in MP. Pointing individual flat mirrors within a module to the diffraction limit requires approximately 30 nm of linear control on one edge of the mirror. Once we have pointed one mirror so that x-rays from it hit the secondary mirror, we will want to adjust the spacing between the mirrors to give us some path length control. We anticipate that capacitance gauges and laser interferometers will be adequate for this. Next, we want to be able to control the relative positions of periscope modules with respect to each other to 15 microns. JPL is developing the MSTAR system[9] for separated spacecraft interferometry missions including Terrestrial Planet Finder (TPF) and Planet Imager (PI). This system should provide sub micron positions over kilometers of range using an RF modulated laser system. For MP, either this or another laser ranging system should be adequate. The required tolerances for MP using the periscope implementation is discussed in much more detail elsewhere[5].

3.4 Line of Sight Alignment and Target Acquisition

The most difficult issues for MP has to do with target acquisition and maintaining tremendously tight line of sight (LOS) alignment of the various interferometer components with the target. Notice that this is different from pointing any individual component of our interferometer to the target. For example, the huge depth of focus affords the pointing of the detector a looseness of degrees (though, to limit the background a collimator on the detector tightens this to arc minutes). As discussed above, the periscope modules are thin lenses and can possibly wobble by many arc seconds without shifting images around. The hard task is that we need to determine the relative alignment of the positions of all the periscopes with respects to a line between the detector and our target to the level of microarcseconds. Specifically, to do 100 microarcseconds imaging as planned for phase 1 of MP, we need alignment to some fraction of that: 30 microarcseconds, the angle subtended by a meter stick lying on a table and lifted up on one end by 3 hydrogen atoms. For Phase 2 of MP, where we want to approach microarcseconds of resolution, the alignment becomes tighter.

The crucial first step in this alignment is to determine how crooked is the line between the detector, a central hub for the optics, and the target. Once this is determined, then internal metrology such as laser ranging would transfer the alignment information from the optical hub to the individual periscope modules. While micron class laser ranging between a hub and outlier periscopes meters to hundreds of meters away is just about within our technological grasp, the first step is truly difficult.

Our current plan is to use something like the Gravity-Probe-B (GP-B) gyroscope/quartz telescope[7] insert in the following innovative way[6]:

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. To extend this to microarcseconds of precision, we will use a more powerful and better collimated laser such as described for LISA[10] to achieve the required $\sim 10^{15}$ 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.

At this point, this is what we consider to be the most viable method for MP alignment. A fuller discussion of how we came to this as well as other options considered is given elsewhere[6]. This is the most technically challenging issue for MAXIM and MP. We expect more development here.

3.5 Mission Implementation

In May of 2002, we took our current concepts for MP to the Integrated Mission Design Center (IMDC) at NASA/GSFC. The IMDC brings together engineers from all aspects of a NASA space mission ranging from integration and testing, launch, mission operations, communications, orbital dynamics, and more to do a concentrated 1 week study for a customer trying to understand the feasibility of putting their payload into space and running it. The IMDC will estimate total mission costs, determine the optimal launch vehicle, point out long poles, and more.

The IMDC prepared a mission profile which had 4 phases as shown in figure 4. A Delta-IV 4240 will take the entire multi-spacecraft observatory to an orbit around the Earth-Sun L-2 position. The transit phase from Earth to the L-2 station will take 6 months. Once at station, MP will operate in science phase 1: a detector spacecraft will fly in formation 200 km from a single optics spacecraft. After a year observing about 1 target per week at ~ 100 microarcsecond angular resolution, MP will enter its second science phase. In science phase 2, MP's optic spacecraft will split into a hub module containing 9 periscope modules and 6 free flyer spacecraft containing 11 periscopes each (figure 5). The hub spacecraft will contain a 1 watt (output power) laser with a 30 cm beam expander similar to that used for the LISA mission. This powerful laser will be used for the GP-B based LOS alignment with the detector spacecraft 20,000 km away. A laser ranging system such as MSTAR will be used to range at the micron level the various free flyer spacecraft. Phase 2 is designed to have a 3 year life (4 year goal) observing targets for about 3 weeks at a time.

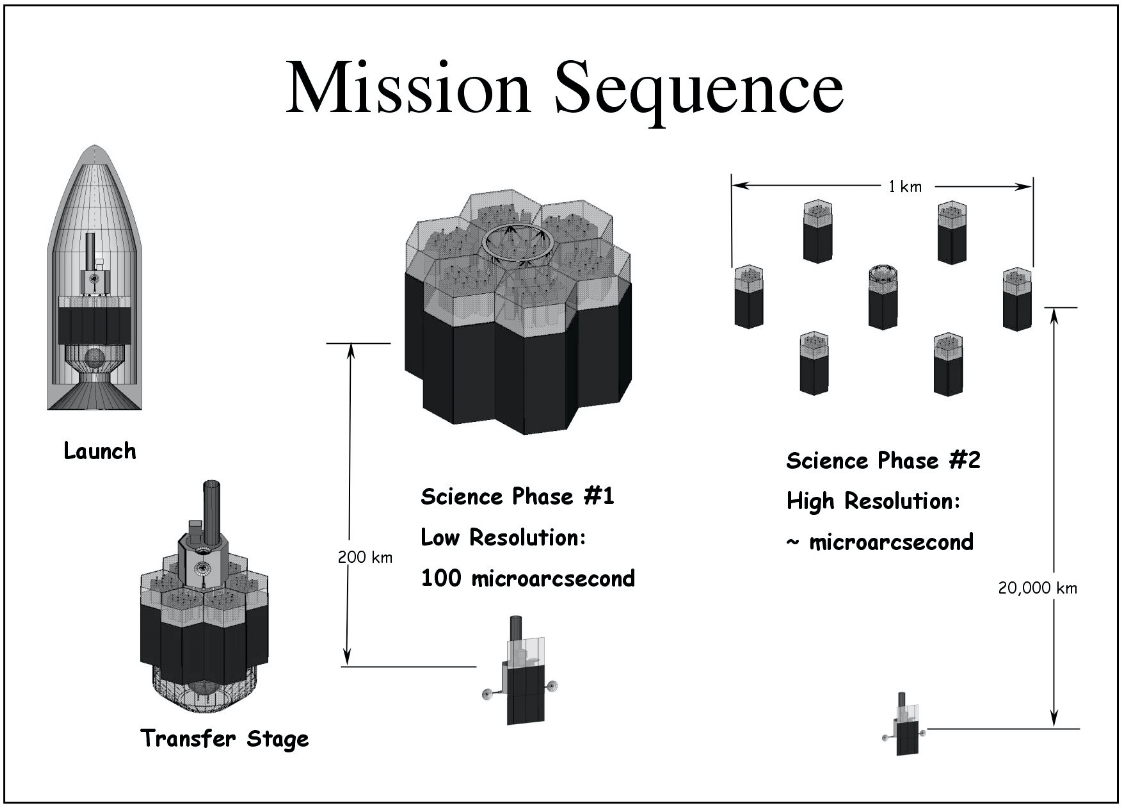

Figure 4: Launch, transfer, science phase 1, and science phase 2 of the MAXIM Pathfinder mission.

We chose L-2 for the orbit in order to minimize gravity gradient forces. We could have also chosen a heliocentric orbit which would drift away at ~ 0.1 AU per year. At either orbit, solar radiation pressures of about 1 microPascal are the dominant environmental force.

In figure 5, we show the optics spacecrafts in both the science phase 1 and science phase 2 configurations. It consists of 7 hexagon shaped spacecraft. The central unit is the hub while the 6 outer units will eventually become the free flyers. Each unit is about 1 meter across. The hub holds laser alignment beacons for the Line-Of-Sight alignment described above. In science phase 1, we use a milliwatt laser to get enough photons onto our LOS telescope on the detector spacecraft. In science phase 2, we use a LISA like 1-watt narrow divergence laser to get more photons onto the LOS telescope in order to achieve microarcsecond knowledge. The hub also acts as an intermediate communication port between the freeflyer crafts and the detector spacecraft. Each hexagon unit contains periscope modules. Since the x-ray aperture of each module is only about 1 cm across, we can easily arrange the satellite subsystems so that there are open holes both in front and behind the modules. The hub contains 9 modules, while each free flyer module has 11- giving us a total of 75 cm^2 of x-ray effective area. The freeflyers use star trackers to look at alignment beacons on the hub spacecraft to determine their longitudinal and azimuthal positions. They also make use of an MSTAR like laser ranging system to get the radial ranges from corner cubes on the hub spacecraft.

The thermal stability requirements for the optics spacecrafts is of order +/- 1 degree in order to control the placement of the periscopes to ~15 microns. The periscopes themselves are maintained at 20C+/- 0.1 degrees in order to maintain the high mirror figure quality. During phase 1, the thermal management is

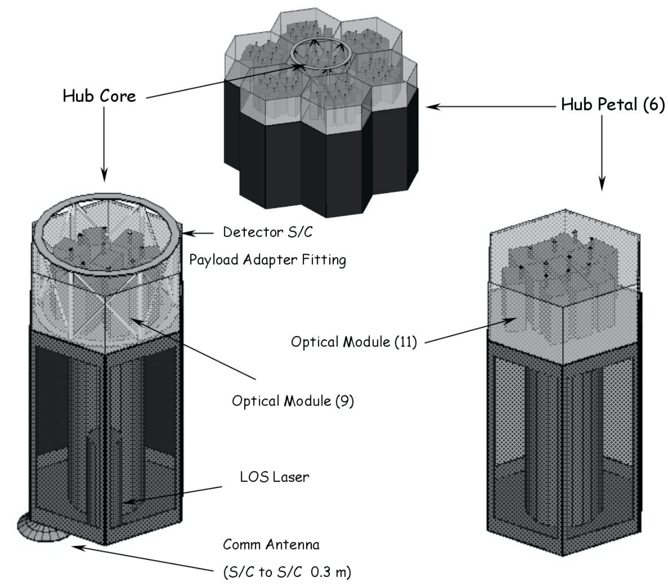

Figure 5: The optic modules: grouped together for science phase 1 and separated for phase 2.

handled by having the radiators of each hexagon unit louvered shut with the exception of one on the outside- which is coupled to the hub hexagon via a removable heat pipe.

The positions of the radiators as well as the positions of the solar panels and laser ranging systems forces the clocking of the free flyers in science phase 2 to be fixed with respect to the sun. Thus, the free flyers are not interchangeable.

In figure 6, we show the detector spacecraft. This spacecraft will communicate with earth on a daily basis using DSN. There are two key science instruments on the detector spacecraft.. First, we have a large 30cm on a side CCD focal plane. Its view is collimated to about 0.5 degrees to reduce the cosmic x-ray background. The full array is used for acquisition of the target. Once the target is acquired, we readout small regions of interest. The large size also allows us some comfort in the lateral control of the spacecraft. We still need extremely fine lateral displacement knowledge- to 15 microns. The second science instrument on the detector spacecraft handles this responsibility. It is the GP-B insert described above and elsewhere[6]. Cryocoolers developed for Constellation X and NGST will cool the GP-B insert to < 10 K for the operation of the super conducting gyroscope package.

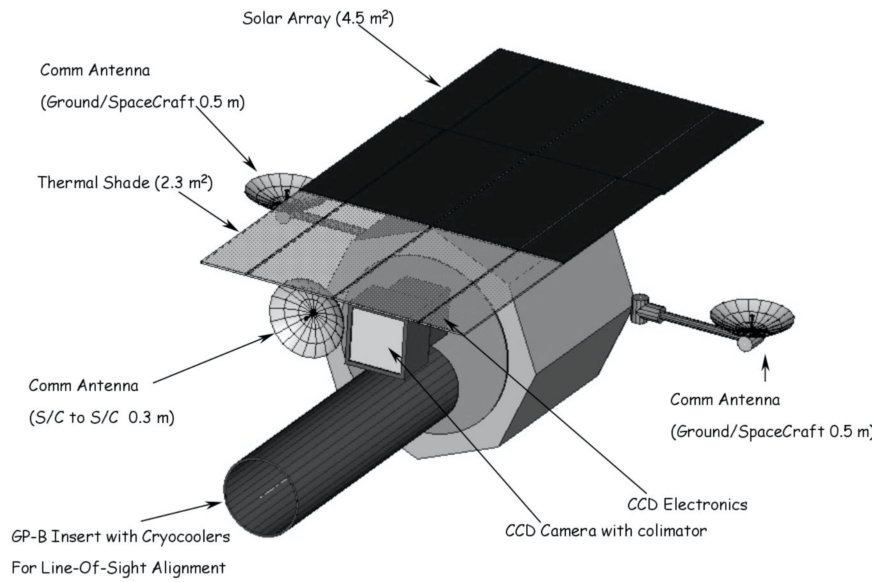

Figure 6: The detector spacecraft

The propulsion systems for this mission span a dynamic range of 5 orders of magnitude of thrust. In order to slew the observatory from one target to the next in a reasonable time (~1day for science phase 1 and ~ 1 week for science phase 2), we need large thrusts of order 0.02 Newtons. But to compensate for environmental forces such as solar pressure, we need ~0.3 microNewton control. At the high end, hydrazine thrusters will be used for orbit stabilization. For fine formation control, pulsed plasma thrusters (PPTs) will be used.

Two independent costs estimates from the IMDC agree to within 2% that the total mission costs would be about $550M ($650M with contingency). This includes the instrument costs, total integration and testing, launch, and mission operations for 4 years. While the CCD and the optic modules are relatively easy to get a cost estimate, the LOS system is the most difficult to determine. We have estimated that it would cost $100M to reproduce a GP-B insert with some modifications. The GSFC cryogenics branch feels that the use of cryocoolers should result in a negligible cost for cooling compared to the dewar now used on GP-B.

4. SUMMARY

We have presented the latest concepts for the MAXIM Pathfinder mission. MP will have 75 cm^2 of collecting area. It will have two science phases- phase 1 will do 100 microarcseconds science using 2 distinct space craft separated by 200 km. Phase 2 will do microarcsecond science by expanding the optics spacecraft into 7 separated spacecraft capable of extending optical baselines to 100s of meters. It will provide scientific context to the full MAXIM mission as well as test the key technologies MAXIM will need to resolve the event horizon of a black hole.

We have described how a good grouping of the various interferometer components can have a significant impact on the mission implementation. The periscope configuration allows us to consider micron as opposed to nanometers levels of formation flying control. Periscopes offer many other advantages which also help to make the mission easier.

Our longest pole is how to solve the Line-of-Sight alignment for the various interferometer components with our target. Currently, we are considering the approach of using gyroscopes like those on GP-B coupled with a beacon alignment system. This is a completely new approach which has many advantages- but still needs some development.

We anticipate a post 2015 launch for MP. With this launch, we will sharpen our pictures of the sky by 3 orders of magnitude and vastly expand our knowledge of the universe.

ACKNOWLEDGEMENTS

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