Interim Report to the NASA Institute for Advanced Concepts March, 2001

Phase II Study

X-ray Interferometry – Ultimate Imaging

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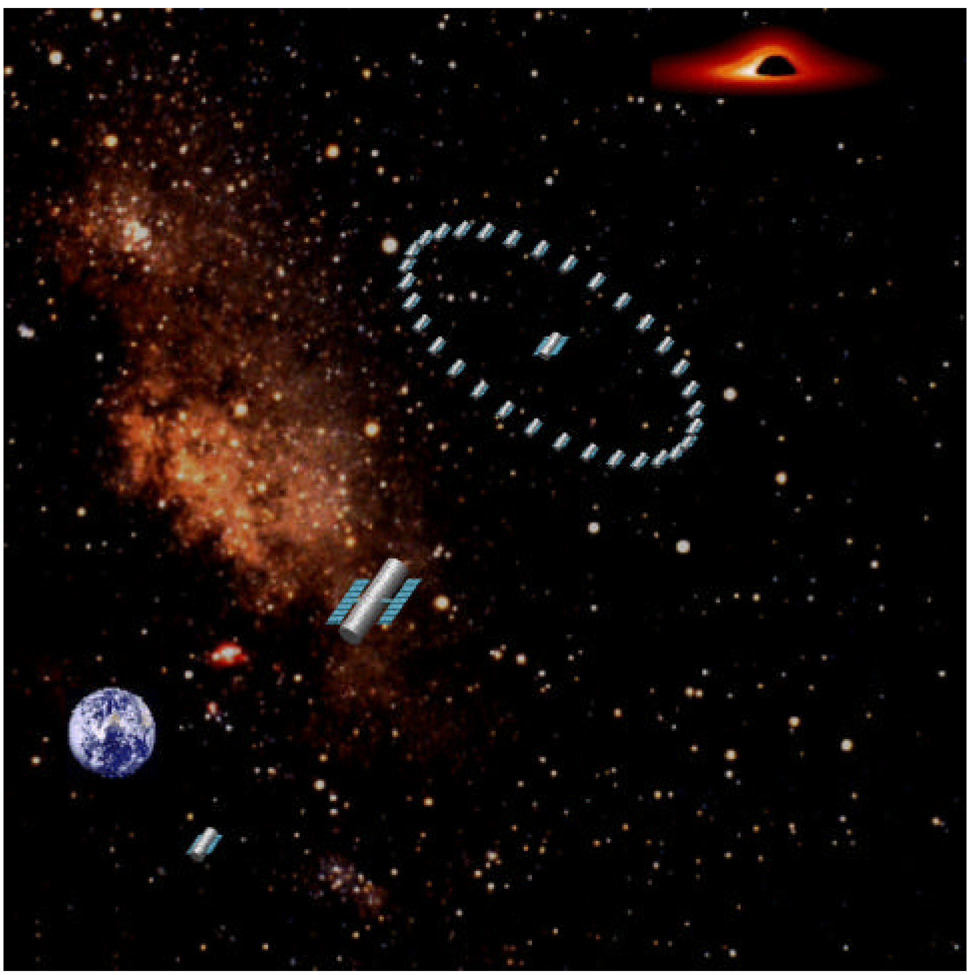


The general goal of this study into x-ray interferometry for astronomy is to better define the feasible mission architectures and to communicate the findings to the world so that support for the expensive missions they represent will be forthcoming. The work thus naturally splits into two general areas. First is public relations. There is an ongoing need to communicate the excitement of x-ray interferometry to both scientists and the general public, and to dispel the old misconceptions. The second area is definition of mission architectures.

Mission Promotion

If x-ray interferometry is to become a reality it needs to enter the consciousness of the astronomy community and of NASA. If there is sufficient support then the missions can enter the long term NASA planning and eventually achieve launch. Through this NIAC support we are actively promoting the concept to NASA and the worldwide astronomy community. The audience has been highly receptive. We are making the realities of x-ray interferometry known through the "3 p's" presentation, publicity and publication. Below are some listings of materials that have gone out in support of this effort.

Presentations

- NIAC Annual Meeting Goddard Space Flight Center June 2000
- General Assembly of the International Astronomical Union Manchester England, August 2000
- X-ray 2000 Symposium, Mondello, Italy September 2000
- High Energy Astrophysics Division in Honolulu, November 2000.
- Chancellors Lecture at CU Boulder, December 2000.
- Material presented as part of speech by Mr Goldin, January 2001
- NIST, February 2001
- New Century of X-ray Astronomy, Yokohama, March 2001
- U of Colorado, March 2001

Publications:

- Shipley, A., Cash, W., Joy, M., "Grazing Incidence Optics for X-ray Interferometry", *Proc. Soc. Photo-Opt. Instr. Eng.*, **4012**, 456-466, 2000.
- Joy, M., Shipley, A., Cash, W., Carter J., Zissa, D., Cuntz, M., "Experimental Results from a Grazing Incidence X-ray Interferometer" *Proc. Soc. Photo-Opt. Instr. Eng.*, **4012**, 270-277, 2000.
- Cash, W., White N., Joy, M., "The Maxim Pathfinder Mission: X-ray Imaging at 100 Micro-Arcseconds", *Proc. Soc. Photo-Opt. Instr. Eng.*, **4012**, 258-269, 2000.
- Windt, D., Cash, W., and Kahn, S., "The Scattering of X-rays by Interstellar Dust on the Micro-Arcsecond Scale", *Ap. J.*, **528**, 306-309, 2000.

- Cash, W., Shipley, A., Osterman, S., and Joy, M., “Laboratory Detection of X-ray Fringes with a Grazing-Incidence Interferometer”, *Nature*, **407**, 160-162, 2000.
- Cash, W., “X-ray Interferometry”, ASP Conference Series, 2001 in press
- Cash, Webster, White, Nicholas, Joy Marshall, “The Maxim Pathfinder Mission: X-ray Imaging at 100 Micro-Arcseconds” ASP Conference Series, 2001 in press

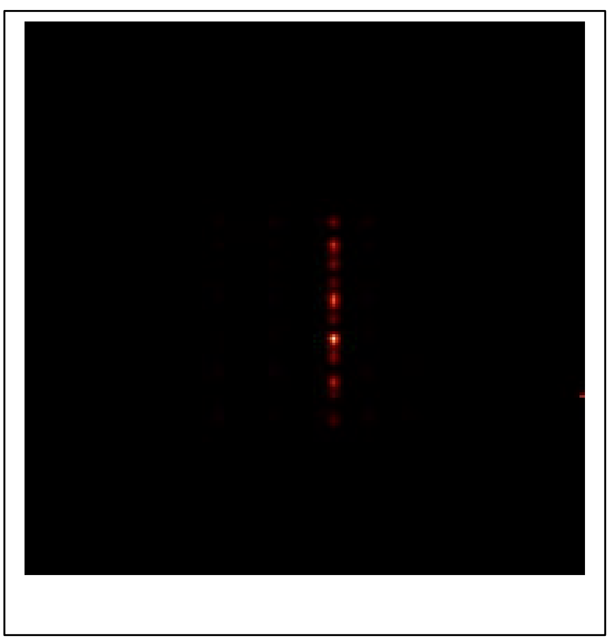
Publicity:

The Goddard publicity office prepared a press release about x-ray interferometry and Maxim and released it in conjunction with the Nature articles. This made a very big splash worldwide. It appears that there are lots of people who are excited by the potential of “Ultimate Astronomical Imaging”. I think the exposure we received will help make the interferometry a reality.

- http://www.msnbc.com/news/SPACENEWS_Front.asp
- http://www.discovery.com/news/briefs/20000913/te_sp_megascope.html
- http://news.bbc.co.uk/hi/english/sci/tech/newsid_924000/924684.stm
- http://www.space.com/scienceastronomy/astronomy/new_xray_scope_000913.html
- http://dailynews.yahoo.com/h/ap/20000913/sc/black_hole_telescope_1.html
- http://www.flatoday.com/space/explore/stories/2000b/091400a.htm

Modeling

One major activity of this program is the modeling and simulation of the mission performance. This is relevant to mission architecture, in that it helps set specifications, but its primary function at this early stage is to communicate the power of the observatory in a quantitative and convincing fashion. A variety of activities are going on in this area.



We need further simulations of the data analysis – the inversion of the fringes into 2-D images. We used our lab interferometer to obtain fringes of a slit at different azimuthal angles. We first tried the famous ART algorithm that was initially used for CAT scans in the early 1970’s. We found that it failed to properly reconstruct high frequencies. We next tried a version of CLEAN, the approach favored by radio astronomers. This worked nicely, creating the image shown here.

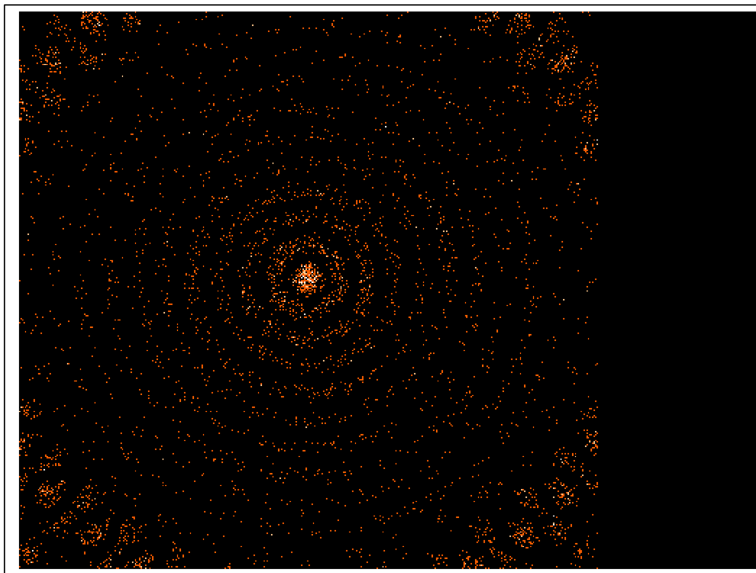
We had to use some (somewhat suspect) shortcuts on this first image, but it gives one confidence that the systems work. The bumpiness along the length of the slit appears to an artifact of the setup. We intend to try fourier inversion and maximum entropy next.

There has been some concern about the sensitivity of the x-ray interferometers due to the signal to noise. During July we did an analysis that showed we could be sensitive to very faint sources with a modest instrument. However, the analysis also proved the importance of multiple channels. While two apertures are adequate for resolution, only bright sources can be observed unless concentrating optics are used. On the other hand, the concentration of signal rises rapidly with the number of mirrors, and the nominal ring of 32 mirrors supports excellent sensitivity. However, the exact sensitivity limit will be the subject of further work.

The Strehl ratio is the ratio of the amount of flux in the central bright spot divided by the total flux. The greater this can be made, the more sensitive is the interferometer. We spent some time in August deriving a formula for the Strehl. We found that while our strehl is good, it can be improved by strategic placement of more mirrors in the secondary.

Randy McEntaffer, working in IDL, has upgraded our simulation programs so they now handle Poisson data in the way an x-ray detector would. A sample output is presented below.

We have been investigating the possibility of shortening the x-ray interferometer designs through the use of concave optics, most notably spheres. It appears that this may be practical. It has the advantage of allowing the pathfinder to be placed on a single craft, and for full Maxim to be significantly reduced in scale. The cost is in increased mass per unit collecting area and in decreased field of view.



Simulation of x-ray interferometer data with 5000 photons and a monochromatic source.

I have also started a senior research project that will directly support the development of x-ray interferometry. Jason Arentz will be re-deriving, from first principles of electromagnetic theory, the expected wavefront from the interaction of an x-ray with a flat mirror at grazing incidence. He will include effects of absorption, scatter, and figure error at all frequencies. This will allow us to evaluate the effects of surface irregularities on the depth of fringes.

Nasa Programmatics

As part of its mission to Explore the Universe, NASA has always maintained an aggressive program in space astronomy. But, there are many worthy projects competing for support. We have to prove that X-ray interferometry will fit naturally into this program and that it should be given priority. From a programmatic perspective x-ray interferometry is a good fit. Like all x-ray astronomy, it can only be done from space. However, it provides some challenges to NASA's engineering expertise, including:

- Precision formation flying of multiple spacecraft
- Interferometric pointing control of spacecraft
- Active metrology for high internal spacecraft stability
- Stable drift-away orbital environments
- High precision target acquisition

Luckily, our requirements do not stand alone. All of the above challenges are also being addressed by other missions in NASA's plans. Chief among these are ST-3, LISA, and SIM.

During this study we have been active in working with NASA to promote the ideas of x-ray interferometry. We have worked closely with NASA's Maxim team, and have membership overlap. Maxim stands for Micro-Arcsecond X-ray Imaging Mission, and consists of a committee chaired by Dr Nicholas White of Goddard Space Flight Center. We have shared the results of our work with them, and they with us. Further information is available on their website at http://maxim.gsfc.nasa.gov.

The Maxim team has spent its time identifying key science projects. There was a general consensus that the natural scientific goal should be to image the event horizons around the black holes in active galactic nuclei. By joining forces with the Maxim group, we have been able to make progress in the acceptance of X-ray interferometry as a future mission for NASA. In recognition of this, Maxim now appears as "New Visions" candidate instrument in the long term roadmap for NASA in the 2015 and beyond time period.

Mission Architecture

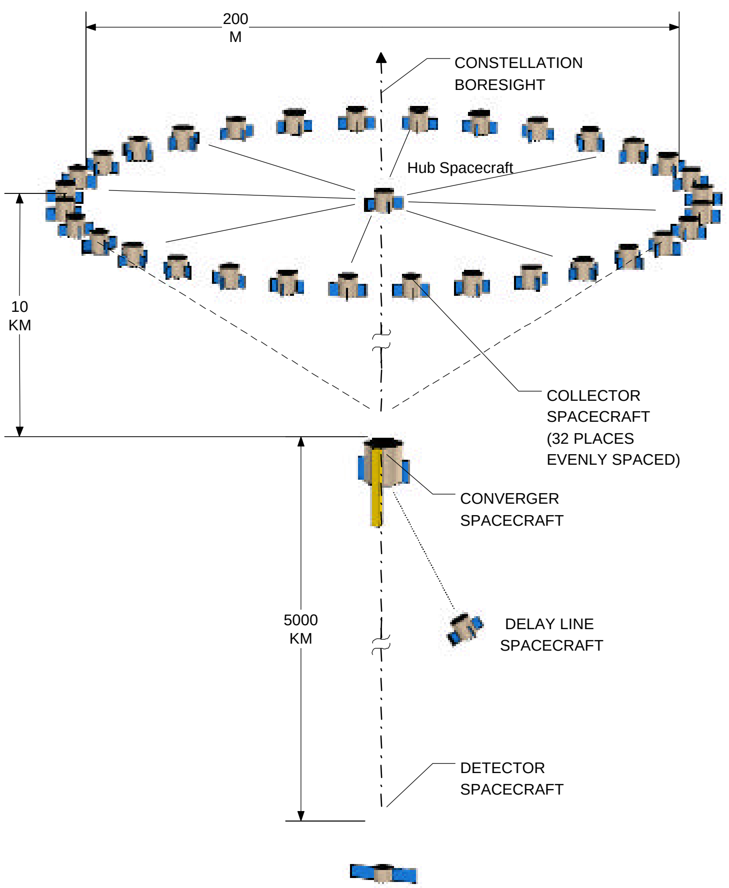
Mission architecture is central to a NIAC Phase II study. We need to use this opportunity to perform the basic tradeoff analyses and present a viable and convincing architecture. Much of our resources have gone into a Ball subcontract, the result of which will be a well balanced analysis of the entire system required for interferometry.

Ball Subcontract:

The core of the effort centers on Ball's use of their proprietary integrated mission design software. This software allows one to simulate all the behaviors of the components of a spacecraft and understand their impact on the scientific data. We plan to build a complete model of both mission levels – the pathfinder and the black hole imager. It is likely we will be able to create a model of the pathfinder that meets mission specifications using currently available components. For the full mission, we hope to meet that level, but, if we fail, we will identify where technology development is necessary.

Further investigation of the integrated approach gives us some confidence of success. Although x-ray interferometry is very demanding, it appears that the superstructure of the Ball software is sufficiently flexible to meet our needs. Ball is currently using the code to create a full model of the Next Generation Space Telescope (NGST) and the interferometric extension of the Very Large Telescope (VLT).

Dennis Gallagher and Mike Leiber, who are the principals at Ball on the NIAC subcontract attended the Pathfinder meeting at Goddard and the site review in Boulder. Leiber presented his integrated mission design software to the groups and explained how we intend to use it to give credibility to x-ray interferometry.



Schematic of the overall layout of the mission. The combiner craft in the middle collects the radiation from 32 collector spacecraft. The hub craft, together with the delay line craft keep the system pointed to high precision.

Dennis Gallagher (at Ball) is looking at the physical optics of an idea I have that may considerably shorten the distance between the beam combiner and the focal plane.

MAXIM:

Throughout the effort we have been working closely with the Goddard Space Flight Center and with the astronomy community's planning committees, attempting to spread the word of x-ray interferometry. These efforts have helped crystallize MAXIM, the Micro-Arcsecond X-ray Imaging Mission, within the planning at NASA. MAXIM is now a "Vision Mission" for the future. Transferring the fruits of our NIAC work to the MAXIM project is a high priority. I am chairing the Maxim Pathfinder Definition Team, and starting to organize an international meeting on the science of x-ray interferometry for next year.

On September 18 and 19 I chaired a meeting of the Maxim Pathfinder Definition Team at Goddard Space Flight Center. We included high energy observers, theorists, and instrumentalists from all over the country. I started the meeting with a review of the progress that has been made on the design of Maxim (mostly under this NIAC grant). They were given lots of opportunities to find errors or omissions in the project, but none were forthcoming. Instead, a general concern about the cost of the Pathfinder mission came to the fore. Specifically, it was felt that the initial $800M estimate was large enough to delay the mission. If we could find legitimate ways to reduce the cost to around $400M, then the mission would fly sooner. A number of constructive criticisms came out of the interchange, and some options for cost reduction are now under study.

Technical Challenges

We are spending time trying to identify the key technical challenges and find satisfactory preliminary answers to achieving the goals.

To the left is a schematic of the full Maxim mission, as configured to image black holes. Supporting this obviously ambitious project requires solving certain basic challenges.

Formation Flying: To minimize disturbances, the constellation of spacecraft operates in a heliocentric driftaway orbit with a semimajor axis of 1 Au and an ecliptic inclination of zero. To minimize thermal stresses on the S/C, the constellation boresight is always oriented at right angles to the sunline, although it is free to rotate 360 degrees around it.

In operation, the Converger, by far the most massive of the S/C operates in the orbit plane at all times to minimize the constellation's propellant consumption. Depending on the orientation of the constellation boresight about the sunline, the collector S/C position will be in a range from 0 to 10 km from the ecliptic plane. The lightest S/C, the detector, will operate in a range of from 0 to 5000 km from the plane.

To keep the S/C in their correct positions to this level of accuracy for all possible constellation boresight orientations, they must be continuously stationkept against forces exerted by solar radiation pressure and solar gravity.

Aspect Control: A number of alternative, higher specific impulse propulsion approaches exist, among them ion, magneto plasma dynamic, and stationary plasma thrusters. Each potentially offers a factor of four or better reduction in propellant consumption, at the price of an equivalent increase in power draw. Our trade study will define which of these options provides the best combination of cost and performance for the operational MAXIM constellation.

Mirrors, Mounts, Alignment And Thermal: The interferometer's active area requirement and proposed instrument configuration drive the mirror geometry to a long narrow shape. This represents a challenging mirror shape to mount even with relatively loose surface figure requirements. Current tolerance studies indicate each mirror's surface accuracy will be required to meet $\lambda/100$ rms surface figure with less than 5Å surface roughness.

Such an accurate surface figure requirement makes many subtle errors significant in estimating the total wavefront error. An acceptable mounted mirror's λ/100 surface must include errors due to alignment, thermal gradient, jitter, stability, assembly, manufacturing, test, 1g release, temperature change, temperature gradient, adhesive cure strain, bolt preload, and even the reflective coating thickness variation. Investigating a smaller mirror mount with similar requirements has given us the ability to quantify the errors and environmental effects most likely to become drivers that will require technology development. This approach allows us to break down the problem into smaller parts to identify areas that require technological advancement uncoupled from the known challenge involved with the mirror's size and shape. Additionally, we have completed the analysis for a smaller system that can be built and tested in a scaled down model of the interferometer. Such tests will be imperative to identifying real-time alignment, thermal, imaging, vibration/jitter, and other unknown subtleties requiring early attention that may not be apparent through analyses.

The analysis of a smaller mirror mount with similar requirements and analytical results indicate a λ/400 rms (λ/100 PV) surface figure is reasonably attainable for a 50mm square mirror made of fused silica. Wavefront error analysis based on those analytical results suggest the most challenging factors include: thermal gradient, and piston and tilt error associated with a bulk temperature increase (optical surface distortion is reasonable). The estimated allowable thermal gradient between the front and back of a mirror may be less than 0.01°C. The piston and tilt error of the mirror associated with a change in the stabilized temperature will probably drive the allowable time length of an observation. The mirror positions will need to be corrected between observations to maintain equal pathlengths. The mirror substrate thermal gradient will be difficult to maintain because heat emitted by motors used to manipulate the mirror position will make temperature difficult to stabilize. Materials with improved thermal properties could make this problem more easily contained in the future. Motors capable of high-resolution, stability, and position knowledge that emit very little heat would also help.

The long narrow mirrors will have the same thermal challenges at a much greater magnitude. A challenging parameter for a small mirror certainly indicates an imperative need for technological advancement to support similar requirements in a much larger mirror. Other factors we expect to be difficult are gravity release, stability due to jitter (a function of the mirror's fundamental frequency and mode shape), and the ability to test the mounted mirror's surface figure. The mirror size and high surface accuracy require a test apparatus beyond standard laser interferogram capability.

Active alignment of the optics on-orbit will be critical to maintaining such ambitious resolving power. Our studies using a single channel instrument consisting of four small mirrors have uncovered alignment issues that will apply to each channel of the instrument. Every mirror in the interferometer will require on-orbit motion in three degrees of freedom (tip, tilt, and piston). Current tolerance studies indicate optic alignment in the remaining three degrees of freedom may withstand launch. Attaining equal pathlengths in each channel will require tilt and piston control of each mirror at an estimated 10 nanometer resolution and knowledge. Equalizing pathlengths in numerous channels simultaneously while providing positional stability over the length of an observation may certainly be considered challenging. Developing continuous on-orbit automated sensing and correction to maintain equal pathlengths in each channel of the interferometer simultaneously could eliminate or greatly reduce these effects. The advent of this capability at the nanometer level would provide incredible imaging capability.

Thermal stability requirements will be a function of the length of time during which each channel's pathlengths may not be optimized. This time constraint may lend itself to the time length of an observation. Continuous automated sensing and pathlength correction could loosen some of these thermal requirements making longer observation sessions a reality. Investigating this avenue as part of the system analysis would be beneficial. A clever mirror mount may minimize wavefront error due to thermal changes, but still cause tip, tilt and piston motions that will far exceed allowable tolerances. Once again this thermal issue may be mitigated with the advent of automated alignment corrections. The thermal challenges are significant, but appear to be integrally tied with mirror, mount, and alignment solutions.

Calibration: It may not be possible to fully calibrate the instrument on the ground. The longest vacuum tank we have available is the XRCF at MSFC, which is 500m. Resolution of one micro-arcsecond at that distance represents a size scale of 2.5nm. We cannot currently even create mask features this fine. We may have to check components, and then perform an in-orbit checkout.

For the development and testing phase of the mission a critical task is to fabricate high-quality target apertures designed to test the diffraction-limited performance of the optical system. The idea is to use microscope optics to image backlit apertures onto the detector. Target apertures of various shapes are useful, such as holes, slits, cross and wagonwheel patterns, and gratings. In order to fully test the optical system, apertures need to be cut into thin, x-ray opaque foils, and need to have sub-micron feature sizes with sharp edges and corners. Specialized laboratory facilities are required to fabricate targets of this quality. MIT is actively engaged in developing these test masks as part of this NIAC study.

StationKeeping: The stationkeeping approach described using existing technology can provide at least a 20 year life for all requirements except along-boresight control for the Detector S/C. The baseline 20 year life could be doubled by simply adding a second set of thrusters to each axis. Accordingly, these requirements are not considered limiting.

Limits are completely dominated by Detector S/C along-boresight control. For equivalent lifetime, total impulse requirements are a linear function of the distance along the boresight; a 10,000 km distance would require twice the total impulse or reduction of the mission lifetime to 5 years. Removing these limits could be accomplished by adding more PPT's, or by using a higher specific impulse propulsion approach such as ion or magneto-plasma-dynamic thrusters. In any case, an absolute limit imposed by propellant load would probably be reached at between 50,000 and 100,000 km separation.

Aspect Information: We expect to obtain aspect information by using a Michelson flat at the hub spacecraft to redirect the signal from a stellar object into an interferometer on the converger craft. As the array flies apart, the baseline of this interferometer grows along with the baseline of the x-ray interferometer. Two effects can limit the effectiveness of this aspect interferometer.

First is the diffraction from the Michelson flat. A ten meter optic will cause visible light to diffract one part in $2x10^7$. If the beam is to diffract to less than 100m across, resulting in a factor of 100 loss in signal, then the baseline of the aspect interferometer can be as high as 2 million kilometers. This indicates an x-ray interferometer with a baseline of 200,000km and resolution of 10^{-17} radians.

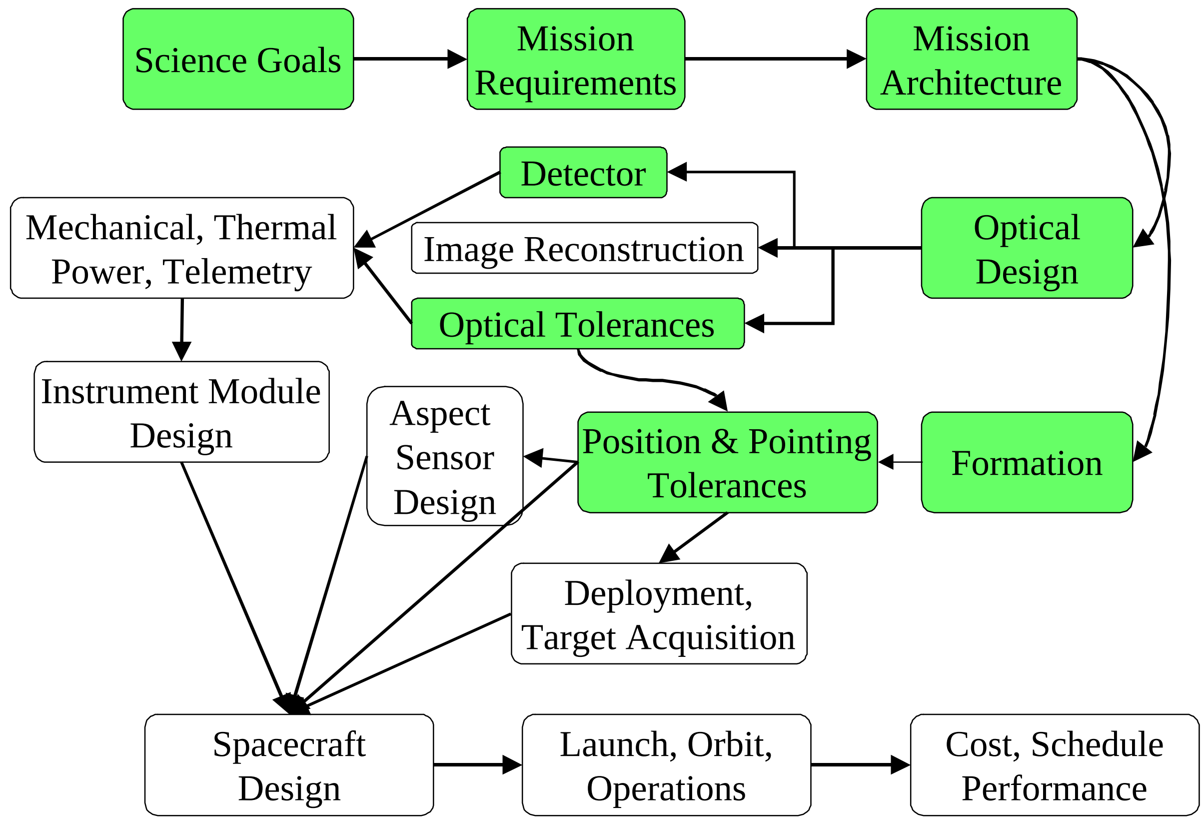
The other effect is the size of the star being used to provide the reference wavefront. We rapidly start to run out of thermal reference information in the visible portion of the spectrum. We can use main sequence stars at a distance as great as 10,000pc, which have an angular extent of around 10^{-11} radians, which will be resolved across a baseline of 100km. We could use white dwarf stars, but, while they are smaller, they are also dimmer, and we cannot see them a great distances. Similarly, the visible emission of AGN's is too extended. This problem is a direct result of the relative faintness of visible emission from objects. The only hope to solve this problem in the visible is to observe non-thermal objects such as pulsars. The Crab pulsar is detectable in the visible, yet is only a few kilometers across, so might give us the needed information. At a diameter of 10km at 2kpc, it has an angular extent of 10^{-16} radians, a reasonable match to the x-ray resolution.

Of course, we can solve the problem by getting our aspect information from an x-ray interferometer. We are looking at this as an option.

Moving Forward

The final figure is the development pathway as presented in our Phase II proposal. At the halfway mark we have addressed every box in the diagram at some level. By the end of the study, with the help of the Ball Integrated design software, not only will all the boxes have been addressed, but the interactions between the boxes will have been modeled and preliminary optimization performed.

Development Pathway



Dark Green = Studied, Stippled Pink = Needs More Study, White = To Be Defined