Evolving design criteria for very large aperture space-based telescopes and their influence on the need for integrated tools in the optimization process

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ABSTRACT

NASA's Advanced Mirror Technology Development (AMTD) program has been developing the means to design and build the future generations of space based telescopes. With the nearing completion of the James Webb Space Telescope (JWST), the astrophysics community is already starting to define the requirements for follow on observatories. The restrictions of available launch vehicles and the possibilities of planned future vehicles have fueled the competition between monolithic primaries (with better optical quality) and segmented primaries (with larger apertures, but with diffraction, costs and figure control issues). Regardless of the current shroud sizes and lift capacities, these competing architectures share the need for rapid design tools. As part of the AMTD program a number of tools have been developed and tested to speed up the design process. Starting with the Arnold Mirror Modeler (which creates Finite Element Models (FEM) for structural analysis) and now also feeds these models into thermal stability analyses. They share common file formats and interchangeable results. During the development of the program, numerous trade studies were created for 4 meter and 8 meter monolithic primaries, complete with support systems. Evaluation of these results has led to a better understanding of how the specification drives the results. This paper will show some of the early trade studies for typical specification requirements such as lowest mirror bending frequency and suspension system lowest frequency. The results use representative allowable stress values for each mirror substrate material and construction method and generic material properties. These studies lead to some interesting relationships between feasible designs and the realities of actually trying to build these mirrors. Much of the traditional specifications were developed for much smaller systems, where the mass and volume of the primary where a small portion of the overall satellite. JWST shows us that as the aperture grows, the primary takes up the majority of the mass and volume and the established rules need to be adjusted. For example, a small change in lowest frequency requirement can change the cost by millions of dollars.

Keywords: Design criteria, space-based telescopes, AMTD, optimization process

1. INTRODUCTION

This paper started out to present some recent trade study results for a possible upcoming project. It rapidly evolved into a discussion on establishing appropriate design criteria for that program. As the initial criteria was based upon a much smaller optical system, it became clear that a different approach was necessary. To help clarify the rationale behind that statement, we will show a little bit of the evolution of the design process for space telescopes. Starting with Hubble, then on to Kepler and ending with James Webb, we will briefly look at how the mirror design fit into the overall satellite. Our basic hypothesis is that as the desired aperture size grows, the influence of how the primary mirror assembly is designed starts to significantly impact all the other components. As this whole activity was part of the Advanced Mirror Technology Development [AMTD] using one of the tools developed, the Arnold Mirror Modeler [AMM], we will show how they fit into the evolving process.

Our Hypothesis

For very large apertures, the primary mirror starts to drive the whole satellite. Another way of stating that is the whole system design is now an optimization problem involving all the systems collectively. Whatever launch vehicle is selected, it will have a maximum payload capacity to the desired orbit, and a limited volume of shroud to package the whole satellite. It is no longer practical to divide (at least during early design phases) the Optical Assembly from sensors and housekeeping satellite functions.

The value functions of this problem are: optical performance, mechanical performance, thermal performance and complexity (relates to reliability and risk)

The constraints are: mass, volume cost and risk (technical, schedule, cost and science mission success).

Every system and subsystem in the satellite is competing for its share of a fixed mass and volume, to make things lighter increases the risk and cost. In the end, if the science is not achieved, there is no point in building it. If the mechanical performance is not achieved, it will not survive launch or function properly on orbit. If the thermal performance is insufficient, then the science again will fail. If in order to achieve the desired mass, the components are so complex that they have a good chance of not working, no matter how we test them on earth (if we can test them at all), it will not get built. Even if all the science is achieved, the thing mechanically and thermally works and everyone believes it will work, if it costs too much or takes too long to build, the project will never get funded.

It is this problem that AMTD is trying to address, to establish the tools to evaluate all the value functions mentioned above as accurately and economically as possible. The individual tools under development both under AMTD auspices or other NASA projects are being integrated into a common analysis framework. This process will take time and effort, but even now they are reaching a worthwhile functionality individually. In parallel with analysis, AMTD is increasing the TRL levels of many promising material and manufacturing methods for large primary mirrors and other optics. Companion papers highlight some of these efforts, and progress is being made towards standardizing the inputs and output formats of the tools to enable the integration. There are generalized optimization programs out there, but none so far seem suitable for the Large Space Telescope situation.

To get back to the subject, how does one go about establishing a reasonable set of design criteria for the primary mirror? Once you have picked a spectrum range, science objective to establish an optical performance goal and picked a launch vehicle, you might be in a position to start the process. One of AMTD's goals is to provide tools that will give an impartial evaluation of all potential materials and construction method. Each vendor has specialized knowledge in the areas of his product, we are not trying to compromise any of that. Our goal is to model any material and method in the public domain (and allow the program user to input his own data) to efficiently design candidates.

2. HISTORIC BACKGROUND

The general trend in telescopes is as large as possible as seen in figure 1.

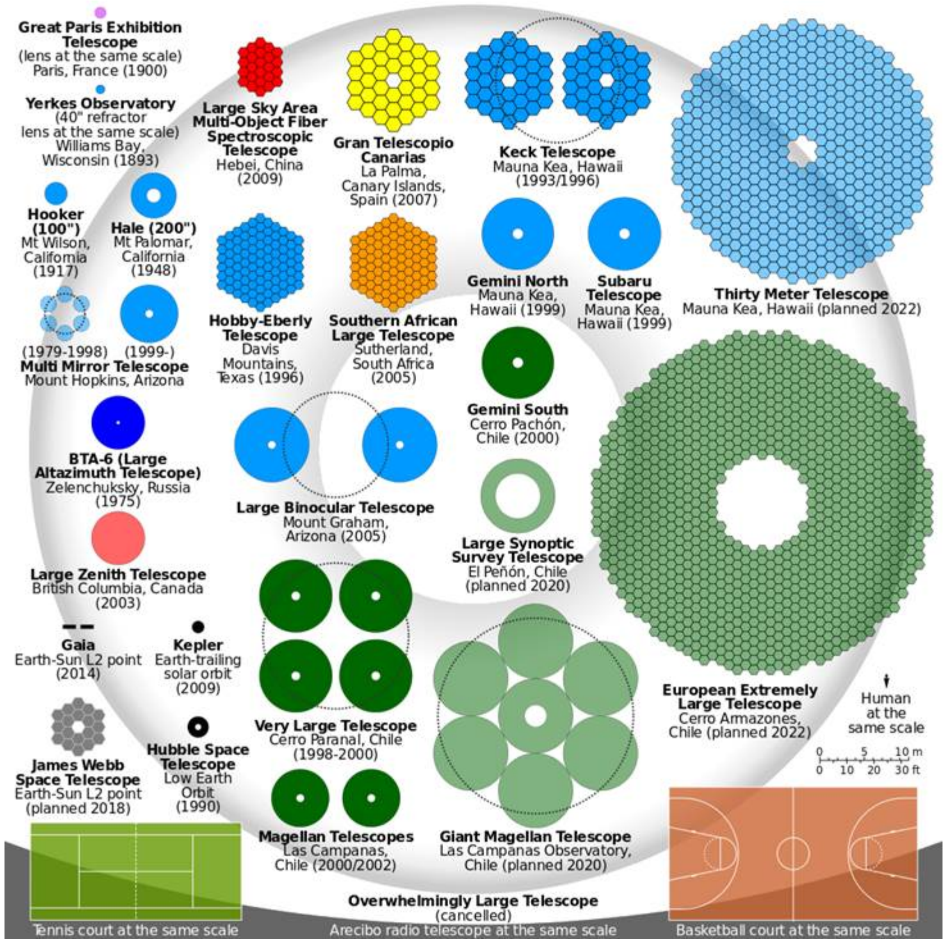

Figure 1 The general trend in telescope size.

The trend in space based telescopes is following the same trend line, but is restricted by launch vehicle capabilities more than the terrestrial variations.

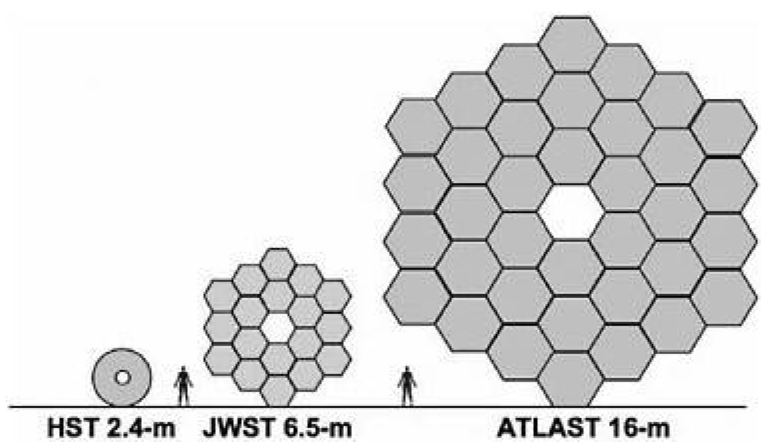

Figure 2 Space based telescopes

Hubble Space Telescope

When designed and built, Hubble represented the state-of-the art, but much of its total cost was actually long term storage of the finished satellite. Each component was designed almost independent of other parts of the satellite and the primary mirror was only a small portion of the total mass. So the mass distribution and component level design criteria were basically established with little consideration for any potential interaction (optimization wise). It's difficult to trace the source(s) for many of the criteria used.

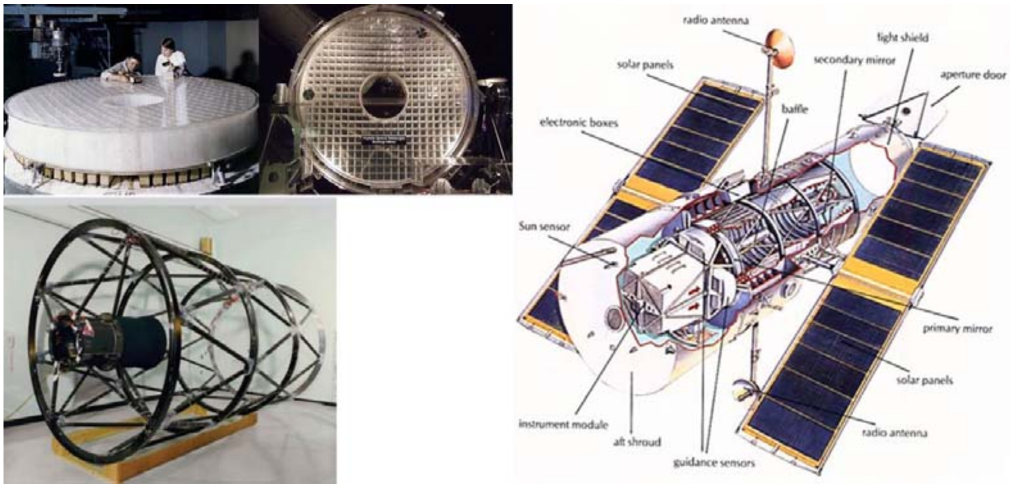

Figure 3 Major elements of Hubble Space Telescope.

Kepler Photometer (Planet finder)

Kepler was cost sensitive and no backup mirror was available for the primary mirror, so the design criteria called for the support system to be designed to have two rotation positions for attachment (in the event of damage during testing). The design process involved an optimization of cell size, hexapod suspension geometry versus weight, peak stress and lowest bending moment of the mirror. In the evolution of the process, the mirror and support were designed as a single unit.

Due to the lightweighting of the mirror, all the manufacturing and handling equipment were design simultaneously with the mirror and special reinforcements added just for tooling.

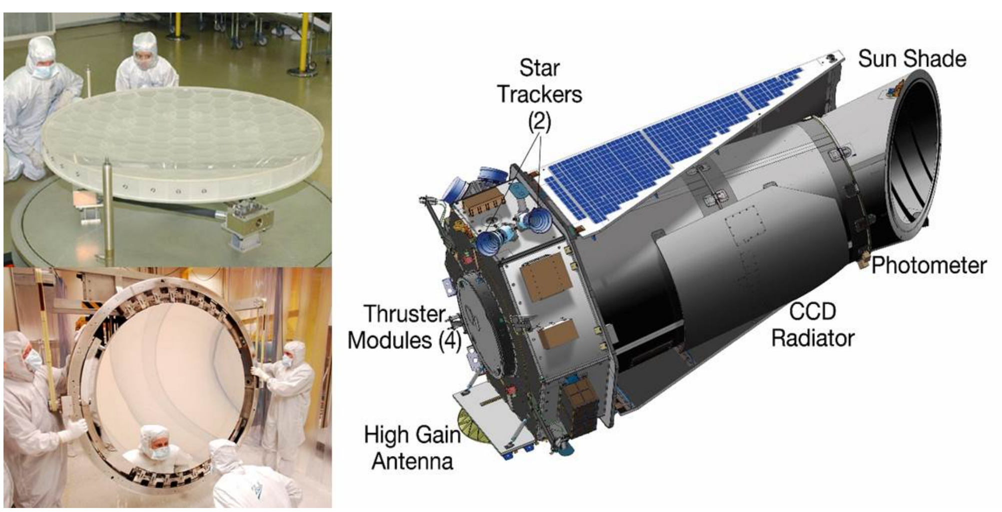

Figure 4 Major elements of the Kepler Photometer.

James Webb Space Telescope

This was the first segmented space telescope, and much of the design was done by different organizations for different assemblies. One of the driving constraints was the shroud volume of the intended launch vehicle. The design process was a hybrid of system level optimization and divided detail component design efforts.

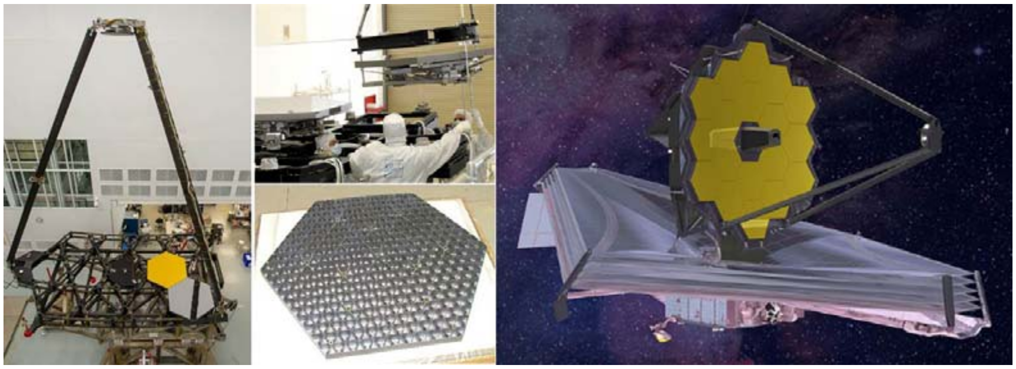

Figure 5 Major elements of James Webb Space Telescope.

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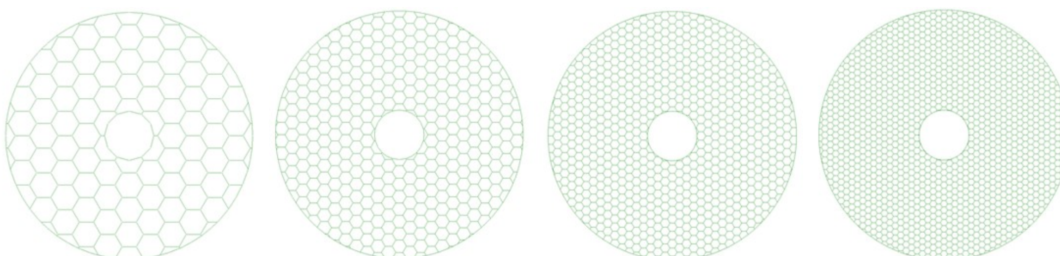
3. EXAMPLE

To illustrate the hypothesis, let's take a simple criteria such as specifying the lowest frequency or bending mode of the mirror. We will look at a typical ULE frit-bonded lightweight, with most of the parameters the same, and we will only vary facesheet thickness. The depth or overall thickness of the mirror will be fixed at 400mm, only a single cell size, say 200mm will be used. We will look at the mass required to satisfy a criteria of 100 hertz, then 200 hertz. What is most important is we will look at 2 meter, 4 meter and 8 meter outer diameter cases.



CRITERIA	2 meter		4 meter		6 meter		8 meter	
	kg	hz	kg	hz	kg	hz	kg	hz
100 hertz	88	100	911	106	14908	106	(2)	(2)
200 hertz	130	231	5727	204	(1)	(1)	(2)	(2)

(1) Doubling facesheet thickness (24010 kg) still only increased f=109 hz.
(2) Upper limits of feasible design (32,312 kg) only produced f=66 hz. at 8 meter OD

Figure 6 Simple trade study to illustrate effect of single criteria choice.

4. SUMMARY AND CONCLUSIONS

The paper uses several trade studies created during the software development phase of the Arnold Mirror Modeler to illustrate the influences of system specifications on the design space. The future telescopes will require better performance, stability and documented feasibility to meet the hurdles of today's budget and schedules realities. AMTD is developing the tools, but the basic system planning mentality also has to adapt to the requirements of these very large and complex physical structures.

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