An Architectural Analysis of the James Webb Space Telescope

Yaakov Schefres
University of Southern California: SAE 549
8/6/19

Abstract

Space telescopes have been essential to expanding human understanding of fundamental questions of astrophysics and the observable universe. The James Webb Space Telescope (JWST) will push the boundaries of this knowledge through technologies proven on the ground along with novel ideas to take these established technologies to unprecedented environments. Most simply, “JWST is a large, infrared-optimized space telescope,” but its mission of detecting first light, galaxy assemblies, birth of stars, and planetary systems, demands the architecture to be much more complex (Menzel, et al., 2010). In order to reach the resolution and field of view necessary to collect the scientific data desired, the JWST observatory must be a space-based system. The JWST system includes three major segments: The Space Observatory to collect data, the Launch Vehicle to transport the Observatory into the correct orbit, and Ground Station to receive the collected data from the Observatory.

As an unclassified NASA program, the architectural discussion, as opposed to technical details that is typically proprietary, dating back to the when James Webb Space Telescope was called the Next Generation Space Telescope (NGST) is all readily available through NASA’s website as well as government archived documents. There are also a number of resources through USC to obtain research papers that one may otherwise not have access to. In extreme cases, asking for information directly from NASA or the contractor, Northrop Grumman, could be done. However, it is expected that this route would yield limited results.

While on the cutting edge of current space telescope technology that can see further back with better resolution than any other system thus far, JWST is also a survey spacecraft. Its mission parameters are broad enough to accommodate a wide range of data types without specializing in any one particular mission. After JWST, specialized telescopes that will collect more targeted data will be launched to acquire definitive answers. The data from JWST will guide future telescopes where to look. One such mission is HabEx which will have instrumentation to specifically look for planets with habitable atmospheres. While JWST does have some ability to scope out these types of planets, it will not display nearly the amount of resolution as HabEx. Another daughter program of the JWST program that would build upon its mission would be to simply increase the diameter of the primary optical element in order to obtain even higher resolution.

1 Introduction and History

The James Webb Space Telescope (JWST) was first conceived in 1989 at the Space Telescope Science Institute with the concept of a 10-meter class Telescope that covered the Ultraviolet, Visible, and Infrared (IR) ranges of light as a successor to the Hubble Space Telescope. At that time, it held the name "Next Generation Space Telescope" (NGST) and its primary mission would be to observe the early universe. Prior to the inception of NGST, Pierre Bely, an engineer at the Space Telescope Science Institute (STScI) had been working on a concept for solving the extremely low temperature requirements required for optical IR high resolution imaging since 1986 (Illingworth, 2016). His concept of using passive cooling via a sunshield would eventually be integrated into the final design of what would become known as the James Webb Space Telescope. This passive cooling technique is an ancient one that surprisingly finds its roots in fashion. Parasols have been used as both a display of wealth and to protect the owner from heat caused by the sun for thousands of years (History of Parasol - Who invented Parasol?, n.d.). It is possible that Bely used the heuristic **"Exploit apt analogies from other disciplines to increase understanding and develop effective solutions."** NASA confirms that, in essence, the sunshield "acts like a parasol providing shade" (Masetti, About the Sunshield, n.d.).

As a successor to the Hubble Space telescope, NGST quickly gained momentum in the scientific community through conferences, workshops, and the like. However, a recession in the early 1990s significantly slowed down work on NGST which eventually picked up again in the mid-1990s. In 1997, industry bidders started developing their architectures for the space observatory segment of the NGST. TRW Inc. (which would later be bought by Northrop Grumman) was selected as the primary contractor in 1999. In 2002, NGST was renamed James Webb Space Telescope after the second NASA Administrator who saw through much of the Apollo missions. Currently, JWST is scheduled for launch in March of 2021.

1.1 Architectural Overview

The Architecture of the James Webb Space Telescope is driven by a number of major performance objectives that were coordinated through various workshops and conferences of the late 80s and early 90s. The main objective, and primary impetus for the JWST system is to observe the early universe. This objective seeks to answer many fundamental questions still being asked by the scientific community today. Coincidentally, this primary mission is also the driver for much of the architecture. In order to achieve a balance between cost and scientific performance, architectural design steps including identifying mission need, exploring key architectural trade options, defining form, function, interfaces, and boundaries, and finally, architecture implementation were performed.

Each of these steps have a consequence to the overall architecture of the JWST system. In the final architecture of JWST, a space observatory that must fit inside a launch vehicle for it to reach its orbit was chosen. This architectural decision transforms later into a unique engineering design challenge as having a large mirror size results in the space telescope not readily fitting inside a launch vehicle. Interestingly, this challenge was known and acknowledged by those preforming the preliminary architectural design (Wehnew, Moses, Lillie, & Johnson, 1998). Another consequence of a spacecraft observatory is that it needs to be able to communicate back to Earth. The architectural decision of a space telescope thus also leads to a need for a support system on the ground to receive telemetry and data from the observatory and to command the spacecraft.

The Launch Vehicle, Ground, and Observatory, form the three arms of the JWST Architecture as shown in Figure 1. Under those segments are the subsystems that comprise each segment.

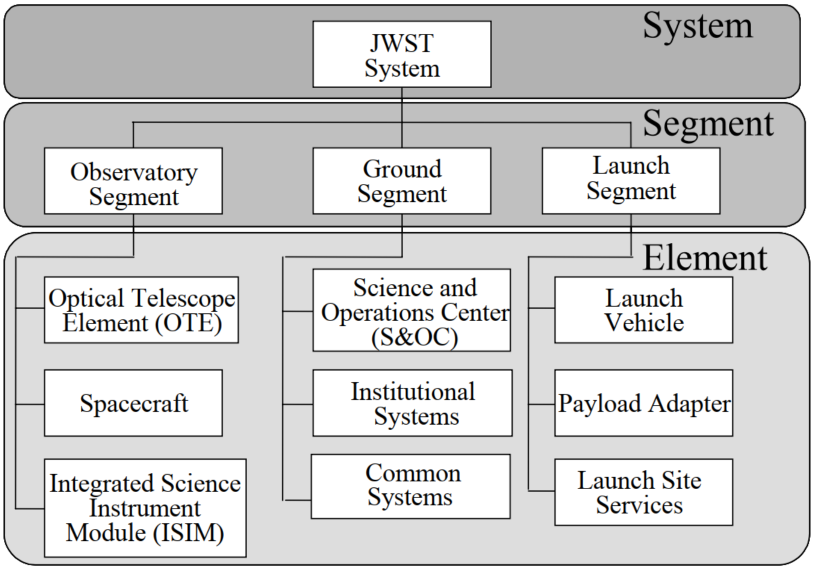

Figure 1 Architecture of the James Webb Space Telescope (Bogenberger, 2007; Mather, 2006)

1.2 Architectural Design Steps Taken

Architectural design is a deliberate process in which there are a number of methodologies that can be used to develop successful architecture. The normative, rational, and heuristic approaches each have their place in the architectural development of JWST. However, the framework of Multi-Attribute Tradespace Exploration (MATE) would likely make the most sense for the JWST System. MATE is a process in which options are generated and analyzed for their benefits to stakeholders, cost, and utility (Madni, Architectire Trade-off Analysis, 2019). As opposed to Decision-Based Design (DBD), the JWST system is not particularly interested in targeting a specific price point, but rather comparing multiple options based on cost and performance and determining which options provide the best performance within a particular cost, schedule, and budget. MATE provides a similar power of analysis without the onerous constraint of firmly sticking to a price point. This allows the designers the potential to significantly increase performance or utility even if there is a small cost increase associated with it. MATE also lends its hand to generating novel options which is especially useful in the case of JWST as it is a novel system. Particularly, MATE allows for Decision Situation Modeling (DSM) that allow architects to consider a wide range of options in a trade space and select the one that confirms the cost and utility constraints (Madni, Transdisciplinary Systems Engineering, 2018). This is similar to Multi-Actor, Multi-Criteria Analysis (MAMCA). However, this tradeoff framework tends to not be iterative which is useful when creating novel architectures. The following sections provide an overview of a rough timeline of the MATE framework in action for the JWST architecture.

1.2.1 Identifying Mission and Need

The only way to create a successful architecture is to first identify the need and parameters for the technology or product. For NGST, this was identified through an "observational gap between the Hubble Space Telescope (HST), which can see galaxies to approximately 5 billion years after the Big Bang, and the Cosmic Background Explorer (COBE), [a telescope] which explores the microwave background several hundred thousand years after the Big Bang" (Wehnew, Moses, Lillie, & Johnson, 1998). Essentially, NGST will be suppling another piece of the timeline to help construct a better picture of the formation of the universe. Later, in the science mission requirements document flowed to industry, this would be translated into four major areas: Universe's First Light and Reionization, Assembly of Galaxies, Birth of Stars and Protoplanetary Systems, Planetary Systems and the Origins of Life (Mather, 2006).

1.2.2 Explore Options, Perform Key Architectural Trades

Only once the underlying "why" of a system is explored, can one begin to entertain architecture options. It is an important distinction here to note that in this phase, one should not perform engineering design trades, but rather architecture design trades. The key difference is that the architecture defines the core structure for the system while engineering design uses that architype to create forms and functions that implement the underlying mission or need. The key tradeoffs for the JWST system are discussed in Section 3.

1.2.3 Define Form, Function, Interfaces, and Boundaries

Effective architects must define forms, functions, and boundaries in order to implement it properly. Decisions from option exploration are used to determine what functions must be accomplished and what forms accomplish that function. Form and function definition is often accomplished iteratively and in parallel with option exploration itself as it helps define the feasibility, cost, and schedule of performing architectures. Again, it is essential to note that these are not engineering design decisions on form and function but rather defining at a higher level that major forms and functions required to accomplish the mission. The definitions of the form and function lend a hand to also defining interfaces and boundaries. These are discussed in Section 2.

1.2.4 Implement Architecture in Design, Deployment, and Retirement

It would be folly to generate a system architecture and not follow through on its implementation. Therefore, systems architects follow the design, deployment, and eventual retirement of a product to ensure that it continuously meets stakeholders' needs. During this time, system architects play a role in generating lessons learned and reacting to Murphy's Law stating that **"If anything can go wrong, it will."** For example, schedule was one of the major sources of pain in the complete development of JWST, especially during the verification phase. During this time, it became increasingly difficult to properly verify optical alignment. NASA, along with the primary contractors identified that this situation was insufficiently anticipated and that in the future, programs need to **"think about verification during the architecture phase."** As part of this, facilities, test strategies, and necessary degrees of freedom need to be considered. Also, the need to create new facilities to accommodate the testing required became a major driver for schedule delay. If the need for new facilities were known during the architecture phase, schedule may have been less of an issue (Feinberg, Arenberg, Lightsey, & Yanatsis, 2018).

2 Interfaces and Boundaries

Understanding and clearly defining the interfaces within an architecture is critical to the smooth functioning of both the system development and deployment. Without strict boundaries, interfaces critical to system functionality can become undefined and underdeveloped. The data gathering and most complex part of the JWST System is the Observatory Segment. Ensuring that the boundaries are clearly parameterized ensures that its interfaces with the other segments work seamlessly. Figure 2 shows the architecture diagram of the observatory segment. The Ground and Launch Segments form two of the boundaries to the Observatory Segment.

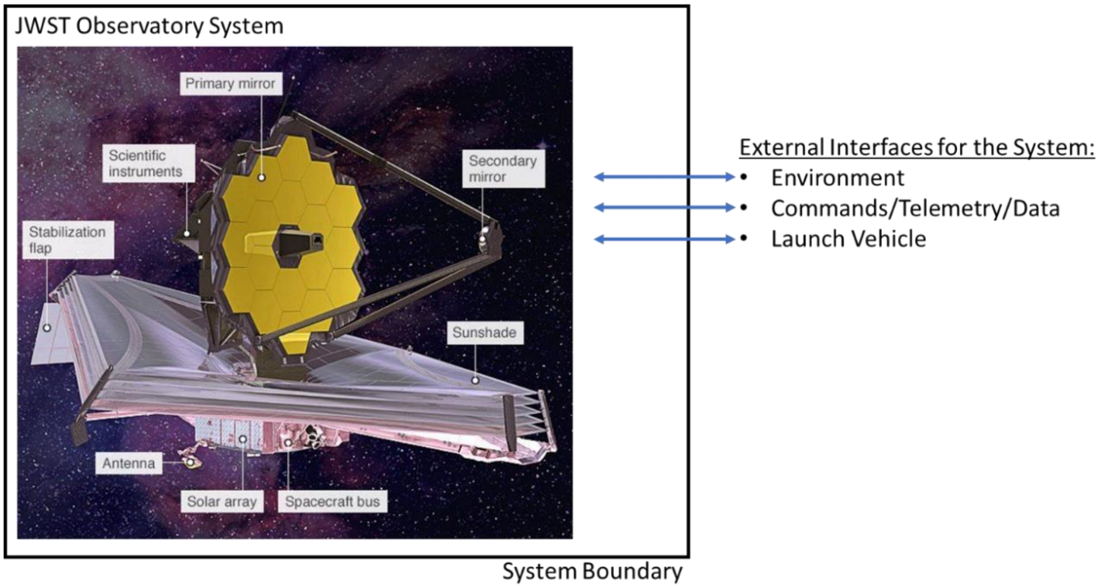

Figure 2 Architecture Diagram of the Observatory Segment (Nichols, 2018)

2.1 Launch Vehicle Segment

The ability to fit inside a launch vehicle is a critical interface in order to reach the Observatory location (the L2 Lagrange point in the case of the JWST). In order to reach the orbit necessary for the nature of the mission, the Observatory needs to be able to be launched via a Launch Vehicle. The primary interfaces to and from the launch vehicle are mechanical fastening and electrical harnessing. The resolution requirements required by the primary objective drive a large optical element design that will not naturally fit inside the selected Launch Vehicle (Ariane 5) or any current launch vehicle for that matter. Therefore, a multi-stage deployable design was selected or order to meet the constraints of current launch vehicle design. The JWST Observatory Segment folds so that it can fit inside the launch vehicle as shown in Figure 3. After launch, a large number of incremental deployments brings it into an operational ready configuration depicted in Figure 4. Conversely, there are many other forms that could accomplish the mechanical interfaces while still technically being a telescope. The Hubble Space Telescope, for example was small enough to fit inside the Space Shuttle without the need to deploy anything. However, JWST is significantly larger and more advanced than Hubble, requiring this architectural decision.

Figure 3 JWST Observatory Launch Configuration (Masetti, About Webb Launch, 2019)

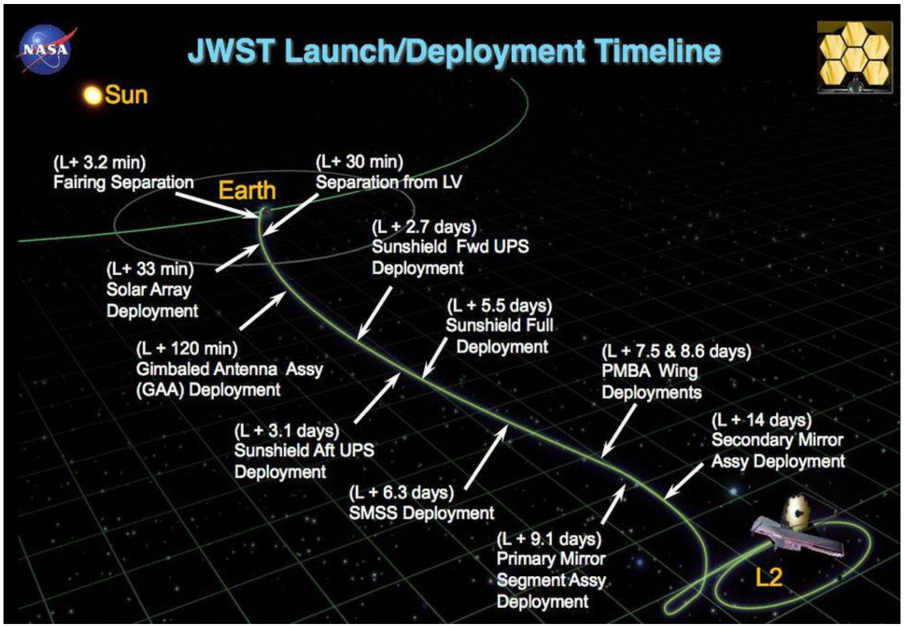

Figure 4 James Webb Space Telescope Launch and Deployment Timeline (Masetti M. , 2019)

2.2 Ground Segment

The ability to communicate and send scientific data to the Ground Segment is critical to the ability for the system to perform its mission. Otherwise, the Observatory might as well be, as Kira Abercromby, Professor at Cal Poly San Luis Obispo would say, "space junk." In order for the JWST Observatory to be useful, it needs to be able to have two-way communication with Earth so that users can send commands to the observatory as to which objects to observe and the Observatory to send the science data to the users. There are three flavors of data that is sent between the Ground Segment and the Observatory Segment. The first is science data from instruments on the Observatory which is sent to the Ground Segment. The second is telemetry consisting of health data of the Observatory, also sent from the Observatory to the Ground Segment. The last data flavor are commands used to control the Observatory Segment from Earth, sent from the Ground Segment to the Observatory. In order to create a proper communications interface across such long distances such as those between Earth and the Observatory, units dedicated to Radio Frequency (RF) communications are employed such as antennas and amplifiers as part of the communications subsystem. RF communication converts information into non-visible light wave patterns and then back into information via antennas to collect the signal. Specialized hardware and software are employed to interpret the signal into information useful to humans.

2.3 Space Environment

Among other things, the Observatory must be able to withstand the heat, particulate, and radiation environment. The space environment forms another boundary to the JWST Observatory must be able to withstand the environment that it is put in. For the JWST mission, thermal, radiation, and particulate concerns are of particular interest. JWST also contributes to the surrounding environment in the form of heat from electronics and outgassing. There are several known forms used to diffuse or add heat to a system such as heat pipes and cryo-cooling. Heat can be added through resistive or passive heating. Radiation cannot be prevented but can be mitigated through rad-hardened parts and soft correcting software. The particulate environment is especially difficult to mitigate. Special care of the architecture must take this into account. There is no current technology employed to completely mitigate particulates but are typically avoided via avoidance maneuvers. Recently, armor plating has also been deployed to help with protecting the spacecraft. Armor also helps protect the spacecraft by allowing smaller particulates to hit the spacecraft without damaging the payload. Heat pipes and cryo-coolers work in similar fashions in that it transfers heat from one area to another. Rad-hardened parts are specially designed to withstand the effects of radiation through materials and coatings. Software also helps by detecting bit flips and correcting for them. For particulates, orbit selection and making necessary orbit maneuvers help in mitigating particulates that could potentially harm the spacecraft via impact.

3 Key Tradeoffs

There were a number of key tradeoffs for the James Webb Space Telescope. These tradeoffs outline a process of questions asked, options generated, and decisions made. Each of these architectural decisions carry a fundamental impact on the system cost, schedule, and complexity that are also considered when analyzing the options and making decisions.

3.1 Mirror Size

One of the major architecture decisions for NGST (renamed to JWST in 2002), is size of the primary optical element as this decision defines several parameters of the architecture. There is a direct relationship between the diameter of the primary optical element and the resolution of the data gathered along with its cost and complexity. In order to make this decision judiciously, it incorporated the heuristic: **"Aid human decision making by recognizing that individuals will often make decisions that 'satisfice' rather than optimize."** In the concept development phase, several different diameter sizes ranging from 4 to 16 meters were proposed for NGST. Garth Illingworth, the Deputy Director of the STScI, notes however that in the 1989 STScI workshop, it was determined that anything less than 6 meters would only be a "modest gain over Hubble and gave low resolution in the mid-IR" (Illingworth, 2016). However, another study in parallel for the successor to Hubble recommended that NASA should develop a 4-meter diameter telescope (Dressler, et al., 1996). This recommendation that would have just sufficed was met with backlash in the 1996 American Astronomical Society (AAS) meeting by those who would rather optimize the telescope's diameter instead of making a relatively small improvement from Hubble's resolution. Finally, a diameter range of 6-8 meters was selected as the diameter range for requirements (Illingworth, 2016).

3.2 Sensor Suite

Another architectural trade that would have major impacts to design and architecture is what sensors suite to include in the payload of the Observatory Segment. To help with this decision making, a heuristic was used: **"A model should be only as complicated as needed to answer questions associated with a particular engineering phase or stage**

in system life cycle." Between 1989-1992 the NGST was included into the Astrotech 21 program designed to identify needed technology for future programs including NGST. In March of 1991, the modeling of the contamination environment showed that the cooling required to achieve high resolution IR would be extremely difficult to achieve UV capabilities due to the fact that cold environments attract contamination. Because of this early modeling, it was decided that NGST would be first and foremost an optical IR telescope (Illingworth, 2016). It is important to note here that there was no further modeling of the structure, optics, cooling mechanisms or the like in order to achieve this study. Adding additional complexity to answer the question of contamination environments would have muddied the ability to make a clear, architecture altering decision.

3.3 Space/Ground Observatory

Another architecture altering decision is the determination of whether the observatory would be on Earth or in space. The decision between a ground-based telescope system and a space-based system would be determined primarily based on performance. For years, diffraction limited observations with extremely fine resolution drove space telescopes so that they would not be riddled with atmospheric distortion and weather-related availability issues. Many supportive of a ground observatory architecture would argue that modern adaptive optics and laser compensation techniques negate the need. However, a ground system would not be feasible in order to get the field of view that would provide the data necessary to answer the scientific questions posed by the mission (Masetti M. , 2019). Thus, a space observatory architecture was chosen. This initial architectural design decision affected further design elements in the architectural trade space. For example, the stability of the spacecraft is vital to maintaining performance and resolution. In order to achieve the stability, a particular orbit, known as the L2 Lagrange point was chosen in this architecture. Furthermore, propulsion was added to the architecture in order to maintain this orbit of relative stability.

3.4 Launch Vehicle Selection

The selection of the launch vehicle is the defining factor of one of the major three segments of the JWST architecture. In fact, this decision was so critical that programmatic schedule delay occurred due to the extra time it took the customer to decide on a Launch Vehicle. First, there is a fundamental option that needs to be considered for launch vehicles. That is, whether to choose an existing launch vehicle architecture and integrate it into the larger JWST architecture, or to develop a new Launch Vehicle (LV) design and architecture specifically for JWST. Because the JWST Observatory is an extremely significant payload and there is a history of potential launch failures with any launch system, an existing architecture with proven flight launch heritage was chosen to minimize the risk of a failure at launch that would destroy the mission before it even begins. After the option for a pre-existing launch vehicle architecture was chosen, the task of choosing which launch provider becomes a significant task. Ultimately, the Ariane 5 LV and associated architecture was chosen for its no cost exchange of services and partnership with the European Space Agency (ESA) as discussed in Section 4.2.2.

4 Stakeholders

Throughout the long life of the development of the JWST there have been several stakeholders. The inclusion of stakeholders and their needs are critical to the validation of the system. If stakeholders are not included, the system will often be different than what the customer actually wants as well as miss opportunities for optimization and cost/schedule reduction. The James Webb Space Telescope has received worldwide attention leading to a large number of stakeholders each with their own interest in the project.

4.1 Political Stakeholders

As NASA (and therefore much of JWST) is an organization run and funded by the United States Government, many of the highest-level stakeholders are political entities. In one instance, during the early phases of NGST (1989), President George H.W. Bush pushed for a lunar based architecture of NGST. Even though the minority of the early study groups were interested in a lunar based architecture, the conference “quickly put a 16-m lunar-based telescope into the baseline discussion.” This relatively unpopular version of the architecture faded away with the change of administration in the early 1990s (Illingworth, 2016). Currently, there have been a number of Congressional reviews, hearings, and audits on the JWST program due to major schedule and cost overrun, discussed further in Section 4.2.1.

4.2 Science and Astronomy Community Stakeholders

Stakeholders do not only come in the form of those with fiscal or political power. A large undertaking with such scientific discovery potential as the James Webb Space Telescope often gets worldwide attention and interest. Public, civil space programs attract many organizations, educational and professional institutions, and even private individuals to make their voices heard regarding a scientific program with such magnitude. This incorporates the heuristic: **"If social cooperation is required, the way in which a system is implemented and introduced must be an integral part of its architecture."**

4.2.1 US Domestic Science Stakeholders

JWST is an extremely large and complex architecture that requires copious social cooperation in order to complete. Its budget increased from its initial cost of $1.6 billion to well over $9 billion (Dunbar, 2019). As a result, in July of 2011, Congress approved a budget that would eliminate JWST when the program asked for a $6.5 billion budget increase (US lawmakers vote to kill Hubble successor, 2011). This proposed cancelation caused a major backlash from the astronomy community and the AAS released a statement in support of continuing the JWST in an attempt to save it (Fienberg & Marvel, 2011). This cry by the AAS as well as scientists worldwide was heard by Senator Mikulski of Maryland who issued her own statement supporting JWST (Mikulski, 2011). The continuation of the JWST was granted in November of 2011 due to the help of the scientific community’s involvement (Koltz, 2011). Without the funds to support an architecture, said architecture cannot exist. As such, the wider scientific community stepped in to reinforce the social support for the program, thus saving the architecture as a whole.

4.2.2 International Science Stakeholders

JWST is a project that attracts many competing institutions and interests that want time on the observatory. Since JWST is a product of NASA, and therefore a US built telescope, it is reasonable that most observation time would be allocated to US scientists with a large fee demanded for international scientists to gain access to the observatory. This was especially disappointing to the European science community. To quell this, the ESA decided to partner with NASA so that it would be easier for international science stakeholders to acquire precious observing time. Since there are intellectual property and defense restrictions on the Observatory Segment itself, it would be impractical for the ESA to make a contribution within the Observatory Segment. Therefore, the ESA agreed to provide full launch vehicle services in exchange for about 15% of observation time. This "no funds" exchange has proven to be beneficial to both parties in that NASA does not need to pay for a launch provider, further increasing the total JWST system cost, and the European science community gains access to what will be the most advanced space telescope to date (Masetti M. , About: Frequently Asked Questions, n.d.).

5 Conclusion

The James Webb Space Telescope's architecture was designed with the consideration as both a novel program and as a continuation of space telescope heritage programs. The steps taken to construct the JWST architecture helped to ensure that it accounted for all stakeholders involved while using heuristics to guide and justify decisions made. Stakeholders can often come from unusual and unexpected places. The ability to cope with these changes can mean the difference between the success or failure of bringing a program to fruition. Even with the cost and schedule challenges of high complexity scientific missions, the advancement, discovery, and humanistic attitude they provide is often well worth the effort and pains. While JWST was not without its hurtles and challenges, the systems architect knows how to address these in a wholistic manner that maintains its integrity.

References

Bogenberger, B. (2007, October 17). *James Webb Space Telescope Project Mission Requirements Document.* Retrieved June 04, 2019, from https://spacese.spacegrant.org/uploads/Requirements%20Config/JWST%20Mission%20Requirements%20Document.pdf

Feinberg, L., Arenberg, J., Lightsey, P., & Yanatsis, D. (2018). JWST Lessons Learned. NASA.

History of Parasol - Who invented Parasol? (n.d.). (Umbrella History) Retrieved June 19, 2019, from http://www.umbrellahistory.net/umbrella-history/parasol-history/

Illingworth, G. (2016). NGST: The Early Days of JWST. *STScI Newsletter*, *33*(01), 6-10. Retrieved from http://www.stsci.edu/files/live/sites/www/files/home/news/newsletters/_documents/2016-volume033-issue01.pdf

Madni, A. M. (2018). *Transdisciplinary Systems Engineering.* Los Angeles: Springer International Publishing.

Madni, A. M. (2019). Architectire Trade-off Analysis.

Masetti, M. (2019). *About Webb Launch*. (NASA) Retrieved June 02, 2019, from https://jwst.nasa.gov/content/about/launch.html

Masetti, M. (n.d.). *About the Sunshield*. (NASA) Retrieved June 19, 2019, from https://jwst.nasa.gov/content/observatory/sunshield.html

Mather, J. (2006, March 23). *James Webb Space Telescope Project Science Requirements Document* . Retrieved June 04, 2019, from https://spacese.spacegrant.org/uploads/Requirements-Writing/JWST%20Science%20Requirements%20Document.pdf

Menzel, M. T., Bussman, M., Davis, M., Golnik, G., Irish, S., & Lawrence, J. (2010). *Systems Engineering on the James Webb Space Telescope.* Retrieved June 18, 2019, from https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20100026389.pdf

Nichols, J. (2018, September 07). *Could Nasa's James Webb Space Telescope detect alien life?* (BBC) Retrieved June 04, 2019, from https://www.bbc.com/news/science-environment-45400144

Wehnew, M. J., Moses, S. L., Lillie, C. F., & Johnson, E. D. (1998). Next-Generation Space Telescope (NGST) system engineering trades. *Proceedings Volume 3356, Space Telescopes and Instruments V.* Kona, Hawaii.