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EDITED ORAL HISTORY TRANSCRIPT

CONRAD WELLS
INTERVIEWED BY JENNIFER ROSS-NAZZAL
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ROSS-NAZZAL: Today is July 10, 2018. This interview with Conrad Wells is being conducted in Houston, Texas for the JSC Oral History Project. The interviewer is Jennifer Ross-Nazzal, assisted by Sandra Johnson. Thanks again for taking some time, we really appreciate it.

WELLS: Glad to be here.

ROSS-NAZZAL: I wanted to start out by asking you how you became involved with the James Webb [Space] Telescope.

WELLS: Let's see. I got my PhD [Doctor of Philosophy degree] in optical engineering in 2000, and I moved to California to work in the semiconductor industry. As we all know, the semiconductor industry goes up and down, and up and down. I was laid off in 2001 or early 2002, and I moved back to the East Coast. Lived in my cabin in the hills of Connecticut and started looking for a job.

I was also partly on disability as well, having some hand problems. As I went to go find a job, it seemed pretty challenging at the time. I had gone to the University of Rochester for my undergraduate in optics and a master's in optics, and [Eastman] Kodak was hiring in Rochester, New York.

I went kicking and screaming, I would say a little bit. I remember the day of my interview there was an ice storm, but it seemed like a great opportunity. I don't know that they mentioned the James Webb Space Telescope to me, but I joined the company in March of 2003 and was immediately put on [the project].

My first job at Kodak was working on the James Webb Space Telescope. The contract had just been awarded to the whole contracting team maybe six months before that, so it was right at the beginning of the work that Kodak did on the program. Although, as I'm sure others have told you, the development of the technology started a decade or more ahead of that.

Kodak had made mirrors. There was a program called the AMSD Program (the Advanced Mirror System [Demonstration]), which was to build and demonstrate a mirror that could operate in cryogenic conditions. We built a mirror, Ball Aerospace [& Technologies] built a mirror; Goodrich in Danbury [Connecticut] built a mirror.

All these mirrors went to [NASA] Marshall Space Flight Center [Huntsville, Alabama] to be tested in what was originally the cryogenic vacuum chamber developed for the AXAF, the x-ray telescope, the Advanced X-ray Astronomy Facility [later renamed Chandra X-ray Observatory]. Kodak actually was the prime systems engineering team on [the AXAF program].

I joined the JWST [James Webb Space Telescope] program right at the beginning, and it remained a fantastic job. I got to participate in the early concept development for how we were going to put this telescope together, as well as how we were going to test the telescope. The beginning of a program like this is a period of discovery, which is a fantastic period.

You get to take the concepts that people developed in the proposal phases and some of the early phases and try to turn them into reality. Some of them can be turned into reality, some of them can't, and you have to solve all those problems. That was a great opportunity to develop the metrology [that was needed to make the telescope a success]. I'm a metrology engineer, I use the science [of metrology]. Metrology is the science of measurement, so I use optical measurement techniques to accomplish things that you need to do.

For example, we needed to put the mirrors together, and we had to put them together to tolerances of half a millimeter or better. If you think about that, that's the size of your pencil lead. We had to place these mirrors onto a structure to an accuracy of a pencil lead. That's pretty challenging to think about. I worked for years with Ball Aerospace and a great team of engineers there to come up with ways to put metrology targets onto the mirrors, so that when we [could] mount them and we could measure them [to make sure they were in the right place].

ROSS-NAZZAL: To make sure it had met that requirement.

WELLS: To make sure that it met that half a millimeter, or one pencil lead, kind of tolerance. In reality, if that's the whole tolerance, you need to do it much better than that. We were really trying to have the knowledge of how well we placed them to one-fifth of a pencil lead—100 microns, which is four-thousandths of an inch, 0.004 inches. That was our tolerance for trying to measure [the placement of each mirror].

And we did it; we did it successfully. Those concepts were probably developed in 2005 timeframe and then eventually were used in 2014, '15 and '16 to assemble what was an engineering model of the telescope that's called the pathfinder, as well as the flight telescope. I got involved in it in 2003, and that's been my career for the last 15 years.

ROSS-NAZZAL: Walk us through that process of trying to align those mirrors and get them within those tolerances. I imagine you were starting off with models. How did you all work together? How did you go from a concept to actual flight hardware?

WELLS: I think one of the most important things in a large science project like this is incremental steps. You don't go from the concept to doing the flight mirror. You go in small steps and small demonstrations.

We used something called a laser tracker, which is built by some Swiss engineers, a company called Leica [Geosystems AG]. They basically make laser ranging systems. You can measure the distance to objects to tolerances [below] 100 microns, a tolerance of one-fifth of a pencil lead. That was our metrology technique, and we worked with Ball over the years to figure out how we were going to integrate, how we were going to put targets onto their mirrors.

As I mentioned earlier, there was a competition to see who was going to make the mirrors for this program, and we made one out of glass. Another team made one out of composites, carbon fiber composites, and Ball Aerospace made them out of beryllium. Beryllium ended up being the right choice for the program.

The fortunate thing about making a mirror out of metal is that you can machine features into it. You can't put threads into a piece of glass, but you can put threads into a piece of metal. We, by working with the Ball engineers, came up with targets that we could put into the sides of the mirrors and very accurately place them with very good tolerances. That allowed us to be able to measure the mirror itself. That gave us something on the mirror to measure.

One of the other challenges in a program like this is it's incremental, and different portions of it are being worked on at a given time. The mirrors were the longest lead-time.

Often the primary mirror in a telescope is what takes the longest to make. Maybe it's the hardest, maybe it's not, but it definitely takes a long time to make it. They had to finalize the design for the mirror well before a lot of the other subsystems were fully defined. They came up with a very simple interface, which was a parallel plane—two [planes essentially one on the mirror and one on the backplane that we mount the mirrors to. There were three pads on the mirror and three on the backplane that needed to be mounted together.]

Basically the feet of the mirror, [there] were three feet. They were about one-inch by three-inch. Those had to be mounted to a one-inch by [three]-inch [matching] interface on the backplane. It's very easy from a design standpoint perhaps, but from an engineering standpoint of putting something together, it's a horrible interface.

ROSS-NAZZAL: Why is that?

WELLS: Because if the two planes aren't parallel to each other, when you bolt them together you're going to strain [them]. You're going to bend them. You might bend the mirror; you might break delicate flexures. You're going to add strain to the system. One of the things that we had to do was to mount these mirrors with no strain. Strain is if you are bending an object; there's built-in strain.

We had to then measure both sides of these two planes that we were going to mount together. We had to measure both sides of them and come up with a compound shim, basically like a wedge, to put these two mirrors together. That wedge needed to be accurate to even a smaller number now. That needed to be accurate to half of a thousandth of an inch, something like 12 microns. We were at a 5th of a pencil lead, now we're at a 20th or a 50th of a pencil lead.

Of course, we realized that probably a little further into the program. That was one of the real challenges, measuring all these things. That's where I got involved.

Another challenge was, "How do you handle these mirrors?" You have a mirror that's 1.3 meters, which is about four feet, four-and-a-half feet. It's not as fragile as glass, but you certainly couldn't drop it or bump it. We had to be able to place those onto this 24-foot, 6-and-a-half-meter structure one by one. The way to do that was basically by making a robot, a gantry crane, that would place the mirror in its place. It had to hold it there to half a pencil lead or better, or a fraction of a half of a pencil lead. I had to work with a team of mechanical engineers coming up with those concepts, and I had to make sure that those concepts were consistent with being able to measure the final mirror position.

Back to the incremental pieces, that system consisted of a gantry, which is kind of like a building frame, with a crane that went back and forth, with a robotic arm that came down to hold the mirror. We tested that robotic arm by itself first. The reason you do the test is because you have to see if the design works, and the initial design didn't work. These mirrors are at a slight angle—six degrees, nine degrees—for the different mirrors. As we held it in place, it slid with the gravity. These weren't mirrors. These were metal simulators.

ROSS-NAZZAL: Right, you weren't working with original hardware doing this.

WELLS: Right, this is well before the mirrors were done. [This was] incremental testing. We tested with these full-size, same-weight simulators of the mirrors and found that this design didn't quite work because the mirrors were sliding. They did some redesigns, and I think we did two rounds of testing to make sure that that concept would work.

A crane and metal fabrication company in Rochester, New York, built this gantry system. It was installed inside a big clean room, a 100-foot by 100-foot clean room, at NASA Goddard Space Flight Center [Greenbelt, Maryland] called the SSDIF (the Space Systems Development and Integration Facility), I believe.

And then demonstrated again. Once we installed it there, before we worked with anything else, we did another demonstration and were basically successful. I think we had to design some additional jigs to hold the mirror so that it didn't drift while it was being glued. Essentially we would put the mirror in place with this compound shim, but then we would add some epoxy to take up any gap in that shim. There'd be this 12 microns, a very small gap, that we would fill with glue. We would let that cure before we would bolt it down, and we'd be measuring this during that whole process.

That was done for two mirrors on what was called the pathfinder telescope, which is a two-mirror version of JWST. We integrated the mirrors onto that system. That system eventually was brought here to Johnson for testing, and we were able to use that telescope to again incrementally—when I get to talking about the things that we did here, it's all incremental. Everything is incremental in the development of a complex system.

ROSS-NAZZAL: You mentioned that the measurements were just a huge challenge. I'm guessing somebody reading this is going to think measurement like taking a tape measure and measuring. Can you talk about those challenges? You've made it quite clear with the pencil lead and the size, you're not talking about a lot of wiggle room.

WELLS: Right. Any precision system, even when you send something to a machine shop, you have tolerances. They have to measure things with a micrometer, which is kind of like a ruler. Those can measure to a thousandth of an inch, or maybe if they're very good they can measure to half of a thousandth of an inch. But that's measuring something that's handheld kind of size. Once you need to measure something larger, you need something that's stable enough, first of all, to make that measurement. We use something called a coordinate measuring machine (a CMM), which are very accurate systems for measuring three-dimensional objects.

Again, it consists kind of like a gantry. Trying to think of an analogy here. It would be like an overhead crane. If you think about an overhead crane in a building, that's basically what a CMM is. You can buy them in a one-meter size. We probably had one that was about two or three meters. We had to measure all the features on the mirror to accuracies of half a thousandth of an inch, and these coordinate measuring machines can do that.

You have to keep the temperature stable probably to a degree or better, half a degree or better, because things will grow due to change in temperature. As things get warmer, typically they get larger. The mirrors were measured, the side holes on the mirrors were measured, the feet of the mirrors were measured, and some datum structures on the mirrors were measured.

If you go all the way back to when the mirrors were made from beryllium powder, they're hot-isostatic-pressed into a metal block, and then that metal block is machined to a blank. Then it's ground, and it's polished. It's tested and polished more, and tested and polished more. Through that process, a coordinate measuring machine is used to measure the features on the mirror so you know essentially where it's located in space.

Laser trackers, these time-of-flight laser-measuring machines, also were integral to every portion of the program. A laser tracker can measure things over a 60-meter range, if you're out that far, to accuracies of a handful of thousandths of an inch. Short range, in a 10-meter by 10-meter by 10-meter volume—if you put multiple ones in a space, you can measure to a thousandth or half a thousandth of an inch.

You measure the mirror by itself to understand what the mirror looks like, and then the backplane has these three parallel one- by three-inch interfaces that we had to measure the angle where they are in space. The mechanical engineers and myself developed a jig that would sit just like the mirror would sit and had probe tips that measured in four points on each of these one- by three-inch interfaces. These probe tips would go down and measure the location of that plane. For every mirror we had to do that. That would help determine the thickness and angle of each of these compound shims that had to be manufactured.

You've measured the mirror; you've measured the backplane. The backplane also had a metrology feature on it that was called the AMAF [Ambient Mirror Alignment Fixtures], a metrology fixture that basically defined the coordinate system of the telescope. We had to measure each mirror. This fixture that we were measuring each interface with, we had to measure that to the telescope coordinate system.

Eventually, once we put the mirror on, we measure that also to this coordinate system, using maybe three or four laser trackers placed on this gantry system. You would measure targets from a variety of locations to get higher accuracy. If you use just one laser tracker, you get a certain level of accuracy.

The more measurements you make, the better they are. The statistics of measurements tell us that the more measurements you make, and if you average them, you get a more accurate result. Hundreds of measurements were made as we integrated it to make sure that it was in the right location. There was a lot of crosschecking.

Kodak, which eventually got sold—

ROSS-NAZZAL: I was going to ask about that, yes.

WELLS: I started with Kodak [Remote Sensing Systems Group], and then in 2004 or ’05 they were purchased by ITT, the old International Telephone & Telegraph, which wasn’t in the telephone and telegraph business anymore. They were an engineering company. They were purchased by ITT. Many companies these days are coming together and forming bigger companies.

The corporate management at ITT decided to split the business into three: a defense business, a water business, and then all the other engineering businesses. ITT remained as one of them, and they sold the other two businesses. A water pump business, which actually has a lot of business here in Houston and the South dealing with floods and flood mitigation. They build big water pumps for places like New Orleans [Louisiana], for example.

We were bought by ITT, and then ITT spun us off and sold us. We were the whole defense business, which included other locations besides Rochester. They made night-vision cameras in Roanoke, Virginia, they made weather satellites in Virginia, and in Rochester we made space telescopes. They sold that whole defense business and their other communication businesses, spun it off, and it was called Exelis. About five years later Exelis was bought by Harris Corporation, which is larger. We were split into a smaller company and then absorbed by a larger company, Harris Corporation, which has a big defense business portfolio. So now we are the Harris Corporation.

ROSS-NAZZAL: I have to ask, being a contractor myself. As you shift companies, of course you change badges and retirement plans, and health benefits change and things of that sort. But there's also a culture attached to each of those organizations. Was that a major shift? Or were you just so involved with the project you were working on that it really didn't have much effect on what you were doing?

WELLS: Yes, I don't think it affected the program per se. It affected maybe the level of support.

When they got spun off into Exelis, their whole goal was to actually get absorbed by another company in the future. You can imagine that the senior managers' bonuses and pay structure—when they get bought out, they're going to make a lot of money. So they trimmed everything down in the corporation to make it look lean and operate very well from a financial perspective. Much of that now has been completely undone by Harris, because it wasn't a very good way to work really. But I don't think that affected the program. Maybe it affected a little bit of how we were supported, how well we were supported, by the company. From a day-to-day perspective, we were not affected.

I think we've covered a lot of this mirror integration. I actually ended up—in about I'd say 2009 or '10, I had to make a choice to stay either with the integration team and work with building the telescope, or to work with testing the telescope, which we'll get to eventually. I chose to stick with the optical testing that was going to happen here at Johnson. As a result, other engineers took my role there and brought it to the end. I was cognizant of what was going on and called in every now and then but wasn't involved in it on a day-to-day basis.

In the end when they were integrating the 18 mirrors, by the time they finished, I think they were integrating a mirror a week, which is really pretty amazing. I think it probably took a month the first time we did it, with all the crosschecks. Or maybe three weeks it might have taken to do it, and they got it down to under a week. I don't know, maybe Gary [W.] Matthews might have told you. He certainly would know that number off the top of his head.

Again, it's all this incremental process. We tested the hardware along each step of the way and did measurements. There were a lot of crosschecks. One of the things that NASA is responsible for on these large programs is to monitor the contractor team, so they cross check our work. Almost ad nauseam, there's a lot of crosschecking.

Every measurement that we did, they repeated the measurement, [and they] certainly repeated the analysis. Their analysis team provided a lot of help to cross check our work and to supplement our work—the team at Goddard—and actually did some of the labor to help put the telescope together.

ROSS-NAZZAL: You've talked about Ball Aerospace and of course Goddard. Would you talk about how you all came together to work on this integration? Did you spend much time at Ball Aerospace? Did you spend a lot of time at Goddard? Or were you primarily working out at Rochester?

WELLS: I was working in Rochester. Northrop Grumman in California, which at the time was TRW, were the winning team. The two main players were Ball Aerospace, which was the telescope designer and telescope systems engineers, and Northrop Grumman was the prime contractor responsible for the spacecraft and for the backplane. Although they subcontracted that out as well to ATK [Alliant Techsystems] in Salt Lake City, [Utah, and now NG owns ATK].

I wasn't involved in the proposal process, but as I mentioned, there were years of development of the individual technologies. Right now there's something called the decadal [study]. NASA scientists and astronomers—every 10 years they come out with a recommendation for what the next space telescope should be and their recommendation to NASA of where they should be spending their money.

Probably in 2010 it was a dark energy mission, which ended up becoming the WFIRST telescope (the Wide Field Infrared Survey Telescope), a donated telescope from the NRO (the National Reconnaissance Organization) to NASA, which was located in a clean room in Rochester, New York, at Harris. That was their recommendation, and now that's a program that's just about to fully start. But the technology development has been going on really since 2010.

The next recommendation is going to be for a planet-finding mission. Right now we're working on the technologies that will be needed for a telescope that probably won't even start until 2030 or something. I wasn't involved in it, but I'm sure that for a decade or two decades, the work to develop the technologies that were needed for JWST was being done by all the contracting teams in the Phase A, Phase B, Phase C studies.

Another reason that there are so many companies involved—if you look at a map, they definitely spread across the United States. It is important for NASA to get the support of Congress to make these large telescopes work. Spreading the work around, both from a technical perspective—Kodak was very good at building telescopes. We know how to put things together very accurately. Bringing us on to a team was a smart thing to do, but it also brought the New York congressional delegation to support it.

Ball Aerospace is a very good telescope system engineering and design corporation. They came up with the basic concept of an adjustable telescope. The James Webb Space Telescope has mirrors that can adjust to compensate for other manufacturing tolerances. We were putting these mirrors together to a pencil lead, but once they're being used in space, they're phased to an accuracy of one-ten-thousandth of a human hair. You're going to a whole 'nother level of accuracy. Instead of having to make a large mirror to those tolerances, the Ball Aerospace concept was to make a segmented telescope where each mirror is that accurate and you use actuators to place them in the right position. They brought a lot of technology, the actuators to accomplish that, the optical designs and systems engineering to make the telescope work.

ATK brought some amazing carbon fiber technology to the program. It had to be able to survive from ambient conditions to 20 degrees above absolute zero—minus 459 Fahrenheit, something in that range. They brought that technology. There were machining companies that brought the machining technology to be able to make the mirrors.

You can go back all the way to the people, Brush Wellman, who mined—or maybe someone else mined it, but they made the blanks with the beryllium powder. No individual company has all the technologies to make it work. The team of companies brought together by Northrop Grumman had all the skills needed to do the work.

You asked where was I located. It's a long story to say we had a lot of phone meetings. Most of what we did involved teleconferences. Back to the beginning of the program, the period of discovery that I mentioned, every week there would be an architecture-working group of the whole team talking about different trade studies to bring the telescope to a baseline design.

Before you go and do the detailed design, you need a baseline concept that everybody agrees that's the way to go forward. There are probably models and analysis that is used for each of those individual pieces—the backplane, the mirrors, the electronics, the instruments, the methods of putting it together, the methods of testing. Every week for the first couple years we were deciding a lot of those trade studies. There were a lot of phone calls, and yes, we would also travel.

I traveled out to Boulder, Colorado [Ball Aerospace offices], which was always a nice place to go from Rochester, New York. Went out there quite a lot to work face-to-face with the engineers on test concepts. Talking with them face-to-face about, "Okay, how are we going to mount these things to the side of the mirror to be able to measure?" I went to Ball Aerospace a lot, and then there were meetings at Goddard Space Flight Center fairly regularly as well.

Most people are probably aware that the Hubble Space Telescope had a failure in its primary mirror when it was put in orbit. Kodak was one of the teams that bid the Hubble Space Telescope as well, and we made the backup mirror for the Hubble Space Telescope that's now in the Smithsonian [National Air and Space Museum, Washington, DC]. We have always believed strongly that you need to do an end-to-end system test. If you don't put light through the telescope, you're not really sure, positive that it's working correctly.

The Hubble Space Telescope was not tested end-to-end on the ground, so there was an error in the testing of the primary mirror that caused really almost a little bit of shame on the country. We spent all this money on this great telescope and put it up in space, and it was blurry because the primary mirror was figured incorrectly. It was figured incorrectly, perfectly. It was perfectly wrong, so they were able to fix it.

They used something called wavefront sensing and control. If you look at a star, which is a point source—you look at the blur of that on the detector, and you can analyze that blur to actually characterize the wavefront of the telescope. Wavefront, it's a hard one to—let's see. When an image comes and it's blurry, there are errors in what we call the wavefront. What you want is a nice spherical wave. A spherical wave comes down and focuses perfectly. If there are errors or little bumps on the mirror surface, you get variations in that perfect sphere. In the case of the Hubble, what it actually was, it came back as a parabola instead of a sphere and they were able to correct that.

They had a team of retired optical industry professionals, university professors, and space science principal scientists from other programs. People from the Spitzer [Space Telescope] program, which was the infrared space telescope program, people actually from the Hubble review board.

Every year, or sometimes twice a year, we had to present our designs and our concepts—not from a mechanical perspective, but from an optical perspective—to this board. My PhD adviser, Jim [James C.] Wyant, was on the board and a number of my professors. Actually, both of my advisers from graduate school, Jim Wyant and Jim [James H.] Burge, were both on that board. I knew a number of the people on the board. They were a tough set of reviewers. I had to convince them that my metrology concept for putting the telescope together was valid. When we get to it, I had to convince them that our concepts for testing the primary mirror were valid. I think I missed the first two meetings perhaps, but we've been meeting with them for 15 years on this program. I think there were something like 24 meetings.

The real purpose was to make sure that we had the crosschecks and the testing plan well thought out so that we wouldn't have another Hubble Space Telescope. We did put light end-to-end through the telescope here at Johnson. I think we know we don't have that type of error.

The flexible concept for this telescope—because it's segmented, you can move the mirrors. If you have a Hubble-like error in this telescope, you could actually compensate it to a large degree. It wouldn't be perfect. I don't remember the exact number, if it's 75 percent of our performance—it would impact science, but it wouldn't be as much of a failure as there was on Hubble, because this flexible architecture can compensate for a lot of problems.

ROSS-NAZZAL: You mentioned all these review boards, you've got NASA—

WELLS: Right, review boards and the team. You asked how we ended up with this large team and where we worked. There were a lot of meetings, a lot of phone meetings, a lot of meetings at Goddard. Everybody would come together there, as well as trips to Ball Aerospace.

I didn't go out to California [Northrop Grumman offices] very much. At one point, in approximately 2010 or so, NASA decided to take charge of the cryogenic testing. We were working for Northrop Grumman designing the test program here, and they were in charge of that testing. In roughly 2010 or so NASA decided that they would take that over, so we worked directly with NASA at that point, which worked very well.

Either way it would have worked very well, but it definitely created a very good communication between NASA (the customer) and ourselves. We still leveraged a lot of the technologies that Northrop Grumman was able to bring to the table. One that we'll talk about in the future I'm sure is photogrammetry, one of the technologies that Northrop brought to the test here at Johnson that was really enabling for the program.

ROSS-NAZZAL: What attracted you to the testing side? You said around 2009 you had to make this decision, you could go one path or the other. You decided you would go down the test path. What was so interesting about that to you?

WELLS: By that point, putting the telescope together you might say was a simple task in comparison to testing it. It's certainly more glamorous to do the testing of the telescope in cryogenic vacuum conditions. It uses something called interferometry to measure the primary mirror, and that was what my dissertation was on. It's one of my specialties.

I think I left the team putting the telescope together in very good shape, and made the choice to do the more challenging, more glamorous thing. Knowing that I would have to move to Houston, Texas, which provided a lot of consternation to me and my family at the time. We really weren't sure that we wanted to do that, to pick up and move here.

The only time I had ever been here, I came out for a PIT (the Product Integrity Team) meeting here one year. I remember driving from the airport. At the time I [Interstate]-45 was just a construction disaster, and that corridor of Houston is really ugly.

ROSS-NAZZAL: You flew into [William P.] Hobby [Airport]?

WELLS: From Hobby. Just coming from Hobby to here, I was shocked. "Oh my god, I'm moving to this place." In the end we like it here, and we're staying. So yes, I decided to go with what was more challenging and more glamorous and where I could have I think the biggest impact. It would last longer. The telescope was being put together in probably 2016 or so. Although actually if I had done that first half, I probably would have been put on the second half anyway.

ROSS-NAZZAL: When you came down, what state was the SESL at that point? What did it look like? How did you start coming up with these plans for the test?

WELLS: What is SESL?

ROSS-NAZZAL: That's the Space Environment Simulation Lab. That's [JSC] Building 32. I don't know how you guys refer to it, but that's what we call it.

WELLS: Building 32, yes, okay, Chamber A. As I mentioned, there were a lot of mechanical engineers. I was responsible for trying to figure out how to test the primary mirror.

Other people had to figure out how to support it, and how to get it cold. I maybe would consult on those, but that wasn't my expertise. There were mechanical engineers and thermal engineers working for years with the team here at Johnson. We had our critical design review for all of our equipment in 2009, and by then we were already coming here. I'm sure the work here was going on for a long time already.

When I came here in 2014, they had already tested the chamber. Again, it was an incremental process. They modified the chamber with the helium shroud, a new helium system, and an upgraded liquid nitrogen system. There's a three-quarter-megawatt compressor for the helium system. I always find that a very impressive number, three-quarter-of-a-megawatt compressor.

The chamber had been tested by itself. It had been baked out. One of the challenges in these programs is cleanliness. We can talk about that some time. They had done a number of cryo [cryogenic] tests to test the chamber and had tested some of our hardware. You have to do survival tests of all your hardware to make sure that they survive, so I think they had put some of our hardware in the chamber and done a test. When I got here they were building the final configuration.

Talking about metrology and putting things together, another plan from a metrology perspective that we had to come up with as a team was to figure out how to put this test configuration together. The chamber is 120 feet tall by 60 feet. It's huge. I can't remember all the dimensions—60-foot door, something like that—but we had to put all of our hardware in there to accuracies of, in some cases, a pencil lead again, a pencil lead, or two pencil leads, or a quarter of a pencil lead, somewhere between 250 microns, quarter of a millimeter, and a millimeter. We used laser trackers again, and all of our mechanical hardware had interfaces for putting something called an SMR (a spherically mounted retroreflector).

Back to when we were putting the mirrors together, I talked about this laser metrology. What it does is it measures the time of flight to a little corner cube, which is this spherically mounted retroreflector. We had to mount those in a variety of locations in order to put the system together. When I arrived, they were in the process of starting to put that whole system together.

The first thing we had to do was to put together what's called the Center of Curvature Optical Assembly (the CoCOA), which is our very complex, fantastic piece of optical and mechanical and thermal hardware that was used to test the primary mirror. I worked to put that together and to pretty much lead [the effort], because sometimes it was hard to get people from Rochester to travel to Houston. I lived here, and there were other programs going on at Harris. Sometimes getting people to travel when you actually don't know the exact schedule that well—sometimes they travel and you're not quite ready, and they have to stay longer.

We almost needed a metrology engineer full-time. I was here, and I was able to do a lot of that, so I helped. I did a lot of the metrology of putting the Johnson test architecture together. I wrote the original metrology plans for it. I certainly understood it. I know how to use the laser trackers and do the analysis. A lot of times I was called upon to do that work, and it was enjoyable. It was long hours, but rewarding and a lot of fun too.

The chamber was all done, and everything was working from a chamber perspective, and we had to integrate our test architecture. The James Webb Space Telescope observatory consists of the telescope, what's called the OTE (the Optical Telescope Element) and the science instruments, the Integrated Science Instrument Module that gets mounted to the telescope.

That was another integration that was done in SSDIF at Goddard to accuracies of less than a pencil lead. It's a carbon fiber box that's about two meters by three meters, held on six points. From a mechanical perspective you want to mount things kinematically, which means you don't overconstrain them.

For example, a table. When you put a table on the floor, typically one of the legs is going to be short and it's going to sit on three points. An object will always sit on three points well; it can be supported by three points. If you add a fourth, a fifth, or a sixth it's not going to sit in a strain-free fashion. Everything is mounted to three points, and often then you can take those three points and split them off and turn them into six points in a hexapod arrangement.

That is also a strain-free, kinematic method of holding an object. In the telescope the science instruments were held by six struts, and the telescope inside the chamber is held by six telescope rods, and the mirror is held on to its support frame and controlled by six motors in a hexapod arrangement. So the hexapod and a kinematic mounting is all over the program.

We had to figure out a way to test this telescope optically. The original plan called for a center of curvature optical test. All primary mirrors are tested with a center of curvature optical test. You shine light from a point source at the center of curvature, and it goes out to the mirror and it comes right back. If it's a sphere that's a very straightforward process, but the primary mirror is an asphere, it's aspherical. It isn't a perfect sphere, it's very close to a parabola.

The test consisted of a center of curvature test to test the figure of the primary mirror. As well as, originally, an interferometer behind the telescope that would shine light through the telescope, and that would come back to the interferometer. That's called an autocollimation test. You basically start with a point source behind the telescope, and it ends up collimating to infinity as though there were a point source at infinity, and then it comes back. It's kind of like simulating the imaging of a star.

ROSS-NAZZAL: How do you do that in a confined space with a chamber?

WELLS: That's a very good question, right. We were challenged. We had this concept—in addition, this interferometer that I just mentioned isn't cryo-compatible and it's not vacuum-compatible. This interferometer is mounted in a pressure-tight enclosure with other optics to help image things properly.

The original test concept called for something like six points behind the telescope. We would put six different cones of light through the telescope to test it over its field. A telescope might be perfect at one point in the image, but you need to test around the whole image to make sure that it's not just that one point. The telescope could be aligned such that it works perfectly at one point, and it's really blurry elsewhere so you need to test over the whole focal plane, or some region of the focal plane, to make sure that there aren't aberrations, that the wavefront is good. We had something like six cones of light going through the telescope, which meant we needed holes through the instrument and electronics package. And we needed a very, very complex optical system at the bottom of the chamber, which was housed in what we called the lower pressure-tight enclosure. Up above, there was an upper pressure-tight enclosure.

In roughly 2008 or so, it became very clear that this baseline concept for our optical test was extremely technically challenging. The probability of it working the way it was engineered was low, and the cost was exceptionally high. You have a meeting of the minds. That assessment basically came to NASA, through all of us, that this is a lot harder than we thought it was going to be. This concept is very expensive and possibly flawed.

NASA started something called the TAT (the Test [Assessment] Team). It was a review board of people external to the program looking at it from a technical, financial, programmatic, schedule perspective. It was acknowledged that this isn't feasible, so we had to think out of the box. We had to say, "Okay, this original concept that we had isn't really the way to go."

We had talked about other concepts, but when you're moving in a given direction it's hard to change direction unless something really happens. And that really happened. We were in a box and we didn't fit into the box, so we had to think out of the box. A team of people—which in this case did not include myself—met in a room and met over the phone for, I don't know, a couple weeks or so and hammered out what ended up becoming the final test configuration.

I think a lot of those concepts had been brought up, as I mentioned, during the test. They were different than the baseline, and sometimes people don't want to change things until it hits the fan. We went to a whole new test concept. Originally, the telescope was being held rigidly on the floor of the chamber. Things were mounted to the chamber itself.

I was really worried that the vibration was really going to be a problem, so to solve that we decided to support the whole test configuration the way in which we support all our telescope tests in Rochester, which is from above on a set of cables. Basically, from the top of the chamber you support the whole payload and all your optical equipment on six telescope rods coming down. We had vibration isolators at the top that actually would reduce the effects of vibration. That was the biggest mechanical configuration change.

The other thing we got rid of was these focal plane interferometers that were causing so much problem from cost, schedule—all perspectives. The people doing this design concept said, "Well, why don't we put fiber sources at the Cassegrain focus." This is a three-mirror anastigmat telescope. The primary mirror and the secondary mirror form an intermediate image just in front of the primary mirror, that is then reimaged by the tertiary mirror to the science instruments. By putting fibers at this intermediate image, we were able to essentially shine light off the secondary mirror, the primary mirror, and then up to something called an autocollimating flat—which was already in the plan—and then image onto the science instruments.

We would image just like they did in the Hubble, by looking at the point-spread function looking at the blur of a star image. That's essentially what we were doing here as well. The fiber was a simulated star, and we would essentially image that through the telescope. So the whole telescope was being tested. Very important thing from the Hubble perspective. It also got rid of a lot of the uncertainties due to the interferometry, and aberrations in the interferometer system that could corrupt the measurements. And it used the science instruments themselves to make the measurements.

In addition, there was another path that would shine light downward directly off the tertiary mirror into the instruments, which tested what's called the Aft Optics Subsystem. Again, you had the primary mirror and the secondary mirror create an intermediate image, and it goes through a hole then in the middle of the telescope. It hits the tertiary mirror and then a fine steering mirror, basically a pointing mirror, puts it onto the instruments. The tertiary mirror and the fine steering mirror are mounted together kind of as a box and are really the only fixed optical elements in the telescope itself. The primary and the secondary can align themselves, but the tertiary is fixed. By having a downward source that would test the tertiary mirror, that provided a very good crosscheck of the alignment of the tertiary to the science instruments.

We came up with a test configuration where we supported it from above, and now our center of curvature interferometer was held on the same structure. Which is good, because any vibration or drift, it will drift with the telescope. That was a pressure-tight enclosure, so we did have a large 5,000-pound piece of optical mechanical equipment up in the top of the chamber that would align itself to the primary mirror and test the primary mirror.

That concept pretty much came unscathed through, I'm sure from the Phase A/B study. You do a center of curvature test. It was really a design problem, not a discovery problem, except for the interferometer. Again, we develop the technologies years ahead of needing them, so NASA had been working with a company called 4D Technology in Tucson, Arizona, to develop this very special two-wavelength interferometer.

A normal interferometer, you can’t measure a step. If you have two mirrors next to each other, you don’t really know where they are with respect to each other. You know the figure, how good each mirror is, but you can’t measure the piston between them, the height difference between them. A two-wavelength interferometer allows you to measure that piston.

When a mirror deploys at cryo, it may be misaligned to each other to a millimeter-like tolerance. You need to be able to measure this millimeter to then consecutively converge. Each measurement, you bring them closer and closer until you get these mirrors phased coplanar to each other to one-ten-thousandth of a human hair. Which is 10 or 15 nanometers, that kind of nanometer range metrology.

We now have a test configuration which pretty much stayed the way [we planned] coming out of this TAT review—we had a cost and schedule problem, and that was actually over the entire program. I guess this was probably 2008 or so, because the whole program had some cost and schedule problems. At that time we changed the test configuration, and it pretty much stayed that way for the rest of the program, supporting it from above. The telescope is supported on a big metal frame down in the bottom of the chamber that is also supported on these rods. Up in the top of the chamber is the center of curvature interferometer, and some structure that holds that. Again, that’s all held by six vibration isolators in the top of the chamber. That ended up, in the end, meeting the requirements that we needed to meet.

The goals of the optical test here—one of the most important things that we needed to do was to demonstrate that you could take these 18 individual mirrors, which had all been tested by themselves, and turn them into a single primary mirror. By doing that, you provide a very important crosscheck that the actuators will have enough range in orbit.

If you were thinking about a Hubble-like error, if we ran out of actuator range in orbit, that would be a real problem. Ball Aerospace, who designed these fantastic actuators that move to nanometer resolution, managed a tolerance budget of these that we would be able to have enough range in orbit. Probably the single most important thing that we had to do was to show that we could phase all these mirrors to a single primary mirror.

Kodak, ITT, Exelis, Harris—that was our job, designing that equipment. We're very good at making primary mirrors and doing optical testing, and we had a great team of mechanical and optical engineers that designed this multimillion-dollar piece of hardware to test the primary mirror. And that had this very critical interferometer inside it a very finicky, very challenging interferometer that did its job. It gave us a lot of challenges over the program.

ROSS-NAZZAL: Can you talk about some of those challenges?

WELLS: One of the design trades that we had to do is, "Where do you locate the lasers?" The lasers are probably, we were thinking, one of the more unreliable pieces of hardware in the interferometer system. The vendor, 4D, wasn't necessarily used to making a highly reliable system. When you build a space telescope, you design things for high reliability.

It became clear that the lasers were probably the short straw there. We pretty much requested the vendor to come up with a way to have the lasers outside the chamber, and have those fiber-fed inside the chamber. In the end, they ended up liking the idea. They actually now have some products that use that same concept. It makes the head of the interferometer smaller, and it now can be fiber-fed and it can be put somewhere else.

Thank God, we did that, because we had a lot of problems with those lasers. There were three lasers in each source module, and we had two source modules so that we had a spare. One of those source modules failed early on in some of the testing and was sent and refurbished with new lasers. Then the other one also failed at one point. It was also sent back. The lasers that were actually used in that were no longer manufactured by the manufacturer. But luckily, the sway of NASA saying, "We need these for the James Webb Space Telescope"—the manufacturer Newport said, "Okay, we'll do a custom build." They built custom lasers for us, which made the test successful. I don't know what we would have done if we didn't have that.

We had a lot of problems with the lasers, maintaining good fringe contrast. We're basically shining a perfect laser beam off of the mirror. When it comes back, you get a pattern of light and dark lines. By analyzing that pattern of light and dark lines, you can measure the surface of the mirror. That's basically how interferometry works.

But you need the laser to be behaving like a good laser. It needs to have good coherence, and that creates the light and dark lines. These lasers at times would come in and out of coherence. It led us to try and change the temperature of the lasers, and to also then, in our processing of the data, throw away images that didn't have good contrast.

We have to measure the primary mirror, and we have to measure where the instruments were located with respect to the telescope. Those are the two important things as far as the system working optically—that this tertiary mirror box that I was talking about, that the instruments are properly located with respect to that, and that the primary mirror works well. That was what we needed to do.

This fiber system allowed them to do wavefront sensing and sense where the instruments were with respect to this Aft Optics Subsystem. Our interferometer would allow us to do the primary mirror test. Our team designed this center of curvature interferometer system with all the features that we needed to align the mirror, different alignment features and a very good optical system.

We used something called a computer-generated hologram. Your Visa [credit] card—that little hologram that you see on the bottom of it, we have something very similar to that. A pattern of circular lines written onto a piece of glass that is used to test our system. The Hubble error was an error in the center of curvature, I didn't mention that. The Hubble error was an error in the center of curvature optical test of the primary mirror.

ROSS-NAZZAL: So you really felt a lot of pressure to get this right.

WELLS: Right. This Product Integrity Team really hammered us on how we were going to calibrate our system and to make sure that we wouldn't have a similar problem. To do that we used a computer-generated hologram to test it. As we built the system, the Product Integrity Team recommended one more additional test that we did in Rochester before we brought it here, and that test was successful as well. We had a really good heritage, good measurements of the system that we were going to use to test the telescope. A lot of companies contributed to this system.

What's interesting—the interferometer has to be kept in an ambient environment, in an air environment. We did have a pressure-tight enclosure in the system that had air coming from the top of the chamber. So we had fresh air coming through there controlling the temperature of that system. We need to remember that this whole optical system is sitting inside of a chamber that's at 20 degrees Kelvin.

The thermal engineers basically designed a thermal system that went around our whole optical assembly to keep it at room temperature. It's almost like we had a little satellite inside the chamber. It had a control system; it had heating panels. It almost looks like a satellite. That was warm, and the rest of the chamber is cold. We're going to hear later what that heat did to the system, and what we found when we did our testing.

Incremental testing, I'm repeating that again. When I first got here and we put everything together, we did a test with our equipment, just our equipment, no other telescope in there. We had a load simulator, basically a block of metal, that simulated the telescope, and we tested our system. That was I think a 30-day test. We brought the chamber cold, and we operated our interferometer, and they tested thermal systems and other things. The thermal, optical, and the dynamics, how much vibration was there? That was the first test. That was called the CCT (Chamber [Commissioning] Test) that we did.

And there's one other—I mentioned that we needed to make sure the primary mirror was right and that the instruments were aligned correctly. Well, we needed to put the primary mirror in the correct location. It's inside this dark cryogenic vacuum chamber. We really don't know where the primary mirror is with respect to the rest of the telescope.

A technology that Northrop Grumman brought to this test allowed us to place the primary mirror in the right location, and that was photogrammetry. Basically photogrammetry is if you have a bunch of retroreflective dots, you take pictures of them with a flash from a bunch of different angles. You can take all those images and process them in software to tell you the three-dimensional relationship of all those dots to each other.

If some of those dots are a calibrated distance—let's say we put some of those on a metal rod, and we measure those in a coordinate measuring machine very accurately. We now can set the scale of those images. Now we know the absolute location of everything in millimeters of all of these dots. Just like we mounted spherically mounted retroreflectors to the sides of the mirrors in order to place them properly, we now mounted photogrammetry dots to the sides of all the mirrors. The James Webb Space Telescope is 18 mirrors, so there are actually 30 mirror edges. If you go around, there are 30 edges on the outside. As one person said, that's a triacontagon.

ROSS-NAZZAL: I would not have known that.

WELLS: It's a triacontagon. There are 30 targets on the outside of the mirror, and then the only thing that's rigid in this entire telescope is this thing in the middle, the Aft Optics Subsystem that holds the tertiary mirror and a fold mirror. That was the coordinate system when we put the mirrors together. When we put the mirrors on the telescope, it was to the center of the telescope.

We put photogrammetry dots on that piece of hardware and were able to then measure where the primary mirror is with respect to that. It would also allow us to determine where the secondary mirror was. Just like the primary mirror actuators have a certain amount of range, the secondary mirror has a certain amount of range. We wanted to make sure that it was in an appropriate place, that once aligned it ended up in a place that made sense within tolerances.

This photogrammetry system allowed us to measure all these dots inside the chamber, and what it consisted of was four cameras on windmills. The chamber is a circular cylinder, and we had four cameras mounted on vertical windmills—just like a windmill actually—and those would take pictures of all these dots from all these different angles. We had four cameras that could change angular orientation as they went around in a circle.

Over a one-hour period we would take 1,100 images of all these dots, which included metal rods with calibrated dots. There's a metal called Invar which is a very accurate type of steel that has a very low coefficient of thermal expansion. We put dots on that, and then we measured those dots, again, on a coordinate measuring machine to handful-of-micron tolerances. There were 16 of those in the chamber and each one of those had multiple dots, so that gave us a way to calibrate the scale of these images.

We were able to measure these primary mirror edge targets, with respect to the center of the chamber, to tolerances of like a quarter of a human hair. It becomes unimaginable that by taking these images, we were able to measure any object inside that whole chamber—and more towards the center we were more accurate. Any object on the telescope, we were able to measure that to an accuracy of something like 25 microns, one-quarter of a human hair.

That enabled us to place the primary mirror in the correct location, or at least to know where it was so that the actuator ranges could be verified. It also allowed us to look at where the secondary mirror was in the testing—once it was aligned, to know where it was to similar-type—maybe to more like 100 microns, because it's 8 meters away. We were able to measure that. That technology was really critical to the testing.

ROSS-NAZZAL: So you tested all of this prior to pathfinder even, which was another test.

WELLS: Right, before pathfinder we tested the photogrammetry system. I ended up spending a third of my time helping with analysis on the photogrammetry system. I don't really run numerical analysis myself. I'm a systems engineer, and I review other people's work and try and understand their work and guide it to the right answer.

In the case of the photogrammetry system, it was always more complicated and nuanced than we thought. NASA Goddard has experience in it, so we always got a lot of feedback from them, which always led to more analysis. You can take that and go back to the beginning, and just do that again and again, like a hamster.

Really from the first test, which was the Chamber [Commissioning] Test, the photogrammetry results were a little puzzling. They didn't make sense, and in every test—first we had the Chamber [Commissioning] Test, and then the pathfinder arrived and we did what was called the Optical Ground Support Equipment (OGSE)-1 test. Then we did the OGSE-2 test, and then we did the thermal pathfinder test, and then we did the OTIS [Optical Telescope Element/Integrated Science Instrument Module] test. We learned a lot in every one of those tests about the thermal system, about the chamber and its systems, about contamination, about the optical performance of our equipment, about the photogrammetry, dynamics.

Every one of those tests we learned significant amounts of information that made the final test successful. And in fact, if we were going to do the OTIS test again we would do it slightly differently. The Chamber [Commissioning] Test we did, and we learned a fair amount about the photogrammetry.

ROSS-NAZZAL: Do you want to just stop here and then pick up with pathfinder OGSE?

[End of interview]