HUBBLE SPACE TELESCOPE OPERATIONAL ORAL HISTORY PROJECT
EDITED ORAL HISTORY TRANSCRIPT

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GREENBELT, MARYLAND – 8 MAY 2015

The questions in this transcript were asked during an oral history session with Frank Cepollina. The text has been amended for clarification and for publication on this website.

GAINOR: Okay, this is May 8th, 2015, and I'm Chris Gainor. Today I am interviewing Frank Cepollina who has had a lot to do with the success of the servicing missions on the Hubble Space Telescope [HST], and lots of other things, too.

Do you want to tell me about your work in the early days of developing what became Hubble?

CEPOLLINA: Well, I guess it's just starting from basics, right? I grew up in California, and I grew up during the Second World War, and one of the interesting things, my interest in space wasn't space. We never even talked about space as a kid. You know, things like going to Mars. That was never even a thought, let alone going to the Moon. But it was the Second World War, and my parents and grandparents had a farm just outside of the Moffett Field area in California. When I was growing up as a kid, during the latter days of the Second World War, there were all these big B-29s, and there were even some experimental B-36s and fighter airplanes. They were always taking off and landing at Moffett Air Force Base, Moffett Field, which was a Navy base in those days, just south of San Francisco.

And so I was always interested in airplanes as a young kid, just watching them fly overhead, making all the noise. So my hobbies started by building model airplanes and basically trying to fly model airplanes with rubber bands, and gliders, and eventually with little engines. And that's how I got interested in aerospace; it was really aero, in those days.

And then I went to college. I went to college at the University of Santa Clara, which was down the coast, and I studied mechanical engineering. And in the junior year of engineering my professor said to me, he says, "You know, the Russians have just launched the Sputnik [satellite], and there's a bunch of activity going on in the Palo Alto area, and there's this space club that gets together," (I can't even think of the official name of it at the time). "Would you like to come and see what the U.S. is doing in terms of developing and launching rockets, and what the present situation looks like? You might be interested, as a career."

So I went, and that was really interesting. I must have watched an hour and a half with the movies of launchings, which was lifting off the pad and blowing up, destroying the pads, and then launch vehicles blowing up before they even lifted off. And there's all the Vanguard [rocket] experimentation going on, for the most part the East Coast; a little bit on the West Coast. But you could see that there was this huge development arena going on, relative to rockets, rocket engines, and so on. I graduated; I went to work for Aerojet General in Sacramento, working in the solid rocket plant where we were designing Sparrows and Tartars and Super Tartars, which were short range missiles.

And then I left; I went into the military and came back here. And that's where I got going with NASA in 1963, and my experience base with NASA was that I went to work on a satellite program called Advanced Solar Observatory, and within a year and a half it got cancelled. It got cancelled because of budgetary reasons, primarily because of budgetary reasons. And then I went to work on another program called Orbiting Astronomical Observatory. And when I was on that program, my boss said, "You know, we're working on a future advanced satellite. Not just an orbiting astronomical observatory, which had a one meter, 40-inch mirror. We're working on one that has three times that, a 120-inch mirror. And we're putting together a study team. Would you like to go on that team?"

So I did. I went on that study team, and that was in the like, '68 or '69 timeframe, and for about six months to a year we had really some very good experts in optics, in sensors, in detectors, and in, more importantly, spacecraft structures. One of the ground rules we had received from George [M.] Low on this team was that he wanted to basically come up with a concept in which we could take advantage of human repairs and human servicing in flight. At the same time, lowering the cost of satellites and making them more reliable by virtue of being able to repair them and upgrade them in space. And so that's how this concept of modularity got started. It got started here at Goddard. And it was really the concept for making all your spacecraft, there's much in new spacecraft and scientific instruments that's possible making them modular, so you could deliver them into a system and have the least amount of integration and tests to be carried out, and that you could fully test these modules long before they ever got to the observatory or spacecraft level.

So that's where this concept of modularity got started, and as we were proceeding with that, the other aspect of in-orbit repair and maintenance started to pick up a bigger and bigger picture in the '72 timeframe as the agency decided to move ahead with the space shuttle. And one of the reasons for moving ahead with the space shuttle (there was lots of reasons) but one key reason was the fact that Mathematica had done an economic study that showed that if you could repair satellites in orbit, you could save a lot of money by virtue of the fact of not having to replace them, but continuously upgrading them. So it was this combined concept of modularity, to make things go together more reliably and easier in the beginning. And then this concept of being able to use the modules to make an easy change-out for the astronauts to go up and service by modular replacement, very much like you would replace a magazine on a camera. In those days we had film cameras. But there were film magazines.

I remember that argument, because that was the argument that I used to convince my boss, who was skeptical of this modularity servicing concept, of how in the devil can you take a very complicated instrument, modularize it, and then stick it in a complicated telescope and expect it to interface and electrically play properly, and optically be aligned, without the module ever seeing the spacecraft that you got to orbit. Very interesting, very challenging. So, in a naïve sort of way, the way I explained it is by the film industry, the way they change out films. They don't change out replacing and winding the film. They have a film magazine, and they load the magazine in, and it has the interface blocks that self-align that magazine, that puts that film right where it wants to be put. So once the electric motor drives the reel in that magazine, that film is aligned with the optical element of the telescope. And we demonstrated that a little bit, to deal with our skeptics about could you ever make modular systems that were scientifically beneficial, and yet, could be replaced. The instruments could be replaced and could be put right back in the optical sweet spot of the telescope. That was a challenge. That was a challenge, even way back when, to convince people of this.

So, we built systems, and the first system that we put together was an all-titanium, engineering model of a three-meter optical telescope, which we called the Large Space Telescope. So that was in the '72 to '75 timeframe. And as we were putting it all together, the Canadian Space Agency, then the Department of Industry, Trade, and Commerce, came down and said, "Well, we're very much interested in getting involved in the shuttle, and we understand that what you're doing here at Goddard is trying to develop a telescope that will take advantage of the shuttle servicing, and we want to be involved in the servicing part." So, we had discussions with them and showed them what we were doing, and they said, "Suppose we build an engineering model servicer for you and bring it down here and then demonstrate how we can make the systems be serviced with the push of a button from inside the shuttle." And so this magazine article, which covers that demonstration test, and also covers the servicing hardware, which the Canadians built for us as part of our teaming arrangement, worked out very, very well. And In '75, we brought a working model, all modular, down to Downey, California, integrated that into the plywood mockup of the shuttle, and demonstrated from the cabin that you could, in fact, push a button, in an autonomous sort of way, change out all the components in the telescope. And this was our version of what was then called the Large Space Telescope.

The Large Space Telescope concept got sold to Congress and to NASA in the 1976 timeframe. Pieces of it were given to Marshall [Space Flight Center, Huntsville, Alabama] to develop, mainly the telescope and the other pieces. They made the modular scientific instruments, and the operations were given to Goddard to do. So, it was kind of a parallel development concept of Marshall does the telescope and servicing, we do the modular scientific instruments and the modular form, and then we deliver them to the Marshall prime contractor, and everything gets integrated in and tested. And during that course of the time, Marshall maintains the capability to service the telescope in orbit.

So the concept held together, even though it became multi-center faceted, and the concept of servicing and modularity, surprisingly enough, pretty much held together from 1976 to roughly, well to time we launch, which was April 24th, 1990. That's a long time ago, and I've got to remember all those dates. But it held together, and that's how we got involved.

Now, there was something very interesting that happened when this mechanical system was given to Marshall Space Flight Center. What [NASA] Headquarters said was, "Goddard, if you really think that modularity will save us money, we've got these other programs, and we are willing to make an investment in a modular, much less expensive program called SolarMax for you to build up these modules and try this concept in orbit. And we have to get SolarMax in orbit. Now this was '76. We have to get SolarMax [SolarMaximum mission] in orbit by 1980. So, whatever you do, we're going to test your concept out here, because you're going to be driven by schedule. You're going to be driven a little bit by budget, but more importantly, you're going to be driven by getting ready and flying a scientific solar telescope, so that we can measure SolarMaximum activity in 1980. And this was 1976 they turned us on.

So, the time is moving, right? We moved ahead, quite smartly, with our modular concept, and during the course of moving ahead, we went and got contracts for the subsystem modules; we started off with an inside design that we contracted out for the subsystems. And then the prices were so attractive, we convinced the agency to move ahead. And by subsequent sets of those modules for Landsat 4, Landsat 5, UARS [Upper Atmosphere Research Satellite], EUVE [Extreme Ultraviolet Explorer] and GRO Gamma Ray Observatory, and they all became modular telescopes. They all have these modules, these subsystem modules. So, if you look at the pictures, (and I don't have them here) but if you look at the pictures that eventually flew, they had a common generic system. And oh, by the way, the DoD [Department of Defense] folks wanted some modular subsystems, and for the reason they were very cost effective, and they could put spacecraft together in six to nine months.

Remember this is now 1976 to 1988, '89 timeframe when we were doing these things, and, and we were proving out these concepts, so this modular concept had some interesting events in terms of it holds some records. The longest spacecraft that we have on record that ever flew was

Landsat 5, and it flew for 29 years, when we finally shut it off. And you know what spacecraft that was? It was a modular MMS [Magnetospheric Multiscale] spacecraft. One of the others was Landsat 4, and it flew for 18 or 19 years before we shut it off. Again, modular spacecraft, never serviced. Never serviced, but it worked fine, well worked in a degraded sense, but worked for 19 years. Yeah, so we set some records.

And then the first spacecraft that we built called SolarMax, guess what, we had a generic design problem with it. We didn't realize it until we got two years into orbit, and the fuses started to let go, and we lost the reaction wheels. And there was enough redundancy that we could spin the spacecraft and keep it pointing at the sun. So in 1984, we can convince the administrator that we should take the shuttle and do the first servicing mission on SolarMax with the space shuttle. And they liked the idea that all of a sudden, we weren't just talking the talk about shuttle economics, but we were walking the talk, and could service, and would try to service.

So we built that tool that you see over there to do the servicing, because we never spent a dime to make it man-rated, so the modules didn't have handles, but we designed tools that could take the place of the handles, and they were power tools, and they could drive the bolts, and plug the modules in and plug the modules out. It was the same concept for modularity as Hubble, instrument modularity. And so once that happened, once we did the April of '84 test, then Westar and Palapa came along for retrieval, and that happened within six to nine months. Then Syncom [synchronous communication] 4, then Intelsat 6, and then 9, and then Compton GRO was launched and it had a generic design failure right off the bat, before they even got out of the cargo bay. They couldn't deploy the antennae. And guess what? The astronauts went out there with their EVA [extravehicular] tools, fixed it, and deployed the mission, and it lasted for something like 12 or 14 or 15 years. This is the Compton GRO Observatory.

So the concept of repair on orbit, the concept of modularity, and the concept of being able to use astronauts and a space transportation system called the shuttle, together to produce more science, just rolled right out. It became fantastic. And I wasn't even on the program when they launched the original Hubble, but the minute they had the failure, they got on the phone with our project, and they said, "We want you to take over servicing of Hubble." And we were willing to do that more than eager. It took me about 15 seconds to say yes.

But my perspective was that the concept has evolved over time, and it evolved to a plan, which I call the master wisdom plan, which the agency hasn't had very much of in subsequent years, post HST. There was this wisdom, this being able to move ahead on what today is called extensibility, and in those days, it was extensibility in terms of using transportation and humans in space, to produce more scientific knowledge for the dollar than you could do if you just built telescope after telescope after telescope, which we never could afford, and try to launch that way, and waited all those years in between development and flight with no data. So the beauty of Hubble is really a manifestation of good wisdom and good thinking and good planning in the '70s.

GAINOR: Now, servicing has long been a part of Hubble, so were you consulted in any way or involved in the design of Hubble?

CEPOLLINA: Yes.

GAINOR: In terms of thinking ahead to those servicing missions? Because regardless of how well it worked, there was going to be servicing missions.

CEPOLLINA: Yes.

GAINOR: And changing out instruments and all that.

CEPOLLINA: Yeah, and we played, initially, a very peripheral role. But eventually a stronger and stronger role in the sense that when we started rolling in and developing SolarMax, one of the things we had to do for the orbiter is build a structure in which you could sit the spacecraft inside the shuttle and clamp it down and carry up storage modules and equipment to repair your satellite. We developed what was called the Flight Support System, which is the workbench, in the '78 to '82 timeframe. We developed this platform that you see right here [shows picture].

But we developed this platform, which you see right here, that allowed the Hubble and SolarMax to come down and be clamped to the shuttle. And this platform rotated up and down. You can see the platform right here. You had all of these structures in front and on the side. That's the platform that we developed. And we developed it so that it would be compatible with SolarMax and compatible with Hubble. So you wouldn't have to spend the money twice for a standard, compatible vehicle.

And we used various versions of this platform, various versions of that, and it wasn't just a mechanical platform, it's also avionics that made spacecraft electronics compatible with shuttle electronics so you could do some check out when you were on the orbiter. You could check out the spacecraft; you could power the spacecraft. We developed those electronic and mechanical systems, and then for various missions before Hubble, but including SolarMax, we used those electronics to support those missions, like UARS that launched on shuttle, like Gamma Ray, and there's two or three other missions that launched on shuttle that all took advantage of sharing this interface platform called the Flight Support System.

Now, while that Flight Support System development was going on, the Canadians and Johnson [Space Center, Houston, Texas] and ourselves were going around as to how do we capture these satellites to get them in the cargo bay in the first place? And the answer came in about '78 to '80 timeframe. Let's go, let us, the Canadians, develop for you folks at NASA a robotic arm that can be used and operated from inside the shuttle to reach forward and capture these satellites while they're flying by. And we called that the robotic arm, the Canadarm, and the Canadarm has been a key facet of the shuttle program all the way through. As we built more shuttles, we bought more arms, and it became the workhorse and became our ability to put astronauts on the end of big booms and carry astronauts and equipment and these heavy 1,000–2,000-pound instruments and modules around in space and be able to restrain themselves so they can install those instruments. So the Canadarm was a very important aspect of the overall concept, overall architecture of satellite servicing. Robotics is still a very important aspect of satellite servicing, whether you use astronauts or you don't use astronauts. It's an important aspect because it does "the heavy lifting." It does the labor work. It does the "I tire out" aspects for the astronauts, to keep them from getting tired out.

GAINOR: So you and your people, were you developing, for want of a better term, the work platforms that attached to the end of the end effector?

CEPOLLINA: Yes.

GAINOR: And were you involved in developing the platform on which the Hubble was parked?

CEPOLLINA: Yes, yes, exactly. We called that whole platform—the carriers and the platform—we call that the Flight Support System: The support system that goes inside the orbiter that supports the spacecraft electronically and mechanically, locks them in, holds them in place, we developed that here.

GAINOR: And I suppose you were doing that in the '80s.

CEPOLLINA: We started in '78, and interestingly enough, when we got started with that, no one wanted to support us financially. So we went to the manned space people and said to manned space people, "This is what we got in mind. This is what it does. This is how we can use it. We want your financial support."

So, they got together with the science people, and said, "Yeah, we'll support you for this just as long as you are willing to be standard, to be useable, for multiple, not just one mission, but for Hubble and SolarMax and whatever other mission, the UARS, that flies." And that was an economically easy decision to make. It was economically easy because it saved all these future programs, and ongoing programs, money. And so the hardest part was getting requirements together and making sure everybody had standard requirements.

GAINOR: Would you have been ready to go if, say, HST had flown in 1986?

CEPOLLINA: In '86, yes. In '84, when we were doing SolarMax, we were just learning. SolarMax, the first servicing issue was in 1984. So between 1984 and '86, I'd say yes, but not before '84 because we were just getting our act together to do that first servicing mission called SolarMax.

GAINOR: And there were some lessons learned during those missions.

CEPOLLINA: Oh yeah. Everything we learned from SolarMax repair, we applied to the principles and the architecture of Hubble. I say everything; I mean metrology, this thing I call the Standard Flight Support System, the powered-up avionics. Now we've got to make changes, we've got to make some improvements, so to speak, based on what we learned, but that became the fundamental architecture for satellite servicing. The architecture became paramount in our design and construction of each of the five Hubble servicing missions. We just went boom, boom, boom with that architecture, saying, "It has to be this way, because we tried it this other way, and look, the results were not good." I used to give lectures and people used to—I felt like that a lot of the times that when the scientists used to throw oranges at me because we were spending their money, but we had to get it right. We couldn't screw up Hubble.

So we spent a lot of time and money making sure we had the metrology right, because metrology of everything we've learned on SolarMax, and everything we learned on Westar and Palapa, and Syncom 4, and Intelsat 6 was metrology is always wrong. When you think you're grabbing where the dimensions actually are, aren't what you think it is, because you're relying on photographs. You're not relying necessarily on drawings, or you're putting the drawings and the photographs together to give you something that's not quite right, and when we go up there to grab it, it's not this, but it's that. So we really had to work very, very hard in building a full-scale mockup, mechanical mockup of the Hubble instrument compartment and the Hubble spacecraft instrument they've redone. And that became the gold standard by which we could assure ourselves that we can build a scientific instrument, have the instrument builder align it, shoot the light through it like it was a Hubble light beam, then bring it to Goddard, double check that mechanically it would fit, then mechanically it would go into these rails, and then mechanically you would lock down and you could mechanically make those electrical connectors and have everything work.

And so that's where this duplicity, this what I call the test-test and retest, train-train and retrain, that's where the triplet came from. It came from doing it first on the instrument, then doing it at our trainer, our mechanical trainer here, and then doing it in the neutral buoyancy lab at Johnson. So we have three different ways of making darn sure we didn't make any metrology errors.

GAINOR: Alright, so we're at 25 years ago now.

CEPOLLINA: Yes.

GAINOR: And HST goes up and they find all sorts of problems, the solar panels, the gyrations.

CEPOLLINA: The gyroscopes. Yeah. There were lots of problems. The computer would upset every so often because it would get hit by single event upsets. Radiation damage, radiation events would screw up the computer and so that would screw up all the onboard calculations, so we had to do a lot of improvements, let's put it that way. Adjustments.

Improvements, adjustments, yeah. There were some things we knew pretty well. We knew we had a spherical aberration. We conducted a series of two years' worth of testing, and it could be argued whether it was 18 months or 30 months. But it was two years of optical testing on the telescope. To arrive at exactly what was the configuration of the mirror, what was the true conic constant? And there were all kinds of very, very clever techniques to do it with, but we took those pictures with an aberrated mirror and lens, and through the aberration and through some very strong bolts we called fiducial marks on the telescope that held the primary mirror down, through the placement, which we knew the position of those bolts very accurately, because we had measured them on the ground. We had drawings and so on. Because we were able to do that, through the taking of the pictures, through this constantly focusing and de-focusing the mirror, primary mirror, secondary mirror, and taking pictures, we arrived at a very hard and true conic constant for the optical system of the telescope.

Now, what nailed it in place was, during that same type of process, there was a deep investigation going on, as how could you get so close and yet be so wrong. How could you polish a mirror that was 100" in diameter and be off by half the thickness of a human hair, which was 50 microns. How could you get that close, and yet miss, when the whole mirror put on a stand, optical stand sagged half an inch? What on Earth? Well it turned out, believe it or not, it was a piece of instrumentation that was assembled incorrectly. And they found that washer, and they found that error, and when they put the two together, all this empirical testing that we had done in orbit, with the washer, the numbers came out very close to each other.

GAINOR: So, tell me about your end of that, what was going on during that period. There's all sorts of ideas being thrown around that some people said, "Let's put a mask around it to make the mirror smaller, so we miss that error." Or they suggested, "Let's send up an astronaut to crawl down the barrel of the telescope." Were you asked for your opinion on any of that stuff? I know, Bruce McCandless is supposed to have shot down the last idea.

CEPOLLINA: Well one of the key players was Bruce McCandless in these solution ideas. The how to fix the problem. One of the key players was Bruce. But there was another guy, his name is Riccardo Giacconi. And I want to say, in a very good way, he was the godfather of Hubble Space Telescope science. He was head of the Scientific Institute [Space Telescope Science Institute] in Baltimore [Maryland].

GAINOR: And he was not the most popular person around here.

CEPOLLINA: No, but the strongest personality here and in the White House. And when he said something, everybody very carefully listened, because if he didn't like your answer, you would be told within a matter of days, "Do it this way, or else." And so, he was very strong. But I don't think he was incorrect, either. I think he was a good astronomer. He was an X-ray astronomer, not an optical astronomer, an X-ray. But he knew enough about optics.

So he said to a group, because remember, NASA only owned 85 percent of Hubble, 15 percent belonged to European Space Agency, and there were like 30 percent of the scientists at the institute were European scientists, so he said, "It's time we get all these scientists together. We've got to go to a neutral ground. We've got to discuss what it is, and what it is that we can do, and I'm going to bring some people." And he brought Bruce McCandless with him, from an astronaut, "what can we do," perspective. And he brought some other people too. And everybody wants to stand up and take credit for the concept of COSTAR [Corrective Optics Space Telescope Axial Replacement]. And the real credit goes to a fellow by the name of Murk Bottema. Never even heard of his name. Have you heard of Murk Bottema before?

GAINOR: Yes. At Ball [Aerospace], right?

CEPOLLINA: Yes. Murk Bottema was a brilliant optician. And he wasn't one of these study opticians for 400 years, you know, he was a hands-on optician. And he and Bruce McCandless had a couple of other people, our people got together at this meeting in Europe, and I think it was in Switzerland. I can't remember the details, now. And they talked about all these different kinds of ideas. Baffles, going down the telescope, changing out the secondary, it was a whole family of different ways to fix it. And by this time, they had not determined how much fix they would have to make. But Murk Bottema and Bruce McCandless said, "What we need is a submarine periscope system on Hubble, to fix the problem." And what they meant was, they needed an instrument to carry up a periscope, collapsed within the instrument so it fit in the body of it, and once it got installed, they'd be able to command this periscope up, and deploy these optics in the light path of the telescope and each of the optics that would be deployed had the ability to correct the light a little bit, so it would go right into a given instrument.

So there were four axial instruments so you had a picture—this one instrument would be scarfed off. It would no longer be an instrument; it would carry the periscope. And the other three instruments would receive the corrected light from each of these folded arms. They would go into the light beam, correct it with the lens or lens combination, correct the path of the light, and pass the light into the instrument. And they would have to be adjustable, so that you could make finite corrections so that once the periscope was deployed, you were sure, against surety, to focus that beam into the instrument, and not someplace else. So they had to have, what I call very exotic, very precision in those days, very precision micron adjustments to make sure that you could change the alignment of these optics to pass a segment of a beam into each individual instrument.

So there were four axial instruments. The photometer was scarfed up, and in place of that came this instrument called COSTAR. And we had a spare instrument structure called STAR that was used as a test article; it was placed all around. It could fit any one of the four spots, and we converted that instrument into carrying these optics, this periscope system. And I think I've shown you pictures of that.

GAINOR: Oh yeah, we've got it at the Air and Space Museum.

CEPOLLINA: Now the guy that really had the wherewithal to make it happen was Murk Bottema. Murk Bottema sat down—and in those days we didn't have the huge computers we have today but we had software and we had computers—but he sat down and did what we call the rate-trace analysis, that would show how each one of these arms would intercept a piece of the beam, correct the figure of that beam and pass that corrected beam, just like your eyeglasses would do, directly into the eyeballs of the instrument. It's just a direct analogy, it wasn't that exotic a fix. What was exotic was the engineering that went behind it because it had to be very, very precise.

GAINOR: Now, going into Servicing Mission 1, what was the big challenge you faced, and your team? What were you working on and worrying about in that time?

CEPOLLINA: The optical prescription was a big thing, and the optical prescription was key to this COSTAR instrument, because you had to know what the overall prescription was to be able to correct it with these little, teeny optics that were only yay-big. The biggest one was quarter in size;

the smallest one was a nickel in size. And they had to be polished so they weren't perfectly spherical. They had, in a sense, bumps on them to take care of this aberration of the beam. So they were not perfectly spherical; they were asymmetric in order to make a correction on the beam. And that took a lot of engineering work, optical engineering work, which I hand to Murk Bottema and his Ball team. And then they took a lot of polishing work, and polishing technology, and measurement work, which I compliment the little team that was 80 people big, called Tinsley Optical, that had become fully invested in just solving the Hubble problem.

It was only 80 people strong. They built a lot of commercial optics for the television industry and for the electronic microprocessors in the industry because they used these optics in microprocessors. In the process of making transistors on large-scale integrated devices, where you layer after layer, you paint this on, and then optically you basically take everything but the active material away. That's the photolithography—we call photolithography—the process by which you make microchips today. Well in those days it was good, but not nearly as good as it is today because of the investment that these guys made in digital processing, polishing, and then the ability to use holograms, three-dimensional holograms to measure the ultimate figure of these aspherical instances.

So that was one of the big pushes. The other big push, believe it or not, was the Europeans. We had to convince the Europeans that something was wrong with their solar arrays, and they had to do it over again, and it was kind of a reluctant push. And finally, after about a year, they came on board and they said, "Yeah, okay, we're still not sure that there's anything wrong, but because you guys are insisting and because we've made so much noise about your falling down on the mirrors, then we will pick up and build a new solar array." And it was a tough battle. We must have made four-five trips a year to BAE [British Aerospace], manufacture of the solar arrays in

England. Pushing this technology through, trying to understand what was wrong, why was the solar array jerking the telescope every time we go in the sun, every time we go in the darkness? Either way it would jerk the telescope, and it was because of the motion of solar arrays. Well the solar arrays are designed not to do that, but they did. Later on when we got within 100 yards of the telescope in orbit with the shuttle and they looked out the window, they saw right away what the problem was. One of the bi-stems was broken.

Yeah, so that one we had to throw away. We never could bring that one back. It was just a way to roll it up. But that was a tough problem. A lot of things that happen in orbit, you can't put your finger on and you have to speculate, you have to try to do designs around those speculations to see if in fact the speculation has any merit. And we face those problems every day of the week; we face them today. That's the beauty of station. Space station allows us to take some of the speculation out of the business by being able to take this stuff up to station, leave it up there for six months or a year, bring it back or throw it away. But you now know what you've got works in space or doesn't work in space. So there's a lot to be said about space station experimentation.

GAINOR: Do you want to tell me—we'd probably be here until dinner time if we covered every servicing mission. But what were some of the big, big challenges you faced in preparing for the other servicing missions?

CEPOLLINA: It's like everything else, right? The first time through, oh, you've got priority, you've got this, you've got that. Don't worry about money, just make the schedule. Do not make NASA look bad. We already lost a vehicle. We had already lost a spacecraft called *Challenger*. We had already lost *Challenger*. And you guys screwed up on Hubble. Don't you do it this time. You fix it. Don't make any mistakes.

So that was a big pressure point. But they gave us the resources to push through that point. Tremendous amount of overview, tremendous amount of bureaucracy, but nonetheless, we were able to stay on track and go.

Second mission now, everybody says, "Oh, well you did it once. What's the big deal?" So now the next big deal is to hold the line on philosophy. Hold the line on philosophy, what everybody wants is to say, "Oh, we did it once, we don't have to do it as good. We don't have to spend as much money." Tough, tough problem. Hold the line. And holding the line was a tough problem, for two reasons. One is everybody thought that because we did it once, we could short-cut all these trainings. We don't have to do train, train, and retrain, test, test, and retest. We can shortcut one of those cycles out. And we had a hell of a time on that one. That was tough.

The second thing is that Hubble was designed to be evolvable. You didn't just fly and replace every time you went up there, the same instruments with the same—no, no, no, no, no, no, no. Every instrument that we flew had to be at least 10 times more powerful than the instrument that we took out. So developing those instruments on four and a half year centers was a tough, tough drive. Developing instruments that would take advantage of modern-day technology, or what I call last minute evolvable technology, and incorporating that evolvable technology into those instruments so that only, only, only six months to a year was the age of that technology before you flew into orbit.

Now that's incredible in today's standards. Today's standards are like five-six years. The instruments for JW[ST] are already built but not going to fly for another four years. So those instruments have four-year-old technology or five-year-old technology. And here we are flying instruments that only have six-months technology? Newness? That's what has made Hubble such a strong, strong knowledge innovator. It's what brought the knowledge of the universe, step by step by step, so much closer to the American public, in faster and faster increments, and I maintain at cheaper increments than would have been the other way had you built a new telescope for every one of those missions. You never would have been able to afford it to begin with.

GAINOR: Right.

CEPOLLINA: And when you did, by the time you flew it, the technology was old. The technology was old. And so the point that I'm making is the toughest part for each successive mission was making darn sure that we flew the latest and best and greatest technology, scientifically, in those new instruments we could possibly get on board. Fight, fight, fight. All the time. Fight the money, fight the budget, fight the schedule, because everybody's trying to constrain your budget to do something new down the pike. That's new money. Let's go for a new investment. But in fact, history will show that the greatest number of technical discovery papers, and the greatest number of inventions, and the greatest number of discoveries were made by virtue of flying fresh, new instruments to orbit every four years. Fresh, new instruments with at least 10 times the resolving power of the previous instrument. That's how Hubble is able to maintain its discovery record.

GAINOR: Right. A lot of people talk about the situations where things broke down that weren't supposed to be serviced then. But you always found ways to deal with them.

CEPOLLINA: Yeah, yeah.

GAINOR: What about some of those situations?

CEPOLLINA: They tell me—and they're right—they say, "You get too good with robotics, and you're going to kill the possibility of our flying astronauts again to space." And I maintain to them, no, no, no, no, no. What we're trying to do is what a surgeon, a neurosurgeon does. We're trying to take, with robotics, we're trying to take the deleterious implications of the neurosurgeon jittering a little bit, and therefore he can't get too close to this optic nerve or too close to this skeletal nerve because he'll zap the patient, permanently. So, he has to be careful. What we're trying to do with robots is basically take the physical limitations that a human has in doing servicing on orbit and incorporating that into the robot.

And take the judgment factor and the controls of that robot and give it to that astronaut. So you have this 55-year-old neurosurgeon that's done 500 or 1,000 neurosurgeries, and he's great. His judgment skills, his ability to look down there and see the effect of cell and so on, and your brain is terrific. He's got one little drawback. He's now 55 years old and he shakes a little bit. So he can't get as close. But now with robotics operating that tool for him, and now his fingers going through a computer and having a red line drawn all the way around that neuro-section of the brain that says, "If you make a move beyond this red line, everything shuts down and stops. You can't go over that barrier, that dangerous barrier." Now he's got those controls. It gives him so much more flexibility, and he can do so much more in terms of removing tumors from the brain, in terms of whatever the problem is.

But the point is marriage, robots and humans are a marriage. Now we proved that very significantly with the last servicing mission. With humans and robots, we were able to not just remove an instrument and replace it, but take an instrument, cut a hole in it, remove the failed circuit boards, and stick brand new circuit boards in that instrument and have that instrument go on and keep playing. And today it's making half the breakthroughs of Hubble.

GAINOR: This is humans working on the end of the robot arm.

CEPOLLINA: Working on the end of the robot arm and with robot tools in their hands, so all they have to do is squeeze the trigger if they wanted some sheet metal cut. They squeeze the trigger to cut the sheet metal. Squeeze the trigger down here, cut the sheet metal out, squeeze over here, cut some more out. So they had a robot that was doing the cutting for them. And all they had to do is place it, look at where it's placed, and squeeze the trigger. No physical can opener kind of operation. Right, twist the can to cut the metal. None of that. It was all done for them, with a robot.

So all they had to do then was use their judgment. Use their judgment where to grab the broken card, how to pull it out safely (and the safety was another aspect), then how to stick the new card in safely, and then how to make the connections on top. Little stuff, critical stuff, fragile stuff, but what they're good at, the fragility and the judgment and the visual aspects of what the astronauts can do better than anything. And the robot stuff, well, that's stuff. That's dirty work, that's hard work, that's physical wear-out work. Turning screws, cranking handles. You see where I'm getting to.

GAINOR: Yeah.

CEPOLLINA: What we tried to do, we brought about an evolution of technology. The evolution of technology is you get robots to do the heavy lifting; you get the astronaut to do the intelligent work. And you need astronauts who don't have to be out there 24-hours a day to do the heavy lifting. They only have to be out there five hours a day. But in the interim use the robots to do the heavy lifting.

GAINOR: When servicing mission four was cancelled during that period, there was discussion about overhauling your robots.

CEPOLLINA: Yeah.

GAINOR: Were you involved in that?

CEPOLLINA: Oh, 100 percent. Yeah, our project took that challenge, and we convinced the administrator that we can do not all of it, but major pieces of the Hubble fixes that would have had to be done between [Service] Mission 3B and 4. We could do a major piece of those fixes with robots. And we were in there building the robots. In fact, what we're doing now is an offshoot, or our robotic work is an offshoot, a continuation really of what we did then. But when we switched over from robots back to astronauts, we had a lot of this technology already under way. So, we used pieces of that technology to give to the astronauts so they could do twice as much work in half the time and not get tired. If you look at the amount of things that we fixed on the last servicing mission to Hubble, it was two and a half times more than we'd ever fixed before. Why? Because we'd given them these tools. We'd given them these robotic-assist tools, for lack of a better word. To be able to get in there, do it easier, manipulate less, squeeze trigger more, visualize the problem, and then go and make the fix.

GAINOR: How much did Hubble impact the work on the station, and how much has the station work impacted Hubble?

CEPOLLINA: Not enough. Not enough. The problem is the station was being developed as we were doing all this stuff. We were a nuisance to them. They were a nuisance to us. They had their own contractors. They never wanted to listen to us. There was a lot of stuff that was missed due to what I call ridiculous arrogance. But there was. There was this typical arrogance, and the arrogance isn't just one NASA center against another. No, no, no, no. It was one company working for one NASA center against another company working for another NASA center. And there was always this back and forth, and I had maintained then, and I maintain now, that's one reason why this station cost so much to put together and build.

And it reflects itself on a difficulty of keeping it up and repairing it and the expense of doing that. And the right hand didn't want to learn from the left hand what was right, what was going on that was right with servicing, or what was going on that was wrong. It was like, "You stay out of it; this is our problem. We'll take care of it. We've got our contractors. We're going to listen to our contractors." And so, when you get into that kind of arrogance building, you've got a problem. You've got big budget problems.

GAINOR: One thing that really impressed me when I walked into here, is that it says Satellite Servicing Office. I feel like I've just walked into some future thing from a sci-fi novel, which of course is really neat.

CEPOLLINA: Yeah!

GAINOR: How long has this had this name, and what's the idea behind that? Are you trying to make a little bit of a point there?

CEPOLLINA: No, because that's all we do is satellite servicing. It's a satellite servicing development office here at Goddard and at NASA. We focus on using tools, humans, launch whatever it takes to do a repair job, and to do mission repair. And so we have been trying to basically develop the capability to service these satellites on orbit and in a robotic way. In other words, keep your astronauts, keep your servicing people on the ground. Keep your robots in orbit. Have them go to these vehicles, grab them, lock them, and then refuel them or repair them. The easy part is grabbing them and refueling them. So far, we haven't found somebody that could do a repair job as well, but it's going to come. It's going to come.

But that's our concept. And we've been at it now since—let's see, our last servicing mission was in 2009, so we've been at it since 2010. And we fly these robotic servicing experiments on station. We do fuel interchange on station with their robots, out in the open, demonstrating that we can go to these very small valves, and cut the wires and move the control valves and exchange hydrazine. So we're doing those kinds of things. And there's a whole family of different experiments.

We've got one that's going up in a couple of years. That's cryogenic exchange. Exchange cryogenic fluid. We've done some xenon exchange, demonstrating that we can refuel robotically, these long duration vehicles using solar-electric propulsion. There's always been an abundance of solar power as long as you stay in the Earth's sun-line, but you will eventually run out of xenon propellant. So eventually you have to be able to refuel the solar-electric propulsion systems with xenon, and when you do that, you basically expand your extensibility into orbit, in deep space orbit. Go to Mars and back. So there's all different kinds of different uses for tugs, solar-electric propulsion tugs. And the major driver is to keep them refueled with xenon.

So those are one of the things we're doing. And then if you've got humans, you want to have cryogenic exchange plans. So if you go to Mars and you can suck out the methane, then the next process is how to convert the methane to oxygen, hydrogen, and usable fuels and water. And one of our experiments on the station is cryogenic exchange of that same principle.

So we're looking into the future. We're looking extensively forward. We're not a backward-looking thing until someone comes and says, "We've got this problem. Can you help us fix it?" And then the answer is of course we'll step back and take a look. We're looking at things like refueling Terra, refueling Landsat 7. Things like that. We're taking a look at GOES [Geostationary Operational Environmental Satellite] 13 and 14 NGO [non-geostationary orbits], refueling it so you can keep those spacecraft up and operational, as opposed to having to spend precious taxpayer money to rebuild new ones that we fly in and fly out. So there's these kinds of forward-looking drivers in our bailiwick of things to do.

GAINOR: One more little question about Hubble. Were there any real moments where you thought you were kind of up against it?

CEPOLLINA: Finished. Wiped out. Done. That's it, I'm getting out of here. I'm ready to retire.

Yeah, there were, oh gosh, all kinds of moments. Every mission had its own heartbreaks, you know. Oh my God, how could we let this happen? What on Earth were we thinking about? Let's get in and let's fix it. Usually it was maybe two or three of the four or five EVA days that something, some thought like that would come up. But in the last servicing mission it was every day, almost every darn task, because we were up against the stopwatch. We had twice as many tasks, and the tasks were all more complicated. Talk about tearing your hair out.

You've got to go back and see this video that I talk about when I gave the talk at the Air and Space Museum.

GAINOR: Yeah, I watched that.

CEPOLLINA: Did you see Dave [David S.] Leckrone, my project scientist, he pulled his hair out. He was going nuts when we had to break off the handle on STIS [Space Telescope Imaging Spectrograph] to get the STIS repaired. Of course, it all came out great, but that was a death-defying moment. [laughs] Breaking that handle? You want us to break that handle? What are you guys thinking about down there? Right? It was those kinds of questions. And that was the only way to get it off. Our people said we can break it, and [Michael J.] Massimino was big enough and strong enough. He grabbed that bar and pulled it right off.

That was just one. Every day there was something. We had trouble getting the gyros into place. We had trouble getting a bolt off of Wide Field [Camera] 3, because it had been torqued on with a different wrench back in 2003, and they never accurately measured the torque put on the wrench. So, when we went to torque it off, our torque wrench was set about 20 percent too low. So we had to keep going up and up and up and up. Well, as we got up higher and higher and higher, the fear was that you're going to just twist that bolt right off. You were going to crack the bolt, and therefore you'll never get the instrument out. And so fortunately we went to about 10 percent of the limit and it came free.

But the biggest moment; the biggest wake-up call I ever got on Hubble came when I was preparing for that talk at the Air and Space Museum, and John [C.] Mather, the Nobel Prize winner, and I, we worked together a lot of collaborations. We got one on something that I'll tell you about in a second. But he sent me the pictures of a talk he gave. And in one of the pictures, towards the end was a picture of the aft flight deck of Hubble, looking right out the window. You could see Hubble. If you were inside the deck looking right across the control panel looking out the aft windows, and there was Hubble seated on a shovel on the outside. And across that deck was a 29" tube, 1" in diameter, and that was, guess who's telescope?

GAINOR: Galileo.

CEPOLLINA: Galileo's telescope. It was a replica built for us by the Uffizi [Gallery] because they didn't want to let the real McCoy go. They said, "We know the shuttles are pretty reliable, but not that reliable." So they built us a replica. And we flew that, and astronaut Massimino looked through it. But it was in recognition of the 400th anniversary of Galileo. There it was, sitting across that cargo bay, 1" in diameter optic. You look through the window of the shuttle, what do you see? 100" in diameter.

So in 400 years, we went from 1" to 100". That is terrible. That is the biggest wake-up call I've ever had. And whenever I give a talk, I always bring up that picture because that is the exact rationale and reason why we are not moving forward in this concept of discovery. It's because, in 400 years, we moved up 100”. Ridiculous. We now should be at 1,000”. So John Mather and I and a bunch of other scientists are getting together, we’re working on a concept for a 1,000” telescope, assembled all in orbit, with humans. Taken to orbit with the space transportation system. Big fairing, big thing, but we’re willing to move forward. Don’t waste your money moving backwards. Don’t waste your money doing little stuff. Go for the important steps. Go for the steps of discovery. Who knows how it’s going to end up?

But I’m hoping, I’m hoping against hope that some way, somehow, we will get enough people together to get this message across. Move into the future. It’s time we move into the future. And we have to do that. And the future isn’t just robots, it isn’t just astronauts, it isn’t just space transportation, it isn’t just scientists. It’s all of them. All of them have to move in unison. They have to move together.

GAINOR: Okay.

CEPOLLINA: That’s all I can say. It’s a wrap.

GAINOR: I think that’s it.

CEPOLLINA: Good. I’m here to help. If you need anything else, just yell.

[*End of recording*]