# NASA DISCOVERY 30TH ANNIVERSARY ORAL HISTORY PROJECT
# EDITED ORAL HISTORY TRANSCRIPT

SCOTT BRYLOW
INTERVIEWED BY SANDRA JOHNSON
MORGANTOWN, WV – MAY 4, 2023

JOHNSON: Today is May 4th, 2023. This interview with Scott Brylow is being conducted for the Discovery Program 30th Anniversary Oral History Project. The interviewer is Sandra Johnson, and Mr. Brylow is in Morgantown, West Virginia, and talking to me today over Microsoft Teams. I appreciate you agreeing to talk to me for the project. I'd like to start by asking you to briefly describe your education and your background and how you first became interested in engineering.

BRYLOW: Sure. Thanks for the opportunity to do this. This should be fun. I grew up in Milwaukee, Wisconsin. Nothing fascinating about that, I think. But when I was 13 or 14 my older sister had a boyfriend who was in an amateur radio Explorer post [Post 373]. Explorers were the old nonuniformed version of Boy Scouts. It was associated with scouting, but it was youth-run rather than having adult leaders. There were just adult advisers.

Through her and him I got involved in the Explorer post and I got my amateur radio license; I would have been age 14. That made me aware that engineering was out there, and then I wandered through high school doing various things, but eventually tried it, and engineering was a good thing to try. I applied and got accepted to Caltech, the California Institute of Technology, in Pasadena.

My high school experience was not really very college prep oriented. It was a very small school without a lot of offerings. Caltech let me in under some program where they tried to give people without those sort of educational opportunities a shot at Caltech. They brought a subset of frosh there six weeks early, and tried to get us up to speed, and then incorporate us with the rest of the freshman class. That worked for a number of people. It didn't end up working for me. I left Caltech in the middle of my sophomore year. But it all circles back to that, so that's worth mentioning.

Also before the actual intro you asked me if I had read any oral histories. The one that I know I read was of a gentleman named Lee [F.] Browne who was at Caltech and instrumental in getting this program started that had Caltech looking at people without necessarily the educational background but maybe with the intellectual horsepower to succeed there. He was a 30 or 40 years ago diversity officer for Caltech effectively. At some point I came across an oral history that he did, and it was great reading and fascinating reading. He did a bunch of good in the world. He was a really cool guy. I met him when I was there.

I left Caltech, I went back to Wisconsin, I got a degree in electrical engineering from Marquette University. But my short time in California had left an impression and I was interested in finding my way back to California. I had always been interested in space stuff. On a backpacking trip with some friends of mine in the Sierras [Sierra Nevada mountains] I ran into an old friend [Jeremy Sommer] and talking about this after the trip he said, "Oh, by the way I know you're looking to get a job after you graduate in California; there are some friends of mine who are working on this camera that's going to Mars." I thought that would have been obviously a really cool thing to work on, when you're just leaving school, so I applied. They flew me out to Pasadena, and they interviewed me, and eventually they offered me a job, which I naturally accepted, because you'd be crazy not to.

The fun thing about that story, the entertaining thing about that story, is I met two guys that I would work with for decades afterwards. They were both young and had gone to Caltech and when they came up for the interview, one of them had shorts on and the other one had ripped jeans and was barefoot and a Hawaiian shirt on. I of course, I had my interviewing suit on, because that's what one does in the '80s when you're applying for an engineering job.

One young gentleman looked at the other and said, "You forgot to tell him not to dress up, didn't you?" Sometimes the interviews aren't necessarily what you're expecting. We had a nice conversation. They ended up offering me the job, and I made my way to California. Maybe that's even a segue into one of your next questions which was how did you get into this, what was the first space instrument you worked on.

JOHNSON: Yes.

BRYLOW: The first space instrument I worked on was the Mars Observer Camera [MOC], which was on the Mars Observer mission. I did that from 1987 right after I graduated from college until—well, we delivered sometime in maybe late 1991. Launch was in 1992 I think in the fall, [September] of '92.

It got to Mars. It approached Mars in [July] of 1993. As part of the cruise calibration and checkout activities we took an image of Mars as we were approaching. It was like a very small disk in our field of view for the telescope. That was the only image of Mars we got because they had a fire on the spacecraft and the spacecraft was lost. That was not the greatest introduction perhaps. My constant refrain about that is I would have spent five years building that camera for free in order to get those pictures. But they didn't pay me enough to lose the camera. There was lots of blood, sweat, and tears.

I don't know how extensive your oral history project is, but I'll strongly recommend that if you ever have the chance you talk to people about the Mars Observer mission and the Mars Observer Camera in particular because there was a lot more fascinating stories in MOC actually than I think there were in LRO [Lunar Reconnaissance Orbiter]. It was a fabulous experience. We sweated blood for years. We got the instrument delivered.

The great thing is eventually we assembled a spare and it flew on the Mars Global Surveyor mission, which launched in '96, got there in '97, and took pictures that changed our understanding of Mars for the next seven years. That was a great thing.

JOHNSON: It was a spare? It was the same camera only an extra version of it?

BRYLOW: We hadn't built the full-up spare because it hadn't been funded for that. But we had built a bunch of the assemblies, so we had a spare set of optics. We had a spare set of electronics nearly complete. We had to put the electronics into the can, we had to put the can on the telescope, we had to do all the testing. It wasn't sitting on the shelf, but it was a tiny fraction of the effort, and it was exactly the same camera.

JOHNSON: That's interesting. I read on your resume you were doing testing and calibration of the camera.

BRYLOW: My job description was ground support engineer. I was responsible for that level of testing and calibration. Also a lot of the integration. It was a very complicated set of electronics and mating the electronics, and integrating them with the telescope was a huge problem. Yes. I did all sorts of stuff along the way. I did some mechanical stuff. I did support equipment. I did optical testing. I did electronics testing. I did some circuit board layout stuff. Yes. Just the kind of stuff you give a not yet jaded 24-year-old.

JOHNSON: You did that working for Caltech with that type of coordination?

BRYLOW: Yes. It was a weird thing because it was a JPL [Jet Propulsion Laboratory, Pasadena, California] mission but it was not a JPL telescope. The principal investigator [PI] was a guy named Mike [Michael C.] Malin who will obviously factor in later since I work for Malin Space Science Systems [MSSS]. He was at Arizona State at the time, and his preferred instrument manager was a guy with JPL experience who worked at Caltech named Ed [G. Edward] Danielson.

JOHNSON: Let's talk about that then. I assume he started his own company and that's how that Malin Space Science Systems started sometime between that time and then the Lunar Reconnaissance Orbiter Camera [LROC]. How did you end up working with him on that mission?

BRYLOW: He was the principal investigator for that mission, the lead scientist for that instrument. He had worked with Ed Danielson in the past in some manner, but I couldn't tell you what. Maybe they were both on probably the Viking imaging teams because I know that there was an interest in Mars on Malin's side even earlier.

When he was proposing, he got Ed to start working on this proposal with him, and Ed knew Mike [Michael A.] Ravine as an undergrad at Caltech and Ravine had graduated from Caltech and maybe had been at Brown [University, Providence, Rhode Island] for his master's in geology, and

Ed roped him into working on the proposal, and Ravine roped a guy named Tom [Thomas A.] Soulanille into working on the proposal too. Tom is one of the smartest people I've ever met. Tom and Mike were the two guys who weren't dressed very well for my interview. There was a lot of drama around whether or not there was even going to be a camera on the mission, which in retrospect feels really odd to me because I think NASA doesn't fly missions without cameras because everybody wants pictures. But at the time the scientists were apparently clamoring, "There are all these other things we need information about on Mars. Camera is not important enough. It's going to be a big resource hog. Just don't put one on."

There was somebody at [NASA] Headquarters I believe who basically said, "What are you talking about? We're not going to Mars without a camera. Put a camera on it." Somehow through some machinations we ended up being selected. It was a very ambitious instrument at the time. Way larger with less weight than anyone thought could be done. There were a lot of technological risks.

Ed Danielson put together this great great team that managed to pull it off. It was touch and go. There were plenty of development challenges along the way and it went on longer than people expected because there was a two-year launch delay from when they originally planned launch until they decided to send it. That rejiggered our plans in the middle. There was a whole other set of adventures because at the same time there was going to be an ESA [European Space Agency] mission that was going to Mars. They planned to have some balloon that would rise during the day and fall at night as the atmospheric temperatures changed. They wanted to generate a lot of data with their instruments and they wanted to use the Mars Observer mission as a relay. But there was no one that had enough memory.

Because we were a camera, we had a ton of memory. So sometime in the middle of all this we had to change the design around and incorporate this relay hardware electronics so that we could take data that was coming up from the Mars balloon and put it in our buffer and then send it back to Earth.

Then they all decided that oh my gosh, now that this is important and international, you need to be redundant too, so then we had to change the design and incorporate two full sets of electronics. It was fraught with peril and living on the edge the whole time with literally a bunch of kids doing this. Everybody was in their twenties. A bunch of us didn't have any space hardware experience before this.

JOHNSON: That's what I was going to ask you. If anybody had done this before. Or was this all just brand new for all of you?

BRYLOW: This was brand new for almost everyone except Ed Danielson. We had a few other people with some relevant experience come in and out along the way [Dave Carter, Nancy Evans], but the core team was very new to spaceflight hardware. There were plenty of culture clashes with JPL along the way, which made it all the more interesting. We were all very frustrated because JPL felt a little skeptical and heavy-handed. We didn't want to do things the way that they did. There was a constant tension there.

We also couldn't do what we said we were going to do with just the acceptable parts on JPL's approved parts list. We're out there looking for commercial parts and trying to qualify them for space and convince everyone at JPL this is all going to be just fine. The JPL people were in retrospect understandably fairly skeptical.

We were all young punks at the time. I will say that in their defense I heard many years later that one of the reasons they were so concerned with what we were doing was because they didn't think they could build a telescope like that. They were even more skeptical that therefore we'd be able to do it. I obviously think that without our youthful exuberance and different approach we wouldn't have been able to do it. So it was a great fabulous project to work on. I'm really proud of what we did.

JOHNSON: It sometimes takes that youth mindset, that "I can do anything," to get a lot of things done as far as exploration is concerned.

In 2004 President George [W.] Bush announced *The Vision for Space Exploration* to undertake more lunar missions; he wanted to go back to the Moon and on to Mars. Where were you when that happened? Were you aware of the opportunities that that might open up as far as another mission for NASA?

BRYLOW: I don't know exactly where I was because I don't know exactly when in 2004.

JOHNSON: It was in January of 2004.

BRYLOW: Okay. I was living in London. It wasn't really on my radar at the time. My wife and I had moved to London in 2001. After the Mars Observer Camera I'd actually left the space business for a while and ended up working on Internet stuff starting in 1994. Which was pretty early on to be doing web things, 1994. It terrifies me that that's almost 30 years ago.

After the first dotcom bust my start-up went under in 2000. My wife's consulting company made their San Francisco offices where we were much smaller, and they offered her a chance to move to London where they still had a going concern. We said yes because it seemed like a great adventure. We jokingly say that we were economic refugees at the time because we were leaving San Francisco when the dot-com bubble burst. We spent three years there and then decided to head back. In late 2004 we came back.

As part of the process of coming back we were back in the San Francisco Bay Area and I ended up having some email exchange with Mike Ravine again. The guy I interviewed with for the Mars Observer Camera who's I think also on your list.

Right around that time in probably late 2004 or early 2005 Malin Space Science Systems, which was at the time a very small space instrument developer, got the relatively large, for them, contract to provide a bunch of cameras for the Mars Science Laboratory. There were a total of four cameras. A suite of three different cameras, and one of them was a pair.

This was going to really swamp the hardware group. They had gone along getting one camera at a time for probably 10 or 12 years at that point. Now all of a sudden new technology, new development, not just reusing and evolving old designs, but starting from scratch on a suite of four cameras for this enormous project. But of course they had other proposals out too.

One of them was for the Lunar Reconnaissance Orbiter cameras. They got that accepted. Now Ravine is pretty stressed out. I think it started with me just emailing him congratulations for the Mars cameras. He said, "Yes, that's great, we're really excited about it too. By the way do you want a job?" I think he's long operated under the attitude that hiring people is really hard and hiring new people is even harder. If you can hire someone that you've worked with before and you trust then you should do that.

I talked it over with my wife in early 2005. The payload complement had already been defined. They were starting accommodation review meetings and things like that at Goddard [Space Flight Center, Greenbelt, Maryland]. He's still trying to hire for this and doing what he can to cover the new project himself. I agreed; I talked my wife into it. Her one amusing comment when I said, "Hey, I want to go build cameras with Mike Ravine again." She looked at me, she said, "Don't you have that T-shirt already?" She agreed and so we up and moved to San Diego in probably April or May of 2005. I think shortly thereafter was the first time I got on a plane and went to Goddard and met the LRO team. Still holding accommodation reviews and obviously working on all of the various interface control documents at the time; the camera's relationship to the spacecraft, how it's all going to work.

That was how I found the job and got the job. I don't really know what that instrument selection process looked like. Dr. Mark [S.] Robinson wrote that proposal. He wrote that with MSSS. Again before I started there. Ravine would certainly know how Mark found us. I actually don't know that. It was one of the first times that we had a principal investigator who wasn't someone who works at Malin Space Science Systems.

JOHNSON: That was one of the things. Because a lot of what NASA was doing with Discovery was to have PI-led instruments or experiments or missions and then also have academia, industry, NASA, international type of cooperation to do this. Of course it was before the faster, better, cheaper that Dan [Daniel S.] Goldin had introduced in the '90s. It's interesting that you say that's the first time. You were working with Arizona State University for that then.

BRYLOW: I say that. For the Mars Observer Camera it was exactly that sort of layout. There was a mission at JPL and there was a principal investigator who also happened to be at Arizona State who was Mike Malin. There was us, the hardware team, which was at Caltech. That sort of layout makes sense. But one of the interesting things about Malin Space Science Systems is it was founded by a scientist. He had in addition to this hardware team that builds instruments, he had an operations group that was the SOC, the Science Operations Center, for the instruments that we built, and he had scientists on staff that he wanted to work with, and so they wrote proposals.

When he got the Mars Science Laboratory contract it was the principal investigators were Mike Malin and Dr. Ken [Kenneth S.] Edgett, who were both at MSSS and the hardware was going to be built at MSSS. It just happened that we were doing it for a JPL mission. That's a standard layout. You've got your scientist somewhere and you've got your hardware team somewhere. MSSS is odd in that we have historically had a bunch of scientists on staff too.

JOHNSON: Talk about that team that was being put together for that camera. Also where they came from and how that team was put together. Since you said that Malin was used to having a lot of people in that team that could do all of those things, talk about how that team grew out of that proposal being accepted.

BRYLOW: For a sense of scale I shouldn't let you believe there was a lot of people because I think the whole hardware team at that point was like 10. Again they got to build like three cameras for this Mars mission and three cameras for the LROC mission because for LROC there are these two narrow-angle cameras which are the big telescopes and then there's also a wide-angle camera which is a little fish-eye thing with like a 140-degree field of view.

MSSS had built something for one of the follow-on Mars orbiters which was called the Mars Reconnaissance Orbiter, MRO. There's a huge telescope on there [High Resolution Imaging Experiment, HIRISE]. It was built at University of Arizona. Then there's something that we built called the Context Imager [Camera] which we call CTX. It's like a 6-inch reflecting telescope. Primary mirror is about 6 inches. It's held on to two sets of electronics associated with it. They had decided before I got there that the only way we were going to be able to do this was if it wasn't all new development. They took the baseline electronics from CTX and started rejiggering to make it do what we needed. That was a little adventurous because the LRO mission is at a really low orbit. Really skimming the surface of the Moon. It makes our ground velocity really fast. It meant that the electronics had to run twice as fast for LROC as it did for CTX.

One of the first things we did is we started breadboarding electronics and trying to figure out if we could really make it run twice as fast. ["We" here means Mike Caplinger, who has been the systems engineer at MSSS for many years. He's really smart, with a software background, and taught himself enough about hardware engineering, particularly electronics, that he can fill that systems role]. That means the pixels are coming out twice as fast. Everything's got to be twice as fast. It's going to use more power. The margins on reading each individual pixel from the CCD [charge-coupled device] and taking it from the analog domain into the digital domain are a lot tighter. We weren't sure we could do that. Mike was able to do that. That made the development problem a lot easier. But it's the kind of reuse thing that I think you have to be good at when you're a small group.

We didn't so much build a team as gently expand a team at the edges. We hadn't really had an optics person on staff. We had always outsourced the optics work to another company. They had hired a guy named Tony Ghaemi who might have been on Robinson's list, I don't know, or we may have known him from our work with Perkin-Elmer on the Mars Observer Camera, as our optics guy. He has been building optics for a long time. He is a fairly unique combination of a designer and a builder. Normally specialization is so great throughout the economy that it's hard to find someone who spans those skills. We were lucky to get him to come on and do stuff for us.

I hadn't met him before I started. I made some comment at some point after I'd been there for a year or so. I said, "You're one of the reasons that I said yes when Malin asked me to do this job." He kind of looked at me skeptically.

He's like, "What do you mean? You didn't even know me then."

I said, "Yes, but the important thing for me was Malin understood that if we're going to build this company and if we're going to keep making cameras, we actually needed an optics capability in-house. We couldn't just keep contracting with optics vendors and trusting them, because that's a hard way to run an instrument. So not you specifically, but the concept of you made a difference in me being willing to accept the offer."

I'll say something else vaguely philosophical about MSSS because we talked about having the scientists on staff before. I think that instruments are better the closer you are to the scientists and the closer the scientists are to the development process. Because as you go through this, you're making decisions all the time that affect how good your images are going to be, what the pictures are going to look like. Do you make the electronics this fast or this fast? Are the filters this good or this good?

The closer the scientists are to those decisions and the more opportunities the engineering staff has to lay out why we want to do what we do, the better the result. I think that's true with optics as part of the instrument as well. Having all the instrument development in the same building is much better than saying, "We're building the electronics and this other team that we're paying for, that we're buying their services, are making the telescope." We still do a lot of that outsourcing, but we try to pick partners that we work with and we try to have a real connection and a real sense of responsibility passed through so we're not just buying a box. I think that's made a big difference in how well our instruments have performed.

Personally one of the reasons I'm doing this is because I think scientific investigation is great and I think space is great. I half jokingly tell people, "I've put myself in the service of science." There's a whole bunch of engineering jobs in the world, and you could do a whole bunch of things and take a whole bunch of career paths. This one always had a certain appeal to me because space is exciting and because science is important. I think we have a bunch of people at MSSS who at some level believe that. Again it makes a difference.

It makes a difference when you're talking to people at Goddard and we want the mission to go well and we care about our interfaces and we want to make everything work. It helps us do better science which is cool.

JOHNSON: You mentioned several things there that I wanted to talk about. The communication. Doing a lot of interviews, I've found that it seems like it's very important for teams to be able to communicate using the same language. Engineers have a language; scientists have a language. Depending on what science they're trying to capture you have people that do planetary geology and all these different specialties that go into these types of missions. As an instrument manager, is communication part of what you're doing between these different team members? Of course then you expand the team to people at NASA versus people at a university or people at your company. Was that part of what you were responsible for, helping to facilitate that communication?

BRYLOW: That's absolutely a part of it. That's a large part of it. Actually if you're interested or even if you're not, after the call I'll try to remember to send you an article that Mike Ravine and Mike Malin wrote that was a bit of a technical obituary for Ed Danielson that described what he did over the years in his career as a space scientist and engineer. He was my first boss on the Mars Observer Camera. He was literally probably one of the people who defined the role of instrument manager for space science hardware. He often found himself in that space between the engineers and the scientists and a little bit of money dealing with budget people. I think that a lot of what I've done, whether I consciously thought about it or not, is probably based on what would Ed do here.

Yes. That is a huge part of my job, the communication between the instrument and the spacecraft, between the instrument and the principal investigator, and trying to make sure that everyone's getting what they want, or that no one's getting what they want but everyone's getting enough of it that we can balance it all out. Yes. The interface definition with Goddard. We've got all this data. We want as much of the data bandwidth as we can because we generate a ton of pixels because we're a camera. How much can we get? When can we get it? The technical details become if we get it continually then we only need this much local memory storage on the instrument. If we get it in big spikes where sometimes we get a lot, sometimes we get a little, then we have to hold those images in the instrument. How those interfaces get defined drives the design. On the Goddard side of the LRO mission, our primary contact was a gentleman named Arlin Bartels, and he was perfect for this role because, as with MSSS, he really cared about the results and about optimizing the system rather than making things easy for his side and hard for our side.

It was a pleasure to work with him – there was always a sense of shared goals rather than an adversarial relationship.

On the other side when the science is driving the design on what kind of pictures do you want to take side. We're stuck in that interface no matter what, and we're having those discussions and doing that communicating.

JOHNSON: Can you think of any anecdotes or any specific instances where that communication was really important either to get something done or to avoid something from happening that shouldn't happen? I don't want to put you on the spot, but I just thought maybe you have something to explain what we're talking about.

BRYLOW: There was a time very early on shortly after I got there when I think the original design called for an 8-inch primary mirror, which is pretty good size. But we ended up looking at—Robinson has requirements and his requirements are for a certain signal-to-noise ratio. That means you're going to have to get a certain signal level in that. That means you need a certain number of photons coming in. Bigger mirrors mean more photons.

At the same time Goddard is on the other side saying, "Here's your mass allocation, this is what you get to use." In all these projects at the beginning you have the whole 30 percent margin. Later on the usual 25 percent, 20 percent. They release margin as the design matures. There's less uncertainty in the rest of the spacecraft.

Initially with a 30 percent margin the whole spacecraft is probably oversubscribed. I've never done that spacecraft systems role. But that's my expectation. Everyone has their budget, and that means if everyone meets their budget, we're okay. If everyone exceeds their budget by 5 or 10 percent things are going to be okay. But if everyone exceeds their budget by 30 percent, we're all broke.

We have a 30 percent margin, but we can't really use any of it. At some level we came up with a design. Our optics constructor had to come up with a design that said, "It's got an 8-inch primary." We ran the numbers and they said, "Yes, there's enough signal here. That'll be okay." It was really pretty tight. When you're designing an instrument, you have margins for everything. You don't just have the margins that the spacecraft gives you. You have all these science margins too. Like we want a signal-to-noise ratio of 50 to 1. It'd be okay if we have 40 to 1. It'd be unacceptable if we have 30 to 1. We were probably at 50 to 1 with an 8-inch primary. Maybe there was no way that we could have argued that we needed more, because hey, we were meeting our requirements, but the real world always interjects. When you've got a design that meets those requirements the implementation is probably going to fall a little bit short.

We eventually told the optics vendor, "Come back to us with a bigger primary mirror, come back to us with a different design." We went to Goddard and said, "We're going to need more of those mass resources. I know maybe you don't want to release them this early, but this is what we need to do to meet our requirements." There were conversations about that. Eventually—and this is one of those places where I don't remember the details. I'm sure Goddard wasn't excited when we went to them with new mass numbers. I can't tell you how much of our margin if any we really ate, but it was more than we originally told them we were going to weigh. We said, "But we got to do this because otherwise we're not sure we can meet the science requirements." They said, "Okay."

JOHNSON: It seems like it's a balance. It's a pretty specific balance.

BRYLOW: It's always a balance. It's a balance overall, and then every time you get into the specifics it's a balance there too.

JOHNSON: The camera was just one of a suite of instruments that were going on LRO. There was a quick turnaround for this type of mission. It was a pretty quick turnaround and was supposed to launch in 2008. Talk about that for a minute. As one of those instruments in a suite of instruments, working towards a deadline, and that integration with LRO and then it gets one more thing with LCROSS [Lunar Crater Observation and Sensing Satellite] being added, and then that delays things. Talk about that timeline and the integration and how you worked with the LRO team to keep things on schedule.

BRYLOW: We never kept things on schedule. Unfortunately I think we were the last instrument to deliver. The great story about this depending on your point of view is that the project directed us to charter a jet and fly the telescopes out to Goddard. This is where everyone goes, "Oh my God, taxpayer dollars." But if you think about it there's how many people crawling all over the spacecraft waiting to put our telescopes on, and Goddard decided that four days of driving across the country versus one day of flying them there, that's three labor days of schedule risk of oh my God, we're not going to make the launch date. We have people sitting around. What are we going to do? We need them here now. I think the charter cost like $40,000. Versus in all fairness it's probably like $10,000 to have FedEx deliver the customer-critical shipments and drive them straight across the country. It was a definite added cost. But on a $6 million or $10 million instrument suite $40,000 to get you over the finish line probably doesn't seem like a bad investment.

It was very funny. It was delivered in 2009, not 2008, as you know. Thanks to the LCROSS delay. We had problems along the way that caused delays as well. We needed a bunch of that extra year. But when the time came to fly, if you're curious, I'll tell you. It's not as glamorous as you might think.

We had some small jet. You can't really stand up in it. Although the seats were mighty comfortable. We had the box. The telescope itself is about 3 feet long and a foot in diameter. The box it has to go in is about 4 feet long, 18 by 24. It's a big box. We had to find a jet that didn't just have seats but had enough storage room to put two of these big boxes and all of the ground support equipment we needed and all of the other stuff.

There's like four of us on the flight, including Jake Schaffner, one of our lead electrical engineers, who is tall, maybe 6'2". The flight is filled with these boxes. The greatest thing I can tell you about it is that this is all post 2001, so flying fundamentally changed because of all the security changes. We walked up to the plane in the morning. We walked into the hangar and the hangar guy said, "Your plane is up there."

The little stairs were down. The guy walks off the plane who was supposed to pilot. He's like, "Are you guys ready to go? Just let me know when you're ready." That was it.

JOHNSON: That is funny.

BRYLOW: Yes, it is. It's not a very big jet. It can't actually fly across the country. We had to stop somewhere. Again this is the lack of glamour of this. We stopped somewhere in Oklahoma to refuel at some general aviation airport. We all got out, stood up, and stretched our legs. But during the approach they said, "Well, we can order lunch for you. There's a Subway or there's something else like a Burger King. You can order Subway or Burger King. We'll have it show up at the terminal." We had Subway. It's not a charter flight. There's no china. There's no service. There's the pilot and there's the copilot. There's like the four MSSS engineers. It was fun and entertaining. But it needed to be done. It made perfect sense. A great story in retrospect.

JOHNSON: Yes. It's interesting because yes, you wouldn't think about necessarily if you have to get it there fast how did they do that.

BRYLOW: There's some other story. We didn't piggyback but JPL had to bring something back for some other mission. I wasn't on this at the time, but Mike Ravine has a picture of a C-17 [military transport aircraft] that's empty except for a box that was our box. They sent our camera back. It had gone somewhere to do something. It was coming back. It just hitched a ride. But this gigantic cargo creature with this one little box in it.

JOHNSON: Seemed like they could have packed it up with something.

Integrating though, you were talking about there were some delays that you needed that extra time. What type of delays were those?

BRYLOW: There were two big redesign events that were design problems. We had an optics vendor, LightWorks Optics. They're in Carlsbad. They're in southern California in Orange County in between LA [Los Angeles] and San Diego and the guy we worked with most closely was Kent Weed; he did a great job for us all the way through the project. They had a subcontractor, want to say Vanguard Composites [Vanguard Space Technologies]. I think they changed names a couple times. We had worked with the people at Vanguard on the Mars Observer Camera. Again it's good to work with people you know and trust and have experience with; they did great work on the MOC, one of the guys was John Richer [*Ri-shay*] and he was still there. They came up with a design that was a composite structure so it's graphite/epoxy. It's really lightweight. The tube is graphite/epoxy. The primary mirror sits at the bottom. There's this thing we call the optical bench which is a disk and it's stiff. You mount the primary mirror to that. Then you bolt the tube to that. They did this design. It went through a review. We reviewed it with what we thought was some level of expertise. But it was the sub of a sub. LightWorks reviewed this too. Then the composite team built an optical bench. Then at some point somewhere in the process we all discovered that they had failed to square some factor, and so they had built it to withstand like 3 g or 4 gs instead of 15 gs.

JOHNSON: Oh. Goodness.

BRYLOW: So we had an optical bench that we thought was just going to absolutely implode if you shook it the way you do during launch. For everyone who doesn't know, the big serious set of testing you do before final delivery are the environmental tests and one of them is a thermal vacuum test usually to simulate space. Another one is the vibration test where you've got to show that you can survive the forces that the instrument is going to be subjected to during launch.

We needed it to be designed for 16g because that's what Goddard had told us the launch environment was going to be like. We designed it for 4g. We had built a bunch of hardware to that 4g design. We hadn't tested it yet but the hardware was built. That was no good. We ended up making new ones from scratch, but we couldn't make them fast enough.

We flew one of the new ones eventually. But for the other one we took the existing 4g design with this composite design. It's got a honeycomb interior. There's a round sheet on the top and a round sheet on the bottom and then a whole bunch of crisscrossed vertical ribs on the inside. LightWorks and Vanguard worked together to figure out a way. The lead engineer at Vanguard, Toan Pham, was great throughout this process. Even though this was all glued down, when you use these glues, these are not reversible activities. They figured out a way to take the sheet off and add doublers to pretty much all of those vertical ribs so they'd be a lot stiffer. Then they destroyed that sheet in the process. They put a new sheet on. We had one new one and one reworked one. I think those are the ones we ended up flying. That was one huge time cost.

We obviously had to also do the redesign and analysis to figure out how to make that new one so that it was going to be stiff enough and strong enough. That set us back a number of months. We were figuring out ways that we were going to deliver anyway. But we were obviously feeling really good once we got that launch relief, which I guess was fundamentally due to the addition of LCROSS. Everyone breathes a sigh of relief and goes on their merry way.

Then the next one that I recall is we have a telescope built and we require LightWorks to do their own vibration test before they give it to us to integrate, because we don't want the first time that we shake it to be when it's all done already. They do a vibration test and there are a couple of cool definitions of success. There's one cool one that I never thought of before.

The way you know if you pass the vibration test—and this is a little geeky but not too detail-oriented I think—is the vibration level could be some number of gs that's going to simulate the whole launch like 10gs or 12gs. Shaking back and forth. But what you do beforehand is you shake it like a quarter g.  A little resonance shake.  You do it at this whole range of frequencies. You slide along in frequency giving a little shake the whole way from like 20 hertz to 2,000 hertz. You look at how it responds.

Everything has some characteristic response.  There are places where it doesn't sympathetically vibrate and there are places where it does and it's a resonance that you get more energy out because it's ringing like a bell a little bit.  You don't necessarily feel it but it's behaving that way.  You characterize it before the test, and you have this graph that shows how it responded from 20 hertz up to 2,000 hertz.  Then you do this full-on grand test where you're hammering away at the thing and hoping everything's okay.

When you're done you can look at it, but how would you know if something inside broke? What they do is they run this exact same sine sweep event and they look at that response, the signature of it, and they overlay that.  If nothing changed then you're golden.  But if all of a sudden you had a peak here and that peak moved over something changed on the inside.  I don't know what it was but something ain't right.  It's very cool.  I'm not a mechanical engineer.  I'm an electrical engineer.  I never knew this, and I just thought it was a little clever way to tell what's going on.  That's the first thing you do.

The second thing you do for at least a telescope is you take pictures.  If something in the optics is no longer aligned the way it was, the image quality will be worse.  We've got this telescope at LightWorks, and they take it through their vibration tests.  They do the sine sweep afterwards and it's different.  Now we know something ain't right.  What changed?  Eventually they narrowed it down to the secondary mirror.  The secondary mirror had shifted and it wasn't bonded well enough to survive the forces.  It's like a big old reflecting telescope.  There's a big primary mirror at the bottom that I've been talking about, the 8-inch, 10-inch, whatever.  The light comes in, it hits the primary, goes up and hits the secondary, and then bounces back down to your focal plane. It's like the amateur telescopes you might have at home.

That secondary mirror shifted. It shifted a very small amount, but it shifted once. Who knows what's going to happen for the real launch? That's not acceptable. We took a whole bunch of pictures. They did. We worked with them to figure out what was going on. We figured out that the bondline had fractured. The adhesive had started to break. It had let the secondary mirror move. They had to redesign the secondary mirror mount and again we had one that probably got built new and one that got reworked. Maybe they both had to get reworked at that point. They added some more composite material. They rebonded. They took the secondary off and rebonded it. It was all much too much of an adventure but also cost us a few months.

One of the hard parts about this is it's not quite as simple as saying, "Oh, this broke, let's fix it." The way you might do with your car. You really want to be convinced that you understand the root cause. There's a whole bunch of poking around. Did we see that much force? The force was more than we expected because we did the analysis wrong? Or the force was more than we expected because the workmanship wasn't right and we didn't bond some other things and so it let more force be transmitted through? There's a long investigation into what's the root cause of this. If we make this fix, we know that this won't happen again. Not just that well, the mirror came off, let's rebond the mirror. That again cost a few months but LightWorks was very thorough and involved us in the process and were very open about their findings. They want this telescope to work as much as we do, and Kent Weed and their team were consistently rigorous and communicated well throughout the failure investigation. Then finally now we have a telescope we can deliver and get that off of the plate, so they did that work, they delivered it to us. We put the electronics on. We did our flight vibration test; we did our flight thermal vac test. We also spent a bunch of longs days with the instrument calibrating it; the science team showed up and we took pictures of specific light sources and targets and determined exactly how the instrument behaved so the science folks can learn more from the images they get back. Mark Robinson spent long days there, so did Brad [Bradley L.] Joliff and a younger guy who may have been a post-doc at the time, Martin Tschimmel. They worked really hard to get everything done quickly so we could deliver Then we got on the plane to pick it up, bring it to Goddard.

JOHNSON: You did the testing there before you delivered it?

BRYLOW: Yes. We had a mechanical engineer through the design phase, and then lost him to parenthood; he took off for paternity leave and didn't come back. That made preparing for the testing more difficult. We ended up getting a lot of mechanical engineering support from a small shop [Quartus] that helped us with lots of the analysis, and provided test support through the flight testing we did. They had a thermal group in Los Angeles that helped us predict temperatures and prepare for the thermal vac test; an engineer named Debbie Detch did a lot of that work. And the San Diego office did the mechanical analysis; Jeremy Gustin and Josh Lukens both did great work.

JOHNSON: Was it tested again once it was delivered?

BRYLOW: There's more technical details in that one. Yes. Yes, it was. The spacecraft undergoes a vibration test too, and those have to be just terrifying. I've never actually seen one.

JOHNSON: I was going to ask you if you were there.

BRYLOW: No. But there's a rule of thumb. They excite the whole spacecraft to the same levels that they excited the camera. But the engineering rule of thumb is every time you go through some joint, the force is reduced. If we make a test to this level, and that gives them a lot of confidence, but then they put it on the spacecraft and they shake the spacecraft to that level, we're actually seeing a lower level. We do the testing conservatively. There's a ton of conservatism in all the space hardware. You never want to be surprised further on in the process. You want to test as hard as you can as early in the process as you can, so you have some time to address any problems you find.

JOHNSON: Do the instruments go through their own PDR, the preliminary design review and critical design review? Talk about that process. You mentioned the flight readiness testing, but there were also those reviews getting ready for that. Talk about that process for a minute and what your role was with any of that.

BRYLOW: Yes. The first thing that we did was the accommodation review. I think I wasn't around for that, like I said. Mike Ravine and Jake Schaffner did that prep and presentation at Goddard. Accommodation review. Preliminary design review. Critical design review. Then instrument delivery review. Sometimes there's also a slightly smaller test readiness review. The instrument is done but before you can go into those tough scary environmental tests you typically have to sit down with the project and show that you're ready and make sure you know we got the levels right, we read your documents right with the requirements. There was one of those too.

The PDR was interesting. There were a bunch of Goddard people there. I'm struggling to remember the difference here, but there were Headquarters people there but there were also, because it was part of the—so SMD is the Science Mission Directorate, but there's some other Exploration Directorate [Exploration Systems Mission Directorate].

We knew all kinds of people in the Science Mission Directorate because we had been canvassing people for a while. But this was in the Exploration Mission Directorate at the time. There were all these Headquarters people that we didn't know. For some reason at our PDR there were military people too. A couple of the review board members or somebody was in attendance who was actually military and was in uniform, and that was a little weird for us.

The other thing I distinctly remember about the PDR is that we've got a guy who is still with us who's now been there for just about 20 years, Jake [Jacob] Schaffner, could have been on Robinson's list, he may not even know the story. Maybe he should be listening to my interview. For the PDR you have to go through all the different sections. Here's what the instrument is. Here's what the science requirements are. Here's what the spacecraft requirements are. Here's how we're going to meet all those requirements. Here's the electrical design. Here's the mechanical design. Here's the optical design. Here's the quality assurance part of this. Here are the risks that we're looking at. Here's the budget. It's a complete review of everything you can think about for the project.

It's usually a long, long day. Because this is how we all communicate; it's a 300-slide PowerPoint deck. We're putting all this together, and I'm up there talking for a bunch of it because I'm the instrument manager. I'm doing all the instructions; I've talked about the requirements. I've talked about the various pieces. But for the things like the software or the electrical stuff or the mechanical stuff we typically have the lead engineer or the cognitive engineer for that section go up and talk.

I talked for a couple hours at the beginning. I go to the back because we're going to talk about the electrical design now. It's a roomful of like 30 people and everything seems to be going okay so far. Jake Schaffner heads up there. He's a lanky kid at the time. He's probably 24 years old, out of college for a little while, been working. I think it was his first job out of college. He's been there for a year or two. He looks like a college kid.

I'm in back making sure this is all going okay and watching the audience and being available for questions. Mike Ravine comes in, my boss still at MSSS. He's standing next to me and I look at him and I said, "Jake looks like just a kid up there." I'm kind of worried about the impression he's leaving and are they taking him seriously, are they going to believe his skills, are they going to push him hard on his slides. Jake is extraordinarily bright. It wasn't a problem at all. But when I said that to Mike, he looked at me and he said, "We were all younger than that when we built the MOC." That put it in perspective to me that we were crazy and young when we did that. I wasn't sure how anyone gave us all that money without sufficient adult supervision.

The output of the PDR is always a bunch of RFAs, requests for action. There was nothing unusual in the RFAs. They said, "We think this is weak or we need to pay more attention to this." Then you have to address all those RFAs before they let you proceed with construction, or before they let you proceed with the rest of the design. The CDR thing is the gate for actually starting to build things. After the PDR we can start ordering parts and finalizing designs and things like that.

JOHNSON: You delivered it and it was integrated into LRO. Were you out there at all for the integration or for the launch?

BRYLOW: I was out there for both. I'll tell you the integration story now. Giulio [Rosanova], the mechanical lead at Goddard, great guy, I'd love to work with him again, he was really good. I kept asking him—the NAC [narrow angle camera] instruments [the big reflecting telescopes] are very back-heavy. It's 3 feet long but the front 2 and a half feet is the optics and it's all this graphite/epoxy composite tube which we use it because it's really light, so it doesn't weigh anything. Then there's the primary mirror most of the way back, and then at the back end are the electronics. The whole thing is back-heavy.

When they integrate it, the way the spacecraft design ended up, it was kind of in a box. There was what we called the adapter plate which had the telescope over to one side and the electronics over to the other. The electronics are just this little box. They weigh a lot but they're smaller than the diameter of the telescope. We got this thing that's got three bolt holes in it and it's going to bolt onto the spacecraft.

But in order to put it there you have to feed it in from the back through this little hexagonal hole that's not much bigger than the telescope. I keep asking Giulio, "When are you designing the fixed ring to do the integration? We need some tooling that's going to have to hold this. We've got holes in the back that we can bolt a couple of handles to or we can bolt some fixtures to. Then are you going to use a jack? Are you going to use some hanging device? Are you going to slide it in? It doesn't feel like we're making a lot of progress."

He's like, "We're working on it. We've got something." I get there. They're just going to install it by hand. I'm a little freaked out by this because I've spent four years building this. It's worth a few million dollars. I'm not looking for any accidents now. They show me one of the guys. They said, "He's going to integrate it." Trick [Carroll Trickey]. His nickname was Trick.

Everyone called him Trick and he was a big guy. He's probably six-three, couple hundred pounds. Good size guy.

I don't want to say I'm warming to the idea. But I'm like, "Well, this is possible." Instrument weighs, I don't know, 15 pounds or 18 pounds. He's going to have to just hold it out and slide it forward for like two and a half feet to get it into this thing without banging it around.

The day arrives. We get there. We do some testing just like on an optical bench. We do some post-delivery testing always. Just like an aliveness test. You put a target in front of the image. You take some pictures. Yes, everything's fine. People always seem to like to do it. I don't think it's worth the time. You look at the instrument. Nothing happened to it during transport. It's fine. Just bolt it on. But anyway that's just my bias.

We do our bench testing and I'm still kind of frustrated by this and I made them gin up a hexagon and bolt it to a bench. Then I had Trick come down and move—we had some engineering model. We built some tube that was the right size, and we put some weight on the end of it. I had him move it in and out there. I'm like, "Really I want you to practice this." We did that.

To their credit, they did an outstanding job of integrating it. All my fears were totally unreasonable. I delivered a couple of six-packs of beer to that team that had to do that.

JOHNSON: That's a funny story.

BRYLOW: It was great.

JOHNSON: Like watching somebody hold your baby for the first time.

BRYLOW: That's a great analogy, but 48-month gestation period. Didn't want anything to happen.

JOHNSON: How long before the launch was the integration?

BRYLOW: A year. There's a lot of stuff that goes on. All this stuff goes on afterwards. I want to say integration was May of 2008 and launch was June 2009. There's all the spacecraft stuff. Once they get it all together, they've got to do all their system testing stuff. They've got to do their environmental tests. A whole bunch of logistics stuff. Then there's all this stuff with the rocket that I don't know anything about. They've got to get the spacecraft up under the cone in the fairing. They've got to get the thing out to the Cape [Canaveral, Florida]. It was a year.

JOHNSON: Talk about the launch and what that experience was like.

BRYLOW: It's not as relaxing as you might think, for two reasons. First of all you're terrified something's going to go wrong. But aside from that a successful launch doesn't tell us anything. We still have to wait till we're there. Does it work?

JOHNSON: Exactly. Did it survive the launch. Yes.

BRYLOW: Right. The launch was nice. Everyone's winding down. You're done with the awful part of the project. You're done working crazy hours. You've done everything you could. Everybody's feeling pretty good about it. It's nice to visit with people and not be freaked out about oh my God, there's still so much to do. That's great. We saw the launch from some enormous distance. It's fun to watch it go up. It's fun to be down at the Cape.

I remember seeing the big Saturn V on its side in some big shed. That's just crazy impressive that you can use some rockets like that again in going places. It'll be great when we do.

JOHNSON: Like you said, you didn't know if your instrument was going to be working right after the launch, so there was that period of time. Talk about when you first knew when it came online and you knew it was working and those first images that came down.

BRYLOW: Then you're really like, "Yes, we did this. This is great." Robinson was obviously ecstatic. But the euphoria wears off too. While Robinson is ecstatic it's like it's working, it's taking pictures, this is great, then because he's a scientist and it's his job, he's immediately nitpicking. He's like, "Well, is this noise? Is this a real feature? What's going on here?" Because there's still when they get the images a whole bunch of post-processing that goes on. Can I line these up? Here's what I thought the field of view was but then I designed this to overlap so what's going on here? That kind of thing.

Everyone's thrilled. But then again, you're back in the day-to-day of is this good enough, can we make it better, what can we do.

JOHNSON: Were you looking at things that you could do to make it better for him? Or was it just suggestions on what could be done if he wanted things a little better?

BRYLOW: There's a handful of operating parameters that are software-controlled. Is the exposure time right? This is what they call a push-broom camera. It's a CCD line array, it's a single line at the focal plane. We build up an image by exposing that line every time the spacecraft would move one and a half meters, you take another line you get off the CCD. The timing has to be right.

We got there, it's like is the timing right. You can change the timing a little bit. You can change the line time and then you can change the exposure time within that line. There's parameters that he can tweak. We don't need to do that. He's got all the tools to do that, but he can ask us, "Well, does this make sense? If I do this, will it affect anything else?" We document the software as much as we can [this is Mike Caplinger again, the systems engineer and lead software architect and author – really impressive he can manage both roles], but you can never imagine all the different things people might try. There's always conversations about well, the software is doing this. Under the hood what's really going on is this. You still have this level of control.

We have those conversations. But mostly it's in the hands of him at his Science Operations Center to develop the commands and send the commands up to the instrument, get the images down, run them through their processing pipeline, and then they look like pictures.

JOHNSON: There seemed to be a push to make sure that they could get those Apollo landing sites and photos of them. They were trying to do it, from what I read, they were trying to make sure they did it in July for *Apollo 11*. Do you remember that time period? Maybe some of those first photos of those landing sites that came back.

BRYLOW: I don't remember the first honestly. I do remember pictures and thinking ooh, that's awesome. There were discussions beforehand. Taking pictures of the landing sites was not a science requirement. I remember discussions where that was a frame of reference. It's like well, if we're doing half a meter per pixel, we'd be able to see the package they left. The lander thing will be this many pixels. That I thought was interesting at least in the back of our minds the whole time.

JOHNSON: Talk about the science requirements for the camera and what the purpose of the camera was to be. About a year is what they were thinking that LRO would work. One of the gentlemen I talked to from NASA said this was an engineering project mission that became a science mission, which I thought was interesting because that's what's coming from it and still coming from LRO, is the science. Talk about what those requirements were for the camera to begin with, as far as what they wanted to do with it. Technically I'm sure there were a lot of requirements. But I'm talking about what they were planning to do with those cameras.

BRYLOW: Those cameras, the thing that was interesting, I'll tell you a little story about that. We always understood that it was looking for landing sites. That was the real motivation. The resolution was I think driven by how much uncertainty do you want about what you could hit on the way down. If we got half meter per pixel, you can see meter size boulders. If you can see meter size boulders you could avoid them when you pick a landing site. That's really important.

Robinson never viewed it as an engineering camera. It was always a science camera because he's a scientist. But it's a panchromatic camera so it would take all wavelengths from 400 to 700 nanometers from blue to red. It just returns. There's no filter so you can't tell what part of the Moon is a different color, which is fine. Because from an engineering perspective if you want to know what color the Moon is go out and look at your driveway. The Moon is gray. It's all gray all the time. That's what color it is. There's not really a lot of science about oh my gosh, what colors are there.

There is in the sense that people try to do mineral composition estimations from different spectral bands. We have some of those on the wide-angle camera. But fundamentally when you and I look at the Moon it's gray. There's not a lot of fascinating science to be done there.

Like I said, Robinson is a slightly different because they're looking for minerals. The mineral thing is interesting because that is the intersection of science and engineering. The scientists want to understand the composition of the Moon so they can decide its history and how it formed and what it formed from. We want to know the composition of the Moon because when we go there, we want to know what we can mine. What are we going to get out of this? What can we make there that we don't have to bring?

There's a Korean mission that just got there that we also built the camera for; it's basically a modified NAC from LROC, but it's called ShadowCam. It's looking for water in the permanently shadowed regions at the poles. Even if there were trapped water at a one or two percent level in some of the rock that's on the Moon, that's something that you could conceivably mine if you went there. That's a really interesting thing. That's again engineering and why do we go to the Moon or if you try to go to the Moon what are you going to do. Trying to figure out how people can live there. People need water. Let's go look for water. In that sense ShadowCam is an engineering effort too although science because how you get water on the Moon is fascinating. Came from comets, came from crater impacts. Maybe you look for it more at crater rims. Stuff like that.

JOHNSON: Of course LCROSS brought some attention to the mission because of looking for that water ice. There was probably—well, I'm not going to say more attention because all the different flights have different amounts of attention from the public. But this one seemed to garner a lot of attention because of course looking for water on the Moon.

BRYLOW: That and blowing stuff up. Not blowing stuff up. Making craters. Making craters has got to be fun.

JOHNSON: Yes, that's always cool, right? Talk about that. Were you aware of the amount of attention that this mission was getting and the part that the camera was playing in it? Because you were bringing those images back. There's always the people that said we never even landed on the Moon and then those images are coming back of the landing sites and the things that they could see. There was a lot of attention in the media and in the public about that. Were you aware of that or did your company work with any public relations people? Or did you have to speak to any press or anything during this time period?

BRYLOW: We're historically pretty cloistered. We don't spend a lot of time doing that. Being really small, that's expensive, we weren't really looking there. But the "we never went there in the first place" thing always struck me as funny because I remember someone, and I don't think it was Mark Robinson, saying, "Once we have these LROC pictures they'll see that we absolutely went to the Moon."

I'm thinking okay, I worked in the web business in the '90s and paid a little bit of attention to image processing or image handling tools like Photoshop. I think it was like 1997 or 1998 when I decided that I just didn't believe pictures anymore because the image manipulation tools are good enough that you can do whatever you want. If there's people that didn't believe we went to the Moon before, they're not going to look at these pictures and decide that we didn't just move those pixels around to make it look like a lander. That's not any additional proof.

JOHNSON: It is interesting. Now with AI you can't believe anything.

BRYLOW: We landed on Mars; did I mention that?

JOHNSON: How long did you stay with Malin after the launch and when things were coming back?

BRYLOW: There's two answers to that. One is a handful of months and the other is forever.

JOHNSON: That's what I was wondering because it looks like you've been with them. I was just curious about that.

BRYLOW: My wife and I were in London from 2001 to 2004. We moved back to the Sierra foothills while we decided what to do. I had some consulting work in the Bay Area. Then we moved from there down to San Diego for LROC. I told Ravine near the time we delivered that I would be leaving. I gave him my 18-month notice. Or I gave my six-month notice when we thought we were six months from launch. I'm like, "I'm going to leave after this." Then there was a launch delay at some point. I'm like, "Okay, that was my 18-month notice. Still I'm leaving after LROC." He said, "Well, that's too bad but okay."

My wife and I have a couple of kids and we have taken turns with somebody always being at home. When we were in London I was at home. When we went down to San Diego she was at home. It's her turn to work again. Then we moved up from San Diego to the Bay Area in like 2009. A year after delivery but just a little while after launch. Moved up to the Bay Area, and she started working again.

But there's always stuff to do. I was doing some part-time contract work for MSSS from 2009 to 2017. At some point that became regular enough I think like 2017. They said, "Well, with all those rulings about what constitutes an independent contractor we can't really have you contract anymore because we're your only client and that doesn't look good for the IRS [Internal Revenue Service]. You have to be an employee." Then I started working for MSSS again. I did that until January of 2022. At that point that's when my wife and I moved to Morgantown. MSSS is still a small enough company that there are HR [Human Resources] hassles about this. They're like, "We don't have out of state employees, so you need to find someone you can work for, some contract house. You'd work for them and they'll contract you back to us and it'll be fine." That's what I'm doing right now. I never left but held three different jobs there at some point.

JOHNSON: Looking at that mission and LROC, as we talked about some of the cameras were similar or had been from other missions. That company, that seems to be what they do is provide these cameras for these different missions. But just thinking about that mission in particular, what were some of the lessons learned that maybe you carried on from that mission? Or working with NASA and continuing to do that in that company on different missions?

BRYLOW: A harder one than you think. What we learned new on that one. Because honestly at that point a number of people had been working with JPL or NASA or Goddard for pretty close to 20 years. It wasn't our first rodeo is I think the phrase. There was a little bit of an adjustment working for Goddard instead of JPL. Some things were easier. Some things were harder. I'm trying to think of examples. It felt like some of the interface stuff was a little easier. But at some level it also becomes very person-dependent. The payload manager is a critical person for us because it's the first person that we deal with before we start talking to the experts. We always dealt with a guy named Arlin Bartels, who could well be on your list.

JOHNSON: Yes. I'm going to interview him the first part of June.

BRYLOW: I have only good things to say about Arlin. Arlin was instrumental in the success of LROC. I would love to be working with him again. I think we're actually working with him on the DAVINCI [Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging] mission to Venus. We have a couple cameras on that. I believe Arlin is leading the payload effort on it out at Goddard. Arlin is awesome. You'll have a great time talking to him. He'll have great stories. Hopefully not too many about me.

JOHNSON: That's interesting that that is an important position. I would think so, but that's interesting that that's something you would highlight.

BRYLOW: It's the sins of commission, sins of omission. He's the interface to the rest of the spacecraft for us. If he thinks something's important it's going to get attention. If you haven't convinced him that you have a good story or good reason for doing what you're doing then maybe that's the one that gets slow-walked because there's a lot of other demands too. He's the judge and jury at some level. Is this the right thing to worry about? It's an important role. He has a lot of wisdom in his ways of working.

JOHNSON: Are there any decisions that you made on LROC that looking at it in hindsight maybe you could have done differently or you would have not made? Or maybe you're perfectly happy with it and you've carried that over into another project. Just anything that you did in your position with that. It's fine if you say no. But I was just wondering if there's any of those kind of decisions that maybe you wouldn't choose to do again.

BRYLOW: I'm thrilled with it because it's been working for 13 years.

JOHNSON: Exactly.

BRYLOW: There was definitely stuff along the way. One of the good ones was that 8-to-10-inch primary mirror change. We did that early enough because if we'd waited too long then it would have been impossible, it would have been too far along in the design.

One of the other good ones was for the wide-angle camera, which we really haven't talked about very much. We got to reuse a design. But maybe one of the bad ones was we struggled with how to make a filter fit on top of the CCD. Like literally on top of that. CCD is a little imager thing like you look into your camera lens, you'll see a little thing in there. We literally designed a filter, had somebody make it, and we set the filter down on the bare die about a thousandth of an inch off the CCD, and we glued it down.

We don't take that design approach anymore. It worked, but it was fraught with peril. We were nervous the whole time. We broke a few CCDs doing that. It's really hard to get that stuff. The filter yield is really low because they make all these separate filters and then they cut tiny little pieces of them and then they glue them together. They make little butt joints. You've got five different filter bands or six filter bands on this little like half inch by half inch.

JOHNSON: Goodness.

BRYLOW: It was hard. We try not to take that approach anymore. I would love to not have done that. Because it was an older design and we just reused it, we didn't want to make any changes at all, we just wanted to use the stuff we had. The connectors were these single row connectors and there were two of them, and they were identical. One of the flight rules is you never make connectors the same because somebody will mess it up. Somebody did mess it up. No fault on them. We should never be delivering hardware that's like that.

Nothing bad happened because they caught it before they got powered. No. I'm sorry. They didn't swap them. But what they did was there wasn't enough material around there. It was possible for them to offset the connectors by one pin. They had the two connectors in the correct orientation but one of them was offset by a pin. That's going to push power where there shouldn't have been power. It would have been bad. But somebody noticed it during inspection. We don't use those connectors anymore either, so that was absolutely a lesson learned. We shouldn't have delivered something like that where there's a possibility of mis-attaching the thing because that would be a lot of work down the drain.

JOHNSON: You were building it to last but I don't think anyone expected it to last this long when it was first launched. Talk about that for a minute, the fact that it's still working, and obviously it's still working well because the photos are still being downloaded for the public to see and for people to use.

BRYLOW: In general once it's through launch there shouldn't be any mechanical problem. It's just around in empty space. Once you get through launch you check the mechanical box, you're like, "Okay, this is great." For the electrical stuff, there's this great thing that electrical engineers know about called the bathtub curve for reliability. You may have run across this from all the people you talk to. Basically electronic stuff fails at the very beginning or it fails at some really long out in the future end of life. The failure curve starts high and then it goes down to almost zero and sits at zero for a really long time. We're down at the bottom of that bathtub with LROC. We're just hanging out. I'd like to say that it should survive for a long time. It should keep working.

The caveat is one of the things that you design space hardware for is the radiation environment. Small electronics don't deal well with too much radiation. We're waiting to see if there's any performance impacts from radiation particularly with the image sensor of the CCD, because they usually can only handle a certain dose over their lifetime. When they start getting noisier, images might not look as great. It's a gradual thing. I think they're still okay for a while.

A phrase I use with my kids all the time when they do something reasonable is I am pleased but not surprised that it's still working.

JOHNSON: That's a good way of putting it. I read an article that they're still finding new impacts because the Moon is being impacted all the time, so for landing purposes for Artemis they're still finding these new impacts.

BRYLOW: This is a cool science thing that I didn't know. I knew there were new impacts but there's apparently a power law rule for impact versus size. It holds up across orders of magnitude. If you know how many really small impacts there are, you actually can make a really strong prediction about how many big impacts there are going to be. They've spent a whole bunch of time I think, in the same way we used to look for planets in the '30s when they were trying to discover Pluto, they'd take these sky survey things. They'd lay one plate on top of the other and look for something that moved. We've had the opportunity—this is one of those science versus engineering things. We've now been up there for 13 years. We've had the opportunity to image the same place over and over if we choose. We have all these different comparisons we can make and we can do these really really thorough impact counts. I think that's great for being able to predict the chances of a large impact or just the ongoing low-level impact that we're going to have when we have bases on the Moon.

JOHNSON: Looking back at that mission in particular and also the other times you've worked on NASA missions, is there anything that you would say you were most proud of?

BRYLOW: Most proud. Like I said, boy, I'm proud that we got there and it's been doing this for 13 years. It made Mark Robinson a happy man. I'm thrilled that that's the case. I'm proud that we didn't screw anything up. I'm proud of the team we assembled to do the work, and Mike Ravine gets most of the credit for that. Honestly, Ravine gets so much of the credit for making MSSS the hardware organization it is today. Malin obviously started the company and plays a huge role, but Ravine has been there running the hardware group and managing camera projects on a day-to-day basis from the beginning. He's been a great boss and friend of mine for decades now.

JOHNSON: That's a good one.

BRYLOW: For the systems engineer, much more so than me, but for me too, someone once described the job as it's all triage [Mike Caplinger said this]. You make the longest list you can of everything that could possibly go wrong and then you try to rank order it in terms of likelihood, and you work your way down the list. The further you get down the list, the more likely it is to work. I'm proud of the fact that we had this challenging instrument to build and we made it far enough down that list that nothing's gone wrong yet. That's huge.

There are a couple of things I'm really proud of from the Mars Observer Camera. They're things I'm proud of and lessons learned. Those electronics were hugely challenging. They had to be again really fast. The boards were round, which is a horrible idea. They sit behind the primary mirror, they're 14 inches in diameter, and they're round. The problem with round boards isn't that they're round. You can make round stuff. It's that all the layout tools are Cartesian. They assume that you're making straight lines. The closer you get to the edges the harder it is to lay stuff out.

JOHNSON: That's interesting.

BRYLOW: That's a lesson learned. Never make round circuit boards.

JOHNSON: You've continued to work on some missions too.

BRYLOW: None of the boards have ever been round again.

JOHNSON: None of them have been round, that's good to hear.

BRYLOW: The boards just kept getting more and more complicated as we tried to make the electronics problems go away, and they kept adding parts. We had to put them in this metal cylinder that was just a little bit larger than the boards. We had reserved a whole bunch of keep clear space like don't put anything here because we're going to need to use it to integrate the boards into the cylinder.

They kept needing real estate and it was my job to put the boards in the cylinders, and I'm like, "Okay, you can have that. Okay, you can have that too. Okay, you can have that." At some point I said, "Take whatever you need. Make the electronics work. We'll figure out how to integrate them later." By the time they became redundant electronics there were three board surfaces, so we had six surfaces. Like I said they're 14 inches in diameter. They were about an inch thick with honeycomb in between them for stiffness. They had these little L-shaped legs around the perimeter. There's three of them, so six surfaces. Altogether the thing weighs like 20 pounds.

We have no space to hold them, but we have three little holes in the middle. We ended up designing some crazy fixture that had three rods that were like two and a half feet long that had blocks on either end, and we'd have one person on one side and one person on the other, and we passed it through so the person reached over to the other side so they had it on the other side of the metal cylinder. Then we had to move it in and clock it, because there was little shelves for the feet, and we had to move it in another two inches and clock it, and we had to move it in another two inches and clock it back. We had to make sure that all of the little rubber feet stayed correctly located. Then we had to bolt it down. There was a focal plane sticking off the end on some flexible harness that couldn't be demated. We did it.

Literally, Mike Ravine tells the story. He's like, "I left the room when they did it because I just couldn't even bear to watch."

JOHNSON: Oh my gosh.

BRYLOW: That was terrifying. I'm really proud of the fact that we gave up everything we needed to so the engineers could do their job. We managed to put it all together in the end. They did great.

JOHNSON: Is there anything that we haven't talked about that you wanted to mention?

BRYLOW: You sent me that great list and I wrote some notes. I wanted to say something about Craig Tooley.

JOHNSON: Oh yes, please do.

BRYLOW: I can't believe Craig is dead. That's awful. There is no justice. Craig was cool. Craig was a great guy. I worked with him and I thought he was really awesome, and I think it's crazy that he was hauling his young children around in a VW microbus for years. But the thing that I took away from my limited interactions with him was that he was a leader of men. There were people that I talked to who knew him better than me who said basically, "The only reason I'm on LRO is because of Craig. I'm doing this for Craig. Want to be here for Craig. Craig said we're doing this. I'm on board. If I get the chance to do something for Craig and with Craig sign me up." Acquiring that level of loyalty is really impressive. Craig was awesome and it's really sad that he's gone. He made LRO work really well. I have all kinds of good things to say about the LRO team in general. They were fabulous to work with.

I enjoyed it more than the JPL missions I've been on, honestly, but I can't tell again if that's a culture difference between Goddard and JPL or if it's just Craig Tooley and the people that he got on the team. Craig was awesome.

JOHNSON: I've heard lots of stories about him from doing these interviews and talking to Cathy [Catherine L.] Peddie too. I've had one interview with her. I'm going to talk to her again. Since she was his deputy, it's the closest I can get.

BRYLOW: Here's something else I'm proud of. Tiny team, hard deadline, oh my gosh, what are we going to do? When we had the instrument and it was already looking really really late, we were just pushing really hard. We brought on a guy [Jeff Zerr] with probably no space experience but just a handy, competent, hard-working guy. He was my right-hand man during prep for thermal vac tests – making drawings, building hardware, assembling all the fixtures. The thermal vac tests went around the clock because you have to, and we had lots of folks from MSSS, especially the operations group (who manage all the uplink and downlink commanding and data handling for our cameras) take shifts overseeing the tests. That's way outside their normal job responsibilities, but we needed the help and they were there for us. This group is led by Elsa Jensen and she made her team available. We're trying to staff the thermal vac tests and the vibration tests. Even all the integration stuff we were working really hard. Calibration. I remember sitting in the clean room with Mark Robinson for long long days, supported by other folks on the science team who wanted to contribute [Brad Jolliff spent days there, as did Martin Tschimmel].

Wes Ousley was out for a bunch of the thermal vac tests just to make sure we were getting the temperatures right, make sure everything was going okay, just keeping an eye on things. At some point he wrote some report to Craig just like a summary of here's what happened in thermal vac this week or whatever. Craig wrote some summary to the team maybe or just a reply to this guy. One of the things he said is—they were waiting for us; we were the last instrument—he said something in his email like what we're watching here is an instrument being completed by force of will, which I thought was very sweet of him. I don't think it was for our consumption. Someone forwarded it to me. Our whole team was working really hard to push that type of work. That was sweet of him to recognize that. Signs of a good leader recognizing in the trenches. Craig was great. Let's see. That was one thing. I think that's most of it.

There was another awesome person who I don't know if she's on your list. Diane Schuster.

JOHNSON: Schuster. Okay.

BRYLOW: She built our thermal blankets. She has some little LLC that's basically just her. But we needed to have thermal blankets built. She came out. It's like a seamstress test where you come out with your measuring thing and you measure the instrument. She made our blankets. They were gorgeous. She was totally fun to work with. I think she worked at Goddard for years and then went out on her own and built blankets for all kinds of people. She's hilarious. She's the one who told me, "Oh, you know what you do on thermal blankets is on one of the inner layers you take an art stick and you mark your initials, so then you go to the Moon too. Doesn't have any effect on the performance or anything. I put a few initials on the blanket before I closed it up."

JOHNSON: They did have that program for LRO to send your name to the Moon. She did hers.

BRYLOW: It's not like marking on the blanket is.

JOHNSON: A little bit different.

BRYLOW: I think that was it. Did I babble enough for you?

JOHNSON: Oh, you did great. That was great. But if there's anything else you want to add you can always do that when I send the transcript. But I appreciate you agreeing to talk to me for the project.

BRYLOW: There was another thing.

JOHNSON: Okay.

BRYLOW: There was a struggle. There was a hard spot. When we were in thermal vac, the thermal lead that I talked about who got that note back from Tooley or whatever was out. One of the other thermal engineers was out. We didn't have a thermal vac chamber at our facility. We were doing the thermal vac test at UCSD, University of California at San Diego. They had a big chamber and the test was there. It's about 15, 20 miles away, 10 miles away maybe. Can't be there all the time. So the Goddard guy is there. I'm in the office. The Goddard guy directs them to change something in the middle of the test. I wasn't there to stop it. It was horribly frustrating.

I called up Arlin and I yelled at him. I regret that, and I apologized to Arlin after the fact, but it was a high-pressure part of the program. I just remember that he came in. He had them do something different with something for the chamber environment. I got on the phone with Arlin, "What's he doing? Get him out of here. I don't want him at my test."

JOHNSON: Did he respond to your desperation there?

BRYLOW: I think he got Charles Baker out of there. Then I went down there. He was gone before I got there. The thermal engineer [Charles] was a totally good guy and I like him and I'd work with him again too. It was just a tough moment. But in the heat of the battle, it was worse than having to trust the guy to install the MOC, to install the camera.

JOHNSON: I can imagine.

BRYLOW: So there's ugly parts to this too.

JOHNSON: Yes. With everything, I'm sure there is.

BRYLOW: But we all made it through and we were all at launch together and everything was forgiven by then.

JOHNSON: Positive results always help, don't they?

BRYLOW: No recriminations when it's all working.

JOHNSON: I will stop now and give you your afternoon back.

[End of interview]