DISCOVERY 30TH ANNIVERSARY ORAL HISTORY PROJECT
EDITED ORAL HISTORY TRANSCRIPT

ARLIN BARTELS
INTERVIEWED BY SANDRA JOHNSON
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JOHNSON: Today is June 30, 2023. This interview with Arlin Bartels is being conducted for the Discovery Program 30th Anniversary Oral History Project. The interviewer is Sandra Johnson, and Mr. Bartels is at Goddard Space Flight Center in Maryland. We're talking over Microsoft Teams for our second interview. I appreciate you talking to me again, and agreeing to talk about some of the instruments, because I think that's really important, since there were seven of them on LRO. So the main reason that LRO [Lunar Reconnaissance Orbiter] flew with those seven instruments was to help NASA achieve the next steps in returning humans to the Moon, which was the president's goal. President [George W.] Bush had set that goal after [Space Shuttle] *Columbia* [STS-107 accident], when he laid out the vision for space exploration. When we were talking last time, we talked about how you came on working with LRO about the same time the instruments were selected. So let's just go through the instruments and talk about them and talk about your experience with each one and with each one of those teams.

BARTELS: That sounds great. Is there any order that you wanted to take them in?

JOHNSON: However you want to do it. I have a list, but we don't have to talk about them in that order. So I don't know if there's ones that you have more of an affinity for that you enjoyed working with more. Just however you want to do it.

BARTELS: Well, if I did, I would never admit it. An important part of when you're a payload manager working with the instrument teams and going back even to the accommodation studies where they were selected, it's very important for all of the instrument teams to know that you're not playing favorites with them and that you're treating them all equally. That was especially important here, because although some of the instruments had more higher profile goals as part of the mission, we did have seven different instrument PIs [principal investigators]. We didn't have just a single mission PI, although we did certainly have a mission project scientist, deputy project scientist. This really was treated as a round table of equals in terms of each of the instrument teams and their individual PIs. When we would meet, we would meet as a group, and although those meetings were proctored and led by our project science team, it was very important that it was egalitarian amongst all the teams of how they worked. I would also like to say, we could take it in any order.

JOHNSON: Well, we can go ahead and talk about the order that NASA has them listed on the webpage. First of all, CRaTER [Cosmic Ray Telescope for the Effects of Radiation] is the first one that they have listed. That was the one that was to test the effects of radiation on humans. They had that very interesting skin substitute that they used to see what would happen.

BARTELS: Right. That's exactly right. It was a kind of plastic that they called TEP, Tissue Equivalent Plastic. What they did then by having a stack, almost a little set of pancakes, if you will, of these little TEP samples with the detectors in between, they could actually, from incoming cosmic rays, simulate how those cosmic rays would affect human tissue. It was very interesting from a human standpoint. That's almost a little bit of a legacy of the fact that this mission was a partnership between the human side and the Science Mission Directorate. It's actually, of course, initially funded by the human side.

The science from the CRaTER team was done by a terrific small group of folks from MIT [Massachusetts Institute of Technology, Cambridge] at the Kavli Institute. Their science was separable from all of the rest of the mission because that's not typically the sort of thing that just the scientific rules of understanding the Moon itself would show. The CRaTER instrument was designed, basically, to help us understand how humans might respond to cosmic rays, astronauts that were there. So their science was initially a little bit separate from a lot of the rest of the teams. It's a small instrument done by a very professional group of folks at MIT.

Part of what made it interesting as we went along with them was, as the Astronaut Office learned of this capability that we had, they got interested in seeing, is it possible that they could get our CRaTER data to Johnson [Space Center, Houston, Texas], as well. One of main ties, actually, to Johnson was folks at Johnson who were very interested in this data. Because of the latency of the time it would take to get the data from LRO and get to the next ground pass and on down, we really weren't able to use it as a predictor of cosmic ray events or anything for the astronauts on the ISS [International Space Station]. But that data was used, certainly, as a second dataset, for instance, if on ISS they had found an unusual signature that they felt might have been a result of cosmic rays. They were able then to go access the CRaTER data, as well, and say, "There must have been an activity at that time."

It was very interesting. They were a fairly small instrument, and I think that team was fairly new to this type of spaceflight mission, but they adapted very quickly and very well. Like I say, it was a very experienced team from MIT that had worked on the Chandra X-ray Observatory before, and so they were used to high-energy missions.

There was a chief engineer who was absolutely instrumental to their development. You may have come across his name, Robert [F.] Goeke. Mr. Goeke was absolutely the driving force of making this whole work happen. There were students who came in and did some work. There were engineers from MIT who were professional engineers who worked there. I believe he pulled in some work from [Charles Stark] Draper [Laboratory], as well, or an engineer or two from Draper Labs, which is in the area. But this was really Bob Goeke's instrument working for Harlan [E.] Spence and Justin [C.] Kasper, very, very well done. They were a team that really kept us on our toes because Mr. Goeke, in particular, was very experienced. He had been on many, many, many NASA missions, and he kept us focused on the things that, as a project, we needed to provide to him. They were a delightful team to work with.

JOHNSON: Okay. It's interesting. I did talk to Harlan Spence, so we do have a pretty good history of that side of it. But I just thought it was fascinating, what they were doing.

BARTELS: Yes, and their data actually got some interest even just in the public, as well. Did he tell you about the singer who got interested in his data and wrote a song about it, and started singing it from the stage?

JOHNSON: No.

BARTELS: Well, this is a very slight digression. It may not be worth it for your group. But there was a rock band that was from the '90s that is still around today. They were called Toad the Wet Sprocket. Their lead singer, who is a space geek, became very intrigued about the CRaTER mission, and from the CRaTER mission, what it's like to be an astronaut on the surface of the Moon getting hit by the cosmic rays. He actually wrote a song about it that he would dedicate it, when he would come into this area—we actually brought his band here on site at Goddard, and they got to see LRO, got to go in and put on the bunny suits, and have their picture taken in the clean room. Whenever they were playing in the [Washington] DC area or Boston area, they would dedicate this song called "Solar Flare" to the CRaTER team from LRO. That was always fun, for a while. That was one of Harlan's claims to fame. We didn't have a lot of celebrities attached to LRO, but that was as close as we came on the CRaTER side, so that was fun. They really were a delightful team to work with, and I think they were the second instrument to deliver of the whole group.

JOHNSON: That's interesting. Okay.

BARTELS: If you were able to find Mr. Goeke—well, Harlan probably already would have put him in touch with him if he was still available. Each of the PIs, I'm sure, identified whoever they felt that the engineers were who contributed.

JOHNSON: Yes. Some of them did. He did talk about him, so I'll have to go back and look. Yes, it's hard to figure out who to talk to on a lot of these missions, because there are so many people involved.

BARTELS: Right, right. That was some time ago, and Mr. Goeke was towards the end of his career, anyway, at that point, so he may not be available anymore.

JOHNSON: It's funny because I got a list from Mark [S.] Robinson. I think I told you that. He sent a list of everybody involved because he didn't want to talk himself. But it was like 250 or more names. I thought, "Oh, my gosh, how do I choose from that?" It's everybody that had anything to do with LRO that he could think of on that list.

BARTELS: That's his style, though. If we want to even move to LROC [Lunar Reconnaissance Orbiter Camera] next, because he's a very inclusive person in that way, and very self-effacing. But it sounded like you did get a chance to talk to Scott Brylow. Scott really was the main engineer on the floor working that work. So as long as you've gotten that with him—we've continued to work with that group on Discovery missions. I think I had mentioned to you before that almost any image you'd ever seen taken from the surface of Mars was done by that company, and I'm sure Scott spoke to that, and many of the images of Mars you'd seen from above, as well.

But when they worked with us, it was the first time that they had delivered a camera to someone outside of their own science team. I might have mentioned before that Dr. [Michael C.] Malin actually started Malin Space Science Systems himself as a way to make the cameras that he then was the principal investigator for, typically, on missions. His team is very unique there, that most of them are PhDs, most of them are coinvestigators on the missions that they work for Mars. For us, when LRO started, Dr. Robinson was at Northwestern [University, Evanston, Illinois] there, and he established this relationship with Malin. Having the Malin company delivering to Dr. Robinson rather than to within their own company was really the first time they had worked in that way.

The operations center—when Dr. Robinson moved to Arizona State [University, Tucson] and brought some of the capability with him, because he was also responsible for all the operations of LROC—the way we worked—I'm sure maybe someone mentioned this to you—some missions will have a centralized planning science center where all of the observations are flowed. The decisions that are made on how we do targeting and what to take images of flow top down. One unique aspect of LRO is that, again, because it was a confederacy of all of those groups, each of the individual instrument teams were responsible for defining their own operations. Many of them, because we were in a mapping mission, just ran continuously, and so it wasn't really complicated targeting that they do. But for LROC in particular, because of the large data volume of these amazing images that they took, it's not possible to just continuously image at all times that we were over the lighted portion of the surface. So not only in terms of data processing that they would do at Arizona State once all the images came down from LRO's White Sands Ground [Terminal, Las Cruces, New Mexico], which would come to them, they also were responsible for choosing the targets itself, as well.

As LRO orbited the Moon, the Arizona State team under Dr. Robinson would choose the points at which we would take new images. They had very complicated software. It worked wonderfully to help them understand where had we never imaged before, maybe on previous passes, because we stay in an orbit, and the Moon rotates beneath it, and so over a month, we would cover most of the surface. But they would build up this model—which was actually provided to them from the LOLA [Lunar Orbiter Laser Altimeter] team, which we'll talk about later—that they could overlay where they had taken images.

Then their software would tell them either if we had never taken an image of that location before, or maybe it would be from a different lighting angle this time, and so it might reveal the topography a little differently than it had the last time they'd taken the imagery. When Dr. Robinson came from Northwestern to Arizona State, he brought the leadership of that planning team with him as well, and they built up a wonderful capability they've had at Arizona State, where a lot of students over the years have had some time to learn about NASA and learn about how we do operations by serving as undergraduates or graduates working at Arizona State in that planning group.

The cameras worked fantastically. We had two imagers that we called narrow-angle cameras, and I'm sure Scott Brylow mentioned this, that we'll say at 50 kilometers, the resolution of each pixel was half a meter. That was specifically chosen because at that time, we were supposed to be looking for safe and interesting landing sites. I'm sure they might have told you that the push and pull between those, because the safest sites tended to not necessarily be the most interesting, on purpose, because the safest would be the ones that are flattest and with the least surface obstructions, boulders, anything like that, slants. The LROC camera, which we had two of them that worked side by side, so as we would go across the surface of the Moon, those cameras were, instead of a normal two-dimensional camera array, like you have in your phone or in a regular camera, it was actually a single row imager that builds up a really long image like a spaghetti noodle by just continuing to go across the Moon and imaging that one row as we go over it. They would make images 25 kilometers long that were all built up from like 25,000 rows of taking those pictures.

I'm sure they all would have told you that one of the biggest challenges that we have on that mission was the intense thermal environment. I don't know if people spoke to that. But what was unique about that is, when spacecraft orbit the Earth, even though they're going over day side versus night side, the ground that they're looking at, because of our atmosphere that does such a wonderful job of keeping us alive, it minimizes a little bit. Day versus night is a change here, but if you're looking at the Moon where it's several hundred degrees' difference between looking at the illuminated side versus the dark side, that flux back to the spacecraft, because we were flying so close to it, made huge temperature swings from being on the day side to the night side. We were constantly in an environment where the temperatures were changing. The LROC team had to be specifically wary of that in the way that they designed their camera. They designed it beautifully to be responsible for that. Most of the data that the public has ever seen from LRO has been from these LROC narrow-angle cameras, because of the exquisite detail they were able to reveal.

The new LRO that's in development now early on is actually extending that farther, so that we have greater resolution. Everything changes, of course, and we always get more pixels. Every time your camera in your cell phone comes, it seems like there's more pixels, and that's the same sort of idea they're doing now, so that as we move to the next phase of choosing sites where humans might actually want to land, people were realizing that in the picture, the LROC data set is tremendously useful for large boulders, and we can measure surface tilts, and stereo, and things, but the next generation will even be of higher resolution.

But those cameras have been absolutely fantastic. We had to align them very carefully on the spacecraft so that when we would have those thermal variations over an orbit, of course, the design of the cameras have to be impervious to the heat, but so do the spacecraft where they were mounted, because what we wanted them to do was to overlap just a tiny bit of the fields of view of those two cameras mounted in parallel. That way, we wouldn't have any gaps in between the two cameras. They were intended to map side by side. I called it a spaghetti loop, but it's actually two pieces of spaghetti side by side that are touching each other, so that we could get a little wider patches as we went. But if we overlapped too much, then they would be seeing the same territory, and that's wasting some area on the outside. But if we allowed them to spread apart, then there would be gaps in the middle, so we wanted just enough overlap so that we could register the images together to make one big image, but not so much that we were losing potential imaging on the sides. There was a lot of work with our thermal team and their thermal engineering design team to make sure those cameras did just that.

They also did another camera for us, which is a smaller one. We called it our wide-angle camera. Scott Brylow would have called that his WAC. He liked to call them his NAC [narrow-angle camera] and his WAC. The purpose of the WAC was to be much larger, a little bit more regional, type pictures. What you could do then is, from this camera that would take wider angle views for context, then across those images, you could lay these spaghetti strips across it and register them together. Together, it was very powerful to have the narrow angle, very highly detailed images that could then be registered for context against these larger images that are more regional, could see more slope and more surface details and things. It was very cleverly designed by the Malin folks based on the experience they'd had on the Mars missions to provide us a sweep that had both exquisite detail and then larger context that they could use together.

Some of the most interesting science results from the mission, from a science side, now, have come from LROC, as well. When we were setting out with LROC, they gave us a list of potential targets that NASA Headquarters wanted us to really image, but they also wanted us to find maybe places that hadn't been seen before, and to come up with a list of—I believe it was 50—possible candidate sites that could be pruned down in later missions after LRO. LROC was the main instrument used to develop those potential landing sites, as well. But because of that exquisite resolution of the cameras, they were able to look at geologic features in a way that no other mission had ever been able to look at before. I would suspect there are probably more papers that have been written in the literature based on LROC imagery than anything else. I think the biggest surprise to the science team was how there were still things that looked fairly recent, or at least recent on a geologic time scale, of activity on the Moon that people hadn't realized. The fact that the Moon is still shrinking some in its lifetime, and so that creates some cracks and things in the surface that would be much more recent than the billions of years we normally talk about. The other thing, as the missions continued to run for so many years, and we reimaged some of the same spots we've been to before, they've actually even been able to detect new bombardments of small asteroids and things that have hit spots, because we see things maybe in 2020 that we didn't see in 2011, even.

It's been a real success story with the LROC cameras, and they're very proud of them. The LROC team has moved on to—they build cameras for a lot of missions, but within the area that you're targeting, they built cameras for OSIRIS-REx [Origins, Spectral Interpretation, Resource Identification, Security, Regolith Explorer] that actually guided us to the surface. When you see the asteroid sampling, those movies you may see in the press about OSIRIS-REx, the big arm moving down to the surface to grab the sample, those cameras are from the same people who built LROC.[1] The Lucy asteroid mission within Discovery that launched in October of '21, the cameras are used for that, as well.[2] In both cases, for OREx [OSIRIS-REx] and for Lucy, they were originally designed to be engineering cameras to help for navigation, for

[1] OSIRIS-REx is the first U.S. mission to collect a sample from an asteroid. The sample return capsule returned to Earth on Sept. 24, 2023 with material from the asteroid Bennu. After dropping off the sample, the spacecraft was renamed OSIRIS-APEX (Apophis Explorer) and sent on a new mission to explore asteroid Apophis in 2029.
[2] Lucy will explore a record-breaking number of asteroids, flying by three asteroids in the solar system's main asteroid belt, and by eight Trojan asteroids that share an orbit around the Sun with Jupiter.

instance, using the stars to navigate. But they're such good cameras that they're used for science purposes as well on both OREx and Lucy.

Then on my current DAVINCI [Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging] mission, where I'm the project manager, we also use their imagers both within our probe that goes down to Venus—the images of Venus will be taken with a follow up to the WAC—and we also have another camera that will be mounted to the spacecraft as we fly by Venus, which will image Venus on the way.[3] It's a very unique company. It's an interesting contrast with CRaTER, because for the most part, I think that the CRaTER team, although they have had other space instruments subsequent to CRaTER, certainly, a lot of their funding comes from the National Science Foundation, from a different direction. But the Malin folks were created by planetary small missions like within Discovery and New Frontiers, and that's what's been sustaining them ever since. They also have a role on the Mars Sample Return mission, as well, using cameras that are very much like the product line that they've developed for LRO. If you've talked to Scott, you probably got quite a bit of info on that.

JOHNSON: Yes. I'd like to talk to him again. I'm going to try to get another interview with him about some of the other things that they've done, like with Psyche and the different ones.[4]

BARTELS: Cool. Of course, he did Psyche.

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[3] DAVINCI will study Venus from its clouds down to the planet's surface—the first mission to study Venus using both flybys and a descent probe—to determine whether the inhospitable surface of the planet could once have been a twin of Earth, a habitable world with liquid water oceans.

[4] Psyche is traveling to a metal-rich asteroid with the same name, orbiting the Sun between Mars and Jupiter. By August 2029 the spacecraft will begin exploring the asteroid that scientists think may be the partial core of a planetesimal, a building block of an early planet.

JOHNSON: Yes. There's just so much. You mentioned that you're working with these different teams. One's more heavily engineering, or this team for LROC, it's a company and it's commercial, but they're working with NASA. It's interesting, because each one of these teams were different. You have a lot of university, or research lab, or commercial interest in them. Was that a major difference as you were working with each one of these teams? Did you have to approach it differently; did the language change with each team?

BARTELS: That's a really insightful question. Yes. You know, when engineers go to design hardware, the engineers think mostly alike, but their cultures can be very different based on their environment and the motivations of their management, and their institutions they work for can be a little different, as well. When you're working with the commercial companies, and Malin was one. We also had Northrop Grumman as part of the APL [Johns Hopkins University Applied Physics Laboratory] radar. Their motivations are a little different as a company, but they're still tied to delivering successful hardware. It's just the contracts get a little more in the way. When we work with the NASA centers, certainly there's no profit motive involved, or even with the universities. But you do need to make sure that they can pay their expenses, all of their expenses, and we do have to control their costs, which can sometimes be more difficult at a NASA center or a university than it is within a private company, because the private companies are a little more attuned to their costs, maybe, than a NASA center is or a university.

Yes, it would be very different when I would work with each of those teams. Of course, the Russian instrument was an entirely different culture there. I'm sure we'll talk some about that. Again, though, like I had mentioned before, we made a decision very early on that it would be easier for the LRO folks just to learn each person's culture, each instrument's culture, and respect their culture, and try to help them be successful within their culture rather than to try to force them to all be the same type of team, because MIT was never going to be the same as Malin, as JPL [Jet Propulsion Laboratory], as the Russians, but we could all speak the language of math for engineering in the same way. So our technical discussions would tend to be very similar with the teams. We all used a lot of the same tools. Even the Russians use some of the same engineering tools that we do. We would hand models back and forth to each other of the spacecraft or the instruments in the same way with each of the instrument teams.

From a systems engineering standpoint, it was fairly invisible that the instruments all came from separate cultures. From a management standpoint, like myself that had to worry about contracts, and funding, and tasks, and things like that as well, certainly I had to keep seven approaches in mind, because even JPL and Goddard are different enough that you almost have to treat them as separate entities, as well.

JOHNSON: Let's talk about some of the other ones. You mentioned the Russian one. Let's talk about that and working with that team on that instrument.

BARTELS: Yes, a very, very interesting instrument team, the LEND [Lunar Exploration Neutron Detector] instrument. I don't know if you've spoken to anyone else on that.

JOHNSON: No, I haven't.

BARTELS: Yes. It's been harder, because they were primarily a Russian instrument that did have a couple of American science team members on our side, and had a connection to the University of Arizona, actually. A really interesting detection they had of—it's a neutron detector, and so it was really looking for not just neutron bombardments but also the presence, maybe, of heavy water, deuterium. You'll see that sort of work. It was a little bit of a controversy on the American side here, because there are American instruments off a different technology that could have been selected instead, and perhaps, some folks think, might have given better results, or at least different results. But what NASA did in their wisdom, when Dr. [James B.] Garvin chose the instruments, was we had worked with that Russian team before—we'll get into them a little bit—and by having the LEND neutron detector contributed to us, basically as a gift of the Russian Space Agency, that allowed NASA the funding, which allowed us to add in CRaTER and LAMP [Lyman-Alpha Mapping Project]. CRaTER and LAMP were not actually part of the original selections that we were accommodating, but by getting essentially a free instrument from the Russians, that funding, which would have gone to an American neutron detector, was allowed to then pay for the cosmic ray instrument and the Lyman-Alpha instrument. Those are the sort of tough choices that those folks have to make, because certainly the Americans felt that they lost their ride.

But with that Russian team, they were a fascinating team to work with. It was from the Institute of Space Research in Moscow that goes by the acronym in Cyrillic of IKI. Americans tend to call them "iki." They're right in the heart of Moscow. Very young, with a very experienced principal investigator named Igor Mitrofanov, just a very gregarious, welcoming, opening person. All of the team were. We were stunned by how amazingly well they spoke English. Their grammar was better than ours. They had learned their English extremely well.

When we worked with them, of course, we had the training from our side, as well, but it's very different culturally to work with a foreign-contributed instrument than an American instrument, because there is a portion of it that is, in a manner of speaking, diplomacy as well. We had special agreements to get work between NASA Headquarters and the Russian version of the same.

We have to realize that because we aren't paying for their instrument, we're only paying for the accommodations of it on our spacecraft, that we have to be very careful in what we ask them to change about their technology, because they're providing an instrument. Because of that, they get to make decisions on the design of their instrument that maybe NASA, for an American instrument, might ask people to make changes to improve the reliability or the performance, or something like that. I personally grew very fond of that team. They very much liked working with us. Myself and one other engineer, Leslie [Hartz], and our thermal engineer, Charles [Baker], were the main technical contacts with them on a daily basis. They were very accommodating and wanting to work with an American team and trying to keep those barriers down. The politics interrupted very, very rarely. It did seem that whenever there was some sort of international kerfuffle, it did happen to be when we were on travel visiting them in Moscow. But everyone that we came across and worked with was very pleasant. I still have a couple of them that are friends, or at least acquaintances, to this day.

Their engineers are very good. Again, I say they were very young. It was a very large, heavy, bulky instrument, because the way that it was designed was—if I'm trying to explain in a sentence or two—in the way that most instruments try to gather all of the source of whatever they're looking at, light, or photons, or something, the Russian instrument was designed by blocking most of the incident radiation it's trying to detect. By having almost four little telescopes that they had built into it that was designed to block out everything else, they could reverse the direction back to identify where on the surface that their data was taken from. That was the controversial part of this because no one had ever actually tried to make those sort of measurements before. That type of technology, even from the American ones, has been more global. What would happen is, as you would go over a surface, you would get a large regional part of the planet you're looking at, and then you'd have to do software to try to average out and calculate. It would be more of a regional, like an American state resolution, versus with the Russians, the way they tried to block out most and then calculate from where on the ground the sources came from, it gave you the resolution more of like from a city location rather than from a state location.

Of course, we had to worry about ITAR [International Traffic in Arms Regulation] and those sort of controls, as well. We had to be very careful about that. Part of the way that we did that was, when we were working with areas where we had to disclose technical information, they had two American members of their team who were here at Goddard and worked with us daily that were their main interfaces. We could describe things to our Goddard LEND colleagues, who would then translate and make sure they only said what was safe to pass along. Like I say, they also had a very good tie to the University of Arizona, the same people who ended up doing OSIRIS REx, actually, which is the way I learned about OSIRIS REx. Those people at Arizona were the ones who did the operations aspects. The Russians delivered the cameras and processed the science data, but in terms of our LRO operations here at Goddard, the people who provided the inputs on how to operate the LEND instrument were all from University of Arizona. It was some of the exact same people who then performed that same function on OSIRIS REx in a much more complicated way.

The LEND instrument also had a big tie here to the University of Maryland and to the Russian space segment that's here at the University of Maryland. We had a highly respected person named Dr. Sagdeev, Roald Sagdeev, who was married to Susan Eisenhower, by the way. She had met him when she was traveling to Europe many, many years ago. Through Dr. Sagdeev, we also got to do a lot of outreach with him with the Russian team, and activities when they would send their folks here to try to show them around. They were huge history buffs, and so they were obsessed with going to—of all places—we took them to Gettysburg [National Military Park, Pennsylvania], and they just loved touring that. They knew more about Gettysburg than I did. It was embarrassing. We would take them for historical exhibits and things, and they were just fascinated by all of it. They would do the same when we went there. They would show us the sights. You were able to develop partnerships with them because of those interactions that were more difficult to do when it's more of just a work relationship with the MIT people or even the JPL folks.

Their science has come off better, I think, than even most folks would have anticipated, and it continues in operation now, I believe, as well. They were the ones that had maybe the biggest adventure, though, that we had in terms of late in the game on the spacecraft. In late testing, they actually had one of their four detectors in their instrument fail on them in the thermal vacuum testing that we do here to simulate that space environment. They actually changed out a significant part of their instrument after we actually had shipped to the launch site. That's not all that unusual in the space industry. You try to avoid it. But they actually did a major surgery, remove and replace of their instrument down in Florida.

Working with a foreign-contributed instrument—that's the term we use, foreign contribution—is very different culturally and from a style standpoint than we do with our own.

It's very satisfying, as well, because it's a dimension you wouldn't otherwise get to see. We certainly had more of our team volunteering to go on travel to meet with the team in Moscow than we did anyone else. It is a shame, in a way, that because of recent tensions, of course, we don't have the same partnership we used to have with them. I even believe on LRO, their participation is less than it was before, and it's still more the American teams that are associated. Those sort of activities get altered by events, we'll just say. Missions that last as long as LRO tend to have more opportunities for disruption, for sure.

JOHNSON: Yes, definitely. I was just thinking, because when LRO—before it launched and when these instruments were being built, it's not like it was the dark ages, but we didn't have some of the same communication ability, like you and I are talking right now. So especially with LEND, that they were not just across the country, they were in a different country, how did that work? How did you communicate with a team like that? I know obviously you traveled back and forth, too, but just on a day-to-day basis.

BARTELS: That's a really excellent question. Of course, we had instruments spread across eight time zones, the three on the U.S. side, and then they were five time zones or, depending on daylight savings, six away from us. That made it more difficult for us to coordinate full team meetings of all the instruments at once. Our meetings with LEND were separate, because they were at least five time zones away from everyone else. We tended to have separate meetings with them than we did the rest of the teams. Skype was in its infancy then, but we did use Skype. We were very heavily telephone based back then, still, telecons, speakerphones. If we were doing it now, I'm sure we would be doing everything on Zoom or Teams, like we're doing right now. Their communications technology is now, it appears, on a par with us, for sure. Moscow's a very culturally forward town, as well. It feels just like any other European city when you're there. I was actually disappointed—I was expecting it to be more exotic than it was.

In terms of communication, it did restrict it a little bit. We had moved, towards the end of LRO, to just starting—WebEx was the one—but that was just getting going. So what we would typically do was, the information that we were going to be discussing—it just shows how much has changed in a few years—we would email that out to them ahead of time, and then we would actually, on our laptops, on the telephone, and them on their laptops at their telephone, we would just step through those charts or those documents together. We would always have to say, "We're on page six now." Whereas now, someone would just grab the screen and share the information, and we would see it in real time. The advantage, though, of doing it that way like we used to was it made you think ahead of time more about the information you were trying to convey. Now, sometimes, like here, we didn't coordinate anything ahead of time, so we're just discussing this in real time.

The Russians preferred to know ahead of time, maybe more than the other teams, what topics would be discussed, so that they knew that they could really prepare to have that discussion, because they took it very seriously to have the answers. Like I say, they were mostly very young, but there were a couple that had been there from the very beginning. One of them actually knew Yuri Gagarin who was still part of the team. For instance, particularly in his case, he didn't want to be embarrassed by not knowing the answer to a question ahead of time, so we always made sure that we respected that and provided them the topics. We didn't surprise them with new topics at the time. We always kept to the agenda we laid out so that they knew that they could be prepared. It was very important to always be prepared, and that showed in the quality of the work that they did.

JOHNSON: Yes, that's understandable. How many times did you get to go to Russia?

BARTELS: Probably five or six total. Yes. It was hard because we had so much going on in so many areas. If we had more people, we could have had maybe some people going over there more frequently, but we had to make sure that we were rationing and keeping tabs on everything. All of the balls had to stay in the air. It was easy for me to once a month make a trip across the country and hit all of the American instruments, but it was more like twice a year to go to the Russians, just because of the difficulty.

JOHNSON: Well, if you were visiting all of them that often, it sounds like a lot of travel during that time period.

BARTELS: Yes. It comes with the job, though. It's endemic in how we build spacecraft that you have to be willing to travel in some of these roles. One of the interesting things was, of course, in the end, all those instruments delivered here to us at Goddard. On a lot of other missions, where we have a Lockheed Martin, or a Boeing, or someone like that, a Ball Aerospace, is the system integrators, once the instruments deliver, they don't deliver here. They deliver to the spacecraft. Then you're traveling even more to be there for that next round. So during the development phase until they all delivered to us in February to May of 2008, I was probably on the road about half time.

I also needed to make sure that I could represent the instruments to the spacecraft team. I think I might have told you the weird part about communications in my job was, the in-house spacecraft team saw me as their way to get information about the instruments that they need to design the spacecraft, whereas the instruments saw me as their advocate within the project office who needed to provide them the spacecraft information they needed. So I couldn't be on the road all the time, even if I wanted to, because the spacecraft team also needed to have us giving them the information about the instruments so they could do their job. That rhythm settled out to be about half time on the road from 2005 to spring of 2008. But from that point on, then I stayed here, and the instrument teams would come at various times to Goddard and join us for testing when their instruments were on.

The way we worked it is, when we were just doing routine daily work that wasn't generating particularly interesting instrument data, the instrument teams delegated to me and my system engineers to monitor their health and safety. We were deputized to be part of their team. But then when there was any specific performance testing or even extended functional testing of their instruments, then they would bring a small team out. Then, of course, my folks would hand over to them and learn over their shoulder more about their instrument, since we would never pretend to know as much about their instruments as they did themselves. For the really important tests, they would support. For the tests that were just day to day, they would delegate to us.

JOHNSON: Let's go on and talk about the Diviner, the Lunar Radiometer Experiment.

BARTELS: Yes, absolutely. That's a really fun one, especially if you hadn't had a chance to meet up with any of that team. I honestly don't know how many more of their team is still available. They were a very experienced team at the time, and I believe they've all retired. Dr. [David] Paige doesn't like to talk to many people. He prefers being in the lab.

It's a really, really interesting instrument. Maybe you can tell from the pictures. It looks like a tiny beer keg that rotates on a pedestal. It does that by then having radiometry, so it measures the heat coming off the surface, and it uses that as a way of determining the surface composition, in the same way that if you think about if you have sand or rocks here on Earth out at the beach, and how they heat up during the day. The sand heats up more quickly, but it releases the heat quicker. The rocks hold onto the heat a little longer. By seeing the story of how the surface heats up and cools down with this radiometer, it can give you a measure of the surface composition. That was really important for the science team to know not just what do things look like, but what are they composed of as part of the chemistry that we did of it.

That instrument was one that was nearly build-to-print from one that they had done called Mars Climate Sounder on the mission called MRO, Mars Reconnaissance Orbiter. That's actually true. We didn't talk about that too much. There are various levels of what we would call heritage that each of the instruments had. Diviner probably had the most heritage other than the LAMP instrument because of that Mars Climate Sounder that they had done. The only thing that we had to change, really, to have them work on our spacecraft—I think I mentioned this in our earlier interview. The way the spacecraft talks to the instrument, we only had a couple of options available. For the Diviner instrument, they rebuilt as best they could, with some little minor enhancements, the instrument they built for MRO but with a little adapter box also in between, so that they could then use that little adapter box to interface between the spacecraft and the instrument they'd already flown on MRO.

They got off to a little bit later of a start than the other instruments , because they were supporting Mars Reconnaissance Orbiter mission, which launched in 2005. In the first six months of the mission, they fell behind the other folks, because that team was supporting final ATLO [assembly, test, and launch operations] of MRO, and they were at the Cape [Canaveral, Florida], and they were getting ready to launch and do initial operations. So they fell behind a little bit at the start. But you could say they started a little later. Then they caught up very quickly, and they were right in the pocket with everyone else. One neat thing that JPL did with them is, even though the hardware design was very much build-to-print, a lot of the team members—it was an opportunity the Jet Propulsion Lab gained for them to be in a new elevated position. So we had a first-time project manager and a first-time system engineer that had both worked on that earlier mission but in lower-level roles, so it was promoted up to a higher level.

It was the first time that those folks had worked with Goddard, and the first time many of our Goddard folks had worked with JPL. Our centers do a lot of the similar kind of work, but we do have things. We also are different culturally between those two centers, as you well know, just as Johnson has its own culture, by the way. It took just a tiny bit of time for the teams to get comfortable with how they did work. One important thing that we did in working between Goddard and the Jet Propulsion Lab is, because they are another NASA center of a sort, there is an agreement made at the highest levels between JPL and Goddard that whenever one institution delivers hardware to the other, the rules that we use to build and process for quality assurance, and reviews, and all of those sort of things, we defer to the institution who's supplying the hardware. In this case, the thing that our mission assurance people had to become comfortable with is that Diviner would follow JPL's rules, and their processes, and their techniques. What we did for them in some of those aspects was like we did with the Russians. They would show us the evidence that they were complying with their own rules rather than adopting rules that we would impose on them.

They were, again, very excellent to work with. Things at higher levels would get a little bumpy every once in a while, because there was some cost growth on their side, but that's not unusual for NASA centers. Our own NASA Goddard instrument had some cost growth of its own. But again, engineer to engineer, they were extraordinary to work with. It was very seamless. Sometimes the two centers call each other frenemies. We work together, but sometimes we have trouble working together. In this case, it really did seem just like a badgeless team in a way that we are still trying to recreate in some of the missions I have been since then with others. What it shows is how personality dependent relationships are because the people on both sides of this mission made a concerted effort not to let cultural differences between the centers get in the way. We just made sure that it didn't. I can imagine different people, particularly on their side, that might have a more parochial view that would have made it more difficult to work with. In terms of communication, what it really shows is people matter more than org charts, sometimes, or roles of responsibility choices. In the end, it comes down, really, to how willing are the people being to sacrifice or adapt what they're used to in the name of building a cohesive team. Amongst all the missions I've ever worked, I think it might have had the best sense of people putting aside their backgrounds to work on common goals. It was one of the most satisfying things of the mission.

JOHNSON: Working across centers can sometimes be interesting.

BARTELS: It can be a challenge, because the interesting thing is, every group, especially if they've been building hardware within their own institution, they know how well those processes work for them in the environment that they're from. When they learn that someone somewhere else does them differently, of course they're a little more suspicious that their way has to be better, because it's always worked in the past. When I was young, I was probably parochial about that, as well, from the company that I came from. But the more you work with the different groups, you see that as their processes all evolve and diverge a little bit, you end up finding that those are the processes that result in success in their institution. It shows there is more than one way to skin these cats in some ways. By allowing each team to do what they need to do, you get a better outcome.

I may be overstating something when I say that they were like the Russians, in that we just had them show compliance to their own rules, because within NASA, we did share review team members. They did reach out to us for some technical consultation, which they didn't have to do. I mentioned that we had like a little beer keg that rotated on a little platform, so that meant motors driving it back and forth. They were very open to our input and bringing us in for some of their motor issues. The Russians were, as well. We just had to be more careful because we could provide our advice or our recommendations for things, which sometimes the Russians took and sometimes didn't. But we do this sort of design oversight even if the instrument comes from JPL, so that if we feel there is a technical challenge here or a technical risk that needed to be addressed, we did have more flexibility to work with JPL than we would have with the Russians, for instance.

JOHNSON: One of the things that they were identifying was potential ice deposits in the poles.

BARTELS: Exactly. Exactly right. Exactly right. They also were very interested when LRO would go into eclipse because that's when things would get the coldest. Remember how I mentioned how one of the challenges for us was the temperature differences and how temperatures were changing all the time? If you're a radiometer, that's what you want. That's the thing that they are most happy about because that's the measurement set that they're trying to take. A radiometer is, indirectly, a thermometer. Their work and LOLA's on finding ice deposits was partially driven by the fact that Diviner wanted to see really cold parts of the Moon. We wanted to see things on the side of the Moon not being illuminated at that point, and to look deep down into those craters, and to find the areas where it was cold enough that the water traps could be. That's also an aspect of what LEND was looking at, as well, and we used with LOLA.

We did a lot of work in looking for spots for human landing. It's always the challenge of finding what they call in situ resources. What everyone always wanted to do was find a place that was near where there might be enough ice to actually get actual potable water. LEND, Diviner, and LOLA, and to a lesser extent, LAMP were very much always looking in the deepest craters, looking for the places that were cold enough to trap ice so that it would actually settle there. We called those permanently shadowed regions in the deep craters, which happens to be mostly at the poles, and especially at the south pole. One of the types of landing sites that we were looking at was an area that would be also at the south pole. An interesting thing about that is if you're right at the south pole, you might be able to actually get, although indirect, constant views to the sun so that you can generate power. The idealized place to land would be somewhere where you always were in dim sunlight so you could have power, and close enough to a deep crater that might actually have water so that you would have both power and water. That was the holy grail of the sites that they came down to, like with Shackleton crater, where they've been looking.

JOHNSON: Let's talk about LOLA, and that team, and working with them. As you said, they're looking at those permanently illuminated or shadowed areas for future human landing.

BARTELS: Although that was a secondary goal for their work, it's one they've done very well. That same team had also found ice in the same sort of craters on Mercury with the MESSENGER [Mercury Surface, Space Environment, Geochemistry and Ranging] mission. I talked about the heritage that a lot of these instrument teams had to previous missions. The LOLA team had heritage that went immediately back to the Mercury mission called MLA [Mercury Laser Altimeter], where I had been their instrument project manager. But before that, as well, to Mars missions. There was a Mars Laser Altimeter. There was a Mercury Laser Altimeter. This was the Lunar Orbiting Laser Altimeter. That type of technology is one that we had been developing here at Goddard as a center of excellence since the '90s.

The LOLA design was a significant improvement over the Mercury mission, though. It took the best parts of it and then improved them even more. One of the things it did most improving was, on the MESSENGER mission and the Mercury missions, we were essentially, if you'll think again of spaghetti, we were only laying one spaghetti stripe across Mars or Mercury as we went, because we had the one laser, and the one optic, and the one detector. The way an altimeter works is it's like a fancy stopwatch. It measures the time from when the laser pulse starts from the instrument, bounces off the surface, and returns back. Even though the speed of light is so fast, if you have an amazing timing system that can measure down to picoseconds and you can actually sample when—they call it the time of flight of the photon—from when it leaves the instrument and returns back. If you're able to measure that exactly, then you can know what the distance was between the two. If you continue to build up that map over the entire surface, eventually you can create an entire grid, and you can make topography maps. I just recently took that one down I've had here for years. Basically, you can make topographic maps of it.

The altimeter teams are always the mapmakers because they produce—they use terms like control grids, and geodesy, and geodetic maps, and things. What they really do is, they create the 3-D model of the surface that all of the other instrument teams use as an input to lay their measurements on top of and create those maps. The laser altimeter folks, when you go to a new body, or even in the Moon, one that you've never looked at in this depth, everyone always interfaces with the laser altimeter team, because they're creating the maps that all the other instrument teams lay their data sets on top of.

This team had worked, like I say, very successfully in the past. This type of technology was one of the last of its type of laser designs that are very finicky and take a very skilled team to do. There are some really extraordinary lidar—lidar is, of course, like radar, except with light beams. In particular, I'm sure the name had come up, John [F.] Cavanaugh, who was the lead system engineer for that mission. He had been my lead system engineer on the Mercury mission, as well, and for previous ones. He's really maybe one of the most renowned people in that whole industry for this type of lidar technology, and he loves the small planetary lidar. So he and the technical team he led, took that design from the Mercury mission, incorporated lessons learned, made it a little more robust, and then changed its technology, though, to basically still have just one laser, but put an optic in that would split out all the beams into it. So rather than have just one laser beam go to the surface and then come back to a single detector, we still had one laser, but then it split out into five beams and then had five different detectors. Instead of just laying one spaghetti strip across the planet, which takes a long time to build up a full map, we could lay five in a row, and then from that create these maps much more quickly. That was the technology advancement that they did.

But this style of laser that is laboriously built up by very precise lining up of many optical pieces, it's not like the little laser pointers we see now or the lidars that you have on your cars for collision avoidance. Because of the power required to get the signal at those distances at that time required a much different technology. It was really a truly amazing piece of engineering, though, that they did then.

JOHNSON: Those maps are so important, of course, for future landing sites, and so we know the topography of where people can go, hopefully.

BARTELS: Very definitely, both regionally and locally. For locally, we could get, where is there a safe landing space for someone to land? Even beyond that, they could find where mountain ranges were and things that you can deduce from optical imagery, but when you make these topographic maps, all of that comes out in really beautiful relief. They really did—between LROC and LOLA, both separately and then in the merged data product, they actually changed the canonical maps of the Moon. When you buy a globe of the Moon now from the Replogle [Globes] company or something, they've actually used the LRO data, which went to the U.S. Geological Service. When you see a globe of the Moon, they've gotten that data from USGS, which is all from LRO. All of the globes that you see now of the Moon are created from LRO data.

JOHNSON: I didn't realize that. That's interesting.

BARTELS: Or at least all the current ones do.

JOHNSON: Yes. Part of that contribution that NASA makes that nobody knows about.

BARTELS: Yes. With LOLA, as well, two other people. I don't want to leave out the project manager, Glenn Jackson, who did a terrific job leading that team under a different type of budget environment than we'd had when I was leading most of that same team for the Mercury mission. Did you say that you got to interview Dr. [David E.] Smith, Dave Smith, and maybe Maria Zuber?

JOHNSON: No, not yet.

BARTELS: The reason I thought you might have interviewed her is because she was—I mentioned LRO of course wasn't a Discovery program mission when it was in inception. It was pulled into it later. But another mission that began in Discovery called GRAIL [Gravity

Recovery and Interior Laboratory], Dr. Zuber is the PI for that GRAIL mission, as well.[5] So as you do Discovery work with the GRAIL mission, you'll come across her.

It's really interesting, because they came from the same group that also has our Dr. Jim Garvin here. I think you interviewed Dr. Garvin. He's my PI on DAVINCI, as well, the Venus mission. Dave Smith actually hired Maria and Jim on the same day many years ago, and those three have worked together and all grown off into different directions. All of them are real titans of this industry, all in their own way. All three of them, Garvin, Zuber, and Smith, are just really, really extraordinary people. They're skeptical of new folks when they first meet them, because they've seen a lot of people come and go with their work, and so I definitely had to prove my way with Dave and Maria on the Mercury mission. But then at least there was already an inherent comfort there with them on LRO, because they had been my PI and deputy PI on MESSENGER. They were the only science team that I actually had a preexisting familiarity and comfort with. They're still two of my favorite people in this industry, for sure.

JOHNSON: That's always good to hear. Let's go on and see what we haven't talked about. We haven't really talked about LAMP yet, the Lyman-Alpha Mapping.

BARTELS: Right. You did get a chance to talk to Randy [G. Randall] Gladstone, right?

JOHNSON: Yes.

[5] GRAIL flew twin spacecraft – Ebb and Flow – in tandem around the Moon to map variations in the lunar gravitational field.

BARTELS: Yes, good. So at least you know some of the details of it. I'm sure Randy mentioned that part of what enabled this—he took over for Alan Stern with the mission when Alan became the Headquarters science mission director AA [associate administrator], and then continues since to this day. The purpose of that mission, by looking for that Lyman-Alpha signature, that was an indirect indicator for water. They were a bonus instrument, in a way, in that they were not part of the original package. They'd had something really clever. I'm sure Randy mentioned this. They basically had almost a completed flight spare that they could end up using. It was very cheap. They were the least development of any of the instruments that we had. They redid the electronics, and some optics, and things, but they had a lot of hardware they were able to reuse. That's one of the reasons they were the first instrument to be delivered.

It's a beautifully exquisite type of small spectrometer. It's not an easy instrument at all to build or to design. The folks at San Antonio [Texas] Southwest Research Institute make that type of instrument extraordinarily well. A lot of that team had been working the Pluto mission, so this was leftover hardware from the Pluto New Horizons mission. They had a good head start from that work left over from New Horizons. They were a smaller team than some of the other groups but very efficient. Again, some really amazing folks that worked on that instrument from San Antonio.

They also were interested in not just the composition on the ground, but their instrument had a unique capability of being able to look at the horizon to see if there's a very, very thin atmosphere on the Moon. Most people don't really know this, but there is a very, very tenuous atmosphere on the Moon. Lay audiences, this won't resonate with them, but it's actually called a surface-mounted exosphere, meaning it's not necessarily a continuous layer across the whole body. Characterizing that very tenuous atmosphere was also one of the science goals of the mission, even though it wasn't necessarily one of the human exploration goals to look for resources. Some of that early tension in operations was, the LAMP team wanted to go off and look at the horizon for exosphere, whereas our mission was to look down, and to do mapping, and to find sites, and to find resources. But the team found a way to do both, of course. We always find the way to do that.

One of the things that, in terms of I&T [integration and testing] we had to account for is the nature of their instrument and the wavelengths they were looking at, because they were in the UV, mean that they had to not only be the cleanest of all of the instruments, but everyone around them had to be just as clean. You have practical things. We talk about cultural, and engineering differences, and things between the groups. But hardware has its own culture, too, in a way, and one of those ways it's expressed is in terms of how clean things have to be kept around it in order for it to work. The LAMP instrument, through no fault of its own—it's just inherent in the technology—we had to make sure that everything around it, meaning all of the other instruments, were cleaner than they would otherwise have needed to be, to make sure that they didn't cross-contaminate LAMP so that LAMP couldn't work on its own. That was a little bit of a concern with the Russian instrument, because their type of instrument was a big, bulky thing that can be dirty and it doesn't matter.

The reason I brought that up is, I mentioned we said we would let each team do their own thing, and with the Russians, we imposed very limited requirements on them. One of them, though, that we did impose on them that they wouldn't otherwise have imposed on themselves was to make sure that they stayed very, very clean, so that it didn't contaminate the Lyman-Alpha instrument.

JOHNSON: That's interesting, because I do remember him talking about that, that the other teams may not have been as happy with them because of that.

BARTELS: The thing is, we do things that we can. We bagged them up separately from each other, and we put these purges. We run a purge line that just continuously blows nitrogen in to keep air flowing through them. It keeps moisture from condensing on them and also those particulates. So it's definitely manageable. If it had been an x-ray kind of instrument, it would have been even harder. There's always some grumbling from teams that have to do more than they thought they would have to do otherwise, but it's always manageable.

JOHNSON: I think we talked a little bit about the Mini-RF [Miniature Radio Frequency] last time, but let's just talk a little more about that team and that instrument.

BARTELS: Yes, absolutely. That one was the one that surprised us a little bit when it was awarded to us, because it was not one of the originally selected. When we announced the selection of the instruments, we had six, the six we've been talking about. What was unique about Mini-RF is, it was funded—now this, again, may be a little obtuse to lay folks that may be reading this information later, but within NASA, there are several different directorates, which means areas that specialize on different types of technology. Although we were funded by the human side, we had close ties to the science side because of the nature of our instruments. NASA also has a directorate that focuses on technology development and operations. One thing that the whole industry had been looking for, for a long time, is how do you make a very powerful radar, synthetic aperture-type radar, and make it small and make it light? Because a lot of times, even now, with some of the most powerful radars, the antennas are huge for these things. They take up an entire spacecraft themselves. They're very bulky and unwieldy to work with. They take amazing data.

But this, in partnership with the DoD [Department of Defense], was an attempt to figure out, how could you make high-fidelity radar measurements in something small enough that it could almost be seen as an instrument? This was an investment overall by NASA in partnership with the DoD that was—I don't think we talked numbers here, but it was probably on par with all of the rest of the instruments put together, because it was part of this strategic development between DoD, the Applied Physics Lab, and NASA to advance the state of architecture of this instrument. That made it a little controversial with the team, just a little bit, because I mentioned how all the instruments that were selected pretty much all had high heritage and could be rebuilt, for the most part, with little tweaks. That's really important when you're in a hurry to get launched, because it means you're less likely to have to still develop the hardware. The Mini-RF instrument is almost R&D [research and development] compared to these others that, while not a product line, were almost a rebuild or just an evolution of an earlier design.

They were added to the mission a little bit after the other six, only a couple of months after. In NASA-speak, we use a term called technology readiness level to describe, how mature is this technology? Is it something you're rebuilding, or is it just a prototype? Is it somewhere in between? This was part of a multistage development with DoD where we were the middle development stage in this development spiral to try to progressively make the instrument smaller and more powerful each time.

It was a real technology challenge for that Applied Physics Lab team. Again, I keep saying how great the engineers were, but they were for all of these instrument teams. It was an extraordinary group of engineers from the Applied Physics Lab who had to catch up to all of the other instruments, because while the other instruments were just deciding which lessons learned to unfold before basically rebuilding the same type of instrument again, the Mini-RF team was having to go all the way back to their design first principles to get to this being the first one of its type. The first one is always the hardest. So the fact that they were starting out just a little bit behind us but having so much more engineering development work to do until there was something that could be flown is really important.

NASA understands that, and so the goals for the mission were a little different. For the other six instruments, their science data products were tied to the definition of success of the mission. In NASA speak, we call those Level-1 Requirements. We had a definition of data products that each of the other six instruments was required to produce in order for it to be judged a success. With Mini-RF, it's what's called a technology demonstrator. The stated purpose of all that work is to advance the design of this new generation of instrument. I don't want to say the data that it takes is secondary, but if the data that it takes falls short of the original goals, that's okay, because they're capped more on time and money than they are on their performance. They have the freedom to accept, maybe, some imperfections in the performance if they have to, because they had to deliver at a certain time and at a certain dollar amount.

But the advances that they made in that time period were absolutely remarkable, and the data that they were able to take has really exceeded everyone's expectations. I'd have to check this. I think they were only required to work for a few minutes, actually, to demonstrate that they had met the technology goals. So the instruments had science data products for which they were responsible. Mini-RF was only responsible for demonstrating that the technology could be shown to work in a relevant environment. The fact that it did well, well, well exceed that before one of its power amplifiers gave out is a tremendous success from their standpoint.

They were also able to work with other groups. There was a point where they were having some trouble with receiving, but they could actually do a measurement that would bounce back off the Earth and back to them with Arecibo [Observatory] in Puerto Rico, and do those kind of measurements, as well. They were very clever with that. We did measurements against other spacecraft that were at that point orbiting the Moon. Very clever team, and amazing results that came from that.

JOHNSON: We talked about last time once the LRO got into the lunar capture orbit, the instruments started coming online. Did they come online in any certain order, or all at once? How was it when each one of those, when those teams knew that those instruments were working?

BARTELS: Yes, that's a really good point. As we commissioned them, we did bring them on one at a time, just so that we could focus on each one of those instruments. There wasn't any immediate pressure to rush at that point. The big deal is, we had gotten there. We'd gotten there safely. Everything was still working. So after just initial checkouts to make sure that each of the instruments had survived, because we hadn't turned them on yet, then after we got through that first survival portion so we could say, "Fantastic news. All seven instruments have survived. They've made their trip to the Moon. It's great." Then we started working with each team one at a time to do what we often would call a first-light checkout of their hardware, where we ran each of those instruments through its paces, all of its functional checkouts, and modes of operation, and things.

As I recall—I'd have to go back and check—my memory is we started with LROC, because there was some expectation of, "Let's get those images down to the public so that people don't think we're trying to hide anything." So my memory was, we put the LROC images out first. I remember that, because in my excitement, I posted one of the images to my—there was this brand-new thing called Twitter back then that nobody knew what it was. I was excited to post that image out that we'd seen. Then I was told, "That's not your right to do that. That's not your data. It has to go through channels." It's supposed to be released through NASA, not through some random engineer's Twitter page. Of course, when I took that down, then people said, "Why did the NASA person take the image down?" So that was a little bit of a kerfuffle. So I remember distinctly that we did the LROC imaging first.

But I don't remember with the rest. I would have to go back and see the order. We did them all consecutively, though. Teams were just coming in one after another for their checkouts. The CRaTER instrument almost operates just on its own autonomously, so I don't remember it being a big functional checkout.

But I definitely remember with the LAMP team us doing it, because one of the neat things we had going is, the LAMP instrument was sensitive enough that even in real time—the Moon takes basically four seconds to get the signal, so almost real time. What we were able to do is, when we were in view of the White Sands ground station, we could get almost real-time data coming down from the instruments on LRO. So we had a computer-generated map of the Moon with a simulated spacecraft overflying it, and we could put that up right next to the LAMP data as it was almost coming in in real time. You could actually see when we would cross over from a bright surface into a crater by watching the LAMP data change out. I distinctly remember the LAMP team being really excited about being able to see that, because it was almost, to them, like they were flying over the Moon themselves in real time.

Each of the instruments, it was a very satisfying moment for them, because for the engineers who developed the hardware, that's their closure stage. They've designed it, built it, tested it, launched it. It's gotten to its destination. It still survives. It's working the way it's designed. For most of the engineers, that's when their job is complete. Of course, for the science teams, it's exactly the opposite. In some way, that's when their job is just beginning, because scientists build instruments in order to take data, not necessarily because they're instrumentalists. Dave Smith from LOLA used to say that. He said, "The only reason I build laser altimeters is, I don't know how to get altimetry without doing that." From the science teams' standpoint, they were really excited to get the initial results, because then and only then could they really say, "Now we can start executing science, and taking data, and writing papers." It's a real inflection point in the mission at the time when the engineers can say, "We did our job," and they hand the keys to the operations team, and the science team thanks them for their excellent work. The whole focus of the mission changes from that point from an engineering exercise to a science data gathering exercise.

I would have to check the order that we commissioned them. If that was important, we could find that.

JOHNSON: I was just curious.

BARTELS: Well, now I'm curious.

JOHNSON: Okay.

BARTELS: I may go. If I find something, I'll email it to you. Because my memory is, Mini-RF was last, and LROC was first, and I don't really remember the order in between of LOLA and Diviner. They were doing similar measurements. If I find that data, I'll send it to you, just to close the loop.

JOHNSON: Okay. It makes sense that the high-profile LROC went first. That just makes sense. So I was just curious if any of the others had to be turned on sooner or later, if it didn't matter.

BARTELS: It's actually not so much about how soon do they have to be turned on as much as, how soon is it safe to turn them on? Because one of the things that happens is, right after you launch a mission and we have these commissioning—that's what we call it when we turn the instruments on and run them through their paces. One thing about it is, even though we try to keep everything nice and clean by putting the instruments into high-temperature bakeouts, we call it, so that it can drive off all of the—we call them volatiles. I don't need to be too technical, but basically the new car smell off of the instruments. As much as you do that on the ground, when you get to the vacuum of space, you find that early on, there's still cases where you are still driving off contaminants.

The biggest contaminant, actually, is water that gets absorbed in the system, because we are in Florida when you're at launching in June, and so even though we put in these large-scale nitrogen purges to keep things as clean as we can, some of the materials, like the LROC telescope baffle material, would still absorb some water.

So one of the things that we had to do, of course, is get through those—what we call an outgassing phase. New car smell is easy to explain. You can visualize it. You VOC [Volatile Organic Compounds Emissions] all of that stuff off of there. Some of the instruments actually even have little heaters on them that, before you turn them on the first time, you run these heaters for a while to try to bake off anything that was there. My memory is that the order of the turn on was a little bit coupled to how soon did we feel that we could safely turn them on, because the outgassing part was complete. I think that was why we had LAMP probably late, because they had to make sure they had driven off any water that it had picked up, so that it wouldn't contaminate the instrument.

JOHNSON: As you mentioned, and it was around the time you left this mission, I think, was when it actually transitioned from an exploration mission to a science mission and went to the Science Mission Directorate for two years, which, of course, has been extended many times. It's an interesting dual role with LRO, because there was that exploration, and the engineering and everything to get there, and then all of the science that has come from it since then. Did you have any idea when you were going through this with these instruments that so much would be gathered and for so long?

BARTELS: That's a great question. I would never in my life have thought that it would still be there. After leaving LRO, I went over to the weather satellites for a while and then worked OSIRIS REx from its selection through just a few months before the asteroid sampling was there.

During that same time, in operations, I was right next to the LRO operations team. I would stop by every once in a while, and ask the flight director, "Still working?" The thing that stunned us so much is because it was designed for a short mission, it means that there are almost no backup systems on the mission. I'm sure someone had talked to you. If not, it's really important to know.

One of the ways that NASA extends the lifetime of missions is to have backups on board. We call that either single string, if we don't have any backups, or redundant or dual string, or words to that effect. LRO was almost exclusively a single string mission with no redundant hardware. It was not designed to run for a decade. It was designed to run for a year, and we hoped we'd get two or three years out of it.

There would be those who say we overdesigned it because it shouldn't still be working. But to be truthful, a lot of the engineering choices you make aren't with an expiration date in mind. The important thing was, there are no backup systems on it. At some point, the big gimbaling antenna, which points to White Sands and tracks as we go, there will have to be a point someday that wears out, if something doesn't wear out first. The LRO operations team, if you talk to any of them, I'm sure they would still tell you how you keep an aging spacecraft still operational. They've done things to extend the way they operate the hardware to keep less stressing on it to extend the lifetime.

The orbital mission that they're in now, they're in a very special orbit that the flight dynamics people found that requires almost no fuel to maintain. Has anyone talked to you about this? Because it's actually an important part of the mission. Okay. So one of the reasons why all the other lunar missions that have orbited from other nations have only been very short duration, no more than a year or two, is that the Moon is very lumpy. It has a lot of—you know, mountains on the moon—but areas where the gravity is much higher than others. Why does that matter? Well, the closer you are to it, the more difficult it is to stay in a stable orbit, because the areas that have more mass are pulling it down. What other missions have done is, they use up a lot of fuel to keep in a good steady orbit. The closer you are to the Moon, the harder that is to do. So the missions that want to stay at the Moon for a longer time typically fly farther away so that those gravity perturbations as you go around it are less. Those gravity perturbations are what actually created the entire project in Discovery that Maria Zuber led called GRAIL. GRAIL is gravity, the GR is gravity. Mapping the lunar gravity field is of great scientific instruments. It's a great engineering annoyance to the flight dynamics team that have to deal with that.

One of the most important things, because we had to do global coverage, so we had to map the entire Moon at close range, is in those first two years, we had to use a lot of the fuel to maintain—it's called station keeping in their speak—to stay in that right orbit. But one of the genius findings from the flight dynamics team is that the same orbit that we used for initial commissioning is not circular but is highly elliptical, so it buzzes the south pole and then goes along far away on the north pole, so like 30 kilometers distance at the south pole and 200 kilometers elevation on the north pole. That's a very stable orbit from a gravity standpoint, so that you don't have to hardly spend any fuel to stay there. If we had stayed in just that really tight mapping orbit, we would have run out of fuel years ago, and we would have had no choice but to end up like every other lunar mission does eventually. But because they found this really interesting orbit—and the really great part of it is, the part where it comes closest to the Moon is right over the south pole where the people are the most interested—we've been able to extend that mission.

We have oversampled that south pole so much now, because they've gotten such a great data set. With LROC, then, as we go away from it, we image the whole rest of the surface. It was finding that very, what they call a frozen orbit, which means it doesn't keep moving around on you and get pulled down. That quasi-static frozen orbit means they don't spend much fuel, which is why they continue to extend the mission out. We always thought that if the hardware didn't wear out first, the gas tank would be empty after two or three years. It was that amazing work by that flight dynamics team led by a man named Michael [A.] Mesarch that found that frozen orbit that has extended this mission year after year after year. If not for that, our mission would have been over years ago.

JOHNSON: No, I don't think I've heard that before, so that's good.

BARTELS: Yes, we would have had to have crashed a perfectly good working spacecraft because it was out of gas, without any way to refuel it. That's the thing with these spacecraft. I think I mentioned before, half the mass was fuel. It's basically a flying gas tank with sensors on it. But when the gas tank's empty, you're going in.

JOHNSON: Whether anyone's there to document that or not.

BARTELS: Yes. Your original question was, am I surprised? I'm still surprised every day, and it just brings a tickle to my heart to know that that thing's still going, because none of us would have bet that. If we had taken bets at launch of how long it would last, nobody would have bet this long. It would have not been seen as an engineeringly logical response to the question of, how long will this mission last? We may wear out the ground station before we wear out that spacecraft.

JOHNSON: They're probably just going to tell you, no, we can't do this anymore.

BARTELS: That's actually a concern they have every year, that we are now really the only orbiting lunar asset. So as Artemis goes back to there, they are using the LRO data sets daily in terms of their planning. The part that's kept the mission going from a science standpoint—all the instruments continue to make great data, but the LROC camera imaging and some of the dynamic surface properties that we continue to see evolve, those have been justifying the continued funding. There's always this push when a working spacecraft has completed its first main mission of, "Well, aren't you spending money now that you should be spending on building something new, because you've completed your mission? Why are you still spending the money?" But the thing that folks mostly don't recognize is, it's a very small team that does mission operations compared to the team that builds an entire spacecraft. There were as many as a thousand people working LRO at one time in its development, and it's a very small operations team now, so it doesn't cost that much.

But the question would be, what's left for LRO to do? The main thing that it continues to do is use that LROC imaging to continuously—to get even the same site from different lighting angles as we go over it multiple times over multiple years, or going over the same site many years apart to see if anything's changed. There are those who say, "We should be spending the money on designing the next LRO," and we actually are. The people who are designing it just live right down the hall from me. The science people kept it alive for many years by justifying the continued new science data products to come from it. Noah [E.] Petro would continue to claim that we are exactly making that same case now. We are still learning new things every month from LRO. The thing that is providing the biggest impetus to keep it going seems to me to be, from my very distant perspective, that the human folks are still finding this useful data, too.

JOHNSON: Right. And it's informing other missions, like you said, like VIPER [Volatiles Investigating Polar Exploration Rover].

BARTELS: It is, exactly.

JOHNSON: VIPER is going to be landing with that information gathered from LRO.

BARTELS: Exactly. Exactly right. It's not just the Replogle globe makers that use our data. The people who are actually designing where to send their landed missions use that data, as well. Because our data is available in the Planetary Data System, that data is available to any commercial team that wants to do a commercial venture. Other nations can tap into that data, as well. We take the scientific data for all mankind, as we always say, and so that data is available to anyone who can use it in any way.

JOHNSON: It sure is. Well, since you've been on several Discovery missions now that we want to talk about, but I was going to ask you. Even though LRO wasn't originally part of the Discovery, but it got brought into it, what do you think the impact has been on the Discovery program's missions, but mainly this model of getting the projects off the ground quickly for a certain amount of money, but the impact on NASA's ability to explore and keep moving forward?

BARTELS: That's a very interesting question, and an open-ended one, which is great. Those are the most fun kind, right? I would say that I don't want to speak for the Discovery or New Frontiers folks at the program office, but I know from my perspective, Discovery was already a mature, ongoing program when LRO was brought into their fold. When you look at their portfolio of work that goes back to the early '90s, they were already a mature, ongoing organization, which was important, because when LRO was handed from the human side to the science side, it needed to be brought into an experienced portfolio where the people can continue that management, because all projects map to programs. Of course, we all know a program is a collection of projects. Typically, unless you're James Webb [Telescope] or Mars Sample Return, a project doesn't stand on its own. It stands as part of a program. So I don't know that LRO changed anything in the way of how Discovery does business.

It's actually more just in line with Discovery. In fact, when we were originally designing LRO, we were told to think of it in a Discovery mindset, in that class of size, although we were not part of the Discovery program. I don't know if any decisions had been even made at that point to do it, or if that came later. But we were told to keep Discovery in mind. We were a good fit for Discovery, because it was almost as if we were kindred spirits and types of missions. Because we were already like a Discovery mission, I think we were a really good fit to come in with them as opposed to someone else.

But to be fair to the Discovery folks, they were already a very successful, mature organization when Discovery came in. I think it's very important, though, for the Discovery program and New Frontiers to continue to exist, because one of the things that is the biggest hallmark of the Discovery mission—now we're getting away from LRO a little bit, which was a directed mission, where NASA Headquarters told Goddard, "Here's the desired outcome. Here's the desired date. Here's your notional budget. Get started." One of the most important things about the Discovery program and why their missions continue, with a couple of exceptions, to really come in on schedule and on budget is the competitive selection nature of the missions, because each time that we have these rounds of proposals—like the one I'm on now, DAVINCI, proposed, I believe, four times before it was selected.

Each of those times, it refines the mission. It makes it more understood and more executable because we've been through many of these discussions many times already. We know who our teaming partners are. We've already had external reviews multiple times from the people who evaluate proposals. We've incorporated their feedback. So it takes a while, like running for president, sometimes, maybe, to be selected on these missions. But when you do, then you know the mission is attainable. It is affordable. It may still be very challenging, because these are exotic missions. But part of what they do is, it's the mission that's exotic, more than the hardware, sometimes. The technology is doable. It doesn't break the bank, typically.

I think what's important with the Discovery missions is, it enables a type of science to be done that could not be done if you have to just rely on giant flagship missions, the ones that NASA's famous for, but that also take so long, and they're so expensive. We could run many, many Discovery missions in a row for the cost, sometimes, of one of these giant flagship-type missions. That means more principal investigators get involved. It means more people can participate. More universities can participate. More students can participate. More people can participate in a diverse range of missions. If you have a large mission like Mars Sample Return that's going on now, there is the group of people who do that Martian geology, for whom this mission is their career pinnacle. Nothing could be more important to them than their mission. That's one group of people. Discovery allows, through the selection of the missions from Headquarters, by the missions they choose to select that align with the Planetary [Science] Decadal [Survey], that shape not only what we learn about the solar system, but who are the groups who get to lead that search for the knowledge?

The competition is severe within these groups. I worked one Discovery round where at least we were aware of 25 initial proposals that went in that then get down selected to a small handful, where each of those missions is given a million or two, and they produce what's called a concept study report phase A. That's just a fancy name for the proposal. Then that initial set of 25 that gets down selected to three to five or so. Then those—view it like being a sports team in the playoffs. They know they've made it through that first cut, and their science is considered worth doing. Then each of those teams is given a limited amount of time and a very limited budget, and they're told, "Produce the best proposal you possibly can." Again, that refining process of distilling these missions down as the result of—what makes Discovery, I think, so important, is it's the right size to allow really interesting science investigations. They're short enough that they can select—they've always got one or two going at any one time. Right now, with Psyche, and with us, and with VERITAS [Venus Emissivity, Radio Science, InSAR [interferometric synthetic aperture radar], Topography, and Spectroscopy], a little bit slowed up, but we have three missions in development.[6] It broadens the participation, as well.

They also have what they call a participating science program from Headquarters where, if you're not a member of the proposal team—maybe you were on a competing proposal that was somewhat similar, so you were firewalled off, so you couldn't be part of the first team. But you can contribute to that first team's mission. Headquarters also has a mechanism where they add more science team membership. Those are called participating scientists.

I tend to give long answers to short questions. Forgive me. I think you asked what's important about Discovery? To me, the fact that we can continue to develop short turnaround missions at a small enough budget that we can allow many missions to be selected, because the performance history of these missions is pretty good, as well. We tend to launch under what we've told NASA, let alone Congress, what these missions will cost. I think it's why this program is over 30 years going and continues to go, because under Marshall's [Space Flight Center, Huntsville, Alabama] leadership and the missions that we've all selected, we've achieved pretty good results.

JOHNSON: I look forward to talking to you about maybe some of those other missions, like MESSENGER. Was that the first one that you were involved with, a true Discovery?

BARTELS: It is. It is. Yes. Because on that time, I was the instrument project manager for the little laser altimeter, the precursor for LOLA. Then after LRO, I was on OSIRIS REx for eight years, from selection through just before we sampled. Then I moved over to Lucy, and I was the

[6] VERITAS and DAVINCI will be the first NASA spacecraft to explore Venus since the 1990s. Veritas will discover the secrets of a lost habitable world, gathering data to reveal how the paths of Venus and Earth diverged.

deputy project manager there from the phase, what they call critical design review, KDP-C [Key Decision Point-C] on through the first nine months or so. I still stay in touch with their operations team now because they're going to have their first asteroid flyby here this fall. Then I moved over to DAVINCI, where I'm the project manager. I have a lot of opinions about Discovery. Opinions are subjective, but I'll tell you, they're all positive. New Frontiers, as well, because they are managed as sibling projects. It's just the size is different, but it's the same management chain not only at Marshall but also at NASA Headquarters. There's a real continuity of those missions. I would never go outside of this program if I have the chance.

The other missions at NASA, all of them are wonderful in their own way, and to some people, they value them more. Some people that work on Earth science missions, to the extent that they know they're working on climate change, that's their personal vision statement, and so they would never leave the climate satellites or the weather satellites if they could. Some of the astrophysics folks, people at James Webb, that's their view of the world. For people like me that have the solar system and planetary missions in our blood, we would never choose to go anywhere, and we feel we're the luckiest people in the world.

JOHNSON: That's a wonderful statement and a good way to stop for the day, I think. We can talk in a minute about the other, but I appreciate you giving me all that extra information. I really do.

BARTELS: Well, what I hope is that it's in line with the information you're getting from the people themselves. I think I told you at the start, one of my concerns about thinking back so far to LRO is, your memories become increasingly romanticized the farther away you get in distance. Even when you're there, it's like that Japanese movie *Rashomon*, you know, where you see your view. Your truth becomes the truth in your mind. So I think one of the really interesting jobs you've got in your team is distilling all of these different inputs and trying to develop the consensus story to tell.

JOHNSON: Yes. Well, we gather it so people can do that. We appreciate it.

BARTELS: All right. Yes.

[End of interview]