# NASA DISCOVERY AND NEW FRONTIERS ORAL HISTORY PROJECT
# EDITED ORAL HISTORY TRANSCRIPT

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INTERVIEWED BY SANDRA JOHNSON
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JOHNSON: Today is December 4th, 2023. This interview with Rich Burns is being conducted for the Discovery and New Frontiers Programs Oral History Project. The interviewer is Sandra Johnson and Mr. Burns is at Goddard Space Flight Center in Maryland today and talking to me over Microsoft Teams. Thanks again for joining me today and agreeing to participate in the project. I'd like to start by asking you to briefly describe your education and your background and how first came to work for NASA.

BURNS: Sure. Thanks, Sandra, thanks for having me, appreciate the opportunity to talk to you. My background is in engineering. I have mechanical engineering degrees, a bachelor's and master's degree, both in mechanical engineering. I worked the first 10 years of my career for the Air Force Research Lab at Kirtland Air Force Base in Albuquerque, then moved to Goddard Space Flight Center in 2001. I was a discipline engineer in guidance, navigation, and control, and I was working formation flying technologies at the time.

I worked a few missions including the Hubble [Space Telescope] servicing. At the time the Shuttle-based servicing had been terminated as a result of the Shuttle accident that had occurred [STS-107, *Columbia*], so we were working on a robotic servicing concept. I was involved in that as a subsystem lead, both from a guidance, navigation, and control point of view and a relative navigation point of view. I was impressed on that mission with the level of effectiveness that project management could have in that there was a large lever arm there to effect change, at least from my perspective.

I took the opportunity to transition from that position into the current organization I'm in as Deputy Project Manager for Space Science Mission Operations [SSMO]. That organization is responsible for the management of a portfolio of missions, space science missions unsurprisingly from the name. All those missions are in the operations phase or Phase E as I'll refer to it.

That exposed me to a wide variety of mission classes, all missions of different scales and challenges, different orbit regimes, and different varieties of science and modes of operation, concepts of operations, utilizing different communications networks, different partnership agreements, and so I was an enthusiastic learner at the time. That really set me up when the project manager transitioned into another position. I took that responsibility in about 2010 and I've been in that role since then.

Our New Frontiers and Discovery-class missions came later after I'd gained some experience in this role, and so they represented some of the larger missions that we were dealing with, with some fairly intense operational challenges, particularly OSIRIS-REx. That was fun and challenging and invigorating to be in missions of that class, and the quality of the teams in solving problems, all things that are very engaging and challenging and rewarding.

JOHNSON: In your position that you started in 2010 as the project manager for SSMO, was it normal for the project manager for those missions to come from your organization? Or the project managers that come from SSMO are the ones that take over once everything is in operations. Is that correct?

BURNS: That's correct. Right. Yes. This was the precedent at Goddard for missions of a different variety of scales. But mostly they had been directed missions like LRO [Lunar Reconnaissance Orbiter][1] and SDO [Solar Dynamics Observatory][2] were both directed to Goddard, and it was the tradition, the heritage, that those missions would move from their development phase project structure to an operations organization like the one I manage.

Really there was an open question when MAVEN [Mars Atmosphere and Volatile Evolution][3] launched in 2013 about what structure it would retain in its operational phase. I think we made that transition successfully and actually accelerated the transition because there were demands placed on the development phase project management leadership that weren't necessarily anticipated before launch. That was challenging and invigorating as I said. Rewarding I guess is the right word to say. I think expanding the—I'll reference my project as SSMO, Space Science Mission Operations. Expanding SSMO's capability into beyond the Lagrange points. We had always managed Lagrange point missions, like ACE [Advanced Composition Explorer],[4] Wind,[5] SOHO [Solar and Heliospheric Observatory],[6] and WMAP [Wilkinson Microwave Anisotropy Probe].[7] Expanding beyond that to the planetary regime, beyond the Moon as well, because we had already been managing LRO for going on five years by the time MAVEN came along, but that

[1] Lunar Reconnaissance Orbiter was the first U.S. mission to the Moon in over 10 years. LRO's primary goal was to make a 3D map of the Moon's surface from lunar polar orbit. LRO continues to orbit the Moon.
[2] The Solar Dynamics Observatory is the first mission to be launched for NASA's Living With a Star (LWS) Program, a program designed to understand the causes of solar variability and its impacts on Earth.
[3] The first mission dedicated to studying Mars' upper atmosphere, MAVEN helped identify how solar wind might have turned the once warm and wet Martian environment to cold and dry.
[4] Designed to collect and analyze particles from near and far, ranging from solar wind ions to galactic cosmic ray nuclei, ACE far exceeded its expected life span of five years and continues to provide data on space weather, and give advance warning of geomagnetic storms.
[5] Wind is a spin-stabilized spacecraft that observes the solar wind that is about to impact the magnetosphere of Earth.
[6] SOHO was designed to study the Sun from its deep core to the outer corona and the solar wind.
[7] The WMAP spacecraft measured temperature differences across the sky in the cosmic microwave background radiation, a remnant of the big bang.

was really the first precedent setting how does Goddard transition planetary missions into their operational phase. I think that MAVEN really set the precedent.

I guess you could make the argument that LRO had, but I think people make a distinction between interplanetary and lunar missions and Lagrange point missions. That's typically where Goddard's sphere of management had been limited to in the past. But MAVEN and then after it OSIRIS-REx and Lucy really expanded Goddard's sphere of management I'll call it.

JOHNSON: That's good to know. I was wondering if this was the normal progression once things went to operations. Let's talk about assuming that position as project manager for OSIRIS-REx once it was in operations. I think you joined that team prior to launch. Did you work with the [operations] project manager at the time for that handover? Talk about that transition time.

BURNS: Yes. We worked with the project management team before launch to plan a transition, which culminated, I can't remember whether it was 30 or 60 days after launch, after the commissioning. Commissioning on OSIRIS-REx was a little bit different because we were immediately into cruise and there was not the traditional kind of commissioning you would do on an Earth-orbiting spacecraft, because we're in a position to do an extensive checkout of the science instruments. It was pretty rapid transition from that perspective. Some of the other missions might take 60 or 90 days. I think it was 30 days on OSIRIS-REx where we made that transition. But like I said we were involved. Not just me of course. All the people in my organization were involved in planning the transition.

That involved participation in reviews in the years leading up to launch, and participation in planning the transition, involvement in all the reviews that led up to launch and followed launch.

Particularly the Key Decision Point for Phase E, KDP-E; convincing our stakeholders that there was a mature plan and the transition was going to be smooth. I think it proved to be so.

That constituted the level of involvement. We've slowly been ramping up my organization's involvement before launch as a value-added proposition because it makes for a smoother transition when there's a more in-depth involvement of the operations organization prior to launch. Probably not surprising to anybody. But it does take some coordination and takes some resources to facilitate that. I think we've shown that it works better and it represents a good investment for the Agency.

JOHNSON: Where were you during the launch? Were you in the control room?

BURNS: I was in the Spacecraft Control Center, so it's called the mission support area for OSIRIS-REx. That's in Denver [Colorado]. On OSIRIS-REx as well as Lucy and MAVEN we're partnered with the spacecraft provider Lockheed Martin. They build and operate the spacecraft, integrate the instruments onto the spacecraft as they're delivered, so all the operations happen at Lockheed Martin with their team. It's part of project management, managing all the partnership agreements and the resources necessary, technical and programmatic resources, to do that job. Yes, I was at Lockheed Martin for the OSIRIS-REx launch.

JOHNSON: Before launch when all of the instruments were integrated into the spacecraft, had there been any issues with any of that at the last minute or any surprises there?

BURNS: No. You always run into some challenges during integration tests or ATLO [Assembly, Test, and Launch Operations] as they're called in interplanetary missions. But I wouldn't say there was major issues at least in the immediate preceding launch. There was no emergency or anything like that. It was fairly smooth. There was some issues with the spacecraft but they were handled smoothly by the development project.

JOHNSON: Nothing that would cause a delay or anything like that.

BURNS: No. The development project maintained very healthy margins and were able to deliver of course planetary missions. You usually have some launch window. I think O-REx launched on the first day. Maybe the first second of the launch window or something along those lines. It was all very smooth and efficient.

JOHNSON: Talk about the launch. The experience of being in that launch room for something like this and the anticipation, because this one had actually been proposed back in 2004 the first time for a Discovery mission and then it went through another round and they were told that they needed to think about maybe New Frontiers. There'd been a long wait for the group that had been working on this. Talk about that day and leading up to that launch and anything that was going on in the spacecraft control room, your memories of that.

BURNS: Yes. It's exciting of course to be involved at launch. My role was as incoming project manager really focused on the ground system in support of the initial operations for the spacecraft. It was really the postlaunch initial operations and assessment of the spacecraft health and deployment of systems that we were focused on, and not so much the interaction with the launch vehicle. But nonetheless you're on the voice loop with all the parties. There's extensive rehearsals that lead into any launch. That was all very exciting and challenging. At least one of the rehearsals normally envisions lots of anomalies, so you get to deal with that, at least in a rehearsal sense. That sort of experience got repeated again and again for our sample collection event and our sample return event.

Really exciting to be part of it and to interact with the team that's a really high caliber team and focused on problem solving. One of the main positive, it's about the people in the end. Lots of our capabilities, our systems, are enabled by our teams. I think sometimes we lose sight of that, focus on the hardware so much that you lose sight of the fact that it's really people that are making it work and solving problems, hard problems which are challenging.

JOHNSON: Since you're talking about teams, talk about the OSIRIS-REx team for a few minutes if you don't mind. Of course you were the project manager. Dante Lauretta was the PI [principal investigator]. Deputy project manager was Arlin Bartels, and lots of other people were involved in it. But talk about that team and you coming in for operations and working with these people at that point for launch and right after. What were your impressions of the team and how they worked together?

BURNS: My impressions were that it is a very high caliber team. We had University of Arizona with not just the PI but also the science team and the science and payload operations aspect of the mission. Then Lockheed Martin with the spacecraft operations. Goddard was teamed with KinetX, a small company called KinetX, to do the flight dynamics. Every aspect of this mission.

Launch was just the first exciting step, but we knew it was going to be a very large challenge. OSIRIS-REx is maybe the most challenging operational mission that NASA has ever done, I think, so we knew there was a lot of challenges ahead of us. But we certainly didn't appreciate all the challenges we were going to encounter.

We knew that there was an ample amount of work in front of us in terms of planning the phase that we call proximity operations. After we arrived at the asteroid Bennu we knew that there were going to be some things that needed to be addressed related to the observations of the asteroid and accommodating uncertainties in the trajectory and the pointing that were going to be challenging. Soon after we launched, we began a process of assessment what the plans were to conduct those phases and where we thought they needed to be improved for efficiency and for effectiveness. To make sure that we got the right observations at Bennu to enable us to not only map the asteroid globally but also to identify areas that we were going to be able to sample. The area where it's both the right combination of sampleable is what we called it. Meaning containing small-grained material that was capable of being ingested into our sample collection mechanism and safe.

Now we didn't really understand how challenging that was going to be before we got up close and personal with Bennu. But planning the observations we knew we were going to take certain geometries that we were recognizing were going to be more challenging than anticipated. These are geometries related to lighting. The specific observational geometries that would give us favorable observations that we were going to need in the mapping and site selection campaign.

We put a lot of effort into that. We put a lot of effort into our planning processes and how long we were going to take to develop our observational plans because we knew we had to be efficient at Bennu. The operations at Bennu largely rely on what we call the 24-hour late update process. That meant in order to plan any particular maneuver or observations you needed a relatively fresh estimate of where the spacecraft was. That estimate relied on images from the spacecraft of the asteroid to update. Those had to be downlinked to the ground. The ground would determine where the spacecraft was and its velocity so that we'd know we could predict where it would be at the time we needed to make a maneuver or the time we needed to make an observation, so that it constrained the amount of uncertainty that we had to plan for.

You can imagine any time you predict a future state based on information in the past there's uncertainty associated with that prediction. Our observations and our maneuvers had to account for that uncertainty. We really were incentivized to reduce the amount of time from the time the pictures were taken to the time we were making our observations or our maneuvers, so that we limited the growth of that error in those predictions.

We put a lot of effort into making efficient our observation cadence and our ability to turn around these late updates. We ended up making some improvements into how we planned observations to be relative to the spacecraft's sense of down or nadir relative to the asteroid. That made a very large improvement in how efficient and effective those observations could be made, because what ended up happening is we could uplink a new trajectory or ephemeris file to the spacecraft. The spacecraft would be able to have a sense for where down is so we could point relative to that, rather than trying to plan observations in a more absolute sense, which would have been more time-intensive and planning-intensive and would have resulted in certainly more error that we would have needed to account for.

Those were immediate challenges from the time we launched until the time we got close to Bennu. Of course we were also planning the trajectory. You have to make a series of maneuvers to get to Bennu and that was also ongoing, and making sure that we had adequate contingency plans. Particularly the maneuvers during the approach scenario, you have a limited time to be able to make those asteroid approach maneuvers is what we called them. We were planning a primary maneuver, also backups in case we missed or had a partial execution or some other problem happened.

We put a lot of effort into the contingency scenarios. Then we knew before launch that the schedule to get to the sample collection was going to be more challenging than it should be. In other words we didn't think we had enough resource or margin against that schedule to really be able to address what we thought would be the challenges, and then eventually we realized the challenges were even larger than what we thought. Fairly soon after launch we began advising our stakeholders that we thought we were going to be moving the actual sample collection event.

First, we moved to July 2020; ultimately, we settled on October of 2020 as the sample collection date. That was a big management effort as well because the way our staffing was structured is there was a big roll-off of personnel after the sample collection event. You can imagine you need a lot of people to operate around Bennu and these 24-hour late updates we did a few hundred times. Those were 24-hour cycles where I described that the images come down, somebody has to find landmarks on the asteroid in those images, then determine an orbit, and then either update a maneuver or an ephemeris file or pointing files for observations, check those products, uplink them to the spacecraft, and verify that they're there. That process had to happen over a 24-hour period a few hundred times.

It was operationally intensive, and so we needed a large staff. Then that was the mapping campaign, site selection was another challenge, and then preparing for rehearsing the sample collection, and then executing it.

Then after all that we were planning to staff down to conserve our financial resources. You can imagine moving the sample collection event months to the right, so to speak, requires resources because we needed to carry a larger staff for a longer period of time.

We had to make our case on why that was warranted. We needed to free up some resources from what's known as unallocated future expense—our stakeholders were holding that. We made I think rather compelling arguments that we want to do the sample collection event once and only once in the area of the asteroid that's going to be the most likely for success, the lowest risk. We were able to do that.

It is also important to note that I'm talking about freeing up some of the unallocated future expense but this was well within the Agency's baseline commitment to execute this mission. We actually completed the Phase E well inside of that marker. It's not like we were overrunning the life cycle costs for the mission. But we did expend some resources, as is the tradition. I think there was a long tradition in development of making proactive decisions to mitigate risk, which paid dividends throughout the life cycle of OSIRIS-REx.

One of those was the very wise decision, although the risk didn't actually materialize in the way it was envisioned, the optical-based relative navigation system called Natural Feature Tracking was added late in the development cycle at the critical design review when there was a struggle. The spacecraft lidar, not the science lidar, was having some challenges with respect to meeting their schedule, and the optical-based navigation was added as a capability. There were already the cameras there but the capability to do the onboard feature recognition and navigation was added at critical design review, which was pretty late to be adding that kind of capability. But our team, as became a theme throughout the development and operations phase, rose to the occasion.

That Natural Feature Tracking capability actually is what enabled us to be successful because—I haven't yet touched on the challenges of Bennu—Bennu is an extraordinarily rugged surface. The lidars as a guidance sensor to get to the surface would have been very challenging to use because the terrain is so rugged that we would have seen large changes in the range measurement to the surface as you fly over surface features that are larger than had been anticipated.

JOHNSON: Talk about that. Once the spacecraft arrived, and you've alluded to it now, those surprises that you found. It had been planned to have an opportunity to get samples from more of a beach-like surface and as you said it wasn't how it was anticipated, and if that Natural Features Tracking hadn't been added, it could have been a real problem and may have prevented the mission from accomplishing what it set out to do.

BURNS: Let me back up a little bit. When we made our approach maneuvers and were beginning to resolve the asteroid in more detail, and it was pretty clear. It's got the right rough shape that was estimated before launch from ground-based measurements and so it was pretty impressive actually from really low-resolution radar measurements that the bulk shape of the asteroid was well understood.

What was a disconnect was there was some thermal measurements of the thermal inertia of the asteroid that as you said indicated that that thermal inertia measurement was consistent with beach-like material on Earth. That combined with the experience of the JAXA [Japan Aerospace

Exploration Agency] mission Hayabusa,[8] the Itokawa asteroid, where there was a lot of fine-grained material, made us believe that we were going to have large areas of Bennu that had fine-grained material that were beach-like.

As we kept getting closer, we kept wondering where they were. Right before we entered orbit an interesting anecdote is, as I mentioned, we were operating from Lockheed Martin in Denver; this is December 2018, and it turns out that there was a widespread regional network outage that affected operations at Lockheed Martin. Just as we were preparing to make the maneuver to uplink the orbit insertion products, we were out of contact with the Deep Space Network and consequently with the spacecraft. That was unanticipated. We didn't really expect to see, and no network outage of that scale has occurred before or since. We're uniquely unlucky on that.

But what do they say? Success is the combination of hard work and preparation and good fortune. We had the good fortune of having an alternate command capability at JPL [Jet Propulsion Laboratory, Pasadena, California] by virtue of the fact that the MAVEN configuration was very similar. We leveraged one of the workstations used for MAVEN at JPL to control its electrical relay to actually command OSIRIS-REx and uplink the critical products that were needed to make that orbit insertion burn.

If we hadn't made that burn, we would have flown past Bennu and that would have been a large schedule hit to us. Wouldn't have hurt us in any other way. But as I mentioned, schedule was money and as much work as we had put into making the planning process efficient, it still

[8] The first mission to return a sample of material from the surface of a near-Earth object, the Japanese Hayabusa spacecraft, which also carried a mini lander named MINERVA, was originally designed as a technology demonstration mission.

would have been probably a month or two of delay. That would have been a large financial implication. Plus also demoralizing to the team. You don't want to miss your first critical event.

December 31st, 2018, we entered orbit due to the fact that we had some alternate capability that we leveraged. We had a very flexible team that was able to get somebody on-site at JPL to do the thing.

We actually also had a capability at Goddard that was envisioned for the sample return event in 2023 that wasn't fully functional yet. We didn't have any certified commanders at Goddard, but we did also leverage that facility to monitor the spacecraft health and the reception of commanded products from JPL. We were using all resources at hand to make that orbit insertion a reality on that one.

It was maybe eye-opening in terms of our ability to adapt on the fly and to get things done when circumstances were radically different than what we had envisioned. That's not the last time they were radically different.

We entered orbit. I remember it very well. New Year's Eve. Massive snowstorm in Denver. But once we got it all done, we drove carefully through the snow and had a nice dinner with our colleagues. The team building aspect of these things is also important. Getting to know and trust one another over organizational and discipline boundaries is also a real key to success in my opinion. That was a lot of fun and also a lot of tension.

Then very shortly after that once we were in orbit, we began observing the asteroid from orbit, which meant looking at the surface and looking at the limb of the asteroid. Shortly thereafter we made the discovery that Bennu was emitting particles, rocks. It was an active asteroid. Nobody had thought that it was possible that Bennu would be emitting particles. That was completely unplanned for once it was discovered. In fact on approach we had done searches for natural satellites because what we had thought is maybe there's a small moon or something like that. All those searches for satellites were negative, but these particles are much smaller than you can detect from the distance we were observing.

We were in this orbit in close proximity to Bennu. That's where you can really start seeing these smaller particles that were being ejected from the surface of Bennu, for reasons that still aren't well understood. This is what you get when you're in a mission of discovery. You go to someplace that has not been well explored. You should expect to be surprised. That is one thing that is very true.

We very quickly assembled a team to assess the risk. Of course you don't want to run into one of these ejected particles. If we do, how big are they, how massive are they, how much energy do they have, in other words how fast are they going? You can imagine we had an incomplete set of information because we didn't have observations happening all the time. We had them when they were scheduled to be made. But we could see particles.

We had a partial set of information. We had to extrapolate "Okay, how frequently do we think these things are being ejected, how do we observe them, what is their path, how many are escaping versus how many are being pulled back to the surface of Bennu by its tiny gravitational field?" By the way, for context, the escape velocity from Bennu's surface is about 60 centimeters per second so it's extraordinarily slow to operate. Everything moves slow in the proximity of Bennu, and if it doesn't, it leaves the proximity of Bennu. That means the spacecraft and these particles themselves.

But we knew there were a fair fraction of them that were energetic enough to achieve their escape velocity. It was shedding mass. We very quickly assembled a team. "Okay, we'll estimate all these parameters and let's get a risk assessment going in terms of how likely is the spacecraft to be impacted by these particles and what is the worst damage that we think that a particle of some typical size of some typical energy could do to the spacecraft."

There was a period of time there, a few weeks, where we were considering if we needed to leave orbit because we don't know how frequently these things are. We don't know what the hazard is to the spacecraft. The expediency of that risk assessment was really key in terms of making the decision to stay in orbit. A decision to leave orbit would have had a similar major schedule perturbation to the sample collection event that would have had major resource implications in terms of money that would have been required to keep a larger team in place for a longer period of time.

That was really unexpected and surprising. But ultimately, we did make the decision, I think correctly, to stay in orbit because it was relatively low risk both in terms of its likelihood, and even if there was an impact the size and energy of the particles, they were unlikely to be damaging to the spacecraft. That bore out to be true.

JOHNSON: Talk about some of the other conditions as far as the terrain and the reaction and planning that had to go into finding those four final sites that had to be assessed.

BURNS: Yes. Sure. Once we were in orbit, we began mapping in an orbit that is stable around Bennu without going onto its anti-sunward side. It's an orbit that's perpendicular to the sunline. You can imagine looking down on the asteroid. You see half a dark asteroid, half-light asteroid, sunlit asteroid. That's not favorable from the optical imaging point of view. We were limited in that geometry to the quality of the observations. That's what I meant. We needed to design trajectories that left that orbit to get more favorable lighting conditions for example.

First, we flew by the asteroid a few times before we entered orbit. We could already get a preliminary assessment that hey, this looks pretty rough, I don't see any patches that are beaches. We kept optimistically thinking, "We must not have good enough resolution. Surely there's places that look like a beach. They're just smaller than maybe we anticipated." Then once we realized the particles were ejecting, we were like, "Well, that material must be collecting somewhere. There's probably a big pool of fine-grained sand somewhere."

We were in the orbit. We had the science lidar which was built by the Canadian Space Agency doing a fantastic job of collecting in range data to the surface and giving us relatively high-resolution topographical measurements. We're building up this map of the surface, always wondering where the beach is.

As I said, making these what we called sorties, these were maneuvers that left orbit—so make a maneuver to leave orbit, you need to plan a post maneuver observation campaign to point the instruments at the surface of the asteroid, and then make some recovery back to orbit afterwards. All those events were what I called late updates previously.

As we're building up this map with global imaging, which took us a couple years to do—so I mentioned everything moves slow in the vicinity of Bennu—makes the mission achievable. It's challenging for humans to do these 24-hour late updates. We were doing it over the course of several years. It was very taxing on our team, but our team had a propensity for making little slogans. Put them on buttons that we had. One of our slogans was, "There's no place like orbit," an allusion to *The Wizard of Oz*. One of the beautiful things about orbit from the team's point of view is that there's no late update. Every time you leave orbit you make these series of late updates that span weekends and people disrupted their family life and "Oh, I got to work this Saturday from 2:00 a.m. to 9:00 a.m. because my part of the late update happens at that time."

But the global mapping campaign was all about those kind of special observations. We gradually began accepting the fact that there's no beach-like area on Bennu. We'd scour, we'd get new observations, scour those observations—and these observations are beginning to become higher resolution gradually. We have a team looking for areas that conform to what we thought our sample collection site needed to look like. We had a requirement on the flight system to touch the surface within a 50-meter diameter area. We were looking for a smooth area 50 meters wide, and there's nothing even close on Bennu that conforms to that. We were thinking that we would have an area like that, not only that contained sampleable material, so material that's smaller than 2 centimeters in its largest dimension, and also an area that size that didn't contain any hazards.

What I mean by hazards are areas where there's large tilts on the surface or just big features that you wouldn't want. The only part of the spacecraft that touched the surface was a sample collection head that was extended on the end of a robotic arm. That head was meant to conform to the surface. Conforming to the surface was a requirement in order to when the sample collection event happened, pressurized nitrogen was released from an annular ring inside the collection head. It disturbed the regolith and collected the regolith inside that sample collection head. If it weren't conforming to the surface, it was on some rock that made it nonconformant to the surface, then that nitrogen gas would have just blown regolith outside the sample collection head. We didn't want that to happen.

There were hazards that we were concerned about just from the fact that the spacecraft could tilt over if it landed on a tilted surface, and that would be dangerous for the spacecraft to potentially come into contact with the surface of the asteroid, either during the sample collection event or as it was backing away, or backing away in a tilted fashion towards a local mountain. We were concerned about that.

It ended up that from 50 meters, what we had our requirements at, we couldn't find areas that were any bigger than 8 meters in diameter. Our sample collection areas were on that order or smaller, and even then, the area that we ultimately picked contained some portion of that 8-meter diameter area that contained hazardous terrain.

Two implications. One, we had to make the system perform better than it was designed to do: from 50 meters' accuracy to 8 meters. Then number two, we had to accept areas that contained hazard, which meant we needed a way to estimate if we were going to come into contact with those areas and then abort if our estimates said yes, we were going to.

We developed that capability in flight, because we recognized once we started seeing the surface a likely outcome was that we were going to need to accept areas that were much smaller and that contained these hazards. We had to create the capability to build what we called hazard maps. Then we had to create the capability on the flight system to assess on its descent on the spacecraft am I going to touch a hazardous area. If so, just 5 meters from the surface fire the engines and abort that attempt.

You mentioned the four sample candidates. We actually had 50 originally. After a team had a very large assessing of the global mapping campaign, we identified 50 sites. I mentioned a couple of criteria. Sampleability. Safety. Deliverability. Our ability to make the estimate of where the spacecraft was going to touch the surface from the landmarks that were available in the vicinity of that site. Then science. We had this beautiful high-resolution map of the spacecraft and that included spectroscopic measurements from our instruments that gave us information about the composition of the material at that site. The scientists were interested in getting a site that had a variety of different characteristics in its mineralogy. I think we were successful in doing that but it was a really large effort to get from a global map to a site. It took us I think 18 months, or something like that, in parallel with the global mapping campaign.

It was a difficult decision and there were real trades that had to be entertained between do we favor a site that's got high sampleability but not as good safety I'll say, not poor, over a site that's got really good safety rating but may not contain as much small material, so we'd be less likely to actually get our required sample. Our sample requirement for mass was 60 grams. We didn't have a real direct way to measure it. That was also a challenge.

JOHNSON: When it arrived and the mapping started, but then the realization that you were going to have to look for these sites, and the lidar wasn't going to be as helpful because of the terrain so that Natural Features Tracking was going to have to be used, what more did you have to do than what was already planned to get to the ability to do the Natural Features Tracking? Were there the addition of a lot more mapping? You mentioned the hazard maps. That wouldn't have been done if you had had the ability to use the lidar, correct?

BURNS: The hazard maps were really a consequence of the fact that the terrain inside our targeted zone contained hazards. That was unexpected. That was not really a function of the sensor we were using but more a function of the rugged nature of Bennu and the fact that there are no sites—they don't exist—of Bennu that were unexpectedly rugged. We knew that even within those 8-meter diameters there were areas we did not want to touch because it would have been unsafe for the spacecraft.

I didn't really touch much on this. We did have an extensive trade in parallel to the mapping campaign about what set of sensors we should be using to get to the surface. Lidar was the baseline. It took some overcoming inertia to come to the realization that we needed to use Natural Feature Tracking, which was a fairly novel technique, and required more logic on board. You can imagine direct measurement of the range is a very straightforward way. You're measuring how far away you are from the surface directly. As opposed to estimating it from pictures of rocks on the surface.

One of the key things that had to happen to support Natural Feature Tracking was getting detailed landmarks mapped at each site, which meant flying what we called sorties to fairly low altitude above the surface to get high resolution images of the surface in vicinity of the collection site that we were considering so that you could have these high resolution maps that are landmarks that the spacecraft would identify as it descended in the sample collection event, so it could say, "Ah, I know that rock is this feature. I know where I am. I can estimate how long it's going to take me to touch the surface and the maneuver I need to make to touch the surface." Those things were all more challenging using the optical-based approach but necessary because, as I said, the lidar was just going to be too discontinuous in its measurement.

Because of the uncertainty in the trajectory and sample collection, really you didn't know with certainty whether you will pass over some large rock and you should expect a change in range or not. There's a lot of information there, but that also made it a lot more challenging as well.

JOHNSON: What had to be done? You were talking about how they added the ability to do that during the critical design review. But were they uploading more information? What were you doing from the ground to the spacecraft as far as the ability for the spacecraft to get to that selected site?

BURNS: Yes. The things that weren't expected, we were uploading a landmark map for the spacecraft to execute its descent from orbit to the surface. We had a map that was derived from the global mapping campaign of features on the surface.

The spacecraft would use images of the surface and then be able on board the spacecraft—when we were doing the sorties and everything else everything was done on the ground. This was the first time we were allowing the spacecraft to make its own update to its estimate of position and velocity. We left orbit, spacecraft begins making its own position and velocity estimates. It needs those updates because we're about two astronomical units away from Earth at this point. There's about a 30-minute delay in the two-way lag time. We send a command to the spacecraft. You don't hear back from the spacecraft whether it's received and verified that command for roughly 30 minutes. There's no way to do any kind of real-time control of the spacecraft. We allowed the spacecraft in the sample collection event to recognize landmarks, update its position and velocity, and then update the two maneuvers that it required to go after it left orbit to descend to the surface of the asteroid and match its relative surface speed.

We had tight controls on the descent speed and the lateral speed that the spacecraft could touch the surface. You can imagine you don't want to be touching the surface with the spacecraft going horizontally relative to the surface. Those maneuvers needed to be updated on board the spacecraft because we couldn't predict from the ground what those speeds relative to the surface of the asteroid were going to be. That was very challenging and a major accomplishment of the team.

JOHNSON: Yes. It's a lot of unknowns there when you got there. Talk about when it descended to that site that you were going to make the collection, and then the decision to do that and to go ahead with the collection. I had read that when it touched it went further in than was expected because of the whole composition of this asteroid. Talk about that for a few minutes.

BURNS: Yes. That was another surprise that we didn't realize until after we touched the surface. There was a lot of discussion before launch and of course during operations about the nature of the surface of the asteroid. Experience from Hayabusa and other asteroid missions were that we were expecting a real surface, a solid surface. It turns out these rubble-pile asteroids are really just loosely held together conglomerates of material that is a variety of different sizes.

The descent rate is all very low energy. The spacecraft was descending at a rate of 10 centimeters per second, so very slow. But nonetheless when the spacecraft—and we realized this afterwards because as I said the two-way lag time is 30 minutes, so all we were getting, and the communication is rather unfavorable in the geometry we were in during contact. What we did know is that the spacecraft sensed the touch and that we had made the maneuver to get back away. But in examining the images that were available to us and the measurements available to us after the fact, we realized that the spacecraft sample collection head, when it encountered the surface, the surface basically yielded completely. In other words it didn't give any resistance. Or almost no resistance I'll say. The sample collection head just kept penetrating the surface.

The robotic arm pushed the collection head almost a half a meter into the surface of Bennu. That was one of the possibilities that was entertained before launch but I don't think anybody really found it to be likely that that was going to be the case. But it turned out that's actually what happened.

Then between the release of the pressurized nitrogen when contact was sensed and the firing of the thrusters to back away from Bennu, there was a wide-scale massive disruption of the surface of Bennu. Turns out we created a crater on the order of a half a meter deep, almost 60 centimeters deep, by 8 meters in diameter. Bennu itself is only a 500-meter asteroid, so by Bennu's standard it's a massive crater.

Then soon after that event we had to plan. I mentioned we didn't have a perfect measurement of the mass. We had planned to extend the robotic arm to the side of the spacecraft and spin the spacecraft as a means of measuring the mass by the centrifugal acceleration that the mass in the head would have imparted to the spacecraft. But before we did that, we imaged the sample collection head by turning the bottom surface of the collection head towards the cameras. What we realized was the material that we had collected, part of it had wedged open a flap that is intended to act like a valve. In other words it's supposed to open when the pressurized nitrogen is being expelled and close to contain the sample contained in the head afterwards. What had happened is a rock had wedged in that flap and that meant that there was sample that was able to escape the collection head afterwards.

I'll say we had a ground test campaign of the sample collection mechanism, hundreds of tests of all different size of simulant regolith in a variety of different conditions. Even on the zero-gravity parabolic plane, the so-called Vomit Comet [KC-135 Stratotanker aircraft]. We had tested it and simulated in zero g. Never once had a rock wedged inside this flap. So Bennu just is—Dante likes to call it the trickster asteroid. That might have been the most fiendish trick it played on us because we had collected this beautiful sample, pushed our collection head well into the surface of Bennu. We could see the sample inside the head because there's a wire mesh on the side. We had imaged it. We knew there was sample inside. But we also knew every time we moved the head, we were exposing ourselves, it was like a saltshaker, every time we moved it more material would leak out, or at least that's what our limited observations showed us.

We very quickly pivoted from okay, we're going to abort this idea that we're going to hold this head out to the side because we're just going to cause more sample to leak out. Then we very quickly pivoted to the stow procedure, which in itself also was challenging because the geometry for stowing is tight, I'll say. Also the added complexity of now we've got material that may be leaking out. Maybe material comes in between the surface of the deck that we're supposed to stow on and the head itself. Are we going to be able to make a good contact with the surface and get that collection head flat so it can get latched in?

We were fortunate again there. I think it was also, like I said, lots of preparation to make sure we were doing everything. We had contingencies in place. Then ultimately it worked on the first try. I think things seem like they're fortunate in retrospect. But you often overlook all the preparation that you did to put yourself in a good position, as good a position as possible to make a success. I think that's what we did.

JOHNSON: When did you know the amount? I know you said you could see it because of that screen. But were you pretty confident with the rock being a somewhat large sample itself, but having at least the amount that you were wanting to collect?

BURNS: Yes. After we stowed, we were able to make some estimates of the mass in the collection head just based on the robotic arm motion from the position it was in to image the collection head to the stow position.

That estimate was favorable but it had large error bars. We were confident that we had enough material and it turns out our confidence was well placed. Although we haven't determined the final mass of the sample yet. But we know that we have more than 70 grams. Seventy grams has already been collected from the head, and there's an issue with a couple of fasteners to remove the baseplate of the sample collection head. So we're waiting for some tools to get fabricated so they can work in the glove box environment that the head is in presently so that the collection head itself can be fully opened and the remaining material can be extracted from it. We know we exceeded the requirement. We're not quite sure by how much yet.

JOHNSON: I read an article where Dante said that he was seeing people's Ph.D. dissertations floating away and it made him almost sick. You got through all the obstacles, and then now this is happening.

BURNS: Yes. That's why it's the trickster asteroid. It has surprised us in just about every dimension that you could imagine and ones we didn't even imagine. We never thought there'd be particles ejected or that the flap would get wedged open. It had never happened. We had done extensive ground testing. But Bennu is good at surprising. I think that's a theme that I touched on previously. We didn't really know this asteroid before we got up close and personal with it. When you're in that situation you can expect that you're going to find some things that are much different than your expectations, and we certainly did.

JOHNSON: Yes. As you said, this is discovery. This isn't going back to someplace that you've been before. Part of the nature of the beast. Then after that you continued to orbit Bennu for a while, but what was happening during that time? I know they were taking more images, and you could see that area where it had blasted the surface of Bennu.

BURNS: Actually we were drifting away. Because after we had moved away, we had gone out of orbit, that was always the plan that we weren't going to go back. Unless we needed to make a second attempt. But there was a strong incentive to go back and inspect that sample collection site. Actually after a lot of debate within the team we decided that's what we'd do because there was the right combination of low risk in doing it and scientific value in assessing that.

It turns out that's how we made those measurements that I referenced, 60 centimeters deep and 8-meter-wide crater. We got a lot of information about how the system performed by doing that assessment, and things that are going to benefit future small body missions, sample collection missions in particular.

It wasn't completely without risk. We had the sample. We knew it was in the collection head. The baseline plan was we would never go back to the asteroid once we had that. We had a lot of experience conducting operations in close proximity.

That decision not to accept that risk was made before we had gained all this experience. I think if we had encountered more operational issues in proximity of Bennu we would have been more trepidatious about going back. But that also proved to be the right decision. We were preparing for our asteroid departure maneuver, which was a major propulsive event to target Earth return in September of this year as we just executed. The final chapter we haven't even really touched on yet. But I do need to go.

JOHNSON: That's fine. I appreciate you talking today and I appreciate you taking the time to do that.

[End of interview]