Troy Hudson

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Erik M. Conway,
Interviewer

Q: My name's Erik Conway. I am interviewing Troy Hudson at the Jet Propulsion Laboratory. Well, I'm working at home. I think *he's* at the Jet Propulsion Laboratory, according to my Webex.

First, Troy, tell me who you are and how you were educated.

Hudson: My name is Troy Hudson. I've been at JPL since 2008. I'm currently the lead engineer for Team X, which is the Advance Mission Design Group. I got my bachelor's degrees from MIT in the year 2000 in material science and engineering and Earth atmospheric and planetary science, and then I went to Caltech after a yearlong internship at NASA Ames. At Caltech, I pursued my Ph.D. in geology and planetary science, graduating in 2008.

Q: And did you have internships that brought you to JPL, or something similar?

Hudson: I didn't, actually. I applied for a few of them, but was never accepted into any of them. But while I was doing my doctoral research at Caltech, I ended up doing some of my work in an experiment facility here at JPL, the Extraterrestrial Material Simulation Lab, so I had some familiarity with, affiliation, and even a badge for JPL while I was still a grad student.

My research eventually moved down to Caltech itself, but made a number of connections through that process that not only brought me back into my postgraduate job at JPL, but also I did end up managing the Extraterrestrial Simulation Lab for a few years after I joined JPL in 2008.

Q: So that also means you came to JPL just about at the beginning of the InSight mission.

Hudson: Nearabouts. I came in, actually, to work on the Phoenix Mars Lander just before it arrived on Mars in May of 2008. Then I became involved with the InSight, then known as GEMS, Discovery 2010 proposal effort. I don't remember exactly when that started, but it must have been either in late 2009 or sometime in 2010 itself.

Q: And how did you get involved in the GEMS? That would have been, I think, the Step 2 proposal, probably.

Hudson: Step 1.

Q: You were in Step 1. Okay.

Hudson: It was called GEMS in 2006 and again in 2008, but I think they had us rename it for Step 2, but I got involved in the Step 1 version because my line manager and the person who actually helped me get my job on Phoenix, Mike Hecht, had been working with the GEMS proposal. Then I think he was called away to work on SAGE [phonetic], which was, I think, a

New Frontiers proposal for Venus. Hecht asked me to come in and succeed him as the science implementation manager for the InSight proposal, and that's what I did, and continued along with that all the way through, well, operations.

Q: You said Mike Hecht brought you on to the GEMS proposal. What initially did that entail? When you're writing a Step 1 proposal, what kind of work are you doing?

Hudson: Well, there are actually two aspects to it. There was the writing aspect, and at that stage it was mostly coordinating and understanding what our foreign partners, the providers of the SEIS and HP3 instruments, were intending to do, trying to understand the instruments. The science implementation is about how do you actually do the science that the proposal was promising from an instrumentation standpoint, supporting equipment such as the robotic arm for deployment, and then all of that data is collected, reduced, sent to the ground, and ultimately analyzed. So it was bringing together inputs from various people at JPL as well as our partners at CNES, DLR and others to write a clear and concise but complete story about how the mission would execute all of that. I didn't have much background information. I hadn't seen the 2006 proposal I think until a much later date, so there was a lot of just really understanding what everyone's intents were, what their expectations were, and then putting that down on paper, along with figures, diagrams, tables, other things that helped tell the story and illustrate what it was we were planning to do for the benefit of the review board.

As I said, there were two aspects to it. One was doing the actual proposal writing. The other was that we had some nascent test beds at JPL for the HP3 instruments, specifically for the Mole and its tether, that would allow us to verify that the temperature-sensing methodology was sound, and also to do penetration testing of the Mole. There were actually three versions of this, but the biggest one was the geothermal test bed, and that was a device that the main piece of it, which is about a 2.5-meter-tall, .6-meter-diameter vacuum chamber, had been purchased, and the insulation that went around it, which was this very large insulation half-shell, those had been purchased, but nothing else had been done. No further work had been done to actually assemble this thing and make it a functioning test chamber.

Mike introduced me to Sue Smrekar, the deputy PI for InSight, who was the one who had, I think, been leading the acquisition of this chamber, and it ultimately became my responsibility and sort of my baby to get that chamber up and running and being used for the purposes of—well, various purposes for InSight.

Q: So was that purchased on JPL funding? Because at this time, it's a Step 1 proposal, right? You have very little money for that kind of thing.

Hudson: I don't know for certain. You would have to ask Sue. I think she actually got it as part of an R&TD proposal or some other sort of work that was still focused around measuring planetary heat flow with a subsurface device, and the intent of the chamber, in addition to what we ultimately used before the penetrating testing as well, was to create a stable shallow thermal gradient from the top of the chamber to the bottom, and then you would have your line of temperature sensors, like the way HP3 had intended to emplace on Mars, to see if that could, in fact, make those measurements and see those very small temperature changes as a function of depth, so creating a chamber full of soil that then has an established temperature gradient in the low temperature, low pressure range. There's no other facility like that on Earth, as far as I know.

Q: And I guess we didn't keep it either. I think Sue told me that it had been sold off by now.

Hudson: Yeah, it was excessed, and I believe Honeybee Robotics are the ones that now own the pieces of that.

Q: I see, I see. Sounds like kind of too bad, but on the other hand, the chances of ever doing this again are—well, in my lifetime anyway, seem small, huh? [laughs]

Hudson: Well, as we saw with HP3, there are enormous difficulties in penetrating the surface of Mars, at least in the place where we landed, and we did demonstrate with the chamber that the methodology that we devised with the sensors embedded in the tether was suitable for it, so if someone in the future did manage to get something that small down deep in the surface of Mars, they could probably leverage the work that we did, at least as far as the design goes.

Q: So we've talked about your winding up on the GEMS proposal, and so when the proposal is accepted, did you essentially keep the same job but go full-time? You kept the HP3 portfolio?

Hudson: So during Step 1, I was responsible for the whole Science Implementation Section, and in Step 2 process, I was again one of the top co-writers for the Science Implementation Section. Ken Hurst had been brought on as sort of the main SEIS contact point, and I was still the main contact point for the HP3 from DLR, so we sort of worked together in the production of the Step 2 proposal.

Following selection, then, yes, my job changed slightly into being the—I think the official title was—it wasn't payload interface engineer. That's what I have right now on VERITAS. It was—well, it was essentially instrument systems engineer for HP3. DLR had their own systems engineer for the instrument on their side of the pond, but myself, I was the JPL version of that, and therefore also served as the technical liaison between JPL and DLR, working both for the payload systems engineer at JPL, who at the time was Jason Feldman, and the payload manager at JPL, who was Ed Miller.

Q: I failed to ask you about the site visit during the Step 2 proposal phase and the demonstration work you did for that. So tell me about that process.

Hudson: Well, so we had up in one of the buildings up near the Environmental Test Laboratories, we had the setup for the hour-, hour-and-a-half-long tour that was part of the site visit, and we had a—I think there was a SEIS there with a leveling mechanism that was being visually shown. We had a couple of other components both of HP3 and of SEIS that were on display, as well as the model of the lander, and we had the geothermal and mechanical test beds. This was in a very large building that had been used, I think, to polish the mirror in the 25-foot space simulator. We had those set up. We had a model of the Mole that was powered and could hammer in your hand.

The thing that stands out to me most about that whole experience is I had dislocated my shoulder in a motorcycle accident about three days prior, so I was wearing my suit with my arm in a sling, giving my presentation. [laughter]

Q: That would make it memorable, not necessarily in the best way, but it was successful, apparently.

Hudson: Yeah.

Q: So you become the liaison for DLR for HP3. With HP3, I guess DLR had a number of different partners within Europe in order to build the entire instrument, the Mole, etc. Talk about how that liaison function happened. How do you manage such a complex set of partnerships for the instrument?

Hudson: Well, the partnership complexity was even grander for the SEIS instrument. For HP3, there was the DLR itself, there was a local—literally across the street from the DLR facility—organization that was doing the overall systems engineering on their side, as well as a company that was producing the electronics. So whenever we would travel to Berlin (occasionally we went to Bremen because they were doing some of the actual construction of the Mole and some of the testing of the Mole happened there) but the main Institute for Planetary Sciences was in Berlin. We would travel there once a quarter for some face-to-face meetings, quarterly management reviews, and at those meetings, those partners, both from Bremen and the other local ones, would attend. So got a lot of face time with those folk in those quarterly meetings. Then we would have weekly tag-ups via teleconference early in the morning here in California, so it was late in the day in Germany.

So there was frequent emails exchanged daily, weekly tag-up telecons, those quarterly management reviews, as well as occasionally we had some topics-focused technical interchange meetings or even tiger team work that was done to help solve some problems that we had with the Mole, the hammering mechanism, the motor, and other pieces of it during that development phase.

Part of that was somewhere along the process, I think we were late in Phase B, we determined that the design of the hammering mechanism in the Mole was unsuitable. There were lots of problems and lots of stresses in the design that had it essentially tearing itself apart every time it would be used. So DLR then made the decision to bring in CBK, the Polish space agency, and their subcontractor, Astronika, to build the hammering mechanism in the Mole. So the partnerships expanded. I had at least one trip to Warsaw, and those folk also came for these quarterly reviews subsequent to that point with their new design.

So it was a lot of building spaceships with email and PowerPoint, and a lot of travel across the Atlantic.

Q: You racked up a lot of frequent flyer miles. [laughs]

Hudson: I did, and I actually got to almost the highest level in my preferred airline's tier system. [laughter]

Q: Well, it's a nice perk, but I don't envy you all the time spend on airplanes. It's not fun anymore.

Hudson: No, it wasn't. Well, the nice thing about being that elevated is that I would *occasionally* get bumped up to business class, but, unfortunately, the current policy is that even for trips that are longer than six hours, NASA doesn't pay for business class for its workers, which I think is silly, but so it goes.

Q: It's a leftover thing from the seventies, actually, when it used to be that management would fly first class, and the Carter administration put an end to all of it. It's been that long. Something about spending taxpayers' money more wisely and less offensively.

So let's see. I was formulating a question while you were answering the last one. We talked about the key players. Tell me about working with the PI that proposed HP3. We haven't talked about him.

Hudson: Bruce?

Q: Yeah, for HP3, the instrument PI, Tilman Spohn.

Hudson: So Bruce Banerdt was the PI for the whole mission. Sue, as the deputy PI, did have, as part of her focus, the HP3 instrument itself. In the sense that there was a division of labor between Bruce and Sue, HP3 fell more under Sue's purview. Then the PI of the instrument itself in Germany, Tilman Spohn, who was the director of the Institute for Planetary Studies at the time, I mean, I had a wonderful working relationship with him and everyone else on that team, actually. I actually am still working with some of them on the VERITAS mission, which I'm working on now, because DLR is providing an instrument for that, and I'm reprising my role as the technical liaison to DLR for the VEM instrument. A friend and colleague who I met early when I started working on the geothermal test bed in these things, Matthias Grott, was the instrument scientist for HP3, and I'm still involved with him on the VEM instrument, and became good friends with the project manager there, and Tilman and I are still corresponding to this day as we finish writing up the final papers about the HP3, the Mole, and everything we learned from it.

Q: So your experience sounds very positive. Great.

Hudson: The experience of working with the individuals was very positive. There were a lot of challenges with HP3, and I think it ultimately comes down to the fact that it was literally a unique instrument. People build cameras all the time, they build spectrometers, they build the sorts of things that fly on orbiters all the time, radar systems, even. Even though every one is different, there's sort of a general set of principles that one follows, and you can make reasonable predictions about how well something will work.

The seismometer was sort of a new animal. They had put a seismometer on Viking, didn't do so great, but they did, and they put ones on the Moon. But an autonomous penetrator that's, as I've said before, smaller than a shoebox and uses less power than a wifi router, designed to go five meters deep into an unknown surface, subsurface, there were so many things about that that had no precedent, and even prototypes on Earth or other attempted penetrators on other bodies, like the MUPUS instrument on the Philae lander from Rosetta, which DLR had some hand in, as did the Polish, there were so many things about it where we had no guidelines, we had no template to follow. So there was a lot of go-backs, a lot of redesign work, a lot of consternation about, for instance, is this thin tether going to be able to withstand the pulling forces that are applied to it whenever the Mole hammers. And there was lots of worry about how would we qualify that, how would we test it, how do we know that it was going to work.

So I think unique to planetary instruments, HP3 certainly fell in a category by itself in terms of its newness, so there were a lot of challenges and there were a lot of very stressful moments during the development of it, to try to see how are we going to solve this problem, how are we going to solve it in time, how are we going to solve it in the resources we have available or DLR has available.

And we were, in fact, helped by the delay in the launch. Even though that was primarily done for the benefit of the SEIS instrument, which was having its own issues again because of its unique nature, we used that time, that twenty-six-month extra time between launch windows, to continue to make improvements on the design [of HP3] and address some things that we had seen in testing that concerned us, and I think due to that, the instrument that we ultimately built was incredibly robust. The forces that this thing experiences within itself are very large, tens of thousands of Gs, and there's sensitive electronics parts and sensors and a motor and wires and all these pieces. And we've done—oh, gosh, what it is—some tens of thousands of hammer strokes in the Martian environment, and as far as we can tell, the Mole is still going strong or would go strong if we asked it to hammer again. So, yeah, we took advantage of that time to really make it as, I guess, again I'll just say robust as possible.

Q: So I usually split my challenges question into two, and you've addressed it to some degree, but the first part I always ask is: going in, you knew you would have some challenges. What were the challenges that you thought you'd have. And Part B is, were those the ones that you actually had, or were the more substantial challenges ones that you didn't expect?

Hudson: Well, the most substantial challenge that sort of blew our original plans out of the water was that the Mole mechanism itself kept failing. We had intended to have a very robust and extensive test campaign of penetrating the Mole into a wide variety of simulant materials under a wide variety of preparation steps and environmental conditions. So we'll use sand, we'll use this simulant, we'll use that simulant, we'll use this other simulant, we'll do them all uncompacted, fully compacted, mixed up with smaller rocks, we'll do it in vacuum, we'll do it at ambient temperature, we'll do it under cold temperatures.

We didn't get to do as many of those options as we wanted, because it took so long for us to get a Mole that could do even one test successfully without breaking in one way or another. So that challenge, essentially the delay, getting us to the point where we had a robust device and then we had to really pare down our testing program into nominal case, and a reasonable worst case. That's really all that we ended up being able to do. So that was the challenge that actually reared its head.

Challenges we expected going in, gosh, it's almost hard to remember what those might have been, because it's so long ago. I think one of the things that we talked about going in was that it was a short time span from selection to launch. It was five and a half years or less. In hindsight looking at it, for these unique instruments—the spacecraft came together with no issues, no significant issues as far as I'm aware, but you may want to ask other people about that to be sure, but the instruments were the really unusual things, and they ended up taking a lot longer than we expected.

Q: Fair enough. You talked about the test program you could do and use of simulants. Did you also try field tests, tests out in the American desert or something, or was that not a useful kind of testing?

Hudson: So we did one, but it wasn't designed to see how well the Mole would penetrate, because—well, what we expected to find on Mars was unconsolidated loose regolith in an area that had never been altered by liquid water, and there's essentially nowhere on Earth that you can find that's like that except perhaps a sand dune, and even then, you'll encounter water under a certain depth. But the deserts here in California or anywhere else, really, there is aqueous alteration that happens. You can form layers of salt, caliche, other things that compact the soil and just make it different.

Thinking about it now from what we've seen on Mars, maybe it was actually a good analog, but we took the Mole out to somewhere in the California high desert, and the intent there was to use the Mole and a SEIS simulator to see what sorts of information we could get from the Mole as a seismic source and the SEIS as a sensor, to understand the local geologic environment. This was done for instrument on Mars itself. Even though we didn't end up penetrating to a significant depth, we could still use that data to understand stuff about the seismic velocity in the near-surface soil, which was important for the way SEIS was operating, because we landed in a region where we expected to find broken-up regolith. That's not what SEIS would have preferred. SEIS would have preferred to have been placed on bedrock, but HP3 could not certainly have dug through bedrock, so we landed at a place that was supposed to be loose material. All the evidence that we had from orbital observations and prior landers suggested that's what it would be. But then SEIS is on this softer sandy material which is not ideal for a seismometer, so those near field effects of the loose material was something they really wanted to know about, and HP3 helped them do that.

Q: So the field test was really to figure out what wavelengths that the Mole would produce and that then might copy over as kind of noise onto SEIS.

Hudson: Well, the theory had been worked out, and the idea behind this coordinated observation and what could be learned from it had already been worked. Sharon Kedar, I think, was the leader for that particular effort. This was a field test to sort of verify, understand, and see if there were any other effects that we needed to be cognizant of.

Q: Right. To understand the model verification, kind of.

Hudson: Mm-hmm.

Q: Let's see. We talked about key development challenges. So you stayed with instrument after launch and into operations, right? And you stay till when?

Hudson: So the intent had been we would land in November. Around late February is when all deployments had finished and HP3 was going to start its penetration. The thought was that it would take on the order of two, two and a half months for HP3 to make its way down to depth, with frequent stops and like three days, three or four days' worth of pauses to do thermal conductivity measurements at different depths, and once it was done, once it was all the way down in the ground, then we would just be measuring the thermal gradient with those temperature sensors, and it would just be an observatory at that point. There's be no additional work, and that was essentially when my job would end. So that would have been mid-2019.

However, we encountered the penetration anomaly, and from the beginning of March 2019 until January of 2021 or '22, twenty-two months, it was twenty-two months that I was leading the Anomaly Response Team for trying to understand what was happening with the Mole, why it wasn't making progress, and what we could do to help it.

Q: First we should talk about placing HP3 on the surface, and then we should talk about the beginning of drilling and the anomaly. But talk about where you decided to put it.

[Note: Audio recording is very spotty from this point on. It's often difficult to understand what's being said.]

Hudson: Well, we were constrained in that there was a certain work space that the arm could reach, and there were preferred locations for the SEIS and HP3, driven in part by their desire to be away from one another and away from the lander for a number of reasons, noise, thermal effects, and so forth, but also the way their tethers were laid out and deployed. It made the most sense for SEIS to go over here, HP3 over there. But we had anticipated that, well, maybe there'll be a large rock or something on the ground that prevents us from putting ourselves in the ideal position. So a whole process was developed for imaging and creating elevation models and assessing the site and finding out what is the best location for each of these instruments.

As it happens, the landing site was completely smooth, flat, boring, and exactly what we wanted, so we were able to put things exactly where we had intended to place them, with no significant differences. So both of the instruments end up far away from the lander and apart from one another, just as we had hoped.

Q: So placement turned out to be essentially a nonissue.

Hudson: Mm-hmm.

Q: Then what kind of timeframe is it before you actually start the Mole operation? Is it a few weeks?

Hudson: We landed at Thanksgiving, the end of November, and SEIS had been put out, the wind and thermal shield had been placed on top of it, HP3 had been deployed, in that order, and ready to go by the end of February, so it was essentially three months to get from landing to the completion of the deployment phase.

The [end of the month] is when we released the HP3 from the grapple arm, and at that point we could still move the support structure, we could put it somewhere else, but once we released the Mole within the support structure and it drops about a centimeter or two to the ground, then we're no longer able to move it, because if you pulled up the support structure, the Mole will just fall out. So we were committed. We were committed at that point. Everything we saw on the surface was small stones, small rocks, no indication of any large stones, except for under the lander. When we took the camera and looked under the lander, we could see that there were some larger boulder-type materials in the hollow where we landed, that were under the surface and had been exposed by the landing jets. But as far as the worst case goes where we had to put in the instruments, everywhere in the region where HP3 might have gone looked essentially the same.

Q: So you start the Mole going, and what happens?

Hudson: Well, we commanded the Mole to—there's a number of complexities here. So the way the support structure is designed with the Mole and its tether and there's a little box that measures how much tether gets pulled out. There's a [service] loop in there that brings the tether from the readout device all the way up to the back of the Mole. The Mole has to penetrate a certain distance before it actually exhausts that loop and start pulling the tether through the reader, and that was the only way we could actually measure distance.

So the intent was that with the first penetration, we were going to try to get the Mole to about .7 meters, and everything we'd seen in all of our testing on Earth suggested that that would happen in the order of forty-five minutes of hammering. All the materials that we tested in in our test beds said that it would be about forty-five minutes. But we wanted to be sure that we got that depth, so we set a time-out of four hours, which is approximately 3,600 hammer strokes of the Mole.

So those commands were sent up, and we expected the following day to see that, ye verily, the Mole had hammered, because we have a way to count the hammer strokes, maybe the tilt changed a little bit, because there's a tilt sensor in the Mole, and that the tether length monitor had engaged and was actually showing us that some tether was being pulled out and down into the ground.

Well, the data came back and said that, yes, in fact, we hammered, but there was no apparent motion in the tether-length monitor. And the way the support structure is designed and built, you can't see what's going on because the structure's in the way of the Mole. So I remember sitting in the room that morning as we were getting the downlink through the ground data system, and we were all just so excited and so keyed up, and then when data started coming through, the energy over the course of about five minutes just *totally* drained out of the room, and we realized that something wasn't right.

Q: You'd been working on this for—what are we talking about, seven years now? Eight years?

Hudson: Well, InSight landed in 2018, and I'd been working on it myself since about 2010 or 2009. Remember how I talked about those test beds before?

Q: Yeah.

Hudson: So in addition to all of the international travel and the weekly telecons and the flood of emails that was always going back and forth, I spent a lot of time up in the laboratory literally getting my hands dirty, filling these chambers up, emptying them out again, digging hardware out, making the geothermal test bed and all of its components, like the chillers and the vacuum systems, making it all work, and it was mostly just me. It was me working in that lab on my own for the most time, unless I needed help wrangling something really big. Because of all those things, I had become very emotionally invested in the success of this instrument, and my colleagues in Germany as well. I mean, a number of them had been working on this for many years, some of them even longer than I had been, but put a lot of effort into making it work, and when we saw that it wasn't making progress in those first days, it was very saddening.

Q: I can imagine. As you say, the energy was drained out of the room, and you must have had a day or two of "Now what?"

Hudson: Oh, well, the "Now what?" went on for a long time. That was just the start of the "Now what?" I mean, as soon as we saw that there was a problem, I essentially knew at that point like, okay—I didn't declare this, but it was essentially obvious, "I'm going to lead this. I'm going to do everything I can, because I am so emotionally invested in it, to do everything we can to make this work." And there was twenty-two months of that, of that effort, and putting together fishbone diagrams and fault trees. What are all the things that could be wrong? What are the things that we can do to test it without damaging it or putting us down a path that we can't recover from?

This put a strain on the instrument mission, because their whole model behind it was we go there, we put the instruments down, and then we would just listen. The data would come in. And now we had to keep a standing army of operations folks who were working on sequences for the robotic arm, sequences for the HP3, and doing all the operations for getting those things up to the spacecraft and the data back down.

I must have produced something on the order of 1,500 different PowerPoint slides and diagrams and storyboards and path trees of, well, we could go this way or this way or this way, and this is what those would mean, and here are the risks inherent in them, and all these things to communicate as clearly as possible to everyone at JPL and everyone at DLR, who mostly stayed here for this, but after a couple of months of this anomaly problem, they went back home and we were doing everything remotely. Yeah, there were so many decision points and still things that we don't understand, that we don't know, and we had literal ups and downs throughout the whole process.

Q: What kinds of things did you try after that initial lack of penetration, to try to diagnose the problem and then try to resolve it?

Hudson: Well, the first things we wanted to do was we took a lot of images initially when the support structure was still covering the Mole, and I remember that there were some who would say, "Hey, it looks like there's like a little bit of a pit under the things, maybe." And somebody, "No, no, no, that's just a shadow." And I'm like, "No, I think that's actually a divot in the ground." So we had a lot of ideas about what might have been going on. We took a lot of pictures. We took pictures at different times of day to see if the different shadow angles would give us some idea of what was going on.

We actually did what we call diagnostic hammerings, where rather than many thousands of strokes, we only hammered for a few hundred, and we had the camera looking—the camera could not take video, it could only take one frame every few tens of seconds, so it was a very sort of low rate, but we could see that the support structure was shifting a bit. We also used the seismometer in a special mode to see if we could hear the way the mechanism inside the Mole was behaving, because the way the mechanism works, it's not just a single strike. There's multiple bounces that happen within the Mole, and the timing of those bounces can tell you about the health of the mechanism, whether there a spring was broken or there was something in the way or it was getting jammed. So we used SEIS not just to understand the soil in that circumstance, but to understand the Mole itself.

So we did all those things and were able to cross some things off of that fishbone diagram of what might be the issue, and ultimately we came to the point where we said, well, it's got to be one of two main things. Either the support structure or the Mole itself it jammed, the tether or the Mole is jammed within the support structure, or there's an external obstruction that's preventing the Mole from moving. The Mole itself, the mechanism inside, all that seems to be working fine. And we got to the point a few months after the anomaly first reared its head, I think it was in May, of like, "We can't do anything more without getting a better view, so we're going to have to do something that we never intended to do on instrument, which is go and re-grapple an instrument after deployment and lift the support structure away, exposing the Mole." And that whole thing, if there had been a snag, we could have ended up pulling the Mole out of the ground, and then we wouldn't have been able to do anything about that. It would have just been ruined.

So we devised a whole process of doing that in stages, bit by bit, and verifying that things still looked good. So we ended up pulling the tether out of that little tether-length monitor, and like, "Oh, yeah, look. It works, but not doing us any good."

Got the support structure set down, and then we saw the Mole, and, "Look, look!" Pit. Big hole around the Mole. Where did that dirt go? The walls of the pit are really steep. We didn't expect that. We thought it would all collapse. Everything that we learned about this place from orbit said that the soil wouldn’t be consolidated or cemented in any way. And look at that. Mars surprises us.

But when we were down to the one class of root cause, which was there’s an external obstruction, something in the ground, something in the ground is preventing the Mole from moving. I said external obstruction, but there’s another option which actually ended up being the real reason, or at least a main part of the real reason, which was lack of friction. The Mole, in order to do its job, it hammers forward and then there’s a rebound force, you know, Newton’s laws. The way the Mole is designed, that rebound force is largely compensated by springs internal to it, but there’s still a little bit of force that gets transmitted to the hull and makes it bounce backwards. That has to be reacted by either the springs in the support structure, which helped guide it in its initial descent, or the soil collapsing around the Mole and then providing friction in the hull. Since the soil wasn’t collapsing, it wasn’t providing any friction for us. We said, “Well, maybe there’s still an obstruction in front of the Mole that’s keeping it from digging or maybe this lack of friction is causing it to bounce, bounce back against the support structure.”

So with those possibilities ahead of us, okay, what can we do? What can we do to help the Mole? We hadn’t planned for this. The back half of the Mole, where the tether attaches, is very irregular in shape, and the tether itself is a copper/Kapton ribbon that could potentially be damaged if the robotic arm was pushing against the Mole and then sideswiped it. So we eventually came up with a plan to add some friction to the Mole by pushing on its hull from the side with the scoop, and it took us a while to get to a place where we were comfortable doing that. I think it was October by the time we got to that point, of 2019.

We got the Mole pinned on the side, and we hammered, and, oh, my god, it moved, like, down. It went down into the ground. The first time we did it was only like twenty hammer strokes, so it was a little ambiguous, but then we did more and it was unambiguous. Like, yes, it's making progress, which I remember how relieved I was when I saw that and how excited at the next Science Team meeting, when I just told everyone, "We're going to get to dig! We're going to get to [unclear] because the Mole moved forward. That means there isn't a big stone in front of it keeping it from going anywhere. So that external obstruction problem is gone, and we've got the arm giving us our friction that we need. This is great! We're going to make it work. We're going to get it underground and it's going to go."

Commented [TLH1]: Penetrate?

It worked for a while, but then we got to a place where the back cap [of the Mole] was pretty much at the surface, and if we went any further, the loaded blade of the scoop, as the Mole went down, would swipe sideways, potentially damage that tether. So we tried something else. We tried moving the scoop into a different position, and then we hammered for, you know, 100, 150 strokes, something like that, very much like we'd been doing already when we were making forward progress, and the Mole backed out of the ground, like backed out like more than half its length, and tipped over and tilted and just, you know, was worse than it had been when we first removed the support structure.

For a while, it wasn't even clear that we'd be able to recover from that, and I remember I saw the pictures and what had happened, I didn't believe it when I first saw it. It was the weekend. I remember I ended up crying in my shower after that happened. I was distraught, just so frustrated and mad and sad, and not angry. There wasn't anything to be angry at. All the decisions that had brought us to that point made sense at the time. But it was just a setback, and I knew that even if we could potentially recover from it, it was going to be a long road. It was going to be months, if not years, because the project was spending money, a lot of money to keep this group of people together working on this problem, and they couldn't do that indefinitely.

So over the course of that twenty-two months, the frequency with which we commanded the spacecraft to do something, or the Mole or any part of it, went from three times a week to twice a week, to once a week, to once every two weeks. The amount of power we had available to us kept going down.

We did ultimately manage to recover from that reversal event, but then we had another one. We tried something a little bit different, but it also failed and the Mole ended up backing out again. Then as we were just slowly slogging through 2020, I think, COVID and all that other stuff, trying to get the Mole back all the way down into the ground, it was slow, painfully slow to get to that point.

Then at the end of 2020, we decided that at a certain point InSight's not going to have any more power, and even if the Mole does start digging into the ground, it's going to take it many months to get to the depth that it needs to get to, given the penetration rates we've seen so far. So in order for us to get the Mole all the way down, let everything cool off so we have a stable measurement set that's not influenced by the action of penetration, at a certain point we have to draw a line in the sand and say if we can't make progress by this date, then we might lose communication with the lander, InSight might turn off before we are able to actually get down and make the measurement that we want to make.

Now it's January of 2021 when we decided that we're going to do one last [test]—we got the Mole all the way down so that the back cap was in the ground, and that had been after pushing against the back cap directly with the scoop, which was a very challenging thing to do because there was very few places where we could put it. The scoop had to be positioned exactly right, and we could only go so far before we had to position it again. It was just a very, very long process, but we got it just underground. We'd been scraping soil and doing other things to try to help it along, tried collapsing the pit several times, a number of other pieces. It's all in the papers that we've written about the whole saga.

But, yeah, we got to the point where we tried that final "Free Mole" test in January, called it a Free Mole test, to see if the Mole could make progress without direct assistance from the arm, so it was free, and, yeah, it didn't go forward on its own. It started backing out again. We had the arm in place to prevent that from being a problem, but that was when we were like, "Yeah, we'd done. There's no more we can do."

And I realize I've been monologuing for the last fifteen minutes, so I apologize if you'd had a lot of questions come up during that. But it's still hard. Not hard in the sense that I don't like to talk about it—I don't really—but it's still hard to talk about all that.

Q: But you've told it very well, so I let you keep talking. I would not have known some of what you said. I mean, some of it came out in news reports and so forth, but not the personal angle, of course, and I'm not sure all the details either. So thank you for that.

Of course, the reason that you have declining staffing and commanding time and so forth is the Discovery Program's cost cap, and you'd already burned far beyond the operations budget that you would have had at the beginning. Did you wind up going part-time during this, or do you remain full-time on instrument for that whole extra year and a half, almost?

Hudson: It's funny, actually, because as we were getting ready to land and the anticipation was that my involvement would be ending in the next six months after we deployed and penetrated, I was courted by Division 312 at JPL, Systems Engineering Division, to come in as the deputy lead engineer, for Team X, working with Al Nash, and it was like "This is great. I like

Formulation and it seems like a good group." I didn't have anything else really bubbling up as something that I was going to do next, so I applied, interviewed, got the position. So I started rolling into that, doing quiet hours and listening in on Team X studies.

Then the anomaly happened, and it was like, "Oh, well, I'm not going to abandon that." So there was this period of limbo—not limbo, but sort of compromise, where I was giving about quarter-time to Foundry and Team X, and about 75 percent of my time to the Mole anomaly. They all wanted to know, "How long is that going to take? When will that Mole anomaly be done?"

I'm like, "I don't know. I mean, I would love it if it were done in four months or five months," but turned out it was twenty-two, so, fortunately, with the proper communication and explanations, everybody was patient and they understood my passion for it. So I continued to be essentially full-time, three-quarter-time, on InSight until we got to that Free Mole test in 2021, and then I remained full-time for another couple months as we wrote the drafts for the two papers.

We wrote two papers. One its working title was *The Mole Saga*, but the actual title is something much more boring. And there was a lessons learned paper. The Saga paper, which I will always call it from here till the end of time, was about what we did on Mars, so everything I've told you but in great detail, and then what we learned about the soil and the thermal conductivity and what it was that we really did glean from the mission. Then there's the lessons learned paper, which was about, "Hey, if you're ever going to build a penetrator on Mars in the future yourself, here's what you should know about what we did." And I think they're actually working on a paper of what the instrument deployment arm did throughout the entire mission, part of which was the Mole anomaly resolution.

So, yeah, I worked on those papers for a while, and then mid-2021 is when I sort of faded away from working on InSight and became full-time on this Foundry job.

Q: We're down to four minutes and almost out of time.

Hudson: I don't care. I'll stay with you and talk about this till you're done.

Q: Oh, okay. Well, my next question, then, is what will you take from InSight to your next project? You said you've gone to VERITAS.

Hudson: Right. So I do really love Formulation, but I also like to keep my feet wet in implementation, and Sue Smrekar and others asked me to come and work on VERITAS when it was at Step 2, when it was preparing for their Step 2 concept study report submission and the site visit. So I did, and became very involved in that, had a great time, gave some very good contributions, I think. Then that was selected, and I was like, "Yeah, I'd like to stay on in implementation and working with the VEM folk at DLR makes good sense, but let's do this 25/75 split, where it's 25 percent VERITAS and 75 percent Foundry work."

I'm sorry, what was the question, though? Sorry.

Q: What are you taking from InSight to your next project, to VERITAS?

Hudson: Well, certainly the working relationship and familiarity I have with the folk at DLR, because there are a number of people who work there, who worked on HP3, who are also working on the VEM instrument, so it kind of makes me a natural choice for serving that role and just understanding all the things about—I had to learn so much about export compliance when I was working on InSight, and definitely keeping those lessons, and how to be comfortable on an international flight sitting in coach for twelve hours.

But as far as, I think, the heart of your question is I have seen a mission go from proposal all the way through operations, "Birth to Earth", or Mars in this case, for a mission, competed mission, in this case Discovery, and now I'm working in Formulation and knowing where it's all going to go and how—I mean, I have studied spacecraft systems engineering and done a couple of sort of early-career-hire development programs, so I kind of had a sense of how JPL did business and things, but I learned so much about safety and mission assurance and the way that systems engineering works, so much about ops, mission operations, which even working on Phoenix ops, it was a firehose at that point, and I didn't really get any of it, but with Insight I had a lot more familiarity and a lot more investment in that. So I got to see so much, not everything, but so much of how a mission actually functions, that it makes my current job in Formulation, it prepared me for that much better, and I really have a deeper understanding and appreciation for why missions are so complex and expensive and take so long. So that's probably the greatest advantage. Working in Formulation, you really should have worked on prior missions and actually been in implementation. I believe that firmly, and that has been my experience.

[Interruption]

Q: So we were just talking, before I had to go run and get a prescription, what were you going to take from instrument to your next project. You were talking about ITAR and preparations and so forth.

Hudson: The three biggest things in increasing order of importance is how to travel internationally, efficiently and with comfort, as best I can, my working relationship with the folk at DLR, which is proving to be very useful in the VERITAS mission with the VEM instrument, and then just having been in the trenches and seeing how a mission and a particular instrument, but the whole mission, goes from a proposal through implementation and into operations. Because when you write something in a proposal and you're like, "Yeah, we're going to do it this way," if you haven't actually worked operations or implementation, you might not understand what the implications of that thing are. It's all too easy to say, "Oh, we're *just* going to do x, y, z," when in reality, "just" is a four-letter word and you can't ever *just* do anything on a space mission. There's always ripples. There's always more to it. And I understand that viscerally now.

Q: Give me an example from InSight where you thought, when you were doing the proposal, things would work out one way, when, in fact, in actuality they worked out completely differently.

Hudson: I've already mentioned the fact that we thought we were going to have a Mole that was robust enough to do this extensive penetration and testing campaign. And we'd seen problems with some of the prototypes that I tested, they also didn't work, weren't working great, but like, "Oh, that's okay. That's an older version. We've got a newer version now, and it's going to be great." It wasn't great. And we had to keep going back and going back, and eventually switched gears and then brought up the Polish and Astronika to build a totally different mechanism design. I don't know if there's any way that I could have foreseen that. Maybe a mechanical engineering expert might have seen something like that. But I guess this is a truism, this is why we build margin into our schedules. It always takes longer than you think.

Q: And R&D projects often go radically differently, but this wasn't an R&D project, of course. It was a flight project.

Hudson: Well, it started out that way. That's where the prototypes for the Mole came from, were various R&D projects in Germany, and I think maybe some partnerships at JPL. Not sure. But the idea for the HP3 instrument was older than 2010 when I first got involved. They already had something that looked like—oh, and the design changed so much. If you look at the original renderings that we had in 2010 of what HP3 might look like and what it ultimately ended up looking like, *so* different. I mean, so many things came into the design consideration that ended up making it look the way it did, I didn't expect that then. I thought, "Oh, yeah, I see the CAD model. That's what it's going to be." No. No, it changed so much.

Q: So we've talked enormously about the Mole, but I've never asked you sort of the simplest question. How big was the Mole? Are we talking the size of a finger, of a hand?

Hudson: Are you recording video or just audio here?

Q: It does record video, but there'll be an audio-only transcript.

Hudson: So the Mole is about the length of my forearm and about the diameter of a quarter, so it's long and slender, silver, a yellowy silver color, with a not conical [tip], but what's called an ogive. It's sort of a bent tip, kind of like the tip of a missile. Then there's this ribbon tether that comes out the back of it and goes to the support structure. The support structure is a carbon fiber thing. It's about half a meter long and another quarter-meter wide and about three-quarters-of-a-meter tall. It's about the size of a large microwave. It's oddly shaped. It's got a central tube, vertical tube, that the Mole was in, and then the payload compartments which held the tethers, the tether that connected it back to the lander and the tether that connected the support structure to the Mole for when it penetrated, that was sitting on four large disc-like feet that were maybe about the size of your palm spread out on the ground. At the top there was the grapple hook that allowed the robotic arm to attach and move the support structure. That's what it looked like. That was the Mole part of HP3.

There's another piece of HP3 which is run by the same electronics, but it's part of the investigation, because HP3 is all about measuring planetary heat flow. The point of HP3 was to determine how much heat was coming out of the surface of Mars at this particular location, and in order to do that, one of the constraints is what is the actual temperature at the surface. So in order to measure that, we had a radiometer, a device that could remotely measure the brightness temperature of the surface. That was mounted on the underside of the InSight deck facing away from the payload deployment area, so the payloads were all deployed in front of the inside, and the radiometer was looking backwards the other direction so that it could look at a pristine field of soil and not have any instruments in its field of view, and that measured the temperature.

That had its own challenges, not as great, but there was a release mechanism for that that had to be designed and qualified, but that instrument worked fine, has worked fine since day one, and was actually used to really understand some thermal properties of the soil, especially during eclipses. Phobos or Deimos would pass in front of the Sun and in the shadow you could actually see the surface temperature over those few seconds that the eclipse was happening with the radiometer instrument, and you could compare that to the energy that was coming off the solar panels. There's some interesting science being done with that information.

Q: That's interesting. I wouldn't have thought it would be sensitive enough, but that's pretty impressive in and of itself.

Hudson: So when I mentioned the geothermal test bed before and I talked about measuring a shallow gradient, the test bed itself was 2 meters tall, and the difference in temperature from the top to the bottom was a degree. So you've got half a degree per meter of temperature difference, and in order for HP3 to be able to measure that low level of a thermal gradient, you need the individual temperature sensors to be accurate to almost—I think it's a few millikelvin, so a few thousandths of a degree. The radiometer also, likewise, has to be very sensitive to the surface temperature, so it's probably not something you would ever be able to feel with your own body and maybe even see on any thermometer you've ever encountered, but at the level of a hundredth of a degree or so, the radiometer and the HP3 sensors can see those kinds of differences, because the differences we actually set out to measure were so small.

Q: Jeez. Okay, thanks for that. That's a good corrective on me. So, finally, I always ask the same question, and that is what didn't we talk about but we should have, which is just another way of asking what didn't I know to ask about that's important?

Hudson: Well, the thing that always dominates my mind when I think back about instrument are the difficulties that we had with the Mole, and it's important for me to understand—and many people told me this, and it's true—that even though we didn't get to dig as deep as we wanted to, we still got good science out of the instrument and we learned some things that we didn't expect to learn. That's still discovery. That's still information that is valuable. It's not the information we had set out to get, but it's useful. It's valuable.

The InSight mission as a whole has been a tremendous success, and what we've learned about the interior of Mars is absolutely incredible, and it continues to impress. It's lived a lot longer than we expected it would. But you can design a system to some assumed set of requirements and constraints, and that's what we did with the Mole, and the system that we designed is performing *exactly* the way we wanted it to. It's doing everything we—the Mole is hammering, or can hammer, rather, and all the bits and pieces within it are working just fine. There's nothing wrong with it, but we designed it based on some assumptions that Mars that turned out to be incorrect, especially for a place like the subsurface, which you can't see before you go there, can't sense in any useful way, we had to make those assumptions. You can't put requirements on nature, and Mars surprised us, and that changed what we could ultimately do. So I take some comfort in that for the thing.

There was something else I was going to say. I lost it. Sorry.

Q: Fair enough. You have to start with requirements somehow, and they may not reflect reality. You just can't know in advance sometimes.

Hudson: I'll tell you a funny story, though. I remember back in one of our early meetings with DLR in Berlin, we had a number of people acting as review panelists or they were part of the JPL crew that went there. There was a scientist, well-respected scientist named Hugh Kieffer. I don't know if he's still around. But I remember him saying—he was worried—"What if the Mole doesn't penetrate the way you expect it to?"

And we were like—and I, being totally naïve and, of course, sort of taking my cues from my colleagues at DLR, "No, it will," or, "There's nothing we can do about it."

I remember him saying, "Well, what if you had a long stick built into the robotic arm that you could use to, like, push on the back of the Mole and get it down into the ground?"

Turns out if we had something like that stick, we might have been able to do a whole lot better than we did.

And I just remembered the thing I was going to say, is that we ended up going down this path, and it was the clearest path, the path with the right combination of low risk and potential reward at any point in time. Now, knowing what we know now, if we were back in February of 2019, I'm like, "Oh, I know exactly what we need to do. We'll remove the support structure, push on the Mole like this, dig with the scoop, do the—," da, da, da, da, da, "and maybe that will help us and we'll actually be able to dig down as deep as we want to." Maybe it would have worked, maybe it wouldn't have, but, you know, we'll never know the answer to that.

There might have been a better path that we could have gone down, but nothing was clear. Nothing was obvious as the right choice that balanced risk and opportunity of what we ultimately ended up choosing to do. Because it was a consensus decision amongst the various players of what we were going to go forth with, and at no point was there any really huge disagreement amongst folk about what was the right thing to do. There might have been disagreement about what the interpretation of what we were seeing meant. Yeah, we might have done better if we had done things differently, but what we ended up doing seemed like the best choice at the time.

Q: Made the most sense.

Hudson: That would be [unclear].

Q: Made the most sense with the knowledge that you had at the time, and hindsight is generally 20-20, but even then not always. [laughs] Even then, not always.

Well, thank you for your time, Troy.

Hudson: You're most welcome. Thank you.

Q: It's great to hear you tell the story, and passionately too. I'm afraid some of the passion probably doesn't come out in the transcript, but that is what it is.

Hudson: Yeah.

Q: Because it will just be text. Again, thanks for your time.

[End of interview]