Kenneth Hurst

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Erik M. Conway,
Interviewer

Q: My name's Erik Conway, and I'm interviewing Kenneth Hurst of JPL about his role in the Mars InSight mission. Today is September something or other. Is it the 19th?

Hurst: Nineteenth.

Q: It's the 19th, okay, of September [2022] already. So, Ken, tell me, where were you born and how were you educated?

Hurst: I was born in Pennsylvania. My father was getting his degree from Penn State. When I was six and a half, we moved to Virginia, went through high school there. Went to Earlham College in Indiana and graduate school in New York at Columbia University, and then I also got a Ph.D. and then I later on got a second master's at USC.

Q: What was your Ph.D. in?

Hurst: Geology.

Q: In geology.

Hurst: Specifically seismology.

Q: So one of my later questions was did you have any experience with seismology before, and the answer obviously is yes.

Hurst: Yes. [laughs]

Q: So how did you land at JPL?

Hurst: In my Ph.D. thesis, I was looking at the effect of water vapor on GPS positioning related to earthquakes, and we were looking at slow deformations of the Earth and how strain and stress build up in the Earth prior to earthquakes. That led to a bunch of work that I did in GPS, led to a postdoc at Columbia doing the GPS survey of the Agean Sea in Greece. At that time, there was a fair amount of competition within the academic community for precision analysis software, and so we decided we were going to use all three of the major competitors, Bernese, GAMIT, and JPL's GIPSY software, to do the analysis of our network. So I came out to JPL and spent about six weeks learning how to use GIPSY in doing the analysis of our network, and at the end of it, the group supervisor of the group that I was working with, Tom Yunck at the time, wanted to know if I was available for hire. I said somewhere in the definition of postdoc there's the word "available." [laughter] So that's how I came to JPL.

Q: Interesting, because I know Tom Yunck via my wife. Sometimes a small world. So you came to JPL working on GIPSY for Tom Yunck. What have you worked on since then?

Hurst: I spent about eleven years working on GPS software, GIPSY, and then I went over to what at that time which was Division 36, which was to be a group supervisor of a group that was doing machine learning applied to data analysis. I did that for about four and a half years. That group was largely soft money, in that it was write a proposal, get funded, and that's what carries you forward to write the next proposal. So we were chronically short of money. I went around to a number of projects and had a conversation that went kind of like, "Hey, we see a new and better way of doing what you're trying to do."

And they said, "Thank you very much. That's very interesting. We have our plan, we have our money, and we'll see you another time."

So that led to moving upstream to mission formulation stuff. I got very interested in mission formulation, which led me to go back to graduate school and get a masters in System Architecting and Engineering from USC. I was also invited to participate in the first cadre of an 'On the job training' program for System Engineers at JPL, and Nagin Cox was assigned as my mentor. Nagin invited me to join the Geophysical and Environmental Monitoring Station (GEMS) proposal to the NASA 2006 Discovery Program. Kim Reh was the Capture Lead and Bruce Banerdt was the PI. Nagin was the Deputy Capture Lead. I was the Payload person.

That 2006 proposal was not selected, though it received favorable reviews.

We started a New Frontiers proposal in 2008 but did not finish it.

In 2010, we reproposed to the Discovery program with Nagin Cox as the Capture Lead, myself as her unofficial deputy and also the seismometer, and of course Bruce Banerdt as PI. This proposal was selected to move on to Step 2. In writing the 2010 proposal we had considerable difficulty fitting into the cost cap, and got to the point where we were facing an internal JPL review that could result in cancelation of the proposal effort. I played a central role in cutting the mission down and focusing on the essential features that were necessary to address the interior of Mars, getting us into the cost cap with acceptable margin, and we moved forward.

Q: So tell me about what did you see as being the role of a capture lead or a deputy capture lead?

Hurst: Basically to shepherd the proposal through and to help the PI with framing the proposal. There's kind of a baseband making sure that the wheels of the proposal machinery turned properly and all the boxes got checked and all that, but that's kind of at a base level. At a top level, your job as capture lead is to produce a fundable proposal in the best possible way, so for that, there's a lot of working with the PI in strategy of what you're going to do and how you're going to do it and how you're going to sell it, a lot of conversations along those lines.

Q: Had you worked with Bruce before?

Hurst: I got involved with Bruce in 2006 with the first GEMS proposal, and then I worked with him on a second proposal which never actually made it out the door in, I think, 2008. Then again in 2010 on the GEMS/InSight proposal.

At the start of the Step 2 GEMS proposal, the Geophysical Environmental Monitoring Station, we had a number of other instruments along for the ride, particularly in the meteorology end of things, atmospheric stuff. And one of the things that we did in Step 2 was a lot of soul-searching about exactly what was the focus of our mission, and we cut the proposal down to just the bare bones of what we needed to do to really get at the focus of the mission, which was the seismometer, and I think that was the key to winning the proposal, and it also served us in very good stead as we went through the project, because in the process of doing that, we really worked really hard on the Level 1 mission requirements and the flow-down of that. And that flow-down helped us immensely once we became a project, referring back to it, and it provided guidance to us on what was important and how we had to proceed.

Sabrina Feldman and Peg (Margret) Frerking were the sparkplugs that drove the writing of the Level 1 requirements and the requirements flow-down. Leon Alkalai came on as the new Capture Lead if I recall correctly, and the mission's name was changed from GEMS to InSight (Interior Exploration using Seismic Investigations, Geodesy and Heat Transport).

Q: It gave you some ability to make prioritizations and choices and remind yourselves of what you had originally set out to do.

Hurst: Exactly. Right. So it helped avoid distractions, if you will.

Q: Yeah, understood. So what were the other instruments kicked off? I think implied meteorology was one.

Hurst: Meteorology was descoped considerably. Later on as a project, we brought some of it back in support of the seismometer, but in the proposal, most of it was left off the table. There was a ground-penetrating radar which was removed entirely and never came back, much to the chagrin of some people. Originally there were two moles, HP3, had two moles that were going to be put out, and it got pared back to one. So it just generally ended up in a streamlining of the mission.

Q: Fair enough. How did you find out you'd been selected?

Hurst: Personally, I found out via email from—I think it was from Bruce. I remember quite clearly reading the email in the kitchen. [laughter]

Q: And a little bit of celebration?

Hurst: Yes, exactly. [laughs] The whole house knew all about it very shortly. [laughter]

Q: Very good, very good. So once InSight's approved, you became the instrument engineer for SEIS right away, or was that later?

Hurst: It took a little while to sort out who was going to do what exactly, and Troy Hudson and I had been holding up the instrument side of the project up until, well, not quite the PDR, but early in the project it was mostly just Troy and myself, with obvious help from our international colleagues who were leading the seismometer and the HP3. But after a while, they fleshed out the project more and they brought in Jason Feldman to be the payload system engineer, so that I was able to concentrate on just the seismometer, and for a little while I was the seismometer *and* what we called APSS, which was the atmospheric measurements necessary to support the seismometer. But then that was split off as a separate effort, and I was encouraged to focus strictly on the seismometer.

Q: So really at JPL how many people were working on SEIS? Just two of you?

Hurst: Oh, no. At various times it was quite a few people. Up until 2014 or thereabouts, it wasn't very many people. It was myself, Jason as the payload system engineer, and a few people here and there for various specific expertise.

In 2014, it developed that Sodern was not able to make a working version of the seismometer. They had made them before, but they were not able to duplicate it.

Q: Oh, gee.

Hurst: So, yeah, oh geez and a half. [laughter] So at that point, there was a lot of discussion about what to do, and the French and Tom Hoffman, who was project manager, decided it would be a good idea for me to come over to France and see what was going on and see if there was anything we could do to help. That turned into quite a few people working. From 2014 through 2016, we would typically have anywhere from six to ten people in France at any given time.

Q: Wow!

Hurst: We had more people here at JPL working as well, so I don't know what the maximum was. I wouldn't be surprised if there were twenty or thirty people overall working on the seismometer, twenty or thirty JPL people working on the seismometer at some of the high periods, because we had several people from Division 35 involved at different times.

I guess in early 2016, I forget when it was exactly, we had one of the spheres collapse. The seismometer, the VBB [Very Broad Band] goes into an evacuated sphere, and the sphere had not undergone a buckling analysis, it turned out. It would withstand the pressures from vacuum, but if there was any kind of a perturbation at all, it couldn't handle it and it would collapse. We collapsed two spheres that way. One of them happened at Sodern when they were working at putting the connectors on to an engineering version, and another one happened when we were doing testing of VBB-11, I guess it was. It was in this sphere and in a vacuum chamber, and we did not intend to put it under vacuum, we did not intend for the sphere to hold a vacuum in that case. The tube that comes out that we would attach the vacuum system to, to suck it down to vacuum, was not connected to anything, but it turned out that it had a plastic cap over top of it to prevent dust from going inside, which acted as a check valve. So when we took the whole thing down to vacuum it let the air out, and then when we re-pressured the pressure chamber, the vacuum chamber, the cap prevented the air from going back into the sphere, so we ended up with a sphere with a vacuum in it that we didn't expect.

I was working on removing the sphere from the equipment in the vacuum chamber prior to taking it out, and I undid one of the screws, and as I brought the screw back over to me, towards my body, my little finger brushed across the top of the sphere and it imploded just like that, with a big bang, scared everybody half to death. [laughter]

Q: Somehow that doesn't sound like it would have survived launch loads. [laughs]

Hurst: No, it would not have, not at all. So any rate, getting back to [Division] 35, that launched a major effort to redesign the spheres, and JPL took on building those. They were two hemispheres to get welded together. So Division 35 got spun up pretty heavily on an emergency basis getting the spheres made. In fact, we even reached out to Marshall and had Marshall made a set of spheres as well, in case the ones they were building at JPL didn't work out.

Q: Good heavens, good heavens.

Hurst: Well, it was on the critical path on a mission-critical instrument, and we were behind schedule, so they pulled out all the stops.

Q: I'll say. Good heavens. Okay. So we skipped forward a little bit to talk about some of the problems with the instrument development, but earlier you were talking about organization. You had a small group of people at JPL early on anyway. What about the foreign partners? Tell me about who they were, because I understand you had quite a number of them for various parts.

Hurst: Yes. So the seismometer is actually two seismometers in one. There is the very broadband seismometer, VBB, which is a design from the IPGP (Institute de Physique Du Globe de Paris) university in Paris, and then there were the short-period, or SP, seismometers, which were MEMS devices, being manufactured at Oxford University and at Imperial College London in UK. So those were the providers.

Now, the whole project for the Europeans was managed by CNES, so you had the IPGP and the UK being managed by CNES, and then the electronics were made by the Swiss, ETH, in Zurich, and the leveling system was made by the Germans, DLR. So those were the major contributors to the hardware for the seismometer.

Q: CNES was supposed to be managing them, so your interaction was primarily via CNES?

Hurst: Well, yes. Officially, yes. In practice, I spent most of my time in Paris either at Sodern, which was the company that contracted with IPGP to actually make the things (VBBs), so the design was IPGP, but the company doing the work was Sodern. Sodern, their bread and butter are star trackers, so they've been making star trackers for many years. They make a very nice star tracker. So this was kind of a side business for them.

Q: Did you have to work much with the PI who was also in France?

Hurst: Yes, that was Philippe. I spent quite a lot of time working with him and his team, yes, and I spent a lot of time at Sodern, talking with the technicians, engineers. Do you want me to talk about the differences in how JPL runs projects versus how other entities run projects?

Q: Absolutely.

Hurst: Okay. So CNES in particular, they have a much more siloed—from my perspective, they have a much more siloed top-down sort of organization to how they run their projects, and you're not supposed to be going above the head of whoever your direct supervisor is, basically. I was in a bit of a unique position in that I was from outside that structure, and I had agreement from everybody that I could basically talk to whoever I wanted to and ask as many questions as I wanted, and go where I wanted when I wanted. So I ended up using the—there's a train that runs between Paris and Toulouse overnight. I used that a lot. [laughs]

So I was in an interesting position for me, and I enjoyed it tremendously. I had no real authority over anybody, okay? Nobody reported to me. I reported to Jason Feldman and to Tom Hoffman at JPL. I had no real budget. I couldn't promise money to anybody for anything, in particular because we're dealing with foreign contribution, so there's an additional wall there as well. But JPL was really good about if I went to Tom or to Jason and said, "Look, here's what I see is going on. Here's what's needed," JPL always managed to find the resources to do what needed to be done, so that's why we ended up having a whole bunch of people over in France helping out with this thing.

We started out in 2014 with just myself, and one of the things that became evident within a few days was that there was a problem with particulate contamination of the seismometer, and so one of the first things JPL did was they sent over some people from Mission Assurance who were really good at particulate control, and so we started working on the clean rooms and their procedures. Then we ended up redesigning parts of the instrument so it's less susceptible to particulates. So that's how we kind of mushroomed into what became a really very close collaborative effort between JPL and CNES and Sodern and IPGP. We all worked together very well and everybody pitched in and carried their part of the stick.

Q: So you had no direct authority, really. All you could do is persuade, essentially, it sounds like what you're saying.

Hurst: Exactly. All I could do was persuade, and initially that was hard. By the end of it, it was relatively easy to persuade, basically because people got used to working with each other. It became an environment where people were not worried about taking credit for things, and everybody just wanted to get the thing working. So people did whatever was needed, and if you asked for something, if that person couldn't do it, they'd figure out how to get somebody else to do it. So it was a very productive work environment, very enjoyable.

Q: Interesting. I would have thought that ITAR would cause you some issues, but it sounds like you—

Hurst: It did.

Q: It did. Okay.

Hurst: It was an ever-present thing on your shoulder. In general, we had some very clever people writing our technology control plans, and they were written in a very permissive way that allowed us to get on and get doing what we needed to get done, so we were very fortunate in that regard, that we were able to get a good set of agreements in place that allowed us to pretty much do whatever we needed to do. That doesn't mean that it was friction-free. We had one or two instances where I had a major hiccup. For example, some pieces left JPL and turned up in France before the paperwork had been fully filled out, and so, oh, my goodness, you know, it turned into a big thing. We had to go down and interview and yadda, yadda, yadda. [laughs] But overall, once again, it worked. We got it to work.

Q: So you talked about one of the problems you had ultimately with the spheres having been incorrectly designed, but take me back to when you first get the proposal accepted and you're funded. What did you expect to be your problems or your challenges, really, with SEIS?

Hurst: Wow. That's an interesting question. Well, first of all, we did not expect any problems with the vacuum system at all, and as I was working through the whole thing, I always had it on my mind that something was going to come along and bite us that I hadn't thought of, and so I tried very hard to think of everything, and, in fact, what came along and bit us the most was the vacuum design, and I didn't pay enough attention to it and neither did anybody else, apparently. I didn't catch that. There were a number of problems with the vacuum design which became evident when we got to that part of the project, and, unfortunately, that part of the project was very late in the game. So that was a case of "This is old technology. We've done this before, Sodern has done vacuum systems before. There's nothing new here. Don't worry about this. It's the new stuff you've got to worry about." And we had a lot of stuff to worry about in the new stuff, that's true, but I didn't catch the vacuum stuff.

Q: What amongst the new stuff concerned you the most when you started?

Hurst: I was mostly concerned about the VBBs, because they were the non-descopable part. We could have descoped the SPs if push came to shove. We could have flown with dummy masses instead of the SPs. Didn't want to do that, obviously, and we didn't do that, but if we'd come down to the mat, we could have done that.

But the VBBs were required, and the VBBs are a very complex electromechanical device assembled by hand, and I was very worried about building them, and justly so, as it turned out, because, as I said in 2014, it turned out that Sodern was not able to duplicate them. So we spent a lot of time and effort understanding the implications of their design. We redesigned a few things here and there. We could not do a redesign from the beginning, but pieces of it we could redesign. And we spent a long time modeling them in detail and understanding why they reacted the way they did in order to make them work.

Q: So you essentially had to reengineer them in order to make something that was constructible? Or was the issue that they could build them, but they did not have the response you needed?

Hurst: Well, they could build them and it would look right, but, as you say, it would not have the right response. The big problem, the heart of the problem, the heart of the seismometer is the pivot. The pivot is the part that allows the pendulum to move. Basically a seismometer is a pendulum, okay? And you have the pendulum and you have a force feedback system, and the idea is to make the pendulum move with the ground, and your output of the seismometer is the force required to make the pendulum move with the ground.

So we have this pivot at the middle of it, and the pivot, it's a flexure joint, because we don't want any friction, and it's supposed to allow the pendulum to move in a strictly linear way.

The way this pivot was constructed, there were twenty copper-beryllium leaves, which are kind of like this [demonstrates], if you can see my fingers. They're interleaved and crossed. They were attached top and bottom to two blocks of titanium.

The problem was that when they made these pendulums, what they would do is they would take these two titanium blocks and screw them into a jig which held them in the right orientation and the right distance, and then they would glue the pieces of beryllium-copper, the leaves, into place. Then they would take that pivot and they'd put it in the seismometer and screw it in. The problem was the pivot was not linear. As the pendulum moved, you could get nonlinear behavior out of it.

So what was going on, it turned out, was that the torque they were using on the screws to fix the two titanium blocks into position in the jig was much less than the torque that they were using to install the pivot into the seismometer, and that meant that it was a single bolt on top and another single bolt on the bottom, and it had to be torqued up pretty tightly in order to be able to hold it. And when they did that, they deformed that titanium block. The titanium block was roughly a-centimeter-by-a-centimeter, roughly, so it's a good-size block. That was putting the outside copper-beryllium strips under compression, and the inside strips under tension. The ones under tension were fine, but the ones under compression, you could get buckling of the blades under some circumstances, and that would lead to nonlinear behavior.

It took us a long time to figure all that out, and then it took us a little while to figure out what to do to fix it, and part of it was to reduce the torque on the screws holding the pivot into the seismometer to approximately the same value as was used to fix the pivot in the jig. But that meant that it was not held in the seismometers as firmly, and so it could move a little bit under some circumstances, so we had to come up with a secondary way of fixing it in rotation around that big screw, and that, in turn, we had to refine that, because that involved some blocks that we glued at the periphery of the pivot block, and if we didn't do that glue joint just right, we could introduce a much larger signal than the one we were trying to eliminate.

So we got that right eventually, and it worked, but it was a long road, a lot of hours of modeling and a lot of debate back and forth about what's going on.

Q: How many did you have to build? Because usually we've got the flight instrument, then a couple of spares and engineering models and so on. But it sounds like it was very unique.

Hurst: Yeah, they were all handmade, basically. That was a problem. So they all had their own idiosyncrasies. I think we built sixteen of them all told—

Q: Wow.

Hurst: —over the several years. Each instrument consists of three sensors, so we needed a flight model and a spare, so there's six right there that we needed to have. Then we also wanted an engineering model and a qualification unit, so that takes you up to eight. Then we had several we just built to try and understand what was going on as we went through the process. So I think we ended up building, I think, sixteen in the end.

Q: Heavens. Okay. So we've now talked about two challenges on the instrument, the vacuum system and the longer-wave sensors. What else? Were there any other memorable challenges?

Hurst: The vacuum system was a whole series of challenges in and of itself, but it wasn't just the sphere collapsing, it was also the problem with we had to develop a new set of getters for the instrument. Getters are—in a vacuum system, you're going to have some residual gases, either because you didn't evacuate it completely or, more likely in this case, you have things like epoxy, which will outgas over time. And so getters are things which will grab those molecules and bind them so that they're no longer floating around and creating a micro atmosphere, if you will.

So we had some getters in the sphere originally, but it turned out they were from a standard getter-maker, a company that makes getters, but it turns out that in order to activate them, you have to heat them up to, I think, 600 degrees, and if you did that, we would cook the seismometer. So we could only partially activate them, which made them not very effective.

So we ended up having to design and build new getters, which worked very well, by the way, and it was a very interesting development in and of itself. We used silica gel as the medium, and then we doped that with a bunch of compounds which would chemically combine with the materials we expected to be outgassing, and they worked out very well.

Q: It was another unexpected thing you had to figure out. [laughs]

Hurst: Exactly. Right.

Q: So let's talk a little bit about time frame. The mission gets delayed because of SEIS, and I think that probably was your vacuum challenge. So is that about the time that you discover the vacuum troubles, or had they been brewing for a while?

Hurst: No, we discovered we had a problem, we were in the final stages of thermal vacuum test before buttoning the instrument up and shipping it back to JPL for integration, actually to Lockheed Martin for integration. But it was in August of, I think, 2015, I think it was, when I got a call.

We didn't have any pressure gauges inside the sphere, but what we did was we could look at the natural period at how fast the seismometers damped out. It's called the Q measurement, quality measurement. But basically if you're in a vacuum, they'll continue to oscillate for quite a long time. If they're in the atmosphere, one atmosphere, they damp out quite quickly because of the viscous dampening of the atmosphere.

I got a call saying, "Hey, it looks like our Q measurement, the damping coefficient is quite low and it damps out quite quickly, and the only real explanation for that is we've got residual gas inside the sphere far more than we want to have."

So we spent about a week doing more measurements and having a series of emergency meetings about what to do about it, and confirming that that really was the case before we did anything drastic, and it was. So we concluded we had a leak in the sphere somewhere, and so we sent it back to Sodern and started working on trying to figure out where the leak was.

We identified the leak as being in the connectors. We had electrical feedthrough connectors going into the sphere. Those were ceramic with—I forget what the material was on the pins. It might have been stainless steel. I forget exactly. It was gold-coated stainless steel, I think. The way that they put them into the—they had the ceramic and they would burnish some molybdenum into the ceramic, and then they would braise the pins in place, into the ceramic, and one of the pins was leaking.

So that led to a lot of efforts, and at first we thought it was just the pin leaking, and so we fixed that, but we still had an apparent leak. It turned out that it was a combination outgassing and virtual leaks inside the sphere, where we had things like blind holes, where you have a screw that goes into a hole, and when you do that, you trap a little gas at the bottom of the hole, unless you have a vent hole. And we had a bunch of these things did not have vent holes, something else that we should have known better, but it would be part of regular good vacuum design, but was not part of our design at the time. So it was one of the things we went back and we took the screws that were going to be used there and we EDM'd little holes down the middle of all the screws so that they would vent. So that was one of the things.

Q: So you had a number of different—well, I guess the screws aren't really leaks, exactly. They were—

Hurst: They're called virtual leaks. Virtual leaks is what they call them.

Q: Virtual leaks is what they call them, okay, in the vacuum world. Good grief. So that discovery that even after you'd redesigned the spheres and rebuilt them, that there was still leaks is the source of the resulting delay.

Was there anything else done? I know, for example, that Troy Hudson's instrument was able to do a lot of positive work during the delay, but what about yours? Were you just trying to solve that problem, or were there other improvements made too?

Hurst: No, I think at that point we were focused on just get the thing to the launchpad. We didn't really add any scope. We just fixed the problems that were in front of us, and that was plenty for us to do.

Q: Fair enough, fair enough. So did you stay with InSight into the operations phase to launch?

Hurst: Yes. In fact, I'm still with instrument.

Q: You're still on it.

Hurst: I'm still doing some data analysis and stuff like that. I am a seismologist as well, so I'm interested in data.

Q: So did they make you part of the science team as well?

Hurst: Yeah, I'm one of Bruce Banerdt's collaborators.

Q: So you're in a somewhat unusual position. You aren't merely functioning as the instrument engineer for SEIS.

Hurst: No, that was a large part of my duties, but I also stuck my fingers into the science end of things as much as I could. I really enjoy going back and forth between the communities.

Q: When you got to Mars, what decisions had to be made about SEIS after landing?

Hurst: Well, the first one was where are we going to put it, and so we had a short period where we looked at all the imagery that was taken down and figured out where we wanted to put it, and because SEIS was the primary instrument, we got first pick of where we wanted to be, and then HP3 had to pick where they wanted to be, given where we were. But that was not a source of friction at all. It's just the way things were organized, and it went quite well. I think we deployed on Sol 22, as I recall. It was my birthday.

Q: Oh, your birthday. Very good. [laughter] Not a bad gift.

Hurst: Exactly! [laughter]

Q: So did SEIS meet your expectations? I mean, I know there've been scientific results, but we were the similar to what you were hoping?

Hurst: Yes. It's performing quite well, pretty much where we expected it to be, or maybe a little bit better. So I've been quite happy about that.

Q: Yeah, given all the work you had to put into it. [laughs] Let's see. What haven't we talked about that's important from the standpoint of SEIS and the InSight project?

Hurst: Oh, gosh. What have we not talked about that's important? We haven't really talked much about the data per se that we got back.

Q: That's true.

Hurst: And one of the things about seismology is that your data comes in bursts, and you have long boring stretches where you're looking more or less at a flat line and trying to figure out something interesting to do with it. It's not really flat, so that gives you something to work with, but it's basically just noise. There are interesting things you can do with noise. But then a quake happens, and you all of a sudden have lots of data, and that's what has happened with InSight. We've had three major quakes, the largest one being the most recent one, and we were very glad to get that, and that has led to a burst of activity in the science team, and it's been quite gratifying to watch how the science has progressed.

I really enjoyed partaking in the science telecons on first finding the core wave, the core SCS, the S-wave reflection off the core, and more recently, looking at the SKS, which is a wave traversing the inner part of the core. From SCS, we get the size of the core. From SKS, we can start to say something about what's inside the core. It's been a fascinating development.

Q: Yeah, I just looked at some of the press releases, but I haven't looked for scientific papers yet, so I only roughly know what you're talking about, very, very roughly. [laughter] What do those things mean to you at this point that we didn't know about Mars before?

Hurst: Well, we are in the process of learning a lot more about its structure than we ever knew before. We're able to talk about what the core composition might be and whether or not there might be a layer right near the core mantle boundary, for example, that has different properties, specifically a lighter density than the materials below it.

In my efforts, I've been focusing more on the very near surface, looking at elastic properties of the ground right underneath the lander. Other people were not doing that so much, and it was something I was very interested in, so that's where I've spent most of my efforts. But I really find it fascinating to follow along and be part of the discussion for the internal structure. We've gotten, from receiver functions, basically you have a wave coming up from below, from a distant quake, and receiver functions allow you to solve for the structure underneath your receiver, and so from that, we've been able to look at layering of the crust underneath the lander, and we've got strong evidence for two and probably three layers below the lander that we can differentiate and talk about their seismic velocities.

We're starting to see results from surface waves. We didn't see any surface waves for a long time. Finally we got a big enough quake to get one, to get some surface waves. And like I said before, you sit around and wait and wait and wait, then all of a sudden, you have lots of data.

Q: Seismology can be a slow science, especially on a planet that hasn't got all that much going on, I mean not compared to Earth.

Hurst: Yeah, exactly. No plate tectonics, for example.

Q: Yeah. No fun plate tectonics. So, let's see. We're basically out of time. What will you take forward from the SEIS project to whatever you do next?

Hurst: The biggest thing that I learned is cast an even wider net than I did before. I tried to cast a wide net before, and I missed the vacuum system because it was well-known and that's not where the problems are going to be. And guess what. [laughs] So in hindsight, at one of the reviews we should have had somebody there reviewing the vacuum design, and it would have saved us a lot. Jason came very close to putting his finger on it. He asked a bunch of questions about the vacuum design. He asked them to make a larger tube going to the interior to improve the ability to evacuate it, which they were not able to do. But he was very close to hitting it, but he didn't actually land on it either.

If we had invited somebody like Mihail Petkov, for example, who came in when we had a problem, he came in and looked at what we had done and said, "Oh, you've got blind holes here. That's a problem. Your getters aren't good." And he had a whole bunch of things, and he helped guide us through the period where we were figuring out what went wrong as well. Had we had him involved earlier on, I think we would have avoided a lot of problems.

So cast a wider net and make sure you have experts in the room who can review even the things that are supposed to be rock-solid old-hat.

Q: Okay, fair enough. Who do you think are the other key people from the SEIS perspective, before we end?

Hurst: At JPL or elsewhere?

Q: Both.

Hurst: Okay. JPL, obviously there was Jason Feldman. Vazrik Gharakanian—I always mess up his last name. I can get it for you. He was in charge of QA for SEIS—if he wasn't there, he made sure that somebody else was there to provide QA for us, and he would undoubtedly have a bunch of insights as well, I bet. Let's see. Troy you already know about. Let's see. Who else? Doug Bernard was the overall project system engineer for much of this as we were going. Let's see. You're familiar with Tom, obviously, and Ed Miller was the payload manager.

Outside of JPL, Philippe Lognonné was the PI for the instrument, and then Tom Pike was the PI for the short-period instruments. Tom Pike spent some time at JPL, and then he went over to Imperial College London later. Let's see. Who else? Sébastien de Raucourt at IPGP was one of the system engineers and project manager for IPGP, and he'd be an excellent source, and he can point you at other members of his team. There are several who would be very good, Sylvan [phonetic] or Tanguay [phonetic] or there are several people that he could point you at there.

On the CNET side, Philippe Laudet was the manager. Gabriel Pont was the system engineer, a very good guy. He could give you good insight into what was going on.

Over at ETH, Peter's retired and so is Devor [phonetic], but Jan Tenperic [phonetic] is still around. And Domenico Giardini is the PI for the electronics, probably start with him. He'd be the right person if you're looking for somebody over there. So I think that's a pretty good summary.

Q: Great. Thank you very much. Anything else before we end? I'm out of my questions.

Hurst: Not that I know of right off. It's been a pretty thorough interview, I guess.

Q: Okay, great. Well, thank you very much for your time. Like I said, you'll get a transcript probably in a couple of weeks to edit and review. Thank you very much. Take care.

[End of interview]