DISCOVERY 30TH ANNIVERSARY ORAL HISTORY PROJECT
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INTERVIEWED BY ERIK M. CONWAY
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CONWAY: I'm talking to Mike Watkins, Project Scientist for the GRAIL [Gravity Recovery And Interior Laboratory] mission. This is Erik Conway, the JPL historian [NASA's Jet Propulsion Laboratory, Pasadena, California]. We're both at our homes still in pandemic Pasadena and Altadena.

So, Mike, tell me how you got involved with the GRAIL mission.

WATKINS: Okay. Let me kind of back up a little bit here. I'm not sure that all of this will unfold in the order of the questions. I had been doing gravity field mapping work since graduate school. We learned from Isaac Newton that the gravity field of a planet affects the orbit of any satellites, both natural and artificial, around it, and there are a couple of reasons you want to measure the gravity field. In the case of the Moon, and the early days of the Earth, you want to understand the interior structure of the planet, what's its thermal history like, how fast did it cool, how does its topography compare to the gravity field, and then later we realized, of course, that the gravity field is also changing mostly because of water moving around, with climate implications. That's really why GRACE [Gravity Recovery And Climate Experiment] turned out to be so successful, although back fifty years ago, people, when they measured gravity, were measuring the average gravity field of the Earth.

I had been doing what's called precision orbit determination, basically navigation, we often call that at JPL, and we were looking at tracking satellites as best we could to try to figure out the gravity field, and the reason we wanted to do that was for a satellite called TOPEX/Poseidon [Topography Experiment/Poseidon], was launched in 1992, and it was to measure the surface of the ocean and look at ocean currents. It turns out that the surface of the ocean isn't perfectly flat. What you would love is that it's perfectly flat and all the deviations are ocean currents. Turns out that's not true, because the Earth has trenches and seamounts and ancient continents buried, and so the surface of the ocean is varying, has all kinds of mountains and valleys on the surface of the ocean, and a lot of those are due to the gravity field.

What you want to do, of course, is say, "Well, I can model all those out and throw them away, and everything left over is oceanography." So we set on a big effort for TOPEX/Poseidon in the late eighties to prepare a gravity field that was so good that we could subtract all of that so-called 'mean gravity field,' or 'static gravity field' away from the ocean topography. It turned out we actually couldn't—we did a great job, us and the Goddard Space Flight Center [Greenbelt, Maryland], in particular, together, us being University of Texas at that time. We were a precision orbit determination team, Texas and Goddard at that time. We did a real good job, but not as good as we really wanted to do, so that we still could tell that there was this gap remaining in the gravity field, and we wanted to solve that.

So there were lots of attempts to make a dedicated gravity mission for the Earth, right?

CONWAY: Yeah.

WATKINS: It was a real common topic, and there must have been five or ten proposals for the best way to measure the gravity field. These were satellite-to-satellite ranging, which I'll come to in a second, gravity gradiometers, just all kinds of stuff, and they were always expensive. NASA just couldn't afford to fly one of these dedicated gravity missions at that time.

So then a combination of technology improving, like GPS [Global Positioning System] and some DSN [Deep Space Network] technology and K-band and a few other activities, led us to propose the GRACE mission, and the GRACE mission got a lot of compelling scientific support. So rather than just saying, "The *only* reason I'm flying this is to get this mean oceanic geoid," we also can watch that change from month to month. So we can watch Greenland melt, right? We can watch other water storage, continental water storage, things like that. So that became a very compelling mission, and it was selected and it was launched in 2002.

That technology was now available to everyone. It was kind of lying around. We talked about, "Hey, maybe we should fly this at Mars or we could fly this at the Moon or other activities." And kind of the view at that time was gravity science at the Moon, because you remember the Moon has no climate, so you're just doing this mean—I don't know if you talked to Maria Zuber yet, but she, of course, is an expert in this, in the science of this. Using the gravity field and the topography together, is that compelling enough or is that a niche science? Would you be able to win a Discovery proposal to do that? There actually were fairly few. The standard wisdom was probably that it wasn't likely to win as a dedicated mission for a while.

So there were a couple of co-flyer proposals. We had a mission called Moon Rise, which was a New Frontiers, actually, to get a sample from the Moon, from South Pole-Aitken Basin, and I was co-PI [principal investigator] on that in order to do a gravity co-experiment. We had a relay satellite and we could actually track on the far side of the Moon, so we could do this sort of GRACE-like tracking. The reason that matters for the Moon is in order to do our Newton's apple thing, you've got to see the satellite, right, when it's flying. And, of course, on the far side of the

Moon, that side of the Moon is always facing away from us, right? People call it the dark side, but it's not dark, because the sun is there. It's always pointed away from Earth. The Moon is tidally locked, so it's always facing us, so I can *never* see that part on the back. Every time the satellite goes over the far side, I don't get that part of the gravity field. You wanted to use satellite-to-satellite tracking when it's not an Earth view.

I tried it with Moon Rise. Moon Rise was not selected. It was a highly complex mission with the [sample return] lander, get the sample back.

I believe there was another Discovery attempted proposal called Moon Light. I think it was a laser on a satellite maybe bouncing off a reflector. There were several proposals for the Earth, too, like this, where you have like a Coke can and that's the other satellite, and you bounce the laser off a retro reflector in that. So I think there was a Discovery proposal. I'm not sure how far it got. I don't recall exactly right now. I think that was called Moon Light. Leon Alkali might remember that.

CONWAY: Okay, Leon again. [laughs]

WATKINS: Yes. So Leon managed both of these two proposals, actually all three of them. Leon was what's called the capture lead or the proposal manager for Moon Rise, Moon Light, and what became GRAIL.

CONWAY: Let me note that, because I've already talked to him about GRAIL, but he didn't mention these other two.

WATKINS: He might remember that we tried to—I'm telling you sort of the long, twisted tale of how we ended up at GRAIL. So what happened on GRAIL was—I was the project scientist of GRACE, and I helped come up with the idea for GRACE back in the nineties, but by the time GRACE was up and running, I had switched to become the—I left the Navigation Section management and became the mission manager of Curiosity [Rover], of MSL [Mars Science Laboratory]. That was kind of an interesting career change, but I wanted to do it because you want to be part of a big flagship at JPL sometimes, and I was doing my own technical expertise, but these flagship missions and these Mars rovers, they just seemed fascinating to me, and there was a lot of energy there. I said "Hey, let me go see if I can do that and help for a while." A lot of folks from the Nav Section were very good at operations and they're very good at planning and stuff, so a lot of mission managers, mission system managers come out of the Nav and Mission Design Section.

I was appointed to that job and I was doing it, and I was happy doing that. When GRACE was very successful and Moon Light and others didn't go, I remember thinking, "Well, what if we just tried to do the cheapest possible mission?" If you kind of think of the Discovery portfolio, it was one where you had "Can I put ten pounds of potatoes in a five-pound sack?" That's one type of a proposal, and you might win it because ten pounds of potatoes is good for NASA. The problem is you get all this high risk, you know, blow the budget, blow everything, so there's a risk with that kind of proposal. And what I thought was, suppose you don't think gravity science is 10 pounds of potatoes. Suppose it's 4.99 pounds of potatoes in a 5-pound sack. But we can win it because everyone will say, "This is easy to do. Yes, we should pick this because it's great science and it can be executed because it's not a complex mission. The payload is just the tracking between the two spacecraft, right?

CONWAY: It's a lower-risk proposal.

WATKINS: Correct, and, for those who understand the science, very compelling. So there are a lot of people maybe who don't do that kind of science, but it doesn't matter. I remember thinking like, well, what if we dropped one of the frequencies? GRACE uses K- and Ka-band both because of the ionosphere of the Earth. We have to remove the charged particle influence. Same reason GPS uses two frequencies. So drop one of those and then, most importantly, don't fly the accelerometer.

GRACE is trying to measure the distance between these two spacecraft as they fly over the Earth. The problem is there's tiny pockets, little blobs of air still that it seems hard to believe that air is enough out there at 500 kilometers or 400, but it is. So that little extra motion from hitting blobs of air drag are enough to really mess up the gravity field very severely. So we fly an ultra-high-precision accelerometer, so that accelerometer measures forces being applied to it. Actually, it's a little floating block of metal inside a cage, and when the spacecraft hits drag, the spacecraft moves closer to that mass, because that mass is isolated, so the spacecraft chassis bus moves closer to it, and we measure that distance with a capacitive measurement. You can see the capacitive changes, voltage changes. That is an ultra complex, ultra expensive, ultra pain-in-the-ass thing to carry. It has to be right at the center of mass, because if it's not, rotations, centrifugal forces of rotation look like drag, and so that's always kind of a huge accommodation problem for GRACE and GRACE Follow-On.

Again, there's very little air around the Earth, but there's zero around the Moon, so the only problem you have to deal with is deal with solar radiation pressure, the force of solar radiation pressing on the satellite. So we said drop the accelerometer, drop one frequency, build the cheapest possible thing, and this looks like a go.

So me and someone—it might have been—I think Leon maybe wasn't assigned at that time. I think I met with Gregg Vane. This is the email chain I'd like to have. I seem to recall meeting with Gregg Vane and saying, "Here's my idea. It's a loss leader mission [joking]. I guarantee it's the world's simplest mission, but the science will be great, and here's how to do it."

So I think I put together a little viewgraph package or something, and it got through. At JPL, of course, to submit a Discovery proposal or let alone a New Frontiers, it's a big investment for 4X, and so are they going to spend hundreds of thousands or a million dollars writing your proposal? It's got to get through a bunch of gates to make sure that it's a credible proposal. So I think I got through the first—you know, there's a gate that allows twenty proposals, and then there's a gate that gets it down to ten, then gets it down to five, so I think I kind of ran it through the first gate, and at some point, because Leon had managed Moon Rise and Moon Light, I think Leon came onto the team, and there came a point where I think I was kind of godfathering it, but you need a PI.

I remember thinking, "(A) I'd really like to stay on Curiosity, because I want to see this thing through to the end. I want to go through the experience of a flagship at JPL and do a Mars Rover mission. And (B) I'm not really an expert on lunar interior science."

I had known Maria Zuber since—we knew each other since probably around grad school days, going back probably twenty, thirty years, at that time probably thirty years or something. She is an expert in this. I'm an expert in navigation and some planetary science, and she's an expert in planetary science and some engineering, so we're a little bit of a Venn Diagram, you know, that overlaps in the middle. I like Maria, and she was at MIT [Massachusetts Institute of Technology, Cambridge], which was great, so she had a lot of attributes that make her just the world's greatest PI for a mission like this. I remember sending her a letter saying, "I came up with this idea. Would you like to hear about it and maybe be the PI?" And I have that email somewhere.

She said, "Yeah, I'm real busy, but let's talk about it and make sure that it's worth my time," you know, worth Maria's time.

Then we put it together and decided that—I think she said, "I'd like to have my old friend Dave Smith from Goddard—." By the way, I knew Dave Smith since grad school also, since my grad school, but he's probably eighty-five years old now or something, I'm not sure, if you talk to Dave. But he's a British guy. He ran the Geodesy group, kind of like the Section 335 of Goddard, you know, that Andrea [Donnellan] and I were in.

They had worked together on a couple of other earlier missions, Dave and Maria had. So she said, "I'd like Dave to be my deputy PI, and I'd like you to also come in and do some role." There's various roles you could have. We chose to call it project scientist. There's a variety of ways you could have named that. Some people called it chief engineer, other things that you could imagine.

I said, "Sure. That's great. I'll help out however I can, particularly on the implementation side, how do we make good decisions that make sure that we get this cost-effective and still meet the measurement requirements." Then I was on the science team, and Maria put together a world-class, fantastic science team.

So this is how it came together. We just kept doing more and more trades to put the mission together. We at some point asked for spacecraft proposals. There was a suggestion that the guys that built GRACE—you know, the Germans built GRACE under U.S. contract, by the way. It was not a contributed spacecraft. But Lockheed Martin was ultimately selected, using a small bus, XSS-11 heritage bus.

We wrote the proposal; we got to step two. We wrote a very complex step-two proposal. I remember I came in—again, MSL was going on, so I sort of would not—you know how the war rooms are for these Discovery missions, right? So there's six guys in there working 24-by-7, but I couldn't (due to MSL duties). I'd miss two days and then come in and say, "Hey, what's going on?" and do heavy editing and things of this nature to make it be the way we wanted. We did a lot of trades about what's going to be a factor, what's not. We did tons and tons of simulations. We do very complex numerical simulations using the navigation software. The navigation software models what we think the trajectory's going to look like, and then you add errors to that that are statistically plausible, and then you use a different model and try to fit that data, right? You simulate the data with a bunch of unknown errors, then you try to pretend that you're fitting that data and see what the real errors are, see how well you did.

We did many, many of those Monte Carlo types and covariance analysis, to show that we would get a fantastic gravity field, which we did, and in step two, we were selected. I believe Alan Stern was the head of SMD [Science Mission Directorate] when we were selected. I heard about it at the AGU [American Geophysical Union]. I think it was selected and announced at the AGU San Francisco 2007, December, is my recollection.

CONWAY: That's the right time frame.

WATKINS: And I remember going to dinner with Maria and Alan Stern. We went and had a drink or something to talk about it, and we looked forward to working together. Then we got into it.

CONWAY: So let's go back. Thanks for that, because you've already made the GRACE connection that I wanted to. But make the connection to Texas for me, since it sure looks to me like a lot of the gravity field people came from Texas one way or another. Tell me about why that is.

WATKINS: There was a program that I went to, and many people in the Nav Section, and, by the way, John McNamee and Richard Cook and Joe Guinn, if you know him. It just goes on and on; there's a gazillion of us from Texas. The curriculum was really precision orbit determination, so you have to know the astrodynamics that do the forward propagation, and then you have to do this least squares-type inversion, Kalman filtering, which it's usually called.

A professor there formed that curriculum, that group. His name is Byron Tapley. He formed this group, and then several of us went off and did our work—some stayed at UT, some did earth geodesy, some did just various random things. I had started the thing that became GRACE when I was still at UT. I stayed at UT after I got my Ph.D. I stayed there for a couple of years as a faculty member, as a young faculty member, and as I mentioned, that was in those days when people were like, "Let's come up with a way to measure the gravity field for TOPEX/Poseidon." So I came up with that idea, and me and Byron Tapley, JPL folks, and a German group, Christoph Reigber, which is now what's called GFZ Potsdam [German Research Centre for Geosciences], we put together the package. It went through the Earth System Science

Pathfinder Program. Earth System Science Pathfinder Program was like the Discovery [Program] for the Earth, even cheaper. It was like 90 million was the cap, believe it or not.

We wrote the GRACE proposal in '96 and won it in '97, launched in 2002, March. So the knowledge that I brought and some of the folks in the Nav Section from Texas was brought into GRAIL, but Texas as an institution was not institutionally part of the GRAIL proposal.

CONWAY: Right. I was looking for more of that intellectual history, which isn't quite right. It's still—it's people interchange to some degree.

WATKINS: It totally is. That's correct, yeah.

CONWAY: So thanks for that, tracking it back to Tapley. Now, I know there were some other gravity missions before TOPEX, right? There was Seasat briefly, which was not also a gravity mission specifically, but there's a bunch of defense missions before that, so there must be some knowledge and some people that drew from that.

WATKINS: Actually, there really weren't any good gravity missions.

CONWAY: Okay. [laughs]

WATKINS: Most of the problem was there's no tracking, so there was no dedicated gravity mission. Now, there was talk—there's a couple ways to go here. Forget about the dedicated mission. What people were doing was just every satellite that's up there, just track the heck out of it and throw it all in the blender and try to solve for all these gravity terms. Now, the way the gravity field works on satellites is it causes a set of periodic perturbations in the orbit, and so if you have a lot of data, you can kind of screw it down. You can pull out some signals, but with a lot of noise, and drag is a problem. This is mostly before GPS, so the tracking was pretty bad. It was Doppler beacon tracking, TRANET, things like that. Actually, that's how TOPEX was originally going to be tracked as well.

But that resulted in a few parts of the gravity field being kind of well known, especially the very longest wavelength part. So you know the Earth is flattened at the poles, it's oblate and it's pear-shaped, right? So you might think that what we do is like a frequency series, like a whole bunch of frequencies. The Earth is oblate, that's one level of asymmetry, and then the pear shape, and then two pear shapes and then five pear shapes. You can keep trying to fit the Earth with a whole bunch of periodic functions that would sum up to make the gravity field, if that makes sense to you. In other words, we didn't really do it by saying, "Let me just solve for India," or South America; we did it by saying, "Let's take everything that looks like it varies twice over the Earth and three times over the Earth and four times over the Earth." Those are called spherical harmonics, by the way.

So we used every tracking system that was out there to do the TOPEX thing, and then we also used—you can actually use the ocean surface at some level, because some part of the ocean is oceanography, but by frequency domain, some part is clearly due to gravity field. So you can use altimetry a little bit.

Now, there were proposals by the Department of Defense in particular to fly missions, and these missions were called things like GraviSat or the Geopotential Research Mission, GRM. One or both of them was from APL [Johns Hopkins University Applied Physics Laboratory], and they were two satellites like GRACE and they were using Doppler between the two spacecraft. They were kind of just notional ideas and never really got going. They were flying very low. They were ideas that could be drag-compensated, which means instead of the accelerometer that I talked about, actually when the bus gets close, you actually fire thrusters on the bus, so you're constantly keeping the proof mass completely isolated, and so basically you can call that drag-free, drag-compensated flight. It's very rare. It's almost never done. The Europeans did a gravity mission called GOCE [Gravity Field and Steady-State Ocean Circulation Explorer]. They pronounce it with the Italian pronunciation "go-chay" instead of "gose." That was drag-compensated.

So these gravity missions—and we studied these in grad school, by the way, at Texas. There were some students, not me, but some students actually did their Ph.D. on how good will GravSat do and what will the errors look like, things like that. And that was kind of the basis, in some sense, of GRACE, and those ideas, if you actually trace them, it goes all the way back to a paper by Wolf in 1969, I think, is the first person to propose mapping the gravity field in a GRACE-like manner, with satellites tracking each other.

For the Earth, the reason that's great, by the way, is because you also don't have tracking stations everywhere on the Earth. Right now with GPS we do, right? But in the old days, we didn't have GPS, so if it's flying over the middle of the ocean, maybe you're not tracking it, and that's a problem, because you want to track it everywhere. The other thing is, you don't control that tracking perfectly, because there could be multipath—like it's bouncing off some other part of the spacecraft or there's too much ionosphere, water vapor, and all these things. Also sometimes the antenna gain is not the same in any direction, so if I'm tracking it from over here versus here, that's a problem. GPS, you've got to calibrate all the antennas, you know, the transit-receive antennas, and all this stuff. So if you do line-of-sight, like if I'm just tracking you directly, then I can just focus on your nose and just hit your nose every time, and then that reduces all of these other errors from look angle and such.

So that's pretty much what led to GRACE, and it never flew until it flew as GRACE.

CONWAY: Amazing. So to switch celestial bodies a little bit, I know the Apollo missions did gravity science with the Moon. There were subsatellites, I think they called them.

WATKINS: Right.

CONWAY: So talk a little bit about that and its relationship to GRAIL, because that and tracking of other vehicles like Lunar Reconnaissance Orbiter [LRO] would have been precursors. Talk a little bit about that. Thanks.

WATKINS: Actually, to be honest, I probably should go back and read a little bit of the lunar subsatellite issues, but we learned a couple of things about the Moon from both tracking of near-side craft plus the subsatellites. I think the subsatellite, I think they didn't—if I recall, we had poor—they're very specific inclinations, right? So they didn't have global coverage even of the near side. I think Lunar Prospector eventually got global coverage of the near side, as I recall.

But what we realized about the Moon was that the gravity field's highly—much more irregular than the Earth, and it was both irregular at kind of low degree in order. So for the Earth, you have this oblateness thing and you have a little bit of pear shape, and then everything else is *way, way, way, way, way* smaller. The Earth is really pretty compensated, as they call it, because it's warm and when there's plate tectonic motion, the plates go down and eventually they sort of melt, and the gravity field kind of smooths all that out over time. So you can still see—you know, continental edge, you can see newly-formed mountains, because they're not fully compensated on the Earth, but on the Moon, we could see that there were these things called mascons, mass concentrations—that's a JPL word, by the way, invented in the seventies, probably, I think by Bill Sjogren maybe—because they could see that the gravity field is highly anomalous. Like, I'm flying over this part of the Moon and all of a sudden, there's a big gravity signal and then it goes away. The belief was that these were meteorites that have hit the Moon and they're a big nickel iron thing, and they're just sitting there and they didn't completely melt away, right? On the Moon, there's no weathering and it would cool off fairly quickly, right? So it goes in there and it creates a mess, and then sort of freezes back over without fully equilibrating.

Part of the problem with that was that that made it very hard to do this Fourier thing that I talked about, right? That Fourier thing works really well when the so-called harmonics, when everything's kind of smooth. It's really hard to do a Fourier series of a step function. You need many, many terms in the series. So what the JPL guys did back in the seventies was to say, "I'm going to actually put in a mascon as a little step function." Then I have a Fourier series plus a step function, and then a Fourier series again. Those mascons, discovering them was one of the first finds of lunar science and people wanted to understand better, but how to deal with them in the processing was also a problem, particularly in the early days of computation.

By the time of GRAIL, we sort of didn't really solve them as mascons necessarily; we actually could just solve our way through them with *very* high degree in orders of spherical harmonics, like degree 1000 or 1500, even. That was enough to cover these mascons. But we didn't have any far-side information at all, so there was a lot of mares and other—you know, the two hemispheres are not identical, and so we wanted to really understand what was back there. Could get no tracking at all, and then also had to deal with mascons. So it was a pretty haphazard data set pre-GRAIL.

CONWAY: Right. So we had photographs of the far side of the Moon, but no gravity data because you couldn't track back there.

WATKINS: Correct.

CONWAY: Okay. That makes sense. So let's see. We've talked about gravity questions, but let me ask in a somewhat different way. What were the key questions in lunar science at the time? There were a number of lunar missions flown in the same decade.

WATKINS: LRO and [Lunar Prospector].

CONWAY: Yeah, LRO, Lunar Prospector, I guess, were the two main ones.

WATKINS: Yeah. So there were several interesting things. The first—and again, when you talk to Maria [Zuber], she'll be a sort of fountain of information on this, I would think. What's hard to believe, probably, for you and for me is that the origin of the Moon is not fully understood, right? The Moon looks a little bit like it just came out of the Earth; it looks a little bit like it's a foreign object. And you look at it with your left eye, it looks like it came out of the Earth. With the right eye, it looks like it's almost like a captured alien object, right? It turns out that there were some theories that when the Earth was first forming, it split off or something like that, or there's some theories that, well, it's actually a foreign body that was captured in.

It looks like when the Earth was very early in that protoplanet, it got hit by another protoplanet that's around the size of Mars, is the current thought. That body and the Earth splashed out a big part of the two melted bodies, and that became the Moon, and that's why the Moon has part of this foreign object and part of the Earth in it. But the fact that we don't know exactly where the Moon came from, I think it's kind of a basic question. If you were to start with questions about the Moon, like where did it come from, would be like number zero. And we did not have a great answer for that.

So, understanding the Moon's internal composition and also understanding what we call its thermal history, when did it cool off; did it heat up again; how much did it heat up; did it have a giant vulcanism episode where everything got resurfaced? The mares look like clearly a resurfacing event. I mean, look at these large basins like Orientale, as well as large impacts like South Pole-Aitken Basin, which are clearly—I think it's the largest impact basin in the solar system that we know of, or that's still extant. So I think the questions are really these kind of basic structural questions of the Moon, and these are the kind of questions that you would think we would know about the Moon. It turns out it's very difficult to answer these questions, and even harder when you pick up one rock from somewhere, there's a lot of value in that rock, particularly radiocarbon dating, things like that, but it's not the best way to understand the Moon as a planet.

What we really wanted to do was understand this long history, this early history of the Moon, the long history of the Moon at fairly large scales. What's the Moon's basic structure and basic thermal evolution? And that's really the question that the gravity field can answer, but the gravity field mostly answers it if you also have the topography, because what you want to do is compare--is this mountain range or this area consistent with its gravity or is it way different? Does the gravity field follow that mountain or it doesn't follow it? And that tells you something about how fast it heated and cooled, in particular.

So I think our science team, led by Maria and other experts in lunar science, were able to really connect the data sets, the altimeter data set and the gravity data set that we would acquire in writing the proposal. And then those papers have flowed out. Most of those questions have been answered.

There were also some little more arcane questions about the lunar core. Does the Moon have a liquid core at all? What does the core structure look like? You generally can tell that by how it's rotating and how it's librating, they call it, and GRAIL can't completely answer that, but GRAIL plus lunar laser ranging—the [Apollo] astronauts left some mirrors on the Moon. We can range those from the Earth, and that lets you see the tilt pretty good. So the combination of gravity field and that tilt let us write some papers about basic lunar core structure as well. That's Jim Williams in 335, who may be retired now. He's quite a character, by the way, Jim Williams. I don't know if he's available. He may be retired now.

CONWAY: Okay.

WATKINS: The thing I love about JPL, the thing I'm sure I'm going to miss the most is you can find somebody behind a door at JPL who is the world's leading expert in just about anything, and Jim Williams is that guy for the lunar core, a really interesting guy.

So if you look at a bibliography of GRAIL, you'd find lots of stuff on basic structure of the mares, basic structure of the core, basic thermal history, thermal expansion history, things of this nature that have all been more or less rewriting the book, or writing the book on those parts of the Moon's history.

CONWAY: You mentioned a couple of times the science team. Tell me who else was on it and how they got to be on it—I assume Maria invited them—and what their functions were, what their specialties were.

WATKINS: For Discovery proposals, because the proposal as a whole is selected, it's different from a flagship [mission]. The PI can select, for example—the team can select the spacecraft contractor without a full proposal, right? You don't have to do a competitive bid, right? Because the proposal is the competitive bid, right? So, for example, we chose Lockheed Martin, and the same for the science team. If it had been Perseverance, NASA puts out a call for the science team, and a thousand people write a proposal and NASA picks them all, then they give the list to the project manager. "John McNamee, here's your science team," right?

But in our case, we chose it, and we chose a few people that knew how to measure the gravity field and solve for the gravity field, so people like me. We had a guy called Sami Asmar. He's in the DSN now, in 9X. But he was the radio science group supervisor in 33. Those are the guys who do open-loop recording of frequencies and different radio science receivers. Alex Konopliv, who's in the Nav Section, another Texas guy, and he had specialized in planetary gravity field using the DSN, solving for the tracking motions of these spacecraft at Mars, at Venus, and he had done Lunar Prospector as well, so he was another example.

Then also planetary scientists and lunar scientists from around the country, who were experts in understanding planetary evolution and particularly terrestrial planet evolution, right, meaning they had looked at Mercury, they had looked at Venus, they looked at Mars, they looked at the Moon, and tried to understand what are the options for how these planets form and evolve, and what are the open questions and why are they different from each other in particular? What's similar about them, what's different about them? So there was Jay Melosh and there was a number of other folks as well. I'd have to go back and look at the list. It's pretty much people that had devoted their lives to studying terrestrial planet formation and evolution. And because you have to make a living in planetary science, a lot of them were not—you know, they're not just lunar guys. They're guys who had studied all the rocky planets.

Maybe I didn't articulate this, but one of the things that's interesting about GRAIL is because there's no atmosphere at the Moon, we could fly incredibly low over the Moon. In fact, at the end, we were flying at 10 kilometers, 10 miles high, right? You could reach up and touch the GRAILs that went by. It's like an airplane flying over. That's pretty incredible, just a few miles off the mountaintops, right? And you could never do this [on Earth]. So we measured a gravity field for the Moon that you will never be able to measure for any other terrestrial planet certainly in our lifetime and probably for hundreds of years, and that also means that you learn about the Moon, but you can also use what you learned about the Moon for other terrestrial planets. We can learn things about the Moon and say, "I can never make this measurement on Venus, but maybe I can extrapolate based on what I learned at the Moon." So it's kind of a terrestrial planet laboratory to some extent, which is why the *L*'s in GRAIL. *L* is laboratory, Interior Laboratory.

Sean Solomon was the PI of MESSENGER [Mercury Surface, Space Environment, Geochemistry, and Ranging]. MESSENGER was the Discovery Program mission from APL that went to Mercury and did a lot of investigations and, again, did the gravity field as best we could do it, which is not super incredible like GRAIL because it's not dedicated, but it's pretty good. Sean was on the GRAIL science team. Sean was—may still be—runs Lamont-Doherty Laboratory of Columbia. So Lamont-Doherty's like a 500-person laboratory that's located offsite from Columbia, and they do a huge amount of geophysics stuff, good work. I think Sean actually came up with the name GRAIL.

CONWAY: Okay. Interesting.

WATKINS: Sean may have come up with that name. I think everybody was trying to—you know, you want to make it sort of like GRACE but not too much like GRACE.

CONWAY: Yeah. I know Lamont-Doherty because they're an old physical oceanography center too.

WATKINS: Okay.

CONWAY: Yeah, yeah.

WATKINS: They do some climate work now, I think, as well.

CONWAY: I think so, think so. So let's see. There's a technology demo as part of the GRAIL selection process. Did you have any role in that?

WATKINS: Remind me what that was.

CONWAY: As I understand it—and I think it was Leon Alkali that told me—they took some of the GRACE hardware, not the flight hardware, obviously, but some of the engineering models of that, to build a demonstrator that was then part of the site visit for GRAIL, and Leon thought that was very important, so I thought I'd ask you, but maybe you just weren't involved in it.

WATKINS: So this is good. By the way, this is why we may even want to do a second swing at the ball at some point. Let me go back. Actually, there's two things we should talk about. One is that, and the other is the Sally Ride—the MoonKAM.

CONWAY: Yeah.

WATKINS: I will say that Leon's real contribution was trying to package this into a winner, right? I mean, these proposals have two parts to them. All proposals have two parts. They have the intellectual core of the proposal, and then they have the packaging and sales job that goes around that. That's writing the proposal correctly in English, making it readable, doing the costing extremely accurately and defending the costs, and then, of course, handling the site visit, and being responsive to the reviewers and all of these things. I will say that Leon was a master at those things. There's no question about it. He's not a lunar expert but he was an expert at how to put these proposals together.

We had a very nice site visit in which we—Dan Goods was part of it, by the way, as well. You know The Studio guys?

CONWAY: Yes.

WATKINS: We actually had a building in which we made it look like you were flying over the Moon, and we could actually move—on rails, you could actually move the antennas and show that you're tracking to ultra-high precision.

And one of the things about GRACE and GRAIL that I always talk about, and people have a hard time grasping this, or if they do grasp it, they then think, well, then that seems very fragile, and that is we make these measurements are about the size of a red blood cell? We measure the distance between these spacecraft to 1/100th of human hair, where a red blood cell—pick your favorite thing—a red blood cell is about 5 or 10 microns. We can measure between these two things that are, in the case of GRAIL, about a coffee table; in the case of GRACE, like a small car. When you tell people, "I'm going to measure between these two 5 microns," or 1 micron, they immediately say, "Well, then here's all the things that are going to go wrong. There's dirt on the spacecraft. The spacecraft was thermally expanding," blah, blah, blah.

What helps you there is that you're averaging like crazy. And you know how this works in science all the time. You're measuring these distances hundreds of times per second, so a lot of stuff averages out. But also the perturbations we're looking for, as I mentioned, are periodic? Again, think of it like a Fourier series. The spacecraft aren't just randomly going like this;

they're going [demonstrates]. Every time they fly over some part, they have the same frequency response. So I can really fit a curve to that signal, right? I fit a curve to all that noise, and then I pull the signal out of it, right? So it's not like I have to measure every one second to 1 micron or I'm dead. It's that I have to, on average, pull it out to some microns. And I think it really helped.

So I helped to try to tell that story at the site visits, because I was used to it from GRACE, you know. "Here's why you shouldn't be scared of this measurement." Then I think them seeing that we could do that on the ground, like realizing that, "Hey, here's a micron-level measure being made right in front of me," in addition to being kind of—it was emotionally cool, like damn good lighting and all that, you know. I mean, it looked cool. So I think those things are important, and, you know, we're all scientists and engineers—you're not; you're a writer. [laughs] But, you know, I think scientists and engineers sometimes don't realize the value of that packaging, right, the emotional way that you tell the story. I think we've gotten a lot better at JPL in that aspect of writing our proposals, and folks like The Studio have done a very good job, I think, in helping tell the story emotionally through art and visuals and things like that. But I think this was maybe kind of early—it was an early example of doing that well, and Leon gets a huge amount of credit for that.

CONWAY: Okay, that's interesting. I don't know when Dan Goods got here, but he can't have been here much longer than me, and I'm 2004, so that would be pretty early for him being around.

WATKINS: Yeah. I don't remember the story fully exactly. I believe that Tony Freeman was running either the proposal center or the organization evolved over time. He was running Section

311, which at that time—it's now called—is it still 311? Maybe it is. But they had the proposal work, mission formulation was—they're the line organization for mission formulation. Now, there's also the program offices and all that, but they were the line side of it. And I believe Tony Freeman hired Dan on a gamble, saying, "I think an artist would help us tell the story, our proposal story, better." So I think Tony Freeman might deserve some credit for hiring Dan Goods to JPL, but not just for GRAIL. He was several years before GRAIL. But I think it started with the notion that telling the story—the proposal is a storytelling.

CONWAY: That's interesting. I should ask Dan. He'd probably know. And Tony's still around too.

WATKINS: I miss talking to The Studio guys. It was great to talk to them when you're having a bad day with NASA Headquarters and then you go talk to those guys, and they're awesome, you know.

CONWAY: This has been good, and we'll have to do it again because I've got more questions; not surprising.

WATKINS: Where did this contract to write from GRAIL come from? Did it come from MIT or it came from NASA?

CONWAY: So it's to do oral histories about the Discovery Program, and what literally happened is I get an email message from Tom Wagner that said, "Call me now." And I'm like, "Okay."

And I did, and that's what he wanted. He wanted to fork over some money to do these oral histories. So some of it's being done by JSC [NASA's Johnson Space Center, Houston, Texas]. There's an oral historian there who's actually a professional oral historian. I've never been trained for it.

WATKINS: Does it just become transcripts? You don't take this and write a novel out of it, right? It becomes edited transcripts or something?

CONWAY: It becomes a transcript, and you will see it in probably a month, depending on how fast my transcriptionist is. You can edit it and we finalize it. Eventually it will go to the Johnson Space Center's oral history site. That's the current deal. JPL doesn't make its oral histories public; that's an OGC decision from when I got here in 2004. But JSC does; NASA does. Since they're funding it, they get to decide. So that's what will happen to it. Slightly longer range, I think Tom Wagner would like to see something written out of it, but I won't do it because JPL wants me to work on JPL stuff, right? Someone else will make use of that material.

WATKINS: I think GRACE is kind of an interesting target as well, but part of the reason this came to my mind was—and we have talked about this a separate time, probably, but these missions are unusual, GRACE and GRAIL, because we made up a little motto for GRACE, which is "The spacecraft is the instrument," right? Because the spacecraft is a Newtonian test particle, as we call it, right? All I'm trying to do is measure where that satellite is going. I'm not using that spacecraft as a platform for a telescope or for a spectrometer, right?

And in a way, some people say, “Well, gee, that’s an easy mission because you don’t have to build a telescope and you don’t have to build a spectrometer.” On the other hand, what that means is that it’s a completely holistic design, right? You cannot make any mistake on the spacecraft that doesn’t then affect the spacecraft.” So things like designing the attitude control system, putting everything at the center of mass, watching the thermal expansion, you know, GRACE and GRACE follow-on, they have hundreds of heaters that come on and off every second to keep everything within a tenth or a hundredth of a degree C. I mean, you think about doing—like the Rover doesn’t have to do that, right? The Rover gets down to -100. So there’s a fascinating system engineering challenge that we had to go through, and I can talk a little bit about that maybe next time on GRAIL. These are one of the areas I need to think a little bit about.

Did you know Duncan MacPherson?

CONWAY: I didn’t know him, but I know of him, yeah.

WATKINS: So he kind of came from the outside and helped us a little bit, and he had to learn a lot because he didn’t work on GRACE, but he was a very smart guy. So I think there’s some interesting—probably worth a paragraph or so in a transcript about how to control the thermal radiation pressure and how do we look about what’s happening if it goes in or out of the terminator, you know, with the sun angle, and things like that. So there’s some pretty fascinating stuff.

Then I know Ralph Roncoli, who I think is retired now, he was the manager of the Navigation and Mission Design Section until just a few months ago. He was the mission design manager for GRAIL, and for a variety of reasons, GRAIL got in a very complex set of maneuvers that had to be accomplished, something like ten maneuvers in a week or something, which is kind of unheard of, and Ralph really helped run that, along with the execution guys at Lockheed Martin. So I think there's kind of a story there as well, because every mission turns out to have its own hard part, right? They're landing on Mars, but doing ten or fifteen maneuvers in a few days is also an unheard-of thing. So there's a few little things buried in there that might be worth just making sure we blow the dust off.

CONWAY: I noticed the orbit materials, just the orbits to get to the Moon were very strange. So he was on my list of people to try to track down.

WATKINS: He's a very experienced, very thoughtful guy. He'll have a pretty clean memory, is my prediction, of this, very clean notes, knowing Ralph.

CONWAY: Okay, great. Thank you very much.

WATKINS: Okay, bye.

[End of interview]