Sami Asmar

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Erik M. Conway,
Interviewer

Q: This is Erik Conway. I'm talking to Sami Asmar. I think we're both working from home today, and we're talking about the GRAIL mission specifically. But, first, Sami, I'd like you to tell me little bit about your background. Where were you educated, born? How did you come to JPL?

Asmar: Oh, that far back.

Q: That far back, yeah.

Asmar: Sure, I'd be happy to. I was born and raised in a small country in the Middle East called Jordan, and came to the States, immigrated with the family when I was seventeen years old, and went to college at Occidental College in Los Angeles, then immediately to work at JPL first as a student part-time intern.

Then I converted to full-time, and while working, went to graduate school at UCLA in geophysics and space physics. Worked in a field called radio science, spent all my career in that. I started supporting a whole bunch of flight projects conducting radio science experiments. Let's see; so those are the types of experiments that primarily measure—there are two primary fields. One is more relevant to GRAIL, which is measuring the gravitational fields of the planets, from which you can deduce information about their interior structure, and that's what we've done at the Moon with GRAIL, but we've done that with most other planets/satellites, different configurations, different types of spacecraft. GRAIL was unique in that there was a twin-spacecraft configuration. And there's other branches, too, radio science having to do with atmospheric occultations.

I ended up joining science teams, doing system engineering, science analysis, publishing a lot, and just published a book, *Radio Science Techniques for Deep Space Exploration*, Wiley & Sons.

Relevant to GRAIL, I ended up being invited to be a team member and then deputy project scientist, where Mike Watkins was the project scientist, and then he stepped down and I became the project scientist, and we completed the mission successfully, then archived the data.

I don't know. I could go into a lot more details forever, but this is a little background.

Q: So what year was it that you started at JPL, just for some time frame?

Asmar: 1985, as I said, initially as a student employee.

Q: So what radio science missions or related missions were you involved in prior to GRAIL?

Asmar: The list is long, but the significant ones are my first job, and that was in the late eighties, was Voyager when it had the Neptune encounter. Then I moved on to Galileo, Ulysses, and Magellan. Then the more interesting one was Cassini, where I spent a lot of time, did a whole bunch of gravity science experiments for Saturn itself and its moons, Titan and the other moons.

Then ended up kicking off the Juno gravity experiment. I'm sure I'm forgetting some, but then GRAIL was one of them.

Q: So then how did you get invited to join the GRAIL mission? Tell me that story.

Asmar: So when the mission was in the formulation phase, Leon Alkalai was the capture lead, formulation was putting the story together for a good proposal, and they needed a radio science expert to do the error analysis, the Science Traceability Matrix, science requirements, converting them to engineering requirements, essentially the job definition of a project scientist, and they looked around and felt that I was *a* qualified person. I knew the PI, Maria Zuber, who was at MIT, from other work on Mars Global Surveyor where I was involved in various functions. I knew the JPL co-Is like Alex Konopliv; he was probably the one person who recommended me for the job. I knew Mike Watkins also.

So, when they formulated the team, they felt that I could fit in that function of deputy project scientist, and we all knew that Mike Watkins, as a project scientist, was going to be very busy. That's how it happened; people know you and invite you, and you prove yourself.

Q: You'd already proven yourself on previous missions, though, it sounds like.

Asmar: Had a track record, yes, luckily, very blessed that way.

Q: So you started at the formulation phase. I think you've already sketched out a little bit about what that entailed, a lot of traceability matrices work and so forth. Tell me what that role became after you won the competition and were approved by headquarters to go into project status.

Asmar: It became the central focal point for all science coordination and science operations. Because the PI was offsite at a university, I became the closest representative for her at JPL. I sat in the project office area; we had to collocate with the project manager so I can respond to him and the chief engineer for any issues that come up, respond to headquarters' inquiries, JPL director's inquiries, etc.; so I became the central focal point for science requirements, science operations, engineering requirements derived from the science experiment.

I became very involved in public outreach. They decided that this guy, despite his accent, can speak well. So, I started doing that. At the mission arrival day, they had me lead the Von Kármán big public outreach Friends and Families event.

So that's really what it involved, a lot of science team meetings, project team meetings, NASA reviews. I presented at every single major gate review, NASA review, PDR, CDR, and the like, essentially convincing them, proving that this mission will meet its requirements. If we had to summarize the project scientist job in one sentence, it's to prove to the sponsor that "We can meet the requirements and your investment is in good hands."

Q: Just a question of interest to an historian who collects documents. Did you keep science team minutes and notes and that kind of thing?

Asmar: I did. I kept my own notes, I kept my own presentation slides. There was an archive in the project DocuShare. As much as I could, I kept my own copies or downloaded copies and kept notes. I was very good at that. I ended up leading one big overview or summary paper in *Space Science Reviews*, which had a special issue on GRAIL, and it was led by the PI's own paper, and one more. It summarized how we did the mission design, instrument design, error analysis, the whole thing. So that was a good historical document that gets referenced frequently by people now trying to come up with similar concepts or take off from GRAIL to do more innovative things. They refer to it a lot.

Q: Great. I'm glad to hear that it's archived the way it should be. Often that doesn't happen.

Asmar: And real quick, the book I mentioned, which just came out two weeks ago, also intentionally is a form of archiving of this collective knowledge, because going from one project to another, people at JPL like "heritage," so the next mission comes along and says "how did Juno do it? This makes sense. Let's do the same." And they call me, "How did GRAIL do it?" Then you scramble to find documents and calling people, "What do you remember about this? So, one of my objectives for the book, among other objectives, was to document the often undocumented oral traditions and collective memory of the institution that I was a key or leading member of in this one book. So, I'm happy that we've done it. If I retire, I feel a little bit better that somebody can find this stuff, as much as possible. [laughs]

Q: Great, great. Thanks. I'll look for that.

So back to kind of the early phases, yesterday I interviewed "Hoppy" Price, who told me a lot about Duncan MacPherson and kind of redesigning the project early on with a clearer focus on the needs of the gravity science. Were you involved in that effort?

Asmar: Yes, definitely.

Q: So talk about that. What needed to change from the initial proposed spacecraft in order to satisfy the stated needs of the mission?

Asmar: What happened was that we were imitating the GRACE mission, which is an Earth orbiter. It was the first concept where we can measure the gravitational field of a planet, the Earth, the Moon, or any other planet—we'll just generically refer to them as a planet for now—using this technique of dual spacecraft. Prior to GRACE, we were using single spacecraft such as Cassini flying by Titan, or Juno orbiting Jupiter. Well, Juno came after, but conceptually orbiting a planet. There's a radio link from the spacecraft to the Deep Space Network, and that's how you measure the Doppler shift from which you can deduce the gravitational forces and from which you can then deduce, with a lot of other geophysical interpretation, something about the interior structure. This was limited to how accurately you can get your data.

GRACE and the University of Texas, Mike Watkins, came up with this brilliant idea of having a link, not from a spacecraft to a ground station, but from one spacecraft to another, and they proved it with GRACE in Earth orbit. There were limitations there because Earth has a very thick atmosphere that had forced the mission to be at higher altitude so that atmosphere does not dynamically disturb the spacecraft when it's trying to measure the gravity; there were natural limitations inherent to the nature of Earth. The idea was to imitate this at the Moon, with the expectation that you can do a lot better because the Moon does not have an atmosphere, so you can fly a lot closer. In fact, we were flying at an average altitude of 50 kilometer in the prime mission, and near the end, we went so low, I joked that we were touching the treetops (there are no trees on the Moon). But we were at one point 2 kilometers above the surface near the end, but we were at that time taking a big risk because we were ending the mission and intentionally crashing it because of NASA directive for how you end a mission like this on the Moon.

But to make a long story short, because we were imitating another mission, we started out with a theoretical approach that you can inherit—it was a mission of the right size that Lockheed Martin had worked on and offered us that spacecraft bus, and they said, “This should do.” Our initial look was positive. “Yeah, it looks like this would do.”

Then we rolled up our sleeves and started studying the error budget and does the spacecraft surface really accommodate thing like solar radiation pressure, lunar albedo reflections, and things of that nature, and we started struggling with that, and things did not look extremely good at some point, but Duncan MacPherson was onboard. I forgot his title, chief engineer; Hoppy, I’m sure, had the right title. He had a very good physics instinct that really helped us out—that’s one way of describing it—and pulled a team together, and I was on that team, and made proposals for what should the spacecraft look like to meet the requirement, down to the paint, because the paint affects the reflectivity of sunlight and solar radiation pressure, the things you normally don’t think of. But because we were after such ultra-high precision with the measurement, historical stuff that nobody’s ever reached, and at the end, the gravity field of the Moon is of incredibly high resolution and there’s nothing comparable to that for any object in the solar system, including Earth. That was only achievable because of these efforts and the innovative and creative thinking by everybody. We should give credit to everybody, but Duncan really was the powerhouse behind figuring out some of the tougher physics problems with designing the spacecraft.

I hope this helps. [laughs]

Q: Yeah. You keep talking about error budgets. From radio science background and I guess from gravity modeling, you have some needs out of the spacecraft, and I guess that's what you're talking about regarding the error budget. So give me an example of something whose errors drove you to have to change it. I'm just trying to figure out how a future reader will come to understand what we're talking about. [laughs]

Asmar: To help future readers, the first important point to know is that normally for any other planetary investigation, you put a science instrument onboard a spacecraft so the measurements are done by this instrument, a box that sits on the bus. So the spacecraft is simply a carrier of a science instrument. That instrument could be a camera, a magnetometer, spectrometer, the usual stuff.

In the case of radio science and GRAIL in particular, you're not doing that. The spacecraft *is* the instrument. So it makes a big difference. Anything that affects the spacecraft motion or disturbs its dynamical stability, will immediately translate into an error in the Doppler shift that you're trying to measure. The gravity field is a result of gravitational force due to the inherent mass of the planet that extends into space, and it can be measured by an object flying by or nearby that senses this gravitational force.

Now, the trick is how to get that sensing by the spacecraft down to us as a quantifiable measurement, and the answer is by a Doppler shift. The gravity of a planet pulls and pushes on the spacecraft, and a radio signal being transmitted from one spacecraft to another (or to Earth, for that matter, in the traditional classical method), the frequency of that radio link, gets shifted up and down by the pull and push, and we measure that shift very precisely, work backwards and find out how much the Doppler shifted, work backwards and find out what forces could have created that Doppler shift, work backwards and reconstruct the gravity field.

Now, these are the measurements. What could degrade on the measurements? That would be the error sources. Is there something between the spacecraft that could intervene and add noise? And the answer is typically yes, but not on the Moon. Typically, at Earth, the atmosphere, Earth ionosphere, Earth troposphere. In the case of the Moon, luckily, we don't have to worry about that.

But then there are dynamical errors introduced by things, as I said earlier, you normally don't think about. When the sun shines on the spacecraft, it imparts a force on the surface of the spacecraft. That is an example of an error source, literally the sun shining on it. I mean, it's incredible. But that's the solar radiation pressure. We had to design the surface of the spacecraft such that it doesn't push back or move as a result of this, but possibly dynamically absorb it without moving—when I say dynamically, I mean motion—without being disturbed too much. Lunar albedo, there's sunshine and there's lunar shining. There's light reflected from the Moon that could also dynamically disturb the spacecraft. So, these were the leading errors.

The thrusters, firing thrusters on the spacecraft, they can't be unbalanced. They can't leak. They can't do anything that would move the center of gravity of the spacecraft beyond our tolerance limit. We wanted the center of gravity of the spacecraft to move only because the gravity of the Moon moves it, and that's what we're trying to measure within an error bar. So my job was to limit that error bar by looking at these error sources, and these were the leading examples. I have graphics, actually, I could send you, that show this in a nice easy-to-understand way.

Q: That's a good explanation. Thank you. Thank you. I can see why our Public Engagement people wanted you to talk for them.

Asmar: I can get passionate about this. [laughter]

Q: So we've talked a little bit about the phase of redesigning. As the project progressed, I guess you would have turned to designing your science systems, the data processing and modeling and so forth, the scientific infrastructure, sometimes I call it, for the mission. So talk about that. What kinds of things had to be developed to support the mission scientifically?

Asmar: So, luckily, because we inherited the GRACE methodology, we could inherit some of the instrumentation and build on those, so we were not starting from scratch in terms of the hardware on the spacecraft, but once the data are collected and delivered to us, then the big job was making sense of the data. So we utilized—in the JPL Navigation Section, there's one group that specialized in this work, so they inherited the Orbit Determination Program, or ODP, and created a version called MIRAGE, specifically for a spacecraft-to-spacecraft links, what we call a crosslinks, which, again, nobody's ever needed to navigate the spacecraft like that before, because traditionally it's a single spacecraft with a link to the DSN.

So what was new here is a new data type we called the DOWR, differential one-way ranging. We love acronyms. This was a new data type, so people like Alex Konopliv, and I helped to some extent, and others had to add to the ODP functions to handle the GRAIL type of configuration. That was the most—well, that was quite challenging. It was a new territory, and we had to prove that it works.

So what we did as a mission, as a project, now putting on the big-mission hat as opposed to JPL hat, was we had Goddard also do the same, so we had two teams do the same job in parallel. At first look, you might think that's duplication of labor, but that was really necessary because you're in new territory, as I said. To convince users and readers and ultimate consumers of the final product that this is valid, you needed to have two separate teams independently do this and come out with comparable results.

So we spent a lot of time—and that was one of my primary roles—coordinating between the Goddard team and the JPL team, creating software and simulating data and ultimately using the real measured data, and comparing notes, comparing results, comparing errors, comparing the gravity field upward. That was the science infrastructure that we had to create in two different places.

The reason it was Goddard was that the deputy PI, Dave Smith, came from Goddard, so he had created a group comparable to the JPL group I mentioned, and we had collaborated on MGS and other missions, so that was a natural place to do it. They had the team and the tools and the supercomputers at Goddard like we did here. In fact, that's why that was in the proposal. Why JPL? Why Goddard? Because we've done this before, but it had to be evolved to a specific mission configuration, so we did as well.

Q: I found it interesting, because I'm aware of one other kind of gravity group in the U.S., and that's Byron Tapley's folks in Texas, but they were never formally part of the mission.

Asmar: Yes. Byron Tapley was one of the brains behind the whole concept, because he was the PI for GRACE. Mike Watkins was in his group at the time, and that's how, when Mike came to JPL, JPL ended up managing GRACE, and then Mike and others said, "Let's try this at the Moon." But then they did not involve the University of Texas and Byron Tapley directly, but Byron ended up being the chairman of the NASA Review Board for GRAIL science, so they used him as the one expert in the country who could actually review our work, and if he didn't, I don't know who else could do this. This was such, again, new concept, that you needed him in that role. So that's what Byron did, a great contribution as a result.

Q: Sounds like it's a fairly small community of practitioners.

Asmar: It is a small community. As a result of GRAIL, however, it grew because half of the team members, including the PI, were academics, so they produced graduate students who worked on GRAIL data to move forward with their degrees and dissertations, and now they, in turn, enough years have passed that they have moved on themselves to other universities and are involved in other missions and concepts and so on. So GRAIL, in that sense, also contributed to enlarging the community, because Maria had a number of graduate students. Jay Melosh and a couple of others were university professors who also produced students. The community grew, but every mission does that. With every mission you get a new generation of people participating and joining this kind of niche community of radio science.

Q: Fair enough, fair enough, but it sounds like most missions have some radio science component, which is not true for lots of other kinds of science.

Asmar: Right, right. I describe that in the book. It's such a fundamental observable that every mission can benefit from. Not only that, because every mission has a radio for communication, you can argue that every mission can automatically have a radio science instrument, so why waste it? Why not measure the gravity, measure the atmospheric structure? These are the two primary branches of radio science, but there are others that we got involved in that are more exotic, like testing theories of general relativity, testing if Einstein was right. We did that with Cassini, for example, using gravity science; studying the solar corona. So there's so much you can do with studying the radio links themselves, and since every mission has radio communication signals; I don't want to give the impression that it's free and easy, but it's opportunistic or available. It's not easy, because you have to have experts who can do what I did in terms of error budgets and interpret correctly. It has found itself to be one of the primary objectives of the bulk of planetary missions. It doesn't make sense not to do it.

Q: And you have to have the radio and etc., anyway, so you don't have the additional costs of a heavy instrument.

Asmar: Right, although depending on your specific science objectives, you could enhance the radio by adding additional radios, higher frequencies to calibrate your signal. You can get pretty sophisticated, but at a basic level, your primary radio would do a decent job.

Q: So in operations, let's talk about the operations phase when you're orbiting the Moon. What did your role become then? What does the—I guess by then you're the project scientist, do for that, about nine months for GRAIL?

Asmar: My primary role was to watch the day-to-day operations and data collection and make sure the data quality is good, nothing has gone wrong on the spacecraft, and reporting that to the PI and the science team, and then ultimately delivering the data to all the science team members. We had levels of data, raw data, called Level Zero, and then we do initial processing at Level 1. So, different team members could accommodate certain levels. Some did not have the tools to handle the Level Zero, so they would wait for us to provide the next level, intermediate products, and so on.

So my day-to-day job was to monitor the successful acquisition of the science data, intervene if there's a problem, find out why, and call on a team to solve the problem, and this had to be done very quickly because we had a short mission. We couldn't take three, four weeks to solve a problem and have a big data gap. Had to make calls in the middle of the night, "What can we do? What's gone wrong?" Luckily, we didn't have too many problems. We were just very lucky and had a very good team, engineering and operations and science and project management. But to summarize, it was to do the day-to-day monitoring of successful science and acquisition, and reporting on it.

Q: So give me an example of a problem that occurred in operations and what had to be done about it.

Asmar: One interesting problem was something called multipath, which is the signal is supposed to go from one spacecraft to another, from the antenna of the spacecraft to the antenna of the other spacecraft, but sometimes we found that we're seeing the primary signal and another signal that's not supposed to be there. So that turned out to be reflected off other portions of the spacecraft surface or the lunar surface and getting into the antenna, then creating a little bit of a confusion in the science analysis.

We thought the magnitude of such a signal would be so small that it would not affect us, or what are the chances that the geometries would line up such that you would see this. But it did happen, and we had to address that. We had to optimize the spacecraft pointing a little bit to avoid the reflection off the surface of the spacecraft, and in terms of reflection off the surface of the Moon, we could suppress that in the signal processing, in the post-processing.

In fact, to me, there was an opportunity there for additional science, which is to study the reflectivity of the lunar surface, like, "Hey, there's a radio signal being reflected. What does that say about the electrical properties of the lunar surface that it can reflect such a signal?" We've done that elsewhere. That's called bistatic radar.

But that's one example of something that was, let's just say unanticipated, but we handled it properly. It did not introduce data gaps or degrade the data quality, because we handled it intelligently.

Q: I think I understood that the multipath got much worse as you got closer to the Moon.

Asmar: Yes, and that's what you would expect as you get closer. The reflected signal is stronger. But there are physical ways of distinguishing the multipath from the primary signal, because they would have different Doppler signatures, so that's what I meant by we kind of were able to sort them out.

Q: You said you got involved in public engagement, so talk a little bit about that. All I know about the public engagement for GRAIL really was the MoonKAM effort. So what else went on?

Asmar: Well, first, the MoonKAM effort was really quite an experience, to meet Sally Ride, an historical figure who, as you know, has since passed away. And just adding a camera for outreach purposes paid off a lot. Sally Ride Science in San Diego did the bulk of that work, but people came to JPL often requesting speakers and material and explanations that Sally Ride Science could really not provide because they just had the images. They didn't have the Doppler or the gravity data. They could share images, and they did a good job engaging students. But when the request came to us to speak about the gravity science, how do you find out what the Moon is made of, does the Moon have a core, is it a liquid-versus-solid core, which was one of the objectives of the mission to sort out, they often came to me and asked me to address that.

At the bigger national level, the PI, Maria Zuber, did that. She often took me along and I sat in press conferences with her at the AGU and at the launch site. She was kind enough to include me in press conferences, so I took press questions, basically to simplify these concepts to the press, because it was their job to pass it along to the average reader in an understandable way. The project manager often relied on me to explain things. I found myself creating graphics to do this that ended up being very helpful.

Again, when GRAIL arrived at the Moon and started the science phase, we did an Open House at JPL, and I was asked to lead the speaking portion in Von Kármán to friends and families and the public and some press.

Q: Fair enough. So what was your favorite part of the GRAIL mission? What did you enjoy about it the most?

Asmar: I enjoyed working with such an incredible team. I mean, I would sit in this room at—Maria Zuber was good at finding very exotic locations, such as the National Science Foundation Conference Center in Massachusetts, Woods Hole, ... I'm at this really incredible place, sitting in a room with these world-class brain powers, it's like *Who's Who* in the field of geophysics and planetary science, and just listening to them on the spot making sense of data, interpreting what does this mean for the Moon, crater sizes, interior structure, correlating gravity and topography, getting to the Love numbers for measuring tidal forces on the Moon, implications for the presence of a core, and just being there with them was like a dream come true. That was my favorite part, listening to great scientists debate and argue on the spot, and just the brilliance of what's going on, and I'm participating in that. That's incredible. Anyway, maybe it's a little romantic approach to this. But, yeah, the day-to-day stuff, I had done this on other missions, still incredible, still exciting, loved it. Met a lot of new people at JPL and different places, but the science team was just an incredible collection of people.

Q: What was the most challenging part of the mission for you?

Asmar: Most challenging part was - - we identified one of our objectives was to investigate the core of the Moon especially the possibly of a fluid layer, and that had to do with the Moon's formation and cooling process, and we tried to contribute to the ultimate question, what is the origin of the Moon, you know. Is it a captured object, did it split from the Earth, which is the leading theory. So we're hoping to contribute to that question by addressing the core question.

So there were times where we had exciting hints in the data, where the team member examining the core saw enough indications, and that would have made news in planetary science. So we came close more than once. Then we'd step back and, "Okay, let's look closer." You want to make sure multiple teams have looked at the data, so we would step back and collect more data. We ultimately didn't announce specific results on a fluid layer, but we handled it properly. The science publications presented the data as they are. "These are the measurements. This is one possible interpretation. So, scientifically that was very challenging, but it was also fun. That's when you scratch your head the most, you know. You see now in the literature that was a lot of follow up work by many investigators.

Q: I take from this conversation that you ultimately couldn't make a determinative claim about that [the lunar core], so what would it take for some future mission to prove that it's really liquid or really not? What beyond GRAIL would have to happen?

Asmar: So, to study the interior structure of a planet, the two leading methods are to put a seismometer on the surface or do gravity like we did. So, for example, on Mars, the InSight mission just landed seismometers on Mars, so that's now complementing what gravity [measurements] had done in the past and will do in the future. And it turns out that in the case of the Moon, the Apollo astronauts had placed a seismometer. For the Moon, there is also another type of data from lunar laser ranging that is also part of the analysis.

By the way, if you hear any noises in the background here, I have a parrot that sometimes decides to participate in the conversations. My laptop microphone sometimes filters this, but sometimes it doesn't, and people ask me, "What the hell was that?"

Q: No worries. [laughs]

Asmar: Okay. So a team member went back to the old Apollo seismometer data and reprocessed them to combine with the gravity data, and some progress was made.

So to answer your question, probably ultimately we need a network of seismometers that would measure lunarquakes, because the seismology wave propagation through the interior of any planet really pins down whether the different layers and their boundaries are solid, liquid, or something in between. That would answer that question for sure. In fact, as you might know, that's how we figured out what the Earth's core is.

Q: The velocity of the signal changes substantially when the density is much different in fluid, solid boundaries, and so forth, yeah.

Asmar: Exactly.

Q: What I get for being married to a geophysicist. [laughter]

Asmar: Is she a JPLer?

Q: Yes. I'm sure you know her. It's Andrea Donnellan.

Asmar: Oh, of course. I never put two and two together, but that's fine.

Q: No worries.

Asmar: She would know. She can fill you in on that. [laughs]

Q: Yes. So let's see. My last question is always what haven't we talked about but should have? In other words, what didn't I know to ask you about, but was very important from your perspective to GRAIL?

Asmar: What would be the next step not necessarily for the Moon itself, but for planetary science, that would be lessons learned from GRAIL since GRAIL was so successful beyond our imagination? Just to give you an example numerically of what I mean by "beyond our imagination," the gravity field of the Moon is measured in terms of degree, degree and order for the resolution. We put in the proposal that at the end of the mission, "We are going to reach the incredible resolution of 180 degree and order, and that is more than anybody's ever done," blah, blah, blah. So then headquarters said, "Wow! That's great! Do it." By the end of the mission, we reached better than 1,500, nearly ten times better. So, to me, that was incredible. The technique proved itself beyond any doubt.

So that made the community think, "Why don't we take GRAIL to Mars, GRAIL to Venus, GRAIL to this, GRAIL to that?" So, often people ask and we do studies. To this day, every once in a while, we deal with this for proposals, "Why not do spacecraft-to-spacecraft links elsewhere?" And we should. Every case is unique. It's obviously more expensive because instead of building one spacecraft, you're building two, and they're not your average spacecraft. You have to do what we did, making sure every detail on the spacecraft fits to our measurement techniques and our error budgets. So you trade that against the classical method of a single spacecraft to Earth. It depends what are your science objectives. Are you just looking for higher-resolution gravity? Are you looking for core quantification constraints and so on?

So, ultimately, what did GRAIL open up in terms of a window for the solar system altogether is a good topic of discussion, maybe a panel discussion where people have different opinions. But I find myself involved in assessing that and contributing to what does it mean to do that elsewhere, the pros and cons.

Q: I guess you could do something like GRAIL at Mars, except the atmosphere gives you more trouble, but GRACE already had to deal with that for Earth.

Asmar: Right, right.

Q: So it's a challenge.

Asmar: That's why every planetary target is unique, in that there are pros and cons, there are constraints in their science, and there are some places where you could do better and there are other places where you cannot because of things like the atmosphere, where it has to be very high, and there might be other problems. If the target is much closer to the Sun, your solar radiation pressure is more extreme. So, yeah, there's uniqueness to each target, so it could work at some asteroids, at some moons of the outer gaseous planets, things of that nature.

Q: You can imagine doing it at Titan or Europa or something.

Asmar: Exactly, yeah.

Q: It would all be unique. Okay. Anything else? We're about out of time and I'm out of questions. Is there anything left for us to talk about?

Asmar: Basically how underappreciated the fact that one can measure gravity from a simple radio link, from a simple concept called the Doppler Effect, which is applied in medical imaging and all kinds of applications and technologies. That simple method can tell you what Pluto—we don't want to call Pluto a planet—Neptune or any planet, the furthest object in the solar system, so far, so remote, you can actually figure out what's it made of in the inside from a simple yet extremely powerful technique. It might be underappreciated, but it's out there and we talk about it, we make it known, and publish and speak to the public. I like the attention that perhaps this conversation can bring a spotlight to the power of this technique.

Q: The power of radio science. Thank you. That's great. I'm going to stop recording here.

[End of interview]