Paul Thies:

Ever since the space age began in the 1950s, manmade objects have been filling the nighttime sky in an increasing number, but what happens to all those rockets and components floating around our world? Though some burn up in reentry, an ever-growing number of artificial objects litter the stratosphere presenting potential dangers to astronauts and costly damages to satellites and spacecraft.

Paul Thies:

Hello, I'm your host Paul Thies. And in this episode of If/When I explored the topic of orbital debris with Dr. Phillip Anz-Meador, orbital debris principal scientist, Jacobs JETS Contract Group. In the discussion that follows, we talked about the size and scope of the problem of orbital debris, the safety hazards it presents and what is being done to remediate the problem. Well, Phillip, thank you so much for joining me today. It's a really fascinating topic, this topic of orbital debris, and I'm really looking to diving into it with you. So thank you for joining me.

Phillip Anz-Meador:

My pleasure. Thank you for inviting me.

Paul Thies:

Yeah, absolutely. To start us off, can you just tell us a little bit, basically, what is orbital debris?

Phillip Anz-Meador:

In the simplest sense, it's anything that has ceased to have provided a useful function. So, in that sense, if we're about the rockets that we use to launch spacecrafts, essentially, after they separate from payload, they are now debris. And, in some cases, they're Greyhound bus sized debris. In other cases, they're smaller. If there were straps or radiator covers or lens covers or things like that, those are now debris, once they separate. And finally, spacecraft, as they reach their end of mission and become delict and such those become orbital debris, as well. In fact, the oldest thing in earth orbit right now, satellite catalog object number five is an early US spacecraft that's been there since 1959, I believe. And it's going to be there for probably thousands of years more.

Paul Thies:

Yeah. Is it like a mercury capsule or what is it?

Phillip Anz-Meador:

No, it was as one of the early Explorer series flights or Vanguards if I recall correctly.

Paul Thies:

So orbital debris, though, to kind of get a sense of the scope of the problem, it's not just spacecraft though, right? I mean, is it satellite parts? And, I mean, when you think about all the things that we're constantly launching into space, telecommunications satellites, and this and that, I mean, can you speak to the size and scope of the problem?

Phillip Anz-Meador:

Yeah, no. You're absolutely right there in the sense that all of the objects I've named so far are essentially intact, right? They may have expended fuel or things like that, but they're essentially in one piece, the same piece that was launched initially. Kind of more pernicious is fragmentation debris, and that's really kind of where I've devoted a lot of my career to studying. And all good things have wiring diagrams or flow charts associated with them, so in the case of fragmentation debris, you can really talk about breakup debris, which is where things explode or collide. And then what we term anomalous debris, cause it's produced, we don't understand really the production mechanism of it, but nonetheless it's there.

Paul Thies:

And so, with this stuff floating around, I mean, it kind of seems like, so you put satellites up there, for the functioning of... particularly in the digital world. I'm curious, with all that debris, how we keep it from interfering with things that we want to be in orbit versus all this just space junk, for lack of a better word.

Phillip Anz-Meador:

Yeah, exactly. And that's an excellent question, because one thing that is motivated by your question is, well, how do we keep track of these things? How do we know how much stuff there is? And of course there are the obvious answers of, well, we know the big pieces because we launch them. You can even see them at night traveling through the night sky. What people thought, in 1957, was Sputnik was actually the much, much larger Sputnik rocket body that went streaking through the skies and garnering all the press attention there. So the very first thing that most people saw in the space age was actually a discarded rocket body, a piece of debris. As you recall, there was a Cold War at that time and we were very concerned about an exchange of ICBMs. And so the US Department of Defense established a, more or less, worldwide network of sensors. So these are radars and optical sites and such, and they kept track of what was there.

Phillip Anz-Meador:

And that goes into even today the wonderful satellite catalog that DOD still maintains and provides on a regular basis. And that was not their original intent to support orbital debris scientists, such as myself, but rather they needed to know what was there in order to identify things that shouldn't be there. So things on circular orbits, good. Things on ballistic orbits, maybe headed towards DC, bad. So the catalog was the background against which they screened everything and it kind of has attained, now, a life of its own. And so with that catalog, with those radar sensors, we can essentially see things that are larger than about 10 centimeters in size or about four inches.

Paul Thies:

Wow.

Phillip Anz-Meador:

So softball size and larger. Just to put this in perspective for the audience, at the current time, we're in February, there are slightly over are 25,000 objects in the catalog. And so, again, larger than softball size in low Earth orbit and because of physics that grows to something about the size of a beach ball by the time we get to geosynchronous orbit. All good.

Phillip Anz-Meador:

However, there are things below the size threshold of the catalog and cataloging itself is very difficult. So how do we know this? Well, we know from experiments on the ground that things exploding or suffering an impact follow what's called a grinding law or, to be more technical, a power law type relationship between number and size. So what that means for us on a practical basis is we have a lot more small things than we have large things and that's relevant here because remember that 25,000 objects in the catalog, if we go down to a centimeter in size or about the size of a marble, then we estimate, based on models, that there are about 500,000 of those in orbit.

Phillip Anz-Meador:

And if we go down to about a millimeter in size, so grain of sand, something of that size, then we estimate that there's somewhere around a hundred million of those on objects. And, unfortunately, things on the order of a millimeter in size are still sufficiently dangerous to pose significant risk or even end of mission risk to spacecraft on orbit and then certainly astronauts and cosmonauts on EVA.

Paul Thies:

Mm-hm (affirmative). Yeah. I seem to remember, I'm trying to remember, but I think that Sandra Bullock movie, Gravity, I think they actually show that where it's these tiny little objects because of, I want to say hypervelocity, because they're moving so quickly, become very dangerous, these tiny objects, is that right?

Phillip Anz-Meador:

That is correct. And that was kind of a significantly accelerated version of what people have come to call the Kessler Syndrome, essentially a runaway condition in which the existing history leads to runaway growth, that is more things being produced than say the earth's atmosphere can remove. And, as a result, it's a chain reaction. So you're exactly right. Now, the good thing for us is that the situation portrayed in Gravity is far in the future, if ever, and we can certainly do things to remedy that before it would ever get to something that dramatic, let's say.

Paul Thies:

Hmm, okay. I'm assuming it wasn't like in 1957, maybe even the early sixties, we weren't necessarily thinking of orbital debris as much of a problem. I mean, as long as the Russians weren't launching ICBMs at us.

Phillip Anz-Meador:

Correct. I.

Paul Thies:

It's like, okay, hey this module that we weren't necessarily categorizing it as a problem, but then, at some point, it seems like there must have been a moment where scientists started paying attention saying, "We've got a lot of stuff up there it's starting to become a problem." When was that? And then has it kind of accelerated, especially now with the advent of all this technology that we're dependent on? Walk us through a little bit of when it really kind of got on our radar.

Phillip Anz-Meador:

Well, good word choice there. To really tell the story properly, I have to introduce you to a young man named Don Kessler. And, in this case, he'd done his time in the army. He went to University of Houston, got his B.S. In physics and joined NASA in the mid-sixties. And with going to the moon and such, it has long been recognized that there are things zipping through outer space, in the sense that we see shooting stars at a rate of about six per hour, those are about the size of a green pea and we see them burn in the upper atmosphere. So, obviously, there were things in space. And so, NASA decided that the Apollo spacecraft and others needed protection from it. So he joined an office that a specialized in that and they had guns, they could shoot things really fast and look at the corresponding damage.

Phillip Anz-Meador:

And they kind of pioneered the concept of protection or shielding of spacecraft from these things. They developed a computer model and as their task was done, they were rewarded with the office shutting down. The product delivered, you're done, thank you very much for your efforts. Go find another job. And then, so Don went into mission control and he stayed there a few years and he was learning about what is on orbit, just like we're discussing today. And he noticed that, oddly enough, when he looked at the satellite catalog of some rather well-known launches, such as US Landsat spacecraft, a great earth observer, you had the payload, Landsat, check. You had the rocket body, Delta, check. But then it said that there were 173 associated pieces.

Paul Thies:

Wow.

Phillip Anz-Meador:

And at least, at that time, no one was launching a 173 or 174 objects at the same time. So what were these things? He discovered that those pieces were associated with these breakup events that I had mentioned previously. In this case, the Delta is powered by what are termed hypergolic propellants that explode on contact, through either just the space environment weathering and the flip-flops in temperature, essentially reversing the common bulkhead between those two things. A crack develops, things that explode on contact came into contact and you had a really inefficient, but nonetheless, energetic event that created these extra 173 pieces.

Phillip Anz-Meador:

And so, that started kind of an inquiry as to was that a singular event or did it happen a lot? And the answer was, it happened a lot. And in fact, he then spoke with McDonnell Douglas, the manufacturer of the Delta. They did some research as to residual propellants on board these things, and they discovered that, yes indeed, these things featured a lot of fuel and oxidizer, again, exploding on contact, that were left onboard after the Delta had. Successfully deployed its payload. So that really initiated a series of studies, which resulted in what's termed mitigation.

Phillip Anz-Meador:

So in mitigation, we try to prevent things from happening. I always like to think of a lot of debris related studies as being very similar to going to your first party and kind of the ground rules for attending a party. Right? So the first thing is don't make a mess. Okay? Next thing may be, well, if you made a mess, clean it up. And finally, if you made a mess, take responsibility for it, don't just stand there and say, "I didn't do it. It wasn't my fault," but go ahead and take ownership of that process. And that's exactly what McDonnell Douglas in concert with NASA and the DOD did at the time. And they introduced these relatively simple mitigation measures to prevent breakups in the first place.

Phillip Anz-Meador:

Now, you had asked about how long this has been a problem. So, essentially, the first breakup was in 1961 and there were subsequent breakups over time. But one of the things that was noted, if we keep track of these things, is that that rate of increase was much larger than the rate of increase of payloads or rockets or things like that. So after 1961, it became the majority component of the population and it was increasing faster than the general population, the attack population, so to speak. So remember Don, he was looking at all these numbers of things being produced and spoke with McDonnell Douglas. They introduced some relatively simple mitigation strategies and kind of by the mid-eighties, those really started to pay off. The number breakups decreased. As a result, it put a kink in that slope, so you weren't creating these objects as fast anymore, and you kind of started to level off in that debris production.

Phillip Anz-Meador:

It seemed great, for a time. And I've kind of, at least personally, come to think of this as the age of mitigation. So not making a mess in the first place. Unfortunately, the age of mitigation did wonders for flattening the curve in the growth rate of debris. However, it has not lasted. And the modern age has become dominated by a couple of significant events. And really the first of those was a test of what's called an anti-satellite weapon, or an ASAT, conducted by the People's Republic of China against one of their derelict low Earth orbit weather satellites in January of 2007. That was a very bad day. In the course of that test, over 3,500 trackable and cataloged pieces entered the environment, by the way, we're still adding to that tally even today, due to cataloging difficulties and such, and the net effect there was in one day to essentially add or increase the number of objects on orbit by about a third.

Paul Thies:

Wow.

Phillip Anz-Meador:

And so, this was a significant event and one could look at it from the standpoint of essentially erasing the previous couple of decades worth of good work that got mitigation in place. Since then, in fact only two years after that in February of '09, two intact large objects collided for the first time accidentally, notably the derelict Kosmos 2251, an old Russian comm satellite collided with the active Iridium 33 communications satellite in orbit producing two distinct clouds. Again, in that one day, we added significantly to the catalog population.

Phillip Anz-Meador:

Since then, we've had a couple of further events, breakups rockets, and weather satellites owned by the US that, in former days, would've been treated as major events, but now only a couple of hundred pieces is much less significant than it was. Unfortunately, things like weapons tests continue. There was an Indian ASAT test conducted couple of years ago, and more recently, and more damaging to the environment, there was the November 2021 Russian ASAT test where they engaged an old military satellite of theirs and broke it up. This has significantly increased the risk to spacecraft in Leo, including the international space station.

Paul Thies:

Hmm. And as you were talking, so use the term Iridium, and it made me think, we've been talking about debris, right? Physical objects, but not necessarily talking about hazardous materials. And I don't know much about satellite manufacture admittedly, so I don't know how much, if any, nuclear material, for instance, gets put into a satellite, but I'm assuming that least there's some chemicals and things like that. Maybe they burn up in the atmosphere, I don't know, but I'm just kind of curious if we're also seeing things like radioactive materials being released in the upper Earth's atmosphere, as a result of these collisions.

Phillip Anz-Meador:

There are toxic things in space, primarily related to propellants and things of that nature. But you raise a good point with the issue of nuclear reactors in space, because they have been launched over the course of the space age. US has launched one, and it is actually a debris producer, anomalous debris producer. But the Soviet Union launched a series of nuclear powered radar reconnaissance spacecraft or RORSATs, radar ocean reconnaissance spacecraft, the goal was to use radar to keep track of, essentially, US Navy carrier battle groups and such. And at their end of life, they would reboost to a disposal orbit about 800 to 900 kilometers in altitude. And to lengthen the life of the reactor core, which is very dense, they would actually separate it from the remainder of the spacecraft and such. In a sense, that's kicking the can down the road in terms of environmental aspects in space.

Phillip Anz-Meador:

So we do have these nuclear reactors in the catalog. It was also a problem in the sense that they used a open loop cooling with their liquid metal sodium potassium coolant, and as the core ejected, so did a bunch of the coolant, which manifests itself now as little droplets that we can see in various high power radars. It was questionable from the environmental perspective, at least, while it worked correctly, and it was terrible from that same perspective when it did not. And there were at least two known cases where it did not. One, Kosmos 954 that reentered over the Canadian tundra in the northwestern part of Canada and resulted in ground contamination. Another spacecraft in the same series actually burned up in the upper atmosphere and high altitude sampling of the atmosphere revealed that it had significantly increased the atmospheric inventory of radionuclides in the upper atmosphere. That was a dangerous system from the get-go. And, in a sense, both with the upper atmosphere contamination, and then just leaving these radioactive reactor cores in orbit will require a hard look at remediation in the future.

Paul Thies:

Now, I can imagine as these things are, I don't want to use the word exploding, because that might be a little too much, but I mean, as things are breaking apart, each piece is taking on a trajectory of its own, right? So they're moving in space in ways not necessarily intended. And so-

Phillip Anz-Meador:

Exactly.

Paul Thies:

... as you're making a mess, I imagine it's getting more and more crowded up there, probably getting more and more dangerous in some regards to space travel, life on the ISS, that sort of thing. Now, I understand you'd introduced me to a term hypervelocity impacts. Can you tell us about hypervelocity impacts in space and how those differ from, say, ammunition based impacts? I think, like bullets and things, like things zipping around in space and the danger that they present.

Phillip Anz-Meador:

Yeah, exactly. When we talk about the types of, say, Earth-based impacts that you had talked about, be they bullets or shells or things like, that's primarily a fracture driven process. So by that, I mean, if we look really hard at materials, like say a piece of aluminum and things like that, from my physics professor day, one of my favorite analogs to that is a bunch of tennis balls that are held together with little springs. In a fracture dominated environment, you're essentially intruding on those tennis balls and springs, and you're breaking some of the springs if things come off and you're compressing other ones in the sense that some of the springs have now sprung and you've kind of damaged that of this solid, but it kind of stays there, hangs together. As I say, some of the springs are damaged, but it's mostly still there, some pieces that kind of come off more or less intact.

Phillip Anz-Meador:

In the case of hypervelocity, it's a very different regime in the sense that you come in and you dump in so much energy so quickly that, essentially, the tennis balls don't have time to get out of their own way. Essentially, you've set up supersonic shockwave in this material. So a lot of energy, very small space, that shockwave is propagating faster than, in fact, the speed of sound in that material.

Paul Thies:

Wow.

Phillip Anz-Meador:

Remember the speed of sound might conveyed by those little springs that are holding all these tennis balls together. So what happens? Well, just kind of like back in introductory physics, when you apply energy to a body, thermal energy, you tend to start cutting those little springs. And now, if you have a sea of tennis balls, not connected by springs, you essentially have a liquid, so that's the key With a hypervelocity impact, you're essentially melting your way into this body. And you may have seen some photos of a huge aluminum block, say, that was actually impacted by a relatively benign seeming little slug of Lexan, a clear plastic, and such, at about five to seven kilometers a second, which is actually less than you would reasonably encounter on orbit.

Phillip Anz-Meador:

And there's a huge crater in that thing. And, unfortunately, that block is about eight to 10 inches thick with this huge crater caused by this benign little piece of clear plastic. So that's the danger of on orbit collision.

Paul Thies:

Wow.

Phillip Anz-Meador:

As I mentioned, five to seven kilometers per second, which we can attain reasonably easily on the ground is not actually representative of the types of speeds we'd encounter on orbit there, because you can actually meet other orbiting things head on based on orbital parameters. You actually strike things at up to about 15 kilometers a second, and that can cause significant damage.

Paul Thies:

Hmm. So what are some solutions on the problem of orbital debris? Can you speak to some of the remediation steps that are being taken for all that stuff up there now?

Phillip Anz-Meador:

Let me just start off by, again, kind of defining some terms for the audience. One of those is mitigation, as we've already talked about, and that's not making a mess in the first place. The second, though, is really touching on your question and that's the concept of remediation. In other words, we're going to remediate or clean up the mess after it's been created in the first place. Here in the us, at least, since about the middle of the last decade, a lot of those efforts have really been aimed more at study and looking at techniques and efficiencies and things of that nature, what targets would we go over to have the most benefit, long-term, to the environment and things of that nature. But due to a variety of non-technical issues that's really the state of the art to today. Other folks have also looked at remediation. The European Space Agency, for example, has a large satellite, ERS-1, one of the largest they've ever launched, which failed. And they're very concerned about its reentry hazard and such that it poses to the surface of the earth.

Phillip Anz-Meador:

And so, they've at things like harpoons, nets, things like that, to essentially capture it and then guide it into a controlled reentry, say over the middle of the Pacific or something like that. Today, private companies such as Astroscale, as just one example, it's a international company started in Japan, but it has European, UK, and US elements as well, is looking at how does one capture a satellite and retrieve it, perhaps attach some sort of deorbit package to it. And then, economically, go on to the next one and repeat. And you recall I'd mentioned nontechnical aspects of these things and those are really two.

Phillip Anz-Meador:

One is the economics of trying to remediate space and other deals with diplomacy and the politic aspects of who owns who, or I should say, who owns what in space and who do these things belong to even today, even in some cases, 50 years after it's broke up. Well, under the terms of the Outer Space Treaty from the 1960s, those objects still belong to the launch agency's so they constitute sovereign territory. And, of course, you can't just go remediating someone else's national property in that sense.

Paul Thies:

Hmm, very interesting. I hope some of those countries are out there listening about the Apollo spacecraft. So let me ask, I understand also that orbital debris can also present hazard to us on Earth. How are those potential hazards identified and evaluated?

Phillip Anz-Meador:

Yeah. And that's something that really entered the consciousness, I think for a lot of folks, back in, gosh, I guess the late seventies, when, and Skylab reentered over Australia. It had a lot of heavy things on board. For example, a film safe, that was used to protect film from cosmic rays and that landed, essentially, intact. We've also seen that with other large spacecraft and space stations and thing of that nature. And so, it became clear that orbital debris is not just an orbital problem, but rather it can reenter the Earth's atmosphere in an uncontrolled fashion, land on the ground, and either the pieces that survive, or at least in one case the concern over a fuel tank that would've survived to the ground and had toxic propellants in it has posed some risk to the ground population.

Phillip Anz-Meador:

And, in fact, some of the tools that Jacobs and our consortium teammates under the JETS contractor at JSC have facilitated the development of look exactly at that. So, essentially, they begin with a model of the spacecraft or the materials identified, what materials burn up in the upper atmosphere, which survive down to lower altitudes, or can even strike the ground. And one of the outputs of that effort is what's termed the casualty area and kind of the casualty probability associated with it. For example, in the last century, due to mankind's activities, humankind's activities, it was noted that about 15 joules, where joule is just, of course, the metric unit of energy, is kind of the threshold for casualty and such. And so, our models can use that as a threshold. It can look at the population density on the surface of the Earth, of course, 70% water, but certainly there are many population concentrations.

Phillip Anz-Meador:

For example, the Ganges Valley of Northern India is the most densely populated spot on earth. And then, we can essentially fly our reentering spacecraft over the Earth. We can update it with new orbital measurements from that space surveillance network and such, and we can then estimate the risk that's posed to the ground population by these reentering objects. Also, we can help out space designers from the get-go cause we can make recommendations of not using materials that will survive reentry, but rather there's a whole design paradigm now, it's called Design for Demise, and it's exactly what it sounds like. If you can design your spacecraft to fulfill its function, maybe using modern materials, such as composites and things like that will demise on reentry, absolutely fantastic. And it can become a design goal.

Paul Thies:

It sounds pretty innovative. Is that widely adopted or is it still kind of in the early days of adoption? How would you characterize that and are there other innovative solutions that are emerging on the landscape that are being explored?

Phillip Anz-Meador:

Design for Demise kind of first came to prominence, again, kind of the middle part of the last decade. And it's certainly easier to integrate those sorts of design paradigms into smaller spacecrafts starting with CubeSats and things like that, working up to MiniSATs and such. Unfortunately, there are a lot of legacy designs out there, both for spacecraft and rocket bodies. So for the time being we'll remain faced with the reentries of these large bodies and the attendant risk.

Phillip Anz-Meador:

Now, I think you had also mentioned or, or asked about what other sorts of technologies are out there and kind of exciting technology right now that hints at remediation is the flight of several spacecraft to the geosynchronous belt in Earth orbit. And their goal is to extend the lifetimes of older communication satellites, in this case. And then, when they've essentially reached the real end of their life, when parts are starting to fail and such to deposit them in what's termed the graveyard orbit located above the geosynchronous ring. There have been several instances of that. And just last week, a Chinese spacecraft

SJ-21 was noted to have grasped an old Chinese navigation satellite called Beidou or Compass and such. And it actually tugged it out of the geo belt where it was a derelict and moved it above geo.

Phillip Anz-Meador:

So those are examples of how remediation would work in terms of moving it up out of the geosynch belt. In lower Earth orbit, they would probably, as I mentioned earlier, attach some sort of package to it to help make it reenter quicker. Now, there's a problem there because that sort of technology is what you might term dual use in the sense that it can be used for great environmental and economic purposes, or it could be used for more nefarious purposes, as you might imagine. And so, that's one of the drivers for a certain hesitancy to deploy these sorts of things on orbit. And of course, as I mentioned, that's where people start taking a really hard look at things like the outer space treaty and all of the rights and responsibilities that are bound up in that in terms of ownership and those sorts of property rights in space, let's say.

Paul Thies:

Yeah, no. I think that's very interesting, because you have all these satellites up there that run communication systems and all kinds of things, and people aren't being diligent, who's to say there's some bad actors who are taking perfectly good satellites or perfectly good technology and appropriating it inappropriately. Which kind of leads me to my last question or set of questions and you kind of touched on it a little bit, but what else needs to be done that so far hasn't been done to address the problem and what are the barriers that are impacting the roll out of those solutions? It sounds like maybe some space treaty action, international trust, some of that kind of thing, but what are the barriers and what needs to be done?

Phillip Anz-Meador:

That's a very interesting question in the sense that we can break those barriers out into a couple of different types. And so, we have the technological barriers and there we can look at the sorts of techniques that could be used for remediation of the environment in the future, be they a robot arm, so to speak, or a proximity operations docking capability with objects. At the same time, other sorts of techniques may prove feasible. For example, lasers. Now, this also is a dual use technology. It's very easy to imagine something like a ground-based laser or space-based laser hitting a satellite with its beam and melting parts of it, knocking parts of it off, things like that. For that reason, kind of the community interested in lasers as a means of remediation have kind of gone back to their drawing board and looked at things such as power levels.

Phillip Anz-Meador:

And so, they've developed some lasers and techniques, which could, in essence, apply essentially the same sort of radiation pressure, the push that the photons give as they reflect off a surface, as you would expect just from the sun. So if you imagine this object would pass over the ground-based laser, it would receive this gentle push from the laser. And over time that would perturb its orbit such that it's perigee or point of closest approach to the Earth may dip down further and further into the Earth's atmosphere. It would enhance the drag. And so, far from being a zap sort of solution where the satellite disintegrates, this would be more of a medium term solution where after these gentle pushes, maybe in five years, the thing would reenter. So there's a lot of interest in developing those sorts of technical solutions.

Phillip Anz-Meador:

The next part are the liabilities and such associated with doing some sort of remediation, because let's suppose that your chosen tool of remediation is a harpoon. Okay? What could possibly go wrong? Well, some of the things that could possibly go wrong are vessels that still maintain pressures of, for example, hypergolic propellants or other sorts of pressurants that are common on many spacecraft and rocket bodies and such. And what would happen if your harpoon accidentally struck one of those? Well, that would not be a good day. And so, just as doctors may have the credo of, "Do no harm," well, we should probably do no harm to the [inaudible 00:38:00] environment in trying to make it better. Kind of the last challenge or direction of development that needs to be considered is that dealing with the diplomatic or international relations realm, and how do we behave in space? Things like rules of the road or a common set of behavioral norms is something that's appeared with increasing frequency over the course of the last couple years.

Phillip Anz-Meador:

One of the other terms you'll hear used a lot is the concept of space as a domain. And in this sense, that was one of the rationales for when we stood up the US Space Force, because it was responding to perceived needs in a domain. And that domain just happens to be space. In that sense, it is equivalent to say the terrestrial domain with the Army and the Marines, the maritime domain with Navy and Coast Guard and the atmospheric domain with the Air Force and such. So it's kind of an interesting take on the environment kind of segueing, perhaps, from a late fifties, early sixties view of space as this infinite space that the starships of science fiction goes zipping through to very much more of a populated space and a finite resource. And that's very true both for some orbits now in low Earth orbit, in other words, top of atmosphere up to about 2,000 kilometers altitude, as well as the geosynchronous belt. Overall, kind of the mental shift is every bit as important as some of the technological aspects that we've talked about today.

Paul Thies:

Oh, that's pretty fascinating. I think with that mental shift, the people will recognize the problems attendant to orbital debris, and then there'll be greater emphasis and hopefully greater resources applied to that and in the mitigating and remediating those. Well, Phillip, I really appreciate it. This has been very fascinating and, I mean, you've really painted a picture for me and for our audience. I really appreciate all the information and I appreciate your time today.

Phillip Anz-Meador:

Hey, my pleasure, Paul.