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THE WEST'S BOOGEYMAN

Hypersonic weapons have been tried in Ukraine and saber-rattled near Taiwan. Here are the technical challenges for defense and how the U.S. plans to meet them. PAGE 24

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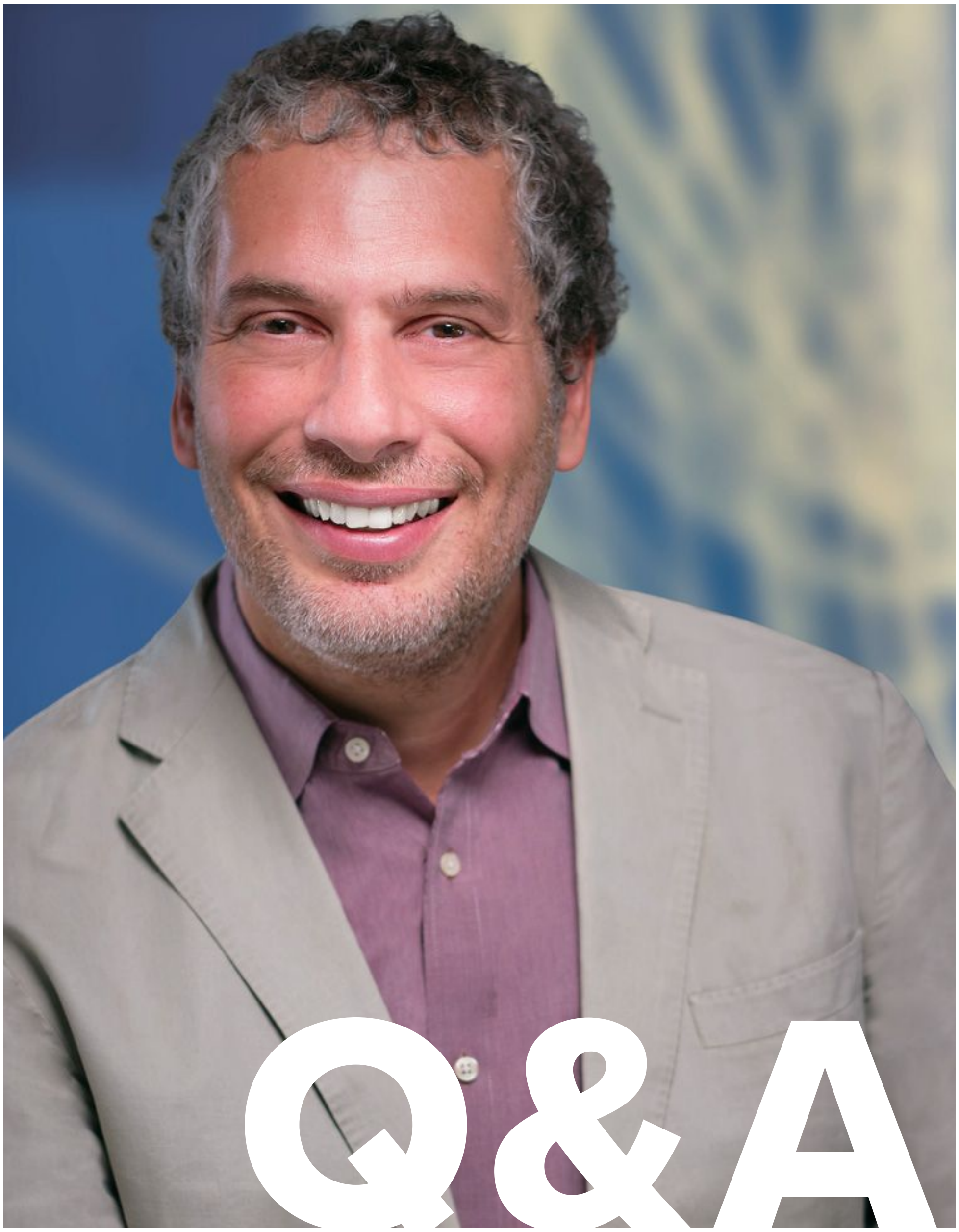

Mission designer

How does one get a spacecraft to fly repeatedly by a moon that's five times farther from the sun than Earth? Figuring that out was only part of the challenge faced by Stefano Campagnola and his fellow astrodynamicists at NASA's Jet Propulsion Laboratory in their role as mission designers for the $5 billion Europa Clipper mission. The Clipper spacecraft, launched last month, will tour one of the solar system's most intriguing but dangerous features: Jupiter's icy moon Europa. The ingredients for life might exist under its shell, but to find out, Campagnola and company had to craft a tour that would limit Clipper's exposure to the radiation produced when Jupiter's magnetosphere sweeps over Europa's closest neighbor, the moon Io. Campagnola, who plans to transition to the navigation team this month, spoke with me by video call about the mission design and the need to be ready with an alternative trajectory five years from now in the event that a new route must be quickly designed because the spacecraft's transistors start to fail due to radiation exposure. — *Ben Iannotta*

STEFANO CAMPAGNOLA

POSITIONS: Since January 2022, mission design manager for Europa Clipper at the NASA-funded Jet Propulsion Laboratory in California, a role that ends on Nov. 24. 2021-2022, deputy mission design manager. 2016-2021, various roles at JPL. 2012-2016, space mission analyst and fellow at the Japan Aerospace Exploration Agency, JAXA. 2011-2012, postdoctoral fellow at Caltech and JPL and contributor to the 2011 Europa Mission Study. 2010-2011, postdoctoral fellow at JAXA. 2007-2010, teaching assistant at the University of Southern California. 2005-2006, assistant research engineer at Caltech/JPL. 2002-2005, aerospace engineer at the European Space Agency.

NOTABLE: Lead designer for Clipper tour option 21F31v7, the one chosen. Has worked on flagship space missions for space agencies on three continents: the European Space Agency, JAXA and NASA. Member of the ESA team that developed BepiColombo's gravitational capture technique that will provide multiple opportunities for it to enter orbit around Mercury in 2026. As a postdoc at JAXA, proposed the recovery maneuver that placed the Akatsuki probe in orbit around Venus five years after a clogged fuel valve foiled the 2010 attempt. Presented a notional Europa mission in his 2002 master's thesis. Born in Italy; became a dual U.S.-Italian citizen in September.

RESIDES: Pasadena, California

AGE: 48

EDUCATION: Ph.D. in aerospace engineering, University of Southern California, 2010; Master of Science in aerospace engineering, Politecnico di Milano, 2002.

Q: You were there at Cape Canaveral for the launch last month. How was it?

A: Last year, I brought my daughter and her whole class to see Europa Clipper at JPL, and so I wanted to show her the launch as well. I wanted her to appreciate how many people really spent their heart on this mission for decades. It's very emotional on the human side. There are thousands of people in the observation deck. We all hug, and we all have the same T-shirt, and we're all very happy and cheering and nervous because it's kind of nerve wracking, the countdown. I wanted her to experience the human side, not only the science side — which is important, that's why we are excited — but the human side of it, which is a human experience.

Q: For the mission design, what were the forces and the objects out there that you had to take into account?

A: A misconception is that people see the rocket going up and think, "Oh, you need a lot of thrust to go up." But you really want to go tangentially. You want to go as fast as possible so that you stay in orbit, because if you don't go that fast, you fall back to Earth. Orbit is a free fall, but because of the curvature of the Earth, you're never catching up, and so you keep on falling. But to do this, you have to go 17,000 miles per hour [27,000 kph], and you use a little bit of propellant to go outside the atmosphere, so the drag is not breaking you.

Campagnola sent me a follow-up email describing how Europa Clipper escaped Earth's gravity and what comes next: "We escaped the Earth at 6.4 km/s, and we will use the Mars flyby to leverage the spacecraft orbit around the Sun, so that on Dec 3rd, 2026 we will approach the Earth at a higher speed of 11.6 km/s. That is the speed, relative to Earth, that we need to get into the transfer orbit to Jupiter." — BI

If you have a huge rocket like SLS, you can go on a direct trajectory.

Q: In fact, there was a proposal to use SLS.

A: Yes, that would make a much shorter mission — a two, three-year transfer to go to Jupiter. But because of delayed development — it's difficult to design a big rocket — we didn't want to wait too long. Falcon Heavy was an excellent alternative, but Falcon Heavy doesn't have all the energy to go all the way to Jupiter. We actually use Mars. When we come back in the beginning of December 2026, we have an Earth flyby, and then we can go to Jupiter. So you can think that the real transfer from Earth is in 2026, and that's called a Hohmann transfer. It's like half of an ellipse connecting Earth orbit to Jupiter's orbit.

Q: You're definitely standing on lessons from your predecessors, I would think.

A: Absolutely. The gravity of Europa you can use very effectively as a fake engine to reorient or change the orbit as much as you want. This idea of using gravity to change the orbit, that's been used since the beginning of space exploration. The dynamical system is not too complicated. The complication comes from the fact that every flyby of Europa changes the condition: the way you approach the moon. If you approach the moon in a certain direction or a slightly different direction; if you have a flyby of 100 kilometers or 200 kilometers, 500 kilometers from the surface, then your trajectory after the flyby is drastically different. Some people think orbital mechanics is easy because we only work with an ordinary differential equation. You need one initial condition, and then you propagate the question of motion, and you get what you get. But all the time you fly by a moon, you introduce large nonlinearities that the system becomes chaotic.

Q: Chaotic means the result is hard to predict?

A: Yes. In some cases, a small change of how you approach something can

"This thing was like a meteorite that hit us two months before launch."

— a reference to the last-minute warning that NASA received about the vulnerability to radiation of transistors aboard Europa Clipper

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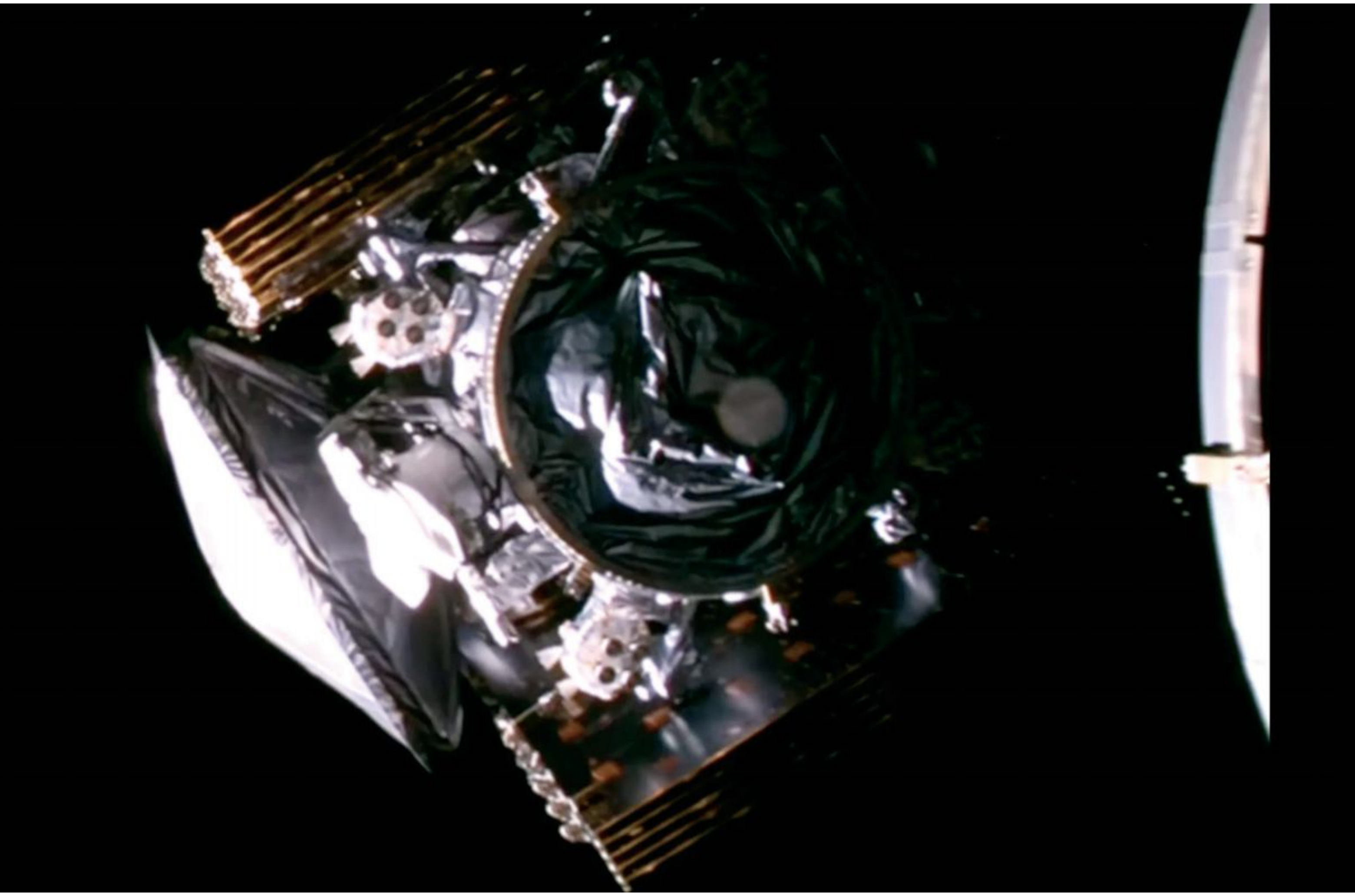


▲ Europa Clipper's 5.5-year journey to Jupiter began in October, when the spacecraft separated from the second stage of the SpaceX Falcon Heavy that lofted it to orbit.

NASA TV/SpaceX

create so very diverse output that it's hard to predict what's going to happen. We have ways to deal with that. When you operate the spacecraft, these things happen in such long timescales that you can essentially correct: I'm here, but if I veer off, I'm going to go to Mars. But you have months and months to control and check that. When we design the trajectory, we have to keep this in mind. We split the trajectory into arcs and say, "OK, we have one arc from Earth to Mars. Then we use the gravity of Mars to go back to the Earth, and then from the Earth, we go to Jupiter." Now you have to find a sequence of moons you want to use, and you need to find the right dates and connect them in a way that makes sense.

Q: Do you wish you had nuclear propulsion?

A: It depends. One of the main concepts for Europa was called JIMO, and that was supposed to use nuclear-electric propulsion.

Q: The Jupiter Icy Moon Orbiter.

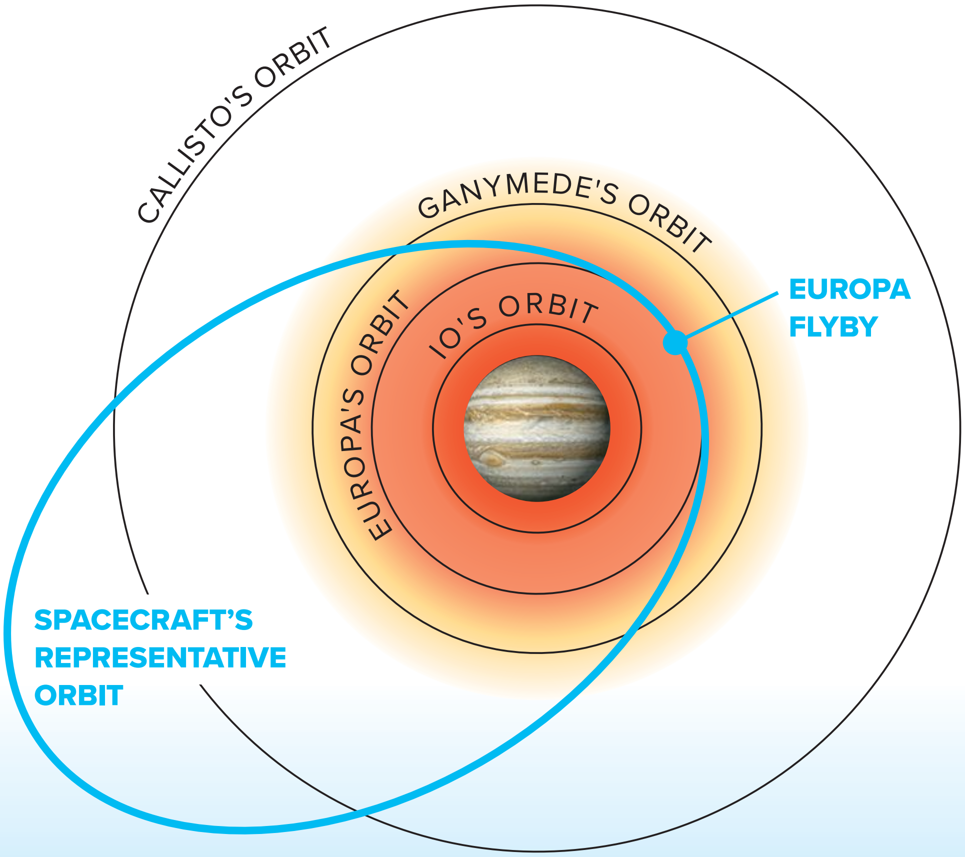
A: Yes, exactly. That was about 20 years ago. From a trajectory design point of view, that's great because you can essentially use this thruster to bend and change the trajectory at very, very little propellant cost. That would allow you to explore all the moons of Jupiter at ease. Then the problem is: We didn't know if we could actually make it work, because you're producing a lot of heat. How do you control this? I need to make sure the radiation is not destroying the system, the heat is not melting stuff. How do you test it? The other thing to consider is that there are other options. It's not that we cannot go to Europa. The most difficult thing about Europa is the radiation.

Q: So how do you cope with that radiation?

A: That's why it took us 25 years for Clipper, right? The tidal forces that heat up the interior of Europa and make the liquid ocean possible also heat up the interior of Io, which is the inner moon. This moon has all this volcanic eruption, and all this material is ejected into space. Now, the magnetic field of Jupiter is very vast and 10,000 times stronger than the one of the Earth, and it's spinning very fast. It accelerates these particles, and so that's what creates all this very harsh radiation. This was the problem when we saw

Surviving Jupiter's radiation

Europa Clipper's elliptical orbit around Jupiter was chosen to minimize the amount of time the spacecraft spends in the intense radiation closer to Jupiter. That radiation is represented here by dark orange. The spacecraft will head back toward Jupiter and dive quickly through the radiation as it flies by Europa some 50 times to within 25 kilometers above its surface.



SOURCE: NASA/JPL-Caltech
GRAPHIC by THOR (thor-studio.com)

from the Galileo mission not conclusive evidence but pretty strong measurements of a liquid ocean, and we wanted to go back to Europa. Until Galileo, it was thought life could only exist in the Goldilocks zone, when you're close enough to the sun that the ice will melt but not too close so it would evaporate. And now we found an entire liquid ocean under another moon. I mean, that was like a revolution.

Q: But if the radiation is so harsh, how might there be life?

A: Because you have a thick layer of ice — like maybe 10 kilometers high — and then underneath, well protected, you have liquid water. And then what else you need is chemical compounds, usually carbon based. Then you need the form of energy, and that's the tide. So the idea is that at the bottom of the ocean of Europa, there are probably vents like at the bottom of our oceans, and around these vents on Earth, there's a lot of life, right? So we think, "Well, why not on Europa?" You have the same ingredients. The general idea to exploring the moon of a planet is that you get into orbit around it, usually a polar orbit. In general, the moon revolves, and you essentially sniff the atmosphere, and you map the entire surface with all those instruments, and then do it again in 30 days.

Q: But you can't do that in this case.

A: You can't do it because, in these 30 days, you get so much radiation. Think about it: We have a $5 billion mission. It takes years to get to this orbit, and they have one month of science, and after that, everything is fried. And, if the spacecraft were to enter safe mode, you're losing a big chunk of your science. Second, you have maybe terabytes of data that you have to send back to Earth in this one month, but you might not have time to send it. So, the idea with flybys is that we are on a two, three-week orbit around Jupiter. We fly by Europa. We spend about one day in the vicinity of Europa. As we approach, we can map Europa, and then when we are really close, we can sniff the atmosphere and make very high-resolution mapping. And then we fly away. We spend one day in the harsh radiation. It's brutal, but we have three weeks to make sure the spacecraft is healthy, to send back the data and to plan

an activity. And we do it over and over again. We will get the same radiation we would get in an orbit around Europa for one month, but it is spread over four years.

Q: There were last-moment questions about the ability of the electronics to handle the radiation during the flybys. Did that affect the mission design?

A: In part. We realized that this transistor that the vendor gave us would not tolerate the amount of radiation that it was supposed to tolerate. The team discovered that there is a process called annealing, by which you can restore it a little bit. The idea is that when you are far, you can heat up the transistor, anneal it and fix it a little bit, and then come back. The other thing they did is install what they call a canary box. Those are basically transistors a bit more exposed on the spacecraft. If something happened to those, you know that you are in trouble. This summer, I was working very hard with my team to try to find a solution that would work well even with much fewer flybys, and we did. But by the end of the day, the project decided we have enough mitigations in place that we don't need, as of now, to change the tour. The problem with Clipper is that if something happens, right now it takes several months to design a tour, but we can't wait several months because every two weeks we're getting a million X-rays. We need to find a way, if something happens, to get out of the radiation very quickly and stay in a safe zone. Come up with a new design fairly quickly, because operations take some time. This is something we always had in mind to do. We always thought, "After launch, we have five years to figure this out." Now, my personal opinion — and so it's not NASA's or JPL's — is that this MOSFET situation makes the risk more likely to happen.

By MOSFET, he's referring to metal-oxide semiconductor field-effect transistors, the centimeter-sized devices that control current in computing circuitry, including aboard Europa Clipper. — BI

If we cannot do 50 flybys anymore because our transistors are failing, so we only have like 10 flybys left, what do we do? How do you prioritize our instruments? This is a much more complex type of work that we have to do in the next five years. It's not millions of dollars. It's one, two persons doing some research for the next few years.

Q: If the MOSFETs fail or degrade, what capability does Clipper lose?

A: The MOSFETs are everywhere. Some are shielded inside the vault, the encasing on the top of the spacecraft, where all the electronics are.

Q: When did you learn about the problem?

A: In July. I was just coming back from Italy, and then we spent like one month working very, very hard. And we did find other good trajectories. But again, the

▲ A table in the office of JPL Director Laurie Leshin (right) shows the flight plan for Europa Clipper. The mission design was created by Stefano Campagnola (second from left) and colleagues, pictured here when they visited Leshin's office a few weeks before Clipper was launched.

NASA/JPL-Caltech

project at the end decided that the mitigation they already found were good enough — this is the annealing and this canary box — and the testing they have done suggested they can fly the baseline trajectory.

Q: Canary as in the bird.

A: Yes. In Italy, actually, we had something similar to the canary box. When you grow grapes in Tuscany, in Montepulciano, you have at the beginning of a row a rose. And the idea is that if a vine is getting sick, the rose gets sick first. Then you can act before it dies.

Q: Was that canary box added to the spacecraft because of this?

A: Yes. This thing was like a meteorite that hit us two months before launch. They actually mounted this canary box at the very last minute, essentially. It was amazing what the team has done.

Q: So, that's created a mission for you for the next five years and your teammates to figure out a contingency.

A: Yes. Again, we had planned this already because we knew the risk of bigger or higher radiation. We need to get ready now. We now have one extra reason to do this. ★

"We will get the same radiation we would get in an orbit around Europa for one month, but it is spread over four years."