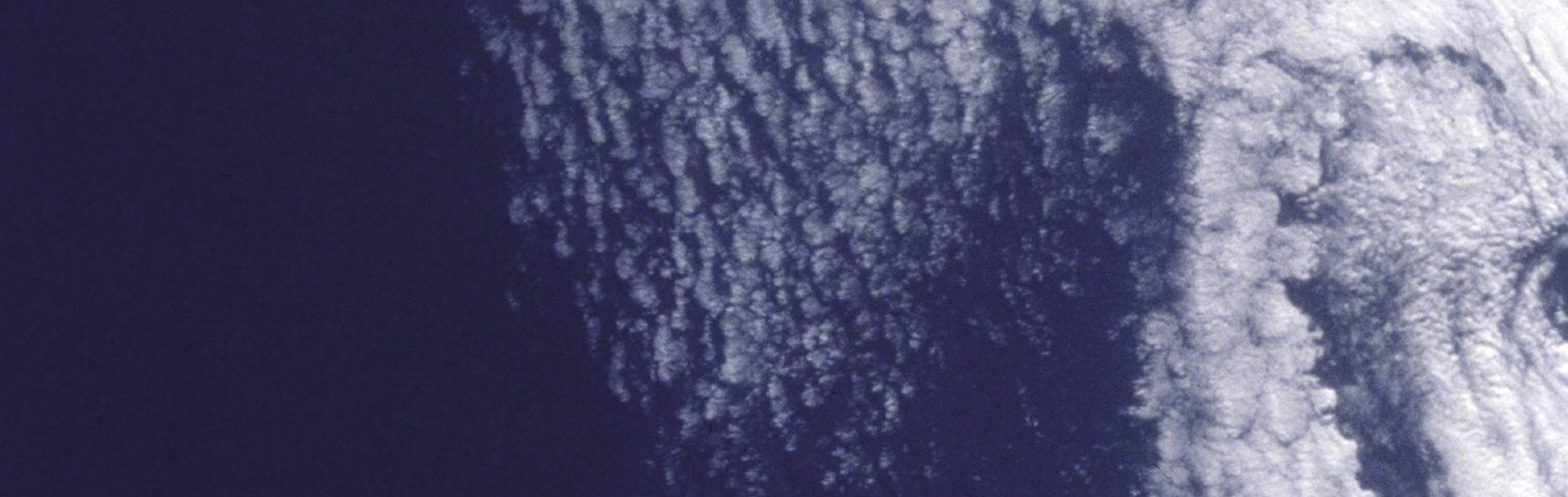


Ad Astra per GALCIT

By Douglas L. Smith

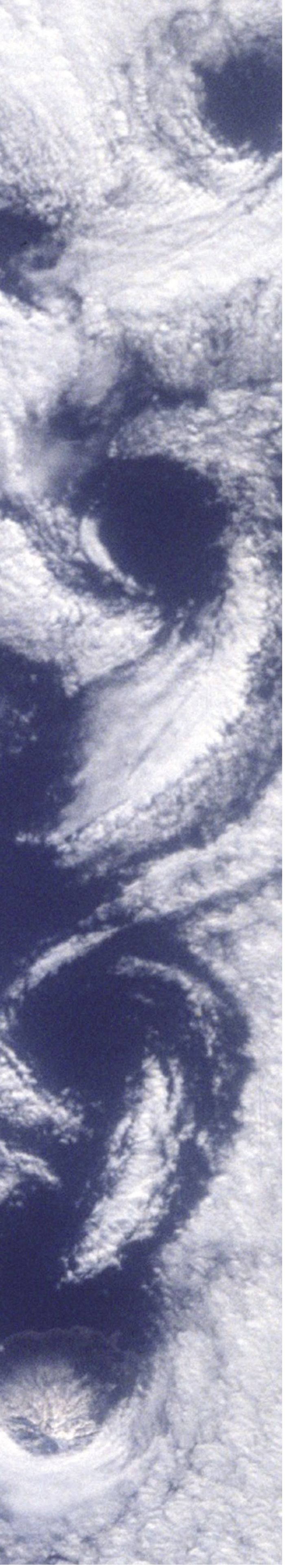
Rendering courtesy of John Friedman Alice Kimm Architects.

Air flowing over and around objects in its path can create trains of spiraling eddies known as von Kármán vortices, as seen (top and right) over the island of Rishiri in the northern Sea of Japan. In Caltech's remodeled Guggenheim Aeronautical Laboratory (above), swirling shapes resembling von Kármán vortices will decorate the ceiling of the conference room named for the man who first described them—aeronautics professor and GALCIT founding director Theodore von Kármán.

Just about every kid wants to be an astronaut at some point. The *Star Wars* and *Star Trek* franchises are still going strong 30 and 40 years after their inception, and the commercial satellite business brought in some $82 billion dollars last year worldwide. Amazing pictures, from Mars to distant galaxies, are only a few mouse clicks away. Yet U.S. aerospace firms can't fill some 10 percent of their MS- and PhD-level engineering jobs, according to industry insiders. The problem will just get worse as the rest of the bright young minds who came of age in the years of the Apollo program retire—28 percent of them will have called it a career by the end of this year, says the National Science Board, which is the governing body of the National Science Foundation.

It's not that kids get bored with space, says Ares Rosakis, the von Kármán Professor of Aeronautics and Mechanical Engineering and director of the Graduate Aeronautical Laboratories at the California Institute of Technology (GALCIT). "Space is actually the easiest way to start teaching science in ages below 16." The problem, he says, comes when those 16-year-olds start thinking like grownups—when they start worrying about a career. "I see it in my own children. They have been indoctrinated since they were young about how fantastic science is, but their classmates tell them it's not cool to become an engineer—not only because it's difficult, but because my father makes much more money than yours." College graduates with engineering degrees tend to go into information technology, biotech, or some other -tech, or even farther afield to business, law, or investment careers that seduce them with promises of millions before they're 30.

If there's any place that can make space engineering cool again, it's got to be Caltech. After all, the Institute founded and still administers NASA's Jet Propulsion Laboratory, which got America into the Space Race and is now exploring our solar system and beyond. Since 2004, Rosakis has been spearheading an initiative to launch a master's



degree program at GALCIT that would go beyond the traditional MS in aeronautics, which keeps one safely within Earth's atmosphere. The new MS in aerospace engineering "reconnects to JPL in a major way," says Rosakis. "It engages JPL, Caltech's seventh division, in curriculum design and classroom teaching. I don't think I would dare do a space-engineering master's program anywhere else that didn't have JPL next to it. This program is illuminated by JPL's existence." In the program, students work on a real spacecraft, solving real engineering problems. "We are not designing entire missions. You could imagine us trying to launch a Mickey Mouse GALCIT experiment. It's much better to isolate a small part of a real mission." Rosakis credits JPL director Charles Elachi (MS '69, PhD '71) for this approach. "His philosophy is to expose the students to something of real importance to JPL that would allow JPL instructors to be enthusiastic because they are working, through teaching, on an actual JPL mission." But although the JPL instructors are working in their areas of expertise, they are paid by Caltech, not JPL. "This is very important," Rosakis emphasizes. "The JPLers are employed as consultants, as instructors separately from their JPL duties. It's against NASA rules to use government contracts for teaching."

The one-year aerospace program, now in its second year, is just as big as the aeronautics program—nine students each per year—and, like the traditional degree, is designed to be a stepping-stone to a PhD. Eight of the students from the inaugural class have, in fact, gone on to Caltech PhD programs in space-related fields. Because the program is not intended to lead to a terminal master's, it focuses on the science behind space engineering rather than on job-specific training. "It's not an applications-based program," says Rosakis. "That's a very big difference from the rest of the space graduate programs you see around the country." Another big difference is the overkill factor. Four GALCIT members—fully one-third of the aeronautics faculty—and six JPLers teach the nine students. The basics of fluid mechanics, solid mechanics, and structural mechanics are addressed in all their gory detail in a set of core courses common to both the aeronautics and the aerospace option. The math is just as strong as it would be for a PhD, "and so of course our students have suffered," laughs Rosakis. "But that's life." But the pain pays off when a prepared mind finds the right situation, as Simon Ramo (PhD '36) did when he went to work for General Electric armed with all the latest physics that was about to revolutionize electrical engineering—see the sidebar on page 17.

The program's elective courses are taught by JPL staff members. This is overseen by JPL's chief technologist, Paul Dimotakis (BS '68, MS '69, PhD '73), who is also Caltech's Northrop Professor of Aeronautics and professor of applied physics. The exact slate varies from year to year, but the current lineup includes four offerings:

Ae 115, Spacecraft Navigation, covers astrodynamics, orbital calculations, and precision tracking systems. The class is being taught by Michael Watkins, who often draws examples from his work as the mission manager for the Mars Science Laboratory (MSL), the "super rover" set to launch in 2009, and as the project scientist for the Gravity Recovery and Climate Experiment (GRACE), launched in 2002. MSL requires ultra-precise navigation to enter the Martian atmosphere at exactly the right time and place for a safe landing. GRACE consists of two satellites orbiting Earth in tandem about 220 kilometers apart, with their relative positions determined to an accuracy of less than one micron—akin to measuring the distance between JPL and San Diego to within the thickness of a red blood cell. That knowledge allows the mapping of minute changes in Earth's gravitational field due to climate-related effects. "We even weigh Earth's ice sheets," says Watkins.

Ae 121, Space Propulsion, looks at solid- and liquid-fueled rockets and their control, plus such exotica as electrical and even nuclear thrusters. This course features James Polk, principal investigator for the NEXIS (Nuclear Electric Xenon Ion System) engine, a high-power electric thruster designed to propel a nuclear-powered spacecraft to the icy moons of Jupiter. NEXIS was an advanced version of the ion drive demonstrated on JPL's Deep Space 1, which flew by comet Borrelly in September 2001 and took the best-ever pictures of a comet's nucleus.

Ae 159, Space Optical System Engineering, includes not just sensors, lenses, and mirrors but all the other considerations needed to bring the universe into focus: the thermal properties of materials, the design of servomechanisms, and the subtleties of image processing. The instructor is James Breckinridge, JPL's Origins theme technologist, which is a fancy way of saying he oversees telescope technology at the Lab. Breckinridge headed the nationwide team that gave an eye exam to the flawed mirror on the Hubble Space Telescope. He also led the JPL team that built the Wide-Field and Planetary Camera 2 to prescription to compensate.

And EE/Ge157, Introduction to the Physics of Remote Sensing, covers devices across the electromagnetic spectrum, from microwave radars that look beneath the sands of the Sahara to infrared spectrometers that take the temperatures of distant planet-forming systems. This very popular class, originated and taught by synthetic-aperture radar scientist Charles Elachi long before he became JPL's director, is now led by Jakob van Zyl (MS '83, PhD '86), an Elachi protégé who started off flying Earth-mapping radar missions on the Space Shuttle and now leads JPL's Astronomy and Physics Directorate.

But the plum course is a required one—Ae 105, Aerospace Engineering, co-taught by Dimotakis, Gregory Davis, and Marco Quadrelli. Dimotakis is an expert in turbulent flows in general and propulsion systems in particular. Davis is the chief technologist for JPL's Mechanical Systems Division; before that he built the advanced deployable structures group, and before that he was a mechanical-systems engineer on the Mars Exploration Rovers, Spirit and Opportunity, and a dynamicist for the original Sojourner rover. Quadrelli is a senior dynamics and control analyst in JPL's guidance,

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navigation, and control section who has been an entry, descent, and landing dynamics analyst for the Huygens probe to Saturn's moon Titan and the Mars Exploration Rover and MSL missions, and has developed control algorithms for multivehicle and tethered spacecraft. Ae 105's fall term covers launch vehicles, fundamental structural and thermal systems, and introductory orbital mechanics. The winter quarter looks at advanced orbital mechanics, spacecraft dynamics, and planetary reentry—taking the students from the ground to space and back again in two terms. Occasional guest lecturers from JPL provide additional spice to this challenging stew.

In the spring term, the Ae 105 students reach the promised land of flight hardware. The class is doing a theoretical analysis of the telescoping mast for the Nuclear Spectroscopic Telescope Array, or NuSTAR, slated to launch in 2011. A partnership between Caltech, JPL, and 10 other organizations and headed by principal investigator Fiona Harrison, professor of physics and astronomy, NuSTAR is an X-ray telescope. Since X rays go through pretty much everything, you have to place any optics intended to focus them at a very shallow angle. This means they have to be quite some distance from the detector, which is a problem if you're designing a compact spacecraft that's relatively inexpensive to launch. Hence the deployable mast—essentially a set of collapsible cubes stacked one atop another—which, when fully extended, will hold the mirrors 10 meters away from the spacecraft.

This summer, some of the Ae 105 students and some JPL new hires assigned to the mission will begin actual deployment experiments with real prototypes. In the fall, the 2008–09 academic year will mark the start of a four-year program of collaboration with the NuSTAR team as the mission develops. That first year, students will be doing mission planning. The second year, 2009–10, will see the hardware design and procurement. The third year, 2010–11, will be NuSTAR's assembly, test, and launch. And the final year, 2011–12, will monitor the hardware's performance in orbit. "We will repeat this cycle every four years with a new JPL mission," Rosakis says.

Next year, Ae 105 will be overseen by Professor of Aeronautics and Civil Engineering Sergio Pellegrino, just recruited from the University of Cambridge, England, where he founded the university's Deployable Structures Laboratory in 1990. (He is also teaching Ae 221, Space Structures.) "There are many joint Caltech-JPL appointments," says Rosakis, "but they took the joint appointment after being hired by Caltech. This is our first professor to be hired by a joint Caltech-JPL committee." This arrangement will give JPL access to a large chunk of Pellegrino's time, and allow him unfettered access to JPL.

Pellegrino is no stranger to expandable structures. His office is crammed—or will be, when he finishes unpacking—with models that would make excellent toys, should someone care to mass-produce and market them. Some of them are solid shapes, like the circular plate that expands into a lacy circle about twice its original size. Others look like bundles of sticks, joined by hinges on their ends. Shake out the bundle, and four sticks become a square, six a hexagon, and so on. Put a wire mesh on that framework, says Pellegrino, and voilà! You have a radar array. Pellegrino and his collaborators have worked out general mathematical techniques for dealing with both classes of objects, so that "when people have a particular problem, they can go to the general theory and pull out the specific geometry they need. I don't like to work on problems no one could make use of."

In the years to come, Pellegrino and Harrison will be co-teaching a course devoted to NuSTAR. It's not yet in the catalog, and so doesn't have an

Pellegrino holds an expandable sphere—a 3-D version of the expandable circle mentioned above—that might make a dandy space habitat as a hollowed-out shell.

GALCIT-JPL connections then and now. Right: Allen Puckett (PhD ’49), a grad student of von Kármán’s, designed several supersonic wind tunnels for the then-Army laboratory. In the front row at the January 1947 groundbreaking for one of them are, from left, Clark Millikan (PhD ’28), professor of aeronautics and future GALCIT director; Puckett; Louis Dunn (BS ’36, MS ’37, MS ’38, PhD ’40), JPL director and associate professor of aeronautics; Caltech president Lee DuBridge; Major General Everett S. Hughes; von Kármán; and Robert A. Millikan, professor of physics and Caltech president emeritus. Far right: Two of the aerospace master’s degree program’s prime movers—Rosakis (at far right) and Dimotakis (at far left)—are alumni of Athens College, a Greek-American high school in Athens, Greece . . . as are (middle left) Sterge Demetriades (Eng ’58), retired from a long aerospace career, and Alexis Livanos (BS ’70, MS ’73, PhD ’75), president of Northrop Grumman Space Technology and chair of the GALCIT advisory council. This picture was taken at the 50 Years in Space conference.

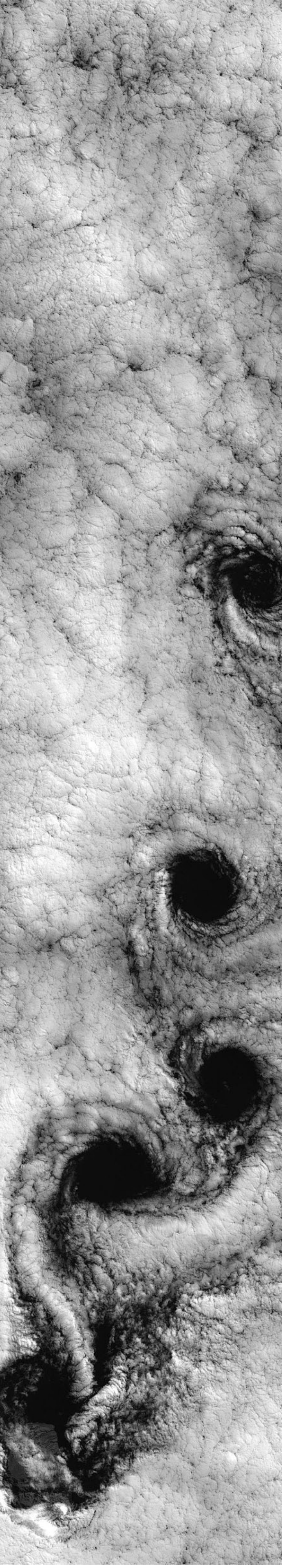
official number, but it will be called On-Orbit Performance of Large Deployable Space Structures. “As the design and construction of the mission continues, the students will be doing hands-on work with the flight hardware,” says Pellegrino. They’ll be creating a diagnostic package that will use cameras and other techniques to watch the boom as it deploys. Rosakis says the package will “look at the mechanics of the expanding boom, and make sure that it goes where it has to go and how it vibrates in the process. That has nothing to do with the science mission of NuSTAR directly. It has to do indirectly, because it helps in the positioning of the instrument, but it is a mechanics and an optics problem.”

The grad students won’t have all the fun—there will also be Summer Undergraduate Research Fellowships (SURF) available. “Fiona was very inspired by President Chameau’s call for new opportunities for the students to learn,” Pellegrino says.

The new program is housed in a completely remodeled Guggenheim Aeronautical Laboratory. Built in the late 1920s as a shell wrapped around a wind tunnel with a 10-foot-diameter working section—the biggest and fastest wind tunnel on the West Coast, capable of generating sustained flows of up to 200 miles per hour—much of the cavernous space has been underutilized since the wind tunnel was decommissioned in 1997. The new interior, designed by John Friedman Alice Kimm Architects, has already won a 2007 American Institute of Architects, Los Angeles Chapter, Next L.A. Merit Award—one of 10 among a couple of hundred submissions. “This project allowed us to do a little more experimentation than usual in terms of design,” says Kimm, the lead architect. “It was a really exciting project, with lots of digital modeling techniques. The design committee [Rosakis; Guruswami Ravichandran, the Goode Professor of Aeronautics and Mechanical Engineering; Morteza Gharib (PhD ’83), the Liepmann Professor of Aeronautics and professor of bioengineering; Assistant Professor of Aeronautics Beverley McKeon; and option administrator Dimity Nelson] was very forward-looking.” The interior’s organic forms “were based on turbulent flow diagrams from the aerospace faculty,” says Friedman. “Now you don’t send mechanical drawings to the shop any more, you send digital files to a CNC [computer numerical controlled] machine.”

All the corridor walls follow graceful curves rather than straight lines. “There are no oblongs here. No circles, either. It’s all about the flow,” says Rosakis proudly. The lobby features a translucent, undulating ceiling with large, shallow, backlit dimples that produce moiré-like patterns. The lantern, as Kimm calls it, is reminiscent of the dimpled wing surfaces that McKeon studies. Decorative elements throughout the building reflect other researchers’ work, and a number of artifacts from the old building have been incorporated as well, including a control panel from the old 10-foot wind tunnel that has been mounted into a wall on a third-floor corridor.

The centerpiece of the new Guggenheim—the Laboratory for Large Space Structures—is Pellegrino’s province. The lab occupies much of the ground floor and includes a two-story-tall “high bay,” an open space big enough to accommodate an Apollo moon lander. Windows look into the high bay from the second floor outside, making it part lab and part interactive display. The high bay’s first occupant will be NuSTAR’s truss—a perfectly rigid structure in the microgravity of space, but incapable of supporting its own weight when extended to full length parallel to the ground. In order to test such ultralightweight—one could even call them flimsy, but in a good way—structures here on Earth, they need to be “gravity compensated,” which essentially involves suspending them from wires like X-wing fighters hanging from the ceiling of a 14-year-old’s bedroom. The suspension systems may include pulleys, counterweights, and



servomotors to balance the changing forces. “As the structure deploys, the suspension has to move with it,” Pellegrino explains. “And so a high ceiling is good, because the angles of the wires change less.” Mounting the pulleys on tracks doesn’t help, says Pellegrino. “Fixed wires are better than tracks, because the structure would only be able to go in a straight line to follow the track. And tracks have friction, so they’ll drag. So wires are actually better, not to mention cheaper!” Pellegrino also works with inflatable structures—if you’ve ever blown up an air mattress straight out of the box, you know that it doesn’t always unfold precisely as planned—and with composite materials that can be formed into thin, stiff things like antenna dishes. Equipment for making and testing these kinds of structures will be housed in the lab as well.

Wrapped around the second floor of the high bay is the Gordon Cann Laboratory of Experimental Innovation. This lab will house Ae/APh 104, Experimental Methods, which, says Rosakis, “is a signature course. No other university has a required full-year graduate-level experimental course. They are all simulations and numerics.” The class teaches solid- and fluid-mechanics methods of all sorts in one dedicated lab space. The facility includes clean rooms, a transmission electron microscope, materials testing equipment such as a coherent gradient sensing (CGS) laser-interferometry system for measuring how materials and structures deform under stress, and particle-velocimetry equipment to see how fluid flows behave, and even small wind tunnels. “Students used to have to go from lab to lab and from professor to professor for all these different things,” Rosakis says. Down the hall will be the new von Kármán Conference and GALCIT Archives room, underwritten by Bob Herzog. The third floor will include two new labs for student experiments, and the Allen Puckett Laboratory of Computational Fluid Mechanics, which includes a seminar room and open-plan computer-lab area, plus open spaces designed to hang out in.

The renovations have even spilled over into the second floor of the adjoining Karman Laboratory of Fluid Mechanics and Jet Propulsion, where the Joe Charyk Biomechanics Laboratory has been located. This facility will house work being done by Gharib and by John Dabiri (MS ’03, PhD ’05), assistant professor of aeronautics and bioengineering, on bioinspired designs of such things as low-power propulsion systems for exploring worlds with dense atmospheres—picture a robotic jellyfish pulsating its way through Jupiter’s clouds, for example. (For more on Dabiri’s work, see his 2007 *Caltech News* profile, in Volume 41, Number 1.)

Cann (MS ’56, PhD ’61), Herzog (BS ’56, MS ’63, Eng ’64), Puckett (PhD ’49), and Charyk (MS ’43, PhD ’46) are all GALCIT alumni. Two of them have left quite a mark on aerospace themselves. Puckett, now retired as chairman of Hughes Aircraft, designed and built the United States’ first supersonic wind tunnel while still a grad student. And Charyk, a former undersecretary of the Air Force, was the founding president of the Communications Satellite Corporation, or COMSAT, which in 1965 launched the world’s first geosynchronous communications satellite to beam TV broadcasts and telephone conversations between Europe and North America.

Even though the new labs will have been in use over the summer, they will officially open on September 26, when President Chameau cuts the ribbon as part of the celebration of the 80th anniversary of Guggenheim’s completion and the birth of GALCIT. But the highlight of this two-day party will probably have been the previous evening, when astronaut Gregory Chamitoff (MS ’85) addresses the banquet attendees from aboard the International Space Station just before GALCIT’s Aerospace Historical Society awards the 23rd Annual International Wings of von Kármán Award to Alexis Livanos (BS ’70, MS ’73, PhD ’75), president of Northrop Grumman Space Technology and a 2008 Caltech Distinguished Alumnus. Incidentally, that afternoon’s keynote speaker, David Thompson (MS ’78), chairman and CEO of Orbital Sciences Corporation, once said, according to Rosakis, that “the reason he left GALCIT, as did Chamitoff—they did not get PhDs with us—is that we did not have a concentration in space. This shows the need. Thompson actually said that that was one of his biggest disappointments, because he really wanted to work in space.”

And work in space these new degree holders will. Virendra Sarohia (MS ’71, PhD ’75), who works in the chief technologist’s office at JPL as liaison to Caltech, is in charge of making that happen. He’s on the Caltech-JPL committee that recruits JPLers to teach in the program, but his broader role, says Rosakis, is to facilitate the research connections between Caltech professors and JPL scientists in a way that will lead to thesis topics for the students. “So that’s why it’s important that he is a GALCIT graduate who is intimately familiar with JPL research and Caltech research.” Besides brokering these “arranged marriages,” Sarohia oversees the JPL summer fellowship program that lets program graduates work full-time in space before going on to a PhD and, Rosakis hopes, a career in the space business. “One cannot change the world with nine students, but perhaps one can. I would be very happy if one of them became a future director of JPL, and a few others become CEOs of major aerospace companies in Southern California, and maybe in 10 years one will become another von Kármán.” □

Von Kármán vortices off the Chilean coast near the Juan Fernández Islands.

PICTURE CREDITS: 36, 37 — Bob Paz; 34–35 — NASA Landsat; 37 — Caltech Archives