If astronomers and agencies from six continents can work together, the world's largest telescope may rise in the next decade—with a radical new design

Tuning In the Radio Sky

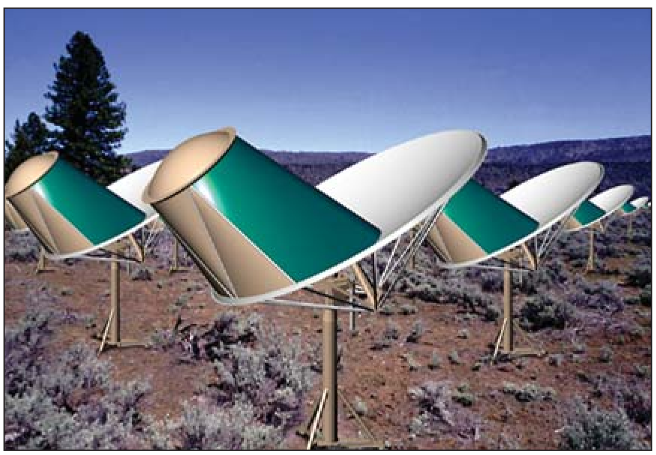
HAT CREEK RADIO OBSERVATORY, CALIFORNIA—From the controls of his Cessna, astronomer Jack Welch points to a clearing in Lassen National Forest. There, in this isolated spot in northeastern California, ten 6-meter telescopes stare at the sky—a modest array by the standards of radio astronomy. But by 2005, something more grand will take its place: a cluster of 350 radio dishes, acting in unison to view the universe and watch for signs of life elsewhere.

Two volcanoes, Lassen Peak and Mount Shasta, overlook the site of this project, called the Allen Telescope Array (ATA). That's fitting, for the array's concept—many receivers linked by cheap electronics—is rumbling through radio astronomy. By cutting the structural costs of huge dishes and instead combining signals from many small detectors, radio astronomers aim to explore the cosmos electronically at a nonastronomical price.

"In a metaphorical sense, we're learning how to build telescopes out of computers, not metal," says physicist Kent Cullers of the SETI [Search for Extraterrestrial Intelligence] Institute in Mountain View, California. "This is the future of radio astronomy," agrees astronomer Leo Blitz of the University of California (UC), Berkeley, which is building ATA with the SETI Institute. "If you want to build a large telescope for a fixed amount of money, I can no longer think of any reason to build a single large dish."

Cullers and Blitz are confident that 12 to 15 years hence, this trend will produce a telescope of breathtaking scale: the Square Kilometer Array (SKA). As its name implies, this instrument would gather radio waves with a combined detecting area of a full square kilometer—making it 100 times more sensitive than any existing array. SKA would expose the now-invisible era when hydrogen first clumped together, tracing the "cosmic web" of dark matter that underlies all structure in the universe. Other studies unique to SKA's radio window include mapping magnetic fields in and among galaxies in exquisite detail, finding thousands of pulsars and using them to track gravitational ripples in space, and extending the search for intelligent life to tens of millions of stars.

Plans call for SKA to reap this scientific harvest by spreading its detectors across more than 1000 kilometers of land. But despite the economy of mass production, it may cost $1 billion to build. That's why a formal international consortium of radio astronomers is pushing SKA as a global project from the outset. Scientists on six continents have contributed ideas for its design and location, sparking a creative outburst that the field hasn't seen in 30 years. "Radio wave astronomy has been so productive, but there is still much to do," says Peter Dewdney of Canada's National Research Council in Penticton, British Columbia. "We think SKA deserves a place among the world's great telescopes of the next decade."



New-wave radio. The Allen Telescope Array, a planned network of 350 radio dishes in California, relies on low mass-production costs.

CREDIT: SETI INSTITUTE

Skating toward SKA

When proponents make the case for including SKA in their future, they often point to radio astronomy's past. For example, three of the five Nobel Prizes in astronomy have rewarded work at radio wavelengths. Moreover, the instrument responsible for the second-highest annual rate of publications in astronomy—behind only the Hubble Space Telescope—is the Very Large Array (VLA), a network of 25-meter radio dishes in Socorro, New Mexico.

That record hides a small surprise: VLA's 27 dishes run on 25-year-old technology. "The VLA was completed in 1980, but it hasn't been upgraded at all," says Welch, who pilots a faded yellow Plymouth Valiant during the half-hour drive to Hat Creek Radio Observatory from the nearest airfield. A $60 million, decade-long project to improve VLA has now begun, he notes, "but it's clear that ultimately we will need a new general-purpose telescope with much more collecting area."

Such wave-gathering prowess would give SKA the sensitivity and breadth of the best optical telescopes, says Welch, who conceived the ATA project at UC Berkeley. Today, astronomers can combine signals from widely separated radio dishes to make sharp images, but the objects must be bright and can't cover much area on the sky. As astronomer Alyssa Goodman of Harvard University puts it: "Radio astronomy leads to Nobel Prizes but not pretty pictures. It would be nice if it led to both."

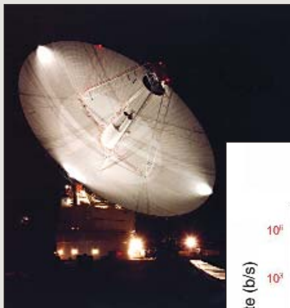
Some efforts are already under way. At millimeter wavelengths—the high-frequency end of the radio spectrum—construction will soon begin on the long-awaited Atacama Large Millimeter Array (ALMA), a joint U.S.-European effort to build 64 12-meter dishes high in the Chilean desert. The U.S. National Radio Astronomy Observatory (NRAO) opened its 100-meter Green Bank Telescope in West Virginia last year, and astronomers at the 300-meter Arecibo Observatory in Puerto Rico and in Australia, France, India, Italy, and the United Kingdom have recently constructed or substantially upgraded their facilities.

Still, many note that the average hair color at radio astronomy meetings is becoming grayer. "A huge number of us entered the field in the 1960s," says astronomer Donald Backer of UC Berkeley, noting that Arecibo and Jodrell Bank Observatory near Manchester, U.K., were vital destinations. "That's not happening now. ATA and SKA are exciting, but they have yet to pull in students."

If SKA does not enjoy the same cachet among astronomers as major plans in the optical, infrared, x-ray, and other wavelengths, it may be because such a huge and radical concept still seems so foreign. "I was so ignorant of this subject that I thought the telescope was built square to make the Fourier transforms easier," joked astrophysicist Roger Blandford of the Cali-

Space Communication for the Video Age

Radio astronomers aren't the only ones enamored of huge arrays of cheap receivers. The concept has also caught the eyes of NASA engineers, who long to overhaul the agency's aging Deep Space Network (DSN).

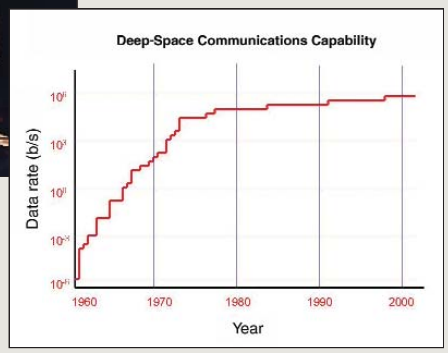


Consisting of three 70-meter dishes and several smaller antennas in Spain, Australia, and Goldstone, California, DSN is NASA's link to probes that explore the solar system. Since the mid-1970s, its capacity has gone up only modestly. This factor, along with basic transmitters and computers on spacecraft, has stuck space exploration on snapshot mode in a video age.

For a near-term boost, NASA has upgraded its Goldstone receiver to work at a frequency of 32 gigahertz rather than 8 gigahertz, says Barry Geldzahler, program executive for space operations at NASA headquarters in Washington, D.C. That conversion throughout the DSN system—to be completed by 2006—will quadruple data transmission above the current rate of about 100 kilobits per second for a probe at the distance of Jupiter. Other plans include more efficient software on spacecraft and refurbishing the ground antennas. "The infrastructure has been allowed to go fallow," Geldzahler acknowledges. "In our budget priorities, missions have come first."

It's vital to hike DSN's capacity much further, says electrical engineer Sander Weinreb of NASA's Jet Propulsion Laboratory (JPL) in Pasadena, California. With a data-transfer rate of 10 to 100 megabits per second, "the virtual exploration of planets could take place," he says. "Instead of a rather coarse image on a newspaper page, we could have real-time television, even high-definition video." Each mission could also send back far more data at other wavelengths for deeper analysis of atmospheres and surfaces. More collecting area on Earth would also mean smaller transmitters on spacecraft, reducing their weight and size and perhaps eliminating the need for orbiters to relay data from planetary landers.

NASA is exploring two options to realize those gains by next decade, Geldzahler says. One is to move communications to the high data rates of optical light, with lasers on spacecraft and 10-meter telescopes on the ground. But if telescope costs prove prohibitive, NASA may mimic the approach of the Allen Telescope Array. Weinreb and his colleagues at JPL will soon submit a proposal to NASA for a prototype DSN array of 100 12-meter radio antennas. Beyond that, Weinreb says, "DSN and the Square Kilometer Array [SKA] could go hand in hand. There is a lot of common technology."



Deep dish. Data rates have gone up slowly since 1976 (graph) for NASA's Deep Space Network.

Radio astronomers think the solution is clear. "I see the connection between DSN and SKA as completely obvious," says Alyssa Goodman of Harvard University in Cambridge, Massachusetts.

–R.I.

fornia Institute of Technology in Pasadena. But after he looked into it, Blandford became a convert. "In a 1° field of view, you'll see 300,000 extragalactic sources," he says. "It will be a splendid probe for cosmology, and it will discover completely new sources as well."

Venture capital

Blandford's latter point is one that SKA's organizers would like to sell. "It's quite possible that the main thing this instrument will do is to show us something that no one expected," says the SETI Institute's Jill Tarter, chair of the U.S. SKA consortium. But Tarter and her collaborators acknowledge that the lure of the unknown won't sway funding agencies. "In today's climate, you need a sharply focused scientific case," Backer says. "We won't get $1 billion to build the next bigger thing just because we can."

So, SKA's partners focus their pitch on the web of primordial hydrogen, which Backer calls "as rich a prize as the cosmic microwave background itself." Hydrogen suffused the dark era between the origin of the microwave background—when atoms first formed and light streamed freely into the cosmos—and the birth of the first stars and galaxies. A neutral hydrogen atom emits radiation at a wavelength of 21 centimeters when its lone electron flips its spin. As space expands, this weak signal from the early universe stretches into tenuous wisps of meters-long radio waves. They will penetrate through everything, giving astronomers a clear view of mass concentrations in the infant universe.

Due for a tune-up. The productive but aging Very Large Array is getting a decade-long upgrade.

CREDITS: (TOP TO BOTTOM) NASA JPL; COURTESY OF DAYTON JONES/NASA JPL; NRAO

"A square kilometer is not a random size," says astronomer Harvey Butcher of the Netherlands Foundation for Research in Astronomy (ASTRON) in Dwingeloo. "If you put the Milky Way at the very beginning of galaxies, you need a square kilometer to be able to detect it, given the sensitivity of receivers today."

Various components of our galaxy's ancestors will pop into focus for SKA. Radio signatures of carbon monoxide and other molecules will trace the history of heavy elements in early galaxies. The whirlings of coherent microwave emissions from vast clouds of water vapor, called megamasers, promise to expose some of the most distant supermassive black holes at the cores of active galaxies. Closer to home, SKA will resolve the magnetic fields that lace through galaxies and the cradles of stars within them.

Within the Milky Way, SKA should find at least 10,000 pulsars, the dense, spinning remnants of exploded stars. The telescope will track the relative rotation speeds of the fastest of these beacons with an accuracy of better than a millionth of a second. Albert

Seeking Peace in a Radio-Loud World

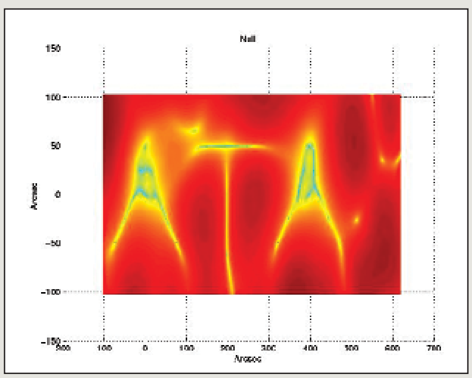
Although radio astronomers adore the technology the communications industry has spawned, they detest some of its byproducts: blaring antennas, swarming satellites, and chatter-filled airwaves that threaten to wash out dim sources in the sky.

For years, treaties have shielded key parts of the radio spectrum from commercial interference. For example, at the 2000 World Radiocommunication Conference in Istanbul, Turkey, regulators preserved big chunks of the spectrum at millimeter wavelengths to benefit the planned Atacama Large Millimeter Array in Chile and other high-frequency observatories. Some facilities—such as the 100-meter Green Bank Telescope in West Virginia—also sit within "radio preserves," where terrestrial signals are curtailed.

However, such measures aren't cure-alls. Commercial pressures squeeze broadcasters and satellite operators into frequencies next to those in which astronomers try to work, and their signals often bleed into the "protected" bands. Satellites, which don't turn off above radio preserves, will only become more numerous. And as astronomers build more-sensitive radio telescopes to peer into deep space, many observations will shift into commercial wavebands—thanks to the expansion of the universe, which stretches all emissions to longer wavelengths.

Planners for the Square Kilometer Array (SKA) crave a true radio-quiet zone where satellites might not transmit, such as the sparsely populated Australian outback. The Global Science Forum of the Paris-based Organization for Economic Cooperation and Development is sponsoring a task force to study this notion—and to convince industry that tight control over signal leakage makes smart business sense. "The satellite community is certainly much more aware of the radio astronomy problem" than in the past, says Tomas Gergely, program manager for electromagnetic spectrum management at the National Science Foundation. "But to have total access to the spectrum at any one place on Earth is impossible in my view."

Fortunately, the arrays of smaller elements in most SKA designs offer a way to cope. By delaying some of the signals relative to others, astronomers can suppress radio waves in arbitrary patterns on the sky—just as a light beam passing through slits creates an interference pattern of bright fringes and dark spots. Astronomer Geoffrey Bower of the University of California (UC), Berkeley, has shown that a seven-antenna prototype of the Allen Telescope Array (ATA) can beat down signals from satellites by a factor of 1000. This technique, called interferometric nulling, will be even more powerful on the full 350-telescope array. "The radio sky over ATA will look like Swiss cheese," says Jack Welch of UC Berkeley. "Each satellite will have a little nulled horizon around it. Otherwise, their emissions would go off-scale."



Null and void. Manipulating waves from the Allen Telescope Array will suppress radio interference in any pattern on the sky (blue).

CREDIT: GEOFFREY BOWER/UC BERKELEY RADIO ASTRONOMY LABORATORY

A combination of more efficient satellites and clever nulling just may make SKA feasible, says astronomer Michael Davis of the SETI Institute in Mountain View, California, former director of the Arecibo Observatory in Puerto Rico. "We are asking satellite engineers and operators to be technically innovative and creative," Davis says. "We have no standing if we don't also do that ourselves." –R.I.

Einstein's theorized gravitational waves—ripples in the fabric of spacetime caused by massive disturbances, such as coalescing black holes in the centers of distant galaxies—may flutter the apparent motions of the pulsars enough for SKA to detect.

SKA's ability to focus on much larger patches of the sky than ALMA also will make it an ideal radio survey tool, says astronomer Jim Cordes of Cornell University in Ithaca, New York. Cordes is eager to observe what he calls the "transient radio sky"—bursts and new objects that may come and go in days or weeks. "We are very behind our colleagues at other wavelengths in exploring the transient sky," Cordes says. For instance, SKA might see the afterglows of distant gamma ray bursts, only 1% as bright as any seen so far, or even bursts that appear only in radio waves.

The wide field of view also will make SKA ideal to search for blips from other civilizations. Electronic processing will let Tarter and other SETI Institute astronomers monitor many stars in the same viewing area as another object being studied. Even if such signals are merely "leakage" of alien radio or TV equivalents, SKA could pick them up from deep within our Milky Way. That's a far cry from the slow pace of searching today, says Welch. "Even with Arecibo, we couldn't hear Howdy Doody beyond Alpha Centauri," the closest star, he observes.

Global by design

Welch and Tarter, who are married, and their colleagues at the SETI Institute and UC Berkeley are building ATA to deepen their own research, but they clearly view it as the forerunner to SKA. At a projected \$26 million, ATA will provide roughly the same collecting area as the single-dish Green Bank Telescope at one-third the cost. Its oddly shaped 20-foot aluminum dishes (the manufacturer disdains metric units) will be pressed out by a satellite-dish outfit in Idaho Falls, Idaho, over the next 2 years at the rate of one every other day. "We're light, we're agile, and we're quick," says UC Berkeley's Blitz.

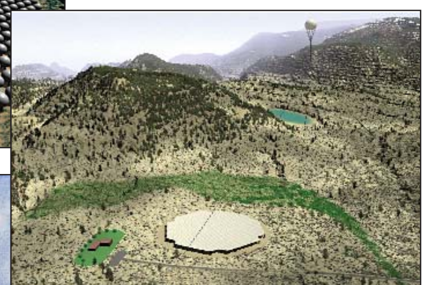
ATA also represents a sociological breakthrough for the field. Its funding is entirely private—nearly all of it from technologist Paul Allen, the co-founder of Microsoft and a big SETI Institute fan. "We run this like a skunk works," says project scientist John Dreher of the SETI Institute. "There are minimal reviews and no ponderous government management structure. We just have to keep one panel happy."

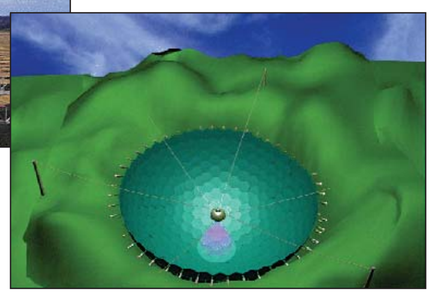
Scaling ATA up to a SKA-sized network would take thousands of dishes, each one perhaps 12 meters across. Making that financially feasible will require further cost reduction by a factor of 3 or 4, Welch estimates. India also is pursuing a similar concept for SKA, so the two countries may exchange ideas about how to bridge that cost gap.

The leading alternative to the many-dish idea, in the minds of most observers, would look like fields full of simple looped wire antennas or wires embedded in tiles. Spearheaded by ASTRON, this concept may arise within 5 years as a \$75 million project called the Low-Frequency Array, or LOFAR. "The basic element of LOFAR is really cheap: It's just a long string of wire," says physicist Joseph Lazio of the Naval Research Laboratory in Washington, D.C., a partner in LOFAR with the Massachusetts Institute of Technology. "It's essentially a big FM radio."

LOFAR would focus on wavelengths between 0.5 and 10 meters. About 10,000 wire detectors would spread out in a 400-kilometer-wide pattern in northern Europe, the southwestern United States, or western Australia—forming a possible precursor to SKA. Unlike ATA, LOFAR would "see" most of the sky at once; computer processing would let the researchers retrace where the signals came from.

The challenge of SKA has spurred creative ideas from other countries as well. Astronomers in China envision 20 giant radio dishes, each 500 meters across, suspended within bowl-shaped depressions in limestone formations. Hydraulic supports beneath the panels would adjust them to the proper shape for focusing on a patch of sky. "We have identified a beautiful site in the Guizhou Province [in south-central China]," says astronomer Rendong Nan of the Beijing Astronomical Observatory (BAO). "It's better than Arecibo." Nan and his colleagues have built prototype panels, and they await decision next year on a $50 million construction proposal to the Chinese Academy of Sciences for one dish.





Sky's eyes. Concepts for the Square Kilometer Array include proposals from (*clockwise from top*) Australia, Canada, China, and the Netherlands.

CREDITS: (CLOCKWISE FROM TOP) EN SIMONS/SYDNEY VISLAB; NRC-CNRC; BAO; ASTRON

Two other proposals have delighted consortium members with their ingenuity. Astronomers in Canada devised plans for a series of 200-meter-wide reflecting panels, gently curved but mostly resting on the ground. An 18-meter-long aerostat far overhead would carry each telescope's detectors. By adjusting the aerostat's position over the panels with a series of taut tethers, astronomers would bring different parts of the radio sky into focus.

Australia, meanwhile, has come up with something completely different: fields full of spherical "Luneburg lenses." Each lens, perhaps 6 meters across, would contain a polymer foam that refracts radio waves to precise focus on the opposite side of the lens. Detectors ringing the lower halves of the lenses would collect the signals.

As for where to put SKA, regardless of its design, Australian radio astronomer Ron Ekers has a simple answer. "If you're going to spend a billion dollars, you build it in the best place on Earth," says Ekers, incoming president of the International Astronomical Union. Consensus is building toward western Australia, says Cornell astronomer Yervant Terzian, head of the SKA site-selection committee. At that site, radio interference is minimal and there's plenty of room to spread the array over 1000 kilometers or more. Brazil and Argentina have expressed interest, as has South Africa. Radio astronomers in the southwestern United States feel that the setting around VLA is a strong choice as well.

Cash across borders

The international SKA steering committee, also headed by Ekers, gathered "straw man" design proposals this week and will debate their merits at an August meeting in the Netherlands. The group then plans to choose a design—or a hybrid of two designs at different wavelengths—and one or two sites to evaluate in detail in 2005. Three years after that comes the big step: approaching agencies in all of the member governments for funding. If that succeeds, mass production would begin by 2010, with "first light" in 2015.

To stick to that timetable—and to SKA's $1 billion cost cap—the project must clear both technological and political imponderables. Will the cost of electronics and computer analysis of thousands of discrete signals keep dropping exponentially for another decade? If so, SKA participants say, their project will be affordable—assuming the money is there. "I'm not so worried about people being chauvinistic about their technologies," says astronomer Douglas Bock, an Australian native now at UC Berkeley. "But I am worried about the politics of getting funding in an international situation. A lot of countries are very parochial about how they fund their science." One or more countries in the consortium may be loath to invest outside their borders, some astronomers say privately.

The rough fiscal menu calls for the United States and Europe each to finance one-third of SKA, with the remaining one-third from other countries. The initial commitment for major construction funding will be the toughest row to hoe, says Paul Vanden Bout, director of the National Radio Astronomy Observatory in Charlottesville, Virginia. He points to the U.S.-European ALMA project in Chile as an example. "We might have talked for a very long time indeed if the National Science Foundation [NSF] had not been willing to fund the millimeter array for design and development work, thus signaling that they were serious about contemplating this for real construction," he says. "Unless one of the parties steps up and throws some real cash at SKA, the conversation about it could go on for a long time."

Ekers smiles gently when he hears such comments. "That's a typically U.S. view," he says. "There are other models to follow. We have always looked at this decade as time for research and development and next decade as the funding one. We know that ALMA will take manpower and resources from the U.S. and Europe, and that gives us time to build prototypes."

Individual countries in the formal SKA consortium are each kicking in about $500,000 to $2 million per year for R&D within their borders. Apart from the private ATA, the U.S. is at the low end. NSF recently granted the U.S. SKA consortium $1.5 million for 3 years via a grant to Cornell University, less than one-third of its request. Last year, a national panel of astronomers recommended that SKA receive $22 million in total funding for technology development in this decade. "A half-million dollars per year is what we can do for now," says G. Wayne Van Citters, director of the Division of Astronomical Sciences at NSF. "We hope to ramp it up as the decade goes on."

Design ideas may differ, but SKA enthusiasts tend to agree on one thing: The flow of the money stream, whether trickle or torrent, simply will alter the year in which SKA first scans the heavens. "I view these developments as inevitable," says ASTRON's Butcher. "If they don't happen in my generation, then my generation has failed."

–ROBERT IRION