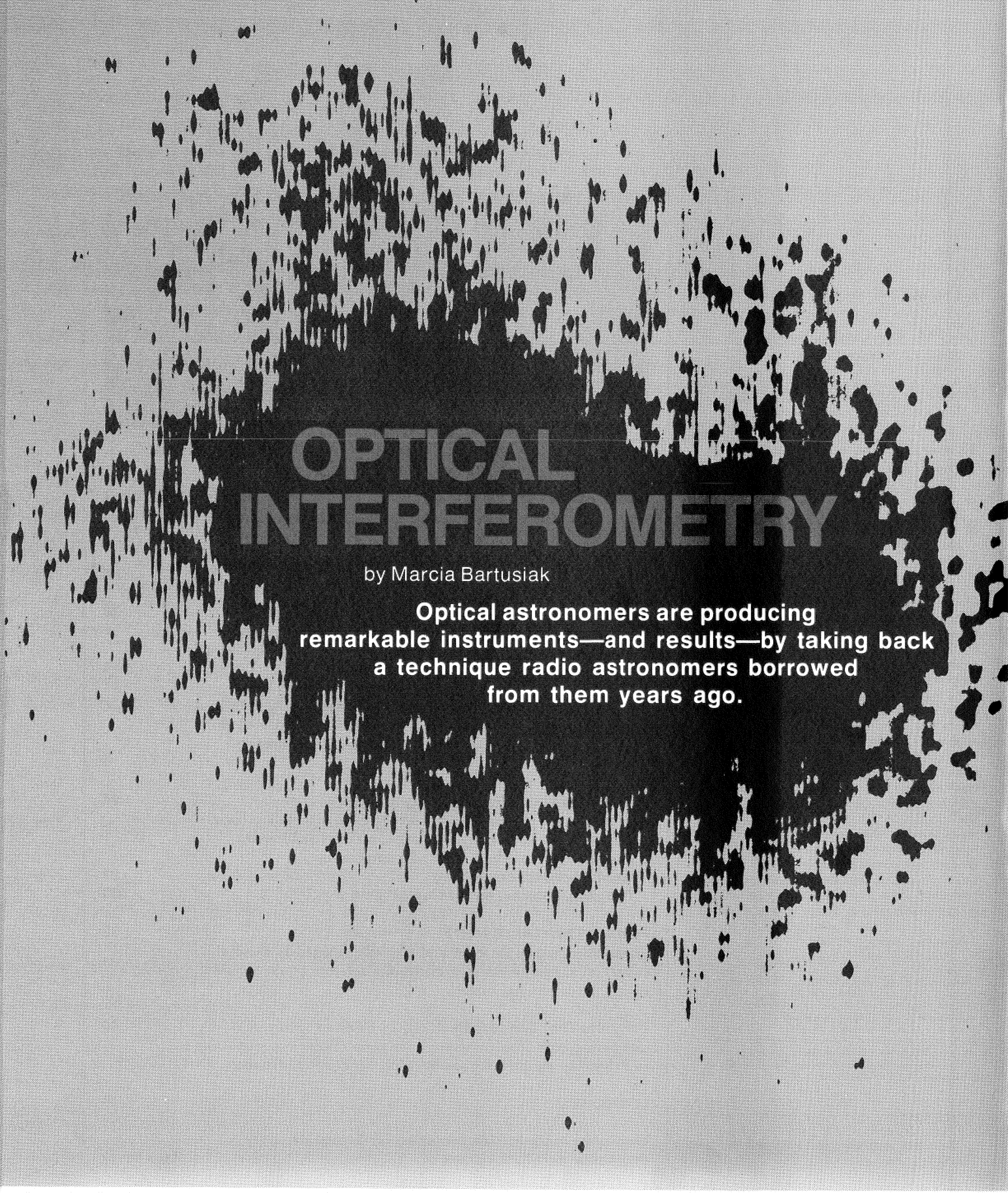


OPTICAL INTERFEROMETRY

by Marcia Bartusiak

Optical astronomers are producing remarkable instruments—and results—by taking back a technique radio astronomers borrowed from them years ago.

As seen from the earth, stars twinkle. Magnified, stellar images dance like objects seen through heat waves coming off the pavement on a hot summer's day, and for the same reason: the refraction of light as it passes through turbulent air. That stellar twinkle is the astronomer's bane. It reduces the resolving power—the ability to distinguish between adjacent points—of their largest telescopes to that of instruments a fraction the size. The diameter of a telescope's light-catching lens or mirror, its aperture, still determines the instrument's ability to gather light, to detect fainter, more distant objects. But as long as telescopes are earthbound, peering through the earth's blanket of atmosphere, enlarging the aperture will not improve resolving power. Even the five-meter Hale Telescope on Mount Palomar can resolve objects no closer together than one arc second, 0.00028 degree. A decent 15-centimeter telescope can do that.

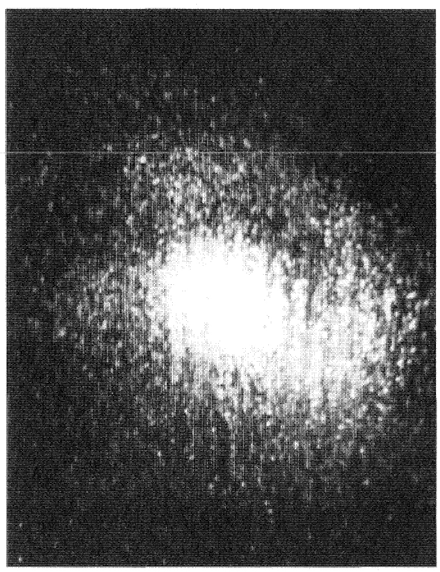
One-arc-second resolution is enough to make the label on a tennis ball legible 15 kilometers away. For astronomers who are trying to resolve the disks of nearby stars, generally visible only as virtually dimensionless points, that is not nearly good enough; they need to be able to see that tennis ball from as far away as the moon. "Even the biggest stars are not resolved with just one-arc-second resolution," says Charles Townes of the University of California at Berkeley, a physicist turned astronomer, "so it's important that we try to get higher resolutions."

Optical astronomers are not the only ones with resolution problems. The resolving power of a telescope depends generally on the ratio of the wavelength of the energy being collected to the aperture of the telescope. Since radio waves are relatively long—tens of centimeters—radio telescopes come out of that ratio faring very poorly. Even the largest radio telescopes have resolutions of roughly only one arc minute, 60 arc seconds. To obtain a one-arc-second resolution would require a radio antenna tens of kilometers across.

To produce such an instrument, radio astronomers turned to an optical technique called interferometry. An interferometer combines signals that are emitted by a single source and received at separate collectors. Analysis of the interference patterns produced by the mixing of the wavefronts arriving at each collector reveals characteristics of the source. The distance between the collectors simulates the diameter of a single collector, or aperture in astronomers' usage.

Radio astronomers have been linking telescopes in interferometric networks for some 30 years. (See "The V[ery] L[arge] A[rray] Turns On," *Mosaic*, Volume 9, Number 2.) Instruments called long-baseline interferometers have produced synthetic apertures as large as 10,000 kilometers, with one end in California and the other in Australia, half a world away. A hemisphere-spanning array of ten 25-meter dish antennas—to produce a resolution of 0.0001 arc second—is being planned, and satellite-to-satellite interferometers stretching across distances many times the diameter of the earth are being considered.

Interferometric astronomy at optical wavelengths, however, has lagged far behind its radio sibling, and for good reason: The wavelength of radiation in the radio region of the electromagnetic spectrum is measured in tens of centimeters, the wavelength of light in thousands of angstroms—hundred-thousandths of a centimeter. For radio frequencies, with their long wavelengths, mismatches of a few wavelengths are acceptable and easily handled. Light waves, however, offer no such easy margins. Wavelengths a millionth the size of radio waves present a formidable challenge to anyone trying to mix and match signals with any precision.



Interferometric fringes. By combining the beams from two separate telescopes, Antoine Labeyrie recorded fringes from the star Vega in the constellation Lyra.

Although the first tentative steps in the direction of optical interferometry were taken more than 60 years ago, it is only recently that sensor technology, automated control systems, and a better theoretical understanding of atmospheric turbulence have enabled scientists in Australia, France, and the United States to approach the problem systematically. So far, they have resolved the disks of a few dozen stars, observed the orbital motions of some binary star systems, and studied what are thought to be stars being born within dusty envelopes of molecular gas. These researchers are pioneers. Nonetheless, they are resuming an endeavor that began, and then faltered, more than half a century ago, long before radio astronomy was even a gleam in founder Karl Jansky's eye.

A stellar diameter

On December 13, 1920, high atop Mount Wilson in southern California, American physicist A. A. Michelson and his colleague F. G. Pease, using an optical interferometer, made the first successful measurement of a star's diameter. Their instrument was cumbersome—a 6-meter steel girder mounted in front of the Mount Wilson Observatory's 2.5-meter reflecting telescope. It collected starlight at two small, movable mirrors, one at each end of the girder. Other mirrors directed the light beams into the telescope, where they were combined at the focus.

As Michelson peered into this telescope-cum-interferometer, the star in view appeared as a coarse patch of light crossed by alternate bright and dark bands, or fringes. Because of their separation on the steel beam, each mirror was receiving a different portion of the wavefront coming in from the star. If the two waves were in step, or in phase, after they were brought together at the telescope focus, they would reinforce one another, producing bright bands. Where they were out of phase, the waves would cancel each other to form dark bands. "Michelson must have had a very fast eye," notes David Staelin, an electrical engineer at the Massachusetts Institute of Technology who has worked in both radio and optical interferometry. "The atmosphere causes the fringes to jiggle and flick through the image. But Michelson could not only see the fringes, he could also say how visible they were."

When the mirrors on a Michelson interferometer are close together, the intensity, or visibility, of the fringes is very high. But as the mirrors are moved farther and farther apart, the intensity diminishes. The diameter of the star is fully determined once the fringes vanish.

Each point on the apparent disk of a star can be thought of as producing its own fringe pattern. When the mirrors are separated just far enough to resolve the star, the patterns produced by the different parts of the star's disk will cancel each other out. The star's angular diameter is directly proportional to the wavelength of the starlight divided by the separation between the mirrors at that point.

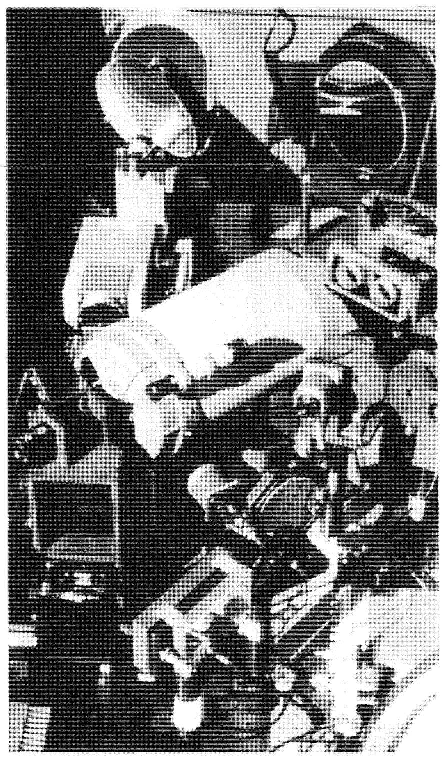
On that chilly December night more than 60 years ago, Michelson and Pease saw fringes disappear for the first time while looking at Betelgeuse, the red supergiant that forms the hunter's right shoulder in the constellation Orion. The mirror spacing was three meters, indicating that Betelgeuse was a disk 0.05 arc second across. In that one night, optical resolutions were improved twentyfold. For the first time, the angular diameter of a star other than the sun had been measured directly. It confirmed the enormous dimensions of objects such as Betelgeuse: The red giant would fill the earth's orbit.

During the following years, Michelson and Pease used their interferometer to measure the diameters of six other stellar objects. They were all nearby giant stars: Arcturus, Aldebaran, Antares, beta Pegasi (Scheat), alpha Herculis (Ras Algethi), and omicron Ceti (Mira). The small mirrors and six-meter baseline restricted observations to the closest and largest sources in the sky. Those successes, however, encouraged Pease, in the early 1930s, to construct a 15-meter instrument. It proved impossible to operate. "The mechanical beam was not stable," says Staelin. "It fluctuated as if it were made of plastic." Stability is crucial in the blending of two beams of light; the pathlengths from each telescope to the point of mixing can be permitted to vary by only a few wavelengths. Pease did not have the technology to keep his 15-meter girder steady.

An intensity interferometer

For the next 30 years the field was inactive, as still as the Michelson-Pease interferometer, wrapped in canvas and stored among the rafters of the 2.5-meter telescope's dome at Mount Wilson. The renaissance began in the outback of Australia, 550 kilometers west of Sydney, during the early 1960s. British radar pioneers R. Hanbury Brown and Richard Twiss, along with Jodrell Bank veteran John Davis, set up a vastly different kind of stellar interferometer near the small country town of Narrabri, under the aegis of the University of Sydney. This intensity interferometer, as inventors Hanbury Brown and Twiss called it, consisted of two 6.5-meter, mosaically mirrored parabolic reflectors that could be positioned anywhere along a circular track 188 meters wide. The advantage of this kind of instrument was that it could be less precise than Michelson's. Pathlength differences could vary by tens of centimeters.

Hanbury Brown's long experience with radio telescopes contributed to the way the instrument developed. According to his chronicle of the project, the function of each of its 6.5-meter telescopes was to collect the light from the star, "like rain in a bucket, and pour it onto a [photoelectric] detector." Early radio interferometers worked that way.



Astrometric star finder. MIT's intricate network of mirrors, beam splitters, and vacuum chambers is designed to pinpoint stellar positions. The two light-gathering mirrors are positioned 3.4 meters apart.

The Narrabri researchers did not look painstakingly for fringes, as Michelson had done. Rather they mixed the outputs from each reflector's photoelectric detector and gauged the correlation of intensity levels. Michelson had measured stellar diameters by noting the mirror separation at which the fringes would disappear. Hanbury Brown's group looked for the telescope spacing at which the correlation would go to zero.

Despite the parrots that occasionally hung from their telescope cables and the need to teach aborigine laborers how to fill out tax forms, the Narrabri observers were able to measure the diameters of the 32 brightest stars in the Southern Hemisphere. They started in 1963 with the blue main-sequence star Vega in the constellation Lyra, and they ended in 1972 with the supergiant delta Canis Majoris. With the interferometer's ability to reach baselines of 188 meters, the ring's diameter, the resolution at times was of the order of 0.001 arc second.

Back to Michelson

This was not the final answer for stellar interferometry, however. The Narrabri observatory was severely limited. Its sensitivity was low. Its interferometer would work only with stars brighter than magnitude 2.5, leaving many spectral types out of reach. This led astronomers back to the more sensitive Michelson-Pease approach. "A belief emerged," French astronomer Antoine Labeyrie wrote in a review of the field, "that modern technology could solve the problems encountered by Michelson and Pease." Artificial sensors such as photomultiplier tubes could replace human vision and produce quantitative measurements of fringe visibility; lasers could measure pathlengths to within fractions of a wavelength; computerized controls could adjust continuously for pathlength variations, to keep fringes in sight.

By the late 1960s, with the Australian observations well under way, a number of attempts were initiated to perform Michelson interferometry using modern instrumentation. Only a few worked. One of the more successful projects was the amplitude interferometer developed at the University of Maryland by Douglas Currie, Stephen Knapp, and Kurt Liewer. "A lot of people were misled at first by Michelson's success," says Currie. "He was a superior experimentalist, one of the best in the history of science. Yet he also had a detector that was very sensitive—an eye and brain that could see entire patterns in the telescope. People failed to fully realize that a photomultiplier tube is not an eye."

The problem is one of integration. The interferometer creates what might be considered an ocean of waves. An observer can perceive that entire system of waves in one glance. But a photomultiplier tube is more like a buoy, fastened to one spot and responsive only to vertical motion, one wave at a time. Currie's solution was to observe fringes with two photomulti-

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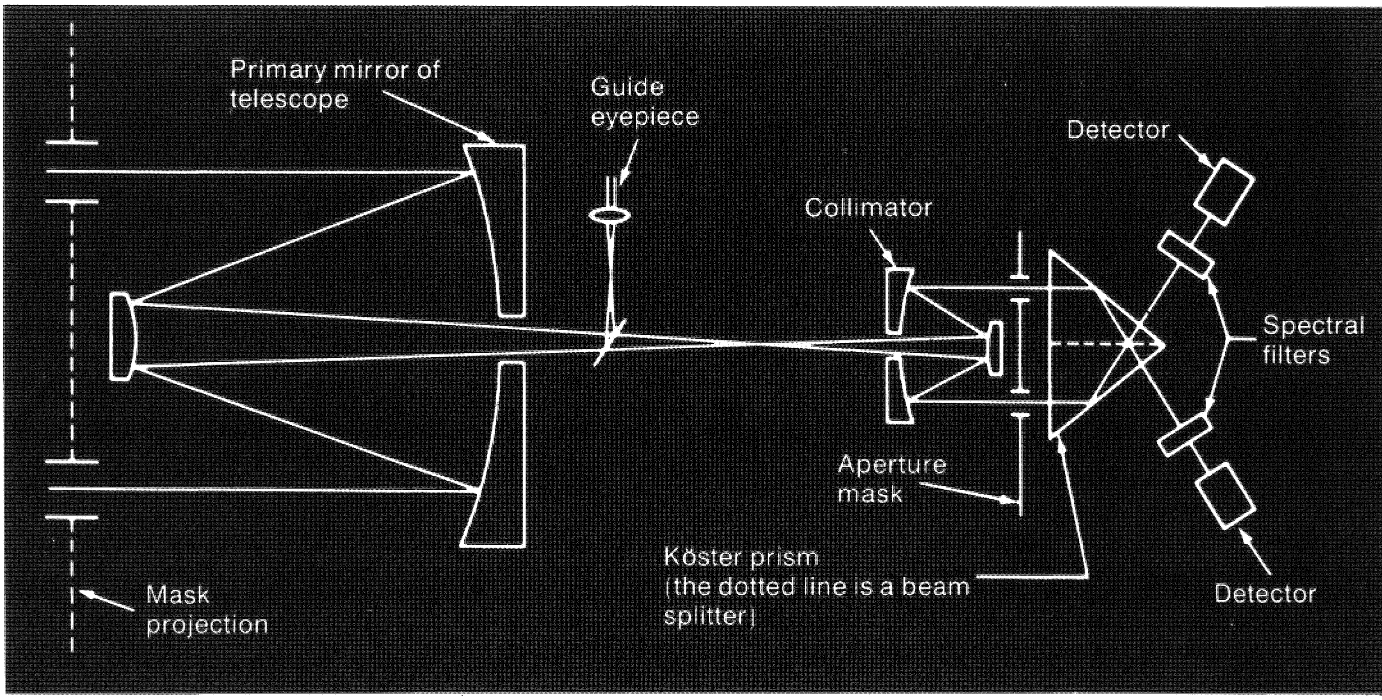
Bartusiak was winner of the American Institute of Physics/U.S. Steel Foundation science writing award for 1982.



Prototype. The amplitude interferometer designed by Douglas Currie at the University of Maryland used two photomultipliers and a mask with moveable apertures.

pliers. The tubes are sensitive to variation in the fringe amplitudes. Correlating the photoelectric counts electronically determines fringe visibility.

As early as 1967, Currie envisioned a two-telescope amplitude interferometer with a kilometer-long baseline. But he knew he first had to test his scheme on a much smaller scale. He and his colleagues constructed a brass mask with two tiny apertures designed to be placed at a collimator in the back of either the 2.5-meter Mount Wilson telescope or the 5-meter instrument on Mount Palomar. Changing the distance between the apertures of the mask gave them baseline equivalents of between one and two meters.

This was not a new idea. In 1890, Michelson had measured the size of Jupiter's four largest satellites by mounting a mask pierced by a pair of holes on the Lick 30-centimeter refractor and examining the fringes as the light beams from each of the holes interfered.

Michelson had viewed the fringes with his eye; Currie's team observed with more than 100 kilograms of mirrors, electronics, and beam splitters. Between 1972 and 1980, the Maryland group measured the diameters of more than a dozen stars and achieved resolutions down to 0.01 arc second. Their list of stellar objects included many that had never been resolved before. The use of sensitive photomultipliers enabled the Maryland astronomers to go down to sixth-magnitude stars, each a fortieth as bright as the objects examined with the Narrabri interferometer.

Mask interferometry is one of many interferometric techniques being used to extend a telescope's vision. Labeyrie, for example, invented a method known as speckle interferometry, which improves the resolving power of a single telescope through statistical analysis of the pattern of speckles that make up a stellar image. The speckles are formed as small cells of atmospheric turbulence cross between the telescope and the target star; the size and shape of the speckles give structural information about the object. Assembling them statistically produces enhanced resolution. (See "An Astronomical Revolution," *Mosaic*, Volume 7, Number 4.)

Active galaxies, binary systems, and even asteroids have been studied by this sensitive method. When Betelgeuse was the target, astronomers at Kitt Peak National Observatory were able to discern for the first time the gross surface features of a star other than the sun. The improved resolution, however, was still limited by the aperture size of the telescope being used. Was there a way to widen apertures further?

Long-base line optical

The initial results Currie and his associates achieved on their masked telescope gave them confidence that they could go out to larger separations. As a start, in 1975 they set up a two-telescope system on the grounds of the Goddard Space Flight Center, near the University of Maryland campus. There the light beams from two 30-centimeter mirrors placed 4.5 meters apart were directed into a central trailer where they were combined and analyzed. Currie and his colleagues were not able to complete their observations then. They are now reviving the project and hope eventually to achieve resolutions down to 0.001 arc second with mirror-to-mirror distances of 40 to 60 meters. John Davis is setting up a similar amplitude interferometer in Australia, with an 11-meter fixed baseline.

The most ambitious pursuit of interferometric synthesis of large optical apertures, however, is the French effort at the Centre d'Études et de Recherches Géodynamiques et Astronomiques, high in the southern Alps overlooking the French Riviera. There Antoine Labeyrie has built CERGA's *Interféromètre a deux télescopes.* Called I-2-T, it employs a pair of 25-centimeter reflectors that move in a north-south direction along 67-meter-long steel tracks. "Europe does not have very big telescopes like Palomar," says Labeyrie, "so there was a general feeling that interferometry was one area where Europe could do better than America. That helped us in getting support for the project."

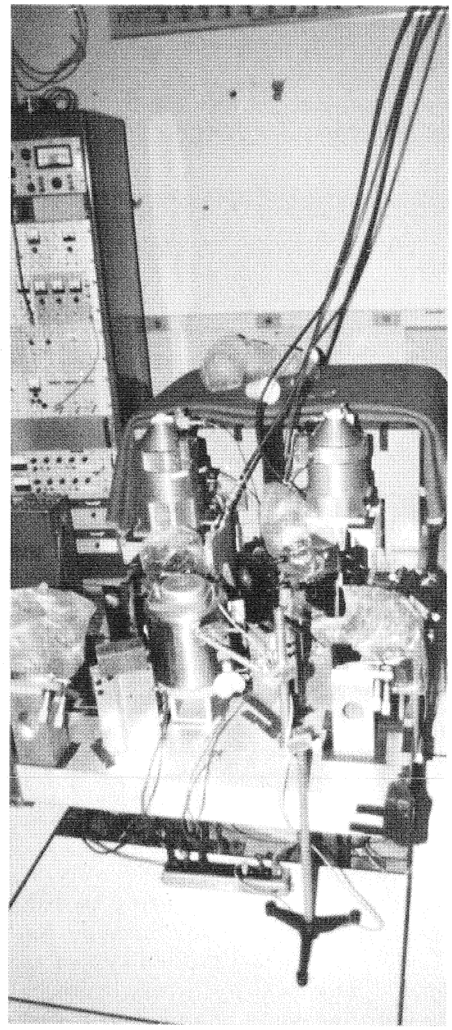
The French system has been operating now for several years. Just as with the old Michelson interferometer, CERGA researchers—most notably Laurent Koechlin, Farrokh Vakili, and Daniel Bonneau—measure stellar diameters by observing fringe visibilities at various baseline lengths. Their system is more like Michelson's than any other; the fringes are detected optically, either through an eyepiece or with a photon-counting television camera. The instrument has worked this way for baselines out to 59 meters, a sort of world's record for the field.

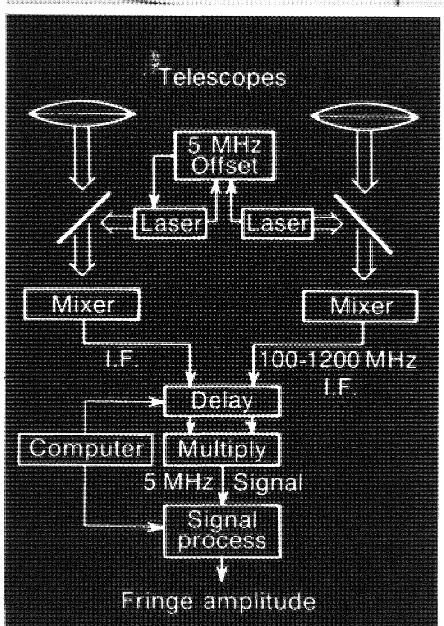
According to Labeyrie, one of his interferometer's most spectacular successes was the resolution of Capella, a binary star system 42 light years from earth in the constellation Auriga. With 15- to 18-meter baselines, CERGA astronomers resolved the disks of both components, one at 0.007 and the other at 0.004 arc second. They then went on to determine the stars' separation by observing beating, or pulsing, effects in a display of the fringes. The accuracy of that measurement was to 0.0003 arc second. "That means that if there were a large planet belonging to that system," Labeyrie says, "we now have the accuracy to detect its perturbations of the stars' orbits quite well."

The 25-centimeter size of the mirrors on the French interferometer has limited its users to observing stars of fourth magnitude or brighter. To extend the limiting magnitude toward the range of magnitude 13 (stars 0.004 as bright), Labeyrie recently set up a second interferometer that uses mirrors six times the diameter of his original ones and mountings modified to match. "Ordinary telescope mountings are not well suited for a large interferometer, because they are difficult to move and prone to flex or vibrate," Labeyrie explains. To get around this problem, he has mounted his two 1.5-meter reflectors inside spherical, reinforced-concrete shells. From afar, these casings look like giant, round-bottomed beakers resting on the desolate mountain plateau. The two concrete bunkers are currently a fixed 70 meters apart, but Labeyrie says he will eventually put the telescopes on tracks and separate them to a formidable 300 meters. "Our future plans call for several more telescopes to be added to the array," he says, "all of them feeding their signals into the central laboratory."

Targets

The efficiency of an interferometer increases rapidly as more telescopes are added to the network. Once you have more than two telescopes, it becomes possible to reconstruct actual images from the fringe information—images almost as detailed as those produced by a giant telescope in space, free of atmospheric disturbances. Radio astronomy has been doing this kind of networking for years. Astronomers who are deeply involved with optical interferometry are the first to admit that such networks of optical telescopes are still far off. Even in their work on simpler, two-telescope systems, researchers are still working out mechanical and electronic problems. As Australia's John Davis puts it, "The achievements of high-angular-resolution stellar interferometry, while remarkable, have hardly scratched the surface of its astronomical potential."





Infrared interferometer. The heterodyne detection scheme developed by Michael Johnson, Albert Betz, and Charles Townes. Stepping down from infrared to radio frequencies makes beam combination simpler.

Once the surface is better scratched, the agenda includes:

- Stellar temperatures. By combining the angular diameter of a star with the flux of radiation received from it, one can determine the absolute flux emerging from the stellar surface and hence its surface temperature. The calculations would be particularly valuable in the case of pulsing, yellow supergiants called Cepheid variables. It would provide an independent calibration of the Cepheid luminosities upon which distance measurements in the universe are largely dependent.
- Stellar surfaces. As soon as optical interferometry can work routinely with angular resolutions of less than 0.001 arc second, assuming increased sensitivity, observation of such intimate details of the surfaces of nearby stars as spots, granulations, coronas, and gas shells will be possible.
- Parallax measurements. The distance to a nearby star can be measured directly by observing the star's position against the celestial background from one point in earth's orbit and then measuring the position again six months later from the other side of the orbit. The star's parallax, its apparent shift in position against its stellar background, enables astronomers to determine distance with a simple bit of trigonometry. At present, this method can be used out to about 300 light years. Greater distances are estimated by a complex sequence of steps using the parallax results for calibration. An optical interferometer would detect smaller and smaller shifts in stellar positions and would extend direct measurements enough to adjust the scales by which the distance across the universe is measured.
- Planetary searches. The gravitational attraction of a planet would tend to put a wiggle in the proper motion, the actual movement across the heavens, of its parent star. An optical interferometer could detect this

subtle effect as it measures both the proper motions of nearby stars and the orbital motions of binary star systems. "At this time," declares MIT's Staelin, "we know of no planets around any stars other than our own. Yet planets are a critical part of the theory of stellar formation. Once we obtain an accuracy of one ten-thousandth of an arc second, we could detect a planet the size of Jupiter at a distance of a few of dozen light years."

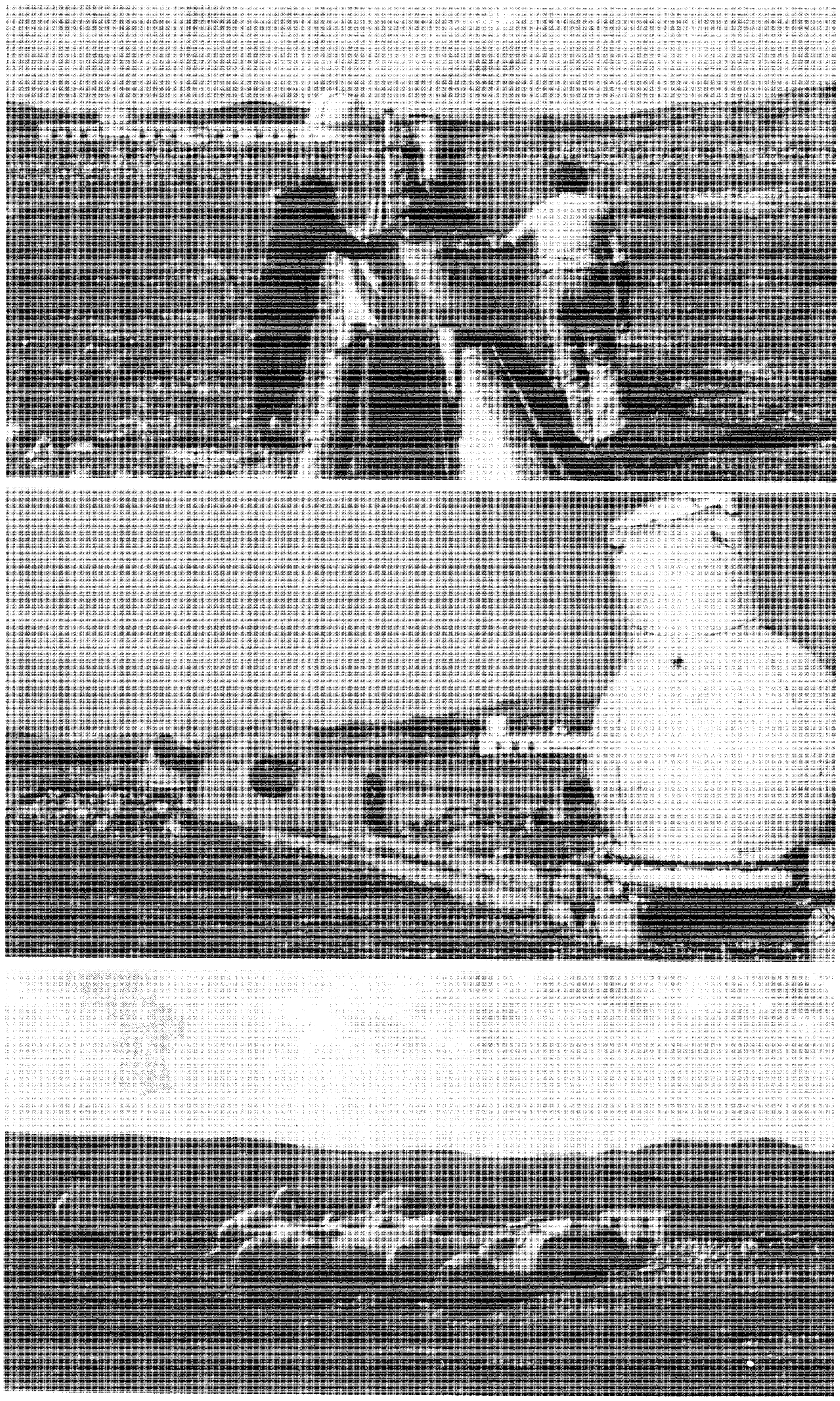
• Galactic nuclei and quasars. To many astronomers, the most exciting prospect for optical interferometry lies in the resolution of the cores of active galaxies. Radio astronomers are already seeing in some galaxies energy equivalent to that of a trillion suns coming from areas that may be not much bigger than the solar system. Radio astronomers map these jet-like cores by using intercontinental arrays of telescopes; optical interferometers could start doing the job when they achieve a 300-meter baseline.

Atmospheric effects

Even though optical interferometry was developed as a means of getting around atmospheric perturbations, it too has its limits. Turbulence in the air causes the interferometric fringes to wobble, too. When the interferometer's bandpass, its range of wavelengths, is widened to improve its sensitivity, viewing the fringes becomes an observational nightmare: The fringes bunch, which makes it difficult to observe them as they race by. Until now, researchers have avoided the problem by keeping their bandpasses narrow. This restricts them principally to measurement of stellar diameters; fringe movement does not matter much when only the intensity of the fringes is being weighed. Nevertheless, it severely affects the astrometric uses of optical interferometry—the determination of stellar positions and the search for planetary systems. Electronics, again may produce the solution of choice.

In 1975, while a graduate student under Staelin, Michael Shao developed a mechanism that compensates for atmospheric effects by locking to an interferometer's brightest fringe and keeping it centered. Once the fringes are frozen in place, for milliseconds, their central positions can be measured; their small, observed offset provides an instantaneous measure of the positional errors.

Traditionally, astronomers take a series of photographs over many nights to pinpoint stellar positions. Averaging measurements over several thousand plates can produce tolerances of about 0.01 arc second. Shao and Staelin believe that their system will be able to obtain the same accuracy in a single night and that a more elaborate version could yield accurate measurement down to 0.0001 arc second.



France's entry. A 25-centimeter reflector (top) is moved along its 67-meter track in Antoine Labeyrie's I-2-T interferometer. A second-generation instrument (center and bottom) will have its 1.5-meter mirrors encased in concrete bunkers 300 meters apart.

Since the fall of 1981, Shao and Staelin have been operating a prototype from a wooden shed at Mount Wilson, just a few dozen yards from the giant white dome under which Michelson made his historic contributions to the field. Their two mirrors, one at each end of an equipment-packed table, are 3.4 meters apart. While that baseline can hardly rival Labeyrie's, Shao's fringe tracker makes the MIT system the most complex and potentially the most accurate optical interferometer in the world. So far, it has successfully tracked the fringes of several stars, including Vega and Deneb. "Ideally, this should make our data look as if there were no atmosphere at all," says Shao, now an MIT research associate temporarily attached to the Naval Research Laboratory. "This is not important for measuring stellar diameters, but it's crucial for astrometry." The fringe tracker could also make interferometric fringes of fainter and fainter objects accessible from longer and longer baselines.

The future

The real future for optical interferometry, says Labeyrie, lies in space. Astronomy extended its vision immensely as soon as astronomers were able to send their telescopes into orbit. Interferometry will be no exception. A space interferometer, Shao says, will be much simpler to operate, since it would not need atmosphere-correcting equipment. "That would sure eliminate a lot of instrumentation errors," he says, "but the best advantage would be the ability to rotate the interferometer's baseline, something we can't do here on earth. That would give us valuable two-dimensional information about a star."

There are many designs for an orbiting interferometer, but the most popular seems to be a three-satellite system now under study by the European Space Agency for possible launching in the 1990s. In concept it is very much like Michelson's. Its three components will be lined up in space—telescopes on two outer satellites beaming starlight to the center satellite for mixing. The fringes would be monitored at a ground station. The present design calls for adjustable solar sails on each satellite to modulate the radiation pressure of sunlight hitting the interferometer. This would be expected

Infrared interferometry: parallel development

A newly born star lies behind thick curtains of dust and gas that block the visible light waves it gives off. But the surrounding dust grains absorb the light and then re-emit it at infrared wavelengths. Thus, dusty clouds that can cradle protostars invisible to optical telescopes may be penetrated with an infrared detector. But for many years the infrared section of the electromagnetic spectrum seemed destined to remain astronomy's forgotten child.

The problem was one of detection. The human eye and photographic plates have served well in detecting visible light waves; antennas and receivers have taken care of viewing radio wavelengths, at the other end of the spectrum. But infrared radiation, from one to one thousand microns, could not be gathered adequately by either technique.

This tantalizing window on the universe was finally opened in the early 1960s, when physicist Frank Low of the University of Arizona built an infrared detector sensitive enough for astronomical work. Using liquid helium, he cooled the instrument to near absolute zero, making it responsive to the faint traces of heat radiation that fell on it at the focus of a reflecting telescope. But in the infrared as in optical and radio astronomy, it soon became clear that details in the sky could be resolved only through interferometry. Because infrared waves are longer than those of visible light, an infrared interferometer would not need to maintain the exquisite precision of an optical instrument. Nor would it require the intercontinental baselines of a radio telescope network. Furthermore, at wavelengths around ten microns, infrared signals traveling through the atmosphere are less distorted by water vapor, a major source of optical error.

During the 1970s, Low and his associates Donald McCarthy and Robert Howell pioneered in the application of the Michelson-type approach to infrared astronomy. They mounted a two-aperture mask on a telescope and observed the interference of the two infrared beams. Their baselines normally ranged from 0.9 to 3.2 meters, depending on the telescope being used. At one point, they were able to go out to 6.9 meters by operating pairs of mirrors on the Multiple Mirror Telescope at Mount Hopkins in Arizona.

"It was not until the advent of infrared interferometry that more detailed measurements of sizes, shapes, and radial structures of infrared sources became possible," says Low. The Arizona group, for example, was able to resolve the circumstellar envelopes of some 25 infrared objects—both older, highly evolved stars that are shedding their outer layers and very young protostars embedded in dust clouds. The star IRC +10216, the brightest in the northern sky at ten microns, appeared to them as a flattened disk. "It seems likely that planets are forming within certain of these circumstellar disks," says Low, "although our resolving power and sensitivity were not sufficient to detect this process directly." Closer to home, at a wavelength of five microns, the Arizona astronomers saw Jupiter as a cold disk, around 140 degrees Kelvin, accented by spots at twice that temperature corresponding to structures in the planet's cloud layers.

Recently, Low has turned his attention to speckle interferometry in the infrared region, believing it is the best way to improve the resolution of any single telescope. Applying this technique on the 4-meter and 2.2-meter telescopes at Kitt Peak, the Arizona group has now resolved 15 previously undetected companions of nearby stars. The existence of these cool, low-mass objects had been inferred from astrometric studies, but "now it is possible to see them directly in the infrared as they orbit slowly around their more massive companions," says Low. The group has also resolved the point-like core of the bright Seyfert galaxy NGC 1068.

Low has not abandoned the Michelson approach entirely. The Arizona physicist is currently involved in a major effort to use the Multiple Mirror Telescope as a full-phased array in both the visible and infrared. He would combine the signals arriving at all six of the instrument's mirrors. Low believes that operating this way will make the Multiple Mirror Telescope the most powerful optical interferometer in the world and lead to more powerful instruments in the future.

But because of the relationship between wavelength and angular resolution, infrared interferometers will eventually have to span distances of 70 or more meters to resolve the full structures of infrared galactic and extragalactic sources.

to generate the minute forces needed to stabilize the system with micron accuracy. This is the way, says Labeyrie, that optical interferometry will finally catch up to radio's interferometric accomplishments.

Ground-based optical interferometry, meanwhile, is reaching a point of decision. The potential for widely spaced, earth-bound optical telescopes in tandem ever to make a significant contribution to astronomy is being questioned—by Frank Low of the University of Arizona, among others. Low, a pioneer in infrared interferometry, contends that it would be more valuable to concentrate now on using interferometric techniques to extend the resolving power of individual telescopes. "I'm unwilling to sacrifice the sensitivity of a single-telescope interferometer such as a speckle instrument just to gain a higher resolution with widely spaced telescopes," he declares. "High resolution without sensitivity leaves you with few problems [to study], involving only the brightest sources. It's not only the baseline, but the sensitivity and accuracy of the fringe measurement that determine what science you can do."

But as R. Hanbury Brown pointed out at a symposium on stellar interferometry at the University of Maryland a few years ago, "The whole history of astronomy shows that angular size measurements have been used to find out what sort of objects we are dealing with. This is very true of radio astronomy. In about 1948-49, we didn't know what we were dealing with in the way of radio sources, whether they were point sources or not, whether they were galaxies, nebulae, or stars. It wasn't until we measured some angular sizes that we began to know what we were talking about. . . . High angular resolution has paid off in radio astronomy, and it will pay off in optical astronomy." •

The National Science Foundation support for its part of the research discussed in this article comes principally from its (astronomical) Instrumentation and Development, and Stellar Systems and Motions Programs.

Physicist Charles Townes, recipient of the Nobel Prize in 1964 for his role in the invention of the maser and laser, became interested in this problem shortly after he moved to the University of California at Berkeley in 1967. Townes became convinced that long-baseline infrared interferometry could best be done by adopting a technique used in radio interferometry—heterodyne detection, a method that involves the pulsing of two frequencies in an electrical circuit to produce useful new frequencies.

In optical interferometry and in Low's early infrared system, the route to interference has been direct: The two beams are brought together, mixed, and the resulting fringes detected. A heterodyne instrument employs a slight detour. In the two-telescope scheme developed at Berkeley, infrared radiation entering each telescope is separately added to the pure infrared light put out by a carbon dioxide laser. What comes out of this mix is a pulsing, or beating, signal in the radio region of the spectrum. The beat depends on the incoming signal and varies with it. Fringes are obtained not by mixing the two infrared beams but by combining these beat frequencies. Since the beats are in the radio region, the interference signal can be amplified electronically, processed, recorded on tape, and analyzed by computer. French scientists have set up a similar instrument at the CERGA observatory in southern France.

Townes concedes that a direct interference system can offer better sensitivity but, he argues, heterodyne is cheaper and more flexible; it should be used for at least the initial combination of infrared signals from two or more widely spaced telescopes. The step-down to a radio frequency greatly reduces engineering difficulties in combining two light beams over a distance of many meters, he says.

Two of Townes's graduate students, Michael Johnson and Albert Betz, built the first infrared heterodyne interferometer in the early 1970s, for their dissertations. They used the two 76-centimeter auxiliary mirrors on the McMath Solar Telescope at Kitt Peak National Observatory in Arizona as their receivers. The system operated for several years and was only recently dismantled. "The five-and-a-half-meter baseline was not adequate to resolve a star disk in the infrared, but we did obtain quite a lot of information on dust shells," says Townes. "We found that dust does not condense as close to a star as was previously thought." For Betelgeuse, for example, the high-density dust begins at about 18 stellar radii, at a temperature two-thirds of that which theory prescribes.

Edmond Sutton, another graduate student under Townes, tested the system's astrometric capabilities and, with Townes and Shankar Subramanian, he measured the positions of three bright infrared sources—Betelgeuse, omicron Ceti, and R Leonis—achieving levels of precision down to 0.08 arc second. His precision was limited by mechanical instabilities in the telescopes, which were not designed for this purpose. Nonetheless, it was somewhat better than typical night-to-night variations that plague optical methods. Townes reasons that, with telescopes designed for the purpose, the precision can be improved by an order of magnitude.

With funds from the Advanced Research Projects Agency and the Office of Naval Research, the Berkeley interferometry group is now constructing an improved heterodyne system, including two 1.5-meter reflectors—"superstable," says Townes—that will be separately mounted on trailers for portability. "That not only allows variable baselines, but we could change sites with the seasons," says Townes. "We expect to go down to Chile, where atmospheric conditions are superb and where we'll get a good look at the galactic center."

There are some suggestions that the core of the Milky Way harbors a black hole of a few million solar masses, surrounded by a sizable accretion disk. If that is true, says Townes, the Berkeley interferometer should be able to pick up the disk's characteristic infrared radiation and examine its size. Another fundamental experiment for which he believes the infrared interferometer is well suited is precise measurement of the gravitational deflection of light. And with the high spectral resolution that heterodyne detection provides, Townes says, the Berkeley scientists expect to detect molecular infrared lines and thus examine the detailed distribution and velocity of molecules like ammonia, carbon monoxide, and silicon oxide that are being emitted from stellar atmospheres. •