Quest for the Astronomical Unit

by Trudy E. Bell

TO THE UNTRAINED EYE, the event might seem rather dull: a black dot resembling a perfectly circular naked-eye sunspot crossing the face of the Sun in less than eight hours. It wouldn't even catch the notice of anyone who was unprepared to watch.

Yet, over two centuries this visually unremarkable astronomical occurrence—a transit of the planet Venus across the Sun—mobilized nations to spend today's equivalent of tens of millions of dollars to commission special telescopes, outfit ships, fund expeditions, and send forth trained observers willing to sacrifice their health and even their lives, all to time four crucial instants.

Moreover, that same event repeatedly frustrated astronomers in their quest, and, ultimately, the prize was captured not by astronomers—but by electrical engineers.

On, after more than 120 years, this past June 8 astronomers once again fanned across Europe, the Middle East, Africa, and Asia and rose before dawn in the eastern United States to observe the most recent transit of Venus.

Why all the fuss?

How many astronomers does it take to determine the distance from the Earth to the Sun? Hundreds, who endured hardship and heartbreak over two centuries in repeated attempts to solve "the noblest problem in astronomy."

THE COSMIC 'HOLY GRAIL'

The ultimate object of the astronomers' quest after Venus was the precise determination of one number: the astronomical unit—the mean distance from the Earth to the Sun.

To astronomers, the astronomical unit is the fundamental "yardstick" to the cosmos. It is the unit in terms of which every other linear measurement to a celestial object beyond the Moon is specified—and absolute distances would remain unknown until the Sun-Earth distance itself could be accurately established.

By the late 18th century, astronomers knew the Sun-Earth distance was somewhere between 90 and 96 million miles. Not bad, you say—until you realize that an uncertainty of five-to-10 percent rendered the astronomical unit about as useful as knowing that the distance from New York City to San Francisco is 2,500 miles, plus-or-minus 200 miles, when you are trying to find a restaurant downtown.

Problem is, directly measuring the distance from the Earth to the Sun is extraordinarily difficult.

True, the Sun is close enough that astronomers on opposite sides of the Earth could, in principle, detect its parallax—the apparent angular shift in the Sun's position against a background of stars (the way your outstretched finger appears to change position with respect to a background wall when you alternately open and close each eye). Knowing the exact distance between observers on Earth (your two eyes), astronomers could in theory calculate the distance from the observers to the Sun (your finger) from the Sun's angular shift with respect to stars (objects on the far wall).

In reality, however, observational difficulties abound—the worst being that the Sun's brilliance makes it impossible to see reference stars in the daytime, even during a total solar eclipse. That and a host of other practical complications thus forced 18th- and 19th-century astronomers to search for an *indirect* method of determining the solar parallax and thereby the astronomical unit.

SIC TRANSIT VENUS

Enter Kepler's laws and Venus. With grace and elegance, 16th-century astronomer Johannes Kepler showed that the orbital periods (that is, the planetary "years") of any pair of planets were related to one another in a defined mathematical ratio, now called Kepler's third law.

In 1716, British astronomer Edmund Halley (1656–1742, who first predicted the return of the comet now called Halley's comet) realized that if the distance from the Earth to *just one planet* could be measured with precision, then the mean Sun-Earth distance—the astronomical unit—could be *calculated* from Kepler's third law with equal precision. Although determining the distance to any planet would do, the most accurate distance could be determined for a planet approaching nearest Earth, that is, one showing the largest parallax to observers simultaneously measuring it from opposite sides of the globe. In the entire solar system, the best candidate was Venus, which approaches within 26 million miles (41 million km) of Earth and exhibits almost four times the parallax of the Sun.

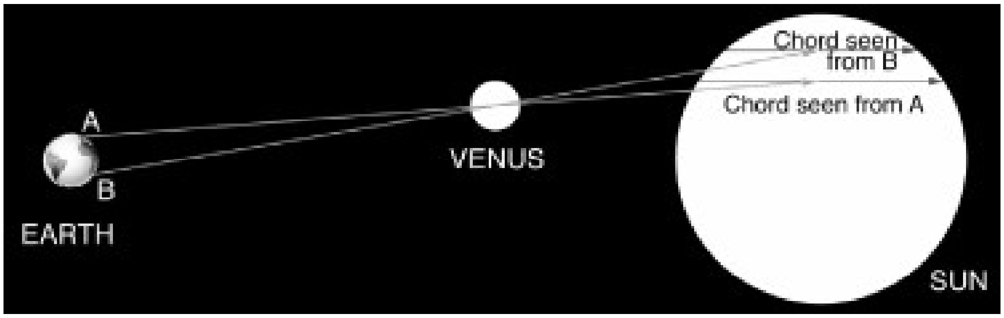


FIGURE 1
Because Venus is closer to Earth than the Sun, observers at different latitudes on Earth would see Venus transit different chords on the face of the Sun, with northern observer A seeing the lower chord and southern observer B seeing the upper chord. Careful timings of the duration of the transit from both locations, combined with precise knowledge of each observing station's latitude and longitude, could yield a measurement of Venus's apparent parallax (shift in angular position in the sky); from that, Venus's actual distance could be calculated, much as surveyors from two different positions on a shoreline can combine their measurements to triangulate the absolute distance of an offshore island. Once astronomers know the precise distance from Earth to Venus, they can further calculate the exact distance to the Sun using ratios specified in Kepler's third law.

SOURCE: SHEEHAN, WILLIAM AND JOHN WESTFALL, *THE TRANSITS OF VENUS* (PROMETHEUS BOOKS, 2004), P. 126. USED WITH PERMISSION.

Just one major difficulty: when Venus is closest to Earth, it's also *between* Earth and the Sun. Its thin crescent, like the crescent of an almost-new Moon, is thus lost in the Sun's blinding glare. Hence, Venus's position at closest approach is no more measurable against background stars than is the Sun's itself. So how could astronomers ever hope to measure Venus's parallax?

Well, Halley pointed out, the one time Venus would be readily visible at its closest approach would be when the planet exactly transits the face of the Sun in a kind of partial solar eclipse. (Actually, a transit is equivalent to an annular solar eclipse, in which the black disk of the Moon is too small to completely obscure the Sun, and is thus surrounded by an annulus—Latin for "ring"—of sunlight.) At such a time, the same relatively small telescopes astronomers used to observe sunspots would reveal Venus as a black disk about 1/20th the Sun's diameter silhouetted against the Sun's bright disk. More importantly, because Venus is so much closer to Earth than the Sun, observers south of the equator would see Venus *cross a different chord* of the Sun's disk than observers north of the equator *[Fig. 1]*. Thus, the transit's duration would be greater for observers at some latitudes than in others. By comparing the transit's duration at different latitudes (and correcting for Earth's rotation and Venus's orbital movement during the course of the transit), Halley calculated that "the sun's parallax may be discovered, to within its five hundredth part"—that is, to within 0.2 percent, or an angular measure of less than 0.025 second of arc—if timings could be "obtained true within 2 seconds of time." In Halley's opinion, such precision was well within the capability of 18th-century "telescopes and good common clocks."[1]

Oh, yes, one last point: transits of Venus are extraordinarily rare. True, Venus catches up to and passes close to Earth about every year and a half. But because the two planets' orbital planes are tilted with respect to each other, most of the time Venus appears to pass above or below the Sun as seen from Earth. Actual transits of Venus across the Sun usually occur in pairs eight years apart separated by alternating intervals of 105½ or 121½ years, always in either December or June. So rare are the events, in fact, that to this day, only *six* transits of Venus have been seen in the nearly four centuries since Galileo first turned a telescope toward the heavens (in 1639, 1761, 1769, 1874, 1882, and 2004). The next transit of Venus is June 6, 2012…and then not again until *the next century*, just before the Christmases of 2117 and 2125.

Because of both the great value and the extreme rarity of transits of Venus, the pressure was on to pursue what Halley described and Britain's later astronomer royal George Biddell Airy echoed as nothing less than "the noblest problem in astronomy."[2] For the 18th- and 19th-century pairs of Venus transits, astronomers and governmental funding bodies succumbed to the seductive siren song of national pride and astronomical immortality awaiting the individual and the mother country that brought home that cosmic Holy Grail.

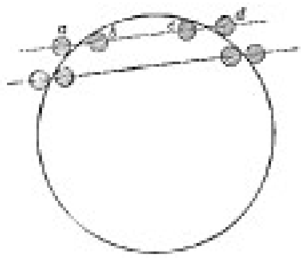
But as the obverse of pride is shame, they were also keenly aware of an underlying chill whisper of ignominy: *don't mess up*….

FROM LONE PIONEER TO 'BIG SCIENCE'

As far as historians know, a 20-year-old British cleric named Jeremiah Horrocks was, in Halley's words, "the first and only one [human] since the creation of the world" to observe a transit of Venus, on November 24, 1639 (Julian calendar, this being before England adopted the Gregorian reform), a brilliant mathematician who died at the tender age of 22 in 1641. One of his greatest contributions was hand-calculating that Venus would cross in front of the Sun in 1639—and, moreover, that the event should be visible from his own parish. Horrocks placed the objective lens of a telescope at an opening in a shutter and projected a 6-inch-diameter image of the setting Sun onto the rear wall in a darkened room, where he watched the black dot of Venus crawl across the bright disk.

The year Horrocks stood his lonely vigil, however, was three years before Isaac Newton was born. Only after Newton had grown to maturity and published his theories of gravity and mechanics, thereby revolutionizing the scope of astronomy, did physics and mathematical tools become available for using the transits of Venus to calculate the dimensions of the universe. And only after the Enlighten-

FIGURE 2



Observers of the 18th- and 19th-century transits of Venus planned to use the same system for timings as has long been used for total or annual eclipses of the Sun. First contact (*a*) was defined as that instant when the leading edge of Venus first notched into the Sun's limb; second contact (*b*) would be the instant the trailing edge of Venus left the solar limb and the planet was full upon the Sun's disk; third contact (*c*) would occur when the leading edge of Venus first touched the solar limb at egress; and fourth contact (*d*) would be that instant when the planet's trailing edge departed, signaling the transit's end. (Example is for two different observers for the Venus transit of 1874.)

SOURCE: NEWCOMB, SIMON, *POPULAR ASTRONOMY* (NEW YORK: HARPER AND BROTHERS, 1878), P. 176.

ment dawned with its restless drive to complete all knowledge about the Baconian and Newtonian "system of the world" was there also a sense of urgency to devote effort to do so. So both the scientific methodology and the psychological will were in readiness when Halley's method (and later refinements) burst onto the scientific world.

What a difference a century makes! Astronomers were so primed for the June 6, 1761, transit of Venus that at least 120 observers were fielded to 62 stations, in expeditions sponsored by Britain, Denmark, France, Germany, Italy, Portugal, Russia, and Sweden. In addition to sites around Europe, astronomers sailed, trekked, or sledged as far afield as Calcutta, Capetown, Constantinople, Newfoundland, Peking (Beijing), and Siberia.[3] Many national expeditions were distinguished in being headed by the first-ranking astronomers of the day. Indeed, the international expeditions launched to observe the 18th-century transits of Venus are often cited as the first example of modern "big science" research—marshalling major funding, international cooperation, and alliance with governmental bodies to pursue a scientific question. So important were these rare observations deemed that the British and the French—who were locked in mortal combat all around the globe during the brutal Seven Years War—offered each other's astronomers safe conduct behind military lines.

As might be expected, some stations enjoyed spectacularly clear and serene weather while others were completely clouded out. By 1763, however, papers published about the results revealed a disconcerting trend: values of the solar parallax calculated from the observations ranged from an angle of 8.28 arcseconds to 10.6 arcseconds. That difference corresponded to a Sun-Earth distance ranging in length from more than 98 million miles to less than 81 million miles—a disagreement of about one part in five, *two orders of magnitude worse* than Halley's estimated precision of one part in 500.

Astronomers seemed no closer to determining the exact value of the astronomical unit than they had been before the transit of Venus.

What had gone wrong?

FIRST DOUBTS

Because Venus projects a sizeable disk onto the Sun, 18th-century astronomers set out to time its passage much the same way they would time the Moon crossing in front of the Sun in a total or annular solar eclipse [*Fig. 2*]. The external (first and fourth) contacts were intrinsically difficult to measure, as the position of the first tiny nibble into the Sun's limb might surprise an observer and delay the timing. So the duration of the transit was defined as the length of time between internal (second and third) contacts, exactly analogous to the duration of totality or annularity during a solar eclipse.

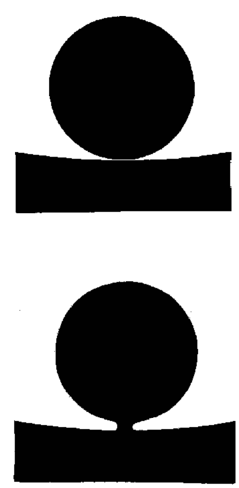
But as a later historian remarked, "in that word 'exactly' what snares and pitfalls lie hid!"[4]

The two crucial internal contacts proved universally difficult to determine, completely unlike what astronomers expected to see from long experience with solar eclipses. At second contact, they expected the planet to present a distinct, round, black disk as does the Moon, whose limb would separate from the inner edge of the Sun's limb at one defined instant, revealing a thin thread of bright sunlight between the two tangent limbs.

Instead, many observers saw Venus appear to cling to the solar limb by a long "black ligament" that stretched like taffy, breaking only when Venus was clearly well onto the Sun's disk [*Fig. 3*]. The reverse happened at third contact: well before the planet actually reached the solar limb, a black pseudopod appeared to reach out from Venus toward the edge of the Sun, thickening and darkening as the planet drew closer to the limb. The whole sequence, which became known as the "black drop effect" (in analogy to the way surface tension keeps a drop of water clinging to a faucet), was about as well defined as watching amoebas separate or merge.

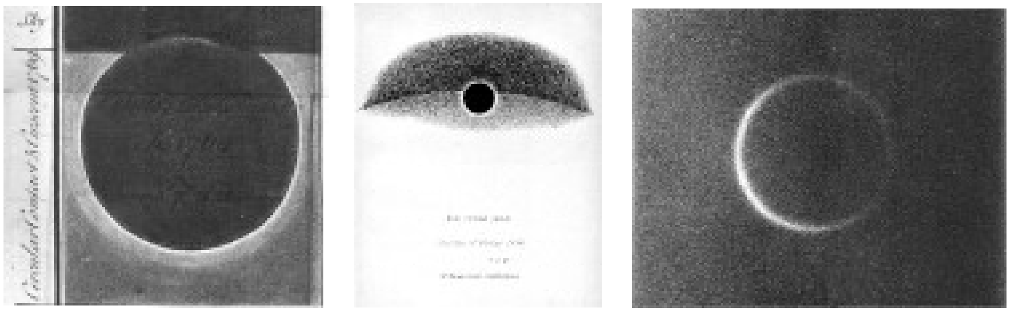
Equally disconcerting, many 1761 observers were puzzled by seeing what they described as a "dusky" or "waterish penumbra" surrounding the entire planet while Venus was completely projected onto the sun. Moreover,

FIGURE 3



Astronomers expected that the moment of Venus's second or third contact with the interior limb of the Sun to be clearly defined (top). Instead, astronomers saw a "pseudopod" extend out to the solar limb, confusing the exact instant of the internal contacts (below). This appearance, now known to arise from a combination of turbulence in Earth's atmosphere and diffraction inside a telescope, came to be called the "black drop effect" or the "black ligament."

SOURCE: NEWCOMB, SIMON, *POPULAR ASTRONOMY* (NEW YORK: HARPER & BROTHERS, 1878), PP. 178–179.



A B C

FIGURE 4
Both 18th-century and 19th-century observers of the transit of Venus reported seeing a "luminous ring" haloing Venus when the planet was still off the Sun's disk, which interfered with the exact timings of the external contacts. And once Venus was silhouetted on the face of the Sun, the halo persisted as a "dusky penumbra." The appearances caused a number of observers to speculate (correctly) that they were seeing an atmosphere around Venus. The 1769 image of both phenomena (**A**) was drawn by British observer Samuel Dunn; the narrow black strip at the top is sky, while the gray area on which most of Venus is superimposed is the Sun. A remarkably similar image was drawn during the 1874 Venus transit (**B**) by W. J. MacDowell in New South Wales. The luminous ring has also been observed surrounding Venus's entire black disk during close inferior conjunctions of the planet with the Sun, as shown in a photograph (**C**) made at the Lowell Observatory, Flagstaff, AZ, on June 19, 1964.

SOURCES: DUNN, SAMUEL, "A DETERMINATION OF THE EXACT MOMENTS OF TIME WHEN THE PLANET VENUS WAS AT EXTERNAL AND INTERNAL CONTACT WITH THE SUN'S LIMB, IN THE TRANSITS OF JUNE 6, 1761, AND JUNE 3, 1769," *PHIL. TRANS. 60* (1770), FOLD-OUT PLATE OPPOSITE PAGE 65;
RUSSELL, H. C., *OBSERVATIONS OF THE TRANSIT OF VENUS, 9 DECEMBER 1874; MADE AT STATIONS IN NEW SOUTH WALES* (SYDNEY: CHARLES POTTER, GOVERNMENT PRINTER, 1892), PLATE XVIII;
LOWELL OBSERVATORY, USED WITH PERMISSION.

they saw a "luminous ring" that surrounded the portion of the planet's disk still *off* the Sun when Venus had advanced halfway between first and second contacts, or between third and fourth contacts [*Fig. 4*]. A few who saw the luminous ring jumped to the (correct) conclusion that they were seeing the Sun's light refracted and diffused through an atmosphere around Venus. Indeed, Englishman Samuel Dunn, observing from Chelsea, calculated from the time it took for the dusky penumbra to cross the solar limb that the Venusian atmosphere was about 50 miles thick, or about the same as the Earth's.[5]

Instead of discouraging astronomers or nations, however, the baffling appearances of the black drop, dusky penumbra, and luminous ring whipped up even greater fervor and hope to solve "the noblest problem in astronomy"—for once and for all—eight years later.

SECOND CHANCE

Efforts mounted for the Venus transit of June 3, 1769, were even more monumental than in 1761. At least 151 observers dispersed to 77 stations around the world. The eight nations that sponsored expeditions in 1761 again leaped into the contest, joined by the Spanish and the Dutch. This time, nearly 40 percent of the expeditionary observers were British—including Captain James Cook as public cover for his secret mission to ascertain whether Australia was mythical or real.

This time, astronomers were far better prepared. Telescopes were bigger and better, the transits of Venus having helped increase the demand for precision astronomical instruments such as achromatic refractors (telescopes with multi-element lenses largely free of the annoying color fringes around images seen through a single-element lens). Observers knew about the dusky penumbra, the luminous ring, and the black drop. They had aired differences of opinion about whether the real second contact occurred the moment the limbs of Venus and the Sun were geometrically tangent (although still conjoined), or the moment the black ligament snapped (although Venus was well past tangency). And they had agreed that second contact should be defined by the former.

Once again, expensive and well-equipped expeditions scattered to the four winds a year in advance. Even more spectacularly, observers saw the black drop even more clearly, disagreeing more than ever on their timings.

Hundreds of articles appeared in the major scientific literature wrangling over the apparition and its cause in English, French, and Latin (still the *lingua franca* of international literati). The black drop was variously cited as evidence of a Venusian atmosphere, of diffraction of light at Venus, or even of an optical illusion—all three explanations now conclusively proven as incorrect. The explanation most widely accepted today is that the black drop results from both scattering of sunlight in the Earth's atmosphere and diffraction *within a telescope*. Together, the two effects smear the thin thread of light that should divide the limbs of Venus and the Sun over a wide region, darkening that area so the two limbs appear to be joined.[6] (Indeed, you can create your own smeared-light "black drop" by holding thumb and forefinger silhouetted before a bright window; you'll see a "black ligament" appear to join the two fingerprint pads clearly before you feel them touch.)

As for the astronomical unit? To everyone's bitter disappointment, it remained cloaked in mystery. Inconsistent timings gave results that ranged from 8.3 to 8.8 arcseconds, corresponding to distances ranging from more than 97 million miles to less than 93 million miles. Several 19th-century astronomers repeatedly pored over the 18th-century observations, with no better consensus. The most widely accepted value came to be 95 million miles. But independent observations—especially from various measurements of the speed of light—made them realize that this value was far too high.

So by the next transit of Venus on December 9, 1874, a new crop of expeditionary astronomers was champing at the bit to try their own skill.

FIGURE 5
Astronomers from more than a dozen nations fielded more than 80 camps similar to this one set up at Eden, New South Wales, for the 1874 transit of Venus. The large wooden hut in the center was a temporary observatory housing the largest telescope at this site, a 7½-inch equatorial refracting telescope (whose objective lens can be seen through the open slit in the conical roof); its observer was Rev. W. Scott (seated at right). Independent observations were also made using two smaller telescopes—a 4½-inch Cooke equatorial refractor (larger instrument in the center), manned by W. J. MacDowell (standing at the eyepiece); and a 3½-inch refractor (smaller instrument at left), manned by J. S. Watkins (seated at the eyepiece). The other two members of the party were a photographer (standing with camera at far left) and a carpenter. The small canvas dome on the right housed a small transit telescope (visible on a brick pier) used for finding the site's latitude and longitude and for correcting the clocks. Unfortunately, clouds—an occupational hazard for field astronomy—interfered with observations at this site.

SOURCE: RUSSELL, H. C., *OBSERVATIONS OF THE TRANSIT OF VENUS, 9 DECEMBER, 1874; MADE AT STATIONS IN NEW SOUTH WALES* (SYDNEY: CHARLES POTTER, GOVERNMENT PRINTER, 1892), PLATE XXXVI.

WAITING FOR THE TRANSIT OF VENUS, EDEN.

VANITY, THY NAME IS ASTRONOMER

Nineteenth-century astronomers determined not to be caught unawares like their predecessors. They had their big guns ready. So to eliminate variability in the observations and leave little to chance, several types of standardized telescopes were specified and built. They also standardized procedures. Techniques for measuring individual reaction times were defined.[7] Official commissions were appointed to dispense standard observing instructions and to receive data and decide upon evidence. To quote the wry account of British historian of astronomy, Agnes M. Clerke:

> "In England, America, France, and Germany, artificial transits were mounted, and the members of the various expeditions were carefully trained in unanimity in estimating the phases of junction and separation between a moving dark circular body and a broad illuminated disc. ... Each observer went out ticketed with his own 'personal equation,' his senses drilled into a species of martial discipline, his powers absorbed, so far as possible, in the action of a cosmopolitan observing machine."[8]

Best of all, for the first time they had, by God, the secret weapon of the new technology of photography, that objective medium that would capture what actually happened, free from human prejudice. Astronomers took care to drop a plumb bob from a fine silver wire in front of the plate and to photograph the wire with each exposure, to give a reference for position angles around the sun's circumference. They also placed a standard *reseau* (etched grid) in front of the plateholder, through which each exposure was made, registering the grid lines on each picture so as to allow the measurement of any shrinkage of the emulsion on the glass plate.

Every nation with a scientific reputation to build or maintain fielded at least one expedition, amounting to more than 80, totaling an investment topping a quarter of a million dollars. "Siberia and the Sandwich Islands were thickly beset with observers," Clerke continued, and "parties of three nationalities encamped within the mists of Kerguelen Island, expressively termed the 'Land of Desolation'...". Because 19th-century travel was scarcely easier or faster than 18th-century (despite the advent of steamships), the "daring votaries of science" were dropped off with enough provisions to last up to a year, setting up posts on the inhospitable and all-but-inaccessible hurricane-swept rocks of St. Paul's and Campbell Islands above the Antarctic Circle with only screaming sea birds for company. In the field, astronomers continued their daily regimen of drills until V-day dawned *[Figure 5]*.

The good news was: clear skies generally prevailed. But as telegrams began to pour into commission headquarters, the bad news became clear: unanimity was as elusive as ever. Although the dreaded black drop proved less troublesome than they had expected, what fouled their timings were the dusky penumbra and luminous ring, whose faint halo of light confused the moment when Venus merged with or separated from the Sun at the two external contacts. Observers with similar equipment standing only tens of feet apart reported timings that differed by as much as *half a minute* of time!

Worst of all, photography simply immortalized on film the ambiguous appearances observers saw with their eyes. When photographs were later examined under magnification, measurement of Venus's position was hopeless, as its edges appeared fuzzy instead of sharp. So ambiguous and unhelpful were the photographic results, in fact, that for the 1882 transit French astronomers broke with their British and German colleagues and recommended against photography, preferring to trust tried-and-true visual techniques.[9]

In short, for all the high technology and rigorous

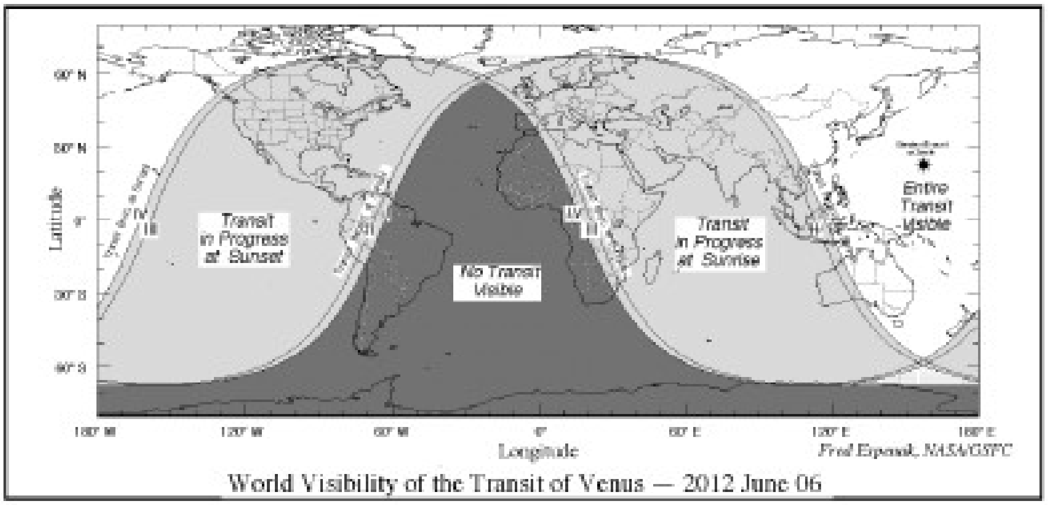


FIGURE 6
Plan ahead! The next transit of Venus will fall on Wednesday, June 6, 2012; from the U.S., the beginning of it will be visible from the continental 48 states, but the ending only from Alaska and Hawaii. After that, no one on Earth will see another transit of Venus for more than a century, until just before Christmas, 2117. Further details are available on a NASA website at *sunearth.gsfc.nasa.gov/eclipse/transit/venus0412.html.*

SOURCE: ESPENAK, FRED, "2004 AND 2012 TRANSITS OF VENUS" NASA GODDARD SPACEFLIGHT CENTER.

training in uniform procedures, after the 19th-century transits of Venus, the final value of the solar parallax that came to be accepted was 8.80 arcseconds, corresponding to an astronomical unit of 92,880,000—although still with an unsatisfactory probable error of at least 100,000 miles.

Gamely, astronomers kept trying other methods of deducing the Sun-Earth distance, such as from nighttime measurements of the parallaxes of Mars or from asteroids that whiz close by Earth.

But it wasn't until 1961 that "the noblest problem in astronomy" was finally solved—and by engineers, not astronomers, working without a transit of Venus.

A RADAR 'TAPE MEASURE'

After the U.S.S.R. had stunned the Western world by lofting basketball-sized *Sputnik 1* into a low orbit around Earth in October 1957, the next half-decade was the chilliest period of the Cold War. As more Soviet triumphs followed in quick succession, including the orbiting of the live dog Laika, the United States seemed to suffer one launch failure after another. The entire nation was desperate for some show of technological prowess.

In the mid-1950s, scientists and engineers at the Massachusetts Institute of Technology's Lincoln Laboratories—successor to MIT's Radiation Laboratory that co-invented radar during World War II—were designing, testing, and building prototype high-powered microwave radars intended to warn the United States of long-range bomber or missile attacks the Soviets might launch using a great circle route over the North Pole. Such warning systems required a new generation of radar with transmitters powerful enough and receivers sensitive enough to detect relatively small targets at greater distances than any predecessor devised in World War II.

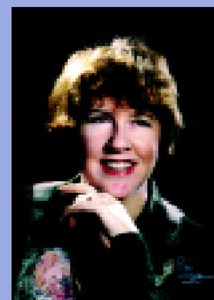
One October lunchtime a few weeks after *Sputnik*, two young MIT postdoc electrical engineers, Robert Price and Paul E. Green Jr., began wondering whether one experimental pulsed radar on Millstone Hill in Westford, MA, had the power to bounce a signal off another planet—say, Venus, which would approach to within five light-minutes of Earth in February 1958. Nights and weekends, they amassed the equipment they needed to give it a try: a pioneering maser receiver with extraordinarily low noise and high sensitivity; an anti-jamming coding system on which Price and Green had been working to eliminate ghosts and echoes from multipath propagation; plus an avant-garde digital computer with magnetic tape that could integrate radar echoes over time.

That February, they gave it a try, first transmitting pulses from the antenna for $4\frac{1}{2}$ minutes and then turning off the transmitter and switching on the receiver for five minutes to listen for returning echoes. When they analyzed their computer tapes and saw two apparent peaks, Price and Green "felt very blessed."[10] Although the timing of the two peaks differed by a few ten-thousandths of a second, implying a difference in Venus's distance of 400 miles (600 km) and leading them to wonder if they were just seeing processed noise, after extensive review they published their results in the March 20, 1959, issue of *Science*. Simultaneously, the Lincoln Lab held a press conference. Within days, the two EEs found themselves on the front page of *The New York Times*, on national television, and receiving a telegram from President Dwight D. Eisenhower congratulating them on their "notable achievement." But at Venus's next closest approach in September 1959, Price and Green were chagrined to find that they could not confirm their own results.

Meanwhile, in October 1958 President Eisenhower had established the National Aeronautics and Space Administration. Among the R&D facilities that became part of NASA was the Jet Propulsion Laboratory in Pasadena, operated by the California Institute of Technology, whose forte had been developing missile guidance and tracking systems for the Army Air Corps. Under NASA, JPL was charged with building a civilian Deep Space Network (DSN) for tracking satellites, lunar missions, and interplanetary spacecraft. JPL's radar antennas at the Goldstone facility in the Mojave Desert were continuous-wave instead of pulsed, with two antennas working as a pair: one always transmitting and one always receiving.

JPL was keenly interested in determining the precise value of the astronomical unit. If NASA intended to send a spacecraft to another planet whose distance wasn't known to better than 50,000 or 100,000 miles, the spacecraft might miss its target by some 10 times the planet's own diameter. Thus, a team of JPL engineers led by Eberhardt Rechtin *[California Beta '46]* (architect of the DSN system), modified the Goldstone equipment to aim at Venus during its next closest approach in April 1961. But a full month earlier, when Caltech EE doctoral candidate Richard Goldstein was testing the new setup by pointing the antennas at Venus, he was astounded to begin receiving echoes in 6.5 minutes—exactly the signal-travel time to Venus at the speed of light.

In 1964 the astronomers' highest commission, the International Astronomical Union, voted to adopt a value of 149,600,000 km plus-or-minus 2,000 km (92,910,000 plus-or-minus 1,250 miles). After two-and-a-half centuries, engineers had finally been the ones to exceed Halley's desideratum of one part in 500 by more than an order of magnitude.



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Her previous articles for THE BENT were "The Victorian Global Positioning System" (Spring 2002), "The Victorian Space Program" (Spring 2003), and "Taking Engineering by Storm" (Winter 2004). She may be reached at *t.e.bell@ieee.org*.

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2. Although the phrase "the noblest problem" is usually attributed to Airy, it appears to have originated with Halley in his 1716 paper, when he urged that on careful observations "the certain and adequate solution of the noblest, and otherwise most difficult problem depends" (*Phil. Trans. Abridged,* p. 246). Airy's quote appears in the paper "On the Means, which will be available for correcting the Measure of the Sun's Distance, in the next twenty-five years," by the Astronomer Royal [Airy, George Biddell], *Monthly Notices of the Royal Astronomical Society 17* (7): 208, May 8, 1857.

3. Woolf, Harry, *The Transits of Venus: A Study of Eighteenth-Century Science* (Princeton University Press, 1959) pp. 134–140. Woolf is the classic reference for the 18th-century transits. There is no book-length history of the 19th-century transits, although there are chapter-long accounts in other books, such as in *Sky and Ocean Joined: The U.S. Naval Observatory 1830–2000* by Steven J. Dick (Cambridge University Press, 2003) and in the still-classic *A Popular History of Astronomy During the Nineteenth Century* by Agnes M. Clerke (4th edition; London: Adams and Charles Black, 1902). As a run-up to the 2004 and 2012 transits of Venus, a spate of new books have been published with varying proportions of history and observing tips. Among them are: *June 8, 2004: Venus in Transit* by Eli Maor (Princeton University Press, 2000); *Transit: When Planets Cross the Sun* by Michael Maunder and Patrick Moore (Springer, 1999); *The Transit of Venus: the Quest to Find the True Distance of the Sun* by David Sellers (MagaVelda Press, 2001); *The Transits of Venus* by William Sheehan and John Westfall (Prometheus Books, 2004). An older one is *Transits* by Jean Meeus (Willmann-Bell, 1989).

4. Clerke, p. 229.

5. Dunn, Samuel, "Observations of the Planet Venus, on the Sun's Disk, June 6, 1761; and Certain Reasons for an Atmosphere about Venus," *Phil. Trans.* 52: 184–195, 1761. Also summarized in *Phil. Trans. Abridged,* 11: 555–557. Dunn also observed the 1769 transit and confirmed his results from eight years earlier; see "A Determination of the exact Moments of Time when the Planet Venus was at External and Internal Contact with the Sun's Limb, in the Transits of June 6, 1761, and June 3, 1769," *Phil. Trans. 60:* 65–73, 1770. Also summarized in *Phil. Trans. Abridged,* 13: 14–17.

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10. A historical article recounting the first radar bounces, including the competition between MIT and JPL engineers is "In conjunction with Venus," by Andrew J. Butrica, *IEEE Spectrum 34* (12): 31–32, December 1997. See also Butrica's book *To See the Unseen: A History of Planetary Radar Astronomy* (NASA History Series SP-4218, 1996).