# Chapter 9
# The Science and Systems of the Atmosphere

## Ionospheric Research for Radar Systems

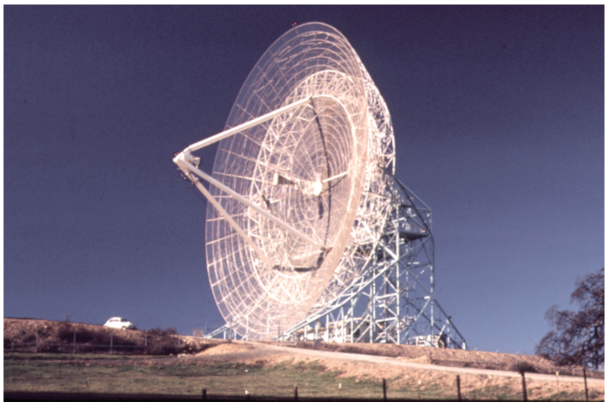

**Figure 9-1. The landmark SRI "Dish" located above the Stanford campus.**

Starting 40 to 50 miles above the Earth is a region of free ionized particles that extends to the uppermost reaches of the atmosphere. During the early decades of this century, research into understanding the propagation of shortwave radio signals led to the discovery of this ionized region, which, naturally, came to be called the ionosphere. Continued research resulted in a deeper appreciation of how the composition, structure, motion, and distribution of the ionosphere are related to solar and terrestrial conditions such as sunspot activity, the aurora borealis, and the day-night and seasonal cycles of its constituents. The density of ionization there is such that at oblique incidence it can reflect radio frequencies below about 30 MHz and thus provide, through multiple earth-ionosphere reflections, worldwide communications channels. For about a half century SRI has contributed both theoretically and experimentally to the knowledge of the ionosphere: its makeup and behavior, the ways it can alter radio and radar signals passing through it, and the opportunities it provides for long-distance, shortwave communications. Before communications satellites were introduced in the mid-1960s, these types of radio channels constituted all long-distance radio communications and were of critical importance to the U.S. government and its diplomatic and military agencies.

### Radar and Ionospheric Studies

Most of SRI's work on the impact of the ionosphere on radar is centered either at high latitudes or in the environment produced by high-altitude nuclear explosions. Some investigations have also been made at equatorial latitudes. SRI's contributions have significantly increased our understanding of:

- The effects of the aurora on radar systems trying to detect hostile aircraft and missiles coming over the polar regions
- The impact on radars of a nuclear attack with high-altitude detonations
- The effects of trans-ionospheric propagation on signals for radar detection and satellite communications.

From these applied efforts and from very directed and fundamental investigations that are ongoing, SRI continues its 50-year contribution to the science of the ionosphere.

SRI's interest in radars and the ionosphere began with Dr. Allen Peterson (see Fig. 9-2). On the faculty at Stanford and an early staff member of SRI (1954), he had written his thesis on how a shortwave signal, when bouncing between the ionosphere and the ground, would scatter back to the transmitting source some energy from each ground reflection point. He was also interested in using meteor trails as a radio reflection mechanism and in studying how the upper atmosphere impacted radar. More importantly, he knew the implications that the ionosphere might have on pending military defense radars and how to turn that knowledge into research sponsorship. Accordingly, he brought Ray Leadabrand (see Fig. 9-2),[1] a student of his, to SRI to pursue research on the impact of the high-latitude

[1] Leadabrand would eventually lead SRI into national prominence in the ionospheric radar field and become one of the important leaders of SRI's Engineering Group.

**Figure 9-2. Dr. Allen M. Peterson and Ray L. Leadabrand.**

ionosphere on radars, particularly that of the aurora borealis. In a new world that held the threat of ballistic missiles and nuclear warheads, an imperative question was whether they could be detected among the influx of naturally occurring charged particles from space; specifically, would they blind U.S. defensive radars to Soviet missiles approaching the United States from the north? The huge BMEWS[2] radar systems were being designed to detect ballistic missiles in flight, and such questions had to be answered. BMEWS was scheduled for implementation in 1960 to 1962.

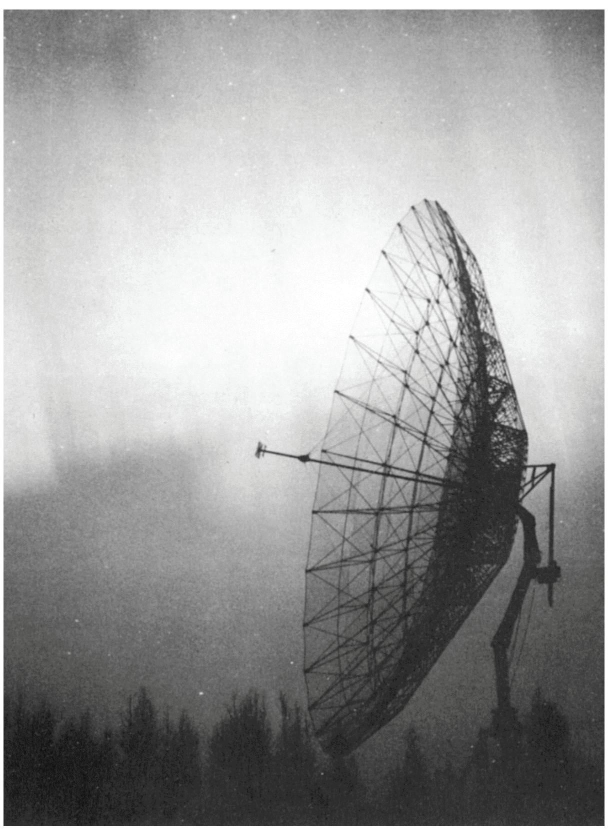

**Figure 9-3. SRI's 60-ft. auroral radar located just outside Fairbanks AK (visual aurora in the background).**

Consequently, in 1956 SRI began a long-term program to help understand the impact of the aurora on such radars. Auroral reflection characteristics such as aspect-sensitivity, frequency and location of occurrence, and radar cross section became important information in the siting and signal interpretation of defense radars operating in that region. The program was sponsored by the Air Force and was generically referred to as Auroral Clutter. To examine these effects, SRI began exploratory work with radars it had built and operated here at Stanford. Quite incidentally, it was one of these that made the first radar detection of an artificial satellite, Sputnik I, on October 10, 1957.[A] In that same year, SRI placed another 61-ft auroral-diagnostic radar near Fairbanks, Alaska, the first of a series of radars to be operated in that area over the next 22 years. The Alaska radar, shown in Figure 9-3, was the first to examine the aurora at higher frequencies—from 400 to 1200 MHz. These frequencies, in combination with the 61-ft parabolic radar antenna, produced sufficiently narrow beamwidths that, with radar ranging, they could pinpoint the location of the auroral ionization.[B, 3] It provided data for the first International Geophysical Year in 1958.

Soon after these Alaskan studies began, however, it became clear that, because of the tilt of the magnetic pole toward the American continent, a European BMEWS site would "see" a somewhat different auroral geometry. To address these differences, SRI proposed to the

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[2] The Ballistic Missile Early Warning Systems were very large ground-based radars located in the far north.

[3] This directivity was also calculated to help investigate the potential for auroral interference by means of the side lobes of the much larger and more directive BMEWS radars. Through the efforts of Walter Jaye and others, the SRI Alaskan radars were also used to explore the effects of ionization from meteor trails. (Personal communication, Ray Leadabrand, May 31, 2004.)

Air Force Rome Development Center that another investigative radar be located in Scotland. The proposal was accepted and the radar began operation in 1960 to look at the naturally occurring auroral events in that hemisphere. This radar was designed and built by SRI and operated just outside Fraserburgh, Scotland, in collaboration with the British Royal Radar Establishment. It was similar to the one at Stanford shown in Figure 9-1 and four others around the world, two of which were built by SRI. In this manner, SRI obtained from both Alaska and Scotland important information on the nature of auroral clutter for the BMEWS program and for depicting the upper atmosphere in general.[C, 4]

Before proceeding further, it is worth noting that from this ionospheric work there grew probably the closest working relationship SRI had with Stanford. Development of both equipment capability and research staff was often a joint affair. SRI owns the big 150-ft dish and an associated 400-MHz transmitter located atop a hill above Stanford and visible throughout the campus, while a 400-KW 50-MHz transmitter located nearby belongs to the University. In the early 1960s the two institutions created the Center for Radar Astronomy, with balanced leadership from Von Eshleman of Stanford, Leadabrand of SRI, and Peterson of both institutions.

## The U.S. High-Altitude Nuclear Tests of 1958

But while this work on the natural ionosphere was proceeding, SRI became engulfed in an experiment resulting from a decision by the U.S. government in 1958 to hold its first high-altitude nuclear test series. The original plan was to hold the tests in the Pacific at Bikini Atoll, where earlier surface bursts had been conducted. But the risk of eye damage to people in that part of the Pacific caused the tests to be moved to Johnston Island, a very isolated coral atoll a thousand miles southwest of Honolulu. The two detonations were called Teak and Orange, and their initial inception and planning revealed no concern for or curiosity about their potential impact on electromagnetic systems such as radar and communications.

But as the test date approached, things would change quickly. A few Air Force people began, just 90 days before the shots, to wonder about the potential effect of such detonations on anti-ballistic missile (ABM) defense systems. These people knew researchers at both SRI and Stanford, and so Peterson became aware of the concern and brought the problem to SRI. The Bikini Atoll location had strongly suggested the need for a sea-mobile radar platform. A proposal was quickly written and carried to Washington to the funding agent who, through attending Stanford himself, was also aware of SRI. After some negotiations, it was accepted and a contract was written within a few days. Design work was begun, the sea-going yacht M/V Acania purchased, the equipment installed and checked out, and the entire package sailed to Wotho Atoll, 100 miles southwest of Bikini, in time for the tests, and all in less than three months! Moreover, through the foresight of a floating radar platform, the relocation of the tests to Johnston Island was handled with ease. *That incredible ability in radioscience to respond quickly, with competent concepts and equipment, to virtually any problem anywhere in the world, has always set SRI apart from its contract research competitors.*

The nation's first high-altitude detonations occurred in early August 1958, and the six radars on the Acania, ranging in frequency from 11 MHz to 780 MHz, were the first to see how totally reflective such high-altitude plasma was. This result meant that for this scenario (the combination of radar frequency, detonation altitude, and location), radars would be effectively blacked out. Although the implications for ABM systems were profound, the United States continued, incredulously, to develop nuclear-tipped interceptors!

In addition to this scene in the mid-Pacific, SRI was, at the same time, busily engaged in another nuclear experiment half a world away in the South Atlantic. The roots of this episode began in early 1958 when Peterson was asked by Herbert York, the first director of DoD's Advanced Research Projects Agency (ARPA), to convene a high-level theoretical group, as part

[4] From received signals that showed wavelength dependence (the inverse seventh power) and aspect (angular) sensitivity (10 dB per degree off perpendicular at 400 and 800 MHz), there were implied elongated, rod-like forms in the ionization with transverse dimensions of 0.7 m and lengths of from 45 to 120 m. Another important event occurred at the Fraserburgh radar when Ray Leadabrand sent Murray Baron there to search for the existence of the then newly postulated radar echoes from individual electrons, called incoherent scatter. Baron recorded them in December 1960, and they became the first such returns ever detected at high latitude.

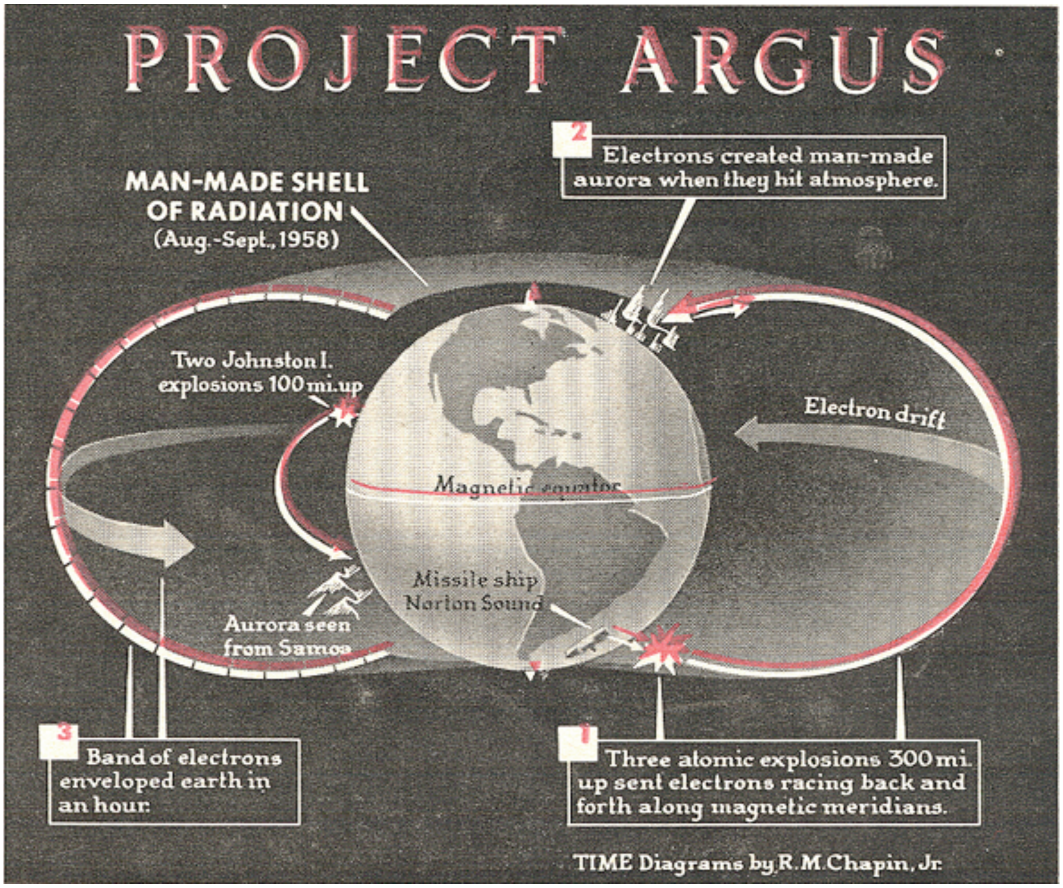



**Figure 9-4. A schematic diagram of Project ARGUS (From *TIME Magazine,* March 30, 1959, page 71).**

of an anti-ballistic missile defense program, to consider the possibility of a particle beam weapon. During those discussions, N. C. Christofilos, a brilliant, self-taught physicist from the University of California's Lawrence Radiation Labs, raised an ancillary proposition he had been thinking about for a year or more: Could a nuclear device, detonated in the ionosphere, produce a temporary radiation belt over the earth that might be inimical to incoming warheads?

The naturally produced Van Allen belts, just becoming evident from radiation counters aboard the Explorer satellite, had confirmed Christofilos' notion about the existence of such radiation belts, but whether man could induce one or not was unknown. So, after internal review, ARPA decided to sponsor a classified experiment, to be conducted in the South Atlantic, that was intended, by exploding a very small nuclear weapon at high altitude, to inject ionization into the Earth's magnetic field to become trapped there and precess around the world (see Figure 9-4). The location of injection was about 1100 miles southwest of Capetown, near the Falkland Islands. Of the numerous atmospheric tests the United States would conduct, this was the only one that was not announced beforehand.

It was August and September of 1958, and the project was called ARGUS. SRI was asked to make several measurements that would indicate whether electrons had been injected. The principal SRI sites were in the Azores; at a U.S. Air Force Base in Torrejon, Spain; and with radar equipment on the launching ship, the Norton Sound, in the South Atlantic. One measurement was to look for synchrotron radiation emitted by electrons trapped in the earth's magnetic field that would indicate whether injection occurred. That measurement was at Torrejon and did not reveal any effect. A second measurement, the monitoring of very low frequency radio stations (60-300 kHz) in the Azores, saw a pronounced absorption effect indicating an impact on the lower ionosphere. The third measurement was of radar reflections made in the vicinity of the shot and at the northern conjugate point.[5] Although only one of three missiles reached the planned 300-km injection altitude, some trapped radiation was seen. SRI's 27-MHz radar data revealed high-energy particles impinging on the atmosphere in both hemispheres for two of the three shots and were the most dramatic of the SRI measurements. Visible aurorae were also seen north of the Azores.[D]


**Figure 9-5. An SRI shelter destined for ARGUS. Top row (l to r): Jim Hodges and George Hagn; middle row: Allen Peterson, two non-SRI people; bottom row: Rolf Dyce, Ray Leadabrand, and Ray Vincent. (Missing is Bob Light who ran the field site in the Azores.)**

The principal indication of the amount and energy of trapped radiation, however, was made with an existing satellite (Explorer IV) and measurement rockets in the United States. Although the effect could be measured for days after the burst, the ability of the new radiation belt to act as a protective shield was not confirmed. ARGUS, noted in the *New York Times*[6] as the "Greatest Experiment," was probably the first scientific experiment to explore physics on such a grand, earth-space scale. Having little military significance, the considerable information gathered, much of it giving unique insights into the Earth's magnetic environment, was soon declassified and submitted as part of the 1958 International Geophysical Year. Some of the SRI people involved in ARGUS are shown in Figure 9-5.

As this first high-altitude testing program wound down, President Eisenhower invoked a unilateral moratorium on nuclear testing on October 31, 1958 and invited the Russians to do the same. They did, at least for a while. Through its participation in these tests, SRI became the preeminent organization in the United States to deal with the effects of the ionosphere on electromagnetic systems both under nuclear and natural conditions. And the M/V Acania would become one of the most widely used SRI facilities for over a decade (see Figure 9-6[7]). It would be used in the Caribbean for examining the radar reflections associated with both the launch and reentry of ballistic missiles from Florida; for following solar eclipses to determine chemical recombination rates in the ionosphere; and, when the Soviets broke their test ban moratorium in September of 1961 and the United States decided to resume its own testing, it was sailed to the South Pacific for ionospheric measurements at the magnetic conjugate of Johnston Island.

[5] The term "conjugate" refers to a point in the hemisphere opposite from where the detonation occurs. It is determined by tracing the magnetic field lines passing through the burst area, across the geomagnetic equator, to an altitude of about 110K in the opposite hemisphere. There, particles from the hemisphere of the burst collide with and ionize particles in the normal atmosphere.

[6] Front-page headline, New York Times, March 1959. Also headlined in the Washington Post, same day.

[7] The Acania was said to have been built in France for actress Constance Bennett. Converting it to a radar platform and overseeing its use for over a decade was the responsibility of SRI's Roy Long.

**Figure 9-6. The SRI M/V Acania in calm sea 300 miles off Samoa (1962) (photo courtesy of Boyd Fair).**

Before turning to a second nuclear test series in the Pacific, a word more about the role of the SRI Acania in the Caribbean is warranted. Over time, the radar-equipped Acania was given the task of examining the ionospheric effects made by both the boosters as they powered through the ionosphere on their way up and by the reentry vehicles on their way down. Both signatures were important to remote detection—in the first instance to recognize that a launch had taken place, and in the second to be able to analyze and target incoming warheads. The ascending, powered missile became much more detectable as it transited the ionosphere, but the very long-range examinations of that transit were not at all precise. So, the Acania was brought close in to make direct examinations that helped understand the phenomenology and improve the detection potential of long-range radars located beyond the horizon. On the other end, the reentry work helped the U.S. ability to distinguish between decoys and the real warhead.

**Figure 9-7. SRI engineer George Durfey in a whimsical pose atop one of the trunnions that now support the Stanford Field Site Dish.**

President Eisenhower's unilateral testing moratorium from 1958 to 1961 was an uneasy one, and the United States continued to look at its preparedness. Accordingly, and in anticipation of one day returning to nuclear testing at Johnston Island, SRI made an unusual proposal to the government around 1961. To explore our ability to use ABM radars in a nuclear environment, where they must assuredly work, measurements were needed of ray paths that transited a nuclear-disturbed region of the ionosphere. SRI suggested using the moon as a reflector to direct energy to a remote nuclear test site such that the radar beam would intersect the affected region. Satellites were not yet available for this purpose, so a proposal was written and accepted. The radar built for this purpose was none other than the landmark above Stanford, the parabolic "Big Dish" shown in Figure 9-1. It was patterned after its predecessor in Scotland, which had been built for auroral studies, but has a slightly larger (150 ft) diameter. SRI engineer George Durfey (Figure 9-7) led the building of the Dish.[8]

But the nuclear tests in the Pacific arrived before the Dish was completed in 1963, so it did not ever see use for its original design purpose. Nevertheless, the antenna has been used for radio astronomy measurements at Stanford, communicating with NASA Pioneer satellites, exploratory incoherent scatter experiments of the ionosphere, testing nuclear-weapon detectors aboard GPS satellites,

[8] Durfey was principally involved in the design construction of the Dish but Dr. Mike Cousins has, for many years been responsible for its operation and maintenance.

and a host of other purposes. I recall taking a Palo Alto teacher's elementary-grade class to the Dish, perhaps in the early 1970s. There we learned that on the previous day the Dish had transmitted to a Pioneer spacecraft that was just emerging from behind the sun—that is, clear across the earth's solar orbit, or 186 million miles away! (See box on Pioneer satellites.)

When the Russians resumed atmospheric testing in September of 1961, SRI went to the field again. The Soviets were to make their first high-altitude nuclear tests in October at their Kapustin Yar missile range—tests that also explored the electron injection mechanism mentioned above in the U.S. ARGUS tests. Like the U.S. weapons, these missiles were small. A few days later, though, the Soviets released from an airplane over their Novaya Zemlya arctic testing site the largest explosion ever seen, some 50 megatons. To determine whether there were any impacts at the magnetic conjugate of these bursts, SRI took instrumentation to the South Indian Ocean aboard two ships. On the way to the conjugate area from western Australia, one of the ships passed through a hurricane that produced 60-ft peak-to-trough waves that flowed over the ship. Nevertheless, the ship reached the spot in time for passive noise measuring devices called riometers, and all-sky cameras were used to try to detect the presence of high-altitude plasma or trapped radiation.

The advent of the ballistic missile threat brought another campaign, first at ONR and then at ARPA, that would explore the use of high-frequency (HF) transmissions, using both ground-backscatter radars and normal forward propagation circuits, to remotely detect missile launches and nuclear explosions. A suggestion by Peterson and Oswald "Mike" Villard at Stanford had pointed to the potential of HF systems to do this. But SRI was naturally not among those seeking to build an operational system. Being free of such an advocacy position, though, SRI was asked by ARPA to become the "objective" collector and reviewer of data from this entire effort. For over a decade, SRI ran ARPA's Detection Data Center for the collection and presentation of data and information on over-the-horizon missile detection. Unexpectedly, this had the unfortunate side effect of denying SRI even experimental roles in that same program. Eventually, this detection capability became attractive enough that both the Air Force and the Navy built operational radars to carry out this mission. SRI's Ed Lyon was the Air Force's chief consultant on such systems for decades.

## The U.S. High-Altitude Nuclear Tests of 1962

Now let us turn to the 1962 nuclear test series in the Pacific. As mentioned, the Soviet Union broke the test ban agreement on September 1, 1961, and on October 10 President Kennedy authorized planning to begin for the resumption of U.S. testing. The test series came to be called Operation Dominic, and SRI's role in its last phase, termed Fishbowl, was pivotal. SRI would again demonstrate its responsiveness, fielding a family of radars, including one 84 ft in diameter, on Johnston Island within the allotted 3 months. This SRI work was funded by the Defense Nuclear Agency (DNA).[9]

Although SRI was required to be in the field by April of 1962, there were then a number of launch failures, including one that blew up the launch pad. But five test missiles were launched between July and November. Similar to the 1958 experience, the SRI radar data proved that the detection of ballistic missile reentry in or above the ionosphere, following a high-altitude offensive or defensive detonation, could not be relied upon using ground-based equipment. The radars were either blacked out (no radar returns) for short periods or, more significantly, flooded with spurious signals from bright reflections from ionization structurally aligned in the earth's magnetic field. SRI drew these conclusions from the data gathered by the SRI Johnston Island radars, plus several airborne radars that SRI operated aboard RC-121 aircraft flying in the vicinity.

As precarious as it would seem, the results showed that a much lower ABM intercept altitude than originally conceived would be needed. The important implication of this is the significantly reduced time available to defend ABM systems. Although billions have since been spent on high-altitude sensors and interceptor weapons (e.g., the Strategic Defense Initiative), to date no real ABM system has been built by the United States for intercept at any altitude. One unexpectedly beneficial by-product of SRI's presence on Johnston Island were the photographs taken by SRI's Walter Chesnut. Taken in support of the radar work, they have become one of the most important

[9] Up until November 1971, DNA was called the Defense Atomic Support Agency or DASA but we will use DNA here.

**IVORY ON THE CORAL**

From the center of the flat, elongated coral slab that was Johnston Island (JI), one could walk north or south no more than a few hundred yards before encountering the ocean, and from there the closest land was at least a thousand miles away. With nary a tree or source of potable water, Johnston Island would make a regrettable shipwreck isle. On the other hand, this austerity meant that the bustle of the mission there didn't have to contend with any serious distractions; there simply were none. Usually, and insofar as possible, the U.S. military tries to bring a sense of home to their troops, but this operation was temporary and a bit austere. Requests for needed technical equipment were honored quickly; niceties were something else. If diversions were to be found, they had to be created. Well, SRI also cares about its people abroad.

The postponements and delays of the operation were getting to the SRI crew. Range safety officers were destroying missiles in flight, and then one blew up on the launch pad, destroying the pad. Experimenters, including SRI, would use these delays to maintain and upgrade their equipment so as to be ready when the real time came. But there is only so much of that one can do. With a concern for those isolated on Johnston Island, Ray Leadabrand and his assistant, Barbara Bunker, who were in Hawaii at the time, got creative.

Like other shipments, the huge wooden crate was delivered outside the SRI radar van on JI and laid there on the coral sand. On the crate, per airlift convention, was stenciled its contents: *VARIABLE-FREQUENCY IMPULSE-ACTIVATED TONE GENERATOR.* Puzzled, the SRI crew broke it open to find a small spinet piano. They quickly placed the piano, appropriately, inside the instrumentation van. Murray Baron, in charge of the SRI radars on the Island and who (Ray knew) played the piano, then positioned himself at the instrument's keyboard and belted out something like ragtime. Joplin could have not sounded better to the assembled bunch. The piano, as it turned out, was riddled with termites, but it served its purpose well. Murray and Jose De Leon wrote the *Johnston Island Blues,* and the instrument was later given to the Island's NCO Club.

sets of information available to understand the complex interactions of the various nuclear energy products with the Earth's atmosphere and its magnetic field. These data are still being studied almost 40 years later!

Following the tests in the Pacific, the government initiated what was commonly known as the Readiness Program. This name reflected the desire on the part of the United States to be ready should another violation by the Soviets enable or force a continuation of our own tests. Given the now proven uncertainty of radar performance in nuclear environments, there was plenty to be learned. Many projects at SRI fell under this umbrella: the examination of field-aligned radar echoes in the aurora as a surrogate to nuclear-produced clutter, the development of a series of satellites to measure the coherent bandwidth of the ionosphere, the development of an incoherent scatter facility in Alaska to study the background ionosphere, and the non-cooperative participation in the French atomic tests in Mururoa in 1971-1974. The latter work was to learn about the impact on radar of low altitude detonations. It came to SRI because of our deep familiarity with assessing the nuclear impacts on future ABM designs.

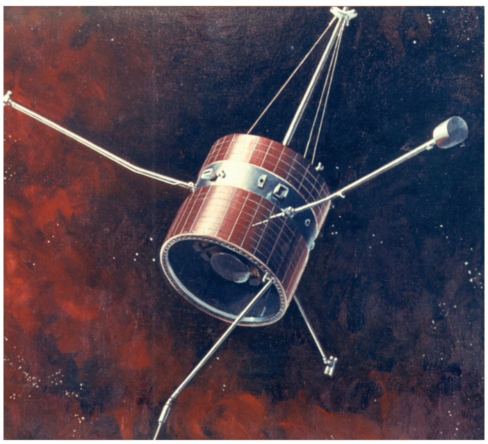
Regarding the limits imposed by the ionosphere on the bandwidth of radars, it is important to be able to resolve individual incoming missiles while they are still at very high altitudes. To accomplish this, anti-ballistic missile radars, of necessity, use very wide bandwidths. It was important then, to assess just how much the ionosphere might limit the resolution such bandwidth afforded. SRI, under DNA sponsorship, came up with a creative technique to measure the coherence bandwidth of the ionosphere. (See box on satellites.)

## Back to More Benign Research Settings

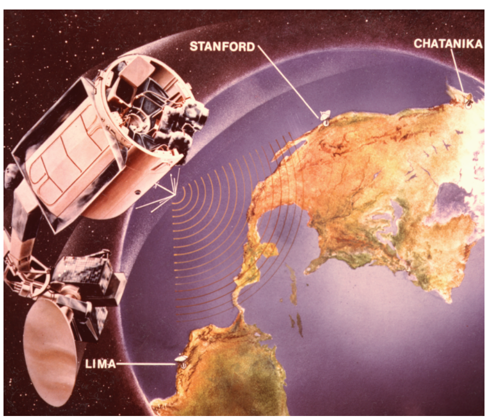
As is often the case in the United States, equipment built for a military research purpose finds good use in basic science. Under sponsorship of the Defense Nuclear Agency, SRI built the incoherent scatter radar mentioned earlier that could look in detail at electron density, temperature, and plasma motion as a function of spatial position, including altitude. This facility was built and checked out at Stanford and then relocated in 1972 to Chatanika, Alaska, to make detailed measurements of the aurora and its more quiescent background. The operation of that radar produced perhaps thirty PhD theses and countless papers about auroral arcs and the electrical behavior of our upper atmosphere.

## SRI SATELLITE WORK

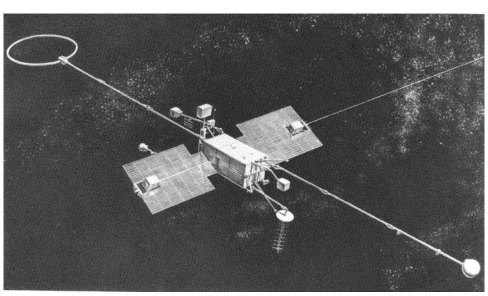
It is not commonly known, but in the 1960s SRI designed and built a series of satellite packages for Stanford University that was used in studies of interplanetary space. These experiments flew on four of the Pioneer Series and on Mariner V after the Pioneer series was interrupted. The Pioneer satellites were legendary in their durability, and were the first satellites to orbit the sun. SRI's "Big Dish" at Stanford was used for both command and telemetry, and was one of the sites that transmitted the dual frequencies used to measure interplanetary electron densities. The package flown on Mariner V was used in the first Venus occultation experiment. As the satellite passed behind Venus, the changes in the characteristics of the signal that was passed from the Earth to the satellite revealed characteristics of the Venusian atmosphere. Four OGO (orbiting geophysical observatory) satellites had SRI-built VLF receivers aboard that were tuned to ground-based transmitters. These and three-axis magnetic field sensors helped in the discovery of the asymmetry of the earth's magnetosphere. According to SRI's Bud Rorden, designer of the OGO series, most of these early satellites were built from scratch using hand-selected parts. Finally, SRI designed and operated a series of innovative wideband satellites that measured the coherent bandwidth of the ionosphere in equatorial, auroral, and the more quiescent mid-latitude regions.



Pioneer 6, 7, 8, and 9 were the first solar orbiting satellites and were used to measure interplanetary features. They measured the dynamics of the solar wind and discovered its spiral nature. The SRI two-frequency package used on Pioneer was also flown later on Mariner V. As of 1996, Pioneer 6 was the oldest working satellite, having been in orbit for over 30 years.




One of three SRI satellites launched in the early 1970s to measure the coherent bandwidth of the ionosphere using a set of phase-coherent spectral lines near 400 and 2300 MHz.



One of four OGO (2 equatorial and 2 polar) satellites. SRI also had experiments aboard Explorer 6 and the VELA (nuclear detection) satellites.

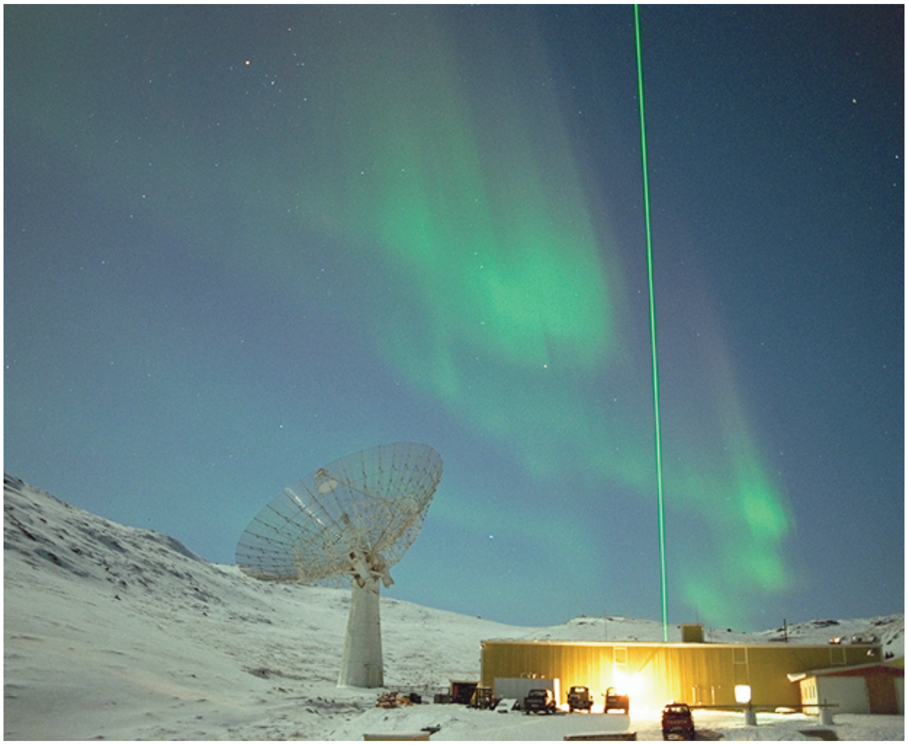


**Figure 9-8. The SRI site in Greenland showing the auroral radar, a lidar beam, and auroral curtains.**

After these studies of the auroral zone had gone on for almost a decade, a similar but newer and more powerful auroral radar was built in Norway. (SRI's Dr. Murray Baron became the second leader of this facility, called EISCAT.) This new radar motivated the SRI leaders to suggest moving its radar to a higher magnetic latitude and there to examine daytime auroral conditions. By this time the Defense Department's interests in readiness had declined, and ownership of the incoherent scatter facility was transferred to the National Science Foundation (NSF). In response to SRI's suggestion, NSF authorized the radar's relocation to Sondrestrom Fjord, Greenland, where it also could explore the effects of the so-called ionospheric cusp—the locations where the earth's magnetic field lines open into outer space. SRI also brought other instruments there to measure airglow and a laser radar (lidar) to look for specific constituents (see Figure 9-8).

As important as SRI's own research using the facility has been, at least as important was SRI's decision to open up the facility to all qualified scientists from around the world. That open policy, started at Chatanika, has made the Sondrestrom facility by far the most prolific source of ionospheric knowledge among the four such sites that NSF funds, and one of the best in the world. The site is efficiently run by just four SRI staff members, and its data are available over the Internet. Some specific knowledge that has come from Chatanika and Sondrestrom includes:

- The first observations of the high-latitude convection pattern; that is, the distribution and movement of the ionic "fluid" in the polar region and the behavior of ionospheric storms caused by the variable impact of particles ejected from the sun's corona.
- Electrodynamic models of the high-latitude ionosphere, also involving neutral components, across high and low ion density regions.
- The constituents of the high-latitude ionosphere, including the presence of heavy ions and their chemical balance.

The Sondrestrom site employs more than 22 different instruments and is used by hundreds of the world's upper atmosphere scientists from 38 different institutions. Information from the Chatanika and Sondrestrom facilities have, between 1973 and 2002, given rise to more than 490 papers in the various research journals of geophysics and more than 45 Ph.D. theses.

The most recent affirmation of the SRI strength in this field was a 4-year, $44 million, 2003 award from NSF to build the world's first modular and mobile incoherent scatter system. The idea was born at a meeting of scientists at SRI some 15 years ago. John Kelly, a leader in SRI's Center for GeoSpace Studies recalls discussing the need for advanced instrumentation to address critical questions in ionospheric research such as dynamics. Current radar systems were, and still are, limited in where they can be and how fast they can be pointed. The new radar will be electronically steered and have three separate panels that can operate independently at the same or separate sites. The first site is in Poker Flat, Alaska, to be

**Figure 9-9. The SRI 1.4 mile long Wide Aperture Receiving Facility near Los Banos, CA.**

followed soon by two at Resolute Bay in Canada. Though remote, its operation will be accessible from anywhere on the Internet.[10]

SRI operates other unique ionospheric facilities. One is a remote laboratory on Resolute Bay for scientific probing of the ionospheric "polar cap," that region within the annular auroral zone. It is sponsored by the NSF and, like Sondrestrom, available to all scientists. Another is the Wide Aperture Research Facility (WARF), a testbed for the technology important to over-the-horizon (OTH) radars; that is, those that use reflection from the ionosphere to operate beyond line of sight. It uses a combination of transmitting and receiving arrays located approximately 100 miles apart in the Central Valley of California. There are two transmitting and two receiving arrays, each pair having different azimuthal orientations. The receiving arrays, one of which is depicted in Figure 9-9, are about 7,500 ft (1.42 mi) long and consist of about 256 vertical, twin-element receiving pairs. This array makes possible azimuthal beamwidths of the order of a half degree. The transmit arrays consist of 16 vertical-element log-periodic antennas capable of transmitting from 6 to 28 MHz. One of the arrays was developed in the mid-1960s. The total coverage area of its associated radar is 1.3 million sq mi that can be swept using an illuminated region of approximately 15,000 sq mi. In the setting of OTH radars, the WARF pioneered the automatic detection and tracking of aircraft and surface ships, ionospheric propagation management, advanced display and signal processing techniques, and remote ocean wave-height measurements. Its design was used to develop the specification for the U.S. Navy's Relocatable Over-the-Horizon Radar (ROTHR) in Virginia, the Air Force's two installations in Maine and Northern California, and the Australian government's Jindalee experimental OTHR. Over the decade of the 1990s the WARF was upgraded to a real-time detection and tracking facility to conduct research and development for wide-area counter-drug surveillance. Coverage can extend from the southern border of Mexico to our own southern states and laterally from Baja California to the Gulf of Mexico. Even small, general aviation aircraft can be followed. The WARF is operated by a crew of six engineers and technicians who continue to improve its performance through capabilities like impulsive noise excision (lightning) and improved tracking and ground positioning techniques. Over its existence the WARF activities have been sponsored by perhaps 10 different governmental agencies.

The above discussion has been but a sampling of SRI's continuous contributions to our understanding of the upper atmosphere, both fundamentally and how it can interact with systems we find necessary to use. The time diagram of Figure 9-10 more completely encapsulates SRI's involvement in ionospheric research. Not only has it continued for over 40 years, it is still going strong today.

[10] While SRI is the leader of this innovative facility other collaborating institutions include MIT Millstone Hill, Stanford University, the University of Alaska and the University of Western Ontario.

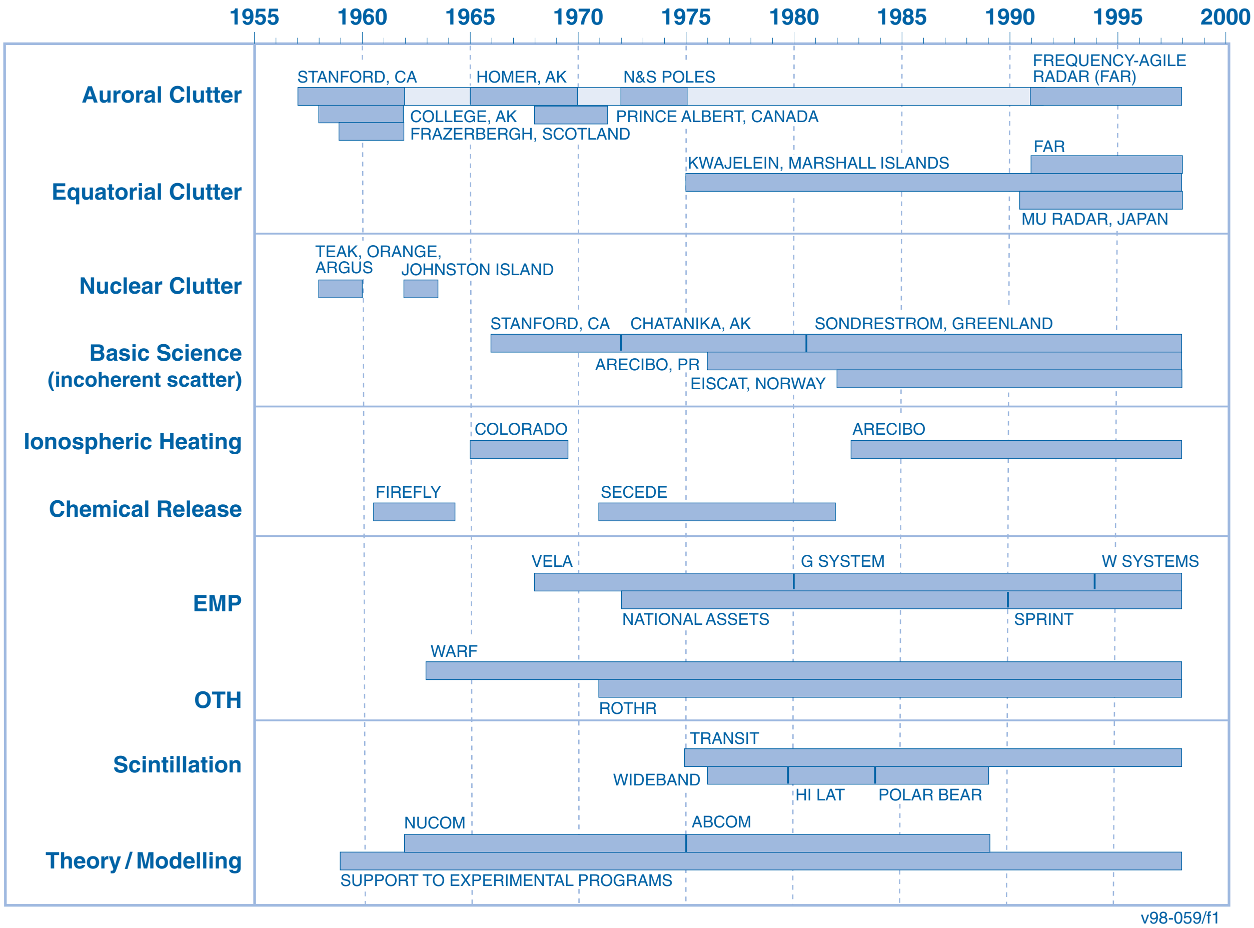



**Figure 9-10. A comprehensive listing of major SRI participation in ionospheric research, only a few of which have been touched on here.**

# Research in Ionospheric Communications

SRI's work in ionosphere-dependent communications[11] dates back to 1951, when SRI was just 3 years old.[E] Work on several innovative approaches to single-sideband modulation techniques began earlier in 1948, but work that directly involved the understanding and use of the ionosphere came with a request from the U.S. Army Signal Corps in June 1951. Over a 2-year period SRI built a simulator that depicted the multiple simultaneous radio paths characteristic of ionospheric, high-frequency (HF) or shortwave communications. The simulator was used to test various modulation techniques. We will return to HF communications after a brief story about SRI's exploration into the use of meteor trails for communications.

## Communications Via Meteor Trails

As mentioned at the outset, Peterson, and later his associate Ray Vincent, were interested in the potential of very small micrometeorites for communications. SRI and Stanford were both investigating their effects, and SRI had built a meteor-burst system for the Air Force as early as 1955 (see Figures 9-11 and 9-12). Radio reflections from these trails could extend line-of-site communications beyond the horizon to perhaps a thousand miles. Because the altitude where friction spelled the end of the meteorite was also one of fairly rapid recombination, the ionization in each trail was

[11] Ionospheric communication relies on the existence of a reflecting layer for radio waves that lies from about 80 to 400 km above the Earth. The propagation of radio energy in the HF or shortwave band is made possible by entrapment between two annular shells, the conducting ground and the ionosphere. Using this corridor is generally limited to frequencies below 30 MHz. The so-called medium and shortwave bands constituted the only long-range communications before the advent of satellites, and are still in use in many parts of the world.

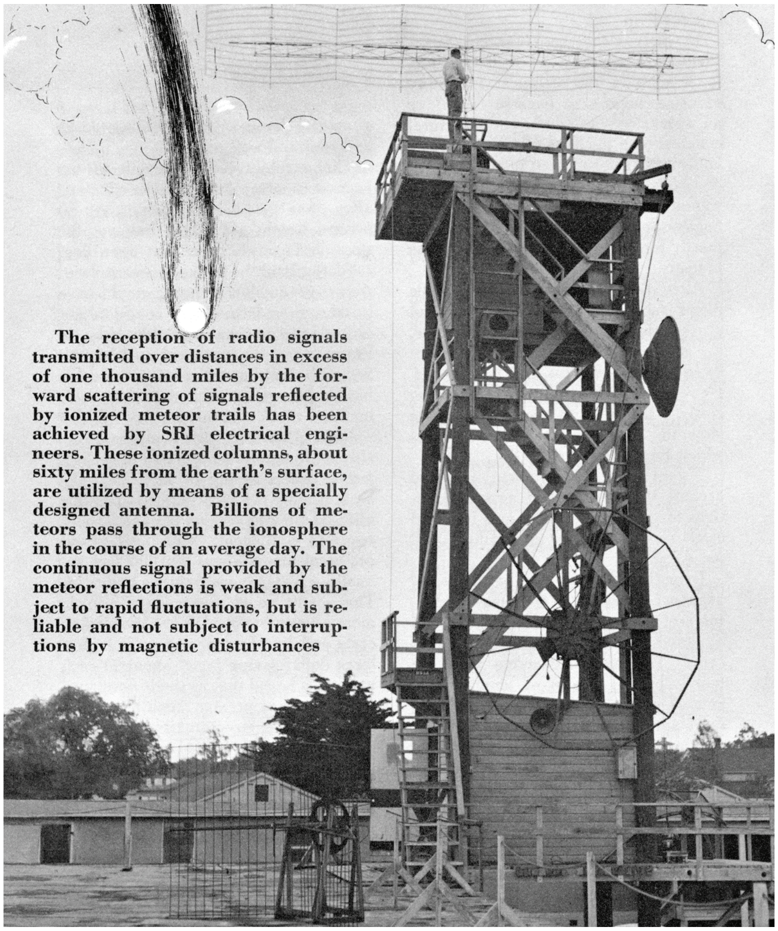



**Figure 9-11. The antenna for SRI's experimental meteor burst system (SRI's *Research for Industry*, 8, 1, 10, November 1955).**

short-lived. To make the channel useful, therefore, it was necessary to store or buffer the flow of information until a new trail of the correct geometry arrived. The stored data was then burst quickly to the receiver. Usable trails could come from grain-sized meteors whose occurrence was frequent enough to sustain effective communications bandwidths of the order of 10 kHz. SRI explored meteor communications for perhaps a decade, both in system design and construction and in modeling the radio reflection characteristics of the meteor trails themselves.

One study determined the locus of trail positions that would be advantageous for a given transmitter-receiver geometry. Geometry was important because normally good signal strength depended on finding a meteor trail whose location provided a specular or equal-angle reflection. Although SRI's work was pioneering and interesting, only a few meteor trail systems were built and used. One need for which meteor-burst communications was ideal was the collection of meteorological (no pun intended) information from remote areas. To gather snow and water level information, the Department of Agriculture's Natural Resource Conservation Service still operates a very large network in the West using such a system, called SNOTEL. Systems are still made and sold, and the Air Force reopened its interest in the medium, sponsoring research in the geographic distribution of reflection sites from a single transmitter. For the most part, however, satellites began displacing meteor burst systems in the late 1960s, and their employment today is only in very specialized situations.

## High-Frequency Ionospheric Communications

Concurrent with this first meteor-burst work, the critical nature of HF communications to the U.S. military enabled SRI to continue its ionospheric communications work. It would last for another 30 years or more. The complexity of the ionospheric medium, including its global, weather-like diurnal and seasonal variations made it very difficult to predict whether communications would be available. Furthermore, because of its long propagating range, the universal (global) demand for HF and its very limited range of usable frequencies meant a very crowded radio spectrum. Because of these complexities, the advent of computers offered a natural approach to harnessing our knowledge of the ionosphere and building computational models of it. In 1956 SRI was awarded a contract from the U.S. Army Signal Corps to look at the use of computers to do just that. SRI built some of the earliest computer models of this type of communications. Subsequently, the National Bureau of Standards in Boulder, CO, began building an improved model of the global and temporal ionosphere using a worldwide distribution of ionospheric data collection stations. These data, together with more accurate propagation models, meant improved frequency allocation and selection for the far-flung HF radio systems of the U.S. government.

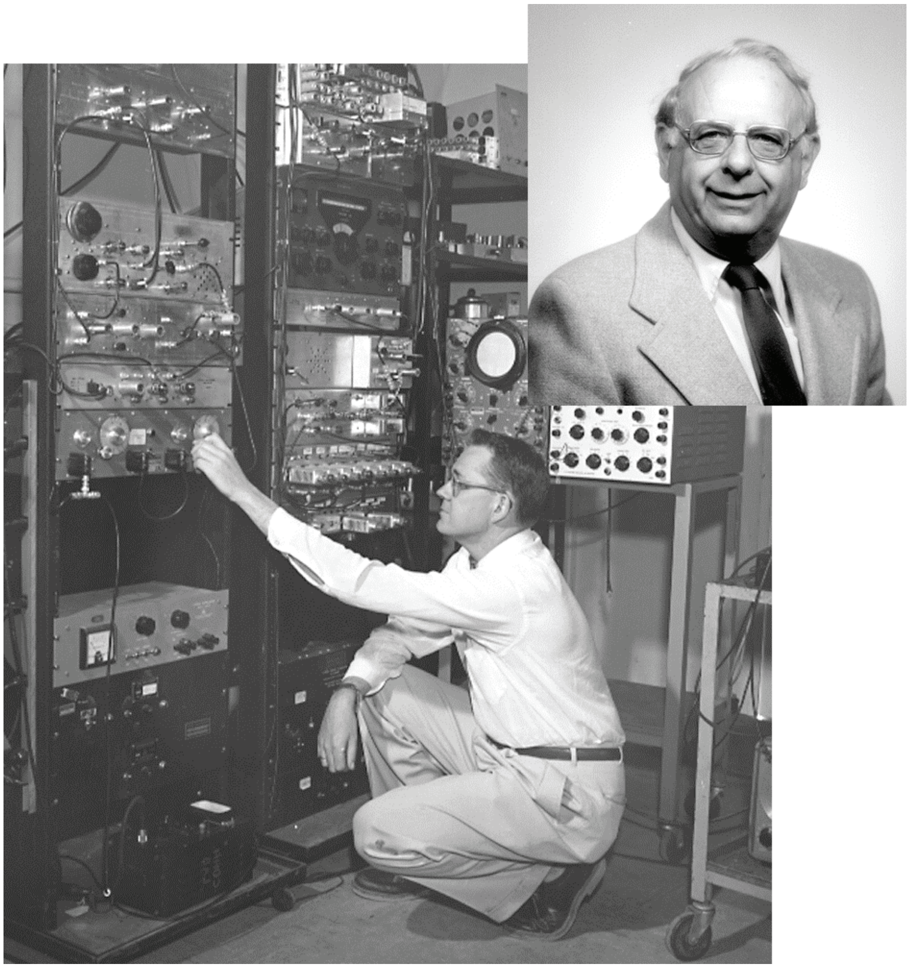


**Figure 9-12. Meteor burst equipment designer Russ Wolfram with lab director Ray Vincent (inset).**

But, though the models improved, the ionosphere, having weather-like behavior, has never been totally predictable, nor the models totally accurate. At best, models deal with average daily and seasonal conditions, yet its wide variability often leaves the mean unmeaningful. Regions like the auroral zone, the polar cap, and the equator were often too dynamic to model, particularly across their vast expanse. But the concern over such unpredictability was taken to unprecedented heights when, in 1958, we saw the ionospheric complexities introduced by the aforementioned high-altitude nuclear detonations over Johnston Island. These explosions brought far more dynamics to the ionosphere than do natural phenomena, at least for a time, and that uncertainty caused an open concern about our ability to communicate at all if the Russians were to launch a thermonuclear war. The substantial degradation of communications circuits transiting the Pacific near the 1958 nuclear tests was appreciated only after the fact.

Neither SRI nor others had made any directed communications measurements, and the test ban treaty that followed the 1958 tests preempted any further exploration of such effects. That situation remained until September 1961 when the Soviets broke that treaty with the huge detonations at Novaya Zemlya. The United States immediately responded with a number of its own tests in the Pacific. This was the same Operation Dominic mentioned before, with its concluding high-altitude tests known as Fishbowl.

Somewhat fortuitously, the modeling work that SRI had been doing for the Army included some planning for possible atomic tests. Among other things this

**Figure 9-13. SRI's Operation Fishbowl's Communications Leader, John Lomax**

involved the testing of a new HF communications tool with the arcane name of "sweep-frequency oblique-incidence ionospheric sounder." From that kind of pre-positioning, and a working relationship with the Defense Atomic Support Agency on the radar side of the house, SRI was in a very good position to design and participate in any upcoming nuclear communications experiments. Given its background, SRI could, within the limitations of the tests, determine just how inimical high-altitude nuclear explosions were to long-distance communications. So when the decision was made by President Kennedy to resume testing, our earlier planning on communications tests could be carried out in a hurry. As mentioned earlier, SRI excels in being able to competently and quickly design and carry out field experiments. But the scope of this experiment would far exceed anything SRI had ever done. Directly testing the impact on long-distance communications of a series of high-altitude nuclear tests in the Pacific required a grid of HF communications trunks that spanned the Pacific and crisscrossed the detonation area at Johnston Island. With SRI engineer John Lomax (see Figure 9-13) leading the effort, SRI rose magnificently to the task.

As with the radar program already mentioned, President Kennedy authorized test planning to begin on 10 October 1961, and by the following April, SRI had designed and fielded a comprehensive set of communications circuits across the Pacific: From Rarotonga in the South Pacific to Fairbanks in the north, and from Okinawa in the west to Palo Alto, CA, in the east, 13 different sites yielded 27 different circuits having a range of distances from the Johnston Island bursts and their magnetic conjugates. The geographical layout is shown in Figure 9-14. As the vast breadth of locations suggests, just visiting the potential sites and negotiating their lease was a big task. The project actually got under way in January of 1962 with an incredible goal of being in the field by April! The type and means of data collection had to be decided, the communications equipment had to be built and

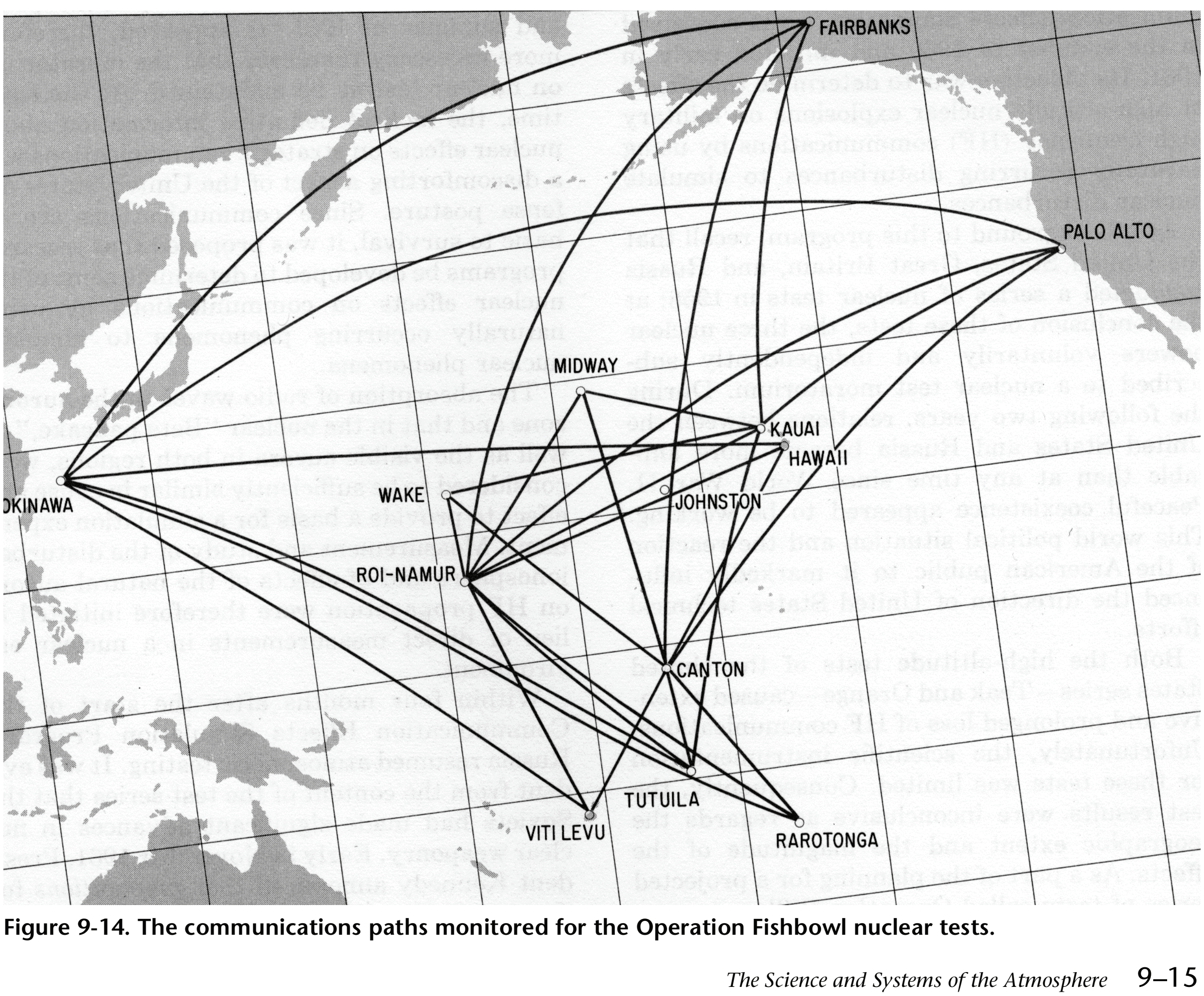



**Figure 9-14. The communications paths monitored for the Operation Fishbowl nuclear tests.**

**Equipment preparation at SRI**


**Sounder van arrival in Samoa**

**The SRI field site in Samoa (Tutuila)**

**Figure 9 15. Outfitting and deploying the SRI communications equipment for fishbowl.**

delivered, and all the provisions for operation in austere environments needed to be assembled. As depicted in Figure 9-15, all this materiel for all of the sites was rapidly assembled at SRI, loaded aboard C-124 aircraft, and flown to the Pacific sites. Amazingly, and a genuine tribute to SRI, all sites were ready by 15 April 1962, an impossibly short 3 months after the order to proceed!

Rather than using normal fixed-frequency transmitters and receivers, SRI drew on its recent instrumentation experience and proposed the use of newly available sounding equipment built by Granger Associates, a company that had earlier arisen out of SRI. This equipment permitted not only flexible, synchronized connections between multiple sites, but also scanned the radio spectrum on each circuit from 4-64 MHz in a matter of seconds. This equipment was operated for the five different high-altitude bursts in the Fishbowl Series that took place from July to November of 1962.

Information derived from this network of sounders gave the United States the ability to calibrate emerging models of communications in a nuclear environment and, in the cases of newly observed phenomena, build supplemental models that, when incorporated, let us estimate whether we could communicate or not. For example, it was the network of oblique- and vertical-incidence ionospheric sounders that recognized the existence of acoustic-gravity waves that propagated out from the burst and had great influence, positive and negative, on the ionosphere. Another was the recognition of new high-altitude, mostly field-aligned, ionization from the burst that could be used for communications under certain circumstances.

Beyond the collection of the relevant HF and higher frequency data in the field, SRI was asked to analyze that data and later build the computer models that would describe the effects seen. These models were embodied in a set of DNA handbooks and used by the United States for over 25 years to predict our ability to communicate at HF under various attack scenarios. Some of the same computer codes were also found to better portray the natural ionosphere and thus found use there. The last test of the Dominic Series in November 1962 was the last U.S. atmospheric test. The subsequent readiness program that was designed to improve the instrumentation for radar also enabled a somewhat smaller continuing development in communications. As in the radar case, the auroral region was taken as a surrogate for nuclear conditions, and these same sounders explored communications at those latitudes, albeit on a much reduced scale.

Soon another benefit from the Pacific sounder network emerged. Those same, hard-to-predict ionospheric dynamics, that now plagued us in both the natural and nuclear conditions, suggested another approach in how to use the HF part of the radio spectrum. The rapidly scanning electronic sounders had shown an ability to assess the available HF channels in near real time and thus, through better operating frequency selection, aid in maintaining the continuity of HF circuits. SRI received a contract from the Defense Communications Agency to explore that use. Properly automated and shared across multiple paths, the sounders could largely remove the guesswork from managing HF circuits. SRI supervised the implementation of this automation in a number of trial sites from about 1964 to 1967, and improvement clearly followed. But communications satellites were becoming increasingly capable and that meant, except in a few special circumstances, that HF was no longer the preferred long-distance communications choice. Therefore, the resulting frequency management system saw but limited operational use.

One other communications aspect of SRI's participation in the Fishbowl operation was a set of measurements at very low frequencies (VLF). Existing worldwide VLF transmitters in this 3-30 kHz range were monitored at various field sites during the tests. VLF is important for communicating with submerged submarines, and few serious effects were observed.

## Some Comments on SRI's Ability in the Field

The SRI contributions to our understanding of the ionosphere and its radio-based systems have been truly legion and, accordingly, this account has been embarrassingly inadequate. Moreover, research and new insights continue to this day. SRI is active in studying the dynamics of the equatorial ionosphere, operating the high-latitude Sondrestrom Fjord incoherent scatter facility for the NSF and analyzing its measurements, operating the world's widest aperture (narrowest beam) HF facility in California's Central Valley, and other ionosphere-related work. Our ability to have such pivotal roles is attributable to those SRI staff who, through their brilliance and accessibility to critical government decision-makers, gave us both insight and influence. Competent researchers could then carry out what was needed in proposals and contracts to give SRI a preeminent national R&D position in ionospheric matters for over 40 years.

Just a final story about those who went to the field. During the early attempts to launch the Thor rockets at Johnston Island in 1962, nearly all of the military personnel were evacuated to carriers lying offshore. During the first few months of the tests, when the safety officers began blowing up errant or failing launch vehicles, pieces would rain down and in at least one case puncture the SRI radar antenna. This led to building bunkers on the Island for the "critical personnel." But throughout the tests, the SRI people were not in those bunkers but instead in their flimsy "shelters," ready to capture the information they came to get. And get it they did. The vans were later shown to be incapable of sheltering those inside from even a modest-sized piece of falling metal. It was not that the SRI personnel necessarily felt safer in them; that was simply where they needed to be.

SRI's Murray Baron recalled one instance where the commanding general on the Island wanted to tell President Kennedy of a successful detonation and requested that the SRI radars be turned off because he mistakenly believed they

One other humorous anecdote occurred on the southernmost site, SRI's communications field site on Rarotonga. The island was, of course, famous for its tropical allure, but getting in and out of the island was not easy. There were no docking facilities for large ships, and the only landing strip was also the golf course! Approval had been given to land the very large C-124 Globemasters like those that brought in the SRI sounder van. But in the early phase of the Pacific tests, things got a bit out of hand. As with any field experiment, sometimes parts were needed, and needed soon. Planes would be dispatched out of Honolulu to the many outlying sites. The problem was that those planes themselves would break down all too frequently and almost exclusively in Rarotonga. The consequence…the golf course was fillitng up with large U.S. military airplanes! A military solution presented itself: Upon specific order from the commanding general, there would be no more aircraft breakdowns on Rarotonga. The problem magically cleared up.

were causing interference to his communication system. Baron knew they weren't but, more important, there were still plenty of radar effects showing. So he kept stalling as the phone calls escalated. By the time a full colonel personally visited him at the radar van, the observed effects were gone and Baron obligingly turned off the radar.

Many other stories came from around the Pacific about how the SRI staff managed their sites—ashore, afloat, and in the air. Support and supplies came via daily sessions on a short-wave net operated out of a picturesque beach house near Diamond Head on Oahu. All sites ran complex electronic equipment for the better part of a year, many under primitive conditions and saddled with finicky diesel generators. Dedicated and competent, the SRI staff helped define SRI's splendid reputation in this field.

## Atmospheric Pollutants and Ozone—Flagging the Troubles of Man's Creation

Ozone, that variant of an oxygen molecule with three atomic oxygen atoms bound together, is both friend and foe. Just as whether a plant in your garden is a flower or a weed depends not only on what it looks like but where it is growing, ozone is either a benefactor or a pollutant depending on where it is found. In that part of our atmosphere near the earth, an overabundance of ozone is toxic to both animals and plants. Yet 20 miles above us, in the stratosphere, ozone becomes not only beneficial, but a lifesaver. In the stratosphere it is a shield against harmful ultraviolet (UV) rays from the sun that can damage the DNA of living things, including important components of the food chain such as the ocean's plankton. In humans, UV light can cause such problems as skin cancer and cataracts. Here we look briefly at these two roles for ozone, the first investigation coming in the late 1940s as SRI itself was just emerging.

### Low-Altitude Ozone and the Causes of Smog

SRI was not quite seven months old when it undertook its first work on a peculiarity of the atmosphere over Los Angeles that the world now knows as smog. That the term was still in its infancy is indicated in brief writings about 18 months after the work began, in which the term "smog" was still introduced in quotation marks. The impetus for the study was the problems of poor visibility and eye irritation that were characteristic of the Los Angeles Basin. Curiously, these characteristics appeared much more severe there than in the more industrialized cities of the eastern United States, and there was a clamor to find out why. The Western Oil and Gas Association[12] sponsored the first work at SRI in May of 1947, and because of the complexity of both the problem and its mitigation, the work lasted for the better part of a decade. During that early effort, SRI contributed monumentally to the understanding of just what the airborne pollutants were and from whence they came. We will see how SRI effectively led the early investigation that would give the local governments in that area the information they needed to attack the problem.

In the beginning it was "not entirely clear" what gave the Los Angeles area its unusual scourge of bad air. Old timers in the area definitely said it was not new, with recollections of its presence as far back as 1912.[F] On the other hand, air problems, particularly eye irritation, had increased in frequency and severity in recent years. From weather records, the SRI investigators had learned that the number of sunshine days, dating back to 1896, had not significantly changed. Measurements showed a decrease in visibility during the World War II years, but the confusion with fog and natural, long-term weather changes made this diagnostic unreliable. Thus, at the outset, the team was left with only qualitative accounts.

The big components were obviously the weather, the topography, and the presence of man…but how did they play together to precipitate the problem? What was the mechanism? So the SRI investigators, led by Dr. Paul Magill of the SRI-Pasadena office,

[12] This association was formed by the petroleum industries operating in the Los Angeles area. Interestingly, it had a committee on smoke and fumes that was the specific SRI client. The initial contract was SRI's third and was for $505,649 over a period of 30 months.

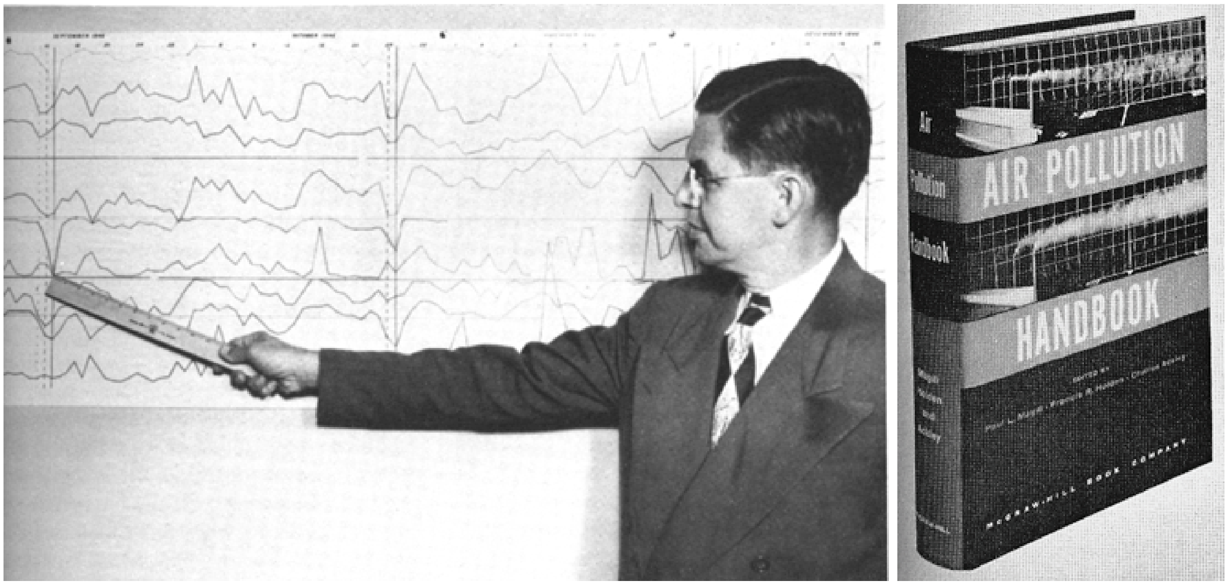



**Figure 9-16. Dr. Paul Magill pointing to a smog index line and the sharp dip on Black Friday, September 13, 1946 (one of the worst smog days in Los Angeles history). Also shown is a 1956 McGraw-Hill handbook, edited and contributed to by the SRI staff involved in early pollution work, that is still referred to today (Magill, Paul L., Francis R. Holden, and Charles E. Ackley, eds, *Air Pollution Handbook*, McGraw-Hill, 1956).**

started with a model of the normal convective atmosphere over Los Angeles (see Figure 9-16). The climate was subtropical, and the presence of barrier mountains on three sides had an impact not only on the ability of the air to mix vertically, but also on the formation of all-important temperature inversions—when upper atmospheric temperatures are higher than those on the ground. Those inversions were also amplified by the presence of coastal water that was cool near the surface. The common high-pressure regions and weak seasonal winds common to the California coast were also factored in. To the extent that such conditions were understood and were influential in forming smog, its occurrence could at least be predicted using meteorological information.

Of course, the formation of smog also depended on some set of noxious constituents. Measurements, many made by SRI over a period of several years, were clearly needed to catalog the type and amount of compounds and particulate matter present in the Los Angeles atmosphere. Early measurements indicated that there were not one or two culprits, but more than fifty, spewed out by a wide, diverse, and increasing range of human activities. The question was, how many of these contributed to the pungent, eye-burning degradation of the atmosphere? Suspected early by the SRI researchers were so-called aldehydes, formed of carbon, hydrogen, and oxygen, and of which formaldehyde is an example. These were known to cause eye irritation. Also suspected were sulfur dioxide and trioxide, the latter having known fog-forming properties. The January 1948 report[G] to the client mentions some of the early suspected culprits such as "burning rubbish (estimated at about 300 tons per day), industrial operations, and the operation of motor vehicles." Nothing, however, had been singled out as the major offender.

SRI built a special test chamber to make controlled, quantitative measurements on individual contaminants and to determine whether they induced one of the most obvious impacts of smog: eye irritation. To gain direct evidence, human volunteers were asked to occupy the chamber and indicate when eye or throat irritation was noticeable. Some of these volunteers were SRI employees. The questions were intended to give approximate, subjective answers only, to rule out those contaminants with no detectable effects; that is, no discernable eye irritation at levels above those known to exist in the atmosphere. From these early screening tests the SRI scientists were able to rule out some of the previously suspected agents. Part of the problem at this early stage was an inaccurate knowledge of the agent levels that did exist in the atmosphere. Improved measurement techniques later showed, for example, 5 to 10 times higher levels of aldehydes, a product of incomplete combustion, than had been estimated in the earliest samplings.

Later, in the Pasadena Lab, SRI built a 40-ft-long cylindrical chamber called a transmissometer in which a concentrated light beam could pass repeatedly through a specifically composed atmosphere of known types and amounts of constituents at controlled humidity and temperature. For the first time they could quantitatively tell how much some of the concentrations they had observed from samples were contributing to what the population experienced.

As this initial work was going on, the world was becoming aware of smog. An indication of SRI's prominent role in this new environmental concern was evidenced when SRI hosted in Los Angeles on 10-11 November 1949 the first National Symposium on Air Pollution. The meeting had a scientific bent and was attended by both academic and industrial researchers from all over the U.S. SRI would again lead the second such conference in 1952.[13] The work continued.

A status report written in 1951 showed a few new conclusions being drawn.[H] From improved gathering and analysis techniques, the focus had narrowed to: oxidants, liquid droplets, crystals, aldehydes, and sulfuric acid. Of these, the category that seemed most correlated with eye irritation was the oxidants, one of which was ozone. But the correlation with eye irritation was still complex. To try to understand better what specifically caused eye burning, SRI returned to "smog chamber" tests. Volunteers were again exposed to potential eye irritants, this time to various combinations of nitric acid vapor, sulfur dioxide and trioxide, diesel and crankcase oils, lampblack, sodium chloride, and ozonized gasoline. As it turned out, the removal of any one of the constituents didn't statistically change the amount of eye irritation. As to attribution, the origin of the candidate pollutants was believed to come from incomplete combustion in its various forms. Of the total combustion and evaporation products released into the Los Angeles air daily, about 60 percent were judged to come from the general public (driving of automobiles, trucks, and buses; heating of homes and businesses; and burning of trash), 25 percent from the petroleum industry, and 15 percent from other sources. Exhaust fumes from the then 2 million vehicles each day, driving an average of 50 miles, contribute over 350 tons of organic substances into the air, not counting 30 and 40 tons of aldehydes and nitrogen oxides, respectively. As with the Pogo imperative, it was becoming clear as to who the enemy was.

The last of SRI's almost eight years of analytical and experimental work on smog in the Los Angeles basin came in a summary report entitled, *The Smog Problem in Los Angeles County*, issued in August of 1954. The 134-page report brought together both SRI's and other scientific work in the area. The following is an extract from an SRI article about the report:[I]

> "The research indicates that substances responsible for smog are always present in the Los Angeles atmosphere and require conditions of strong sunlight, stagnant air, and temperature inversion for smog to develop. The sun is apparently the 'motor element' which drives the chemical reaction, producing an atmosphere with unusual chemical activity.
>
> Ozone—a highly reactive molecule consisting of 3 atoms of oxygen—is one of the best indications of smog intensity and Los Angeles has the highest known concentration of ozone on the earth's surface."

SRI chemists isolated in the lab the active wavelength, between 3,600 and 4,000 angstroms, that forms ozone. From field measurements its concentration in the Los Angeles area was well correlated with commute traffic. Significantly, SRI measurements also showed that, although values of smog intensity may differ with location across the LA basin, its formation on a typically smoggy day begins everywhere at first sunrise. SRI determined the critical constituents of smog, estimated the vast amounts that were being released daily into the Los Angeles atmosphere, and concluded that automobile exhaust was the largest single source of pollutants. It contained hydrocarbons, oxides of nitrogen, aldehydes, and particulate material that, collectively, represent about 7 to 9 percent by weight of the gasoline fed into the automobile motor!

[13] Dr. P.A. Leighton, one of SRI's founders and a chemistry professor at Stanford, was instrumental in the conferences and, significantly, influential in getting SRI into this field. A session chairman in both conferences was A.O. Beckman, who during that time founded Beckman Instruments and later became a member of the SRI Board.

Although some of the major culprits had been identified, SRI continued its measurements and analytical work, and the SRI Pasadena lab became noted for its collection of the best smog analyzing tools in the world.[14] The lab used instrumentation ranging from huge (500 $ft^3$) mixing chambers with artificial sunlight to new mass spectrometers. SRI also continued very controlled human testing of the irritation qualities of various exhaust gas components and worked to find ways to reduce the automobile exhaust components in smog.[J] As the constituents themselves, the role of the sun, and the important diurnal and meteorological inversion characteristics of the Basin became well understood by the late 1950s, SRI's studies on the constituents of smog came to an end. However, investigations on the effect of smog on agricultural plants, including citrus, continued in the Pasadena or Menlo Park laboratories until at least 1961. Then SRI's long, continuous, and clearly beneficial effort, nearly all sponsored by the petroleum industry, finally ended.

## Stratospheric Ozone

The Earth's ecological balances are often finely tuned. Over the past 20 years, the public has become increasingly aware of one of those balances: the presence of ozone in the stratosphere (between about 15 and 35 km altitude) and the amount of UV radiation that reaches the Earth's surface. That particular balance is precarious because a high exposure to UV rays can be harmful to both plants and humans. Amazingly, the UV shield offered by upper atmospheric ozone occurs with the presence of only a very small amount of ozone, typically a few parts per million of normal stratospheric constituents.[15] The alarm that has raised the collective attention of chemists and governments worldwide is the decreasing amount of stratospheric ozone.

The culprits in this saga are now confirmed to be some of the by-products of man; namely, chlorine, bromine, and a few related elements. They exist in many of the compounds man has created for refrigeration, inert pressure gases, cleaning chemicals, and manufacturing. A certain class of these compounds and those inimical to our atmosphere are called chlorofluorocarbons (CFCs). Over eighty percent of those observed in the stratosphere are manmade. Hence, protocols have been written and laws established to drastically reduce their production.

What was SRI's role in this first scientific, then governmental, awareness? The basic realization of the role of CFCs in ozone depletion came from University of California, Irvine, chemists Sherwood Roland and Mario Molina, for which they shared the Nobel Prize. Postulating the presence of highly reacting forms of chlorine in the stratosphere, they showed that such molecules could directly deplete ozone. The question remained: How did they get there? Many CFCs are very stable and do not react well with near-Earth gases. Although they are heavier than the normal constituents of our air, through turbulent air mixing they can reach high into the atmosphere unchanged because of their stability. That stability continues until they reach the stratosphere, where sunlight wavelengths that normally don't reach the Earth can decompose these compounds into active forms of chlorine or related gases. SRI's contribution involved showing that one of these CFCs, chlorine nitrate, reacted with some of the naturally occurring constituents to yield more reacting chlorine forms: chlorine alone and hypochlorous acid. These were verified in laboratory tests that simulated stratospheric conditions. A resulting paper, by Margaret Tolbert, Michel Rossi, Ripudaman Malhotra, and David Golden, won the prestigious Newcombe-Claybourne Award as the best paper in *Science* for 1987 (see Figure 9-17). But more importantly, it helped solidify our understanding of a balance in nature critical to us all.

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[14] The San Gabriel Valley newspaper, STAR-NEWS, of September 10, 1956, carries the following statement by a participating scientist: "No other place in the world is studying natural and artificial smog under controlled conditions with anything like the battery of precision instruments we have assembled here." Some of these instruments were on loan from other groups participating in the research. They included UCLA, Cal Tech, UC Riverside, The Franklin Institute, and the American Petroleum Institute. (Courtesy of Betty Neitzel, an SRI staff member in Pasadena.)

[15] On the average, ozone concentrations are about 300 molecules per billion of all air constituents. At its peak concentration in the stratosphere it is but a few parts per million, and if one integrates through the entire atmosphere, the total amount of ozone available for UV protection would be no more than 2-3 mm thick at the standard temperature and pressure at the Earth's surface. Moreover, even small reductions in ozone levels can have large effects on the level of UV. Indeed, the shield is a very "thin" and sensitive one.

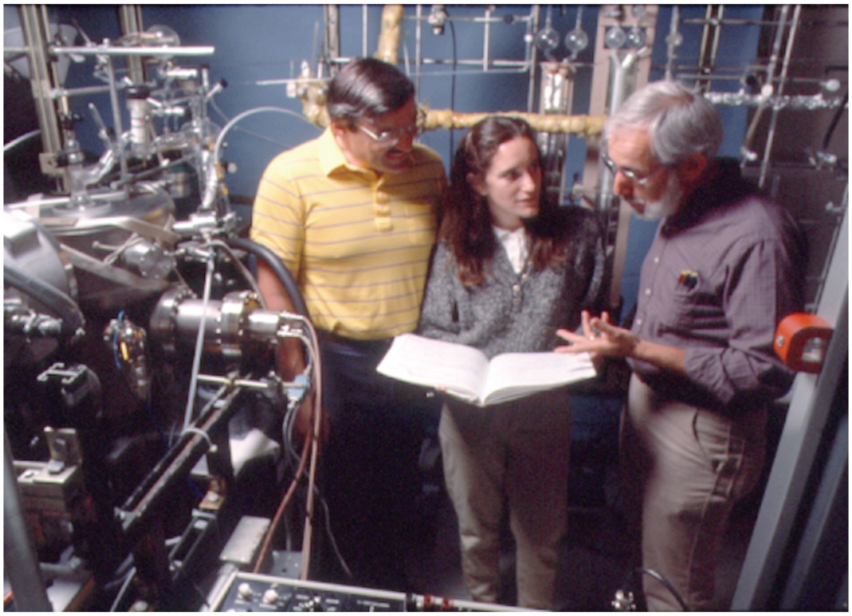

**Figure 9-17. In SRI’s ozone modeling laboratory are Michel Rossi, Margaret Tolbert, and Dave Golden.**

As a footnote to this discussion, it should be mentioned that SRI has worked in atmospheric sciences throughout almost its entire history. Beginning in about 1967, the increasing worldwide interest in environmental impacts led to the formation of an Environmental Research Department under Elmer Robinson. Here the studies were wide-ranging, even containing some projects that tried to model both natural and manmade forms of air pollution, both sources and sinks, on a global scale.[K] Later the SRI Atmospheric Sciences Center conducted measurements of all types of air pollution for many years, employing, among other things, the lidar system developed in the meteorological group at SRI (see later in this chapter).

The decision by the U.S. government to name NASA the U.S. agency with responsibility for dealing with the ozone depletion problem stemmed from the early belief that rocket fuels may have promoted the presence of chlorine. However, the chlorine compounds generated by rocket fuels turned out to be present only in the troposphere and did not have much influence on ozone. SRI’s Dave Golden has been on NASA’s committee to keep track of the chemistry and the models since their role began. Dave is also on a similar National Academy of Sciences committee. In a continuation of the search for other influences on ozone depletion, the effect of jet airplanes is also now being studied and SRI has two related grants. With new capital equipment resources, three different SRI groups are contributing to the study of the aircraft problem.

## Lidar—A Light-Based Radar

In the middle of a very long hall of one of the old World War II hospital buildings in which SRI was housed, morning and afternoon coffee breaks took place every day. It was in the very early 1960s, and in retrospect such gatherings now seem a luxury. In a discipline-centered place like SRI, these interludes took people away from the intensity of their own investigations and by doing so sometimes fostered cross-discipline discussions and innovations. One such case occurred when the leader of the Aerophysics Group, Dr. Myron “Herb” Ligda, approached one of the laser specialists, Dr. Dick Honey of the Electromagnetic Techniques Lab. He raised the question as to whether SRI could build a laser that would work like his meteorological radars. “Why of course,” was the reply, and so quite easily the notion of a meteorological lidar first arose at SRI. Lidar is an acronym that mimics the term radar and stands for light detection and ranging; in other words, a light-based radar. The term lidar was actually coined much earlier in the 1950s by those working on another meteorological application, the incoherent pulsed light measurements of cloud levels. While at this time lidars employing coherent light or lasers were being used for other radar-like applications at Hughes[L] and MIT, but along with NYU and MIT, SRI was among the first to apply laser lidars to meteorology.[M,N,O,P]

Pulsed-light sources, built from electric sparks, had been used as early as 1938 to probe the cloud heights above France and were perhaps the first radar-like system used in atmospheric observations. Such systems were still in use in the early 1960s but, with the development of radar over the postwar years, microwave radar had by then become a principal meteorological probe. But the advent of the laser suggested to Ligda, Honey, Ron Collis, and others at SRI that this new mechanism offered much greater sensitivity to the detection of atmospheric constituents by providing a powerful, monochromatic, coherent light. Consequently, starting with internal funds first allocated in 1962, SRI designed, built, and tested the first of what would become dozens of different types of lidars to emerge from SRI over the next 40 years.[16]

That first lidar's capabilities were indeed modest. SRI researchers placed a donated laser from Trion Instruments, a photocell, and some government surplus optics on a gun mount, and the result is the instrument shown in Figure 9-18.[Q] The lidar used a pulsed ruby laser of a very modest 5-mW output, emitting just one 30-ns pulse per minute, and its 4-in. optics gave a 0.5-degree beamwidth. The pulse and its return were observed on a new, fast oscilloscope. The whole system was placed on the roof of Bldg. 404, and the time of its first operation was remembered well: it was Ron Collis's birthday, July 22, 1963.

Just what were the expected meteorological uses of lidar? Like any radar, the lidar depends on the amount of signal scattered or reflected back to the receiver as a function of range. The directivities of the source and the receiver, along with range, locate in space where the specific scattering occurs. Hence, some of the lidar's first meteorological uses were analogous to that of microwave radars: looking at the location and movement of clouds and precipitation. Only now one could, under certain conditions, probe the cross-sections of clouds and the exact nature of their turbulence, roughness, and flow patterns.[17] Even more remarkably, lidars could "see" constituents that are part of what would be considered visually a clear sky.[R] A good case for its utility was made on its very first night of operation. Ligda found that he could detect "things" in the upper atmosphere as high as 30 miles up, where there was presumably very little to reflect a light beam.[S]

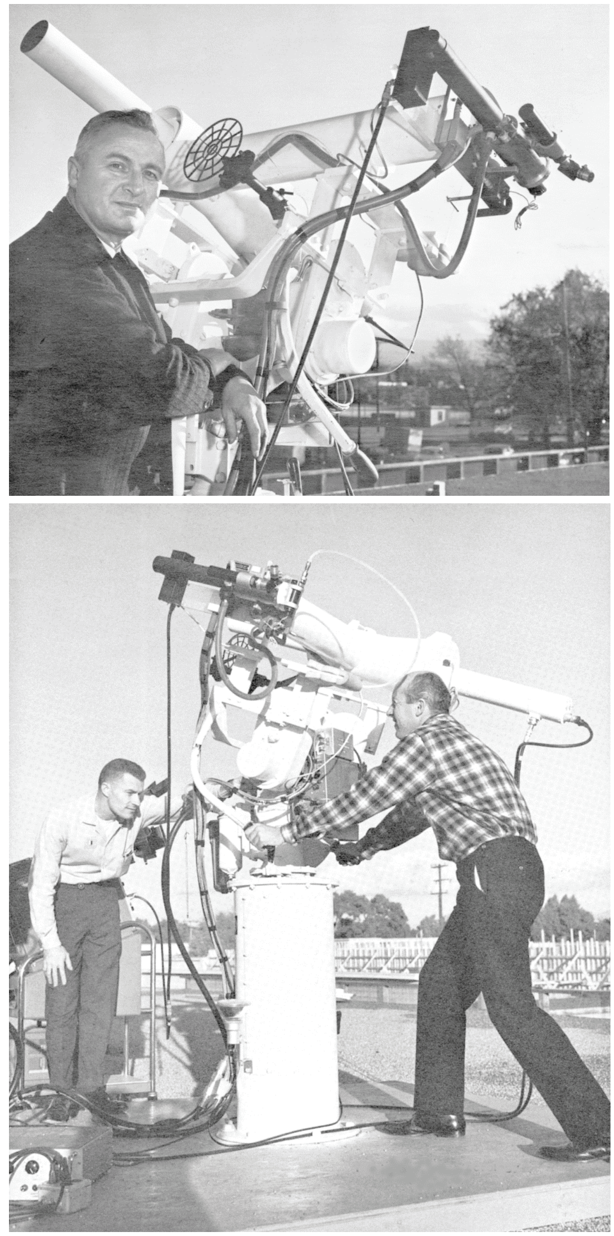

**Figure 9-18. The SRI Mark I Lidar atop SRI Bldg 404 and (top) Myron "Herb" Ligda (bottom), Lloyd Alterton and Earl Scribner.**

By February of 1964, lidar data were revealing horizontal structure in the lower atmosphere that was being missed by more conventional sources such as radars and balloon-born radiosondes.[T] By 1965, through continued improvement in the power, sensitivity, and wavelength of SRI lidars, vast

[16] The 1962 expenditure was $9,197 but by the end of 1965, SRI internal funding of laser and lidars was almost $75,000. Other money of the order of $10,000 to $20,000 was spent on their meteorological uses. This early team consisted of the above-mentioned players plus Earl Scribner, Lloyd Alterton, Robert Pierce, Bill Evans, C.A. Northend, Paul Perich, George Davis, and Bernard Belt.

[17] Because of the high scattering and absorption of water vapor, lidar has a hard time working *through* heavy precipitation. However, depending on the moisture content of a cloud, the lidar can probe clouds to see their internal dynamics.

new areas opened up. In September of that year SRI meteorologists were tracking individual layers of dust in the altitude range of about 20-40 km.[U] A four-color instrument, using two lasers and some frequency-doubling devices, was also developed that year. Its frequencies ranged from the infrared to the ultraviolet, and made possible the identification of cloud constituents, precipitant formations, and atmospheric pollutants. This ability to detect and track particles, particularly pollutants, opened up an entirely new field of environmental sensing.[18]

But it is a lidar's ability to detect and track specific species of atmospheric constituents that really sets it apart. The ability to tune the laser wavelength of the lidar allows the detection and tracking of specific aerosols and particulate matter. Remarkably, lidar can also determine whether particulates are being synthesized in the air from different effluents entering it.

**Figure 9-19. An SRI lidar in the field being used to detect effluents from smoke stacks in western Pennsylvania in 1968.**

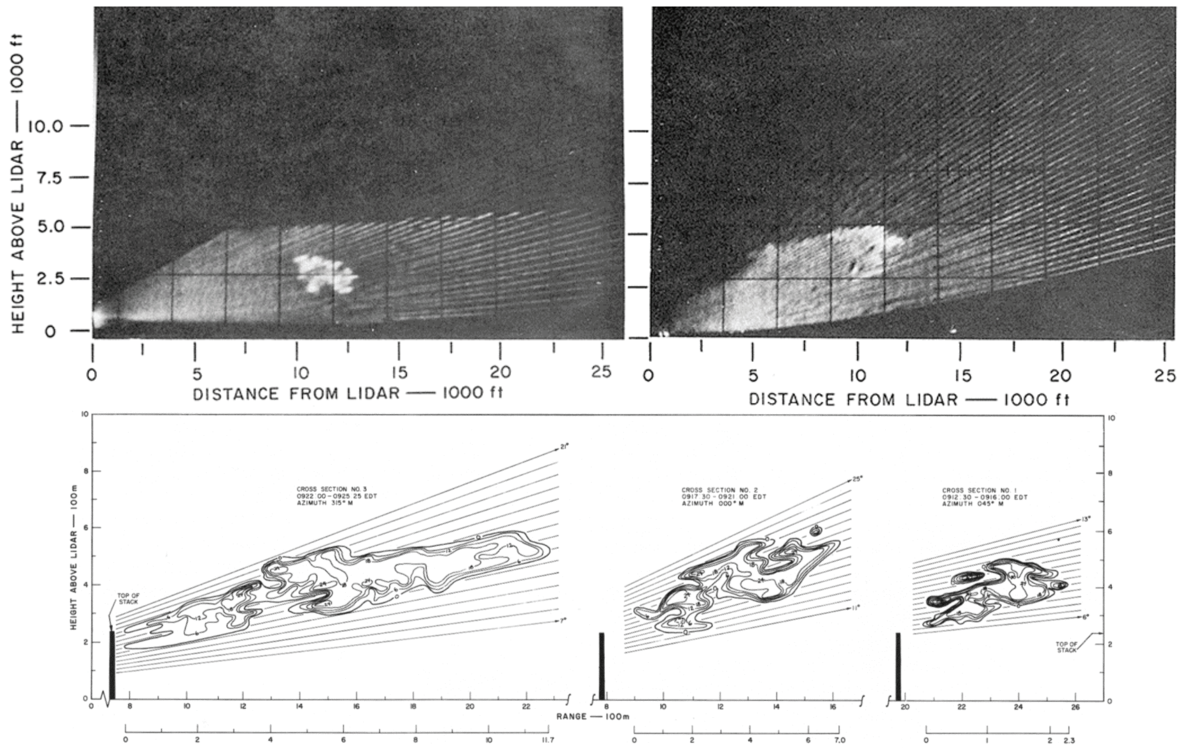


**Figure 9-20. Plume of effluents from a Pennsylvania power plant. Measured flowing through a vertical plane located (top left) 1 km and (top right) 4 km away. The plume was invisible to the eye, yet showed appreciable particulate concentration and, on the left, a turbid layer with ceiling at about 5,000 ft (May 1970). These plots also conveyed concentration levels at another location (bottom). (From *SRI Journal*, No. 27, December 13–14, 1969) Some of the participants in this phase of lidar work at SRI were Warren Johnson, Ed Uthe, Jim Hawley, and Bill Grant.**

Computer analysis of the received data can show the observations made in a single horizontal or vertical plane. Working with the National Air Pollution Control Administration, SRI lidars, such as the one shown in Figure 9-19, were used through the 1960s and 1970s to study airborne pollution. Figure 9-20 shows an

[18] Sponsors of the new lidars were the Office of Naval Research and the Lear Siegler Corporation.

example of effluent data taken downwind from the Keystone power plant in western Pennsylvania in 1968. The plume was not visible to the eye. Lidars have come into extremely wide use as a means to monitor our atmospheric environment.

Figure 9-21. SRI lidar van used in the detection of trace levels of atmospherically transported chemical agents.

Finally, starting in the mid-1980s, SRI made a series of sophisticated improvements to its lidars that have given them an ability to detect trace amounts of chemical warfare agents in the atmosphere. The risk of these agents to both soldiers and civilians lends great importance to such investigations. Detecting such agents requires an ability to finely tune the wavelength of the lidar and to greatly increase its sensitivity over the earlier meteorological lidars. One of the principal innovations in this direction was differential absorption lidar, or DIAL.[19] To detect specific agents, DIAL uses two or more wavelengths to help calibrate out the intervening atmosphere and obtain range-resolved returns from concentrations of various gas species along an extended path. Ranges may extend to several kilometers. These tunable lidars operate in the visible, ultraviolet, and infrared spectral regions. Figure 9-21 shows one of the larger, van-mounted instruments. In contrast with the first lidar, units like this may have 12 megawatts of peak power that can operate at ten pulses per second over a wide range of wavelengths.[V] Their light sources, though, are large gas lasers. Much smaller, portable units that use infrared diode lasers have also been designed and built at SRI, along with countless other types of lidars and remote sensing instruments, including airborne ones.

This aspect of the SRI lidar program has been very successful. SRI received an Army Services Commendation Award for a variety of test results that included specific vapor detection at long range (5-8 km) in the presence of fog, rain, dust, and infrared smoke, as well as detection of two vapors simultaneously. The award also recognized the ability to detect vapor deposits on soil and concrete surfaces. SRI also showed its quick reaction capability when it was called upon to create specific sensors for the Gulf War. When it became clear that a chemical warfare threat existed there, SRI staff worked continuous 15- to 20-hr. days to design and fabricate point sensors that could detect the presence of certain agents believed to be in the Iraqi weapon inventory. Even after the Gulf War, SRI participated as part of the inspection teams searching for caches or stockpiles of chemical and biological agents.

SRI has conducted remote and point sensor work not only for the DoD, but also for utility companies and their research consortia, such as the Electric Power Research Institute. Over the nearly 40 continuous years of the above efforts, including both ground- and aircraft-based lidars, SRI has become a leading innovator in the sensing of environmentally harmful substances in a variety of settings as well as in the modeling of atmospheric properties and its constituents. As evidence, SRI received the American Meteorological Society's 1985 award for outstanding services to meteorology for the "creative development of laser-oriented remote sensing systems which have produced new levels of information on atmospheric transport of gases and fine particles."[W]

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[19] The term DIAL was coined by SRI, but the first differential absorption lidar, built using temperature-adjusted ruby lasers, was made by a colleague of Ligda's, Dr. Richard Schotland, now emeritus professor at the University of Arizona.

# Upconverting Phosphors for the Detection of Undesirable Agents

The technology of upconverting phosphors (UCPs) seems ripe with opportunity. The basic mechanism makes use of the property of certain phosphors to absorb radiation, in this case in the infrared portion of the spectrum, and radiate at different wavelengths (colors) in the visible region. Since this type of conversion does not take place in nature, the background for this detection process is very quiet, giving it great sensitivity. Different phosphors with characteristic color reradiation can then be linked to tailored sensors that are designed to reveal the presence of very specific harmful agents. As such they can be used to create diagnostic sensors for clinical health care, food supply screening, and military and civil defense needs.

Right now, the growing threat of biological agents and the difficulty in knowing when they are present and where they came from seems the most important first use of UCPs. The concern comes from possible terrorist use of such weapons or the unintended migration of deadly viruses such as ebola to more populated areas. But regardless of their origin, deadly agents released in large and mobile populations possess great potential for confusion and hysteria, particularly when the location and extent of the pathogens are unknown. DARPA, the DoD's prominent R&D body, is exceptionally aware of this threat and is acting to deal with it by sponsoring a set of inexpensive, UCP-based sensors that can cover a family of chemical and biological agents. The relevant scenarios show critical needs in both military and civil defense settings and in worldwide healthcare.

## Point Detection of Biological Agents

As mentioned earlier, lidar is one of the only means for the remote detection of specific chemical agents. It can stand kilometers back from a threat and thus provide needed warning time. But while lidar has been shown at SRI and elsewhere to detect the presence of biologic-bearing aerosols, its ability to identify specific constituents is extremely limited.[20] Such identification is, of course, critical. So, practically speaking, the detection of biological agents is now the province of point sensors which, when handheld, would most likely give warning too late. But point sensors can be valuable if there is a means to deploy them remotely and then assure that they communicate their findings reliably to a safe distance. Such remote sensors must ideally be small and consume little power. Over the last several years SRI has developed a family of new, small detectors that can detect a wide range of very specific biological agents. The goal was to build a detector with greater sensitivity, more discrimination or specificity, and faster detection time.

The detection technique SRI has developed is very general, but its characteristics are quite remarkable.[21] In simple terms, the sensor consists of three parts: a probe designed to interact strongly and uniquely with the target biological agent, a reporter that signals the existence of the agent, and a detector that is sensitive to the reporter. The process is shown schematically in Figure 9-22. A surface is built with "docking" configurations that are very specific to each expected agent, using a technique called polyclonal antibodies. Molecules of the target agent are then introduced and come to reside on the prepared surface. To test for the presence of the specific biological agents, small reporter-probes are introduced. These are small spherical particles of very special phosphors that are chemically linked to even smaller probe units that have the

[20] Back in the 1970s, SRI showed that bacteria fluoresce in the long-wavelength part of the UV spectrum when excited by a shorter UV wavelength. But this sensing technique tells almost nothing about the kind of pathogen present. Even indications that a particular biologic-containing aerosol cloud might be dangerous has to be inferred from other factors. Simply, the remote lidar sensing of *biological* agents is not yet practical.

[21] The SRI Independent Research and Development (IR&D) report for 1994-5 shows a proposal for $20K to "prepare and conjugate phosphor particles to the detection antibodies and perform assays at various serial dilutions" to determine system sensitivity in detecting a specific toxin. Early work on upconverting phosphor technology came in part from SRI's subsidiary, David Sarnoff Laboratory. Building such an instrument has been truly interdisciplinary. Some of the important contributors beyond the leadership of Drs. David Cooper and John Carrico have been Greg Faris, Yihong Chen, Naheed Mufti, Luke Schneider, Gary Rundle, Jan van der Laan, Karen Nashold, Angel Sanjurjo, and James Kane of Sarnoff.

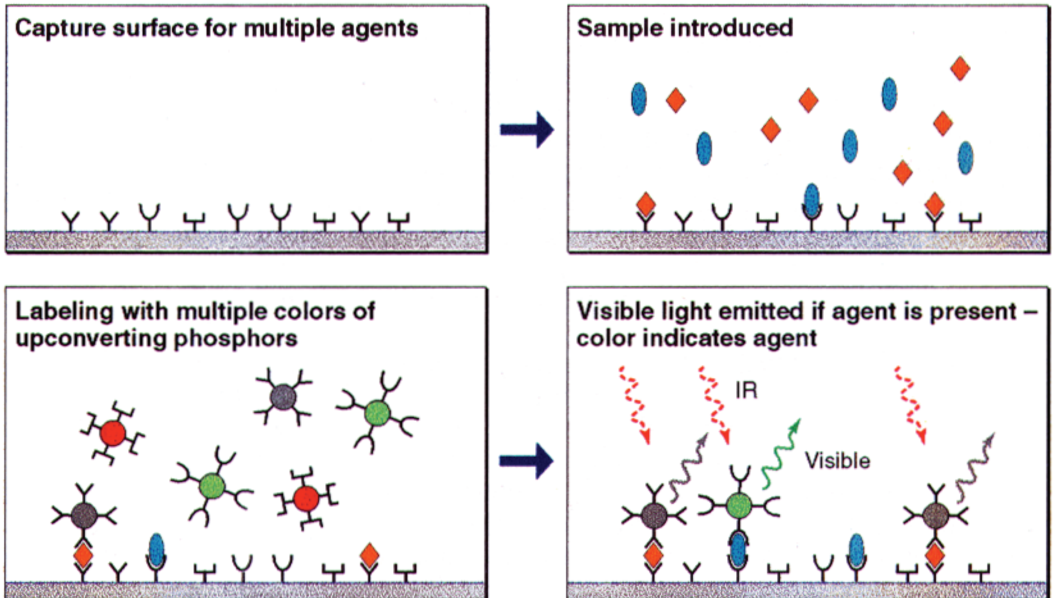


**Figure 9-22. The SRI phosphor-based detection process.**

same "docking" properties as those on the surface. Each different agent has a unique phosphor. Once the reporter-probes are docked, the surface is scanned with infrared light and the individual phosphors reradiate visible light whose color is unique to each agent-phosphor combination. Those specific emissions are then monitored using very small versions of photomultipliers, each of which incorporate the very narrow filters appropriate to the agent-phosphor combinations. These narrow filters reject extraneous noise and also contribute to making the whole system very sensitive.

This approach to biological agent detection permits sensitivities of the order of 10-100 picograms per milliliter of small antigens (virus or toxin) in 5-15 min with a 1-ml sample volume. The 5-15 min wait is because at the moment the process takes place in a liquid bath. For spores and bacteria, the estimated goal is sensitivity below 1000 cells per milliliter. Importantly, the device can be battery operated and is small enough to be handheld. But its most logical use is to be stationed remotely or made airborne on remotely piloted aircraft to grant both safety and early detection.

## A Healthcare Diagnostic

In the area of clinical healthcare there is a test administered to those suspected of a heart attack called CKMB (creatine kinase – MB). In healthy people certain enzymes found in the blood are associated with origins in different parts of the body. Skeletal muscle produces creatine-MM, the brain, creatine-BB, and the heart, creatine-MB. In the presence of an acute myocardial infarction (heart attack), cell deaths produce an elevated level of CKMB four to six hours after the onset of chest pain and peak at 12 to 24 hours. Coronary surgery can also cause elevated levels, but they don't have the characteristic time history exhibited by infarctions. The procedure for the administration of CKMB tests requires that the patient not be released until the results are known, several hours later. UCP technology can make the results of such a test known immediately with greater accuracy and less cost than present methods.

## Commercialization of UCP Technology

To illustrate the utility of the UCP technology, SRI, under the sponsorship of DARPA and other, more operational governmental agencies, has built a prototype system. The sensing unit is small enough to be handheld and battery operated. A version of the prototype is shown in Figure 9-23 along with an image of a test strip and, in the background, the fluorescence of phosphor reporters.

To help bring such technology into existence, SRI licensed it in 1998 to a diagnostic company called STC Technologies. In September 2000, STC merged with another company in HIV diagnostics and became OraSure Technologies. The license is exclusive for the measurement of biological agents but

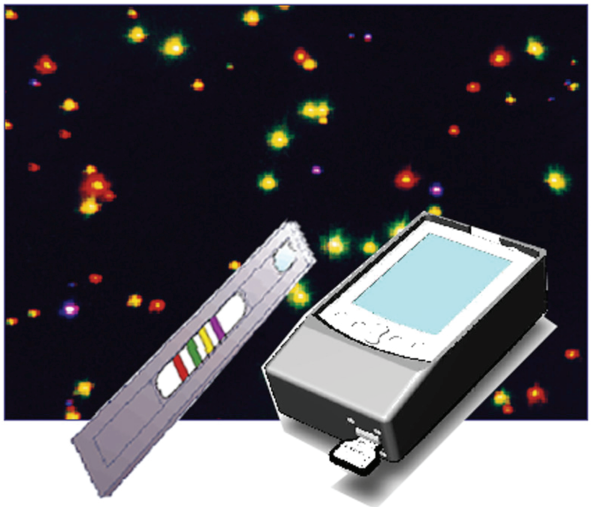

**Figure 9-23. An early SRI prototype sensor and a notional view of a test strip multiplexed for four agents. The background is a photomicrograph of a suspension of different upconverting phosphor particles of different colors that would be scanned for quantitative measurement.)**

the company is directing the technology strictly toward the healthcare industry, specifically to detect minute quantities of antigens, proteins, and even DNA. Their name for the process is called UP*link*™, and the portable, benchtop processing unit produces a very sensitive, multiple-analyte assay in less than 10 minutes. The results can also be read out digitally. Although DARPA has given some support to OraSure, use of the technology against the threats of the battlefield or terrorist action has remained the interest of SRI.

## Endnotes

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[Q] From “My Days at SRI” by Earl J. Scribner dated December 13, 2000.

[R] R.T.H. Collis, F.G Fernald, and M.G.H. Ligda, Laser Radar Echoes from the Clear Atmosphere, *Nature*, 203(4944), 508, August 1, 1964.

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[U] *SRI Journal*, No. 9, page 13, January 1966.

[V] Clinton B. Carlisle, Jan E. van der Laan, Lewis W. Carr, Philippe Adam, and Jean-Pierre Chaironi, $CO_2$ laser-based differential absorption lidar system for range-resolved and long-range detection of chemical vapor plumes, *Applied Optics*, 34(27), September 20, 1995.

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