PROFESSIONAL
SURVEYOR

On the Cover

Surveyors working in the Swiss Alps, circa 1933-35. Photo courtesy of Leica AG. Story on page 10.

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Siting a NEXRAD Weather Radar System

Dave Schurian, LS, Jim Hodges, PE, and Earl Burkholder, LS, PE

In 1994, the National Weather Service (NWS) was deep into a very large project to replace all of its aging weather radars with 117 modern Next Generation Weather Radars (NEXRADs). Only a month or two passed from the time the units were shipped from the factory to the time they were operational. All, that is, except for the Tucson, Arizona NEXRAD. A dozen sites south of Tucson had been found, then rejected, by the astronomical community. Without an acceptable site, the delay in the installation schedule would cause the government considerable extra expense. A survey team solved this special problem and helped the NWS keep its schedule on track. From the surveyor's perspective, it represented a sudden challenge from an important and unusual rush job, one that would consume the entire schedule even though the customer was unknown the day before.

This article was written by individuals from three different organizations; each author is identified by section.

Protecting Mt. Graham's Observations

by Dave Schurian

Jim Hodges of SRI International in Menlo Park, California called me at my office in Tuscon on Thursday, January 13, 1994, to explain that radio emissions from a NEXRAD planned for the area might have an effect on radio astronomy telescopes (and, to some extent, optical telescopes) used in the finer observatories. Weather radars and astronomical observatories were not a part of my everyday work experience. Jim said it would be necessary to have a blocking mountain somewhere between the Submillimeter Telescope (SMMT) on the mountain next to Mt. Graham and the NEXRAD, which was to be in the Empire Mountains southeast of Tucson. The blocking mountain would prevent the radar pulses from interfering with observations made from the mountain. The radar pulses would add phantom stars and "spots" to the observatory's sky charts.

When Hodges came to me, he already had identified two small mountains that lined up just about right. Our job was to verify that this would all work out. I scratched my head a little, but he spared no effort in helping me to understand the principles and methods used to make his determinations. I thought it best to ask him to jump in and give an overview of just how he did this magic, and to save my efforts for the surveying part.

Early Rough Survey Measurements

by Jim Hodges

As I found sites for radars, I developed my own brand of surveying—using a Brunton compass and stepping off distances. This time, however, I needed a real surveyor who could employ GPS, laser rangefinders, total station instrumentation, new computer hardware and the latest computer software. Why? Well, the SMMT is located two miles west of Mt. Graham, on top of Emerald Peak, 73 miles northeast of Tucson. The proposed NEXRAD site is 24 miles southeast of Tucson in the Empire Mountains. The extremely small blocking mountain, only 200 feet across, is 8,100 feet from the NEXRAD site, pretty much in line with the SMMT on Emerald Peak. That's enough to smoke a Brunton compass.

Analysis Made With Topographic Model

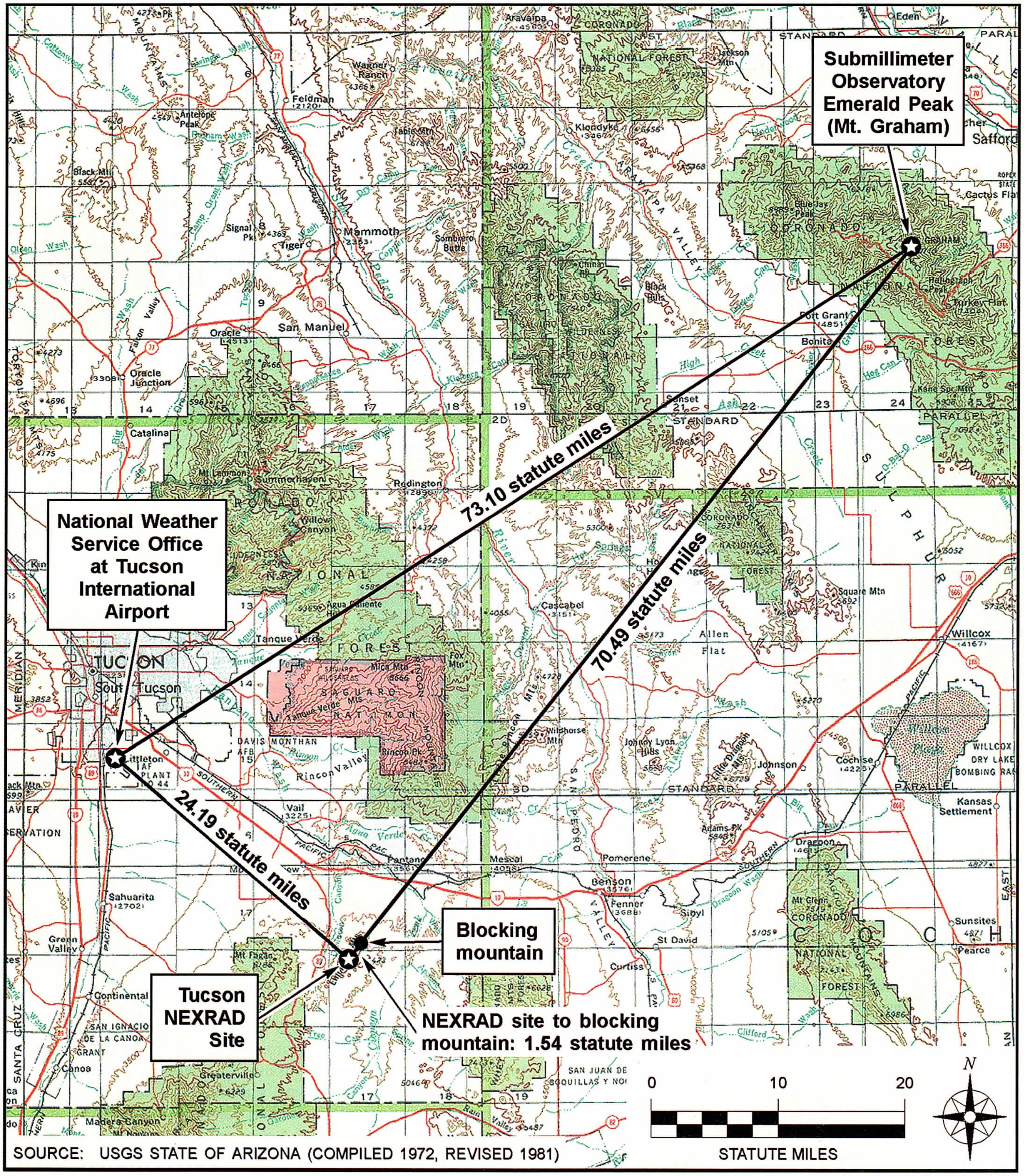
by Jim Hodges

Steward Observatory had received $200 million funding for the Mt. Graham Observatory, and universities from all over the world were planning to use the instruments already built there, as well as those planned to be built there soon. It would be a major, international incident if the NEXRAD interfered with any of the work at this new observatory, and we knew there was line of sight from the Empire Mountains to Emerald Peak. We had to find a place in these mountains where there was no line of sight to the observatory. We did not have to worry about the other observatories in this "dark sky" region because there is no line of sight from the Empire Mountains to them. That is why the Empire Mountain site was such a good one; we only had to worry about one observatory.

The usual routine was for my company to pick several prospective sites for each radar in the national network. The Joint Spectrum Center (JSC) in Annapolis, Maryland, then estimated the radar coverage for each prospective site using their Topographic Analysis System (TAS). This system includes an extensive topographic database and calculates the coverage (and, conversely, the blockage) for each site, including the effects of earth curvature and atmospheric refraction. Because of the curvature of the Earth's surface, the farther a radar beam travels, the higher it becomes. Therefore, when the beam is 142 miles from the radar site, its altitude reaches 10,000 feet; 142 miles is the maximum radar range at 10,000 feet, unless a hill blocks the beam. In the direction of blocking hills, the coverage decreases from the maximum to perhaps only a few miles. The job of the TAS calculations, then, is to find out how the surrounding hills affect the coverage from each site that is studied. The TAS-calculated coverage allows the sites to be ranked, best to worst.

The opposite approach was taken for this site because we needed to know if the radio and optical observatories on Emerald Peak (the Mt. Graham Observatory) would be blocked, that is, radar energy from the NEXRAD would not reach the observatories directly because of intervening topography, but coverage in the other directions would still be good. We decided to have JSC run their analysis as though the radar was located at Emerald Peak, not at the proposed site; that way the reverse-coverage maps would show the intensity of the false radar signal at ground level everywhere within about 100 miles of the observatory. The sites that were blocked from the observatory would show on the map as very low intensity radar energy areas. That is where the radar could be located, provided it still gave the coverage the NWS needed for southeast Arizona and the Tucson area.

Marv Shogren, the meteorologist in charge at the Tucson Weather Service Office, had found a site area he liked in the Empire Mountains. It provided good coverage of the critical areas, and several surrounding mountains provided obvious blockage toward the Mt. Hopkins Multiple Mirror Telescope Observatory and toward Kitt Peak, the location of the National Optical Astronomy Observatory, also known as the Mayall Observatory. The reverse TAS plot, with Emerald Mountain at its center, showed a very small area in the Empire Mountains where a NEXRAD site was a possibility. It was so small that we decided that it would be necessary to make a long-distance survey of the site, the blocking mountain and Emerald Peak. Using the survey information, we could also calculate the detailed radio propagation paths around the blocking mountain from the proposed an-



tenna at the radar site.

Signal Blockage Not Obvious at First

by Jim Hodges

The radar has a beam pattern that moves with the antenna. This pattern is much like that of a flashlight, with maximum power on the centerline that decreases as the angle away from the centerline increases. The radar power falling on a "target" is maximized if the target happens to be on the centerline, and is less if the target is off the centerline. When the target is off the centerline, the power arriving at the target can be calculated or looked up using a graph, provided the angle between the antenna pattern centerline and the line between the antenna point and the target point is known. (The antenna pattern centerline moves as the radar moves to look at different parts of the sky, but the target line stays fixed.) However, if there is a blocking object, another more complicated calculation of how much power reaches the target must be made. A series of concentric, circular power zones is calculated around the fixed line that runs between the antenna and the target at the range of the blocker. The total power reduction is a combination of what fraction of the power zones are blocked and how far off the beam's centerline the target line is at that moment.

We need to take a closer look at how the radar power surrounds the target line. For this calculation we proceed as if all the radio energy comes from a single point. The power going to some distant target point can be represented in cross-section as a bright central spot surrounded by a series of thin, not-so-bright rings. The bright, central spot, which has most of the energy, is called the First Fresnel Zone. The diameter of the First Fresnel Zone at the distance of the obstructing mountain is 104 feet. So the First Fresnel Zone is smaller than the focused antenna beam. Look at it this way: What engineers call the antenna beam width (or beam pattern) is the width of the beam after it is far enough away from the antenna to be in good focus and to be "shined" around like a flashlight. On the other hand, what the engineers call the First Fresnel Zone describes the radio energy traveling between one point (the antenna) to some fixed target point. How much power is blocked by an obstruction (whether it is within the main antenna beam or not) can be calculated using the Fresnel Zone model. Finally, the effects of the antenna pattern and the Fresnel Zones are combined by assuming the antenna beam centerline and the target line are coincident, a worst-case combination.

Figure 1. Blocking mountain with surveyors Ron Stoll and Earl Burkholder in foreground.

How Critical Was Survey Going to Be?

by Jim Hodges

From the location of the proposed NEXRAD, the obstructing mountain is triangular-shaped, with the highest part of the peak being the top of the triangle and the 200-foot width being the base of the triangle (Figure 1). Inside that triangle is the 104-foot diameter First Fresnel Zone. Since the 104-foot circle fits inside the 200-foot triangle, it would seem the mountain would block most of the radar signals. It turns out, however, that the First Fresnel Zone starts peeking out around the sloped sides of the triangle if the radar site is moved even a few feet one way or the other from right-on.

What Kind of Surveyor Was Needed?

by Jim Hodges

We wanted to select a surveyor who was very familiar with long-distance geodetic surveying. The GPS would give us the best results, because our survey distances were going to be much larger than the maximum distances recommended for optical surveying. Besides, it is almost 70 miles from Emerald Peak to the blocking mountain; that's a lot of stepping off! We put out a Request for Proposal to a dozen survey companies and only two responded. One was out-of-state; the other was more expensive, but was in Arizona. We chose the in-state one (and our final bill was much less than bid).

Special Coordinate System Chosen

by Dave Schurian

We had to get it within a foot or so. Because centimeter accuracy was not a must, we decided on long (in time) GPS observations over the 73-mile line between the observatories, the shadow mountain (or the blocking mountain), and the proposed location for the radar. As I thought about the survey, the possibility that I might be in over my head when considering the geometry of the situation caused me to call my colleague, Earl Burkholder (what I needed was straight-line calculations not related to the Earth's curvature). Earl is a land surveyor and geodetic engineer, then living in Klamath Falls, Oregon, now in Circleville, Ohio. He recommended earth-centered Cartesian coordinates. I immediately concurred, then asked, "What are they?" It became obvious that he had to be a member of the team. Because time was of the essence, it was decided to bring him to Tucson to oversee the higher mathematics involved.

Shadow and Height Computations

by Earl Burkholder

Schurian contacted me about computing the location and height of a shadow cast on a proposed radar site southeast of Tucson by an intermediate mountain from a light ray originating from one of the observatories on Mt. Graham. The reverse (from the observatory) geometry was necessary, since the radar site location was the unknown. Given this unique 3D application, I suggested the answer could be readily found if we had the position of key points defined in the Earth-centered, Earth-fixed geocentric coordinate system. Dave assured me that would be the case, as he was using GPS to establish the location of all control points. The prospect of making a working trip to Tucson in the middle of winter was quite attractive to one living in the Cascade Mountains of southern Oregon. The trip was interesting, productive and most enjoyable, except for that white stuff we waded through on top of Mt. Graham.

GPS surveying operations, including the position and movement of the NAVSTAR satellites, are conducted in the geocentric Earth-centered, Earth-fixed coordinate system which has its origin at the Earth's center of mass. The Z axis is coincident with the Earth's mean spin axis and the X/Y plane is coincident with the Earth's equatorial plane. The X axis pierces the equator at its intersection with the Greenwich Meridian. It is a rectangular Cartesian coordinate system using meter-length units for which rules of solid geometry and vector algebra are universally applicable. Any point within the "bird cage" of GPS satellites is uniquely defined with a triplet of X/Y/Z coordinates. There is no "up" in the geocentric coordinate system; instead a height is tacitly assumed to be perpendicular to the local horizontal.

Carrier phase GPS data are collected and processed to determine precise 3D vectors defined by delta X, delta Y and delta Z components. Irrespective of elevation or gravity, these vectors can be placed head to tail in a loop or a network of loops that demonstrate the absence of blunders by their internal geometrical consistency. Just as the sum of backsights and foresights around a differential level loop should add up to zero, so should the individual loop summations of the X/Y/Z GPS baseline components. With the internal consistency of the network established and the network attached to at least one monumented control point (minimal constraint), it is possible to compute geocentric coordinates for each surveyed point. Of course, standard practice (followed during the shadow survey) is to attach a network to multiple control points in a constrained adjustment.

With geocentric coordinates of key points determined, the process of computing a shadow height is greatly simplified. A vertical plane through the proposed site was determined (mathematically) from the top of the blocking mountain by backsighting the observatory (approximately 69 miles away) and prolonging the line of sight to the proposed NEXRAD site, 8,100 feet away. This procedure defined a plane containing the ellipsoid normal at the top of the blocking mountain. The direction of the plane was fixed by the location of the observatory "backsight." Within the plane so defined, a straight line was projected from the Mt. Graham Observatory to the top of the blocking mountain, extending over the proposed radar site. Shadow height computations within that plane were performed using the intersection of the projected line and the local vertical line at the radar site. Another computation (which gave essentially the same answer) was to find the perpendicular offset distance from the projected line to the ground at the proposed site.

The 3D computational environment and rules of solid geometry provided an efficient method for determining a geometrical solution to the shadow-height problem. Our solution was refined by SRI engineers, who added the appropriate corrections to accommodate the curvature of radar beams traveling through the atmosphere.

Figure 2. Conventional survey of antenna site.

Staging Instruments and Troops

by Dave Schurian

We employed three Trimble 4000ST GPS receivers that my associate, Mike LeJeune, and I own. In addition, I contacted Ron Stoll, operator of the Survey and Optical Instrument Company in Tucson and owner of six Trimble 4000SE units.

The team was together: Hodges was the leader, Burkholder was the geometric guru and Stoll and I were the survey leaders, assisted by Danny Larriva, Dave Southerland and Cris Rosco. The team then split up with Stoll, Larriva, Rosco and Southerland handling the shadow mountain and the future radar site, while Burkholder and I took the observatory and intermediate observations.

Control Points Are Found near the Line

by Dave Schurian

The coordinates of all our important points would be measured in a single half-day period. Prior reconnaissance was essential. Everyone scurried to find control monuments and to become familiar with the access and location of key points. In lieu of using a helicopter, Southerland, a former Army Ranger, was sent up the shadow mountain to locate not only the high point but also tri-station Empire, which lies about a quarter mile down the ridge (the climb was worthy of his special talents). Hodges and Stoll selected three points near the future radar site. Two of the points, intervisible, defined a line that was perpendicular to the long line from Mt. Graham through the shadow mountain. It was relatively short, only a few hundred feet, but we were sure that the long line crossed it somewhere. We just had to find out where. The third point was an additional control point farther downrange and a little closer to where we thought the site would be.

We Trek to the Farthest Points

by Dave Schurian

Hodges had been in contact with Buddy Powell, associate director of the University of Arizona Steward Observatory in Tucson (the University manages the observatories at Mt. Graham), and Dr. Robert Martin, director designate of the SMMT. We were told that a geodetic control point existed near the observatory on the mountain. That sounded good, and the map showed a control point that we had data for. In an effort to create some semblance of order and harmony, we made a preliminary trek from Tucson to Mt. Graham, having to stop near Safford to get permits, keys, and a two-way radio.

As you can guess, those of us who abide in places like Tucson and San Francisco expect warm temperatures, and accumulations of white stuff are somewhat foreign to us. But white stuff there was, about 18 inches deep, and crusted. It did not break until you were standing on top of it. Those of you who are from the north country know how exhausting that can be, to say nothing of operating above 9,000 feet rather than at the usual 2,000-foot elevation.

It was a long walk, the wind was getting ever stronger, and snow was beginning to fall. When we got to the top, our hopes of a well-documented control point began to dwindle. Our guide had lost some of his earlier assurances, and after scuffling in the snow for some time, finally informed us that a prior surveyor, not having geodetic tendencies, had reestablished the point and set a rebar. By the time we trudged back to the observatory, a blizzard was beginning, we had no control point, and observation day was only two days away. So much for semblance of order! This being before the days of CD-ROMs, and since my control sheets had not yet arrived, I had no option but to return home, collect the sheets (which had arrived that day) and return early the next morning, accompanied by Burkholder, who was just in from Oregon. Our new control points were on the flatlands along Highway 191 (formerly Highway 666) rather than on top of the mountain.

Previously, about halfway between Mt. Graham and the future radar site, I had completed a project which tied to a second-order NAD 83 monument at the Apache Station Generating Facility of the Arizona Electric Power Cooperative. I stopped and obtained permission to leave a GPS receiver on the point I had previously established in a protected area.

We now had locations for all nine GPS receivers. Three were situated around the potential radar site, with one on the shadow mountain, one on control point Empire, one at Apache Station, two on Mt. Graham, and one on control point Art, 11.5 miles south of Safford.

Long-distance Communications

by Dave Schurian

Being very concerned about our ability to converse on our high-band radios over the 70-mile distance, and knowing that team-to-team communication was critical should any one of us falter on our game plan, I purchased a cell phone and signed up for service. Stoll already had a cell phone, so we were set.

For those of you familiar with artillery, D-Day was much like a time-on-target exercise. Everyone left at a different time to assure arrival at his destination at the appointed time. For Burkholder and me, it was oh-dark-thirty. The first stop, about an hour-and-a-half out of Tucson, was Apache Station, where we left a GPS receiver, setting the session to begin at the appointed hour. Second stop, an hour later on Highway 191, station Art, where again we set a session and left. Larriva had received the worst job of all and had set out for control point Empire, beyond shadow mountain, packing nearly 50 pounds of GPS receiver, tripod, radio and other gear, a genuine blood, sweat and tears trek.

After getting our permit and radio, we headed up Mt. Graham. (The guys doing the radar site were probably leaving the coffee shop about that time, making the short 30-minute drive, setting their receivers, and returning to their trucks for the three-hour wait.) When we reached the observatory site, we had two goals. First, being tight on time, we immediately set one receiver and got it started. The receiver was placed in the center of a clearing, the home of the future Large Binocular Telescope (LBT) and one basis for the line-of-sight calculations. The second objective was to determine precise geographic coordinates for the SMMT, a few hundred feet northwest of the LBT and the observatory of most concern, together with relatively accurate coordinates for the Vatican Telescope, just across the clearing from the SMMT.

On my first visit to the SMMT with Hodges, I had found that the observatory control mechanism reads out the horizontal arc position to 1/10 of a second. When Burkholder and I arrived, not being able to occupy the top of the observatory, we securely affixed a range pole, with a GPS dome antenna, to the railing on the outer perimeter of the catwalk. After one hour of observation, we stopped the session and had the SMMT operator rotate the antenna exactly 180 degrees. We then started a second one-hour session. Of course, the latitude and longitude of the center of the observatory was exactly halfway between the two sets of coordinates. The location of the third occupation hour was just a short distance away on the observatory owned and operated by the Vatican.

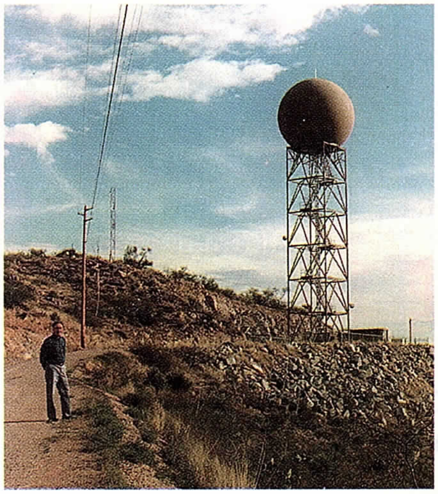


Figure 3. NEXRAD in place.

After our three-hour observation, Stoll did a couple of additional sessions to establish ground control for aerial mapping in the area of the radar site. It was late, and Burkholder and I were tired by the time we drove down the mountain toward Tucson.

The processing went without a hitch. The coordinates we calculated for the point at Apache Station were pretty interesting. When the point was allowed to "float" (the coordinates, as measured by our GPS receivers, were used rather than set to the known coordinates) it varied but a few centimeters from the correct values we had established in earlier surveys. As soon as the basic computations were complete, Burkholder took over and calculated the radio shadow created by the shadow mountain, finding a potential line for the location of sites that neatly eliminated all direct interference to the observatories from the NEXRAD. Establishing the projected centerline was nothing more than setting the intersection point, turning the angle, checking to make sure we hit the mountain, and then projecting the line ahead through three potential sites. The only problem was that it was the coldest day of the year (spring-like for you northerners). We froze our bottoms.

The Final Determination

by Dave Schurian

On February 3, 1994, 12 people from the organizations involved met at the NEXRAD mountain site. People were all walking different directions in an effort to pick the site that satisfied all the criteria of radar coverage, constructability, access and minimal environmental impact. We surveyors did our best to act like professionals while we waited (approaching hypothermia) for the others to pick the optimum site on our line.

That afternoon, with a lot of help from the topographic maps we had generated for this project, we agreed on the exact site. The remainder of the surveying was trivial and routine, except that only the NWS representative could talk to the press or the public. There were public meetings; some people were for and some were against construction of the radar. The county ruled in favor of safety and progress. Construction began on January 10, 1995, followed by power and telephone line installation. After the radar crates arrived, it was only a month before the radar dome was lifted into place on April 20. 1995. It was operational the following month. (See Figure 3.)

Now that NEXRAD is up, it covers a huge portion of Arizona (the useful range is 288 miles) without disturbing any of the important work being done at the surrounding observatories. We repeated the exercise in California for the Santa Ana Mountains NEXRAD, that time surveying a site that needed blockage toward the Palomar Mountain Observatory. But that is another story for another time. ■

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