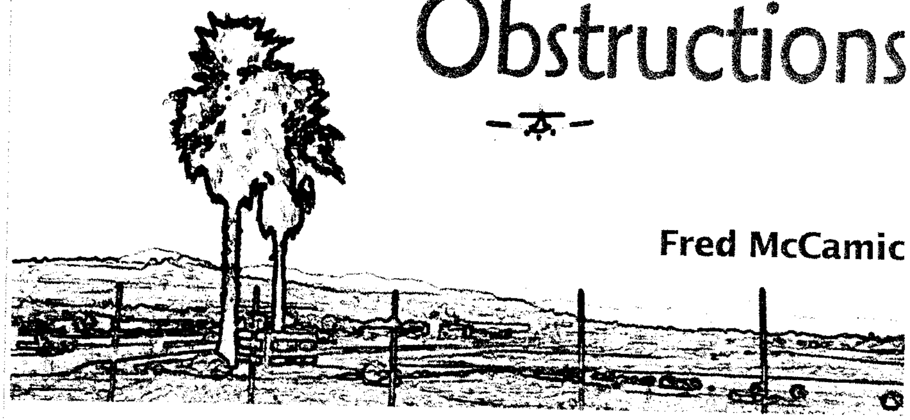
Cleared for Take-Off

GPS, GIS, and Removal of Airport Obstructions



Fred McCamic

Two months to deadline, underequipped, and underfinanced: The San Diego Airports Division and Department of Public Works GIS Division used a backpack GPS, GIS mapping, and simple instruments to identify trees obstructing the flight path at San Diego County Airport. Data collection and analysis targeted 22 trees for trimming or removal.

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Late in 2001, the Federal Aviation Administration (FAA) alerted the San Diego County Airport to the presence of numerous trees that appeared to be intruding into airspace in runway approach fans and clear zones adjacent to Gillespie Field. Because of the hazard that such obstructions posed to aviation in these areas, FAA mandated that the county airports division survey several dozen suspect trees and trim or remove any that exceeded height limitations.

The federal agency allowed the county only about two months to complete the project. That tight timeline and the absence of a preallocated budget for the work were complicated by the county survey section being overbooked and unable to respond in time to meet the deadline. Consequently, the county's Airports Division and the Department of Public Works GIS Division devised an inventory plan that used real-time differential GPS (DGPS) positioning, geographic information system (GIS) mapping. and other measurement instruments to identify trees for trimming or removal.

The process required determining the location of each tree, plotting it on a base map, and identifying the elevation of the top of each tree and the elevation of the approach fan. Once county GIS personnel had completed the inventory, the County Real Property Division contacted affected land owners and supervised the trimming and removal of the trees. The project demonstrated that ingenuity, good project design and planning, and appropriate tools can solve a time-critical problem that might suggest higher-tech and more expensive approaches under other circumstances.

Solving the Problem

FAA regulations specify "imaginary surfaces" for various classes of runway (see Figure 1 for an example of such surfaces associated with one of the runways at Gillespie Field). According to FAA regulations (Part 77), obstructions that are higher than an imaginary surface must be removed or a waiver must be granted. Surface specifications are a function of the class of runway and therefore differ from runway to runway.

As shown in Figure 1, surfaces relevant to the San Diego County project include the

- primary surface: a rectangle centered on a runway with elevation the same as the runway centerline. For Gillespie Field Runway 27R, the surface is 500 feet wide and extends 200 feet beyond the runway threshold or displaced threshold.
- approach surface: a surface longitudinally centered on the extended runway centerline and extending outward and upward from each end of the primary surface. The inner edge of the Runway 27R approach surface is 500 feet wide (same as the primary surface) and expands to a width of 3,500 feet at a distance of 10,000 feet at a slope of 34:1.
- transitional surface: a surface extending outward and upward at right angles to the runway centerline at a slope of 7:1 from the sides of the primary surface and from the sides of the approach surface.

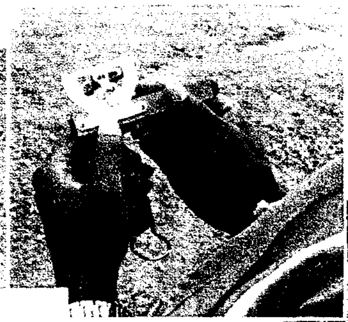
The airports division staff conducted a preliminary inventory to identify probable offending trees. We plotted a work map of the airport area using a digital aerial photo overlain by parcel lines and street names. The overlay data were from the San Diego Geographic Information Source (SanGIS) database. Airport Division staff went into the field and noted the approximate location of trees that appeared to be too tall.

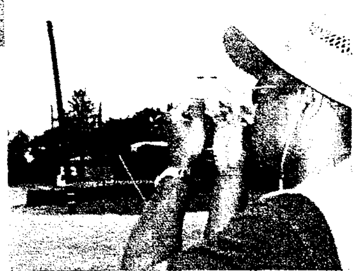
The formal field survey by Public Works personnel to measure and identify obstructing trees would require three steps:

- determining the location of each tree by triangulation from observation points whose location was established by corrected GPS

⊕ calculating the elevation of each treetop by trigonometry using the angle above horizontal, measured from eye height at one of the observation points

⊕ comparing the elevation of the treetop to the calculated elevation of the lowest imaginary surface at the tree location.





Instruments in use in the field. Upper left: magnetic compass. Lower left and top center: clinometer, which presents a split view of the target and a bubble level. Angle is read on the arc scale with vernier. Right: GPS position is captured into a handheld computer.

Instrumentation

We collected location data using a real-time differential GPS system that incorporates pseudorange corrections transmitted via geostationary satellites (GEOs). The backpack system includes an antenna, receiver, two camcorder batteries, and a cable to a handheld computer. The antenna was mounted on a pole and cabled to the receiver, which processed the GPS satellite signals and correction data to calculate the positions that processed the GPS satellite signals and correction data to calculate the positions, in three dimensions, from which we triangulated the locations of the trees. The receiver was cabled to the computer, where separate software read the GPS input and further processed and captured data.

The commercial DGPS service provider uses what it calls "virtual" base station calculations to generate corrections. This method uses a global network of high-accuracy reference stations that monitor the GPS satellite signals. These stations pass the GPS error data to network control centers where it is compressed and uplinked to the GEOs for broadcast. Users' receivers use the error data from the geosynchronous earth orbit (GEO), plus atmospheric modeling, to generate a differential correction.

Gillespie Field is in the El Cajon valley. The airplane is approaching the airport above a backdrop of hills that form a box (*cajon* means box).

This airplane is on short final approach to runway 27L, crabbing into a crosswind from the southwest. The trees look close to its passage, yet they were not surveyed as potential obstructions.

The GEO that we used for this project is located above the equator at 101 degrees W longitude. In San Diego County, the satellite appears approximately 50 to 55 degrees above the horizon in a south-southwest direction (approximately 157 degrees T). As with GPS signals themselves, these line-of-sight correction signals from the GEO can be obscured by terrain or buildings.

Our receiver equipment can also access corrections from the U.S. Coast Guard radiobeacon-based DGPS service or from FAA's GEO-based Wide Area Augmentation System (WAAS), both of which are free. In the San Diego area both WAAS satellites are approximately 12–14 degrees above the horizon, making them prone to obstruction. However, we chose to use the commercial service because it is reportedly less subject to signal blockage and provides greater accuracy (one meter versus two to three meters horizontally).

Our GPS unit reportedly provides submeter accuracy 95 percent of the time. We usually were able to obtain a differential position determination within less than one minute from a cold start. Occupying a single position for 10 seconds generally provided the claimed one-meter horizontal accuracy. For quality control, we confirmed this accuracy by operating our GPS receivers at survey control monuments selected from the county's GIS database. These monuments seemed to confirm submeter horizontal accuracy 95 percent of the time. Curiously, we have experienced slightly better accuracy in the z (elevation) coordinate than in x or y. Information from the DGPS service provider suggests that one can expect vertical errors of 2 to 2.5 times that of horizontal errors. This is an important consideration because, as this article notes later in discussing error sensitivities, GPS vertical error in our methodology converts directly into errors in the final calculations of tree height. However, as the article will also discuss, our z-component results were better than predicted.

Magnetic Compass. We determined bearings using a handheld magnetic compass. The compass proved to be the weakest link in the instrumentation, being subject to several problems. The circular card with the degree marks attached to the compass needle tended to stick unless the compass body was held absolutely level. Moreover, the compass was affected by masses of metal such as chain link fence and automobile engine blocks, and it was somewhat hard to read.

We achieved quality control for the compass by comparing the instrument's readings to those of another compass and by shooting runway and road centerlines, whose true bearings were measured from our map, and converted to magnetic bearings for comparison to the compass. If we

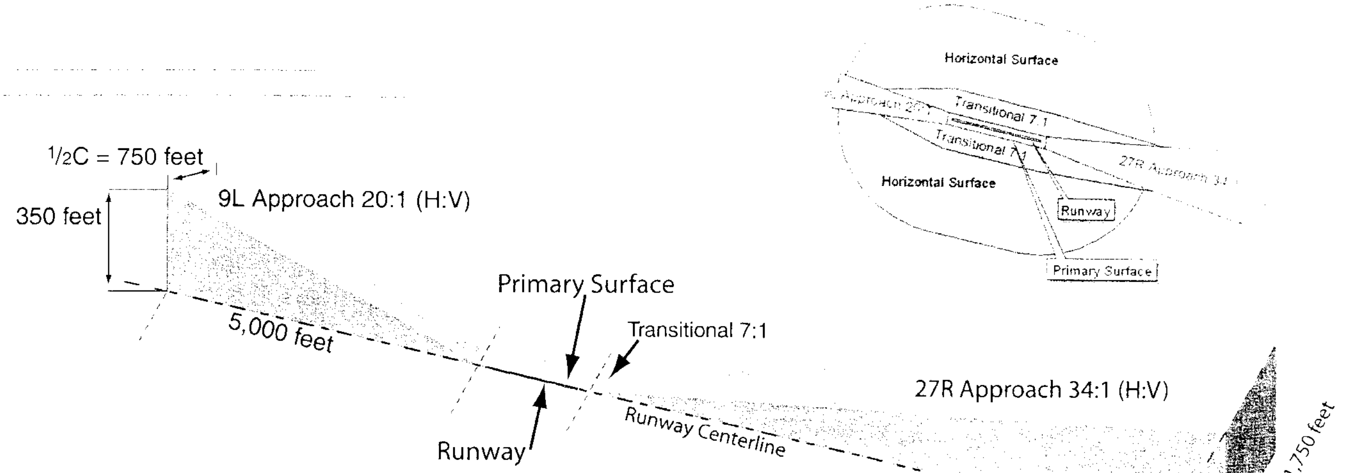


FIGURE The approach surfaces to 27R and 9L and the transitional surface along the north side of the airport. The heights of the outer ends of the surfaces are relative to the runway and primary surface elevation. The ground surface rises to the east, contributing to the obstruction problem.

kept the compass away from sources of magnetic deviation described earlier, we eliminated associated deflections. Independent compass readings by various operators were generally within one degree of each other.

Clinometer. We measured the angle above horizontal to the treetop with a clinometer, which provides a split view of a bubble level and the target (see accompanying photo). The instrument had been adjusted by the vendor at the time of purchase. Comparing two additional independent readings on the treetop supplied further quality control. In practice, repeatable accuracy appeared to be within approximately one-half a degree, the limitation being the observer's ability to determine when the bubble level was centered.

We collected the GPS data in the handheld computer using vendor-supplied software. We configured the software to record data in California State Plan Zone 6, North American Datum 1983 (NAD83), because our other GIS data were stored in that system. We exported data as ascii text because it preserved elevation and correction code data. A programmable vertical offset allowed us to collect GPS observation points with the elevation of the ground rather than with the antenna. We later transferred data from the handheld computer to a desktop PC for processing.

Field Procedures

We collected data for clusters of trees by occupying a location, indicating the placement of the GPS operator's right foot with a marker, allowing 10 seconds of corrected GPS averaging, and then logging the point to the handheld computer with an observation point identifier. We could verify DGPS by checking a lock LED on the GPS unit, by a visual message in the software display, and by the synthesized voice messages "corrected GPS" or "no corrected GPS."

The compass and clinometer operator then replaced the GPS operator, put his right heel on the same mark and took compass and clinometer readings for one or more trees while the GPS operator recorded the observations in a notebook. The team then moved to a second location to observe the same trees and repeat the procedure.

Processing the Data

We organized data in two text files, one with observation points and the other with tree data. Observation points were created by exporting them from the software with one line per point configured as follows:

```
pointnumber, y, x, elevation, name
```

For example, the data for two observation points would look like this:

```
1,1881065.7505266,6343649.2749577,427.479,'Obs 1'
2,1881414.2322601,6343622.5847365,430.070,'Obs 2'
```

Tree information was placed in a file with data for each tree occupying three lines as follows:

```
Tree_name
Obs_pnt_num,magnetic bearing, angle above horizontal
Obs_pnt_num,magnetic bearing, angle above horizontal
```

For example, the data for one tree would look like this:

```
"teton pine"
1,124,11
2,34,17
```

Horizontal Position of a Tree. We wrote scripts to process the data and create two GIS feature files — one with observation points and one with intersecting bearing lines and tree points. We converted bearings from magnetic to true by adding the local magnetic variation of 14.5 degrees. This step furnished an angle clockwise from true north, which we then converted to an angle counterclockwise from true east. The slope (m) of a linear equation representing the sightline is the tangent of the angle counterclockwise from true east.

We derived equations in the form $y = mx + b$ in which y is the coordinate or "northing" in the California State Plane NAD 83, x is the x coordinate or "easting," and b is the y intercept of the straight line for each observation point and bearing. We solved the resulting pair of simultaneous linear equations and added a point attributed with the tree name to the coverage at the x,y coordinates of the solution.

Elevation of a Treetop. The height of a treetop above the observer's eye is calculated by

$$h_3 = d \times \tan(\theta)$$

in which

- h_3 is the height above eye height
- d is the distance from the observation point to the tree
- θ is the angle above horizontal to the treetop.

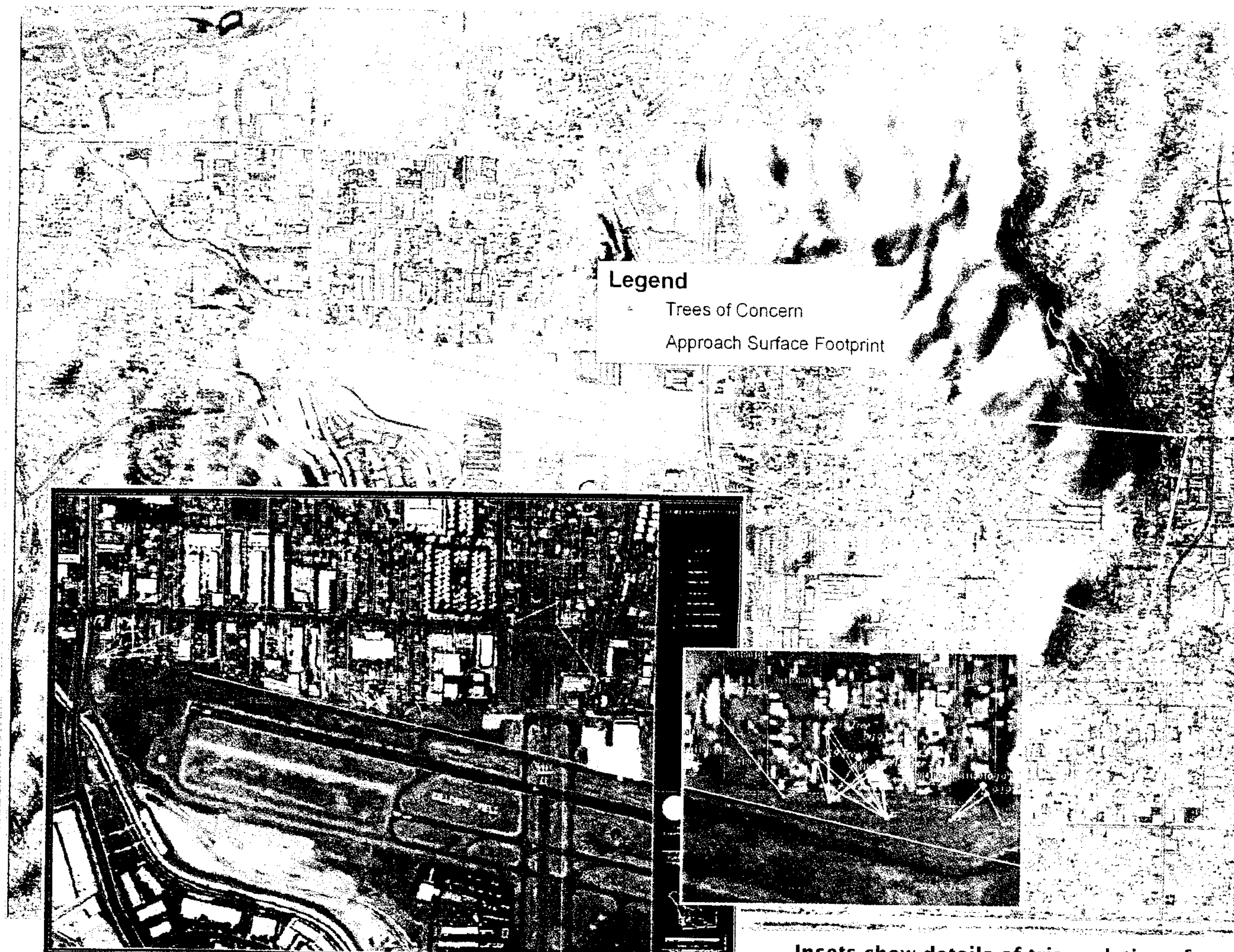
In each case, we used the observation nearer the tree for this calculation.

As shows, the elevation of the treetop was calculated as follows:

Elev(treetop) = elev(obs pt) + eye height + h_3

in which

- Elev(treetop) is elevation above mean sea level of the treetop
- elev(obs pt) is ground elevation above mean sea level of the observation point — the GPS data collection software includes a user-settable correction for the antenna height



Aerial view of Gillespie Field and El Cajon valley showing approach surface footprints for all runways. The blue line marks the outer edge of the primary surface and the inner edge of the transitional surface. The trees of concern were all in the approach to 27R and the transitional surface.

Insets show details of triangulation of trees in the transitional area.

- eye height is eye height (and thus clinometer height) above ground — assumed to be 5.5 feet
- h_3 is treetop height above eye as calculated above.

This data collection and analysis process resulted in a coverage with tree locations and the elevation above mean sea level of the treetops.

Imaginary Surface Elevation. Once we determined the locations and elevations of the treetops, we then compared each treetop elevation with the elevation of the applicable FAA imaginary surface. A detailed and careful reading of FAA regulations yielded descriptions of a set of imaginary surfaces for each runway.

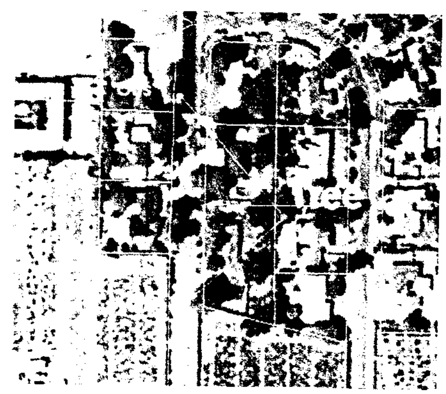
To accomplish the comparisons we followed these steps:

- constructed footprints using the GIS editing software, including its COGO functions
- identified the slope of surface
- approximated the elevation of the surface at the tree location for each treetop and each footprint containing the tree location
- identified trees with tops higher than the lowest imaginary surface.

For example: The approach surface footprint for runway 27R begins 200 feet east of the displaced threshold and extends 10,000 feet eastward. Width is 500 feet at the west end and 3,500 feet at the east end. Slope is 34:1. As shown in [illegible], elevation above runway elevation of the surface at any point was approximated by

$$h_2 = d/\text{slope}$$

in which h_2 is the elevation above runway elevation, d is the distance from the centerline at the west end to the point, and slope is the slope for the specified fan (e.g., 34:1).



A tree in a backyard was surveyed from the street. The ability to collect data from the public street enabled us to work quickly. This pine tree was identified for trimming.

Note that it would be strictly correct, on the basis of the FAA description, for d to be the distance from the tree location point to the line (extended) marking the western end of the fan. In the worst case, for trees closest to the runway and farthest from the centerline, the approximation overstates h_2 by slightly more than one foot. For most trees the error resulting from approximation was much less.

Sensitivity Analysis

The sensitivity of analysis of tree elevation and imaginary surface elevation to instrument reading errors presented some concern. Total sensitivity depends on the particular geometry of observation points and trees. The following analysis addresses typical rather than worst-case geometry. It assumes that site lines intersect at 60 to 90 degrees (smaller angles would produce greater sensitivity), that the distance from the observation point to the tree is approximately 200 feet (longer distances produce greater sensitivity), and that the GPS unit delivers accuracy similar to what we observed relative to survey monuments (we actually experienced better vertical accuracy than the vendor has claimed). The elements of analysis are

- error: GPS elevation
- maximum expected error: 1–2 meters
- sensitivity: 1:1; that is, a 1-meter error in observation point elevation causes a 1-meter error in treetop elevation
- error: GPS *xy*
- maximum expected error: 1 meter
- sensitivity: low; elevation error is horizontal error times slope, so for an altitude angle of 15 degrees, a 1-meter horizontal error causes, at most, a vertical error of 1 × tan(15 degrees)meters or 0.27 meters (approximately 0.9 foot). For an imaginary surface with 34:1 slope, a 1-meter horizontal error causes a vertical error of 1 meter × (1/34) or approximately 0.1 foot vertical error.
- error: compass
- maximum expected error: 1 degree
- sensitivity: low; for site lines intersecting at 90 degrees and distance of 200 feet, a 1-degree error moves the intersection by 3.5 feet. The sensitivity of the elevations to that movement is low (see prior item); given the above assumptions, a 1-degree error in compass reading causes about 0.1-foot vertical error. Note that more-acute intersection angles increase the sensitivity: at 60 degrees, a 1-degree error moves the intersection 4.6 feet and at 30 degrees a 1-degree error moves the intersection 14.4 feet.
- error: clinometer
- maximum expected error: 1 degree
- sensitivity: moderate to high; at a distance of 200 feet and an angle above horizontal of approximately 15 degrees, a 1-degree error in clinometer reading causes an elevation error of approximately 3.7 feet.

Targeting for Trimming

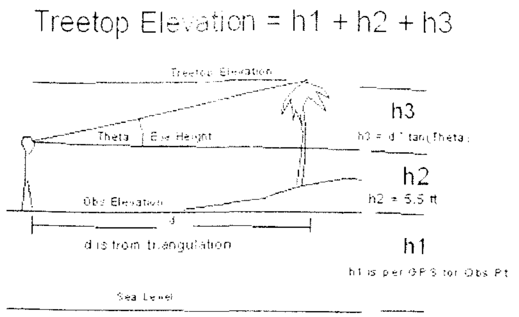
We surveyed 30 trees using GPS and the other means of instrumentation and one more using a measuring wheel and the clinometer. Of those 31 trees, 22 were identified as too tall with respect to the relevant imaginary surface.

If the treetop elevation of each tree was higher than any imaginary surface elevation, we earmarked that tree for trimming and calculated the amount of height to be trimmed.

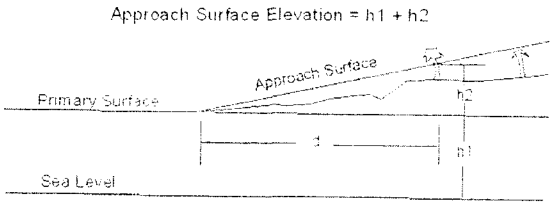
We produced maps using mapping software that shows fan boundaries, trees, parcel boundaries and assessor parcel numbers, and street names, all overlaid on a geo-orthorectified digital aerial photo. We identified trees by number and prepared a table that listed trees, treetop elevation, fan elevation, and the amount of necessary trimming. We then provided this information to the county's Real Property Division, which would be responsible for arranging the tree trimming.

The Real Property Division staff asked us to complete the table by adding the after-trimming height of the treetop from the ground. This was somewhat of a problem because, in most cases, we had not occupied the location of the tree and therefore had not collected the elevation at the base of the tree. Instead, we used the elevation of the nearest observation point as a base elevation, and in a limited number of cases, we revisited the tree and collected or estimated a corrected base elevation. The revised table provided the Real Property Division with the information it needed to complete the project.

Real Property staff made one additional request — they asked for a general height-above-ground limitation for tree height by neighborhood to help them manage tree trimming in the future. We were unable to accommodate their request because the sloping terrain made it impossible to provide a single valid number for a neighborhood.



Treetop elevation is the sum of ground elevation, eye height above ground, and treetop height above the eye.



Approach surface elevation is the sum of the primary surface elevation and the elevation of the surface above the primary surface.

Trimming the Trees

Property owners are legally responsible for trimming their trees so they are not obstructions. In some cases, the Real Property Division determined ownership of a tree simply by examining the map. Many tree crowns straddle property lines, however, so sometimes Division staff determined ownership in the field by observing the location of the base of the tree.

Several property owners doubted their trees were obstructions. Airport staff responded by providing a tour during which owners stood at the end of the runway and looked back toward their homes. From that vantage point the tall trees were conspicuous; property owners recognized their trees, generally accepted that they were obstructions, and most submitted to the work within the necessary time frame. Only one homeowner has not complied and is applying for an FAA exemption.

Conclusion

For all practical purposes, the tree survey project was a success. The work was completed in a timely manner, and, given effective follow-up by the county's Real Property Division, the trees were trimmed or removed as required, and the airport operations continued without interruption.

Still, in looking at the error analysis, it is impossible not to ask, Could it have been done better? Assuming that we had allowed the worst case for every variable identified in the error sensitivity analysis and that all the errors were in the same direction, the error total would be approximately 10.7 feet. We used a typical distance of 200 feet from observation point to a tree even though most distances were less than 200 feet. A couple of distances were a bit more than 300 feet, making the worst-case error closer to 12–15 feet. The majority of cumulative elevation errors, however, were approximately 3–6 feet.

Could we have done better? Yes and no.

The largest single source of potential error was the elevation of the observation point, as captured by the GPS unit. The most salient factor driving the way we did the project was the pressure and tight deadline imposed by FAA. So, in a sense, we couldn't have done much differently.

On the other hand, we did pass up the opportunity to use a conventional transit that would have provided better accuracy. We used the compass and clinometer in part because we wanted to travel light and avoid drawing too much curiosity from local residents. Although the clinometer and compass appeared to give us repeatable measurements to within about one degree, the transit would have read angles to one minute, or one-60th of a degree. That would have reduced the error from vertical angle measurement from approximately 3.25 feet to approximately 0.05 feet, or effectively zero for our purpose. In retrospect, we should have borrowed the transit.

Since project completion, non-survey grade GPS units with decimeter accuracy have become available at moderate prices. Their ability to reduce possible error from approximately six feet to approximately four inches is pretty close to eliminating it entirely.

Acknowledgments

Eric Nelson, an engineer in the San Diego County Department of Public Works Airports Division and the project coordinator, interpreted the Part 77 regulations, classified the function of each runway, and determined the dimensions and slope of the various surfaces.

Mike Binge, San Diego County Department of Public Works GIS section manager, enabled DPW/GIS to acquire GPS equipment and apply it to current projects.

SanGIS, a joint powers agency of the city and county of San Diego, is responsible for regional digital geographic databases (map records) used with GIS software products. This project used data from the SanGIS data warehouse.

San Diego Association of Governments (SANDAG), the forum for regional decision making, builds consensus, makes strategic plans, obtains and allocates resources, and provides information about a broad range of topics pertinent to the region's quality of life.

This article is based on a paper presented at the Environmental Systems Research Institute (ESRI) 2001 International User Conference held in San Diego, California.

Manufacturers

The GIS software for this project was developed by **ESRI** (Redlands, California) and includes *ArcInfo GIS, ArcEditor, ArcPlot,* and *Arc Macro Language.* The project used a **Sokkia** (Olathe, Kansas) *AXIS3* GPS unit and the company's *Imap* software, *Virtual Base Station* DGPS corrections from **OmniSTAR** (Houston, Texas), a **Hewlett-Packard Company** (Palo Alto, California) *Compaq iPAC* handheld computer, and *Activesync* software from **Microsoft** (Bellevue, Washington).