Floating Lines and Cones for Use as a GPS Mission Planning Aid

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Abstract

This paper presents a new method for generating obstruction diagrams as a function of site obstacles for GPS observations. The proposed method takes advantage of the human ability for stereoscopic vision. Instead of going on the site and measuring the azimuth and elevation angle of every obstacle in the vicinity of a prospective GPS point, the photogrammetric approach proposes using a visibility cone injected into a stereoscopic model. In this way, the time consuming and costly phase of site reconnaissance is eliminated. In the presence of obstructions, the cone rays that are lower than the obstacles are raised like floating lines. Afterwards, by recording the azimuth and elevation angles of these rays, obstruction contours can be generated. With this diagram, superimposed on the satellite track plot, the mission planner can evaluate the best GPS observation window based, for example, on Geometric Dilution of Precision (GDOP). A practical test shows the applicability and feasibility of the method.

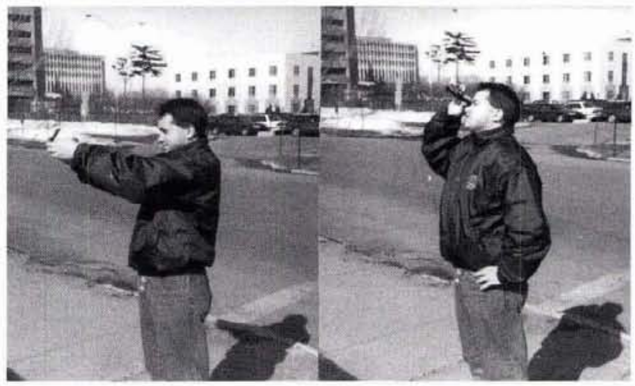

Figure 1. Compass and Abney hand-level (clinometer) survey.

Introduction

The Global Positioning System (GPS) is now widely used in geodesy and surveying. With the full deployment of the satellite constellation, the availability of satellites is no longer a problem except where obstructions prevent signal reception. Indeed, because of its radiowave frequencies, the GPS signals cannot penetrate, for instance, buildings, bridges, and trees. This fact constitutes the main limitation for the use of GPS. In urban areas where numerous obstructions are found, GPS mission planning becomes important and is, in fact, required to make GPS surveys a success.

Mapping of obstructions above potential GPS stations constitutes one aspect of that mission planning. In practice, the obstructions are surveyed with a compass and an Abney hand-held level (also called "clinometer") as illustrated in Figure 1. This process becomes tedious when many sites have to be visited and when many obstructions exist at each site. Some authors have proposed alternatives to this method. Colcord (1989) has suggested the use of a fish-eye camera to photograph the site obstructions. Hofmann-Wellenhof *et al.* (1993, p. 126) have mentioned that an image of the local horizon can be generated from a digital terrain model. In this paper a new photogrammetric method of generating obstruction diagrams based on floating cones is presented. More details on GPS mission planning are also given, as well as a comparison between the results obtained from the use of floating cones and those from classical survey methods.

Floating Cones

Because the floating cone concept is implemented in a particular softcopy photogrammetric workstation called the Digital Video Plotter (DVP), some general information about this system is first presented. The DVP was developed by a research team from Laval University (Gagnon *et al.*, 1990). Today, more than 250 copies have been distributed in 45 different countries. The DVP's greatest success is its contribution to making photogrammetry accessible to anyone having a simple microcomputer. Concerning the model formation, DVP essentially emulates analytical stereoplotters. In fact, image carrier movements, for the removal of *y*-parallaxes, are replaced by an image panning process of the stereopairs displayed on the PC split screen. Stereovision is achieved using a special mirror stereoscope placed in front of the screen. This simple optical instrument is the only hardware addition to the personal computer. Orientations are carried out analytically, generally giving an accuracy of a half-pixel at ground scale (Agnard *et al.*, 1992). On this solid base, a prototype module for GPS site obstruction, called DVPGPS, has been implemented.

Two photogrammetric solutions can be adopted for the determination of satellite visibility. One would consist of creating a digital terrain model in the vicinity of a prospective GPS point and computing the highest obstacle at every azimuth. Despite the feasibility of this approach, considerable effort would be required for the acquisition of ground points. Futhermore, the operation would be totally irrelevant if no obstruction higher than an elevation mask angle, for example of 15°, were present around the studied site. Also, because the closer a feature is to the point considered the more likely it is to represent an obstruction, the sampling process would have to be progressive, which could become a very te-

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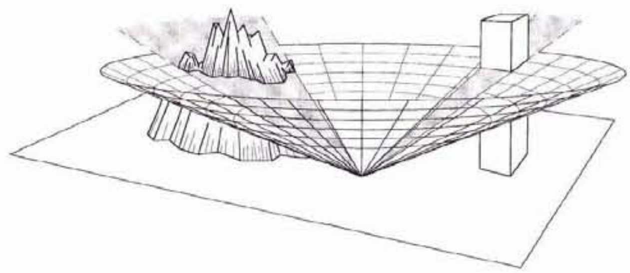

Figure 2. Visibility cone and obstructions.

dious job (especially for sites with numerous obstructions). A more elegant solution is to take advantage of the natural human stereoscopic power to detect visually the obstacles without having to make measurements.

In the DVP, a "floating cone," injected into the stereoscopic model, makes possible this visual inspection. This virtual cone is represented as a wire-frame model composed of a user-defined number of rays, converging on the GPS observation site, and of a certain number of concentric circles (Figure 2). The opening angle of this inverse cone (150°) is based on the usual satellite elevation mask angle (15° above the horizon). All objects higher than the cone surface are considered to be obstacles and must appear on the satellite visibility plot.

The proposed photogrammetric reconnaissance method for a GPS site is composed of three main steps. The planner's first task is to put the floating cone on the prospective GPS site. This operation is achieved, after the stereoscopic model has been fully oriented, by placing the DVP floating mark on the selected ground point. A vertical offset, corresponding to the known approximate elevation of the GPS antenna, is then given to the floating mark. Then, the command "cone-on" determines the spatial coordinates of the wire frame elements of the cone at this location. To visualize this cone in the model, the wire frame representation is projected onto the image stereopair using the well-known collinearity equation (Figure 3).

The second step consists of visually checking whether the cone surface interferes with parts of the terrain or with infrastructures and trees in the vicinity of the site. At this point, only a global view of the obstruction's distribution is sought. In the presence of obstacles, the cone surface is seen as being under them. To facilitate this subjective model investigation, especially when obstacles are very close to the cone surface, the operator may rely on the DVP floating mark to determine if the obstructions are higher or lower. Based on the cone equation, determined in the ground coordinate system, the floating mark is made to appear of a distinct color depending on its position above or below the cone surface.

The third phase of the photogrammetric reconnaissance is the rectification of cone sections, previously identified, in contact with obstacles. For that purpose, the command "cone-off" erases the visibility cone and activates the function, allowing the manipulation of cone rays as floating lines (Boulianne *et al.*, 1991). Obviously, the lower extremity of

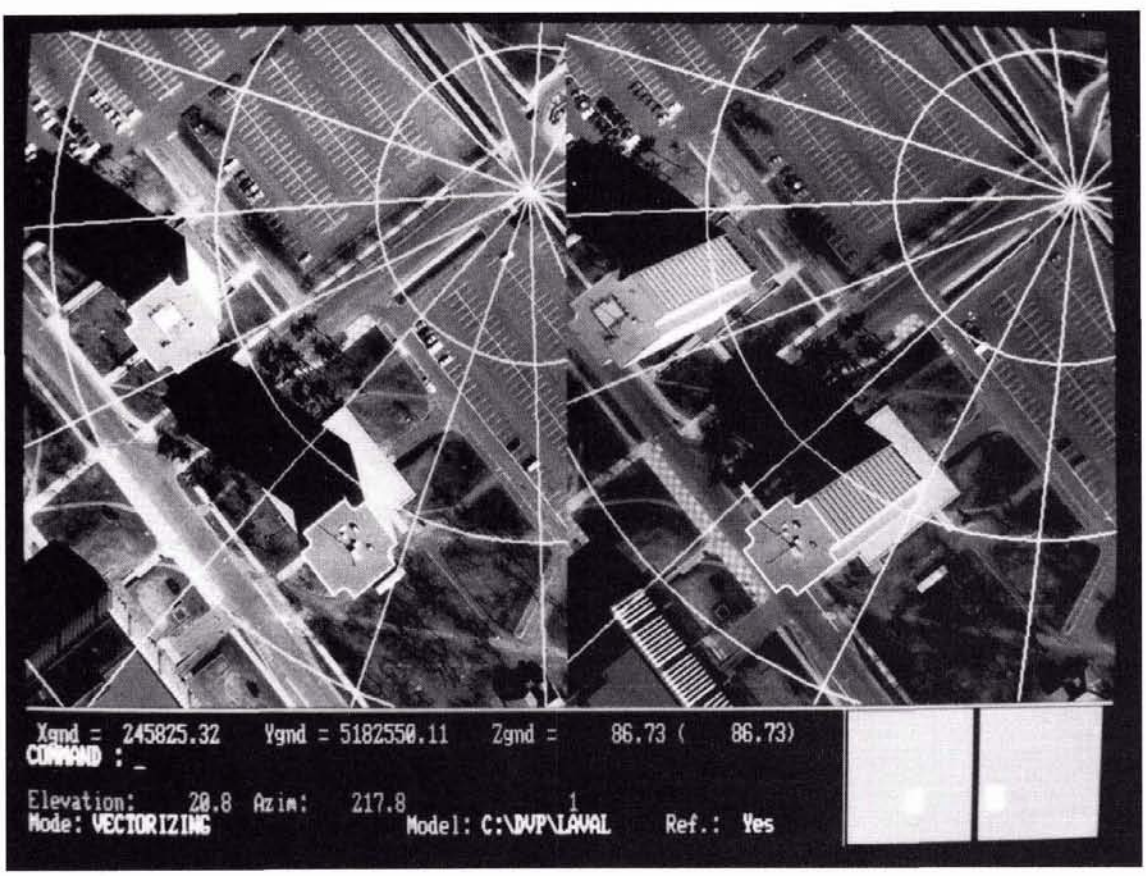

Figure 3. Stereoscopic cone display.

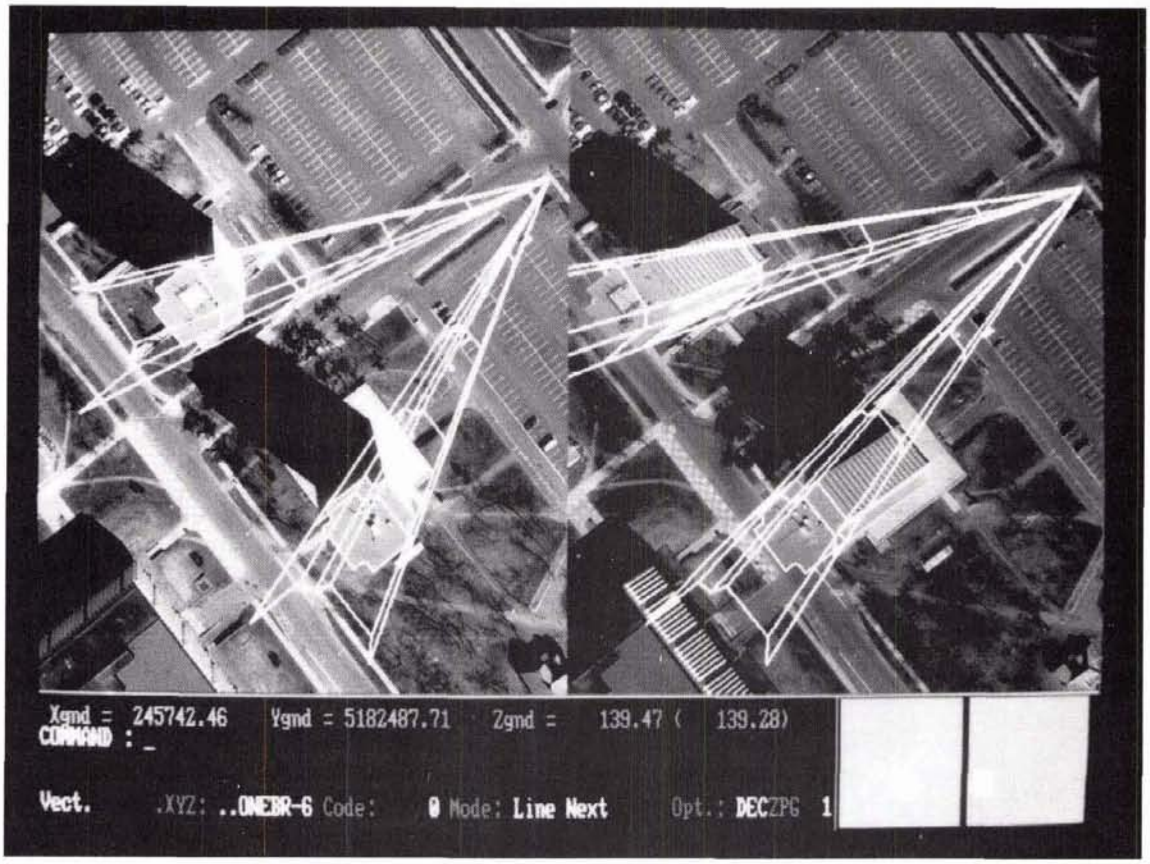

Figure 4. Stereoscopic obstruction representation.

the rays remain fixed at the GPS station. By modifying the position of an arbitrary point along one ray and constantly redrawing a line between this point and the anchor point, a floating line or a rubber band illusion is given. In the same way as can be done for the floating mark, the operator can tell if the line is above or below the terrain even though the terrain itself has not been digitized. A short training period with the floating line permits the user to place the rays over the highest obstacle for every azimuth without major difficulties. Again, the color of the floating line changes as the elevation angle is greater or smaller than 15°. When enough floating lines have been positioned, a simple function draws crossed lines between them and creates a spider's web representation of the conic surface related to a given obstacle (Figure 4).

Once these three steps are completed, the DVPGPS program automatically records the azimuth and the elevation angle of all rays. With this information, an obstruction diagram is produced. This graph, superimposed on the GPS satellite track plot, allows the mission planner to evaluate the best observation window based, for example, on Geometric Dilution of Precision (GDOP). Should the results be unacceptable, the user can return to the stereoscopic model and select another site or can raise the cone, providing that an antenna telescopic mast is available.

Of course, depending on the image scale, the scanning resolution, and the terrain roughness, the model section displayed on the screen might not show all potential obstacles. However, the closer are the objects, the more likely they are to produce obstructions. At the present time the prototype software considers only the obstruction visible on the screen at the original image scale. A future version of the DVPGPS module will first show the model at the initial scale and, after the operator has placed all rays over the obstacles, will resample the images to display a larger portion of the model with the cone. This zoom-out operation will end when the operator estimates that there is no object high enough and close enough to create an obstacle. A graph, showing the elevation angle, the height, and the proximity of an obstacle, is very helpful for visualizing this.

GPS Mission Planning

As explained earlier, interruptions of GPS signals caused by obstructions complicate data processing and, more importantly, have an adverse effect on the precision of GPS surveys, because the geometry of the satellite sky distribution becomes weaker. A sky plot is shown on Figure 5 illustrating portions of the sky masked by obtructions (symbolized by hatched areas) and its impact on the visibility of GPS satellites. On this plot, the outer circle represents the local horizon, the other two concentric circles are for 30° and 60° elevation angles, and the zenith is located at the center of the circles. The north, east, south, and west directions are represented by azimuths of 0°, 90°, 180°, and 270°, respectively. The satellite trajectories of one hour, in this case, in the observer's sky, are represented by arcs, the arrows indicating the directions of the satellite tracks. On Figure 5, satellites 3, 9, 12, and 17 are partially observable while satellite 6 is completely hidden, at the particular time of observation considered.

The prediction of the satellite number and distribution in the observer's sky is calculated from satellite almanacs and approximate coordinates of the observation site. The instantaneous geometric strength of the satellite distribution is represented, for example, by the GDOP value which is computed from the unit vectors from the site to the satellites.

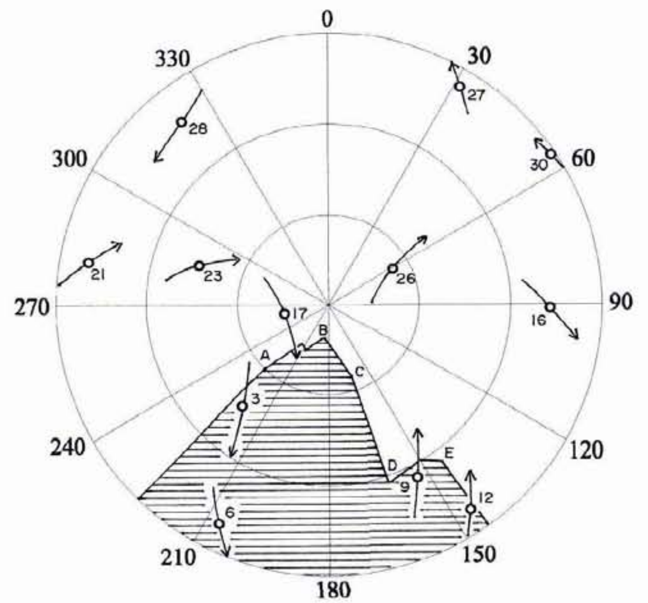

Figure 5. Obstruction diagram from theodolite survey and satellite visibility plot.

From the approximate values of the satellite orbital elements taken from the almanacs, satellite positions can be calculated. The unit vectors between the site and the satellites are computed using satellites and site coordinates. From the unit vector components it is possible to extract the satellite azimuth and elevation angle for the observing site, at any epoch. This prediction must also consider the obstructions over the GPS site.

In practice, the satellites below an elevation mask angle of 15° are not used in the GPS data processing because the effects of multipath error and tropospheric refraction become too important. In consequence, only the obstructions above an elevation angle of 15° have to be identified. In relative GPS positioning, a method where two or more receivers are used simultaneously to reduce common errors at observing sites, the obstructions present at both sites must be considered.

One disavantage of conventional obstructions surveys (with compass and clinometer) is related to their interface with the computer program used for satellite visibility prediction. For instance, the mission planning program used in this paper requires that every obstruction point be manually entered in the sky plot display, using a mouse. With the proposed photogrammetric approach, the direction of the obstructions are already in the computer memory and the information can be automatically displayed over the GPS satellite plot.

One way to avoid obstructions is to elevate the GPS antenna by mounting it on a telescopic mast. A telescopic mast (Canadian patent pending number 2,097,774) has been developed at the Centre de Recherche en Géomatique (Santerre and Roy, 1993). It is composed of four tubular telescopic sections which are stretched out or retracted by means of a single cable operating through a pulley and a winch. The mast is held in place by stays, the verticality is ensured by spherical levels, and the centering is achieved with the optical plummet of an inversed tribrach. The centering and the height determination of the mast can be achieved within about one cm. Surveys with compass and clinometer give no indication about the usefulness of a mast, and neither does a fish-eye camera, unless it is also elevated with the mast. In such a case, the disadvantage is that the mast must be used twice: once at the planning stage and once during the GPS survey itself. On the other hand, using the floating cone method, one can quickly tell whether or not the use of a mast would help in the reception of satellite signals just by raising, in the stereoscopic model, the base of the cone to the height of the telescopic mast.

For further details on GPS mission planning, the reader is refered to Hofmann-Wellenhof *et al.* (1993, Chapter 11).

Practical Results

A practical test has been conducted in order to evaluate the performance of the proposed method. The Laval University campus, with its quantity of potential obstacles, was selected for this purpose. Aerial photographs at a scale of 1:5,000 were scanned at a resolution of 300 DPI (Dots Per Inch), giving a ground pixel size of 84 cm. The test consisted in comparing, for three sites, the proposed photogrammetric site reconnaissance method with a theodolite survey and another survey conducted using a compass and an Abney hand-held level (clinometer). As mentionned earlier, this last operation is the usual way of producing the obstruction diagrams. For purposes of comparison, the theodolite survey was considered as giving the "true" obstruction graph.

The comparison has been realized in two different ways, namely visually and by taking check points. Figures 5, 6, and 7, respectively, represent the obstruction diagrams for one site obtained by the theodolite survey, the compass and Abney hand-level method, and, finally, the photogrammetric method for one site. For the sake of conciseness, graphs for only one representative site are given in this paper. A close examination of the diagrams shows no major differences between the three methods. To confirm this fact, 15 prominent obstruction points, in the neighborhood of the three sites, were selected. Among these points, starting and ending points of obstructions as well as some of the highest features received particular attention (see, for example, points marked as A to E on Figure 5). Table 1 shows the results of the comparison in terms of azimuths and elevation angles obtained with the three different approaches. For the conventional method, with respect to the theodolite survey, RMSEs of ± 1°

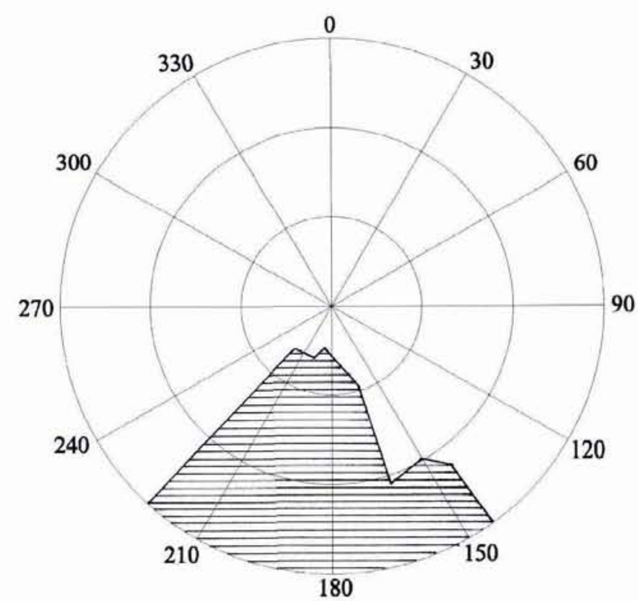

Figure 6. Obstruction diagram from compass and Abney hand-level (clinometer) survey.

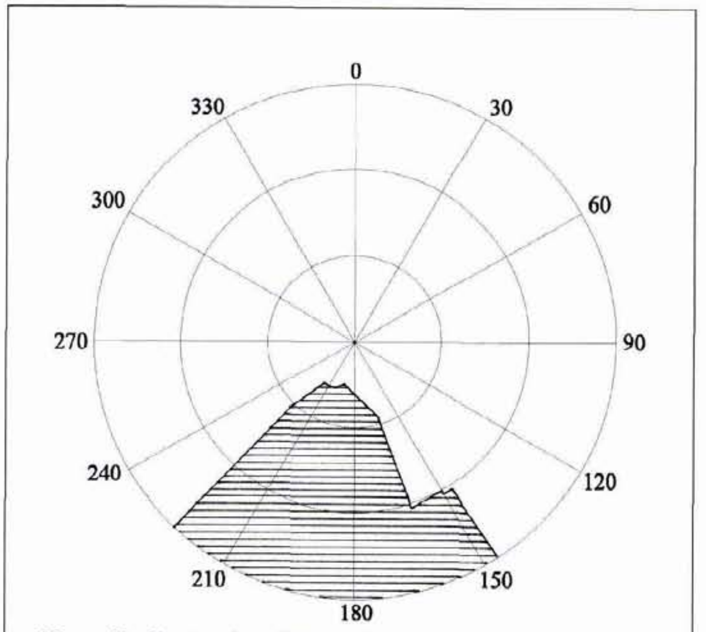

Figure 7. Obstruction diagram from floating cone survey.

15' and ± 1° 35' were obtained for the azimuths and elevation angles, respectively. For the photogrammetric method these values were reduced to ± 0° 59' and ± 1° 06'. Locating an obstruction at ± 1° is more than acceptable for GPS observation planning. An even better accuracy could have been achieved by simply using a higher scanning resolution. In fact, the accuracy obtained with the photogrammetric method corresponds to the theoretical accuracy of angles measured in the DVP in such conditions.

Due to the presence of a very strong magnetic field perturbation on one site, the azimuth of points F through K have been removed from Table 1. The perturbation had been detected when an azimuth variation of about 20° was noted depending on the compass height over the site. Subsequent examination of the campus underground plans provided the explanation for the phenomenon: 60 cm-deep electric cables and steel pipes.

The photogrammetric site investigation takes about 1½ hours. Of this, about 45 minutes are needed for the photograph scanning and model orientation. Thus, a time estimate per model can be obtained from the formula 45 ^{min} + 15 ^{min} × number of prospective sites. In contrast, 30 ^{min} × number of points would be required for the conventional surveys in the field. Obviously, the photogrammetric method becomes more efficient as the number of points grows. Of course, additionally, the photogrammetric site reconnaissance method has the most important advantage of eliminating the transportation time of the survey crew in the field.

Table 1. Comparison of the Three Site Reconnaissance Methods

	Theodolite		Compass + Clinometer		Floating Cones	
No.	Az.	El.	Az.	El.	Az.	El.
A	224° 19'	60° 19'	223°	60°	224° 18'	59° 24'
B	188° 21'	77° 13'	189°	76°	190° 48'	75° 54'
C	160° 46'	63° 37'	162°	63°	163° 12'	63° 06'
D	160° 50'	27° 35'	162°	26°	161° 06'	27° 12'
E	145° 50'	25° 15'	144°	25°	145° 54'	25° 30'
F	263° 23'	23° 29'	—	24°	263° 06'	23° 12'
G	249° 30'	22° 48'	—	25°	249° 30'	22° 36'
H	220° 10'	23° 51'	—	25°	220° 06'	23° 36'
I	205° 58'	25° 15'	—	27°	205° 54'	24° 48'
J	53° 39'	28° 40'	—	28°	53° 42'	29° 12'
K	36° 48'	27° 58'	—	28°	37° 06'	27° 36'
L	176° 41'	37° 29'	177°	36°	177° 42'	35° 18'
M	173° 51'	31° 32'	172°	27°	174° 36'	28° 30'
N	93° 30'	38° 17'	93°	39°	92° 36'	37° 30'
O	8° 34'	15° 20'	8°	16°	8° 30'	15° 30'
RMSE	—	—	± 1° 15'	± 1° 35'	± 0° 59'	± 1° 06'

Conclusions and Recommendations

A new method for generating obstruction diagrams at GPS observation sites has been presented in this paper. This method has the definite important advantage of eliminating the need for visiting a site for the reconnaissance. Because controlled stereomodels are usually available in urban areas, major economies in terms of time and money may be realized. In addition, the photogrammetric reconnaissance method allows the GPS planner to select the optimum location for future sites with regard to achieving the best possible accuracy. Visibility cones coupled with floating lines also permit the generation of obstruction maps that are otherwise impossible to produce with conventional field surveys. Indeed, when a telescopic GPS mast is used, the obstructions are much more complicated to map due to the inaccessibility of the antenna location. Other applications for floating cones might be considered. For example, the method can be used for solar easement surveys or for scenery analysis.

The limitations of the floating cone model investigation concern essentially the availability and quality of the aerial photographs. In order to obtain a good obstruction diagram, the photos must have been taken recently so as to show the actual situation on the ground, and they must be at an appropriate scale.

In the near future, some minor improvements will by added to the system presented. For example, the DVP second monitor will be used to display visibility diagrams, satellite tracks, and all tables derived from the GPS mission planning program. With this tool, the mission planner would have simultaneous access to a stereoscopic view of a GPS site under investigation on the main screen, and to all the relevant numerical or graphical information on the second monitor.

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