Table 7.—Apparent Causes of SV Signal Losses

Apparent Cause of SV Signal Losses

Record Date	Signal Loss Causes Trunk	Branch	Foliage	Unknown	No Signal Loss Clear	Obstructed	%SNR ≤ 5[1]	η[2]	3D Positions on Stations
100888	20%	25%	28%	15%	2%	10%	32	132	B13, B14
102088	30	30	28	1	3	7	37	150	B15
102188	20	37	30	0	2	10	49	124	B16
102288	18	17	51	3	3	8	33	211	B11, B17
102388	15	33	41	3	3	5	35	206	B12, B23
110288	38	26	35	0	0	0	95	65	A31
Mean	23	28	36	4	2	7	47		

[1] *SNR is a numeric value for the signal noise ratio.*
[2] *η is the number of data points.*

RESULTS

Although a large amount of quantitative data were collected and processed primarily through the PFINDER reduction routines, the analysis presented here is still largely qualitative, consistent with the exploratory nature of the study. Previous experience has suggested a number of outcomes for the conditions that have been examined. These results tend to point more directly to specific outcomes with a better rationalism of the causes. It should be recognized that this was a very limited study, conducted over a short period of time, because the compared conditions seemed imperative to the progress of GPS forest applications.

Helix to Microstrip Comparison

As an example, our experience had suggested that differences should be observed between the helix and microstrip antenna configurations. Due to the vertical orientation of the helicoils of the helix, it should be a better receiver of low elevation signals, while the flat horizontal orientation of the microstrip should make it a better receiver of high elevation signals. This may be true, but the data results shown in Table 1 indicate very little difference between the two antennas when operated side by side in the open at station A11. The same is true under a very closed canopy at station A31. The number of position records obtained by each antenna are nearly the same for the operating time. The apparent discrepancy for the first receiver/antenna setting at A31 resulted from a recording error. The number of records is consistent for the recording time period. In each case, the position comparisons are very good in all three axes and the accuracies are consistent with our experience with autonomous operation. A comparison of the data root mean squares shows the only consistent difference between the two antennas. The helix RMS is almost always larger, indicating a greater spread of the data from the mean.

In the comparison of the helix and microstrip antenna under the canopy, some similar results occurred. This comparison was drawn from data collected over long observation periods for two consecutive days. On day one (111088), the microstrip was at station B15 and the helix was at station B16. The antennas were switched between stations on day two. The receivers stayed on the same station. The data summary in Table 2 shows that the helix antenna produced more total records and 3D records at each station, ie., the time (seconds) required to produce a record was lower for the helix antenna in each case. The average 3D production for the helix was 45 to 51 percent compared to 30 to 42 percent for the microstrip. The microstrip antenna appears to be more accurate than the helix, but this difference may be slight, since both antennas produced relatively large position differences. Differences in latitude, longitude, and height above ellipsoid are noted as dlat, dlon and dhae in Table 2. A dlat of 0.318 seconds /9.5 m/31.4 ft was obtained for station B16 using the microstrip. Conversely, an excellent autonomous position was obtained at station B15 on the previous day with this antenna.

Open to Canopy Comparison

The results of the comparison between receiver operation in the open and under the canopy are shown in Tables 3,4, and 5. These data were collected over short time-periods at each station occupied by the remote receiver. The recording and positioning parameters were identical for both receivers (remote and reference) and all stations (elevation mask 10, PDOP mask 12, PDOP switch 8, and SNR mask 5). The position time intervals vary slightly between the remote and reference receivers and the record lengths differ somewhat between remote receiver stations and a great deal between the remote stations and the reference receiver station. The reference receiver was set to a five-second position interval and the remote receiver was set to one second (Table 3 column 1). The average least time required to generate each new position is about one an a half seconds. Table 3 shows the results of the data means for each station. The station name, data file name (date) and position record interval are shown in the first column. The next column shows the record length in seconds, the total number of positions, and the number of 3D positions recorded. Line one shows that the reference receiver recorded for 5640 seconds at the Lubrecht Base Station. The autonomous position mean minus the known position was 0.105 seconds (difference in latitude), 0.024 seconds (difference in longitude) and 1 meter (difference in height above ellipsoid). differences for Lubrecht Station transform to 3.16 meters dlat, 0.56 meters dlon. Seventy-nine percent of the total position records were three-dimensional at Lubrecht and the rest (21 percent) were 2-dimensional. The existing PFINDER software required a record of 3-dimensional positions at the reference and remote receivers acquired at nearly the same time from the same four SV's in order to calculate differential corrections for the remote receiver position. In this case the reference receiver was affected by poor PDOP (position dilution of precision) near the end of the recording session, which resulted in a loss of 3-dimensional positions. This effect is also evident at stations A17 and A21 of the remote receiver. Table 3 lists the stations by time. Tables 4 and 5 are derived from Table 3. The stations are sorted between the "in open" (top of Table 4) and the "in canopy" (bottom of Table 4) comparisons. The record lengths for the stations in the open were approximately the same (mean 171 seconds). For the open stations, 99.7 percent of the records were 3-dimensional and 95.4 percent were usable for differential corrections. Some of the loss of 3-dimensional positions was due to high PDOP conditions like those at the reference station. The bottom of Table 4 shows the record length to be more than twice as great (mean 407 seconds) for the remote under canopy stations (B Course) as that for the open stations (A Course). This reflects the attempt to acquire about 120 position records at each station under canopy (B Course) to match the open stations. Tables 3 and 4 show the results for two days (082488 & 082688) of observations. The reference receiver recorded 79 percent and 100 percent (B082488) and 90 percent (B082688) 3-dimensional positions on each day (Table 3). The average 3-dimensional position efficiency for all of the under canopy stations was 27 percent and 24 percent were usable for differential corrections (bottom of Table 4). Also it required more than 10.2 seconds per 3-dimensional position at the under canopy stations.

The position accuracy in the open (Table 4) average dlat and dlon was 0.109 seconds/3.3 meter/10.8 feet and 0.170 seconds/3.9 meter/12.9 feet in the autonomous mode. After differential correction, these differences became 0.055 seconds/1.6 meter/5.4 feet and 0.049 seconds/1.1 meter/3.7 feet. The maximum dlat and dlon was 4.9 meter and 6.2 meter in the autonomous mode and 2.4 meter and 1.2 meter in the differential mode. These results are consistent with previous experience for stations in the open and for short time-period observations.

In the canopy (Table 4), the average dlat and dlon was 0.217 seconds/6.5 meter/21.4 feet and 0.223 seconds/5.2 meter/ 16.9 feet for the autonomous mode. The differential corrections resulted in dlat and dlon of 0.100 seconds/3.0 meter/9.9 feet and 0.175 seconds/4.0 meter/13.3 feet respectively.

Although this was our first careful look at short observing times under the canopy, the results were not too unexpected if two stations are removed from the array. Table 4 shows the resulting dlats and dlons without B31 in the open and A21 under the canopy. The mean differences in the dlat and dlon become comparatively small for both the autonomous and differential mode of operation. This suggests that accuracies under the canopy may not be much different than in the open, providing enough fairly continuous and usable 3-dimensional positions are obtained with similar PDOP values. Basically, this means that both receivers should be receiving signals from the same four SVs and this set of SVs should produce the lowest PDOP values for any group of four SVs.

Subsequent observations under the canopy show similar results as indicated in Table 5. They show that out of eighteen stations occupied for short time periods, the remote receiver failed to produce 3-dimensional positions for only four stations. The receiver did not produce 3-dimensional positions usable for differential corrections for six stations. Although stations B23 and B24 contribute large differences, the overall mean difference for the autonomous mode are still reasonable (dlat 0.162: and dlon 0.268 seconds on 082988). The results for the six differential mode stations are very acceptable for many of the navigation and positioning activities of operational forestry. The autonomous mode positions obtained on 091388 and

091488 are similar, even somewhat better. The differential mode results, however, are not as good as those achieved on 082988. The general receiver efficiency was about the same, with more than 4.2 to more than 12 seconds required to produce a 3-dimensional position. The average time required to produce a 2-dimensional or 3-dimensional record was less than two seconds, or less than that reported by Table 4.

Longer Time Periods Under the Canopy

Longer time periods of observing the satellite signals and recording the data should produce overall better positions with a navigation receiver. Obviously more 2-dimensional and 3-dimensional records should be produced. Table 6 shows the total record production rate ranging from 1.95 to +0.62 seconds of time, and the 3-dimensional record rate ranges from 3.1 65.2 seconds if we discard Station A31 where the 3-dimensional rate was 460 seconds per record. Looking at accuracy, Table 6 shows considerable differences between stations. The autonomous mean dlat was 0.100 seconds of arc and the dlon was 0.143 seconds. This compares to a dlat of 0.164 seconds and a dlon of 0.123 seconds for the differential mean results. The autonomous mean position differences are only slightly better than those obtained under the canopy for shorter time periods, and the overall differential results are about the same. It should be noted, however, that for the nine stations only one (B16 on 102188) failed to produce differential correction records and 3-dimensional records were achieved at all nine stations. A recording failure occurred at the base station receiver, eliminating differential corrections at B16.

Canopy Structure and Signal Loss

In this part of the study a TV camera recorded data and these data were used to plot satellite skytracks for nine observation periods. The current SV ephemeris data was displayed on the POLYCORDER and recorded at about five minute intervals. This data was plotted on an elevation and azimuth graticule to produce real-time skytracks as shown by Figure 6. The SV skytrack figures were produced at the same circular scale as the hemispheric station photographs. When a skytrack figure was overlaid onto the hemispheric photograph, the signal pathway could be estimated relative to obstructing canopy material. If the pathway was obstructed, then a signal loss could be expected. A numeric signal noise rating (SNR) was recorded at each interval for each SV. A signal loss was estimated according to the SNR value on an arbitrary scale which changed with SV elevation. SNRs decrease naturally as the SV elevation decreases (or the pathway distance through the atmosphere and to the satellite increases). The obstructing material (trunk, branch, foliage, and unknown) was interpreted by examining the skytrack in relation to the photographic image of the canopy as shown by Figures 3, 4, and 5. Table 7 shows the results of these interpretations for all of the stations observed.

It seems that the type of obstructing material depends on what is in the picture. A small diameter trunk close to the antenna may block a larger portion of the track than a large diameter trunk at a greater distance. A study of Table 7 does not indicate as much variation between stations as one may perceive at first inspection of the photographs. Again, the percentages in Table 7 are overall averages for all SVs observed on the indicated dates. By these estimates, 91 percent of the signals were attenuated in some way. Of the 9 percent showing no signal loss, the pathway appeared to be slightly obstructed for 7 percent of the observations. Only 4 percent of the signal losses were identified as unknown. Also, 47 percent of the signals were below the SNR mask (<6). This means that only 53 percent of the SV signals were available for position determination. Yet, very usable positions were obtained under these canopies as indicated in Table 6 (102188, 102288, 102388, 110288). This is the first and rather rough attempt to analyze the obstruction of the canopy, and these methods can be refined and quantified in future efforts.

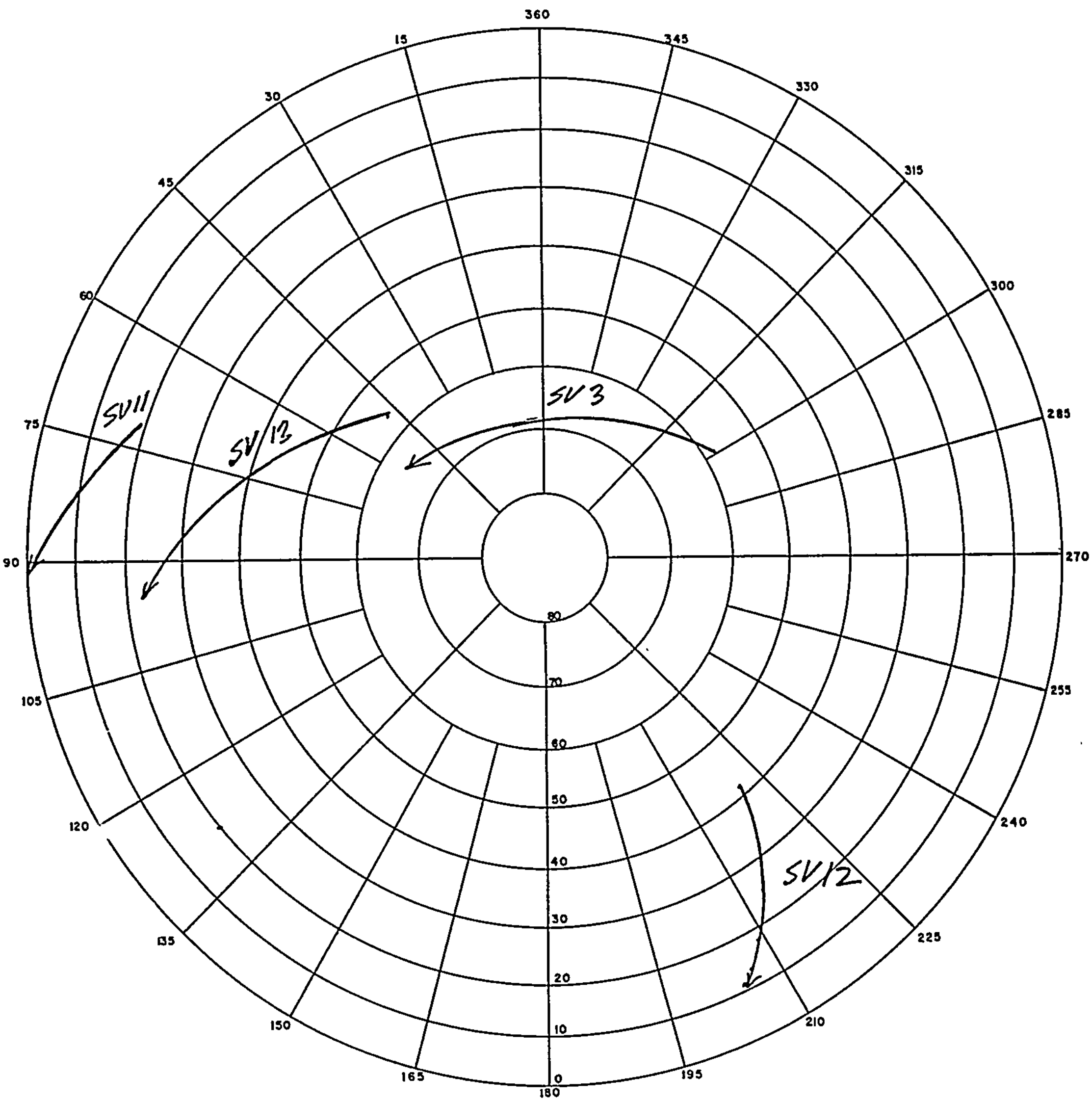

Figure 6.—SV skytracks for A31 on November 2, 1988.

DISCUSSION

Antenna Type

The helix and microstrip antennas seem to perform almost equally well in open sky conditions, but the RMS values were consistently larger for the helix antenna. This indicates a greater range of position values compared to those for the microstrip antenna. The mean positions results are still very similar for each antenna, although the helix produced somewhat larger vertical position differences in the open. At stations B15 and B16, the helix produced a higher percentage of 3-dimensional records and the total record efficiency (seconds per total records) was better than the microstrip. Both antennas produced similar horizontal position results in the canopy and the accuracies are similar to those in the open.

The antenna configurations should produce some differences. The microstrip should be a better receptor of signals from high elevation SVs and the helix should be a better receptor of signals from low elevation SVs. This could result in the better accuracies indicated for the microstrip (especially vertical) and a better record production rate for the helix antenna (especially under the canopy).

Antenna Height

The antenna height comparisons are qualitative. The experience here has shown that movement of the antenna in any direction will change the antenna's view through the canopy, changing the SVs that are received at that time. Raising the antenna under the canopy should increase the opportunity for SV signal reception. Often the number of SVs received and/or the SNRs increased soon after the antenna was raised from its former height. But, the opposite effect did occur several times. The critical condition seems to be the canopy view into which the antenna is being raised. The most positive effect occurred when low elevation SV signals were reacquired upon raising the antenna from 5.5 feet to 15 feet and again to 25 feet. The experience leads us to continue to believe that raising the antenna will help to acquire more SVs and stronger signals. But, there are situations where raising the antenna can result in a loss of signals. Obviously, raising the antenna to a point above the canopy would avoid the pathway obstacles. This may be practical in young stands and naturally short vegetation.

Open Versus the Canopy

The short time periods (120 to 600 seconds) clearly show receiver efficiency differences between the open stations and those in the canopy. Position record production rates are slower under the canopy. The efficiency of 3-dimensional position production is reduced the most. It takes more than five times longer in the canopy than in the open to produce the same number of 3-dimensional records. This is simply a result of the availability of SV signals. If five SVs are available, a 3-dimensional position can be obtained if one signal is lost and a 2-dimensional position can still be obtained if two SV signals are lost. Table 4 shows that 2-dimensional positions were acquired at the eleven stations in the canopy. The GPS receiver failed to acquire 3-dimensional positions at three of these eleven stations during the time period allowed. One of these stations was affected by high PDOPs (>12). Similar results are shown in Table 5, where 2-dimensional positions were acquired for all eighteen stations over three days of observation. The receiver failed to produce 3-dimensional positions at four of these stations.

The autonomous latitudes and longitudes are slightly less accurate in the canopy than in the open (Table 4). The height differences (dhae) are about twice as great in the canopy, but the height above ellipsoid values are generally more variable than latitudes and longitudes. Differential corrections produced dlats and dlons three to six times greater in the canopy than in the open. The differential corrections for the vertical (dhae) have not produced good results so far. Therefore, the dhae comparisons were not carried further than that of Table 4.

The results of supplemental short time period observations are shown in Table 5. These results are similar to those in Table 4 for stations in the canopy. Interestingly, the differential corrections improved station positions greatly on 082988. The positions were improved for all six stations having correctable 3-dimensional records. Poor corrections occurred for stations B22 and B25 on 091388 and B11 on 091488. Fifty-six percent of the records were usable at B22 and only six percent were usable at station B11.

Long Periods Under the Canopy

The data for seven observation days are summarized in Table 6. These time periods were relatively long (1580 to 7115 seconds). The average 3-D efficiency was 27 percent. This is substantially lower than that shown in Table 5 and nearly the same as that shown in the bottom of Table 4. The efficiency values (seconds per total record and seconds per 3-dimensional record) tend to be higher, indicating less efficiency for long periods compared to short time periods. Recalling that 3-dimensional positions were not acquired at four out of eighteen short-period stations, Table 6 shows that 3-dimensional positions were acquired at all nine long-period stations.

The overall autonomous position and differential position accuracies show no real improvement over that produced in shorter time periods. The long periods display three obvious differences: 1) increased number of total records; 2) increased 3-dimensional records; and 3) better chance for 3-D records usable for differential corrections.

Signal Losses Under the Canopy

The canopy has a substantial effect on total signal loss and the reduction of SNRs. With only half of the SV signals strong enough to be above the SNR mask (Table 7), it is surprising that the receivers function as well as they do. Stations B12 and B23 on 102388 (Table 6) provide an interesting comparison. At B12, 44 percent of 2500 position records were 3-D while 29 percent were usable for differential corrections. At B23, 28 percent of 1900 records were 3-D and only 4 percent were differentially correctable. The hemispheric photographs at these stations (Figures 4 and 5) help to explain these differences. Station B12 (Figure 4) is much more open to the sky than station B23 (Figure 5). Interestingly, the differential corrections were good for both stations and the resulting accuracies were nearly identical. Also in Table 6, station A31 represents a worse case on 110288. Only 2 percent of the acquired 260 position records were 3-dimensional but they were all usable for differential corrections. You may note that the autonomous position is fairly good, but the differential corrections are not considered good. The canopy condition at A31 is shown in Figure 3.

Considering the worst case scenario at A31, the position records were produced with only four SVs available. Table 6 shows that the total observation time was 2760 seconds. The canopy effect can be visualized by superimposing the SV skytracks (Figure 6) onto the photograph at A31 (Figure 3). By chance, signals were received from SV11 through small openings in the canopy while it was above the 10° elevation mask. Two tree trunks were the major obstacles to the signals from SV 12. Intermittent signals were received from both SV3 and SV13, but their skytracks were almost completely obstructed by the crowns (foliage and branches) of trees overhead. Signals were obviously penetrating the canopy from these two satellites at high elevations. The average time for a position solution was 10.6 seconds and the autonomous position accuracy was acceptable.

CONCLUSIONS

This study does not provide a basis for many conclusions, and those made should be recognized as tentative. The study was conducted with just two GPS receivers. The antenna type and the antenna height comparisons could have benefited from having more receivers available. The receiver efficiency and accuracy comparisons could have been made using fewer stations and fewer observation days with more receivers. For example, several diverse canopy conditions could have been instrumented to run simultaneously over two or three observation periods. This lack of simultaneous data makes conclusion drawing difficult. The study did explore the nature of the canopy problem and this should make it easier for future studies to focus on specific problems.

The results indicate little difference between antenna types. But, the user might prefer the Helix when low elevation SVs are critical to the position solution, and the microstrip when high elevation SVs are expected and when height (elevation) determinations are more important.

It still seems reasonable to increase the antenna height in canopy conditions, especially when SVs are at low elevations. The effect of raising the antenna seems to be greatest for SVs near to or approaching the elevation mask. The results clearly show the canopy to be an obstacle to receiver operation. The greater the canopy density, the greater the obstacle it becomes. The study did not consider the effects of tree diameter and tree proximity to the antenna.

The open to canopy results leave little doubt that canopy effects do make GPS receiver operation more difficult. This means that much more time will be needed for GPS work in the forest. The overall planning will require more care. When planning, a practical elevation mask may be higher than that required for good positioning in the open. The occurrence of good autonomous position accuracies in this study is very positive for operation in the forest. The differential corrections were also good for many stations. In this respect, the remote receiver was able to lock onto and record four SVs at one time. The receiver selects the four SVs producing the best PDOP and solves for position with these until a better PDOP configuration of SVs happens. The best (lowest) PDOP value produces the most accurate positions. Remote receiver accuracies are affected when a higher PDOP set of SVs is selected because of signal losses from one or more of the preferred SVs. Also, differential corrections were affected by signal losses, which produced discontinuous records and differing sets of SVs between the remote and reference receivers. Good differential corrections were obtained for short time periods when the position's determinations were continuous. Poor differential corrections for long time periods resulted when the few position determinations were widely separated by time. The best differential corrections seem to happen when only one set of SVs are compared, even for a short time.

The skytracking through the hemispheric photographs provides the first opportunity to actually look at the probable obstructing object. In the field, it is largely a guess using a compass and clinometer. The SV skytracks produced here lack precision from the receiver, the recording methods and plotting. Computerizing the entire process of skytrack construction and SNR comparisons should improve this precision considerably.

The canopy presents some interesting problems in the application of GPS Navigation/Low Precision receivers to resource management activities. These tests were run in canopy conditions, of low to moderate density. The tree heights and trunk (bole) diameters are probably low to average for second growth stands in western Montana. The tests have covered much of the variation as it exists in the B evaluation course. The PATHFINDER receiver produced 2-dimensional and 3-dimensional positions at all of the stations sometime. These tests and experiences indicate the canopy to be a significant obstacle to the transmission of the SV signals, but the success achieved supports the continued development of forest applications. Other users have achieved successful applications of GPS receivers in a variety of natural resource problems and in a variety of vegetative cover conditions. The canopy cover may be an obstacle, but it is not a deterrent to the application of GPS receivers.

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