NOAA Technical Memorandum NOS NGS-56

# PSEUDO-KINEMATIC SURVEYING BASED UPON FULL-WAVELENGTH DUAL-FREQUENCY GPS OBSERVATIONS

**Benjamin W. Remondi**
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Silver Spring, MD

November 1993

U.S. DEPARTMENT OF COMMERCE / National Oceanic and Atmospheric Administration / National Ocean Service / Coast and Geodetic Survey

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Silver Spring, MD 20910

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ABSTRACT. Although the concept of pseudo-kinematic GPS surveying is nearly a decade old, and has been in practical use since 1988, important improvements continue to be made. Pseudo-kinematic GPS surveying, in this paper, will mean from one to three very short (e.g., 2-5 minute) occupations of a survey monument which are separated by 3 to 4 hours in time. The emphasis here will be with respect to two visits over baselines typically shorter than 15 km.

What has contributed to these recent improvements are, primarily, the introduction of full-wavelength L2 carrier ranges for civilian use, improved C/A code ranges, a nearly complete GPS constellation, and improvements in postprocessing methods and algorithms. Continuing improvements in computer performance are also a contributing factor.

Whereas a triple difference algorithm provides a good first guess to the correct position, a carrier-smoothed code differential GPS (DGPS) algorithm, for either PPS or SPS, is typically better. In DGPS mode one can expect (95% of the time) to be within 0.35 m horizontally and 0.75 m vertically with state-of-the-art P code receivers and within 0.75 m horizontally and 1.5 m vertically with state-of-the-art cross correlating receivers. Combining the carrier-smoothed code DGPS solution with the triple-difference solution will provide somewhat better results.

After generating the above first-guess solution a search technique may be used to determine the correct position. Two fractional-phase-only search algorithms will be highlighted in this presentation. Such processing methods are impervious to cycle slips. The supplied integral number of cycles, in the carrier measurements, are used only to achieve the meter-level first guess and even this is optional. In short, neither the fixing of cycle slips nor the determination of initial integer ambiguities is required. In fact, the integral number of cycles is not required as part of the raw carrier range data. These pseudo-kinematic postprocessing algorithms can be applied to medium-baseline (e.g., 40 km) traditional static surveying as well.

Pseudo-kinematic results using P code receivers and new dual-frequency, cross-correlating C/A code receivers are presented.

## INTRODUCTION

### BACKGROUND

Although the concept of pseudo-kinematic (PK) surveying originated in the mid 1980s, it did not become a practical method until 1988 (Remondi, 1988). Since then there have been significant development efforts directed toward performing static surveys in the shortest possible time.

The term pseudo-kinematic derives from the fact that the GPS surveyor "appears" to be performing a kinematic survey as he sequences from one station to the next with very short occupation times. Thus PK appears to be something that it is not, which is how the dictionary defines "pseudo." An alternative moniker for PK is intermittent static. This is good since it does imply short occupations and, the name itself, does not require that any specific monument be occupied more than once. "Stop and go" describes the activity fairly well but leaves unanswered whether or not continuous carrier phase tracking is required (the term "stop and go" has been used to describe kinematic GPS surveying rather than PK).

## PURPOSE

The purpose of this paper is to report recent progress with respect to the PK method. A number of advances have occurred since 1990, particularly with regard to the capability of advanced dual-frequency cross correlating GPS receivers to perform while Anti-spoofing (AS) is on. Today, even in the presence of AS, civilians have: full-wavelength L1 and L2 carrier range measurements, very high quality L1 and L2 code ranges (in differential mode), and independent L1 and L2 code ranges. In fact, the civilian GPS community anticipates a non-military GPS receiver which incorporates all of these features into a single model. Other receiver enhancements are also anticipated such as improved antennas, better ground planes, and higher signal to noise ratios on L2 signals.

In addition to improvements in receiver technology, there have been other factors influencing PK as well. An obvious example is the GPS constellation. A full constellation provides six to eight satellites above 7.5 degrees much of the time. Other improvements with respect to PK are in the realm of postprocessing algorithms. The ambiguity function method (AFM), highlighted in a 1991 report (Remondi, 1991), has been enhanced substantially with regard to speed and simplicity and now accommodates dual frequency carrier observations. An alternative fractional phase method, Ambiguity Resolution Using Trial Position (ARUTP) is under development. This method allows the possibility of increases in speed and accuracy and may be attractive over lines somewhat longer than those relevant to AFM processing. The important advances in kinematic GPS "On-The-Fly" (OTF) are also affecting the development of PK. In fact the OTF method (Remondi, 1993) has proven to be an excellent alternative for single-occupation PK processing and has demonstrated promise with respect to multiple-occupation PK.

## ORDER OF PRESENTATION

In the sections which follow we will first discuss two methods to achieve a first guess position accurate at the 1-meter level. One of these methods is based on the triple difference method and the other is based on a carrier-smoothed code differential GPS (DGPS) method similar to what is used to provide a meter-level first guess to OTF kinematic GPS. These two first-guess solutions can be combined as well. This is followed by a presentation of two fractional-phase-only methods for processing carrier phase measurements: AFM and ARUTP. Both are positional search methods rather than lane search methods. A positional search method evaluates a set of positions whereas a lane search method evaluates a set of integer ambiguities. In both methods we search for the position, in a neighborhood about the meter-level first guess, which best fits the fractional phase portion of GPS carrier observations. More details will be provided in a later section.

The subsequent three sections discuss results for: the initial first guess, the AFM method, and the ARUTP method, respectively. The section following these shows an example of the repeatability of the AFM method. All data collected were from either the Allen Osborne Associates, Inc. TurboRogue receiver or the Trimble Navigation Ltd. 4000SSE GPS receiver. Examples are provided in P code mode or in C/A code, cross-correlated L2 mode; the latter mode represents the situation when AS is on and may ultimately be more important. For the sake of brevity the latter combination will be hereafter referred to as the X mode.

The final two sections will then present the summary and conclusions.

## THE FIRST STEP: ACHIEVING A METER-LEVEL FIRST GUESS

In the section following this one we shall describe two positional search methods to isolate the precise geodetic coordinates of the rover receiver during its one or more static occupations. However before the positional search grid can be described three elements are required. First, we need to determine an approximate position about which to search. Second, we need to describe a search volume which has a very high likelihood of containing the correct position (e.g., 95-99%). Complete certainty is neither possible nor necessary since, most of the time, a miss will be obvious and an expanded search volume can be defined. Third, we need to define the granularity of the search grid within the search volume (e.g., 3 cm). In this section we concentrate on the first of these elements: achieving a meter-level first guess. Throughout this paper this will be referred to as the first step.

### TRIPLE DIFFERENCE PROCESSING

Whether the PK survey is composed of one, two, or more occupations, the data will is processed as one set of triple difference carrier phase observations. For example, with two occupations of 3 minutes each, observations might be recorded every 5 seconds. Should there be, for example, six satellites during each occupation, then approximately 360 triple difference observations can be generated. One can process these triple difference carrier range measurements in L1 only, L2 only, as L1 and L2 averages, or combined in the ionospherically free linear combination. Which strategy is best is often apparent but the decision is not too critical. For example, with dual frequency receivers whose L2 carrier ranges are of the same high quality as the L1 carrier ranges, the average observable may be superior and the ionospherically free combination may be inferior for very short baselines. Roughly speaking this triple-difference solution is good to about a meter.

### DGPS PROCESSING

An alternate strategy for achieving a meter-level approximate solution is carrier-smoothed code DGPS. It is certainly possible to compute a code-range-only DGPS solution but a carrier-smoothed code solution will be superior. This is dependent somewhat on the receiver model used. In the current investigation only TurboRogues and Trimble 4000SSEs were used due to their full-wavelength dual-frequency capability even when AS has been activated. For these receivers operating in P code mode (i.e., with AS off) one can generate a carrier-smoothed code solution based on P1, P2, C/A code, or all of them independently. Furthermore, such solutions can be generated either separately for each occupation or combined as a single solution using data from all the occupations.

With state-of-the-art P code receivers it can be useful to form a combination of these solutions since the pseudorange measurements are somewhat independent (except when AS is on, in which case these particular receiver models generate an L2 code range which is dependent on L1). One can improve the first guess further by combining the triple difference and carrier-smoothed code first guesses. The DGPS first guess results (1 sigma) achieved within this investigation and based on two occupations were, roughly, 0.20 m, 0.20 m, 0.50 m in the latitudinal, longitudinal, and vertical directions, respectively.

### REMARKS

Both triple difference and DGPS first guesses were generated when processing the PK data for this paper. Although they were both quite good the DGPS solution was better and was used. Later triple difference and DGPS solutions were combined and there was a clear improvement. In particular the 1-sigma vertical error was reduced to 0.30 m. These results were achieved with L1-only code and carrier processing, using either P code or C/A code ranges. This could be refined, somewhat, by optimally combining all observables.

## ESTABLISHING THE SEARCH VOLUME

The above methods are used to generate a good approximation of the correct geodetic position. As stated, one can achieve the optimal solution by combining solutions using the resulting covariance information. In this way one could describe a tri-axial ellipsoid as the best search volume. Although this may be optimal, it is not what was done in this presentation and such improvements, while beneficial, are not too critical. For this investigation the search volume was first a vertically oriented cylinder and, later, a vertically oriented ellipse of revolution which shall be referred to as an ellipsoid. The semi-minor axis of the ellipsoid will approximate the 2-sigma horizontal uncertainty and the semi-major axis will approximate the 2-sigma vertical uncertainty. Although suboptimal, it was easy to implement and gave complete control to the operator during the processing. Search cylinders, later ellipsoids, ranged from (r=0.5, h=1.0) to (r=1.0, h=2.0) where r is the semi-minor axis of the ellipsoid or the radius of the cylinder, and h is the semi-major axis of the ellipsoid or the half-height of the cylinder.

## THE SECOND STEP: USING A SEARCH METHOD

Recall that when performing PK field operations there is no requirement for maintaining continuous tracking from mark to mark such as was the case with the original kinematic GPS technique or the antenna exchange method. This requirement for continuous tracking has been significantly reduced for the newer OTF kinematic GPS survey method as well.

Thus, in general, it is assumed that "between-occupation" cycle slips may occur for cases where there was more than one occupation and where a satellite pair was common between occupations. Of course cycle slips can also occur (and satellites may rise or set) "during" any of the brief occupations.

The starting point for both of the strategies below is the approximate solution generated during the first-step process discussed above. The following discussion assumes TurboRogue or Trimble 4000SSE observations available when AS is on.

## THE AMBIGUITY FUNCTION METHOD (AFM)

This strategy, similar to the one presented in the 1991 report referenced earlier, is the primary processing method of this report. It does not attempt, at least initially, to restrict positional candidates to lanes. Instead a very dense spatial grid (e.g., 2 cm) is searched within the defined search volume. At each grid point candidate, the L1 and/or L2 fractional phase carrier observations are compared with the fractional phase carrier observations generated from a model based on the grid candidate's coordinates. The maximum score which can be attained by a grid point is identical to the number of single difference (i.e., two receivers, one satellite) observations. When a candidate scores among the top few hundred it is saved for later evaluation and possibly for further processing. All scores are normalized so that the maximum theoretical score is 100%. A candidate is accepted as the correct position if its score is reasonable (e.g., about 95% for 1 km baselines to 80% for 15 km baselines) and if it is at least 5% greater than all others. This strategy does not require common satellites in separate occupations and generally benefits from longer time intervals between occupations. This method works moderately well based on a single occupation and very well based on two or more occupations. For two occupations a 3 to 4 hour time interval between occupations is recommended to provide the best satellite geometry consistent with a regular working day. If one is not restricted to a normal 8-hour workday then any time interval between occupations which maximizes the change in geometry is fine (one must avoid, however, the similar geometry period of subsequent days). In general 3 to 21 hours should be fine. Theoretically, the second occupation can be made days, weeks, months, or years later.

It should be noted that an hour or less separation between occupations was once promoted to be consistent with the earlier processing software which exploited satellite commonality. In effect the original PK processing software depended on common satellites and fixing the "long cycle slip" was an important aspect of the method. Today PK processing has been generalized and does not depend on satellite commonality among occupations. Furthermore the new processing software performs satisfactorily for even a single occupation -- provided there is sufficient geometry in the occupation. It should also be noted that the data sets used in this study often did not satisfy the preferred 3 to 4 hour time interval but were used because it was convienient to do so.

The ambiguity function method has been described before (Counselman and Gourevitch 1981; Remondi 1984, Remondi 1991). Suppose one of the positional grid candidates is $\vec{r}$, the L1 and L2 single difference carrier phases in fractional cycles are $\Phi_1^k$ and $\Phi_2^k$, and that $\rho^k$ is the modeled range between $\vec{r}$ and satellite k in meters. We seek to find the $\vec{r}$ which maximizes the following function known as the ambiguity function:

$$f(\vec{r}) = \sum_{epochs} \left( \left| \sum_{sats} e^{j\left(\Phi_1^k - \frac{\rho^k}{\lambda_1}\right)} \right| + \left| \sum_{sats} e^{j\left(\Phi_2^k - \frac{\rho^k}{\lambda_2}\right)} \right| \right)$$

An important aspect in the implementation of this equation is the computational algorithm (i.e., how it is coded). One needs to use great care to avoid all duplicative computations and to remove all calls to functions so that what remains are a few loops and branches and the only operators are the four arithmetic ones (i.e., +, -, *, /). In particular calls to math functions such as sine, cosine, square root, etc. have been eliminated.

Shown below is a benchmark case which was run on an HP 730 workstation. This computer is 2 to 3 times faster than a 66 mHz 486 and roughly the same as the 66 mHz Intel Pentium.

BENCHMARK CASE:

| | |
|---|---|
| Occupations | : 2 |
| Separation | : 1.25 hours |
| Grid points searched | : $101^3$ |
| Grid spacing | : 2 cm |
| Observations | : 286 |
| Computational units | : $286*101^3$ = 294,666,086 |
| Total time | : 41 seconds |
| Effective per unit time | : 139 nanoseconds |

What the effective per unit time does not reflect is that not all grid points are processed at all observation times. After approximately 15 measurements a decision is made (thereafter), for each $\vec{r}$, to quit or proceed (i.e., process the remaining observations) depending on how well the data and the model agreed thus far. If at any time after 15 measurements a grid position is scoring worse than 65% that grid point will be eliminated. This is conservative in that it requires many observations to disagree before the point is eliminated and not just a single observation. This protection is built in for the case where we have the correct grid point but a few very poor phase measurements.

With a normal set of PK observations, based on two occupations, a 2 cm grid is not necessary (at least not on the first pass) and a 5 cm grid is often adequate. It is important to note that if the grid size is much larger than 5 cm there is a risk of missing the correct point. With a 5 cm grid the above processing was accomplished over a 2 meter cube in just 3 seconds. Once the correct peak is found one can perform a refined search (e.g., 1 cm grid) over a decimeter cube search volume -- also in seconds.

This case was presented as a benchmark case. In practice the quit parameters (15 observations and 65%) above can be adjusted and the search cube can be, instead, a vertically oriented cylinder or ellipsoid. These factors alone can speed up the overall time by a factor of 15 and the effective per unit time by a factor of 2.

The probability of finding the correct solution within a 2-meter cube is only somewhat better than of finding it in a correctly proportioned ellipsoid/cylinder oriented in the vertical direction and proportioned according to positional uncertainties of the first guess. An (r=0.5, h=1.0) cylinder has less volume by a factor of 5.09 than a 2.0-meter cube. For an ellipsoid this factor is about 7.5. Using this cylinder the search required only 12.0 seconds based on a 2 cm grid spacing. A somewhat larger cylinder (r=1.0, h=2.0) was searched in 75 seconds using a 2 cm spacing. There should be little need to search a cylinder of much greater volume than this. Using a 5 cm grid spacing this decreases to 5 seconds but would require a second search which would take additional seconds. With the state-of-the-art receivers used in this study, cylinders/ellipsoids ranging between (r=0.25, h=0.50) to (r=0.75, h=1.50) are reasonable depending on conditions. Typical peak values over, for example, a 5-kilometer baseline are 90% to 99%. If there is sufficient data and the correct position falls outside the specified search volume, a peak value such as 75% might result. In this case a larger search volume would be specified and a new run would be made.

## AMBIGUITY RESOLUTION USING TRIAL POSITION (ARUTP)

This search method is similar to the one above. Here, also, only the fractional phase portion of the carrier ranges are used during the second-step processing. A positional grid like that used in AFM processing is used; however the grid spacing, particularly for the shortest baselines, might be 12 cm instead of 3 cm -- resulting in a factor of 64 fewer positions to evaluate (this is explained below). For longer baselines (e.g., 40 km) the grid spacing might be reduced to, say, 3 cm. With this scheme one uses the candidate grid position to create unambiguous double difference carrier ranges for both L1 and L2. This explains the name given to this method: Ambiguity Resolution Using Trial Position (ARUTP). After creating unambiguous carrier ranges without cycle slips one can perform an integer-fixed double difference least squares procedure on L1, L2, and/or the ionospherically free linear combination of L1 and L2.

Thus we start with the L1 and L2 fractional phase observations from, for example, two occupations. (However, any number of occupations, including just one, is allowed.) We start with a candidate $\vec{r}$. We compute the modeled L1 and L2 carrier ranges from $\vec{r}$ to the satellite and compare these with the respective data. If $\vec{r}$ is near to the correct position we will correctly compute the missing integer ambiguities for all L1 and all L2 double difference observations. If $\vec{r}$ is far from the correct position incorrect integer ambiguities will be computed. With all fractional-phase carrier ranges now converted to unambiguous carrier ranges, for both L1 and L2, the least squares procedure can be performed where multiple iterations and outlier editing is valid.

Unlike the AFM solution, which does not alter the grid coordinates, ARUTP does alter them. There are some advantages to this approach. First the grid is formed on a positional basis (and, like AFM, this grid is not hurt by poor geometry) and altered based on all satellites, not just four as in methods where the grid points are three integer lanes. No single measurement need be trusted in the formation of the grids as is the case for other methods. Admittedly this could be overcome partially in these other methods. In fact, this methodology has been applied to the OTF initialization problem reducing its vulnerability to the vageries of GDOP and reducing the need to trust a single phase measurement. A previously stated advantage of this method over the AFM is the search grid can be very coarse for short baselines. It might, however, be similarly spaced to AFM for longer baselines. This method should apply to baselines somewhat longer than those appropriate for AFM processing. Another advantage to this method is the solution is definitive and does not require a refinement as might be the case with the AFM. Finally this method can yield directly an ionosperically free double difference solution. This can be achieved with AFM processing as well but requires additional steps.

## FIRST STEP RESULTS

The first step results are extremely important to highly-reliable, highly-efficient PK methodology. We want to minimize the 95%-probability search volume (i.e., the search volume which has a 95% likelihood of containing the correct position). If we can reduce the 95% search volume then we not only reduce the processing time but, far more importantly, we eliminate candidates which in a greater search volume could be attractive alternate (but incorrect) candidates -- possibly making unclear the correct solution.

Tables 1a. and 1b. below represent the first guess results for a NGS PK survey done in South Carolina on Nov. 23, 1992 (day of year: 328). The typical time interval between occupations was 1.5 hours. The 12 baselines were measured using Trimble 4000SSE receivers in P-code mode. All values are given in meters. These tables present the mean of all the errors from all the baselines (for each component) along with standard deviations from these means for all three baseline components. The first three main columns give the XYZ results while the last column gives the North, East, and Up results for the DGPS solutions (the DGPS solutions were used as input for the search methods). Since there are several baselines which are meaned here, the reader should pay particular attention to the standard deviations. Note the differences in the standard deviations for the triple differences versus the DGPS solutions, and the differences between the one-occupation and two-occupation cases.

Table 1a. -- First guess results for 36 one-occupation cases, Trimble 4000SSE, P-code mode, Day 328

| | Triple L1 (m) | | Triple L2 (m) | | OTFDGPS (m) | | | OTFDGPS (m) | |
|---|---|---|---|---|---|---|---|---|---|
| | Mean | StdDev | Mean | StdDev | Mean | StdDev | | Mean | StdDev |
| X | -0.26 | 1.27 | -0.08 | 1.25 | -0.02 | 0.24 | N | 0.00 | 0.32 |
| Y | -0.06 | 0.89 | 0.12 | 0.79 | -0.26 | 0.68 | E | -0.05 | 0.24 |
| Z | -0.08 | 0.43 | -0.02 | 0.42 | 0.05 | 0.65 | U | 0.34 | 0.76 |

Table 1b. -- First guess results for 36 two-occupation cases, Trimble 4000SSE, P-code mode, Day 328

| | Triple L1 (m) | | Triple L2 (m) | | OTFDGPS (m) | | | OTFDGPS (m) | |
|---|---|---|---|---|---|---|---|---|---|
| | Mean | StdDev | Mean | StdDev | Mean | StdDev | | Mean | StdDev |
| X | -0.24 | 0.78 | -0.10 | 0.41 | -0.02 | 0.16 | N | 0.01 | 0.23 |
| Y | -0.20 | 0.51 | -0.01 | 0.26 | -0.28 | 0.48 | E | -0.05 | 0.16 |
| Z | -0.01 | 0.26 | 0.04 | 0.21 | 0.04 | 0.52 | U | 0.33 | 0.51 |

Tables 1c. and 1d. below represent the first guess results for a NGS PK survey done in South Carolina on Nov. 24, 1992 (day of year: 329). The 13 baselines were measured using Trimble 4000SSE receivers in P-code mode. The units and the column headings are the same as in tables 1a. and 1b. Again, note the differences between the one-occupation cases and the two-occupation cases.

Table 1c. -- First guess results for 38 one-occupation cases, Trimble 4000SSE, P-code mode, Day 329

| | Triple L1 (m) | | Triple L2 (m) | | OTFDGPS (m) | | | OTFDGPS (m) | |
|---|---|---|---|---|---|---|---|---|---|
| | Mean | StdDev | Mean | StdDev | Mean | StdDev | | Mean | StdDev |
| X | -0.12 | 1.36 | -0.04 | 1.21 | 0.00 | 0.39 | N | 0.09 | 0.32 |
| Y | 0.19 | 0.93 | 0.26 | 1.27 | 0.12 | 0.66 | E | 0.00 | 0.31 |
| Z | 0.03 | 0.49 | 0.01 | 0.44 | 0.03 | 0.55 | U | -0.01 | 0.99 |

Table 1d. -- First guess results for 37 two-occupation cases, Trimble 4000SSE, P-code mode, Day 329

| | Triple L1 (m) | | Triple L2 (m) | | OTFDGPS (m) | | | OTFDGPS (m) | |
|---|---|---|---|---|---|---|---|---|---|
| | Mean | StdDev | Mean | StdDev | Mean | StdDev | | Mean | StdDev |
| X | -0.09 | 0.65 | 0.07 | 0.72 | 0.00 | 0.27 | N | 0.08 | 0.23 |
| Y | 0.06 | 0.33 | 0.02 | 0.41 | 0.11 | 0.41 | E | 0.04 | 0.21 |
| Z | 0.02 | 0.24 | 0.05 | 0.28 | 0.03 | 0.40 | U | -0.01 | 0.79 |

Tables 2a. and 2b. below show Trimble 4000SSE X mode results based upon a NGS/Corps of Engineers (COE) /John E. Chance survey performed on December 18, 1992 (day of year: 353) in Louisiana. Two-baselines were measured. There were six occupations of the two rover sites.

Table 2a. -- First guess results for 12 one-occupation cases, Trimble 4000SSE, X mode, Day 353

| | Triple L1 (m) | | Triple L2 (m) | | OTFDGPS (m) | | | OTFDGPS (m) | |
|---|---|---|---|---|---|---|---|---|---|
| | Mean | StdDev | Mean | StdDev | Mean | StdDev | | Mean | StdDev |
| X | -0.08 | 0.31 | 0.00 | 0.35 | -0.08 | 0.21 | N | -0.03 | 0.22 |
| Y | -0.03 | 0.59 | 0.05 | 0.62 | -0.26 | 0.35 | E | -0.06 | 0.20 |
| Z | -0.01 | 0.19 | -0.05 | 0.18 | 0.13 | 0.29 | U | 0.30 | 0.40 |

Table 2b. -- First guess results for 10 two-occupation cases, Trimble 4000SSE, X mode, Day 353

| | Triple L1 (m) | | Triple L2 (m) | | OTFDGPS (m) | | | OTFDGPS (m) | |
|---|---|---|---|---|---|---|---|---|---|
| | Mean | StdDev | Mean | StdDev | Mean | StdDev | | Mean | StdDev |
| X | 0.10 | 0.18 | -0.06 | 0.23 | -0.13 | 0.11 | N | -0.05 | 0.14 |
| Y | 0.18 | 0.38 | -0.02 | 0.34 | -0.10 | 0.24 | E | -0.12 | 0.10 |
| Z | -0.07 | 0.06 | -0.09 | 0.08 | 0.01 | 0.24 | U | 0.10 | 0.30 |

Note that the overall results in tables 1 are worse than those in tables 2 in spite of the fact that table 1 presents P code results. The reasons for the somewhat inferior results are primarily three: (1) the table 2 occupations were much longer (e.g., 10 minutes vs 3 minutes); (2) there were more satellites used in table 2 (e.g., 6-8 vs 4-6); and (3) the South Carolina results presented in table 1 were from a survey with vegetation and obstructions whereas the table 2 Louisiana survey was in an open area. The 25 baselines from table 1 ranged from 3 to 15 kilometers. The baselines from table 2 are 17 kilometers long. The time intervals between occupations varied from 30 minutes to 3 hours.

It is important to note that the carrier smoothed DGPS solution and the triple difference solutions are all very good. For the second-step results, presented later, the DGPS solution was always applied as a first guess. Nevertheless the triple difference results are usually excellent and tend to be rather independent from the DGPS results. It is clear that the optimal combination of triple difference results and DGPS results is superior to either one. It should be noted that in earlier processing, not reported here, the triple difference first guess was applied.

A consistent result is that the triple difference solutions tend to be best in the z-component and worst in the x-component. The x component, here, is approximately longitudinal. This contrasts with the DGPS results which tend to be superior horizontally and inferior vertically. Based on these data the combined triple difference L1 and DGPS solution is better and will continue to be investigated. On the other hand, based on these data, the "independent" P1-Code and P2-Code DGPS results were correlated so that the combination solution did not show much improvement. The same remark holds for the L1 and L2 triple difference solutions.

In tables 1a through 1d a 3-minute occupation was typical. One can see from the two-occuption results that a reasonable search cylinder is (0.75, 1.50). The search volume should be defined so that it includes the correct solution roughly 95% of the time. Recall that if occasionally the correct solution is not within the search volume a larger volume can be defined.

In tables 2a and 2b a 10-minute occupation time was typical. For the Louisiana survey all the single-occupation PK surveys were successful. For either one or two occupation surveys a satisfactory search cylinder is (0.50, 1.00). There should be no need for two ten-minute occupations, and two 5-minute occupations are more relevant. On the other hand, the single-occupation results are indeed interesting.

Tables 3a and 3b below present first guess results based upon a NGS/COE/Allen Osborne Associates survey in California October 2, 1992 (day of year: 276). The data were collected using TurboRogue receivers in P-code mode. All values are presented in meters.

Table 3a. -- First guess results for 19 one-occupation cases, TurboRogue, P-code mode, Day 276

| | Triple L1 (m) | | Triple L2 (m) | | OTFDGPS (m) | | | OTFDGPS (m) | |
|---|---|---|---|---|---|---|---|---|---|
| | Mean | StdDev | Mean | StdDev | Mean | StdDev | | Mean | StdDev |
| X | -0.04 | 0.38 | -0.12 | 0.65 | -0.07 | 0.13 | N | 0.06 | 0.11 |
| Y | 0.10 | 0.70 | 0.60 | 1.41 | -0.02 | 0.24 | E | 0.06 | 0.09 |
| Z | 0.11 | 0.24 | 0.13 | 0.43 | 0.10 | 0.12 | U | 0.00 | 0.26 |

Table 3b. -- First guess results for 14 two-occupation cases, TurboRogue, P-code mode, Day 276

| | Triple L1 (m) | | Triple L2 (m) | | OTFDGPS (m) | | | OTFDGPS (m) | |
|---|---|---|---|---|---|---|---|---|---|
| | Mean | StdDev | Mean | StdDev | Mean | StdDev | | Mean | StdDev |
| X | -0.08 | 0.20 | -0.20 | 0.39 | -0.06 | 0.10 | N | 0.05 | 0.08 |
| Y | 0.00 | 0.47 | 0.26 | 0.76 | -0.03 | 0.18 | E | -0.04 | 0.05 |
| Z | 0.03 | 0.12 | 0.08 | 0.21 | 0.08 | 0.09 | U | 0.10 | 0.21 |

Tables 4a and 4b below show first guess results based upon a NGS/COE/Allen Osborne Associates survey performed in California on October 1, 1992 (day of year: 275). The data were collected using TurboRogue receivers operating in X mode.

Table 4a. -- First guess results for 26 one-occupation cases, TurboRogue, X mode, Day 275

| | Triple L1 (m) | | Triple L2 (m) | | OTFDGPS (m) | | | OTFDGPS (m) | |
|---|---|---|---|---|---|---|---|---|---|
| | Mean | StdDev | Mean | StdDev | Mean | StdDev | | Mean | StdDev |
| X | -0.01 | 0.50 | -0.10 | 0.96 | 0.09 | 0.21 | N | 0.17 | 0.25 |
| Y | 0.05 | 0.39 | 0.61 | 1.39 | 0.32 | 0.69 | E | -0.07 | 0.28 |
| Z | 0.00 | 0.26 | -0.30 | 0.81 | 0.01 | 0.24 | U | 0.00 | 0.68 |

Table 4b. -- First guess results for 20 two-occupation cases, TurboRogue, X mode, Day 275

| | Triple L1 (m) | | Triple L2 (m) | | OTFDGPS (m) | | | OTFDGPS (m) | |
|---|---|---|---|---|---|---|---|---|---|
| | Mean | StdDev | Mean | StdDev | Mean | StdDev | | Mean | StdDev |
| X | -0.08 | 0.21 | -0.15 | 0.50 | 0.09 | 0.17 | N | 0.19 | 0.19 |
| Y | -0.02 | 0.19 | 0.24 | 0.96 | 0.33 | 0.52 | E | -0.09 | 0.17 |
| Z | 0.02 | 0.16 | -0.03 | 0.53 | 0.01 | 0.16 | U | -0.26 | 0.51 |

For both tables 3 and 4 the surveys were carried out in an open area. The duration of the occupations were just 80-120 seconds. There were typically 7 or 8 satellites. The baseline length is 7 km in all cases. There was typically a 2 to 3 hour time separation between occupations.

The TurboRogue P-code DGPS results shown in table 3 are excellent. Under these conditions a search cylinder defined by (0.25, 1.00) might be adequate. Although these results are impressive, the reader is warned not to compare them directly with the table 1 Trimble 4000SSE P-Code results. The observing conditions for the TurboRogue survey were ideal, but not for the Trimble survey.

The X-mode DGPS and triple-difference results of table 4 are also impressive. They are very similar to the Trimble X mode results presented in table 2a. The TurboRogue survey had the advantage of more satellites while the Trimble 4000SSE survey had the advantage of a total occupation time of 600 seconds versus 100 seconds for the TurboRogue.

In summary, both the TurboRogue and the Trimble 4000SSE achieved excellent first guess DGPS and triple difference solutions using either P-code mode or X mode observations.

Under good visibility conditions, and assuming two 3-minute occupations, search cylinders on the order of (0.5, 1.0) are realistic for X mode operations. We are encouraged to believe, based on these results, that an optimized combination of observables, or at least solutions based on different observables, can reduce this significantly. The table 3 P-code results clearly show the potential and the advantage of P code measurements.

As a final example we include P-code carrier-smoothed DGPS results over a 37 km static baseline which were obtained using data collected during a NGS/COE/Allen Osborne Associates survey performed in California on September 29, 1992 (day of year: 273). For both P1 and P2 the L1 carrier was used to smooth the code. For 36 cases, 26 epochs (250 seconds) of observations were mapped to the earliest epoch. Table 5 presents the differences from the truth for the mean DGPS position along with the standard deviations from the mean for this TurboRogue data. All values are presented in units of meters for North, East, and Up. The three main columns show that positions were computed using: P1 code and L1 carrier, P2 code and L1 carrier, and an average of all 72 cases using both P1 and P2. This shows that there is an advantage to using both the P1 and P2 data. The reader should also note that similar results are achieved when the receiver is in motion and that the data shortly before and shortly after the static occupation periods of a PK survey may be exploited in achieving the DGPS first guess.

Table 5. -- First guess results for 36 one-occupation cases, TurboRogue, P-code, Day 273

| | P1 only (m) | | P2 only (m) | | P1 + P2 (m) | |
|---|---|---|---|---|---|---|
| | Mean | StdDev | Mean | StdDev | Mean | StdDev |
| N | 0.23 | 0.18 | -0.18 | 0.18 | -0.21 | 0.15 |
| E | 0.04 | 0.08 | 0.08 | 0.08 | 0.06 | 0.07 |
| U | 0.21 | 0.39 | 0.18 | 0.34 | 0.19 | 0.31 |

In the next section we present the second step processing results. Here accuracy statements will be deemphasized. In general single-occupations, when successful are not as accurate as two- or three- occupation PK surveys. For two-occupation surveys one expects 1-2 cm horizontally and 2-4 cm vertically. Here accuracy is deemphasized because ground truth was not available for all of the surveys, and because the more important question is whether or not the correct lane or correct ambiguity function peak was isolated. We will later on, however, present an example of the repeatability one can expect from one-occupation AFM versus two-occupation AFM.

Table 6. -- AFM results (peaks given in units of %), Trimble 4000SSE, P-code mode, Day 328

| | | OCCUPATIONS USED | | | | | | |
|---|---|---|---|---|---|---|---|---|
| From To | | A | B | C | AB | AC | BC | ABC |
| GASS 4012 | 1st Peak: | 88.89 | 98.04 | 97.91 | 90.07 | 87.84 | 95.09 | 89.40 |
| P-code | 2nd Peak: | 88.52 | 94.79 | 95.57 | 77.77 | 83.89 | 89.45 | 79.84 |
| 9.2 km. | Outcome | QF | QS | QS | CS | CS | CS | CS |
| GASS CANN | 1st Peak: | 87.52 | 95.07 | 91.55 | 84.77 | 85.35 | 86.49 | 84.91 |
| P-code | 2nd Peak: | 86.16 | 91.66 | 91.47 | 81.72 | 82.83 | 84.18 | 79.71 |
| 10.5 km. | Outcome | QF | QS | QF | CS | QS | QS | CS |
| GASS ROEE | 1st Peak: | 96.12 | 97.36 | 95.81 | 95.82 | 95.86 | 96.00 | 94.63 |
| P-code | 2nd Peak: | 95.33 | 94.76 | 93.69 | 81.31 | 84.91 | 79.32 | 74.30 |
| 7.6 km. | Outcome | QS | QS | QS | CS | CS | CS | CS |
| GASS HOLL | 1st Peak: | 97.00 | 87.42 | 96.26 | 92.28 | 91.71 | 91.77 | 91.31 |
| P-code | 2nd Peak: | 91.31 | 86.06 | 93.29 | 76.44 | 74.94 | 78.34 | 70.61 |
| 11.7 km. | Outcome | CS | QF | QS | CS | CS | CS | CS |
| GASS DORM | 1st Peak: | 96.20 | 95.08 | 99.21 | 92.54 | 93.92 | 95.23 | 92.24 |
| P-code | 2nd Peak: | 95.22 | 91.93 | 93.36 | 85.06 | 87.69 | 79.05 | 76.90 |
| 8.2 km. | Outcome | QS | QS | CS | CS | CS | CS | CS |
| GASS SHEL | 1st Peak: | 87.87 | 97.85 | 99.89 | 89.80 | 88.89 | 96.25 | 90.89 |
| P-code | 2nd Peak: | 86.79 | 94.99 | 99.81 | 78.17 | 88.08 | 87.54 | 81.29 |
| 9.5 km. | Outcome | QF | QS | QF | CS | QF | CS | CS |
| GASS 2304 | 1st Peak: | 94.87 | 93.65 | 95.96 | 87.50 | 89.88 | 91.21 | 87.49 |
| P-code | 2nd Peak: | 97.30 | 90.63 | 95.92 | 79.87 | 88.75 | 82.52 | 73.34 |
| 13.3 km. | Outcome | QF | QS | QS | CS | QS | CS | CS |
| GASS HSEI | 1st Peak: | 88.86 | 90.99 | 96.30 | 78.76 | 86.80 | 81.79 | 79.55 |
| P-code | 2nd Peak: | 88.58 | 88.24 | 92.69 | 73.90 | 81.11 | 76.13 | 65.96 |
| 13.7 km | Outcome | QF | QF | QF | QS | CS | CS | CS |
| GASS 2312 | 1st Peak: | 93.83 | 98.69 | 95.33 | 95.33 | 94.09 | 95.82 | 93.88 |
| P-code | 2nd Peak: | 91.14 | 98.38 | 92.17 | 81.20 | 78.21 | 85.16 | 72.83 |
| 11.1 km. | Outcome | QS | QS | QS | CS | CS | CS | CS |
| GASS 3901 | 1st Peak: | 94.06 | 97.98 | 94.74 | 92.56 | 90.82 | 96.78 | 92.29 |
| P-code | 2nd Peak: | 93.25 | 93.25 | 87.30 | 82.64 | 80.09 | 78.53 | 68.90 |
| 7.8 km. | Outcome | QF | QS | CS | CS | CS | CS | CS |
| GASS TINK | 1st Peak: | 95.80 | 98.06 | 97.05 | 96.08 | 95.17 | 96.58 | 95.96 |
| P-code | 2nd Peak: | 92.78 | 94.82 | 93.57 | 87.03 | 88.49 | 89.93 | 87.46 |
| 7.6 km. | Outcome | QS | QS | QS | CS | CS | CS | CS |
| GASS 23CR | 1st Peak: | 95.59 | 98.35 | 95.81 | 96.67 | 95.73 | 96.27 | 96.20 |
| P-code | 2nd Peak: | 92.00 | 94.19 | 87.64 | 77.12 | 80.82 | 83.97 | 71.37 |
| 4.2 km. | Outcome | QS | QS | CS | CS | CS | CS | CS |

Table 7. -- AFM results (peaks given in units of %), Trimble 4000SSE, P-code mode, Day 329

| From To | | A | B | C | AB | AC | BC | ABC |
|---|---|---|---|---|---|---|---|---|
| | | OCCUPATIONS USED | | | | | | |
| 4023 4025 | 1st Peak: | 95.74 | 95.63 | 85.96 | 94.22 | 81.13 | 85.18 | 83.87 |
| P-code | 2nd Peak: | 88.33 | 90.15 | 83.68 | 79.89 | 76.28 | 82.08 | 74.64 |
| 8.8 km. | Outcome | CS | CS | QF | CS | QS | QS | CS |
| 4023 4024 | 1st Peak: | 96.91 | 96.59 | 97.97 | 96.16 | 94.62 | 95.87 | 95.69 |
| P-code | 2nd Peak: | 93.38 | 92.86 | 93.23 | 83.13 | 79.92 | 80.79 | 73.06 |
| 4.2 km. | Outcome | QS | QS | QS | CS | CS | CS | CS |
| 4023 HARV | 1st Peak: | 91.04 | 97.69 | 94.07 | 93.96 | 91.32 | 94.94 | 92.87 |
| P-code | 2nd Peak: | 87.22 | 92.85 | 91.90 | 75.38 | 79.54 | 84.76 | 72.56 |
| 6.4 km. | Outcome | QS | QS | QS | CS | CS | CS | CS |
| 4023 PINE | 1st Peak: | 91.68 | 95.23 | 86.91 | 86.70 | 86.65 | 85.71 | 84.95 |
| P-code | 2nd Peak: | 91.64 | 91.50 | 82.00 | 80.20 | 76.95 | 74.04 | 69.17 |
| 9.9 km. | Outcome | QF | QS | QS | CS | CS | CS | CS |
| 4023 FAIT | 1st Peak: | 98.65 | 96.69 | 99.06 | 97.37 | 98.43 | 97.23 | 97.13 |
| P-code | 2nd Peak: | 95.11 | 93.02 | 96.13 | 79.14 | 84.43 | 84.62 | 74.50 |
| 2.8 km. | Outcome | QS | QS | QS | CS | CS | CS | CS |
| 4023 CAMP | 1st Peak: | 92.89 | 97.99 | 90.32 | 93.68 | 90.43 | 91.93 | 92.08 |
| P-code | 2nd Peak: | 90.72 | 94.33 | 84.43 | 81.68 | 74.90 | 73.77 | 67.72 |
| 8.4 km. | Outcome | QS | QS | QS | CS | CS | CS | CS |
| 4023 TT35 | 1st Peak: | 92.71 | 97.94 | 97.82 | 94.16 | 94.67 | 97.27 | 94.47 |
| P-code | 2nd Peak: | 88.66 | 92.77 | 95.80 | 83.16 | 78.05 | 88.95 | 74.02 |
| 6.2 km. | Outcome | QS | CS | QS | CS | CS | CS | CS |
| 4023 HENC | 1st Peak: | 93.43 | 96.21 | 85.41 | 89.76 | 84.94 | 87.93 | 86.17 |
| P-code | 2nd Peak: | 92.50 | 94.39 | 80.89 | 81.34 | 73.63 | 75.89 | 68.23 |
| 10.0 km | Outcome | QF | QS | QS | CS | CS | CS | CS |
| 4023 PAIG | 1st Peak: | 96.02 | 94.32 | 97.75 | 94.80 | 95.34 | 95.59 | 94.88 |
| P-code | 2nd Peak: | 92.45 | 89.07 | 92.41 | 81.19 | 77.91 | 79.12 | 74.34 |
| 3.6 km. | Outcome | QS | CS | CS | CS | CS | CS | CS |
| 4023 MCCA | 1st Peak: | 96.05 | 98.13 | 88.75 | 96.28 | 95.84 | 96.16 | 96.25 |
| P-code | 2nd Peak: | 93.31 | 92.93 | 87.31 | 81.47 | 81.80 | 81.24 | 74.92 |
| 5.6 km. | Outcome | QS | CS | QF | CS | CS | CS | CS |
| 4023 BLK2 | 1st Peak: | 89.66 | 96.38 | 96.34 | 91.91 | 91.26 | 96.29 | 93.58 |
| P-code | 2nd Peak: | 88.67 | 93.33 | 93.26 | 73.89 | 75.83 | 74.85 | 70.03 |
| 6.6 km. | Outcome | QS | QS | QS | CS | CS | CS | CS |
| 4023 R051 | 1st Peak: | 89.76 | 94.38 | 86.55 | 87.94 | 92.24 | 94.40 | 90.30 |
| P-code | 2nd Peak: | 88.34 | 88.37 | 85.05 | 77.77 | 81.96 | 84.24 | 71.28 |
| 13.2 km. | Outcome | QF | CS | QF | CS | CS | CS | CS |
| 4023 SHIR | 1st Peak: | 89.40 | 94.27 | | 87.11 | | | |
| P-code | 2nd Peak: | 84.47 | 93.15 | | 72.23 | | | |
| 13.8 km. | Outcome | QS | QF | | CS | | | |

## AFM RESULTS

In this section the search results based on AFM processing are presented. In general we intend to emphasize two-occupation results and deemphasize single-occupation results or results based on more than two occupations. Single-occupation results based on AFM are mixed but are good under the right conditions. Single-occupation "On-The-Fly" results mentioned elsewhere (Remondi, 1993) are significantly better. AFM results based on three or more occupations are normally extremely good and possibly overkill. In this report we classify the outcome of a search using four labels: CS, QS, QF, and CF. CS means "Complete Success"; QS means "Qualified Success", i.e. the position is correct but the statistics are inconclusive; QF means "Qualified Failure" meaning the position is incorrect and the statistics verify that it should not be trusted; and CF means "Complete Failure" where the statistics indicate a good position but the solution is incorrect. Both QS and QF are benign failures. Our processing parameters need to be selected so that a CF result is extremely rare. Accuracy numbers are not provided here since all "CS" or "QS" results imply centimeter-level accuracies (c.f. Table 12).

### TRIMBLE 4000SSE P-CODE RESULTS (DAY 328, 1992)

Table 6, above, presents the results of AFM processing for day 328 of the South Carolina PK survey using Trimble 4000SSE receivers operating in P-code mode. This is the same data presented earlier for the first guess. Occupations were of 3 to 4 minutes duration. The survey is a real-world survey in that there were substantial obstructions and opportunities for multipath. A 15-second epoch spacing and a 15-degree elevation mask were applied. Typically, four to six satellites were tracked. The time interval between occupations was on the order of 1.5 hours -- far less than the 3 to 4 hours we now recommend. Broadcast orbital data were used for this day and for day 329 below.

Twelve baselines were processed from station GASS. The two-occupation results (given in the columns AB, AC, and BC) are of most interest at this time. Of the 36 two-occupation cases: 31 met the statistical requirements (CS) and were correct, 4 were correct (QS) but the statistical indicators were not adequate, and 1 was wrong (QF) but the statistical indicators implied inconclusive results. Thus these last 5 baselines represent benign failures and need to be resurveyed. There were no complete failures (CF). As a footnote, two of the CS baselines required more complex procedures to achieve CS status. The two-occupation results in Table 6 show that, most of the time, we were completely successful in determining the correct peak. These results are very good but are the worst of those to be presented. It has been verified that processing with precise orbital data would have shown only marginal improvement over these results; poor geometry, short occupation times, and numerous obstructions were the primary causes leading to the results shown in table 6.

### TRIMBLE 4000SSE P-CODE RESULTS (DAY 329, 1992)

Table 7, above, is similar to Table 6 but presents the results for Day 329. The specifics of the survey data on day 329 are the same as those on day 328. Broadcast orbital data was used. Thirteen baselines were processed from station 4023. Again, the two-occupation results in columns AB, AC, and BC are of primary interest here. Of the 37 two-occupation cases, 35 met the 5% requirement (CS) and two did not. The latter two did achieve the correct answer, however (QS).

Table 8. -- AFM results (peaks given in units of %), TurboRogue, P-code mode, Day 275

| | | OCCUPATIONS USED | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| From To | | A | B | C | D | AB | AC | AD | ABCD |
| M703 704A | 1st Peak: | 99.26 | 98.78 | 95.99 | 98.46 | 98.37 | 96.61 | 98.13 | 96.61 |
| P-code | 2nd Peak: | 94.76 | 88.59 | 87.13 | 91.34 | 86.39 | 79.50 | 84.35 | 74.33 |
| 6.6 km. | Outcome | QS | CS | CS | CS | CS | CS | CS | CS |
| M703 704B | 1st Peak: | 98.17 | 97.64 | 97.45 | 97.64 | 97.98 | 97.11 | 96.84 | 97.65 |
| P-code | 2nd Peak: | 88.56 | 85.84 | 85.42 | 91.71 | 90.53 | 76.31 | 76.90 | 76.08 |
| 6.6 km. | Outcome | CS | CS | CS | CS | CS | CS | CS | CS |
| M703 704C | 1st Peak: | 98.44 | 95.74 | 96.83 | 98.78 | 96.48 | 95.90 | 97.89 | 95.99 |
| P-code | 2nd Peak: | 91.20 | 91.16 | 82.78 | 93.27 | 79.43 | 73.41 | 79.63 | 76.69 |
| 6.6 km. | Outcome | CS | QS | CS | CS | CS | CS | CS | CS |
| M703 704D | 1st Peak: | 97.71 | 95.41 | 98.17 | 98.92 | 95.62 | 96.36 | 97.33 | 96.95 |
| P-code | 2nd Peak: | 90.65 | 90.20 | 82.30 | 97.08 | 77.31 | 77.24 | 82.14 | 74.85 |
| 6.6 km. | Outcome | CS | CS | CS | QS | CS | CS | CS | CS |
| M703 704E | 1st Peak: | 98.74 | 95.83 | 97.30 | | 96.29 | 97.70 | | 96.70 |
| P-code | 2nd Peak: | 88.77 | 90.96 | 92.94 | | 76.87 | 77.89 | | 72.60 |
| 6.6 km. | Outcome | CS | QS | QS | | CS | CS | | CS** |

** For the last station (704E) there were only A, B, and C occupations.

TurboRogue P-CODE RESULTS (DAY 275/SESSION B, 1992)

Table 8 above presents the results of the AFM processing for October 1, 1992 (day of year: 275) of a Mountain View, California PK survey done using TurboRogue receivers operating in P-Code mode. Occupations were 80-120 seconds in duration. This survey was a test survey performed in an open area mostly free of obstructions and reflective objects. The time interval between occupations was typically 2-3 hours.

A 10-second epoch spacing and a 15-degree elevation mask were applied. Typically 5 to 7 satellites were tracked -- this is more than in the South Carolina surveys presented above.

Five baselines were processed with the five unknown stations being close to one another. The two-occupation results are in columns AB, AC, and AD. Here occupation A was used in each two-occupation case (no BC or CD cases) since the B, C, and D occupations were too close together to be paired productively for PK operations. All of the 14 two-occupation cases were completely successful (CS).

TurboRogue CROSS CORRELATION RESULTS (DAYS 275, 276 SESSION A, 1992)

Table 9 shown below is similar to table 8 except that the receivers were intentionally set to operate in X mode. The same 5 monuments were occupied as in the P code case shown in table 8. The two-occupation results are presented in columns AB, AC, and AD. All of the 13 two-occupation cases were completely successful. Table 10 below shows the results of a shorter survey, again performed over the same 5 monuments used in table 9. All of the 7 available two-occupation cases were completely successful.

Table 9. -- AFM results (peaks given in units of %), TurboRogue, X mode, Day 275

| | | OCCUPATIONS USED | | | | | | |
|---|---|---|---|---|---|---|---|---|
| From To | | A | B | C | AB | AC | AD | ABC |
| M703 704A | 1st Peak: | 99.36 | 98.53 | 96.98 | 98.70 | 95.92 | 96.91 | 96.55 |
| Cross Corr. | 2nd Peak: | 93.98 | 88.86 | 88.27 | 79.38 | 79.92 | 84.20 | 75.39 |
| 6.6 km. | Outcome | CS | CS | CS | CS | CS | CS | CS |
| M703 704B | 1st Peak: | 98.18 | 98.80 | 98.99 | 98.29 | 98.34 | 98.64 | 98.59 |
| Cross Corr. | 2nd Peak: | 91.18 | 88.49 | 97.20 | 89.18 | 92.92 | 90.68 | 88.32 |
| 6.6 km. | Outcome | CS | CS | QS | CS | CS | CS | CS |
| M703 704C | 1st Peak: | 99.37 | 97.97 | 98.44 | 98.09 | 98.99 | 98.14 | 98.05 |
| Cross Corr. | 2nd Peak: | 93.81 | 91.16 | 93.74 | 90.22 | 88.49 | 84.74 | 88.23 |
| 6.6 km. | Outcome | CS | CS | QS | CS | CS | CS | CS |
| M703 704D | 1st Peak: | 99.08 | 90.13 | 98.47 | 94.46 | 98.28 | 93.71 | 95.24 |
| Cross Corr. | 2nd Peak: | 92.81 | 85.98 | 90.26 | 85.14 | 85.98 | 79.27 | 83.30 |
| 6.6 km. | Outcome | CS | QS | CS | CS | CS | CS | CS |
| M703 704E | 1st Peak: | 98.49 | 95.76 | | 97.15 | | | |
| Cross Corr. | 2nd Peak: | 90.64 | 87.70 | | 83.10 | | | |
| 6.6 km. | Outcome | CS | CS | | CS** | | | |

** For the last station (704E) there were only A and B occupations.

Table 10. -- AFM results (peaks given in units of %), TurboRogue, X mode, Day 276

| | | OCCUPATIONS USED | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| From To | | A | B | C | D | AB | AC | AD | ABCD |
| M703 704A | 1st Peak: | 95.93 | 98.16 | 97.88 | 98.90 | 97.38 | 96.81 | 96.27 | 96.37 |
| Cross Corr. | 2nd Peak: | 88.87 | 87.92 | 92.14 | 95.33 | 74.72 | 80.31 | 77.89 | 72.67 |
| 6.6 km. | Outcome | CS | CS | CS | QS | CS | CS | CS | CS |
| M703 704B | 1st Peak: | 95.50 | 97.25 | | | 97.31 | | | |
| Cross Corr. | 2nd Peak: | 90.80 | 90.92 | | | 84.34 | | | |
| 6.6 km. | Outcome | QS | CS | | | CS | | | |
| M703 704C | 1st Peak: | 98.00 | 96.85 | | | 96.98 | | | |
| Cross Corr. | 2nd Peak: | 85.77 | 91.23 | | | 84.51 | | | |
| 6.6 km. | Outcome | CS | CS | | | CS | | | |
| M703 704D | 1st Peak: | 97.02 | 95.09 | | | 96.19 | | | |
| Cross Corr. | 2nd Peak: | 88.40 | 88.40 | | | 82.45 | | | |
| 6.6 km. | Outcome | CS | CS | | | CS | | | |
| M703 704E | 1st Peak: | 98.05 | 97.82 | | | 97.33 | | | |
| Cross Corr. | 2nd Peak: | 86.88 | 89.35 | | | 85.28 | | | |
| 6.6 km. | Outcome | CS | CS | | | CS | | | |

Note: For the last four stations there were only A and B occupations.

Table 11. -- AFM Results (peaks given in units of %), Trimble 4000SSE, X mode, Day 353

| Occupations Used | From Breaux to Rover1 | | | From Breaux to Rover2 | | |
|---|---|---|---|---|---|---|
| | 1st Peak | 2nd Peak | Outcome | 1st Peak | 2nd Peak | Outcome |
| A | 92.27 | 89.17 | QS | 93.56 | 89.04 | QS |
| B | 93.10 | 90.94 | QS | 95.67 | 87.52 | QS |
| C | 97.01 | 88.01 | CS | 86.63 | 78.44 | CS |
| D | 93.00 | 86.53 | CS | 91.69 | 84.73 | CS |
| E | 92.93 | 87.02 | CS | 95.58 | 81.19 | CS |
| F | 97.12 | 91.01 | CS | 94.13 | 85.55 | CS |
| AB | 89.17 | 78.52 | CS | 91.05 | 80.77 | CS |
| AC | 92.93 | 78.86 | CS | 87.20 | 78.83 | CS |
| AD | 91.06 | 81.71 | CS | 88.55 | 84.97 | CS |
| AE | 89.57 | 78.96 | CS | 93.73 | 73.40 | CS |
| AF | 94.19 | 74.59 | CS | 92.40 | 74.34 | CS |
| ABCDEF | 91.27 | 69.19 | CS | 88.73 | 65.20 | CS |

TRIMBLE 4000SSE CROSS CORRELATION RESULTS (DAY 353, 1992)

On December 18, 1992 (day of year: 353) John E. Chance and Associates performed a PK survey in Louisiana. Here only two monuments were used. The reference station (Breaux) was 16.9 km from the two monuments occupied by the rover receiver (Roverl and Rover2). The Trimble 4000SSE receivers were intentionally set to operate in the X mode. Table 11 above presents the AFM results for this survey. The time interval between occupations varied from 1 to 5 hours.

The epoch spacing was 5 seconds, the elevation mask applied was 15 degrees, the duration of the occupations were 5 to 7 minutes, and typically 6 to 8 satellites were tracked. The bottom part of table 11 shows that all 10 two-occupation cases were completely successful (as well as many of the one-occupation cases).

In summary, for all the experiments discussed in this report, the two-occupation results were completely sucessful 108 out of 115 times and the other seven were benign failures. More complex processing elevated two of the benign failures to complete successes. These results imply that two-occupation PK surveying is operationally viable. On the other hand there are a number of enhancements to be implemented which will increase the reliability.

## ARUTP RESULTS

At this time only the two-occupation ARUTP processing from the Trimble 4000 SSE P-Code South Carolina survey has been completed. The results are 59 CS, 12 QS, 1 QF, and 1 CF.

These results are somewhat inferior to the AFM results just presented above. On the other hand ARTUTP processing is new and not as well developed as AFM processing. It is believed that a fully developed ARUTP processing capability will be superior to AFM processing due to improvements with regards to outlier editing. One benefit from using two dissimilar processing methods is the results are somewhat different. Thus best candidates should agree and if second-best candidates do not agree they can often be eliminated which aids in the isolation of the correct candiates.

Table 12. -- AFM repeatability (compared to a three-occupation solution), Trimble 4000SSE, P-code mode, Day 328

| | | OCCUPATIONS USED | | | | | |
|---|---|---|---|---|---|---|---|
| From To | | A | B | C | AB | AC | BC |
| GASS 4012 | North (mm) | -18 | -41 | -7 | 1 | 1 | -16 |
| P-code | East (mm) | 54 | 12 | -3 | 3 | -2 | 3 |
| 9.2 km. | Up (mm) | -65 | -26 | -52 | 18 | 0 | -38 |
| GASS CANN | North (mm) | -11 | -98 | -2 | -12 | -6 | -4 |
| P-code | East (mm) | -3 | 14 | -1 | -1 | -2 | 1 |
| 10.5 km. | Up (mm) | -5 | -49 | 2 | -5 | -2 | -7 |
| GASS ROEE | North (mm) | -3 | -2 | 0 | -1 | 0 | -1 |
| P-code | East (mm) | -10 | 11 | 0 | 0 | -4 | 7 |
| 7.6 km. | Up (mm) | 15 | -6 | -36 | 6 | -6 | -4 |
| GASS HOLL | North (mm) | -6 | 5 | -31 | -2 | -3 | 0 |
| P-code | East (mm) | -17 | 1 | 4 | -4 | -1 | 1 |
| 11.7 km. | Up (mm) | 60 | 2 | -48 | 20 | -1 | -14 |
| GASS DORM | North (mm) | 24 | 1 | -8 | -1 | 2 | -5 |
| P-code | East (mm) | -46 | -16 | -4 | -8 | 7 | -4 |
| 8.2 km. | Up (mm) | -22 | 11 | -45 | 34 | 7 | -26 |
| GASS SHEL | North (mm) | -9 | -7 | 16 | -8 | 2 | 12 |
| P-code | East (mm) | -5 | 9 | -35 | 2 | -5 | 4 |
| 9.5 km. | Up (mm) | 5 | 9 | -18 | 3 | -8 | 10 |
| GASS 2304 | North (mm) | 9 | -68 | -31 | -16 | -3 | 0 |
| P-code | East (mm) | -13 | 21 | -66 | -4 | -28 | 11 |
| 13.3 km. | Up (mm) | -48 | -38 | 49 | -22 | 47 | 2 |
| GASS HSEI | North (mm) | -8 | -7 | 38 | -9 | 10 | 7 |
| P-code | East (mm) | -17 | 3 | 14 | 1 | -12 | 21 |
| 13.7 km | Up (mm) | -10 | 4 | 49 | -4 | -9 | 16 |
| GASS 2312 | North (mm) | -1 | -11 | 11 | -3 | 2 | 1 |
| P-code | East (mm) | -4 | 13 | 18 | -2 | -4 | 10 |
| 11.1 km. | Up (mm) | 4 | 10 | -17 | 3 | 2 | -12 |
| GASS 3901 | North (mm) | -13 | 23 | 7 | -9 | -1 | 8 |
| P-code | East (mm) | 27 | -6 | 1 | 4 | 2 | -1 |
| 7.8 km. | Up (mm) | 4 | 23 | 12 | -19 | -4 | 12 |
| GASS TINK | North (mm) | 0 | -9 | 7 | 0 | 2 | -5 |
| P-code | East (mm) | -4 | -3 | 17 | -2 | 1 | 0 |
| 7.6 km. | Up (mm) | 19 | -11 | -34 | 6 | -1 | -11 |
| GASS 23CR | North (mm) | 6 | 17 | -7 | 6 | -1 | -3 |
| P-code | East (mm) | 3 | 7 | -7 | 3 | -2 | 0 |
| 4.2 km. | Up (mm) | -5 | 26 | -3 | 5 | -2 | 1 |

## AFM REPEATABILITY

Table 12 above presents an example of the repeatability in millimeters that can be expected from AFM using one-occupation and two-occupation surveys. The data used is the same as that shown for the South Carolina survey in table 6. The North, East, Up results for all 12 baselines were differenced from a three-occupation solution (ABC) which was used as "truth". Considering all three components for the baselines together it is obvious that the accuracy of the two-occupation cases will be significantly better than that for the one-occupation cases. Note the excellent horizontal repeatability in the last three columns.

## SUMMARY

In this paper we presented dual frequency, full wavelength PK methodology with emphasis on two occupations of, say, 2-5 minutes where the occupations are separated by 3-4 hours. The actual data used generally did not meet the separation specification but data collected from now on will specify these greater intervals. This report is considered to be an interim report; one more research and development phase should be adequate to complete this effort. At that time a definitive report can be expected.

The first section was a presentation of processing alternatives for obtaining a good first guess position from one or two brief static occupations using either the triple difference or the carrier-smoothed DGPS technique.

This was followed by specific descriptions of the fractional phase methods AFM and ARUTP, the latter of which was introduced in this paper.

Results for first-step processing to achieve a meter-level approximate position were then presented.

Second-step processing results, to determine the definitive (cm-level) solution, were presented for AFM processing of two-occupation PK. A brief summary of preliminary ARUTP results was included.

Finally, an example of the repeatablity of AFM was given to show the importance of two-occupation surveys versus one-occupation surveys.

## CONCLUSIONS

The first conclusion is the AFM processing of two 3-minute occupations should meet operational needs if occupations are separated by at least 3 hours. More research and development is required, but we are close to achieving a satisfactory level of performance (accuracy and integrity).

The next conclusion is that ARUTP and OTF processing are promising but require further development.

The third conclusion is that one-occupation PK is promising but needs further development. In wide open areas one-occupation PK was remarkably successful. This is consistent with results reported regarding OTF processing of moving platforms at sea.

## ACKNOWLEDGEMENTS

Mr. John Lee is gratefully acknowledged for his assistance in processing the data presented in this report.

## REFERENCES


Counselman, C. C. and Gourevitch S. A. 1981: Miniature Interferometer Terminals for Earth Surveying: Ambiguity and Multipath with Global Positioning System. IEEE Transactions on Geoscience and Remote Sensing, Vol. GE-19, No. 4, October.

Remondi, B. W. (Center for Space Research, The University of Texas at Austin, Austin Texas), 1984: Using the Global Positioning System (GPS) phase observable for relative geodesy: modeling, processing, and results. Ph.D. dissertation, 360 pp. National Geodetic Information Center, NOAA, Silver Spring, MD 20910.

Remondi, B. W., 1988: Kinematic and pseudo-kinematic GPS. Proceedings of the Satellite Division's International Technical Meeting, The Institute of Navigation, Colorado Springs, CO, September 19-23, 115-121.

Remondi, B. W., 1991: Pseudo-kinematic GPS Results Using the Ambiguity Function Method. NAVIGATION, Journal of the Institute of Navigation, Vol. 38, No. 1, Spring 1991.

Remondi, B. W., 1993: "On-The-Fly" Kinematic GPS Results Using Full-Wavelength Dual-Frequency Carrier Ranges. Presented at the 49th Annual Meeting of the Institute of Navigation, Cambridge, MA, June 21-23.


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