APPLYING KINEMATIC GPS TECHNIQUES AT OUR NATION'S AIRPORTS

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ABSTRACT

Kinematic Global Positioning System (GPS) techniques have finally achieved operational status, at least in the realm of "stop and go" kinematic GPS surveying. The National Geodetic Survey (NGS) began surveying the Nation's airports using a mixture of static, kinematic, antenna swaps and pseudo-kinematic techniques. The methodologies and the associated theoretical rationale are the central theme of this paper.

INTRODUCTION

Research and development in kinematic GPS has been underway since the 1982-1983 time frame (1). Actual field testing began in early 1985 (2), (3), (4). In March 1989 the NGS began performing airport surveys using a variety of static and kinematic techniques (5). The field instructions for performing these surveys are complex and are designed for productivity, reliability, and accuracy. From March 1989 to November 1989 66 airports in Florida were surveyed during what NGS refers to as an "on-line" operational test. Each NGS kinematic survey vehicle was outfitted with a pole attached to an adjustable arm upon which a GPS antenna is mounted (4). After the vehicle is parked beside the survey monument, the pole is unlocked and placed over the mark (allowing the antenna to be) within 3-5 mm horizontally and within 1 mm vertically within a period of 20 seconds. All vehicles have poles of identical height. The NGS airport survey procedure was designed conservatively to fully experience the data gathering and data processing associated with these methods. Furthermore, the surveys were designed to ensure that success could be verified. The complete details and rationale will be given in the following discussion.

Now that this on-line test has been completed, NGS will enter into routine operations using these same methods. NGS will next conduct airport kinematic surveys in the State of Missouri. The survey design has been modified, somewhat, from that used in Florida, to increase reliability, productivity, and flexibility. These modifications will not be a major factor when a single airport is surveyed during one day since there is sufficient five-satellite visibility available to allow full redundancy. On the other hand, this becomes an important factor when attempts are made to survey two or more airports, in a single day, with these techniques (especially during the present, limited, five-satellite visibility window). The survey procedures now include options to allow the survey team to reduce occupation times and make tradeoffs between redundancy and productivity. These issues also will be elaborated below.

GPS SURVEY TECHNIQUES

This paper will be restricted to the four techniques being employed in GPS airport surveys: static, pseudo-kinematic, kinematic, and antenna-swap methods. We shall briefly review each of these methods.

Static GPS

In traditional static GPS, receivers 1 and 2 occupy geodetic monuments A and B, respectively, and they are not removed from these monuments until the static GPS survey is completed. The geodetic coordinates of mark A are normally available and those of mark B are computed using some parameter estimation method. Frequently cycle slips occur on one or more satellites. This is rarely a problem as cycle slip fixing has become automatic. A typical post-processing procedure would be to perform, sequentially, triple-difference processing, float-double-difference processing, and finally fixed-double-difference processing. Normally, these steps are performed automatically.

Pseudo-kinematic (p-k) GPS

This method is, in reality, static GPS surveying with scheduled gaps. It is called pseudo-kinematic or "false" kinematic since many observers, who have witnessed actual field operations, believe it to be a kinematic method; it is not (5). In this method the GPS receivers occupy marks A and B, simultaneously, for a 2-

to 5-minute period. After that, either receiver 1 or receiver 2, or both, will perform survey activities at different locations. After an extended time period (e.g., 40 minutes), receiver 1 returns to A and receiver 2 returns to B for another brief occupation of 2 to 5 minutes. In a p-k survey there may be more than two gaps and revisits. (In the airport surveys discussed below, the azimuth mark is revisited by the rover vehicle four times.) The post-processing is performed just as in traditional static surveying but, naturally, only those data gathered while at A and B are isolated and processed. In p-k mode lock is not required between visits to a baseline; for best results, however, any cycle slips must be fixed. Other processing techniques are possible but they will be the subject of another paper.

Kinematic GPS

The kinematic survey method has been extensively documented elsewhere (1), (5). Briefly, receiver 1 starts at A and receiver 2 starts at B where either A and B are both known or will become known by other methods (e.g., "A" might be determined by code point-positioning and B, relative to A, might be determined by an antenna swap as described in the following section). When tracking begins on five or more satellites, the receiver at B, known as the rover receiver, moves to an unknown site C.

During the transition between baseline vectors AB and AC, there must ensue continuous carrier phase tracking by both receivers on five satellites. More specifically, we must connect consecutive measurement epochs with four satellites (assuming good geometry) throughout the transition from B to C. Any satellites in excess of four are permitted to have cycle slips between consecutive epochs and different satellites can have cycle slips during different epoch intervals without causing undo difficulties. In fact, during the transition from B to C, all satellites may have cycle slips, at some point, so long as every epoch interval has four cycle-slip-free satellites (assuming good geometry). Under these conditions, cycle slip repair is automatic. With extremely poor geometry, which occurs occasionally, five satellites must connect consecutive epochs. The NGS procedures require that after cycle slips are repaired, at least five satellites connect consecutive epochs. A procedure could be based on four-satellite tracking, however this would require a knowledge of the geometric strength throughout the survey and redundancy would be a more critical element.

Antenna Swaps

An antenna swap or antenna exchange is performed as follows. Receiver 1 starts at mark A and receiver 2 starts at mark B. The geodetic location of A is known (or will become known by some other technique), whereas that of B is unknown. When tracking begins on five or more satellites, receiver 1 goes to B while receiver 2 goes to A. (In theory, four and sometimes fewer satellites are adequate; in practice five are recommended.) During the entire transition, continuous carrier phase tracking is required on at least four and possibly five satellites. Unlike kinematic GPS surveys, as described earlier, continuous carrier phase tracking must be maintained between marks on four or more satellites during the entire transition period. For the kinematic survey, the requirement is less severe in that only epoch to epoch connection of any four satellites is required. Although there are exceptions to this antenna-swap requirement, it is, in general, as stated. This difference between antenna-swap and kinematic survey manifests itself on airport survey design and will be discussed below.

AIRPORT SURVEY EXAMPLE

The kinematic survey instructions for the Florida project were prepared with sufficient generality so that the NGS survey team could adjust to changing satellite visibility. The survey procedures are best described by using a typical example. First, we need to define what comprises an airport survey as currently performed by NGS. At each airport there is a primary monument, P, an azimuth mark, AZ, and, typically, 1-3 runways where the locations of the runway endpoints (RWEPs) are desired. (P and AZ are actually indistinguishable; one is arbitrarily called P and the other is arbitrarily called AZ. In fact, AZ is not a traditional surveyor's azimuth mark.) P will usually be directly connected to the National Geodetic Reference System (NGRS) using static GPS procedures. AZ must be determined relative to P to approximately 1-2 cm so that the azimuth of AZ relative to P can be determined to approximately 5 seconds of arc. The RWEPs do not require centimeter accuracy but, by the nature of kinematic surveys, centimeter accuracy will be achieved.

Below is the actual survey time and site occupation history for Apalachicola airport in Florida. The team was required to perform a static survey (from P=APAL to AZ=APAZ) for 1 hour, ending when five-satellite visibility began. The crew would then perform two antenna-swaps between P and AZ; next the receiver at AZ would loop around all runway endpoints twice, ending each loop at AZ. Finally, they would perform an additional 1-hour static survey under whatever visibility conditions remained (possibly some five-, some four- and some three-satellite visibility). The team was directed to occupy APAZ for 5 minutes and the RWEPs for 2 minutes on all visits. It should be clear from the time and site log that the survey team faithfully followed the specified procedure; this was the case throughout the Florida test. AP06, AP13, AP18, AP24, AP31 and AP36 are the RWEPs. GPS measurements were recorded every 15 seconds. (Each "????" in this log represents a period of travel.)

Step	Date	Start	End	Rcvr1	Rcvr2
01	4-25-1989	1:28:00	2:31:45	APAL	APAZ
02	4-25-1989	2:31:45	2:36:45	APAL	APAZ
03	4-25-1989	2:36:45	2:41:45	????	????
04	4-25-1989	2:41:45	2:46:45	APAZ	APAL
05	4-25-1989	2:46:45	2:52:00	????	????
06	4-25-1989	2:52:00	2:57:00	APAL	APAZ
07	4-25-1989	2:57:00	3:01:31	APAL	????
08	4-25-1989	3:01:31	3:03:31	APAL	AP18
09	4-25-1989	3:03:31	3:07:15	APAL	????
10	4-25-1989	3:07:15	3:09:15	APAL	AP36
11	4-25-1989	3:09:15	3:12:31	APAL	????
12	4-25-1989	3:12:31	3:14:30	APAL	AP31
13	4-25-1989	3:14:30	3:17:45	APAL	????
14	4-25-1989	3:17:45	3:19:45	APAL	AP13
15	4-25-1989	3:19:45	3:24:30	APAL	????
16	4-25-1989	3:24:30	3:26:30	APAL	AP06
17	4-25-1989	3:26:30	3:32:15	APAL	????
18	4-25-1989	3:32:15	3:34:15	APAL	AP24
19	4-25-1989	3:34:15	3:36:30	APAL	????
20	4-25-1989	3:36:30	3:41:15	APAL	APAZ
21	4-25-1989	3:41:15	3:45:30	APAL	????
22	4-25-1989	3:45:30	3:47:30	APAL	AP18
23	4-25-1989	3:47:30	3:51:15	APAL	????
24	4-25-1989	3:51:15	3:53:15	APAL	AP36
25	4-25-1989	3:53:15	3:54:45	APAL	????
26	4-25-1989	3:54:45	3:56:45	APAL	AP31
27	4-25-1989	3:56:45	3:59:45	APAL	????
28	4-25-1989	3:59:45	4:01:45	APAL	AP13
29	4-25-1989	4:01:45	4:05:45	APAL	????
30	4-25-1989	4:05:45	4:07:45	APAL	AP06
31	4-25-1989	4:07:45	4:11:30	APAL	????
32	4-25-1989	4:11:30	4:13:30	APAL	AP24
33	4-25-1989	4:13:30	4:18:00	APAL	????
34	4-25-1989	4:18:00	4:23:00	APAL	APAZ
35	4-25-1989	4:23:00	5:23:00	APAL	APAZ

The solution baseline vectors, with respect to APAL, are listed to aid the reader in correlating travel times with the distances traveled.

Site	X-comp(m)	Y-comp(m)	Z-comp(m)
APAZ:	18.922	-498.506	-870.132
AP06:	-1259.690	-866.182	-1316.798
AP13:	-1051.289	-271.130	-312.914
AP18:	55.671	26.833	38.907
AP24:	94.675	-352.460	-626.007
AP31:	121.735	-738.090	-1302.890
AP36:	-115.938	-765.755	-1350.218

In this particular survey session there were no cycle slips during the antenna-swap procedures and none during the kinematic survey procedures. In other sessions there were occasional repairable cycle slips during the antenna swaps and/or during the kinematic survey portions. Occasionally a total bust occurred where cycle slip repair was not possible. Design of the survey is such that occasional complete busts can be tolerated. Dealing with cycle slips is theoretically interesting to many readers, but that subject is outside the scope of this paper.

Should a total bust occur on one antenna swap, the other swap, presumed successful here, is processed and the cycle slips repaired on the failed swap. Should a total bust occur on a runway endpoint loop, one simply processes the marks from the initiating APAZ forward to the bust and from the terminating APAZ backwards to the bust. The cycle slips can then be repaired if desired. This is not really necessary as there is a second loop. Both loops could experience one total bust and occasional individual satellite cycle slips without a problem. One antenna swap can have a total bust and either or both antenna swaps can have one or more individual cycle slips as long as four to five satellites remain totally connected during the transitions. These considerations dictate survey design. As part of the on-line operational test, the Apalachicola survey was conservatively designed. The vector APAL to APAZ can be computed using the initial static period (68 minutes), the final static period (1 hour), the four 5-minute visits to APAZ, or any combination of these APAL-APAZ baseline occupations--including all of them. Naturally all the occupations of the P-AZ baseline, taken together, produces the strongest geometry and should yield the best solution. It should be mentioned that all possibilities suggested were independently successful and are in agreement at the centimeter level. Success or failure is obvious for all the techniques: Ambiguities must be near integers; Residuals must be at the millimeter-level; All solutions, from the above four techniques, must agree at the 1-2 centimeter level.

FUTURE NGS KINEMATIC SURVEY OPERATIONS

For an isolated airport survey the 1-hour static periods are not required. Normally airport surveys are performed while other receivers are set on points of the NGRS. Under such circumstances static segments would be required. However, for the reminder of this paper, let us ignore the early and late static occupations. The p-k solution from P to AZ based on the four 5-minute occupations (e.g., steps 2, 6, 20 and 34 of the Apalachicola log) with five or more satellites, is, in general, sufficient in itself. The data from AZ to P (e.g., step 4) may, if desired, be applied to the solution from P to AZ. This would add little since it is so close in time to the neighboring two occupations. Thus, without the 1-hour static portions at the beginning and end, there are three possible solutions (antenna swap 1, antenna swap 2, and the p-k solution) for the P-AZ vector and four possible kinematic solutions (plus a p-k possibility--see below) for each of the RWEPs. The p-k solution with four visits, lasting 5 minutes each while tracking five satellites, is so strong the antenna swaps can almost be skipped. Note that 1 hour and 52 minutes were needed to perform the kinematic portion of the Apalachicola airport survey (composed of 7 independent vectors) with extreme redundancy and with the achievement of centimeter-level accuracies. It will be shown below that this survey can be done in significantly less time.

Before doing so, it should be pointed out that the two 2-minute occupations at AP06, AP31, and AP36 were sufficiently strong to perform a correct p-k solution. A loss of tracking on all satellites between the two occupations would not have affected this result (5). To state it simply, centimeter accuracy in p-k (i.e., static with gaps) mode can be achieved with two separated occupations of just 2 minutes each (even if the receivers are turned off between the visits). (This has been considered impossible by some investigators.) With minor enhancements to the post-processing software, the other RWEPs (i.e., AP13, AP18, and AP24) might have been successfully determined by p-k as well. Using existing software, 3-minute occupations would probably have been adequate. More important, however, is that some p-k solutions were successful, and those successes were obvious in that the integers were obvious and the residuals (after integer fixing) were at the millimeter level. The p-k solution from APAL to AP06 presents a new solution avenue for the determination of AP13 or AP24 in the event of a bust on both loops between AP31 and AP13 and between AP24 and APAZ (for example, due to obstructions). These p-k solutions provide an inexpensive extra layer of redundancy and safety.

Considering the above discussion, future airport survey design will be as follows. In all cases five-satellite visibility is assumed. Travel times are not shown. For kinematic surveys limited to 1-2 km intersite travel distances, the surveyor might budget an average of 5 minutes between sites. Possibly a better rule would *be 2 minutes plus 3 minutes per* kilometer. It should be mentioned that NGS typically uses a 15-second data collection interval. In general, this interval is fine. Although the author prefers epoch intervals of either 5 or 10 seconds for stop and go kinematic surveys, this is not critical.

Rcvr1	Rcvr2	Occupation	Comments
P	AZ	5 min.	N >= 5 Sats
P	TEMP	1 min.	"
TEMP	P	1 min.	"
P	TEMP	1 min.	"
P	AZ	2 min.	"
P	RWEPs	3 min. each	"
P	AZ	5 min.	"
P	RWEPs	3 min. each	"
P	AZ	5 min.	"

The above describes the revised airport survey procedure. TEMP is a temporary mark placed approximately 20 m from P. Antenna swaps are riskier than kinematic surveys; this reduces the riskiest period to 1-2 minutes where the surveyor should be more attentive or careful. This scenario would take 44+16*NRWEP minutes, where NRWEP is the number of RWEPs. This formula assumes 5-minute kinematic-survey travel times and 2-minute antenna-swap travel times. This means that the survey would take 76 minutes, 108 minutes, or 140 minutes for one-, two-, and three-runway airports, respectively. This procedure is still quite conservative.

The survey crew has the leeway to reduce the occupation times if the time saved can be utilized. This becomes an issue if more than one airport is to be surveyed per day kinematically within a restricted five-satellite visibility window. First the RWEP occupations may be reduced progressively, in 1-minute increments, down to 1 minute. This saves 8, 16, and 24 minutes, respectively, and reduces the survey time to 68 minutes, 92 minutes and 116 minutes, respectively. Next the occupations of AZ can be reduced to 2 minutes saving 9 additional minutes for the one-, two-, and three-runway cases (thus reducing five-satellite visibility use to 59, 83, and 107 minutes, respectively). Next TEMP could be removed from the procedure and two long swaps could be used. That would save an additional 6 minutes but add some risk. Finally one of the long swaps could be removed, adding a little more risk. Removing one antenna swap saves 6 more minutes of five-satellite visibility. This latter action should be countered with additional static occupation of P and AZ during the initial period when less than five satellites are visible. These latter two savings of 6 minutes reduces five-satellite visibility usage to 47, 71, 95 minutes, respectively. In general, these latter two procedures are *not recommended*.

From these deliberations and assuming airports are within about 1 hour (travel time) of each other, it is easy to figure how many airports can safely be surveyed kinematically in a given window of five-satellite visibility. If the period is 3 hours, such as currently in Missouri, two one-runway airports could be surveyed, in one day.

SUMMARY

The National Geodetic Survey performed an on-line operational test of GPS kinematic surveying at several Florida airports. It was a complete success. The theoretical rationale for the survey procedure has been emphasized in this paper, and various processing scenarios have been discussed. All successful processing variations, in the Apalachicola example, agreed at the 1-centimeter level. An isolated kinematic survey does not require the early or the late static sessions. However when the NGS carries out the upcoming airport surveys in Missouri, these airports will be, simultaneously, tied into the NGRS and, thus, these static portions will be important. Antenna swaps will be performed with the less risky technique of using a temporary mark. The survey party also understands where site occupation times can be reduced. This is important because by accepting a small risk that one airport survey may fail, significant average productivity gains can be realized.

CONCLUSIONS

Kinematic survey scenarios are more complex than static scenarios. Nevertheless, with an understanding of the theoretical principles involved, surveyors can establish procedures that are flexible enough to be applied at selected risk levels. Whatever risk level is chosen, the level of risk should be balanced throughout the survey so as to avoid a weak link. Although airport surveys have been considered, these principles should apply to a wide variety of kinematic survey activities. The techniques discussed in this paper, if applied wisely, can yield substantial increases in productivity --especially when the five-satellite visibility window expands.

REFERENCES

(1) Remondi, B. W., 1985: Global Positioning System carrier phase: Description and use, Bull. Geod. 59, 361-377.

(2) Remondi, B. W., 1985: Performing centimeter-level surveys in seconds with GPS carrier phase: Initial results, Navigation, Vol. 32, No. 4. Winter 1985-1986.

(3) Wells, D., 1986: Guide to GPS positioning, Canadian GPS Associates, December.

(4) Minkel, D. H., 1989: Kinematic GPS land survey: Description of operational test and results, Journal of Surveying Engineering, ASCE, Vol. 115, No. 1, 121-137, February.

(5) Remondi, B. W., 1988: Kinematic and Pseudo-kinematic GPS, Proceedings of the Satellite Division's International Technical Meeting, The Institute of Navigation, 115-121, September 19-23.