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APPLICATION OF NAVSTAR GPS GEODETIC RECEIVER TO GEODESY AND GEO--ETC(U)
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A prototype geodetic receiver is being developed for application with the NAVSTAR Global Positioning System. Data obtained with an experimental version of the receiver applied to simulations of performance of the prototype version indicate that the relative positions of stations 10 to 100 km apart can be obtained with 1- to 2-cm accuracy after 6 hr of observations provided that water-vapor radiometers are used to obtain tropospheric refraction correction data. Initial studies show that the use of surface weather data, but without water-

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vapor radiometers, would give 2- to 5-cm accuracies, but a more realistic modeling of the errors under these conditions is required.

FOREWORD

The Naval Surface Weapons Center, with sponsorship by the Defense Mapping Agency, is developing a receiver to obtain precise geodetic positions from observations of the NAVSTAR Global Positioning System. Two experimental receivers have been built and two prototype receivers are under development. This report discusses the accuracy to be expected in the positions computed from data obtained with the receivers.

Project management at the Naval Surface Weapons Center is under Bruce R. Hermann who provided source data used in the error model developed in this study. Robin Hicks assisted in the debugging of the computer program and Linda Lynch in operating the program.

Released by:

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CONTENTS

INTRODUCTION

The NAVSTAR Global Positioning System (GPS) is a satellite system being developed to provide an observer his three-dimensional, instantaneous position and velocity anywhere in the world when the system is fully deployed in 1987 (Parkinson, 1979). There are currently six satellites in orbit which allow instantaneous positioning a few hours each day in four geographic areas for test purposes. The satellites transmit ephemeris data, a pseudorandom noise signal which can be used for ranging on frequencies of 1227.6 MHz and 1575.42 MHz, and the time of day of the range signals. The two frequencies are used to eliminate propagation delays due to first-order ionospheric effects.

For normal navigation purposes, range is computed from the time delay between the broadest time of the ranging signal and the measured time of receipt of the signal. Since the observer's clock will be in error, these measurements are referred to as "pseudoranges"; pseudoranges to four satellites are used to determine the three coordinates of the observer and the error in the observer's clock. For the expected signal strength and omnidirectional receiving antennas, the expected range measurement accuracy is approximately 1 m. This measurement error and the uncertainties in the satellite ephemeris and clock are the major sources of the 10-m uncertainty in the determination of the position of the observer. For a stationary observer, repeated measurements can reduce the uncertainty in position to 1 m in about 24 hr, while the effects of satellite orbit and clock errors on the relative positions of two observing stations are only about 20 cm (Fell, in press).

In order to obtain higher accuracies in shorter periods of time, the Defense Mapping Agency initiated development of a geodetic receiver by the Naval Surface Weapons Center (NSWC). The geodetic receiver differs from the navigation receiver developed to date in that it measures phase on both transmitted signals rather than on only one signal. Since phase measurement can be made to an accuracy of about 0.5 cm, the geodetic receiver has the potential of achieving accuracies desired for geodetic and geophysical applications.

An experimental model of the geodetic receiver was tested in 1979 to determine measurement precision, and a second experimental receiver was developed in 1980 to permit tests of the accuracy of determination of relative station coordinates. Specifications have been written and development has begun of prototypes of an operational receiver that will meet the requirements of the Defense Mapping Agency, the United States Geodetic Survey, the National Geological Survey, the National Aeronautics and Space Administration, and the Bureau of Land Management.

EXPERIMENTAL GEODETIC RECEIVER SYSTEM

Two experimental geodetic receiver systems have been developed (Hermann, in press). The first, tested in 1979, recorded pseudorange at 1575.52 MHz to about 1 m precision and recorded phase at 1575.42 MHz and 1227.6 MHz to 0.2 cm and 0.3 cm precision, respectively. The second system, completed in 1980, differed from the first primarily in the addition of the measurement of pseudorange at the lower frequency.

The receiver portions of the systems were developed by Stanford Telecommunications Incorporated to NSWC specifications while the computer control was developed by NSWC. The receivers observed one satellite at a time, sequencing among satellites according to the computer control. Each acquisition of a satellite required up to 45 sec, and Doppler and phase measurements are recorded over a 60-sec interval. (Range measurements are recorded at 6-sec intervals.) Therefore, the minimum switching time between satellites is 120 sec. Each receiver, together with its computer and supporting equipment is housed in a van (Figure 1).

Tests of the first receiver showed that specifications on the measurement precisions were probably met. Measured random errors on phase were 2-3 cm which is consistent with expected oscillator errors, and the errors were the same magnitude for raw range or refraction corrected range, showing that the errors were correlated on the two frequencies as they should be if individual measurement precisions were being met. (The random error of the ionospheric correction was about 0.5 cm, which confirms the measurement precision.)

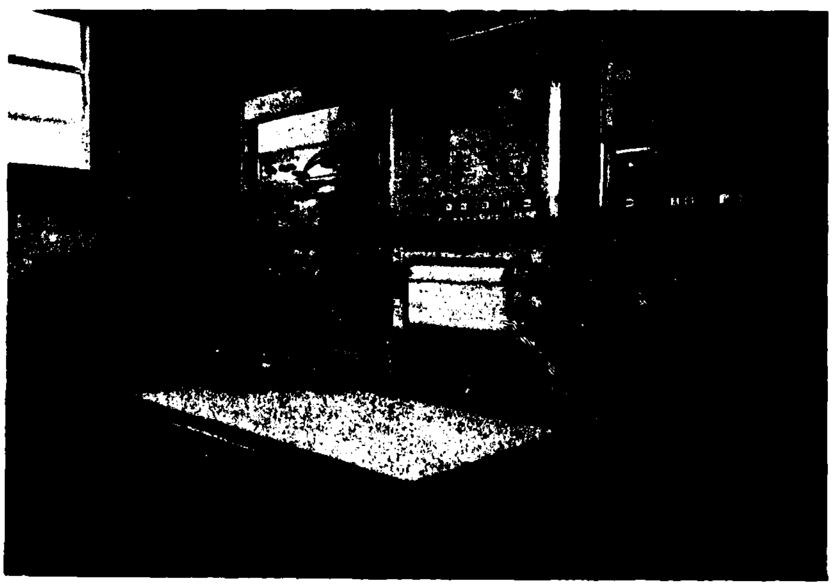

Figure 1. Interior of Van Housing Experimental Geodetic Receiver System

PROTOTYPE GEODETIC RECEIVER SYSTEMS

Prototype receivers are being developed by the Applied Physics Laboratory of the Johns Hopkins University and NSWC to meet the specifications of the agencies named above. The prototype receivers will be man-portable and rugged (Figure 2). Like the second experimental receiver, the prototypes will record pseudorange, phase, and Doppler at both frequencies for a single satellite at a time.

The precision of the observation will be similar to that for the experimental receiver: 45 cm and 63 cm in range and 0.18 cm and 0.33 cm in phase for the frequencies 1575.42 MHz and 1227.6 MHz, respectively. However, the time required to switch from one satellite to another will be reduced, since this is a key problem in achieving high precision as will be discussed below.

Three fundamental switching times will be available: 60 sec, 12 sec, and 6 sec. The 60-sec time is composed of a 45-sec acquisition time and range, Doppler and phase measurement over two 6-sec intervals. The two faster switching times require additional receiver aiding which allows a 3.8-sec reacquisition time. With 12-sec switching, the range, Doppler, and phase measurements will be made over a 6-sec interval. With 6-sec switching, the range, Doppler, and phase measurements will be available over a 1.2-sec interval.

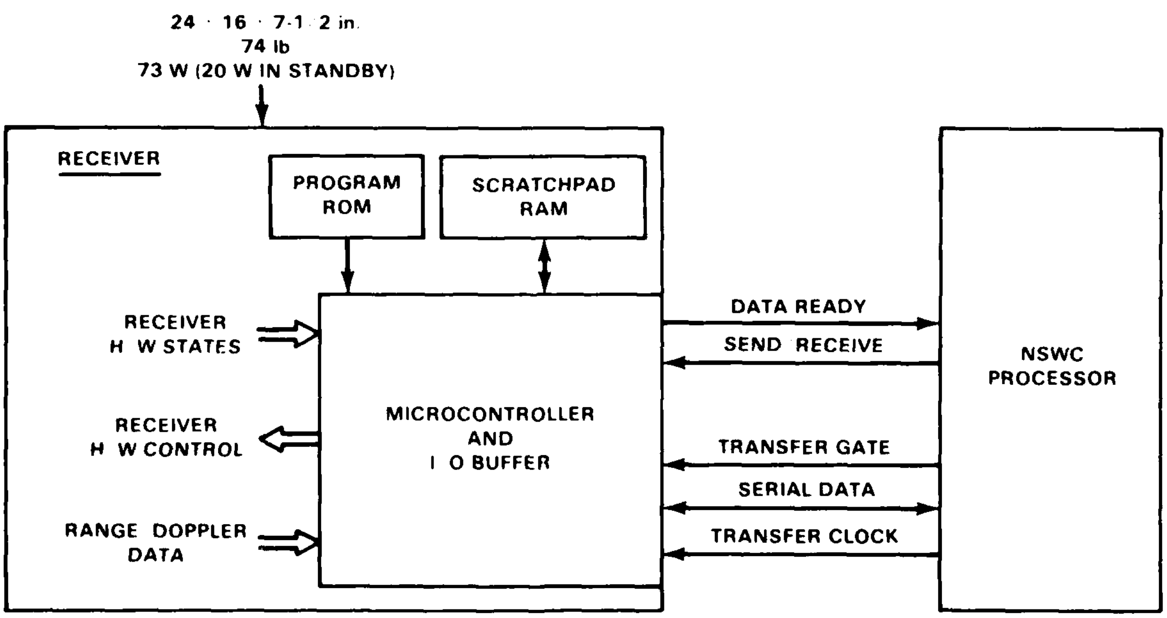

Figure 2. Data Flow Between Receiver and Computer of Prototype Geodetic Receiver

METHODS OF COMPUTATION

In this report, only near-simultaneous observations by two stations of one or more satellites will be considered in order to reduce the effects of satellite orbit and clock errors on the computed relative coordinates of the stations. Four methods of computation will be considered corresponding to different models of the observation error. The first is the model conventionally applied to Doppler observations of Navy navigation satellites. Although the GPS carrier signal is fully suppressed by the pseudorandom noise code sequence, it is recovered after the receiver is locked on the code sequence and phase and Doppler measurements are made on the difference between the carrier and a ground station signal. (The term "Doppler" refers here to a range difference from one station to one satellite over an interval of time; the term Doppler is used rather than range difference to avoid confusion with a difference between ranges from two stations to a satellite at an instant of time.)

Usually, the Doppler-derived range differences to a satellite over successive observational intervals are treated as if they were uncorrelated. If the receiver does not reset the Doppler count at the observation times, the counts can be accumulated at successive observation times; these techniques are usually referred to as Continuously Counted Integrated Doppler (CCID) data. CCID data, which are equivalent to range observations subject to a range bias over the sequence of counts, is the second model to be considered. If the receiver is switching observations among satellites, CCID data is not directly available; but in the next section, it will be shown that the counts lost in switching can be recovered for certain operation modes of the prototype geodetic receiver.

However, both the Doppler and CCID modes incur serious errors due to oscillator instability. Colquitt and Anderle (1979) showed that for NAVSAT data, CCID representation of data provides overly optimistic estimates of accuracy for crystal oscillators commonly employed and that Doppler representation underestimates accuracy for rubidium oscillators. Anderle (1979) showed that even with Cesium oscillators, GPS accuracies would be limited to about 40 cm for an 8-hr observation interval using either data representation; this accuracy is considerably worse than that predicted neglecting oscillator error (Anderle, 1979).

In order to reduce the effects of oscillator error, it is proposed that at least two satellites be observed nearly simultaneously by two stations and at each instant of time the satellite clock epoch errors and the clock error at the second station be determined. Thus four pseudoranges with three parameters still yield one degree of freedom. Another interpretation of the four ranges is as a double range difference between satellites and stations without clock parameters. Either interpretation requires that a unique event generated by the satellite be identified by both ground stations. But phase measurements by the two ground stations cannot be directly synchronized to the same carrier cycle of the emitted signal.

Two approaches have been suggested to achieve synchronization. First, Counselman of the Massachusetts Institute of Technology proposes to synchronize by finding the carrier cycles difference between the two receivers for each measurement time which minimizes the residuals of fit (Counselman et. al., 1979). This technique is referred to as the interferometric solution. Second, Bender and Goad (unpublished) have found that with a 6-hr continuous CCID measurement, the cycle count ambiguity can be determined directly. In the former method, a continuous count is not required, but speed of computation and direct elimination of solutions corresponding to relative minima in the residuals is affected by the accuracy of a-priori data on the parameters. The latter method provides greater strength of solution for the ambiguities, but requires a continuous Doppler count.

Since, as mentioned above and discussed in the next section, it is believed that a continuous count can be recovered even when the prototype geodetic receiver is sequencing among satellites, the latter approach will be discussed in this report. This approach leads to the last two methods of computation. The third method, which will be called the "ambiguity solution," determines the cycle count ambiguity between stations for each sequence of measurements to a satellite. The satellite clock epochs and the clock epoch for the second station at each measurement time are parameters of the solution along with other unknowns such as station coordinates, satellite position, refraction, and frequency parameters. The fourth solution, which will be referred to as the "phase comparison solution," will have the same parameters as the third except that the cycle count ambiguity will be known as a result of the ambiguity solution. In principle, the phase comparison solution is equivalent to the interferometric solution if the ambiguities are correctly resolved in each case.

RECOVERY OF MISSED CYCLE COUNTS

Two general approaches can be followed to recover carrier cycles missed for one satellite during the period the receiver is observing other satellites. First, a fit of a model of the expected ranges to the satellite can be fit to the sampled range difference data and the missing data can be filled in from the model. Secondly, a polynomial fit can be made to the observed data and the missing data filled in from the polynomial coefficients. While detailed analysis of these approaches is under way, preliminary reviews have indicated either method is capable of recovering the missing data provided that perfect sample Doppler data and perfect oscillators are available.

This section will therefore consider errors in the Doppler data and in the oscillator. It will be assumed that the Doppler measurement will be made over a given interval with phase errors at each end of the interval and that the phase will be linearly predicted over a gap interval immediately following the measurement interval. This approach is pessimistic, since the effects of measurement could be reduced by least square fitting over several measurement intervals. Table 1 gives the prediction errors at the

Table 1. Phase Prediction Error for Prototype GPS Geodetic Receiver

Tracking Mode	1	1	1	2	2	3
Switching Interval (sec)	180	120	60	12	24	6
Doppler Measurement Interval	132	72	12	6	18	1.5
Time Gap* (sec)	585	405	225	42	78	22
Random Error (3σ)						
Doppler Accuracy, L_2** (cm/sec)	0.011	0.018	0.115	0.231	0.076	0.92
Prediction Error, L_2 (cm)	6.0	7.8	26.4	9.9	6.0	20.7
Prediction Error, L_1 (cm)	3.3	4.2	14.3	5.4	3.3	11.2
Oscillator Error						
Oscillator Accuracy† x 10^{13}	3.0	3.0	5.5	19.0	11.0	28.0
Prediction Error (cm)	5.3	4.0	3.7	2.3	2.6	1.8
Total Error (3σ)						
At L_2 (cm)	8.0	8.8	26.7	10.1	6.5	20.8
At L_1 (cm)	6.2	5.8	14.8	5.9	4.2	11.3
At L_3 (cycles)	0.3	0.4	1.1	0.4	0.3	0.9
At L_1 (cycles)	0.3	0.3	0.8	0.3	0.2	0.6

* 45-sec acquisition time for mode 1- or 4-sec acquisition time for modes 2 or 3 plus time allotted to 3 other satellites.

** 1.4 x 0.33/interval = 0.46 cm/interval; for L_1 1.4 x 0.18/interval = 0.25 cm/interval.

† Efratom specifications for length of time gap.

two carrier frequencies for selected satellite switching strategies for each of the three modes planned for the prototype geodetic receiver.

The phase measurement error for each frequency is multiplied by $\sqrt{2}$ to account for the measurement errors at the beginning and end of the measurement interval and divided by the interval to obtain the Doppler accuracy. This result is multiplied by the time gap to reacquire the satellite giving the phase error due to measurement error, and then multiplied by three, since a highly reliable prediction accuracy is required. The effect of oscillator instability is computed by multiplying the fractional frequency stability for a rubidium oscillator (linear from 5×10^{-12} at 100 sec on a log-log plot) by the time gap. Since these fractional frequencies are specification values for the oscillator, they are considered 3σ values. (This prediction error computation is an approximation which was reasonably accurate in experiments for other applications.) The rms of these two errors is under 0.5 cycles for both frequencies for four of the six cases studied, indicating that recovery of the missed cycle count is reliable for these four cases.

Effects of variation in the ionosphere and troposphere were neglected but are small for those conditions. Hermann (in press) shows the ionospheric fluctuations to be no worse than 1 cm over 1-min intervals. Recovery of missed cycle counts on the refraction corrected data was not attempted because the refraction correction process amplifies the basic errors on the two carrier frequencies to a value of 0.97 cm. It is therefore preferable from a reliability standpoint to recover the missed cycles on the transmitted frequencies and then make the ionospheric correction.

Although the satellite oscillator error is common to both sites, it will cause the error in the missed cycle count at each site to center about a nonzero mean, increasing the probability at an erroneous relative cycle count recovery, unless the cycle count recovery is performed using the relative Doppler measurements at the stations. However, use of the relative Doppler measurements introduces another $\sqrt{2}$ factor on the error, making the recovery marginal, particularly considering the number of recoveries required to perform one solution for station coordinates. Fortunately, the current estimate of the errors in phase measurements is pessimistic considering the various possibilities of raising signal strength (probable increase in transmitted power, better antenna design available, and data selection). It is believed that careful design of the hardware and software will ensure reliable recovery of continuous Doppler data.

DATA SIMULATION

Full simulations of the recovery of missed cycle counts have not been completed. It was therefore assumed that the preceding section demonstrates that recovery is possible and has been completed. Data were synthesized at 1-min intervals for the first four Navigation Development satellites for six days for a base station at Vandenberg Air Force Base and for stations

10 and 100 km northeast of Vandenberg. Random measurement errors of 0.5 cm were imposed on the data, clock offset and frequency errors were imposed for each satellite and station, and data were disturbed in a manner consistent with the Allan variance measured for the satellite and ground station oscillators (Figure 3).

No satellite orbit or refraction errors were considered in the generation of the data or residuals because of the cost of obtaining Monte Carlo estimates of these effects, but parameters representing these errors were considered in the solution. Simultaneous data at the stations from four satellites were available for a 92-min interval of time each day while data from at least one pair of satellites were observed by the stations over a 516-min time interval using a 5° elevation cutoff (Figure 4).

While most solutions considered simultaneous data at 60-sec intervals, tests showed that the difference between simultaneous and sequential data at 240- or 480-sec intervals was small. The results are therefore considered representative of those expected for the Mode 2 cases shown in Table 1.

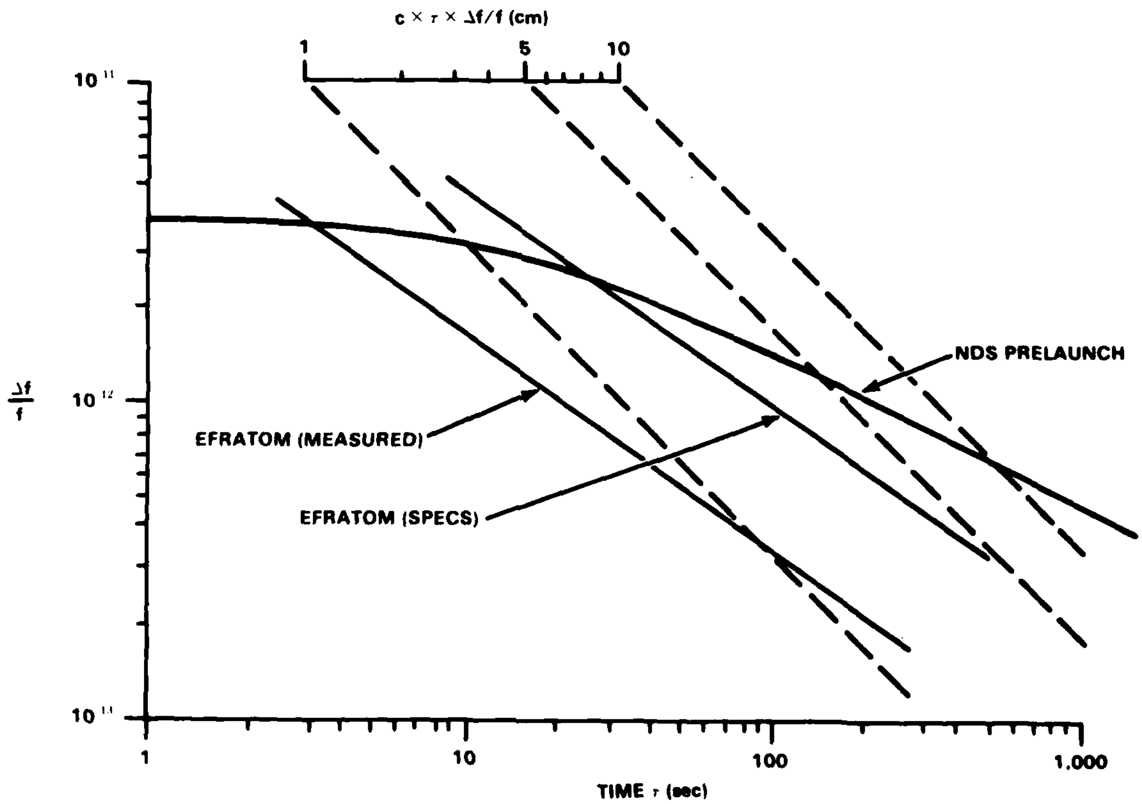

Figure 3. Allan Variance

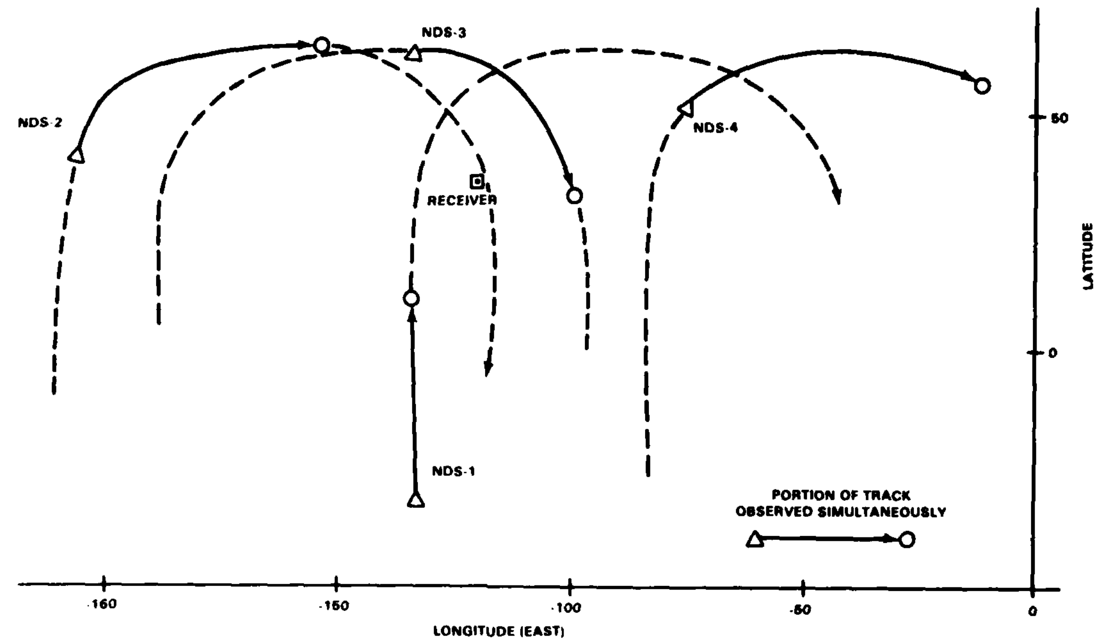

Figure 4. Satellite Tracks

SAMPLED DOPPLER SOLUTIONS

Range difference data over 1-min intervals were used to determine the relative coordinates of a pair of stations separated by 10 km and a pair separated by 100 km. Solutions for satellite passes 14, 30, and 92 min long were obtained, with two geometries for the 15- and 30-min passes (the first two segments of the 92 min during which the four satellites were visible at the two stations). Solutions were obtained for each of six days giving a sample size of six for each case.

Parameters included six orbit bias parameters for each pass of each satellite representing coefficients of periodic (orbit period) errors in the radial, tangential, and normal components of the satellite position; the a-priori orbit errors were assigned standard errors of 2, 10, and 6 m, respectively, for the three components. A random refraction error parameter for each observation of each satellite by each station was given an a-priori uncertainty of 1 percent of the model correction. A bias parameter for the refraction model for each solution was assigned an uncertainty of 3 percent. The 1 percent random error is considered somewhat pessimistic and is a limiting factor in the accuracy, as will be shown in the next section. However, gradients in the atmosphere were neglected. An attempt to bound this error is discussed in the section on the ambiguity solution. A frequency parameter was considered for each satellite and station without bounds for the a-priori except for that for the reference station which was assumed to be perfect. The coordinates of both stations in each solution were parameters, but the a-priori value for Station 1 was assigned an uncertainty of 1 m. Results of the simulations are given in Table 2.

Table 2. Sampled Doppler Solutions

Orbit Accuracy:
2, 10, 6 m Radial, Tangential, Normal

Refraction Accuracy:
1% Random
3% Bias

Station Separation (km)	Data Span (min)	Sample (6 Sol'ns/Sample)	Rms Error* (cm) Vertical	East	North	Standard Error** (cm) Vertical	East	North
10	15	1	38	91	25	25	103	89
	15	2	27	102	39	27	133	77
	30	1	26	148	102	20	83	63
	30	2	59	128	57	23	102	54
	92	1	93	158	63	13	32	21
100	15	1	315	933	728	154	539	346
	15	2	161	827	826	147	543	300
	30	1	342	1355	634	121	448	228
	30	2	474	1040	560	131	410	203
	92	1	729	1144	838	68	136	97

* Includes oscillator error, but excludes orbit and refraction error except as aliased by oscillator.
** Excludes oscillator error, but includes orbit and refraction error.

The rms of the six solutions for each case grows with an increase in the pass length or station separation because the oscillator variations are not modeled. The standard error of the solution obtained from the covariance matrix decreases with pass length because of the increase in strength of solution. Overall, the shorter pass lengths appear preferable, but give results which are quite poor with respect to the goals of the receiver development.

While better results would be obtained for a better model for the random refraction error, the principal purpose of these calculations is to display the weakness of this mode of calculation for GPS data relative to the methods discussed below, despite the success obtained in applying it to NAVSAT data.

CONTINUOUS COUNT INTEGRATED DOPPLER (CCID) SOLUTIONS

Continuously integrated Doppler data were treated as range data at 1-min intervals with a range bias parameter for each pass of each satellite over each station. All other assumptions and parameters were the same as those discussed in the previous section. There is a dramatic improvement in both the rms and standard errors over those for sampled Doppler data given in the previous table for most cases because of the better separation of parameters possible with the increased data strength. (The slightly increased standard error for the first case is not understood.) For CCID data, the optimum passlength is about 30 min; the shorter span suffers larger standard errors due to weakness of the solution while the longer span incurs larger rms errors due to the buildup of effects of oscillator instability. A still better solution would be obtained for frequency bias parameters over 30 min but range bias and orbit bias over longer intervals.

It is of interest to determine whether the standard error of the 30-min solution is driven more by the random refraction error or the bias since successive 30-min spans would rms random error but be less effective for bias error. Table 3 shows that the source is primarily the random error, so that the rms of successive 30-min solutions over an 8-hr interval might be expected to give about 10 cm accuracy. This accuracy and time would be

Table 3. Continuous Count Doppler Solutions

Orbit Accuracy:
2, 10, 6 m Radial, Tangential, Normal

Refraction Accuracy:
1% Random
3% Bias

Station Separation (km)	Data Span (min)	Sample (6 Sol'ns/Sample)	Rms Error* (cm) Vertical	East	North	Standard Error** (cm) Vertical	East	North
10	15	1	16	22	17	44	135	91
	15	2	4	10	7	62	123	61
	30	1	1	6	4	16	46	29
	30	2	7	14	15	29	47	26
	92	1	13	35	20	4	9	5
100	15	1	35	64	37	49	139	91
	15	2	13	60	22	60	129	69
	30	1	7	36	23	16	50	31
	30	2	18	55	20	29	53	28
	92	1	13	22	52	5	12	7

* Includes oscillator error, but excludes orbit and refraction error except as aliased by oscillator.

** Excludes oscillator error, but includes orbit and refraction error.

suitable for geodetic purposes, but higher accuracies are desired for geophysical applications. For geophysical applications, the CCID solution would yield accurate frequencies for use in ambiguity and phase comparison solutions discussed in the next section. Table 4 shows that the uncertainty in tropospheric refraction has a significant effect on the accuracy of the solution.

Table 4. Effect of Refraction Errors on Continuous Count Doppler Solutions

Orbit Accuracy:
2,10,6 m Radial, Tangential, Normal

Station Separation: 10 km
Data Span: 30 min

		A-Priori							
		Random	Refraction						
	No. in	Refraction	Bias	Rms Error* (cm)			Standard Error** (cm)		
Sample No.	Sample	(%)	(%)	Vertical	East	North	Vertical	East	North
1	6	1	3	4	19	34	24	60	48
2	5	1	3	13	24	13	29	47	26
1	6	0	3	6	8	13	1.8	3.5	3.6
2	1	0	3	--	--	--	1.8	5.9	3.0
1	6	0	0	6	6	13	1.7	3.5	3.6
2	5	0	0	3	16	6	1.7	5.9	2.9

* Includes oscillator error, but excludes orbit and refraction error except as aliased by oscillator.
** Excludes oscillator error, but includes orbit and refraction error.

AMBIGUITY SOLUTION

All the parameters of the CCID solution are included in the ambiguity solution but additional parameters are added for the epochs and frequency of each satellite clock and the epoch and frequency of the second station clock for each set of simultaneous observations. The frequency from the Doppler solution is used and assigned an a-priori uncertainty corresponding to the Allan variance (equivalent to 36 cm/day). Data spans of 1.5 hr and 6.6 hr were considered; the 1.5-hr span of simultaneous data frequently failed to give sufficient strength of solution to resolve the ambiguity; the longer passes usually allowed resolution of the ambiguity even though only one pair of satellites was visible at both stations at the beginning or end of the span.

As shown in Table 5, various assumptions were made about the refraction model since the refraction error was critical to the results. The first pair of standard errors for the refraction parameters, 1 cm for the random error and 1 cm for the systematic error, is intended to represent the use of water-vapor radiometers. The last pair, 1 percent and 3 percent, is intended to represent the use of only surface weather data. The second pair, 2 cm and 3 percent, is to isolate the relative importance of random and bias refraction errors. The third pair, 2 cm random and 3 percent bias at each station, is an attempt to learn something about the effects of horizontal gradients: for closely spaced stations the results of this case would be pessimistic since both stations would see the same refraction effects but it cannot be said that it is even an upper bound for the results for stations separated by 100 km.

Table 5. Standard Error in Station Position From Ambiguity Solution (cm)

Station Separation (km)	Orbit Error (m)	Refraction Error	1.5-hr Data Span			6.6-hr Data Span (1.5-hr 4 Satellites)		
			σ_H	σ_E	σ_N	σ_H	σ_E	σ_N
10	2,10,6	1 cm, 1 cm	2.4	7.5	3.7	1.2	0.8	0.4
		2 cm, 3%	3.6	10.5	5.6	1.3	1.0	0.5
		2 cm, 3%/station						
		1%, 3%	6.7	16.7	9.4	2.0	1.7	1.1
100	2,10,6	1 cm, 1 cm	9.7	20.0	10.7	4.3	4.6	2.8
		2 cm, 3%	10.8	25.1	12.7	4.7	5.4	3.1
		2 cm, 3%/station	12.9	33.0	16.3	5.6	5.8	3.3
		1%, 3%	17.3	48.4	21.7	6.5	6.3	3.3
10	10,50,50	1 cm, 1 cm	4.1	9.7	5.3	3.7	3.0	2.1
		1%, 3%	7.1	18.1	10.8	4.6	4.0	2.0
100	10,50,50	1 cm, 1 cm	40.0	69.5	37.2	18.3	21.7	10.4

Further work is needed to determine the effects of time and space variations in the atmosphere. As mentioned above, the table shows that the ambiguity would rarely be resolved for 1.5-hr data spans. However, resolution is successful with 6.6 hr of data for all cases except where the orbit is bad and the stations are also separated by 100 km. Only standard errors are given for the ambiguity and phase comparison solutions since the rms errors were always reasonable with respect to the standard errors (unlike the Doppler and CCID cases, the oscillator error is well represented in these computational modes). Table 6 shows that oscillator instability has only a small effect on accuracy (two components of standard error for the 100-km, 1.5-hr case were better for sequential data because an additional data point was used in this solution by accident of the fall of the sequential data within the definition of data span).

Table 6. Effect of Oscillator Error on Station Coordinates From Ambiguity Solution (cm)

(Data at 120-sec Intervals)

Orbit Accuracy: 2, 10, 6 m
Refraction: 2 cm, 3%

	1.5-hr Data Span			6.6-hr Data Span		
	σ_H	σ_E	σ_N	σ_H	σ_E	σ_N
10-km Station Separation						
Simultaneous Data	5.8	16.7	10.5	1.8	1.9	1.1
Sequential Data	6.0	18.6	11.8	2.3	2.0	1.2
100-km Station Separation						
Simultaneous Data	18.4	54.4	25.5	5.7	6.2	3.2
Sequential Data	22.2	51.5	24.5	6.5	6.3	3.2

PHASE COMPARISON SOLUTIONS

The phase comparison solutions were performed under the same conditions as the ambiguity solutions except that the ambiguity for each satellite/station pair was held fixed at the value found in the ambiguity solution. Table 7 shows that 1- to 2-cm accuracy in the relative positions of the stations can be obtained in 6 hr for stations separated by as much as 100 km provided that the nominal orbit accuracy is achieved and water-vapor radiometers are available. With surface weather data, the accuracy ranges from 2 to 6 cm for station separations of 10 to 100 km. Table 8 shows that sequencing the observations has a small effect on accuracy. (As in the case of the Table 6 results, an additional data point for the 1.5-hr case resulted in even better accuracy for the sequenced data.)

Table 7. Standard Error in Station Position From Phase Comparison Solution (cm) (Simultaneous Data at 60-sec Intervals)

Station Separation (km)	Orbit Error (m)	Refraction Error	1.5-hr Data Span σH	σE	σN	6.6-hr Data Span (1.5-hr 4 Satellites) σH	σE	σN
10	2,10,6	1 cm, 1 cm	1.5	1.9	0.5			
		2 cm, 3%	2.1	2.5	0.6	1.2	0.4	0.4
		2 cm, 3%/station						
		1%, 3%	3.9	3.4	1.2	1.9	0.7	0.6
100	2,10,6	1 cm, 1 cm	8.5	5.4	2.8	3.7	2.3	1.8
		2 cm, 3%	8.9	6.6	2.9			
		2 cm, 3%/station	10.4	7.1	3.3			
		1%, 3%	10.7	11.1	3.4	6.0	2.4	2.7
10	10,50,50	1 cm, 1 cm	4.1	3.3	1.6			
		1%, 3%	5.7	4.6	10.8	4.3	1.7	1.5
100	10,50,50	1 cm, 1 cm	36.3	23.1	14.9			

Table 8. Effect of Oscillator Error on Station Coordinates From Phase Comparison Solution (cm)

(Data at 120-sec Intervals)

Orbit Accuracy: 2, 10, 6 m
Refraction: 2 cm, 3%

	1.5-hr Data Span σH	σE	σN	6.6-hr Data Span (1.5-hr 4 Satellites) σH	σE	σN
10-km Station Separation						
Simultaneous Data	4.4	3.8	1.2	1.7	0.6	0.6
Sequential Data	4.4	3.7	1.4	2.1	0.7	0.6
100-km Station Separation						
Simultaneous Data	11.3	13.2	3.4	5.4	2.3	2.6
Sequential Data	11.4	11.8	3.3	5.9	2.4	2.6

SIGNIFICANCE OF REFRACTION ERROR

The foregoing discussion shows that the prototype geodetic receiver with water-vapor radiometers having random and systematic errors of 1 cm will provide results useful for geophysical applications after 6 hr of observations. Because of the cost and complexity of the radiometers, an attempt was made to determine the accuracy to be expected with only surface weather data. The assumed a-priori random error of 1 percent corresponds to a 2.5-cm random error for a zenith observation, which is high compared to that measured with water-vapor radiometers (Guiraud et. al. 1979) or in local areas with the SEASAT-1 satellite scanning multifrequency microwave radiometer (unpublished). A reduction in this error estimate yields results approaching those predicted for the water-vapor radiometer.

However, horizontal gradients in the atmosphere are another possible source of significant error which are difficult to determine without the use of the radiometer. Further studies need to be performed to define the space-time spectrum of these variations, their effects on results, the possibility of correcting for them, or at least the possibility of identifying periods of greater uncertainty according to synoptic weather data.

CONCLUSIONS

The prototype GPS geodetic receiver is expected to be capable of determining the relative positions of stations 10 to 100 km apart to 1 to 2 cm after 6 hr of observations if water-vapor radiometers are available. Preliminary estimates of 2- to 6-cm accuracy with the use of only surface weather data need to be refined with better estimates of the magnitude and character of the uncertainty in the predicted tropospheric refraction correction and its effect on positioning.

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