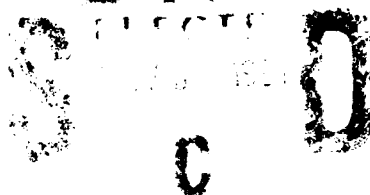AD-A242 360

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SATELLITE RADIO INTERFEROMETRY

Charles C. Counselman III

Massachusetts Institute of Technology
77 Massachusetts Avenue
Cambridge, MA 02139

31 July 1991

Final Report
29 April 1986 - 30 April 1991

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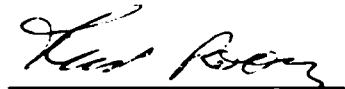
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This technical report has been reviewed and is approved for publication.

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Satellite radio interferometry techniques of geodesy, whereby relative positions of earth surface points and orbits of earth satellites are determined from phase difference measurements of radio signals propagating from the satellites to the earth surface points (or vice versa), were investigated under this contract. R.m.s. scatter of relative position vector determinations was 2 millimeters for horizontal coordinates of earth surface points separated by about 150 kilometers in the vicinity of Houston, Texas, when the orbits of the NAVSTAR Global Positioning System satellites whose carrier signal phases were measured at these points were determined simultaneously from seven hours of phase measurements at a network of stations spanning 320 kilometers, without atomic frequency standards.

Related techniques for determining positions of earth surface radio transmitters observed via repeater satellites were also investigated.

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CONTENTS

1. Introduction

This is the final technical report submitted by the Massachusetts Institute of Technology (MIT) to the Geodesy and Gravity Branch of the Phillips Laboratory (PL; formerly the Geophysics Laboratory, GL), Air Force Systems Command, under Contract F19628-86-K-0009, entitled "SATELLITE RADIO INTERFEROMETRY." The period of performance of this contract was 29 April 1986 - 30 April 1991.

The contract title "Satellite Radio Interferometry" refers to techniques for determining the orbits of earth satellites and the positions of earth-surface points by interferometry with radio waves. "Interferometry" involves measuring phase differences between otherwise similar waves. Two techniques of satellite radio interferometry were investigated under the contract. The first involved measuring the phases of radio waves transmitted by earth-orbiting satellites and received at earth-surface points. The second technique involved transmitting radio signals from earth-surface points to earth-orbiting satellites. The two techniques are closely related, and either may be used to determine satellite orbits and/or earth-surface positions.

In late 1980 under a previous contract (F19628-80-C-0040) with GL, MIT demonstrated that by satellite radio interferometry relative-position vectors between earth-surface points could be determined with centimeter-level accuracy in all three coordinate components. The lengths of the relative-position vectors measured in this demonstration were of the order of 100 meters; thus, the fractional accuracy was about 1 part in 10^4. This demonstration used radio signals transmitted by NAVSTAR Global Positioning System (GPS) satellites. The orbits of these satellites were not determined by radio interferometry; orbital data of sufficient accuracy (uncertainty less than 1 part in 10^4) were available and were obtained from other sources.

Between 1982 and 1985 under another contract (F19628-82-K-0002) with GL, MIT extended the capabilities of the satellite radio interferometry technique.[1] Fractional accuracies of a few parts in 10^7 in relative-position determinations over distances ranging from a few hundred to a few thousand kilometers were obtained, and satellite orbits were also determined by radio interferometry. Orbit-determination uncertainties limited the accuracies of the earth-surface relative-position determinations.

---

[1] Counselman III, C. C., Research in Geodesy Based Upon Radio Interferometric Observations of GPS Satellites, Air Force Geophysics Laboratory Tech. Rept. No. AFGL-TR-87-0091, 17 pp., 31 December 1986. ADA184040

To achieve parts-in-10^7 accuracy under that contract, heroic measures were taken. A transcontinental network of interferometric tracking stations equipped with atomic hydrogen maser frequency standards was used to determine the orbits of the GPS satellites whose signals were being used. Observations from these stations spanning several days were combined to determine the satellite orbits.

For geophysical research purposes, an order-of-magnitude better accuracy — *i.e.* parts in 10^8, or sub-centimeter-level accuracy over more than a hundred kilometers — is needed. Under the present contract such accuracy was finally achieved, as described in §2 of this report. Other contract reports, listed in §3, provide further detail. Contractor personnel who contributed to this achievement are listed in §4.

2. Contract Performance

Immediately upon inception of this contract (29 April 1986), effort was concentrated on (1) publishing results which had been obtained too late for publication under the preceding contract, F19628-82-K-0002, and (2) developing a way to determine satellite orbits accurately without a huge tracking network and without atomic hydrogen maser frequency standards. Interferometer terminals (radio signal receiving and phase measuring apparatus) which had been built under the preceding contract were also resuscitated and refurbished for use under the present contract.

On 29 & 30 April 1986, two technical papers were presented at the Fourth International Geodetic Symposium on Satellite Positioning at the University of Texas, Austin. Summaries of these papers follow:

Title: "GPS Orbit Determination"

Authors: R. I. Abbot, Y. Bock, C. C. Counselman III, and R. W. King

Abstract: In order to perform precise interferometric tracking of the GPS satellites, we have installed Air Force Geophysics Laboratory dual-band receivers at the three VLBI stations of the POLARIS network: the Haystack Observatory in Massachusetts, the USNO Time Service Alternate Station in Richmond, Florida, and the Harvard College Observatory in Ft. Davis, Texas. With these three stations we have been able to determine orbits with a precision of 2 parts in 10^7 [Ref. 1]. The March 1985 High Precision Baseline Test [2] provided the opportunity to add a fourth station to our tracking network. It also made available repeated observations of regional baselines with which we could test our orbital analysis.

For our analysis we used singly differenced phase observations between the three POLARIS stations, each equipped with a hydrogen-maser frequency standard, and doubly differenced observations between the TI 4100 receiver at the Owens Valley Radio Observatory (OVRO) and the other three receivers. The relative coordinates of

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these four sites are well determined from VLBI observations [3]. In order to determine the coordinates with respect to the earth's center of mass, we estimated a 7-parameter transformation between the (NGS) VLBI and (Univ. Texas) satellite laser ranging (SLR) [4] coordinates of four sites (Haystack, Ft. Davis, OVRO, and Wettzell) which have been well determined by both techniques [5]. Using these transformation parameters we computed the coordinates of the four VLBI antennas in the SLR reference system. We then used high quality local surveys between the VLBI and GPS antennas to compute the coordinates of the latter in the same system [6]. We obtained earth orientation parameters from a combination of VLBI and SLR determinations [7].

We modeled the satellite orbits by numerically integrating over 2-day arcs the equations of motion from estimated initial conditions. The force model consisted of a GEM L2 8 x 8 gravity field [8], luni-solar accelerations from numerically integrated models, a direct solar radiation pressure acceleration with a free parameter, and a spacecraft y-axis acceleration with a free parameter [9]. We modeled the tropospheric delay in the received signal using surface values of temperature and pressure, plus a free zenith delay parameter to account for the wet component, which is poorly determined from surface measurements.

We combined observations of NAVSTARs 3, 4, 6, 8, and 9 in three 2-day spans. For each span, we estimated six initial conditions and a y-axis parameter for each satellite, a tropospheric zenith delay for each site on each day, a clock epoch offset for OVRO on each day, and a clock rate offset for two of the three POLARIS sites on each day. The uncertainties of the satellites' initial conditions were typically 1-4 m, or 1-2 parts in 10^7, with the dominant component of the error being along-track.

To obtain an independent test of the quality of our orbits, we used them to estimate coordinates of three baselines observed simultaneously during the March test: a 30-km baseline in Massachusetts [10], and a 70-km and a 250-km baseline in California [11]. For the two shorter baselines, the (unweighted) rms scatter of 9 determinations was 2 parts in 10^7 in the two horizontal components, and 5 parts in 10^7 in the vertical. The rms scatter of four determinations of the 250-km baseline, which is less affected fractionally by errors in the tropospheric model, was 3 parts in 10^8 in latitude and 1 part in 10^7 in longitude and height. The better repeatability in latitude was expected from the superior north-south coverage provided by the present satellite constellation. A test of the accuracy (as opposed to precision) of the orbits is possible using the estimated coordinates of the 250-km baseline, which has also been measured by VLBI and SLR. Our estimates of the coordinates of this baseline (OVRO to Mojave) differ from the VLBI estimates by less than 2 parts in 10^7 (5 cm) in each of the three coordinates. Our estimate of the length differs from the SLR estimate by 1 part in 10^7 (2 cm).

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11. Bock, Y., R. I. Abbot, C. C. Counselman III, and R. W. King, A Demonstration of 1-2 Part in 10^7 Accuracy Using GPS, submitted to Bulletin Geodesique, 1986.

Title: "Processing of GPS Phase Observables in the Network Mode"

Au's: Y. Bock, R.I. Abbot, C.C. Counselman III, R.W. King, and A.R. Paradis

Summary: In the most general network scenario, a number of receivers, deployed at sites that are not uniformly distant, simultaneously track the phases of the signals received in two GPS frequency bands (L1 and L2) from a number of satellites, over a time span ranging from several minutes to several hours. One such series of observations is called a session. The receivers are deployed, in several sessions, over the totality of stations until a sufficiently redundant network is achieved. The processing of the typically thousands of carrier phase measurements thus collected yields a consistent set of coordinates for all the stations, and possibly corrections to one or more sets of satellite ephemerides. In another scenario, a set of receivers deployed at known locations tracks the GPS satellites in order to determine the satellite ephemerides.

We have developed an interferometric method of analyzing GPS phase observations in the network mode. Relative positions are best determined from between-stations differenced observations, in which common-mode errors (atmosphere, satellite clocks and orbits) are canceled. Station clock errors may be canceled by taking a second difference, between satellites, or by modeling the clock behavior epoch by epoch [Ref. 1]. The errors remaining in the differenced observations are dependent on baseline length and orientation, and on other factors such as the variability of the atmospheric delay during the session. In view of this dependence, an optimal network analysis requires relative weighting of the observations. We have also considered differencing algorithms, and problems related to the analysis of dual-band observations, integer-bias fixing, and automatic cycle-slip detection. A complete description of our interferometric method can be found in [2].

We applied our analysis technique to a three-station network in California, with baselines of 70-, 250-, and 310-km length [3]. Using the ephemerides of Abbot et al. [4], the rms scatter of four determinations of the baseline components was less than 1 part in 10^7. For the 250-km baseline between Mojave and Owens Valley, we compared our estimates with values determined by VLBI and found differences no larger than 2 parts in 10^7 in any component. Our estimate of the length differs from the value determined by laser ranging to LAGEOS by 1 part in 10^7 (2 cm).

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1. Goad, C. C., Precise Relative Position Determination Using Global Positioning System Carrier Phase Measurements in a Nondifferenced Mode, Proc. 1st Intl. Symp. on Precise Positioning with GPS, Vol. 1, pp. 347-356, C. Goad, ed., NOAA, Rockville, Md., 1985.

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3. Bock, Y., R. I. Abbot, C. C. Counselman III, and R. W. King, A Demonstration of 1-2 Parts in 10^7 Accuracy using GPS, submitted to Bulletin Geodesique, 1986.

4. Abbot, R. I., Y. Bock, C. C. Counselman III, and R. W. King, GPS Orbit Determination, presented at this Symposium April 29, 1986.

In May 1986 the following advance abstract was submitted for an oral presentation to be made at International Astronomical Union (IAU) Symposium No. 128, "Earth Rotation and Reference Frames for Geodesy and Geodynamics," to be held October 20-24, 1986:

Title: "Earth Rotation from Radio Interferometric Tracking of GPS Satellites"

Authors: R. I. Abbot, R. W. King, Y. Bock, and C. C. Counselman III

Abstract: Radio-interferometric tracking of the Global Positioning System (GPS) satellites offers a new technique for regular monitoring of variations in the earth's rotation. The observations are sensitive to pole position and length of day at a level of precision which may make this technique competitive with satellite and lunar laser ranging and VLBI. The present limitations are the number of satellites and tracking stations available, and inadequate modeling of non-gravitational forces on the satellites. The potential advantages are rapid turn-around and minimal incremental cost.

We have estimated pole position and length-of-day values from six days of observations obtained in April 1985 with a four-station network. We will discuss the precision of our estimates and present a comparison with values from VLBI and laser ranging to LAGEOS.

On May 27, 1986, a 25-page manuscript was submitted for publication in the scientific journal manuscripta geodaetica. In due course this paper was published in manuscripta geodaetica, vol. 11, pp. 282-288, 1986.

Title: "Interferometric Analysis of GPS Phase Observations"

Authors: Y. Bock, Sergei A. Gourevitch, Charles C. Counselman III, R. W. King, and R. I. Abbot

Abstract: We present an interferometric method of analyzing GPS phase observations to determine relative position coordinates of stations in a geodetic network. Relative positions are best determined from between-stations difference observations, in which common-mode errors (propagation-medium, satellite clocks and orbits) are cancelled. A second difference may be taken, between satellites, to cancel station-associated errors. The errors remaining in differenced observations are greater, the greater the distance between the stations. In view of this distance dependence, we consider relative weighting of observations, optimal differencing algorithms, and problems related to the analysis of dual-band observations, integer-bias fixing, and automatic cycle-slip detection. The methods developed are also applicable to orbit improvement.

Another full-length article (17 pp. of text plus 8 tables and 3 figures) was submitted July 2, 1986, for publication in the scientific journal *Bulletin Géodesique*. This article appeared in *Bulletin Géodesique*, vol. 60, pp. 241-254, 1986.

Title: "A Demonstration of 1-2 Parts in 10^7 Accuracy using GPS"

Authors: Yehuda Bock, Richard I. Abbot, Charles C. Counselman III, and Robert W. King

Abstract: By interferometric analysis of GPS phase observations made at Owens Valley, Mojave, and Mammoth Lakes, California, we determined the coordinate components of the 71-245-313-km triangle of baselines connecting these sites. A separate determination was made on each of four days, April 1-4, 1985. The satellite ephemerides used in these determinations had been derived from observations on other baselines.

The rms scatters of the four daily determinations of baseline vector components about their respective means ranged from a minimum of 6 mm for the north component of the 71-km baseline to a maximum of 34 mm for the vertical component of the 245-km baseline.

To test accuracy, we compared the mean of our GPS determinations of the 245-km baseline between Owens Valley and Mojave with independent determinations by others using very-long-baseline inteferometry (VLBI) and satellite laser ranging (SLR). The GPS-VLBI difference was within 2 parts in 10^7 for every vector component, and 7 parts in 10^8 (16 mm) in height. The GPS-SLR difference was within 6 parts in 10^8 in the horizontal coordinates, but was 103 mm in height.

On 10 September 1986, an invention disclosure entitled "Method of Determining Satellite Orbits," comprising a drawing, 15 pages of text, and the *manuscripta geodaetica* manuscript as an appendix, was submitted through the Administrative Contracting Officer to the Patents Officer, ESD (AFSC). With this submission MIT also notified the Air Force of its election to file a patent application for the disclosed inventions, which included tech-

niques for determining satellite orbits accurately without a huge tracking network and also without atomic hydrogen maser frequency standards. An abbreviated abstract of the patent application appears on page 12 of the present report.

Also in September 1986 the following advance abstracts were submitted for poster presentations at the December, 1986 Fall Meeting of the American Geophysical Union:

Title: "Interferometric Determination of GPS Satellite Orbits"

Authors: R. W. King, R. I. Abbot, Y. Bock, and C. C. Counselman III

Abstract: We have investigated a variety of methods for determining the orbits of the GPS satellites, all using interferometric phase observations over a six-day span obtained at stations in California, Texas, Florida, and Massachusetts. The coordinates of all the tracking stations were well known from VLBI observations, and three of the stations used hydrogen-maser frequency standards. For our analysis we used singly or doubly differenced phase observations between the three maser-equipped stations, and doubly differenced observations between the fourth station and the other three. We analyzed the observations in various ways, using 1-, 2-, and 3-day spans and making different assumptions about the behavior of the non-gravitational forces on the satellites and the hydrogen-maser frequency standards at the tracking stations, and using different combinations of singly and doubly differenced observations. To test the quality of our orbits, we used them to estimate coordinate components of a 313-km baseline in California and a 2036-km baseline between California and Texas. With our best orbits, the rms scatter of five determinations of the longer baseline was 1 part in 10^8 in the north and 5 parts in 10^8 in the east and vertical components. This scatter was not a strong function of the span or type of observations (single or double differences) used in computing the orbits. When observations from only three stations were used in the analysis, the scatter in the north components for both baselines was 2 parts in 10^8, but the scatter in the east and vertical components increased to about 1 part in 10^7.

Title: "Assessment of GPS Accuracy on a 250-km Baseline"

Authors: R. I. Abbot, Y. Bock, and R. W. King

Abstract: The baseline between the Owens Valley Radio Observatory and the Mojave station of the NASA Goldstone complex in California was measured in April and November 1985 as part of multi-station GPS measurement campaigns. We analyzed the observations from four successive days during April campaign and estimated the components of the baseline with an rms scatter of 3 parts in 10^8 in the north, 1 part in 10^7 in the east, and 1.5 parts in 10^7 (34 mm) in the vertical component. To test accuracy, we compared the mean of our GPS determinations with independent determinations by others using very long baseline inteferometry (VLBI) and satellite laser ranging (SLR). The GPS-VLBI difference was within 2.5 parts in 10^7 for every vector component. The GPS-SLR difference was within 1 part in 10^7 in the horizontal coordinates, but 103 mm in height. We will extend our analysis to include the observations from the November campaign in order to determine the longer-term repeatability and to reassess the accuracy of GPS measurements of this baseline.

In the fall of 1986 a full-length manuscript was also completed and submitted for publication in the Proceedings of International Astronomical Union (IAU) Symposium No. 128, "Earth Rotation and Reference Frames for Geodesy and Geodynamics."

Title: "Earth Rotation from Radio Interferometric Tracking of GPS Satellites"

Authors: R. I. Abbot, R. W. King, Y. Bock, and C. C. Counselman III

Abstract: Like the Navy Navigation (TRANSIT) satellites and LAGEOS, the satellites of the Global Positioning System (GPS) provide an opportunity for monitoring the earth's rotation as a byproduct of routine orbit determination. The high altitude (20,000 km) of the GPS satellites makes their orbits less sensitive than those of the other satellites to errors in the models for the earth's gravity field and the solid-earth and ocean tides. However, the GPS satellites are more affected by non-gravitational forces, which stem from direct and reflected radiation pressure on the large solar panels, from accidental discharge of battery and thruster gases, and from unbalanced forces produced by the attitude control system. The best accuracy in GPS orbit determination, achieved with three or four tracking stations and arc lengths of a few days, has been of the order of 1 part in 10^7, equivalent to an error of 0.02" in the orientation of the earth. However, future increases in the numbers of tracking stations and satellites, together with improved modeling of the orbital dynamics, promise a significant reduction in the errors in earth rotation from GPS tracking. The accumulation of errors due to non-gravitational forces will necessarily limit the contribution of GPS to the determination of short-term variations in the rotation. Nevertheless, the low cost of data acquisition and processing make GPS an attractive component of a service for rapid determination and distribution of earth rotation parameters.

There are secondary benefits to estimating earth-rotation parameters as part of GPS orbital analyses. The operational orbital adjustment performed by the Defense Department and civilian agencies can be freed from dependence on an external source of rotation information, which might not be available in a timely fashion. For high-precision geodetic applications, comparison of the values of earth-rotation parameters determined from GPS with values determined from very long baseline interferometry (VLBI) and satellite and lunar laser ranging observations provides an independent check on the accuracy of the GPS orbits.

In order to better understand the use of GPS for determining variations in the earth's rotations, and to ascertain the current accuracy, we performed a limited, preliminary analysis using observations performed over a 6-day period in March 1985. In this paper we describe the method used in our analysis and compare the earth-rotation parameters estimated with results from VLBI.

In 1986 and early 1987, computer simulations of some of the new techniques of orbit-determination were performed; preliminary results indicated that utilization of these techniques would improve accuracy at least threefold relative to previously known techniques. On 20 March 1987, a patent application entitled "TECHNIQUES FOR DETERMINING ORBITAL DATA" was filed in the United States Patent and Trademark Office. Copies of this application and confirmation of the paid-up license granted to the

Government were forwarded to the Administrative Contracting Officer. An abbreviated abstract is reproduced here:

Abstract. Improved techniques have been invented for determining orbital data of space borne vehicles including earth satellites such as those of the NAVSTAR Global Positioning System. Each of a set of such satellites transmits signals which include carrier waves which may be suppressed, or only implicitly present. The signals are received from the observable satellites concurrently by means of an antenna at each of at least three ground stations forming a network of baselines. The stations are arrayed such that the ratio of the maximum to the minimum baseline length is much greater than one. From the signals received at the station pair forming each baseline a time series of doubly-differenced phase measurement data is formed which is biased by an integer number of cycles of phase. The data series for different satellite and station pairs are processed together to determine the orbits of the satellites and the doubly-differenced phase biases. Unique determination of the integer values of at least some of the biases is facilitated by the above noted spatial arrangement of the stations such that the ratio of the maximum to the minimum baseline length is much greater than one. This integer bias determination enhances the accuracy of the related orbit determination. Unique determination of the integer values of at least some of the doubly-differenced carrier phase biases may also be facilitated by the use of a plurality of carrier frequencies with the ratio of the maximum to the minimum frequency being much greater than one.

During the spring and summer of 1987, the concept that certain spatial arrangements of earth-based satellite tracking stations could yield improved orbit-determination accuracy by facilitating resolution of the integer cycle ambiguities of doubly differenced phase measurements was tested through further computer simulations, and also by analyzing data from actual observations. The simulation results confirmed that orbit-determination uncertainties would be reduced even if phase ambiguities could be resolved only on short baselines within a network of short and very long baselines. The power of bias-fixing or ambiguity-resolution to improve orbit determination was also demonstrated by the results of the actual data analyses. For example, GPS satellite orbits were determined from a six-hour span of observations at six stations on April 3, 1985. Three of these stations, at Owens Valley ("OVRO"), Mammoth Lakes ("Mam. L.," 71 km away), and Mojave (245 km away), all in California, were relatively closely spaced. The others, at Ft. Davis, TX, Miami, FL, and Westford, MA, were much more widely spaced (min. distance 1500 km; max. 4000 km). (See Figure 1.)
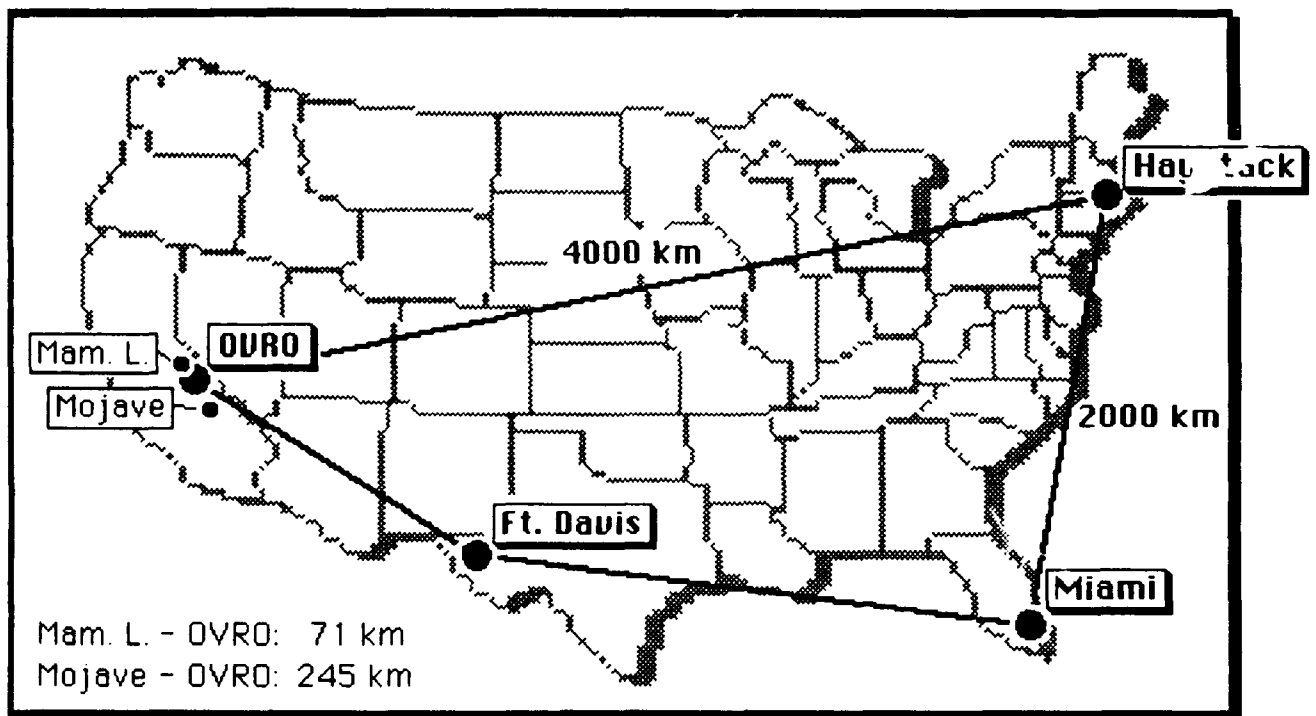
Figure 1. Stations whose GPS satellite observations were used to test new orbit-determination techniques.

Orbits determined initially without benefit of bias-fixing were sufficiently accurate to fix all of the doubly differenced phase biases for the shortest (OVRO-Mam.L., 71 km) baseline, but not for the next-longer (OVRO-Moj., 245 km) baseline. However, fixing the OVRO-Mam.L. biases so improved the orbit determination that all OVRO-Mojave biases could be fixed. Fixing the latter biases further improved the orbit determination.

As a standard to test orbit-determination accuracy, additional observations were used which, unlike the others, had been governed by atomic hydrogen maser frequency standards. The test results showed that bias-fixing, done just for the under-250-km baselines within the 4000-km network, had cut the orbital errors in half. (See Figure 2.)
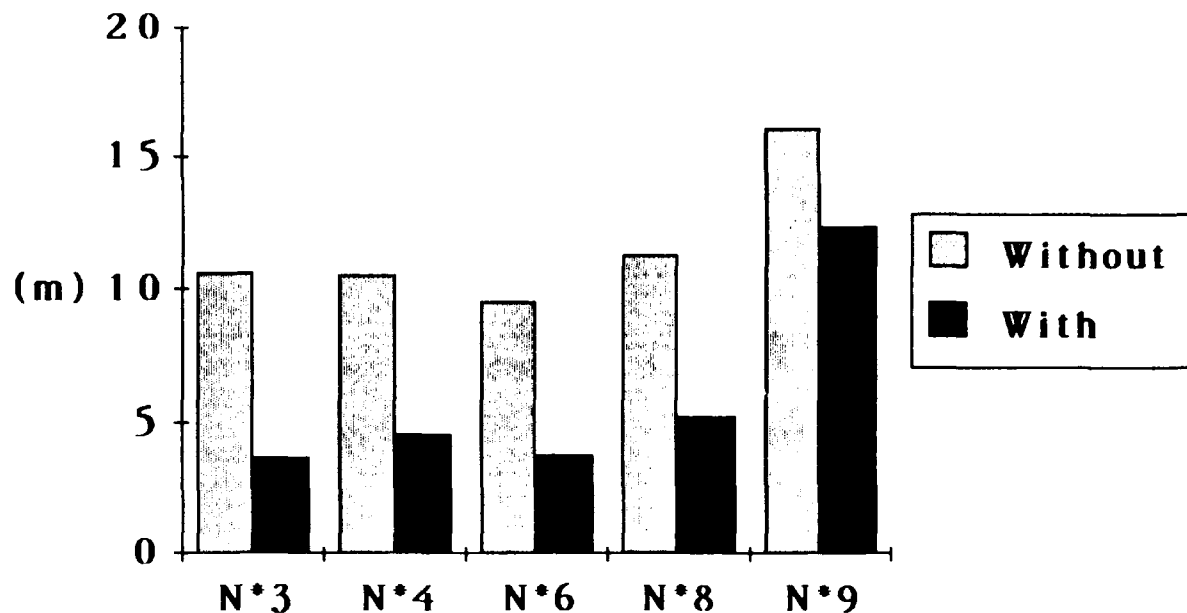
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Figure 2. Actual error (not "formal" error) of orbit determination from 6 hours' observations, without and with ambiguity resolution of the observations from the 71- and 245-km baselines. The value plotted in each case, for each satellite (N*3 = NAVSTAR 3, etc.), is the peak magnitude of the satellite position error, in meters, occurring in any direction, at any time while the satellite was in view.

These results showed that ambiguity resolution, even if done only for relatively short baselines within a large network, enhanced orbit determination accuracy by about a factor of two.

Abstracts of two papers were submitted for presentation at the 1987 Fall Meeting of the American Geophysical Union. The first paper explained the concept for enhancement of orbit determination accuracy through ambiguity resolution; the second paper gave the results of simulations and tests with actual observations from the network of Figure 1.

Title: "Resolving Carrier Phase Ambiguity in GPS Orbit Determination"

Au.:   C. C. Counselman III

Abstract: When GPS satellite orbits are determined from series of carrier phase observations by double-differencing or equivalent algorithms, the orbital errors can be reduced dramatically by resolving the ambiguities, or "fixing the biases," of the observations. To facilitate this ambiguity resolution, the observing stations should be arranged to form both long and short baselines. Preferably, the baseline lengths span a 30-to-1 range and include a progression of intermediate values. Then, the observations from the longest baselines, even with their biases unknown or "free," determine the orbits so accurately that the biases of the observations from the shortest baselines can be fixed. Fixing these short-baseline biases reduces the orbital

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uncertainties so that longer-baseline biases, otherwise impossible to fix, can also be fixed. Preferably, observations from all stations/baselines are processed together simultaneously to estimate ambiguity and orbital parameters.

This method of orbit determination is analogous to the method of radio-source mapping by aperture synthesis, used in radio astronomy, and to the method of delay or range resolution by bandwidth synthesis, used in geodesy by very long baseline interferometry. Aperture and bandwidth synthesis are synergetic. Thus, phase observations for satellite orbit determination are best made with a plurality of frequencies (*e.g.* GPS L1 & L2 band-center carriers, code "chipping rate" sub-carriers, etc.) as well as baselines.

Title: "Demonstration of GPS Orbit-Determination Enhancement by Resolution of Carrier Phase Ambiguity"

Au's: R. I. Abbot and C. C. Counselman III

Abstract: It is suggested in the preceding paper that the accuracy of GPS orbit determination can be enhanced by combining observations from closely spaced stations with observations from widely spaced stations, and thereby "fixing biases." To test this idea, we have processed data from observations at six stations, on April 1st, 2nd, and 3rd of 1985, of the L1 and L2 band center frequency carrier phases of the signals received from five NAVSTAR GPS satellites. Three of these stations, at Owens Valley ("O.V."), Mammoth Lakes ("M.L.", 71 km away), and Mojave ("Moj.", 245 km away), all in California, were relatively closely spaced. The others, at Ft. Davis, TX, Miami, FL, and Westford, MA, were much more widely spaced (min. distance 1500 km; max. 4000 km).

We found that the orbits determined without benefit of any bias-fixing were sufficiently accurate for us to fix, with confidence, every day, all of the L1 and L2 phase biases for the shortest (O.V.-M.L., 71 km) baseline, but not so for the next-longer (O.V.-Moj., 245 km) baseline. However, fixing the O.V.-M.L. biases so improved the orbit determination that all O.V.-Moj. biases could be fixed with confidence every day.

That the orbit determinations were in fact enhanced was shown by the improved resolution of the O.V.-Moj. bias ambiguities, by reductions of the formal standard errors of the orbital elements, and by reduction of the day-to-day scatter of related station-coordinate determinations.

By mid-1988, further analyses and simulations of the improved orbit-determination techniques had been performed. Orbit- and baseline-determination software developed originally on a microcomputer system was expanded, enhanced, and adapted to a Unix/Sun computer system which was 25 to 60 times faster. This speed would be needed in analyses of orbit-determination experiments which were being planned. Work began on improving the tropospheric and ionospheric refraction models used in this software, and on improving the method of combining group delay and phase observations.

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In May 1988, contract Scientific Report No. 1 (printed as GL-TR-88-0129; ADA 205826) was submitted to GL/SULR, and also submitted for publication in the *Journal of Geophysical Research:*

Title: "An Improved Strategy for Determining Earth Satellite Orbits by Radio"

Authors: Charles C. Counselman III and Richard I. Abbot

Abstract: For satellite orbit determination, the most accurate observable available today is microwave phase, differenced between observing stations and between satellites to cancel both transmitter and receiver related errors.   For maximum accuracy, the integer cycle ambiguities of such observations must be resolved.   To perform this ambiguity resolution, a bootstrapping strategy is effective.   The tracking stations must have a wide ranging progression of spacings.   Then, by conventional "integrated Doppler" processing of the observations from the most widely spaced stations, the orbits can be determined well enough to permit resolution of the ambiguities of the observations from the most closely spaced stations.   The resolution of these ambiguities can reduce the uncertainty of the orbit determination enough to enable ambiguity resolution for more widely spaced stations, which will reduce the orbital uncertainty further, and enable ambiguity resolution for still more widely spaced stations, and so on.   In a test of this strategy with a total of six tracking stations, both the formal and the actual errors of determining Global Positioning System satellite orbits were reduced by a factor of two.

An orbit-determination experiment intended to test this Improved Strategy was conducted for 14 days in November 1988, with twelve dual-band receivers in a "Nautilus" spiral network. (See Figure 3.)
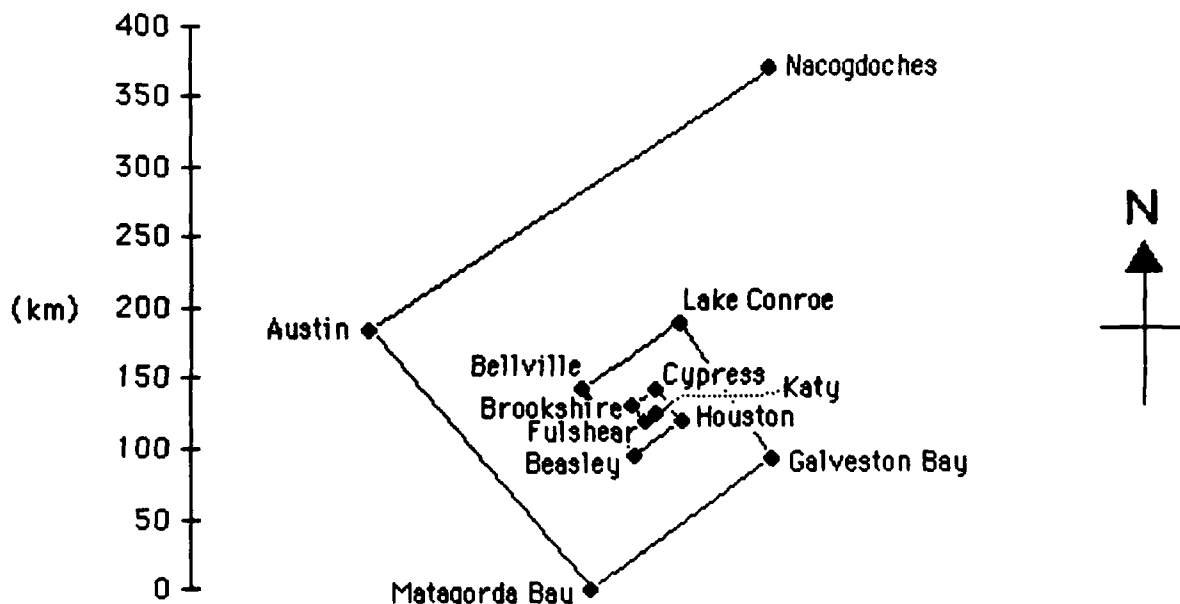

Figure 3. Scale drawing of twelve-station "Nautilus" network, surrounding Houston Texas, used in November 1988 orbit-determination experiment. Each station is labeled with its geographic place name.

A preliminary abstract entitled "GPS Orbit Determination: Bootstrapping to Resolve Carrier Phase Ambiguity" was submitted to the program committee of the Fifth International Geodetic Symposium on Satellite Positioning, in anticipation of the March 1989 symposium:

Abstract: For GPS satellite orbit determination, the most accurate observable available is carrier phase, differenced between observing stations and between satellites to cancel both transmitter and receiver related errors. For maximum accuracy, the integer cycle ambiguities of such observations must be resolved. To perform this ambiguity resolution, a bootstrapping strategy is effective. The tracking stations must have a wide ranging progression of spacings. Then, by conventional "integrated Doppler" processing of the observations from the most widely spaced stations, the orbits can be determined well enough to permit resolution of the ambiguities of the observations from the most closely spaced stations. The resolution of these ambiguities can reduce the uncertainty of the orbit determination enough to enable ambiguity resolution for more widely spaced stations, which will reduce the orbital uncertainty further, and enable ambiguity resolution for still more widely spaced stations, and so on. In a test of this strategy with six tracking stations spaced from 71 km to 4000 km apart, both the formal and the actual errors of determining Global Positioning System satellite orbits were reduced by a factor of two. Another test, involving stations spaced from 10 km to several thousand km, is underway at this writing. Results of both tests will be presented.

The article previously submitted to the *Journal of Geophysical Research* was revised in response to reviewers' comments and resubmitted on January 27, 1989, with a new title and abstract as follows. This article appeared in the *Journal of Geophysical Research*, vol. 94, No. B6, pp. 7058-7064, June 10, 1989.

Title: "Method of Resolving Radio Phase Ambiguity in Satellite Orbit Determination"

Authors: Charles C. Counselman III and Richard I. Abbot

Abstract: For satellite orbit determination, the most accurate observable available today is microwave radio phase, which can be differenced between observing stations and between satellites to cancel both transmitter- and receiver-related errors. For maximum accuracy, the integer cycle ambiguities of the doubly differenced observations must be resolved. To perform this ambiguity resolution, we propose a bootstrapping strategy. This strategy requires the tracking stations to have a wide ranging progression of spacings. By conventional "integrated Doppler" processing of the observations from the most widely spaced stations, the orbits are determined well enough to permit resolution of the ambiguities for the most closely spaced stations. The resolution of these ambiguities reduces the uncertainty of the orbit determination enough to enable ambiguity resolution for more widely spaced stations, which further reduces the orbital uncertainty. In a test of this strategy with six tracking stations, both the formal and the true errors of determining Global Positioning System satellite orbits were reduced by a factor of 2.

An oral presentation entitled "GeoBeacon System" was made by C. C. Counselman III on January 11, 1989, to the Committee on Geodesy of the National Academy of Sciences, National Research Council, in Washington, D.C. Copies of the 14 viewgraph transparencies shown in the course of that presentation were submitted with DD Form 1473 to GL/SULR on January 9th. The GeoBeacon System is a proposed satellite radio interferometry system in which transmitters whose positions are to be determined are located on (or near) the ground (possibly in vehicles). Satellites relay the signals from these transmitters to a central site where the phases are measured, etc. Scientific Report No. 2 (GL-TR-89-0031; ADA209958), analyzing this system, was submitted to GL/SULR in February 1989. An invited presentation of this report was also made at the Fourth Annual Workshop on Global Positioning System Geodesy which was held at the Jet Propulsion Laboratory in Pasadena, CA, on April 10th.

Title: "Feasibility of Millimeter-Accuracy Geodetic Positioning and Vehicle Tracking With Repeater Satellites"

Author: Laureano A. Cangahuala

Abstract: A proposed satellite system (named "GeoBeacon") can detect and locate transmitters of a geodetic positioning system as well as transmitters of an emergency search and rescue (SAR) system. Simple, low-power transmitters on the Earth's surface will broadcast code-modulated signals. These signals will be received and rebroadcast to a processing site by a constellation of repeater satellites. A SAR transmitter can transmit at one frequency. For geodetic applications, a transmitter must transmit signals at more than one frequency, including a relatively low (e.g. 100 MHz) and a relatively high (several GHz) frequency. The low frequency signals would aid the acquisition and tracking of the higher frequency signals. By virtue of this aiding, the transmitted power required to enable tracking of signals at 10 GHz is about 100 times less than the power needed for tracking such a signal alone.

Uplink power requirements both for aided tracking and for unaided acquisition are calculated as functions of frequency from 100 MHz to 50 GHz. The chief uncertainty in the calculations concerns the man-made radio noise environment in earth orbit.

An algorithm is developed for the selection of frequencies by which aided tracking of the highest frequency signal can be maintained. This algorithm is based on a stochastic description of the kinematic and ionospheric contributions to the received signal frequencies and phases. Discrete Kalman filter equations are derived for estimating the covariance of phase and frequency estimates. Frequency selections and corresponding power budgets are presented for a vehicle-tracking/SAR system and for a geodetic positioning system.

Scientific Report No. 3 (GL-TR-89-0039; ADA209974), entitled "GPS Orbit Determination: Bootstrapping to Resolve Carrier Phase Ambiguity" was submitted to AFGL/SULR on May 19, 1989. This was a later version of the paper which had been submitted in preliminary form to the Fifth International Geodetic Symposium on Satellite Positioning:

Title: "GPS Orbit Determination: Bootstrapping to Resolve Carrier Phase Ambiguity"

Authors: Richard I. Abbot, Charles C. Counselman III, Sergei A. Gourevitch, and Jonathan W. Ladd

Abstract: For Global Positioning System (GPS) satellite orbit determination, the most accurate observable available is carrier phase, differenced between observing stations and between satellites to cancel both transmitter and receiver related errors. For maximum accuracy, the integer cycle ambiguities of such observations must be resolved. To perform this ambiguity resolution, a bootstrapping strategy is effective. This strategy requires the tracking stations to have a wide ranging progression of spacings. Then, by conventional "integrated Doppler" processing of the observations from the most widely spaced stations, the orbits can be determined well enough to permit resolution of the ambiguities of the observations from the most closely spaced stations. The resolution of these ambiguities can reduce the uncertainty of the orbit determination enough to enable ambiguity resolution for more widely spaced stations, which will reduce the orbital uncertainty further, and enable ambiguity resolution for still more widely spaced stations, and so on. We have tested this strategy with two different tracking networks. In one network, six stations had closest-pair spacings of 71, 245, 1500, ..., and 4000 km. Resolving ambiguities for the 71-km pair made it possible to do so for the 245-km pair. This limited ambiguity resolution reduced both the formal and the actual errors of GPS orbit determinations by a factor of two. In the second network, twelve stations were arranged in a spiral with geometrically increasing spacings from 10 to 330 km. By bootstrapping, all ambiguities for baselines up to about 100 km long were resolved. The distance was limited by strong ionospheric variability. Still, orbit-determination uncertainty (3σ) was reduced to about 1 part in 10^6. Improved handling of ionospheric effects in ambiguity resolution, and the use of observations spanning more than one day, should further reduce the uncertainty.

Scientific Report No. 4, entitled "Enhanced Satellite Geodesy Through the Addition of a Pseudorange Observable," was submitted to GL/SULR on August 8, 1989. The abstract of this report is reproduced below. This report describes a computer simulation whose purpose was to study the utility, if any, of combining single-band (L1 only) C/A-code group-delay observations with dual-band (L1 and L2) carrier phase-delay observations when dual-band P-code group-delay observations are not available. Theoretically, it is always useful to add another independent observation; and the utility of combining GPS code and carrier observations had been recognized since 1982. However, C/A code delay observations are often so badly corrupted by systematic errors (due to the relatively narrow bandwidth of the C/A code modulation) that combining them with carrier phase observations can do more harm than good. Theoretically, the harm results from incorrectly characterizing the statistics of the errors of observation. In practice, it is difficult to know the correct characterization.

The report concluded that, for the particular situations studied, it was not worthwhile to combine single-band (L1 only) C/A-code group-delay observations with dual-band

(L1 and L2) carrier phase-delay observations. This conclusion is not universally valid although it may apply in particular situations such as the November 1988 "Nautilus" experiment in which very long continuous time-series of dual-band carrier phase observations were made.

Title: "Enhanced Satellite Geodesy Through the Addition of a Pseudorange Observable"

Author: Jayant Sharma

Abstract: The Global Positioning System (GPS) satellites transmit suppressed carrier signals which are modulated by pseudorandom "ranging" codes known as Coarse/Acquisition (C/A) and Precise (P) codes. Range information can be derived by measuring the reconstructed carrier phase or the delay of the code modulation of a received signal. Subcentimeter-level relative positioning has been achieved by measuring carrier phase. Improvements in relative positioning have been achieved by combining P code delay or "pseudorange" observations with phase observations. Since changes in the GPS will eventually make P code observations impossible for civilian users, this study examines the effect of combining C/A code observations with carrier phase observations. Carrier phase observations represent relatively precise, but biased, measurements of the satellite-to-receiver range. If phase observations are differenced between receivers and satellites, the bias is an integer number of cycles. If this integer value can be determined, position-determination accuracy is improved. Range measurements based on code delay may help to determine the integer bias. Unfortunately, the C/A code provides a relatively noisy range measurement.

In this study, C/A code observations were simulated using actual phase observations. The mean values of the ionospheric contributions to the simulated observations were determined from the International Reference Ionosphere (IRI) model, and variations about the means were derived from actual dual-frequency phase observations. These phase and C/A code observations were used to estimate biases and baseline vectors, for baseline lengths of 10, 100, and 330 km. The results of the simulation indicate that no significant improvement in positioning accuracy is obtained by adding C/A code to carrier phase observations. A possible explanation for the lack of improvement may be the assumption, in the analysis of the observations in this study, of zero a priori ionospheric contribution to the observations.

Scientific Report No. 5, entitled "Feasibility of Millimeter-Accuracy Geodetic Positioning and Vehicle Tracking With Repeater Satellites," was submitted to GL/SULR on 9 September 1989, and was presented orally at "ION GPS-89," the Institute of Navigation, Satellite Division, 2nd International Technical Meeting, in Colorado Springs, CO, on 25-29 September 1989. This report was an extension of Scientific Report No. 2 (GL-TR-89-0031; ADA209958) giving more attention to vehicle tracking and to the optimal selection of frequencies for minimum total transmitted power.

Abstract: A proposed satellite system (named "GeoBeacon") can detect and locate transmitters of a geodetic positioning system as well as transmitters of an emergency search and rescue (SAR) system. Simple, low-power transmitters on the Earth's

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surface will broadcast code-modulated signals. These signals will be received and rebroadcast to a processing site by a constellation of repeater satellites. A SAR transmitter can transmit at one frequency. For geodetic applications, a transmitter must transmit signals at more than one frequency, including a relatively low (e.g. 100 MHz) and a relatively high (several GHz) frequency. The low frequency signals would aid the acquisition and tracking of the higher frequency signals. By virtue of this aiding, the transmitted power required to enable tracking of signals at 10 GHz is about 100 times less than the power needed for tracking such a signal alone.

Uplink power requirements both for aided tracking and for unaided acquisition are calculated as functions of frequency from 100 MHz to 50 GHz. The chief uncertainty in the calculations concerns the man-made radio noise environment in earth orbit.

An algorithm is developed for the selection of frequencies by which aided tracking of the highest frequency signal can be maintained. This algorithm is based on a stochastic description of the kinematic and ionospheric contributions to the received signal frequencies and phases. Discrete Kalman filter equations are derived for estimating the covariance of phase and frequency estimates. Frequency selections and corresponding power budgets are presented for a vehicle-tracking/SAR system and for a geodetic positioning system.

On 6 September 1989, abstracts of three reports were submitted to GL/ SULR in advance of the 1989 Fall meeting of the American Geophysical Union in San Francisco on December 4 - 8, 1989. The first of these reports, entitled "Ionospheric Modeling Enhances Ambiguity Resolution in GPS Orbit and Baseline Determination," was ultimately presented as a poster paper at that meeting, and copies of the posters were submitted as contract Scientific Report No. 7. The second report, entitled "A Day in the Life of the Ionosphere," was also presented as a poster paper at that meeting; copies of these posters were submitted as contract Scientific Report No. 8. The third report, entitled "Feasibility of Millimeter-Accuracy Geodetic Positioning and Vehicle Tracking with Repeater Satellites," was presented orally at the AGU meeting. This report was basically the same as Scientific Report No. 5, described above. The three abstracts are reproduced below.

Ionospheric Modeling Enhances Ambiguity Resolution in GPS Orbit and Baseline Determination

R. I. Abbot, C. C. Counselman, and S. A. Gourevitch

The "bootstrapping" strategy for resolving integer cycle phase ambiguities in GPS orbit and baseline determination, proposed by Counselman (*Eos, 68,* 1238, 1987) and demonstrated by Abbot and Counselman (*ibid.*) and Counselman and Abbot (*JGR, 94,* 7058-7064, 1989), is enhanced substantially if a simple model is used to account for ionospheric refraction, including latitude and solar-time variations. The bootstrapping strategy requires the GPS receivers to have a wide ranging progression of spacings. By conventional integrated-Doppler processing of the observations from the most widely spaced stations, the orbits of the satellites are determined well enough to permit resolution of the doubly differenced phase ambiguities for the most closely spaced stations. The resolution of these ambiguities reduces the uncertainty of the orbit determination enough to enable ambi-

guity resolution for more widely spaced stations, which further reduces the orbital uncertainty.

Ionospheric refraction interferes with ambiguity resolution in much the same way as orbital position error; either affects the phase observable by an amount which is time-variable, but spatially coherent, with a virtually uniform gradient across a few-hundred-kilometer-size tracking network. Thus, the same boot-strapping principle which facilitates ambiguity resolution in the presence of orbital uncertainty, will be effective in the presence of significant ionospheric refraction.

To test this prediction, we analyzed GPS observations from a recent period of high solar activity, with daily observation periods spanning the morning hours during which the ionosphere varies most rapidly. The ionospheric refraction effects in these observations (5 am - noon, November 1988, in Texas) were some 20 times stronger than in the night-time, April 1985, observations originally studied by Abbot and Counselman.

Using a very simple, five-parameter, ionospheric model, we processed observations from 12 dual-band receivers which were arranged in a logarithmic "Nautilus" spiral with spacings from 10 to 320 km. The use of this model increased the interstation baseline length for which ambiguities could be resolved by a factor of two (to the maximum length available). Observations on successive days were processed independently; i.e., the ionospheric parameters, the position coordinates of nine receiving stations (three stations served as "fiducials"), and all the orbital elements of each satellite were determined from "single-day" arcs. The horizontal station-position coordinate estimates changed, from one day to the next, by a few parts in 10^8 of the distance to the nearest fiducial.

A Day in the Life of the Ionosphere

S. A. Gourevitch, C. C. Counselman, and R. I. Abbot

The "Nautilus" experiment, whose geodetic results are reported at this meeting by Abbot, Counselman, and Gourevitch, provided a data-set capable of showing the local structure of the ionosphere in great detail. The experiment involved 12 dual-band receivers, arranged in a logarithmic spiral with spacings from 10 to 320 km, observing six GPS satellites for most of their visible arcs, daily from 5 am to noon local time, for 14 days in November 1988. From these data we have determined the vertically integrated electron content of the ionosphere at a densely spaced set of up to 72 points, as a function of time. We show maps of the ionospheric structure observed, and discuss implications for choosing a parametrized model of the ionosphere for use in GPS geodesy.

Feasibility of Millimeter-Accuracy Geodetic Positioning
and Vehicle Tracking with Repeater Satellites

L. A. Cangahuala and C. C. Counselman

A feasibility study of the "GeoBeacon" system will be presented. In this proposed system, which is modeled on existing Search And Rescue Satellite ("SARSAT") systems, low-power (< 1 watt) radio transmitters are placed on vehicles or at other points whose positions are to be monitored. Tropospheric and ionospheric refraction may also be monitored. The number of simultaneously operating transmitters may be very great (> 10^5). Signals from all transmitters in view are relayed by small, "bent-pipe" repeater satellites to a central site (or sites)

where detection, measurement, and data processing take place. To enable precise geodetic positioning, signals are emitted at multiple frequencies, including relatively low (*e.g.* 100 MHz) and relatively high (several GHz) frequencies. The lower frequency signals aid the acquisition and tracking of the higher frequency signals in order to reduce transmitter-power requirements.

Further information can be found in:

C. C. Counselman, "GeoBeacon System," presented to National Research Council, Comm. on Geodesy, Jan. 11, 1989. Text + 14 figs. included in minutes available from NRC, Wash., D.C.

L. A. Cangahuala, "Feasibility of Millimeter-Accuracy Geodetic Positioning and Vehicle Tracking with Repeater Satellites, " S.M. thesis presented to the Dept. of Aeronautics and Astronautics, Jan. 27, 1989. Also available as Air Force Geophysics Laboratory report AFGL-TR-89-0031; ADA209958.

L. A. Cangahuala, "Feasibility of Millimeter-Accuracy Geodetic Positioning and Vehicle Tracking with Repeater Satellites," in Proc. of ION GPS-89, the Institute of Navigation Satellite Division 2nd International Technical Meeting, Colorado Springs, Sept., 1989.

On 9 October 1989, Scientific Report No. 6, entitled "Ambiguity Bootstrapping to Determine GPS Orbits and Baselines," was submitted to GL/SULR. This report was presented orally at the Second Symposium on GPS Applications in Space held at AFGL on 10-11 October 1989, and was printed as GL-TR-89-0278 (ADA218206). The abstract follows:

Ambiguity Bootstrapping to Determine GPS Orbits and Baselines
Charles C. Counselman III

For GPS satellite-orbit and interstation-baseline determination, the most accurate observable available is carrier phase, differenced between observing stations and between satellites to cancel both transmitter- and receiver-related errors. For maximum accuracy, the integer cycle ambiguities of the doubly differenced observations must be resolved. To perform this ambiguity resolution, Counselman (*Eos, 68,* 1238, 1987) proposed a bootstrapping strategy. This strategy requires the tracking stations to have a wide ranging progression of spacings. By conventional "integrated Doppler" processing of the observations from the most widely spaced stations, the orbits are determined well enough to permit resolution of the ambiguities for the most closely spaced stations. The resolution of these ambiguities reduces the uncertainty of the orbit determination enough to enable ambiguity resolution for more widely spaced stations, which further reduces the orbital uncertainty.

Abbot and Counselman (*ibid.,* 1987) and Counselman and Abbot (*JGR, 94,* 7058-7064, 1989) applied this strategy to a network of six tracking stations spaced by 71 km, 245 km, ..., up to 4000 km. Resolving ambiguities for the shortest, 71-km baseline made it possible to resolve them for the next-longer, 245-km baseline, and reduced both the formal and the true errors of determining the GPS satellite orbits by a factor of 2. The precision of baseline determination was also significantly improved.

Ionospheric refraction interferes with ambiguity resolution, by systematically biasing the doubly-differenced phase observations. However, the signature of ionospheric refraction resembles that of orbital position error; either effect, although time-variable, is spatially coherent, characterized by a nearly uniform gradient across a few-hundred-kilometer-size tracking network. Thus, the same boot-strapping principle which facilitates ambiguity resolution in the presence of orbital uncertainty, can be effective in the presence of significant ionospheric refraction.

To test this prediction, Abbot, Counselman, and Gourevitch (*Eos*, in press, Fall 1989) analyzed GPS observations from a recent period of high solar activity, with daily observation periods spanning the morning hours during which the ionosphere varies most rapidly. The ionospheric refraction effects in these observations (5 am - noon, November 1988, in Texas) were some 20 times stronger than in the night-time, April 1985, observations originally studied by Abbot and Counselman.

Using a very simple, five-parameter, ionospheric model, Abbot *et al.* processed observations from 12 dual-band receivers which were arranged in a logarithmic "Nautilus" spiral with spacings from 10 to 320 km. The use of this model increased the interstation baseline length for which ambiguities could be resolved by a factor of two (to the maximum length available). Observations on successive days were processed independently; *i.e.*, the ionospheric parameters, the position coordinates of nine receiving stations (three stations served as "fiducials"), and all the orbital elements of each satellite were determined from "single-day" arcs. The standard deviations of the horizontal station-position coordinate estimates were 2.5-4 mm, or 2-3 parts in 10^8 of the distance to the nearest fiducial.

Software changes (mostly minor "bug fixes") made during the next few months improved the precision of these horizontal relative-position determinations by a factor of two. The horizontal-coordinate standard deviations were reduced to less than 2 parts in 10^8. (See Figure 4.)
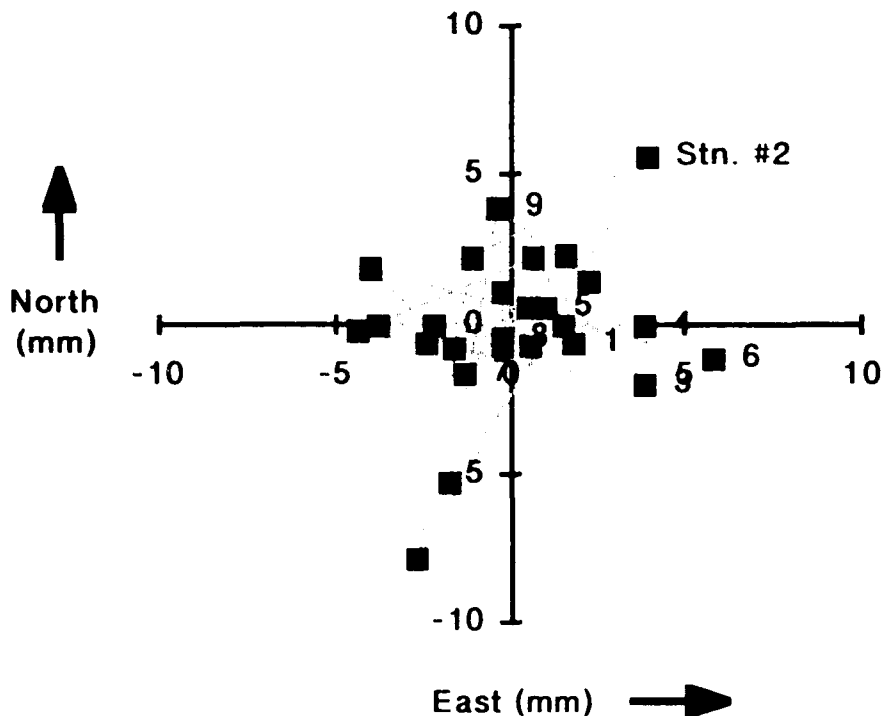
Figure 4. Scatter of repeated determinations, on three days spanning a week, of the positions of the first nine stations shown in Figure 3 (Katy = Stn. #1; Fulshear = Stn. #2,...; each trio of points is labelled with its stn. no.), relative to a coordinate frame defined by the positions of the last three, outermost stations (Matagorda Bay, #10; Austin, #11; Nacogdoches, #12).

These results were noteworthy because they were the most precise ever reported by anyone, especially because they had been obtained with a satellite tracking network only 320 km across, with only seven hours of tracking having been used to determine the satellite orbits, without any atomic frequency standards. The only other researchers who had reported anything approaching this level of precision had required a *worldwide* tracking network, atomic hydrogen-maser frequency standards, and *14 days* of tracking to do so. The keys to MIT's superior results were the methods of "ambiguity bootstrapping" and (relatedly) determining ionospheric gradients which had been invented and developed under this contract.

United States Patent No. 4,912,475, entitled "Techniques for Determining Orbital Data," covering these and various related inventions, issued March 27, 1990. Australian Patent No. 602,198, covering much the same inventions, issued October 4, 1990. Related

applications are pending in other countries. Copies of the printed U.S. patent were forwarded to GL/LWG.

Methods and systems for determining earth-surface point positions by means of repeater satellites continued to be investigated during 1990 and early 1991. A particular topic of investigation was the cost of establishing a suitable repeater-satellite system — and how this cost could be minimized. The cost depends strongly on the choice of satellite orbits. A system having multiple orbit planes and high orbit altitudes (*e.g.* the NAVSTAR Global Positioning System) would be most expensive to launch. A system having just one orbit plane and a low orbit altitude would be least expensive. A key question is what sort of orbits are actually needed to do the job, particularly if the job description does not require continuous, 24 hr.-per-day, worldwide coverage. Through computer simulations it was found that excellent geodetic position determinations — comparable to those obtained with the NAVSTAR Global Positioning System — are obtainable with a repeater satellite constellation having as few as two satellites, orbiting in a single plane of medium (*e.g.* 45°) inclination, at an altitude of the order of 1000 km. Such a constellation could be launched very inexpensively, perhaps by "piggyback" on another, larger satellite launch.

These findings were the subject of a poster presentation at the 1990 Fall Meeting of the American Geophysical Union. The abstract of this presentation was submitted to the AGU and to GL/SULR on 5 September 1990 and was published in *Eos Trans. AGU*, vol. 71, no. 43, on pp. 1277 - 1278, October 23, 1990. Reduced-size copies of the posters were submitted to GL as an Interim Technical Report under the contract. A copy of the abstract follows:

GeoBeacon Satellite Orbit and Launch Possibilities

L. A. Cangahuala, T. A. Clark, and C. C. Counselman

In the proposed GeoBeacon system for crustal motion monitoring (see *Eos 70*, p. 1062, 1989), signals from low power radio transmitters on the ground are relayed to a central processing station by small satellites. GeoBeacon satellites in orbits like those of the NAVSTAR GPS could provide continuous, instantaneous, global monitoring with better accuracy and lower cost than GPS. However, intermittent (*e.g.* once or twice daily) monitoring with GPS-level accuracy could be performed with a few GeoBeacon satellites orbiting at much lower altitudes and in fewer planes. An entire constellation of the latter type could be established by a single launch of a low cost vehicle such as Pegasus or the ASAP platform on the Ariane 4. Geodetic measurement frequencies and accuracies achievable

with various numbers of sat llites, orbit planes, and altitudes are being estimated through computer simulations and covariance analyses. Results will be presented and discussed.

Contract Scientific Report No. 9, entitled "Millimeter-Accuracy Satellite Navigation," submitted 8 April 1991 and published as PL-TR-91-2087, explained how the instantaneous position coordinates of a point on a moving platform (land/sea/air/space vehicle) could be determined with respect to a reference frame defined by points fixed on the ground with millimeter-level uncertainties, by means of the satellite radio interferometry techniques which had been developed under this contract. The abstract of this report follows:

Millimeter-accuracy satellite navigation, defined as the determination of instantaneous position coordinates of a point on a moving platform (land/sea/air/space vehicle) with respect to a reference frame defined by points fixed on the ground, with millimeter-level uncertainties, is possible using the satellite radio interferometry techniques developed under Contract F19628-86-K-0009 and its predecessors. These techniques include use of doubly-differenced, dual-band, reconstructed-carrier phase observations of the NAVSTAR GPS satellites simultaneously from the "unknown" point and from fixed reference points suitably arrayed on the ground so that the integer-cycle ambiguities of their observations can be resolved to reduce satellite orbit uncertainties. For instantaneous ambiguity resolution of the moving-platform observations, at least seven satellites must be observed simultaneously. If the available number of NAVSTAR satellites is insufficient, GLONASS satellites may be used. Other options for ambiguity resolution are also available.

Contract Scientific Report No. 10, entitled "Origins of GPS Surveying," submitted 26 April 1991 and published as PL-TR-91-2088, discussed relations between radio-interferometric geodetic-survey techniques and their historical and technical antecedents. The abstract of this report follows:

Conceptually, GPS geodetic surveying is a descendant of hyperbolic radio-positioning systems such as LORAN and Omega, of the "very long baseline" interferometry technique of radio astronomy, and of satellite Doppler tracking. Satellite Doppler positioning systems such as TRANSIT may have paved the way for GPS politically and economically, but conceptually they were strongly opposed to and probably retarded the development of GPS geodetic surveying.

The period of performance of the contract ended 30 April 1991.

3. Publications

Bock, Y., R. I. Abbot, C. C. Counselman, and R. W. King, A Demonstration of 1 - 2 Parts in 10^7 Accuracy Using GPS, *Bulletin Géodésique*, vol. 60, pp. 241-254, 1986.

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