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MILLIMETER-ACCURACY SATELLITE NAVIGATION

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PHILLIPS LABORATORY
AIR FORCE SYSTEMS COMMAND
HANSCOM AIR FORCE BASE, MASSACHUSETTS 01731-5000

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18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*: NAVSTAR Global Positioning System, GPS, satellite navigation, satellite geodesy, space geodesy, radio positioning, radio interferometry

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

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.

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83 APR edition may be used until exhausted
All other editions are obsolete

SECURITY CLASSIFICATION OF THIS PAGE

UNCLASSIFIED

MILLIMETER-ACCURACY SATELLITE NAVIGATION

Definition:

Determining 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 1-mm uncertainties.

"Satellite navigation" means navigation using satellites. (The moving platform may also be a satellite.)

MILLIMETER-ACCURACY SATELLITE NAVIGATION

Object of this talk:

To convince you that mm-level navigation is possible.

Plan:

1. Show you how positions of fixed points have been determined with millimeter accuracy.
2. Show you how positions of moving points have been determined with centimeter accuracy under certain conditions.
3. Discuss problems and solutions.

Re: HOW POSITIONS OF <u>FIXED</u> POINTS HAVE BEEN DETERMINED WITH MILLIMETER ACCURACY

1. The basic method.
2. Some results.
3. What the major problems have been, and how they have been solved.

BASIC METHOD (simplified):

1. Observe L1- & L2-band radio signals transmitted by GPS satellites.
2. Use observations from 3 fixed reference points to determine satellite orbits with respect to the coordinate frame defined by these points.
3. Use observations at an unknown position to determine the unknown position coordinates.

TRICK #1:

Observe & use the *carrier-wave phases* of the GPS signals.

Easy to measure within 0.1 radian, equivalent to 3 mm of path length.

Possible to measure within 0.03 rad, equivalent to 1 mm.

TRICK #2:

Use only *doubly-differenced* carrier-phase observations.

Difference between simultaneous observations of same satellite at two receiving points cancels sensitivity to satellite-transmitter phase.

Difference between simultaneous observations of any two satellites at any receiving point cancels sensitivity to receiver-related phase.

Double-Differencing (continued):

In general, sensitivity to any "common-mode" effect, including any

- receiver-related (satellite-independent) effect, or any
- satellite-related (receiver-independent) effect,

cancels when observations are doubly-differenced.

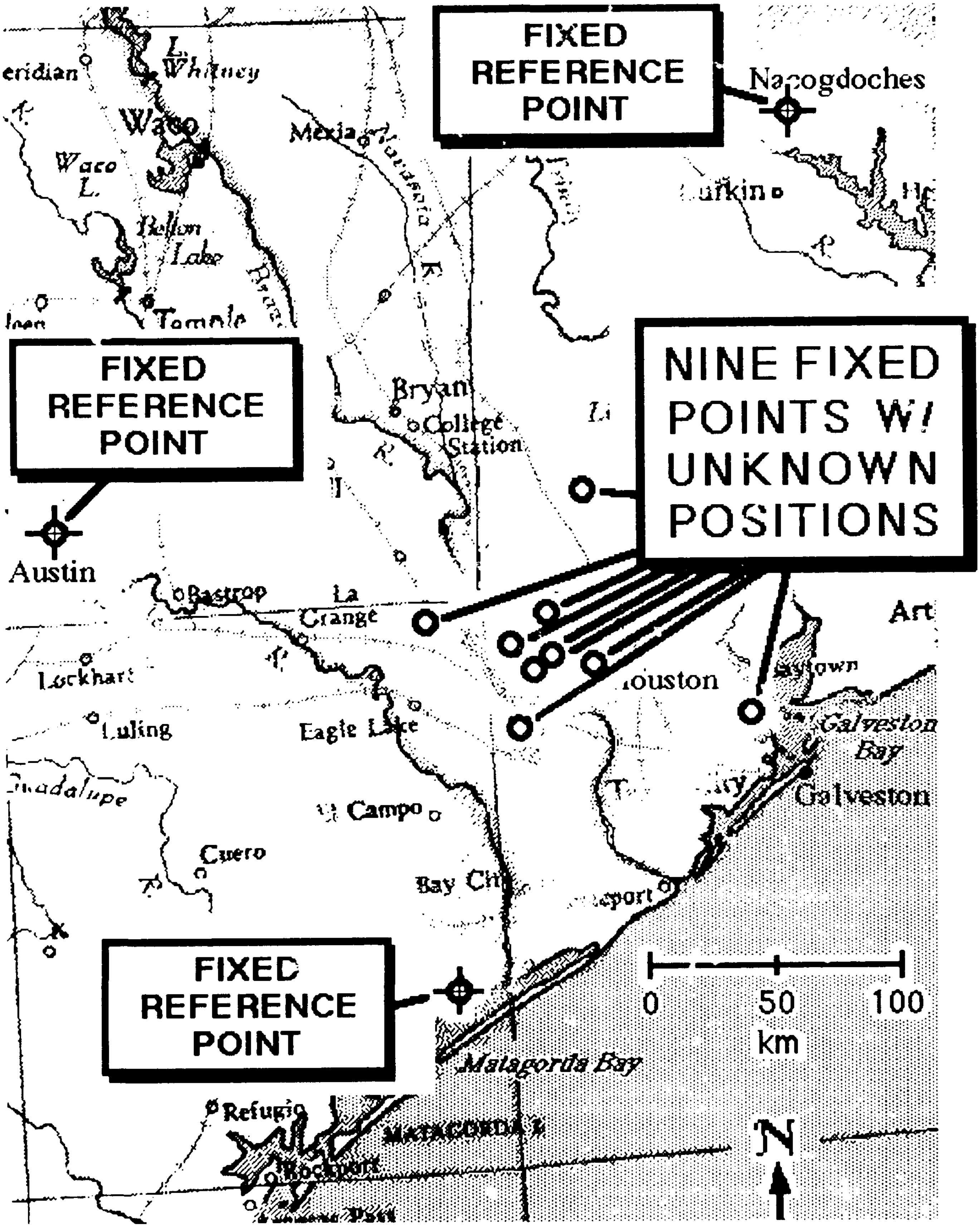
The only surviving effects are those which are "doubly different,"

i.e., different for observations of different satellites, ***differently*** at different receivers.

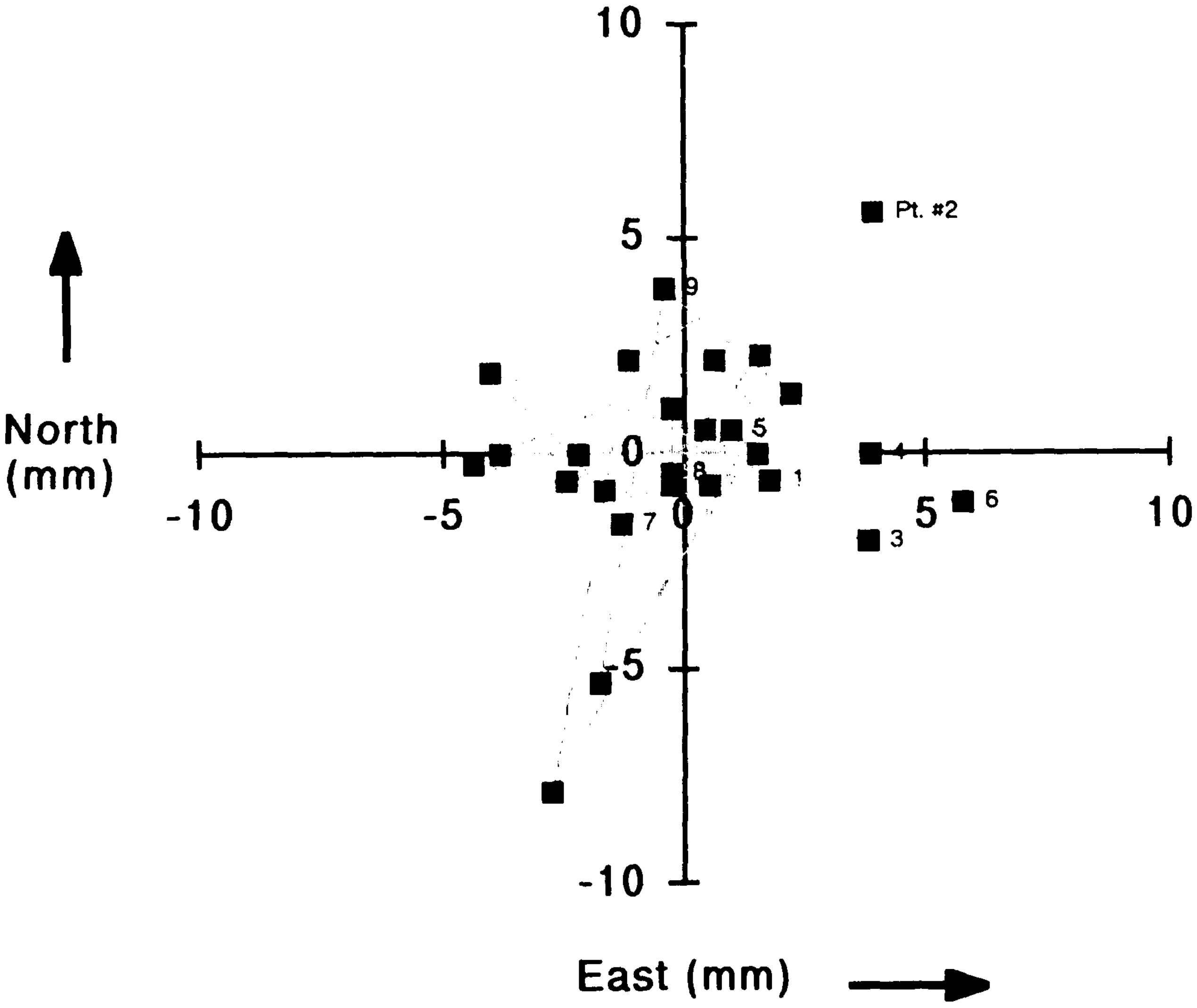
Surviving Effects, Bad & Good:

Chief of the **baddies** (error sources) is tropospheric refractivity. *E.g.* at one of the receiving points but not the other, one of the satellites but not the other appears behind a cloud. A problem if observing from under the weather.

The **desired** sensitivity of the observations (to the unknown position) is not at all reduced by differencing between this position and another, and is not much reduced by differencing between satellites if these satellites are well separated in the sky.


FIXED REFERENCE POINT
Nacogdoches
FIXED REFERENCE POINT
Austin
NINE FIXED POINTS W/ UNKNOWN POSITIONS
FIXED REFERENCE POINT
Waco
L. Whitney
Mexia
Lufkin
Bryan
College Station
Bastrop
La Grange
Lockhart
Luling
Eagle Lake
Houston
Baytown
Galveston Bay
Galveston
Campo
Cuero
Bay City
Freeport
Guadalupe
Matagorda Bay
MATAGORDA
Refugio
Rockport
0
50
100
km
N

Scatter of Repeated Determinations on Three Days (spanning a week) of the Nine Unknown Positions



R.m.s. in ea. coord. ~2 mm.

FIXED-POSITIONING DEMONSTRATION

COMMENTS:

1. All antennas/receivers* removed and replaced each time.
2. All receivers were codeless (immune to GPS "A-S" and "S-A").
3. Nothing but crystal oscillators.
4. No observations except from the 12 points shown (3 ref. + 9 unk. pts.)**
5. Daytime, solar maximum (high and rapidly varying ionospheric refraction).
6. Gulf coast weather (humid, lots of clouds)

---

* except at two of the reference points, at Austin and Nacogdoches.

**Three other stations were used, on one day, to determine coordinates of reference points.

WHY IT'S FUNDAMENTALLY HARDER TO DETERMINE POSITION ON A MOVING PLATFORM (AS OPPOSED TO A FIXED POINT):

Errors can't be time-averaged. (The worst error source, doubly-different tropospheric refraction, varies over minutes to hours.)

WHY IT MAY (OR MAY NOT) BE HARDER IN PRACTICE:

Resolving the integer-cycle ambiguities of the doubly-differenced phase observations is harder if you can't wait for the satellites to move to different positions in the sky.

AMBIGUITY RESOLUTION

The interpretation of a (doubly-differenced) phase observation in terms of position is ambiguous. The "likelihood" function of position, given a set of phase-difference observations $\Delta\phi$ of one or more satellites, differenced between the unknown position $\vec{r}$ and some reference position, is

$$L(\vec{r}) = \underbrace{\sum}_{\substack{\text{over all}\\ \text{observ'n}\\ \text{times, j}}} \left| \underbrace{\sum}_{\substack{\text{over all}\\ \text{satellites, k}}} e^{2\pi i \,(\Delta\phi_{jk} - \vec{r}\cdot\hat{s}_{jk}/\lambda)} \right|$$

($\hat{s}_{jk}$ = unit-vector in direction of k^{th} satellite at j^{th} observation time;

λ = carrier wavelength; sum may include observations at multiple wavelengths.)

AMBIGUITY EXAMPLE:

Suppose that there is just one observation time (*e.g.* because we want instantaneous position on a moving platform) and that two satellites, in directions $\hat{s}_1$ and $\hat{s}_2$, are observed at this time. Then the position-likelihood is maximized by

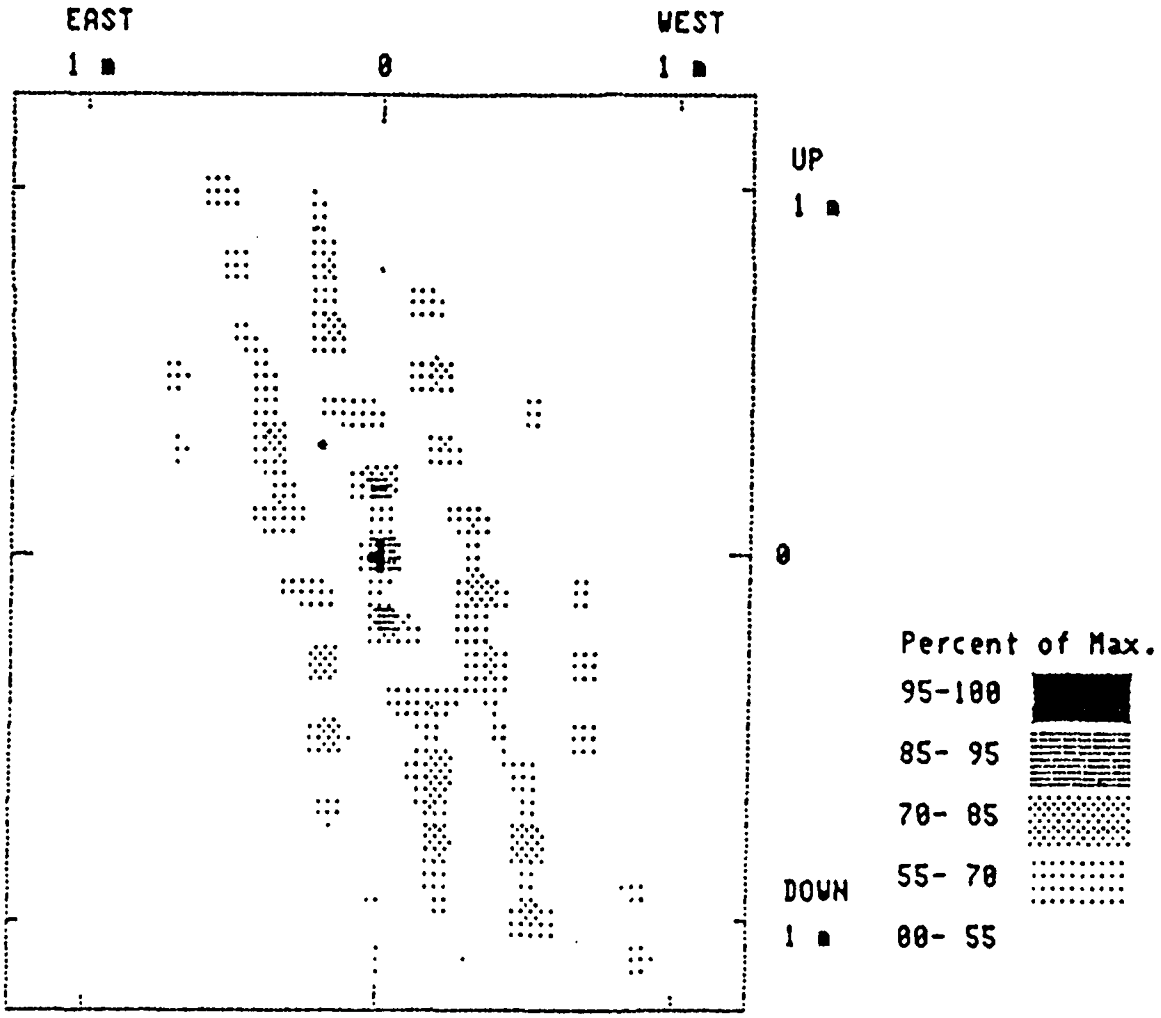
$$\vec{r} \cdot (\hat{s}_1 - \hat{s}_2) = \lambda \, (\Delta\phi_1 - \Delta\phi_2 + n)$$

where n is any integer. The maximum-likelihood position estimate is the locus of points on an infinite set of parallel planes, perpendicular to $(\hat{s}_1 - \hat{s}_2)$ and separated along this direction by $\lambda / |\hat{s}_1 - \hat{s}_2|$.

ANOTHER EXAMPLE:

Six satellites observed at L1 wavelength only, for 15 min. (each satellite moves ~1/8th rad.).

LIKELIHOOD FUNCTION (in E-W plane):



SAME EXAMPLE, except obs'ns continue for two hours (each satellite moves ~1 rad.).

LIKELIHOOD FUNCTION (in E-W plane):

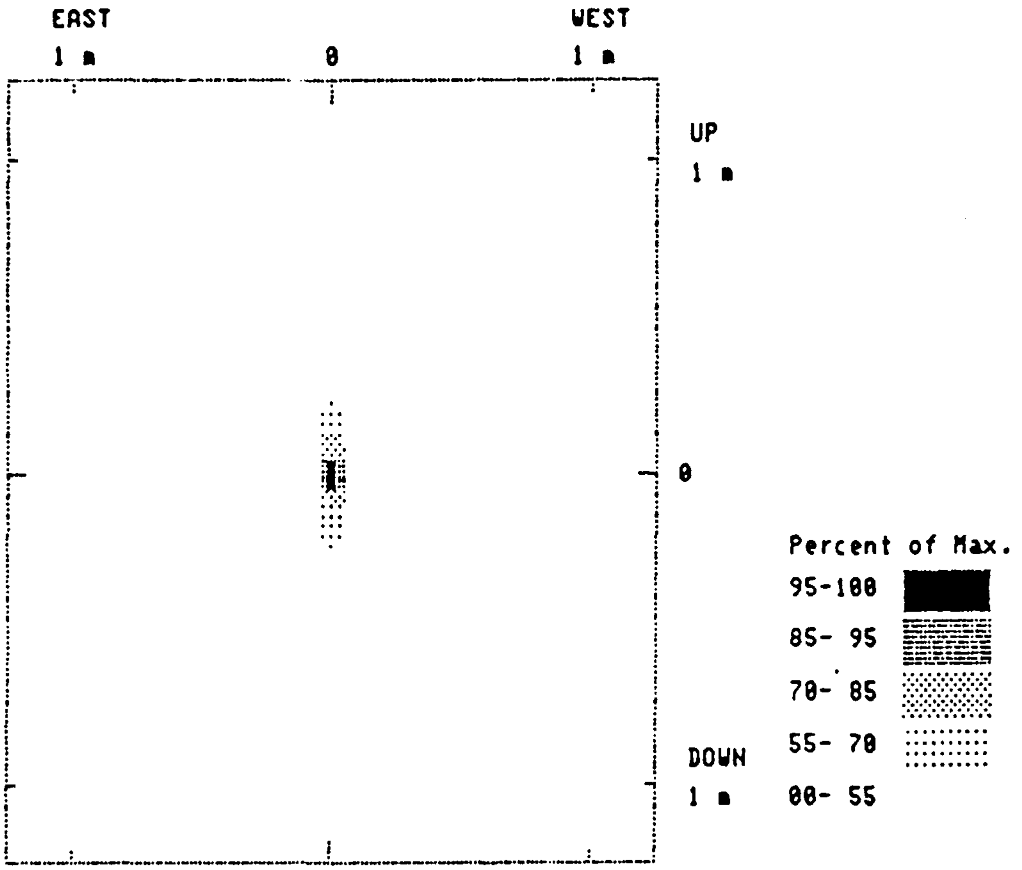
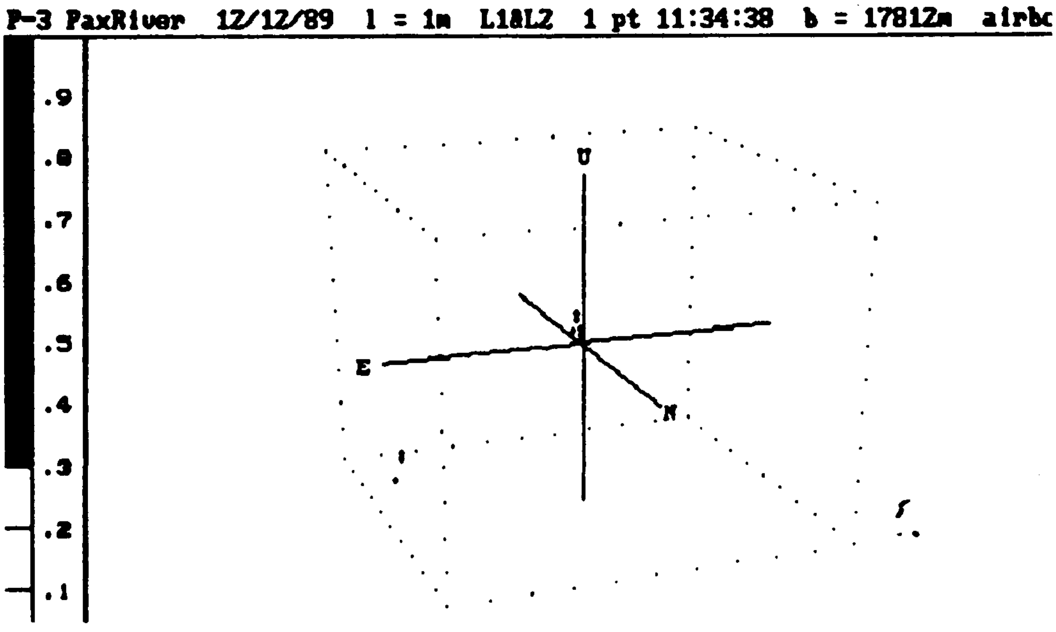


Fig. 2. Like Fig. 1, except the period of observation is 2 h instead of 15 min.

ANOTHER EXAMPLE (provided by G. L. Mader of NGS, Rockville):

- 7 satellites
- L1 & L2 wavelengths
- 1 point in time
- moving platform (P-3 airplane nr. Pax R.)

LIKELIHOOD FUNCTION (3-D, perspective view):



FOR *INSTANTANEOUS* AMBIGUITY RESOLUTION:

- observe both L1 & L2
- account for ionosphere (unless very near reference point)
- observe at least 7 satellites

OPTIONS:

- resolve ambiguity once and maintain track
- combine GLONASS & GPS
- use other satellites (MARISAT; GEOBEACON)

SUGGESTED READING

GL-TR-89-0231

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

Laureano Alberto Cangahuala

Massachusetts Institute of Technology
77 Massachusetts Avenue
Cambridge, MA 02139

27 July 1989

Scientific Report No. 5

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GEOPHYSICS LABORATORY
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
HANSCOM AIR FORCE BASE, MASSACHUSETTS 01731-5000

United States Patent [19]

Counselman, III

[11] **Patent Number: 4,912,475**

[45] **Date of Patent: Mar. 27, 1990**

[54] TECHNIQUES FOR DETERMINING ORBITAL DATA

[75] Inventor: **Charles C. Counselman, III**, Belmont, Mass.

[73] Assignee: **Massachusetts Institute of Technology**, Cambridge, Mass.

[21] Appl. No.: **330,976**

[22] Filed: **Mar. 29, 1989**

Related U.S. Application Data

[63] Continuation of Ser. No. 28,712, Mar. 20, 1987, abandoned.

[51] **Int. Cl.**^{4} **H04B 7/185**; G01S 5/02; G01C 21/00

[52] **U.S. Cl.** **342/352**; 342/424; 364/459

[58] **Field of Search** 342/352, 356, 357, 358, 342/424; 364/459

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(List continued on next page.)

Primary Examiner—Thomas H. Tarcza
Assistant Examiner—Gregory C. Issing
Attorney, Agent, or Firm—Morgan & Finnegan

[57] **ABSTRACT**

Techniques are disclosed 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 a 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.

18 Claims, 6 Drawing Sheets