

# N91-24073

## HIGH PRECISION APPLICATIONS OF THE GLOBAL POSITIONING SYSTEM

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### ABSTRACT

The Global Positioning System (GPS) is a constellation of U.S. defense navigation satellites which can be used for military and civilian positioning applications. The GPS will ultimately include at least 21 satellites at about 20,000 km altitude equally spaced in six orbit planes by the early 1990s. A wide variety of GPS scientific applications have been identified and precise positioning capabilities with GPS have already been demonstrated with data available from the present partial satellite constellation. Expected applications include: measurements of Earth crustal motion, particularly in seismically active regions; measurements of the Earth's rotation rate and pole orientation; high-precision Earth orbiter tracking; surveying; measurements of media propagation delays for calibration of deep space radiometric data in support of NASA planetary missions; determination of precise ground station coordinates; and precise time transfer worldwide.

### INTRODUCTION

The Global Positioning System (GPS) is designed so that typically six to ten navigation satellites can be tracked above 5 deg elevation from any ground site. The GPS satellites transmit carrier signals at 1.227 and 1.575 GHz (L-band) which are modulated by a pseudorandom noise code, the P-code, at 10.23 MHz. Two frequencies are provided so that ionospheric signal delays can be calibrated. A second code, the C/A (coarse acquisition) code, is somewhat noisier than the P-code due to its lower frequency at 1.023 Mhz and the lack of dual-band ionospheric correction (see Fig. 1)

The GPS codes include a navigation message with GPS clock and orbit information which can be utilized for real-time point positioning by users equipped with GPS receivers. GPS *pseudorange* to four satellites determines three position coordinates plus the user clock offset from GPS time (Fig. 2). The term *pseudorange* is used since the range calculation is based on the difference between the transmit and receive times and will include any offset between the transmitter and receiver clocks. With the P-code, user positions can be determined in near-real time to about 10 m.

The Department of Defense plans to turn on *selective availability* (SA) for the operational GPS satellites. SA includes a clock dither and changes to the broadcast ephemeris. Authorized users will be equipped with keys to correct for these effects. Other users will see transmitter clock variations of the order of 30-50 m and the broadcast ephemeris will be accurate to 50-100 m as well. Few scientific and non-military GPS users will be equipped with the keys for selective availability. Simultaneous GPS tracking from multiple receivers can differentially eliminate GPS and receiver clock offsets. This method of differential GPS tracking is appropriate for non-real time applications for which simultaneous data from distant sites must be brought together and combined. Because the broadcast ephemeris provides only coarse orbit information, for higher precision the user must estimate and improve the GPS orbits *and* use differential GPS techniques (Fig. 2).

The primary data type for highest precision in non-real time GPS applications is the carrier phase, which can be tracked with sub-cm precision in modern GPS receivers. The carrier phase, continuously tracked over hours, provides a precise time history of *range change* which can be used with a dynamical model to obtain precise orbit solutions (Fig. 2). The GPS carrier phase is ambiguous by some integer multiple of carrier wavelengths, but changes in the phase from point to point measure range change. Pseudorange data, even when it is some orders of magnitude noisier than the phase, is still useful since it can be used to constrain the carrier phase integer ambiguities, which in general must be estimated from the data.

The Department of Defense may also encrypt the P-code data (anti-spoofing, or AS), making it unavailable without special devices. There are several methods discussed below which enable recovery of a noisier pseudorange data type using codeless techniques when AS is on. Although AS is presently generally off except for intermittent testing, with the full operational GPS constellation it may be turned on routinely.

With AS *off*, a number of commercial receivers can provide dual-frequency calibrated pseudorange data with intrinsic receiver system noise of tens of cm over five minute averaging intervals. Most of the actual observed scatter, however, is much higher, about 50-200 cm, and is due to multipath. The Rogue digital GPS receiver [1] developed at the Jet Propulsion Laboratory (JPL), incorporates both a very low noise pseudorange system noise (< 5 cm) and an antenna with choke rings designed to minimize multipathing. Fig. 3 shows samples of data demonstrating the low noise capability of this instrument. Studies have shown that low noise pseudorange is beneficial in high precision positioning applications.

With AS *on*, GPS users without the classified decryption keys can still make precise measurements with carrier phase provided they use codeless receivers. There are several different types of codeless receivers. The squaring-type of codeless receiver uses the fact that the P-code [P(t) in Fig. 1] has +/-1 values in a

pseudorandom pattern whose square is always +1. An alternative approach is used in the Rogue receiver [2], which cross correlates the L1 and L2 signals and relies on the C/A signal together with the P1-P2 delay (from cross correlation) to produce carrier phase as well as pseudorange with an ionospheric correction. Codeless Rogue carrier phase is much noisier than code tracking phase, as is the pseudorange. For example, P-code pseudorange with the Rogue has receiver thermal noise at the cm-level, while the codeless pseudorange has noise at the 20-30 cm level [2]. Additional multipath errors tend to reduce the contrast between code and codeless pseudorange. The Rogue receiver defaults to P-code tracking but reverts to codeless mode as soon as it detects that AS is on.

The cross-correlation type of receiver has several advantages over the squaring receivers. First, the effective wavelength is not changed by the cross correlation, while squaring codeless receivers result in an effective wavelength one-half the original  $\sim 20$  cm L-band wavelength. The shorter wavelength makes phase connection, data editing, and phase ambiguity resolution more difficult since all these procedures rely on determination of signals and parameters to a fraction of a wavelength. Secondly, the cross-correlation receiver such as the Rogue can produce an ionospherically calibrated pseudorange from the C/A signal and L1-L2. Although this pseudorange may be somewhat noisier than P-code pseudorange, it can be considerably more accurate than pseudorange from codeless receivers which rely only the single frequency C/A signal.

Future government policies will determine in part how effective different GPS receivers are for unclassified applications. With AS off, GPS receivers which fully exploit the P-code have the advantage. However, since in the future AS may be turned on, a backup codeless capability is imperative for maximum accuracy.

GPS receivers and antennas are relatively small and portable. They can be transported to and set up in remote locations by one person and can be run from batteries or small generators. A number of different code and codeless models are presently available from various manufacturers. The market for GPS technology has grown enormously over the past few years. Although early models were relatively expensive, modern high-precision GPS ground terminals can be purchased for well under \$100,000 and lower-accuracy receivers cost under \$5,000. Inexpensive GPS receivers are now available for installation in automobiles, with accuracy claimed to about 100 m [3]. Space-qualified GPS receivers for Earth orbiters require on the order of \$1 million or more, but production costs are expected to drop after component parts are reduced.

#### HIGH-PRECISION GPS TRACKING

##### Least Squares Estimation

Many high-precision GPS applications require estimation of GPS orbits and other parameters. With SA turned on, the GPS broadcast ephemerides are accurate to approximately 50 m. On the other hand, geodetic experiments designed to measure Earth crustal motions must detect ground motion at the cm or even sub-cm level from one year to the next; this in turn, requires sub-meter GPS orbit accuracy. For global geophysical studies or precise low-Earth orbit determination, GPS orbit accuracy of 10-20 cm is the goal.

Many high-precision GPS scientific applications therefore involve studying ways to determine GPS orbits to very high accuracy. This is a least squares estimation problem to which square-root Kalman filtering and smoothing techniques are well suited [4]. Differential GPS tracking is used to remove errors due to transmitter and receiver clocks or selective availability. This requires combining GPS data from different receivers to estimate parameters which include: GPS orbits and solar pressure coefficients, ground site coordinates, biases and clocks, and tropospheric signal delays. Considerable research at JPL has led to a GPS data processing strategy which incorporates a number of refinements designed to improve accuracy. These refinements include improved physical modeling of the Earth and of the satellite motion, and stochastic representation for atmospheric signal delays. The JPL software also includes a rapid, automated data editor [5], and incorporates specialized techniques to resolve carrier cycle ambiguities [6]. The launch of the Topex/POSEIDON oceanography satellite in 1992 into low-Earth orbit (1336 km altitude) will result in the first high-quality GPS flight data from the GPS experimental receiver on Topex. The techniques for orbit determination of a satellite using GPS data collected with a flight instrument are similar to those which have been used to determine ground station coordinates with GPS. The main difference is that the solution for an orbiting receiver is influenced by force mismodeling, which could include errors in the gravity field, solar radiation pressure model, drag coefficient, etc. The *reduced-dynamic tracking* strategy [7] is a filtering technique developed at JPL to minimize or eliminate such force mismodeling errors. Stochastic acceleration parameters are estimated to absorb dynamic mismodeling. The constraints on the stochastic parameters are chosen to correspond to the level of confidence in the dynamic models. When reliable dynamic models are available (e.g. for GPS satellites themselves in high-altitude, circular orbits), very tight constraints are placed on the stochastic acceleration parameters, while for satellites in low-Earth orbit where dynamic modeling is poorer due to geopotential uncertainty, the stochastic acceleration parameters are loosely constrained so that more weight is placed on GPS tracking data to fit out unmodeled forces. With this technique, GPS-based orbit determination for Topex is expected to be accurate to the 10-cm level or better [7].

Current research in least-squares estimation techniques for GPS applications includes approaches to reducing computation. With the full GPS constellation and dozens of ground tracking sites, the computational burden of solving for hundreds of parameters will be significant. Determination of geopotential parameters may involve thousands of parameters and even supercomputers may be inadequate with a standard least-squares approach. Recent studies at JPL have identified new approaches to matrix partitioning and decentralized processing

which show promise for reducing computation time for these demanding GPS tracking applications by more than an order of magnitude [8, 9].

### Ground Positioning Applications

Ground positioning GPS applications can be classified into three categories: (1) global geodetic and geophysical studies, including measurements of intercontinental distances, Earth rotation rate, and position of the Earth's pole to an accuracy of a few cm; (2) regional geodetic measurements of crustal motion and deformation oriented towards sub-cm level ground measurements over distances ranging from ~ tens of km to 1000 km; (3) surveying applications, which are usually local measurements over relatively short distances. The first category is among the most demanding in terms of GPS orbit accuracy due to the long distances (thousands of km) involved. The second category also requires highly precise orbital modeling. The third category generally requires less accuracy for the GPS orbit solutions than the other geodetic applications.

#### Global Measurements

The determination of the Earth's variable rotation rate is very important for astronomical and deep space tracking applications. Also important is the determination of the rotation axis of the Earth relative to the Earth's crust, which moves back and forth relative to the pole. Presently, the determination of Earth orientation is made with very long baseline interferometry (VLBI) measurements using large, fixed radio telescopes; with satellite laser ranging (SLR); or with lunar laser ranging (LLR). Although the VLBI, SLR, and LLR Earth orientation measurements are accurate to the level of a few cm, the results are available on a routine basis with resolution of only several days and a delay of a few weeks. A better understanding of Earth rotation requires higher time resolution to better than 1 day, and to properly calibrate NASA deep space tracking data, the results should be available within 24 hrs. Analysis [10] indicates that GPS tracking from a worldwide network with the full satellite constellation can provide daily or better time resolution for cm-level changes in Earth orientation, thus complementing nicely the precise but less frequent absolute measurements available from VLBI. The incorporation of GPS data could reduce the demand for Earth orientation calibrations using VLBI with NASA's deep space network (DSN), while at the same time improving the accuracy of these calibrations. Initial pole position measurements with GPS [11] are encouraging, with agreement with VLBI demonstrated at the level of 5-10 cm. Further improvement to the cm-level is anticipated in the next few years as additional GPS satellites are launched. Other global measurements expected from GPS with few-cm accuracy include determination of the geocenter (Earth center of mass) and long baselines. Measurements of long baselines, for example over intercontinental distances of thousands of km, will be useful in studies of large scale plate motions and continental drift. Presently VLBI is the most accurate technique available for making these measurements; however the relatively small and portable GPS terminals will enable many long baseline measurements to be made which had previously been unavailable due to the limited number VLBI and SLR observatories. Initial GPS solutions for intercontinental baselines determined from the limited configuration of a worldwide 1988 GPS experiment show good agreement — about 5 cm over 5,000-6,000 km, or 1 part in  $10^8$  — with independent VLBI solutions for the same baselines [11, 12]. This experiment will be repeated in 1991, by which time the number of GPS satellites and ground tracking sites will have more than doubled as compared to 1988 and solutions should improve to several parts in  $10^9$ .

#### Regional Measurements

Regional geodetic measurements are usually made over distances of hundreds of km. Hundreds of GPS receivers have been deployed worldwide in numerous regional geodetic experiments in the past few years, and GPS is well established as a new and important high-precision technique to measure crustal motion. Present-day GPS errors for relative horizontal ground measurements include a system noise component of a few mm which does not depend on the baseline length being measured, and a baseline length-dependent error component of about 1 cm per 1000 km of length (1 part in  $10^8$ ) [13]. Although most plate motion is horizontal, vertical displacements can also be determined with GPS, although with somewhat less accuracy (~ 3 cm level). There are many high-quality GPS geodetic results which have been published in the literature. In this paper, I will present three recent samples of results.

1. *Measurement of volcanic fracture opening in Japan with GPS.* A recent paper [14] presents results of monitoring a seismically active region in Japan with GPS. In July 1989, there was a swarm of earthquakes, the largest of which was magnitude 5.5, near the Izu Peninsula. Just after these earthquakes, the GPS solution indicated ground motion of nearly 15 cm had occurred. Shortly thereafter, a volcano nearby on the sea floor erupted. The crustal movements detected using GPS were interpreted as a fracture opening around the swarm region. The fracture of the crust was associated with upward motion of magma. The Japanese GPS experiment demonstrated that GPS measurements can reveal the time sequence of seismic and volcanic events.

2. *Measurement of plate motion along the San Andreas fault in California.* The San Andreas fault in California marks the boundary of the Pacific and North America plates. The Pacific plate is moving northwest relative to the North America plate at approximately 5 cm/yr. In order to understand the risk of earthquakes and their relation to plate motion and deformation, numerous GPS sites have been occupied in California for several years. Fig. 4 shows one example of the measurements recently made using GPS [15]. The two ends of the baseline are on opposite sides of the San Andreas fault. The plate motion is clearly detected and agrees with independent measurement techniques to the level of a few mm/yr. By making measurements such as these annually throughout tectonically active regions such as California, a better understanding of the connection

between earthquakes and the rates of plate motion and associated deformation can be reached. The only feasible technique for occupying dozens of ground sites along the complicated fault networks in California is use of portable GPS receivers.

**3. MM-level precision for a geodetic measurement.** A recent paper [16] presented measurements of ground baselines in California of length 245 and 729 km. The measurements were repeated daily over a 1-week period in 1988. In the horizontal components, the daily solutions agree with a rms scatter of 1-4 mm. The GPS orbits determined simultaneously are believed to be accurate to about 50-100 cm [17]. These results indicate the high precision which can be achieved with GPS techniques.

#### Surveying Applications

Surveying applications abound for GPS. One advantage of GPS is that areas can be surveyed even when there is no clear line of sight between pairs of sites. In an interesting example of a GPS surveying application [18], a GPS satellite survey was utilized to support construction of the Stanford Linear Accelerator Center (SLAC). The accelerator plans called for a loop ~ 1 km in diameter. Approximately 1,000 magnets had to be placed in the arc tunnels, requiring a network of reference marks. The GPS survey, using codeless GPS receivers, revealed systematic errors in the terrestrial solution, and was reported to be accurate to 1-2 mm horizontally and 2-3 mm vertically [18]. Other users of GPS for surveying include the Pennsylvania Department of Transportation, Department of Lands and Survey of New Zealand, the Canadian Geodetic Survey, and the U.S. National Geodetic Survey (see ref. [18], proceedings to a GPS conference in which numerous other surveying applications were discussed). Surveying applications have less demanding GPS hardware and orbit accuracy requirements since relatively short distances are typically involved. Over shorter distances there is greater cancellation of errors from the atmosphere and from GPS orbits.

#### Orbiting GPS Users

The illustration in Fig. 2 shows schematically differential GPS tracking for an Earth orbiter equipped with a GPS flight receiver. Differential positioning requires a ground network of GPS receivers. This technique will be used for the Topex GPS demonstration [7]. Topex/POSEIDON will be launched in 1992 and will carry an altimeter precise to about 2 cm to map the topography of the ocean surface. In order to exploit this high-precision altimetry data, a goal of ~ 10 cm orbit accuracy has been set. With simultaneous estimation of all parameters (including GPS and Topex orbits), Topex orbit accuracy at the 5-10 cm level is expected [7]. Other future Earth orbiters which may carry GPS receivers include Gravity Probe-B, the Aristoteles gravity satellite, and the Earth Observing System (EOS) platforms. By the late 1990s, advanced GPS technology may enable user orbit accuracy at the level of a few cm [19]. High-Earth and elliptical orbiting satellites may also be able to utilize GPS flight receivers for precise orbit determination [20].

The *reduced-dynamic* GPS tracking strategy was designed to minimize the effect of gravity model uncertainty on the Topex orbit. By isolating the gravity accelerations, however, this same strategy can directly improve our knowledge of the gravity field [8] by as much as an order of magnitude for certain geopotential coefficients. For lower altitude satellites or for spacecraft undergoing maneuvers, less weight may be placed on dynamic models: in cases where the dynamics are unpredictable, the GPS data are relied on exclusively for the orbit solution. This is referred to as kinematic (or non-dynamic) tracking and will probably be the approach for precise orbit determination of large, low altitude platforms such as EOS and the Space Station [19].

#### Other GPS Applications

GPS signals can be used for precise determination of media propagation delays, in particular through the ionosphere [2] and through the troposphere [21]. Precise (sub-nanosec) clock sync or time transfer between distant tracking sites may also be feasible with GPS, which would be useful at astronomical observatories and NASA's deep space tracking sites. Analysis and experiments are underway at JPL to study the accuracy of clock sync with GPS.

#### FUTURE DEVELOPMENTS IN GPS

**Receiver technology.** Lighter, lower noise receivers are expected to be offered by a number of different manufacturers for high-precision applications. As production increases, the prices are expected to drop. A number of geodetic networks, including NASA's proposed FLINN (Fiducial Laboratories for an International Natural science Network), will deploy hundreds of GPS ground receivers for long-term geodetic and geophysical studies. GPS flight receivers should also improve in performance as well as in weight and power requirements during the 1990s as additional GPS instruments are flown in experiments which require higher and higher accuracy. A key issue for receiver designers is the handling of SA and AS and the precision of the pseudorange. Since policies may change for GPS transmissions with SA and AS, it is important that flexible codeless techniques be available if needed. As discussed above, there are different approaches to codeless receiver technology with significant implications for tracking performance.

**Antenna technology.** The minimization of antenna multipath is an important issue for GPS tracking applications. In some cases, multipath may be a limiting error source. GPS users will be looking for antenna designs with improved multipath suppression, particularly in difficult ground environments or for cluttered spacecraft where a clear view of the GPS constellation is not always available. The geometry of tracking GPS from satellites in high-Earth or elliptical orbits may require special antenna designs.

*Algorithms and processing.* Because of the relatively large number of GPS satellites (eventually to include 21 satellites plus three operational spares) and expected dozens of ground tracking sites, the efficiency of GPS data processing is a major aspect of GPS analysis. A continuously operating GPS geodetic network in California has just started to operate to routinely produce orbit and baseline solutions [22]. Other similar permanent networks exist in Canada and Japan. Streamlined data collection and analysis techniques are being utilized and automated procedures are used whenever possible, including autonomous operation of receivers. Communication between computers and receivers in the field, including downloading of data, occurs over phone lines. One of the key enhancements for such permanent, continuously operating GPS ground networks is deployment of an advanced GPS receiver which internally pre-processes the data, saving considerable computing time later. Ideally, such a receiver will contain a chip which is programmed to do many of the tasks, but operators will be able to communicate with the receiver remotely and control various parameters. A potentially fruitful area of research is parallel processing: it may be possible to streamline GPS data reduction by doing many computations in parallel before the final step of combination of data from different receivers. Included here would be filtering mechanizations which enable parallel methods to be used to maximal advantage. Incorporation of higher order ionospheric effects into the data processing and calibration software may be necessary for high-precision regional geodesy [13].

The 1980s saw the initial development of GPS positioning techniques with a relatively small subset of the GPS constellation, with demonstrated positioning accuracy of about 1 part in  $10^8$ , corresponding to about 50-100 cm for GPS orbits, or about 1 cm for 1000 km ground baseline distance. The next few years will bring the filling out of the GPS constellation, the refinement of GPS technology, and the beginning of what will become routine and in some cases automated GPS tracking and data processing. In the 1990s, we expect to see further improvement to the level of a few parts in  $10^9$  (10-20 cm GPS orbit accuracy) and the first sub-decimeter orbits determined for Earth orbiters carrying GPS flight instruments.

**Acknowledgment.** The work described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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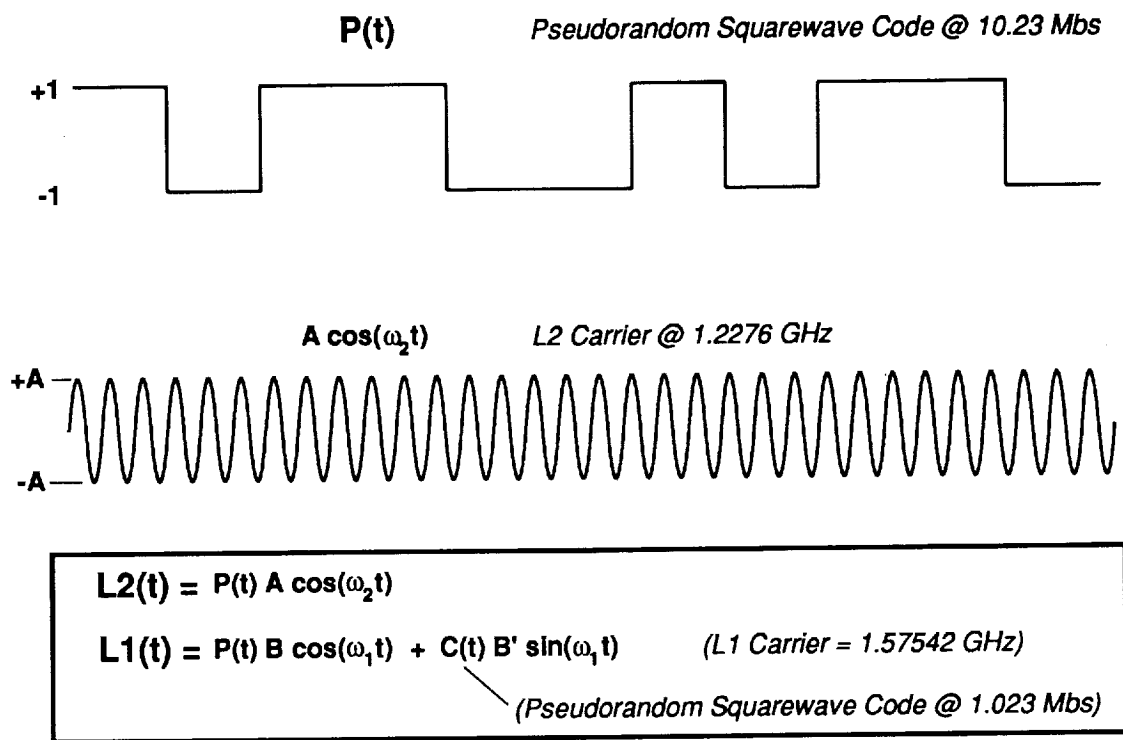


Fig. 1 GPS carrier phase is modulated by the P-code [P(t)] and the C/A code [C(t)]. The codes include information about the GPS orbits and clocks. Carrier phase and high-precision pseudorange obtained from either code or codeless tracking techniques are used in high-accuracy GPS applications. For relatively coarse accuracy applications, an inexpensive C/A-code only GPS receiver may be adequate.

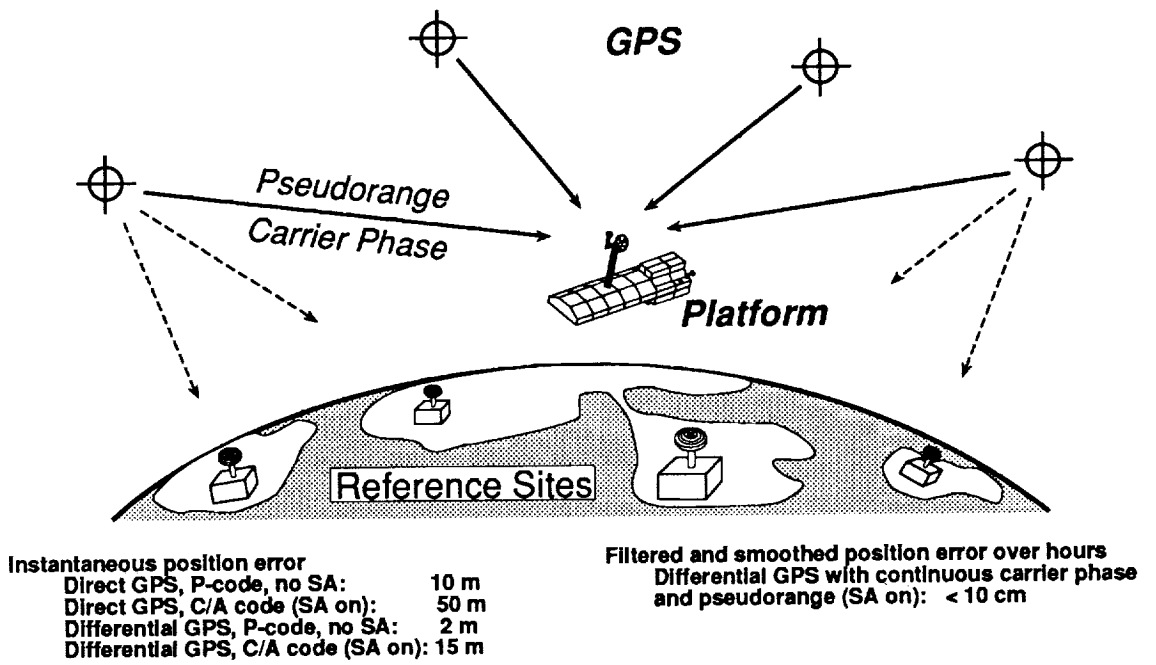


Fig. 2 Simultaneous GPS tracking data from ground and/or orbiting receivers can be combined to eliminate clock and clock-like errors and substantially reduce the effect of GPS orbit error. Non-differential (direct) instantaneous positioning accuracy is generally much less accurate. For very high accuracy applications, carrier phase continuously tracked for hours and processed together with pseudorange should enable sub-10 cm positioning accuracy in non-real time.

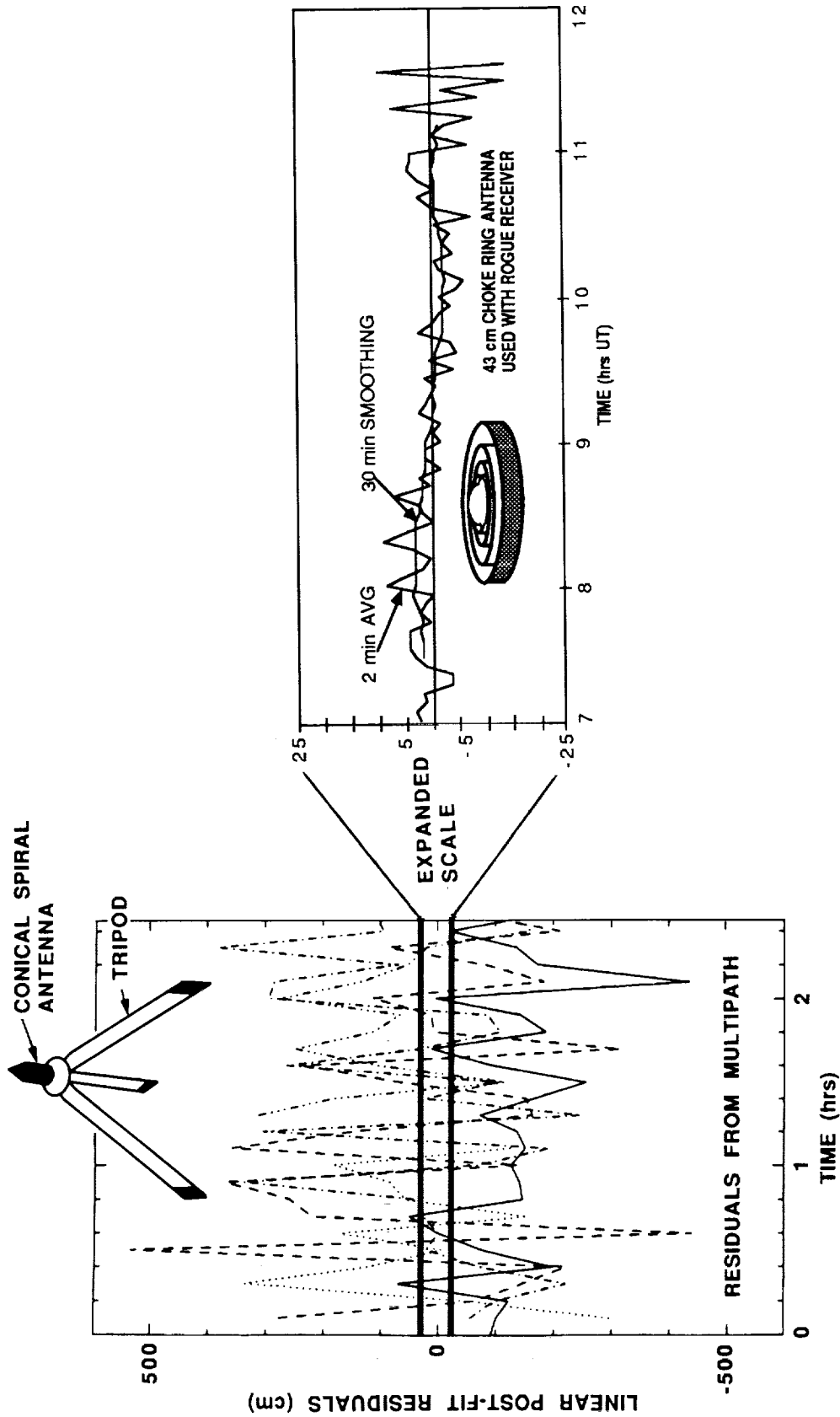


Fig. 3 A number of commercially available GPS instruments use an antenna similar to the one shown at the left. This configuration produces high levels of ground multipath for GPS pseudorange, resulting in high measurement scatter. The choke ring antenna on the right reduces the multipath by more than an order of magnitude.



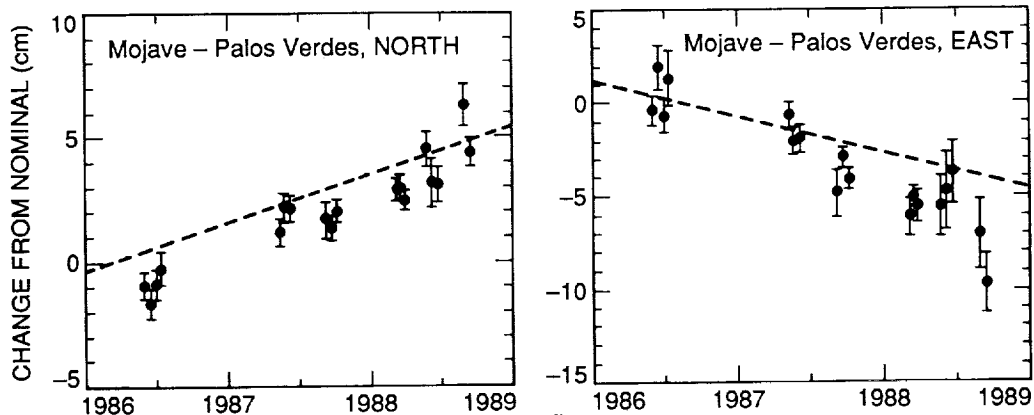
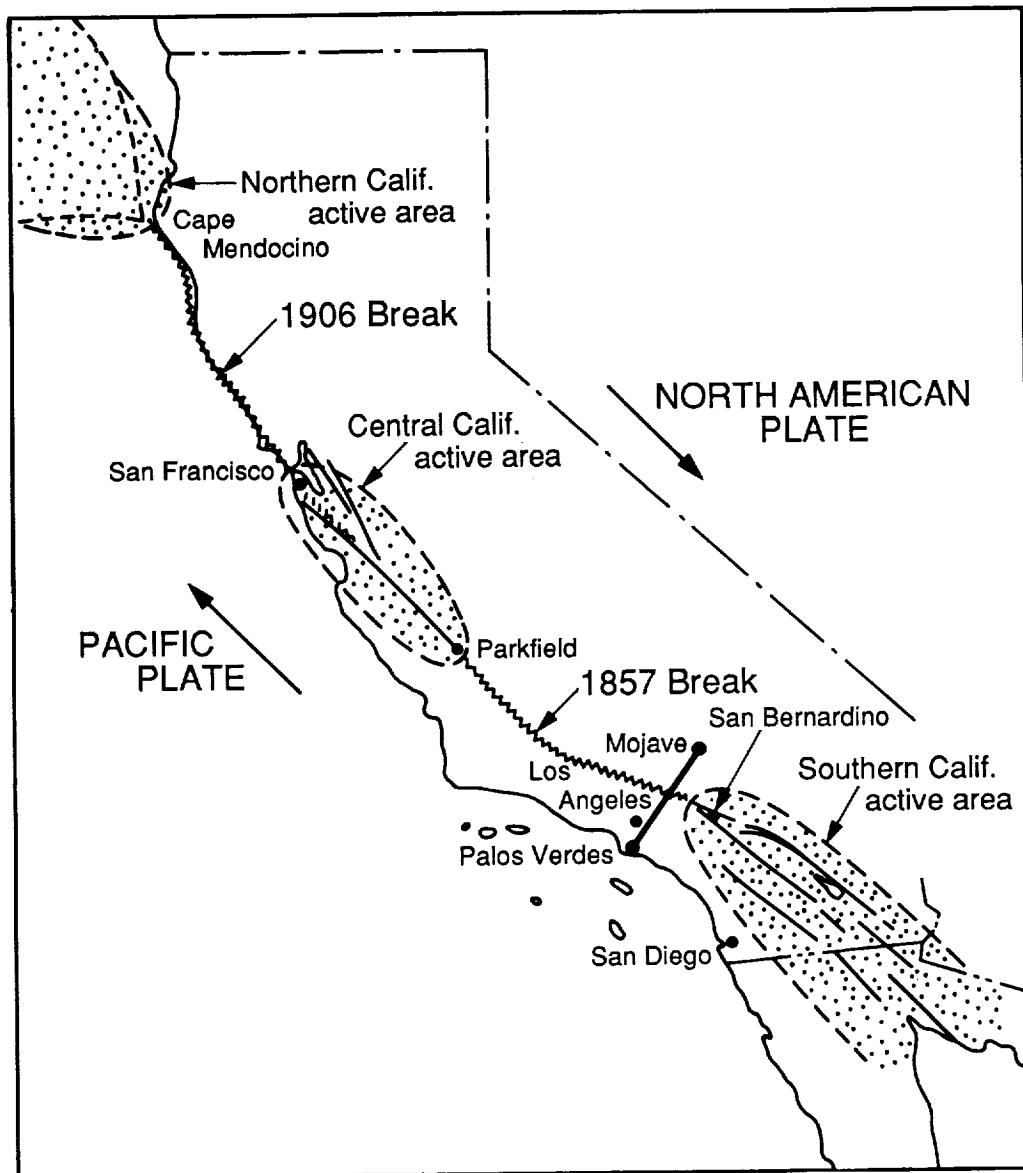


Fig. 4 Map of California shows the San Andreas fault where the North American and Pacific plates meet and are moving relative to one another. Large earthquakes in 1857 and 1906 occurred along the fault as shown. Dozens of GPS instruments have been monitoring the crustal motion in Southern California over the past several years, including GPS receivers at Mojave and Palos Verdes, which form a baseline crossing the San Andreas fault. Bottom graphs from [15] show the plate motion in measured with GPS: the Pacific plate is moving to the northwest at  $\sim 5$  cm/yr. Dashed line shows the rate as measured independently by VLBI (radio astrometric) techniques: the VLBI and GPS rates agree to a few mm/yr.

**SESSION G - SENSORS AND MEASUREMENT TECHNOLOGY (PART 2)**

**Wednesday November 28, 1990**

- **Quantitative Nondestructive Evaluation - Requirements For Tomorrow's Reliability**
- **Robotic Control And Inspection Verification**
- **The Transfer Of A Technology To Measure Skin Burn Depth In Humans**
- **Frequency Domain Laser Velocimeter Signal Processor**
- **A Field-Deployable Digital Acoustic Measurement System**
- **Laser-Optical Disk Position Encoder With Active Heads**