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SATELLITE EMISSION RADIO INTERFEROMETRIC EARTH SURVEYING SERIES – GPS GEODETIC SYSTEM

Abstract

The satellites of the Global Positioning System (GPS) offer an important new geodetic resource making possible a highly accurate portable radio geodetic system. A concept called SERIES (Satellite Emission Radio Interferometric Earth Surveying) makes use of GPS radio transmissions without any satellite modifications. By employing the technique of very long baseline interferometry (VLBI) and its calibration methods, 0.5 to 3 cm three dimensional baseline accuracy can be achieved over distances of 2 to 200 km respectively, with only 2 hours of on–site data acquisition. The use of quasar referenced ARIES Mobile VLBI to establish a sparse fundamental control grid will provide a basis for making SERIES GPS measurements traceable to the time–invariant quasar directions. Using four SERIES stations deployed at previously established ARIES sites, allows the GPS satellite apparent positions to be determined. These apparent positions then serve as calibrations for other SERIES stations at unknown locations to determine their positions in a manner traceable to the quasars. Because this proposed radio interferometric configuration accomplishes its signal detection by cross–correlation, there is no dependence upon knowledge of the GPS transmitted waveforms which might be encrypted. Since GPS radio signal strengths are 10^5 stronger than quasar signals, a great reduction in telecommunications sophistication is possible which will result in an order of magnitude less cost for a SERIES GPS station compared to a quasar based mobile VLBI system. The virtually all–weather capability of SERIES offers cost–effective geodetic monitoring with applications to crustal dynamics and earthquake research.

Introduction

It is the intent of this paper to explore a radio interferometric method by which the signals from the satellites of the NAVSTAR Global Positioning System, GPS (Henderson, 1978), can be used as a geodetic resource without any modifications to the spacecraft or system design procedures intended by the U.S. Department of Defense. The technique presented here is that of independent station interferometry or perhaps better known from its radio astronomy origins as very long baseline interferometry (VLBI) (Broten, 1967 ; Bare, 1967) with transportable applications initially presented by Shapiro (1970).

The technique of VLBI geodesy using fixed (Hinteregger, 1972 ; Fanselow, 1978) and transportable antennas (Ong, 1976) has demonstrated sub–centimeter to few decimeter measurement precisions for baseline lengths of 1 to 10,000 km . The quasars, which form the frame of reference for these VLBI measurements, are extremely distant

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and as such constitute a set of spatial directions which are virtually time–invariant. However, the quasar microwave signals are very weak and thus require substantial sophistication in instrumentation for data acquisition, signal detection, and computer software for parameter estimation. The availability of much stronger point–like radio signals to serve as quasar substitutes would clearly be useful. Artificial satellites can satisfy this strong signal desire but with the added complication of the satellite's motion.

The specific goals for this study have been to exploit existing satellite radio emissions as a resource for cost–effective high accuracy geodetic measurements with emphasis on geodynamic applications. The use of spacecraft signals for VLBI geodesy is given in this paper the name SERIES for Satellite Emission Radio Interferometric Earth Surveying. Several artificial radio sources, such as the S–band (2 GHz), signals from ALSEP (Apollo Lunar Surface Experiments Package) (MacDoran, 1976) C–band (4–6 GHz) communications satellite transmissions, could be used as SERIES system illuminators. However, because of frequency system stability requirements, baseline vector geometric strength and the desirability of full three dimensional measurements, the dual L–band (1.227 and 1.575 GHz) transmissions from the satellites of the GPS are considered the best candidates for meeting the geodetic goals stated above.

The objectives which SERIES–GPS will be capable of accomplishing are :

(1) 0.5 to 3 cm baseline vector measurement accuracy for station spacings of 2 to 200 km.

(2) Less than $ 1,000 per site measured.

(3) Moderate cost field equipment (< $ 100 K per station).

(4) Short time on–site (less than two hours).

(5) Options for real–time and unattended station operations.

(6) Virtually all–weather operations.

(7) Use of GPS transmissions without a knowledge of the coded waveforms which could be encrypted.

(8) Use of GPS signals with only a crude knowledge of their orbital characteristics.

(9) Geodetic measurements traceable to the time–invariant quasar directions.

(10) Ability to leap tall buildings in a single bound.

Conventional GPS Mode

In the conventional GPS mode, four or more satellites in 12 hour period orbits transmit L–band microwave digitally encoded positioning signals, derived from an on–board atomic clock, together with satellite ephemeris information. The system will be composed of 24 satellites when fully operational in the mid–1980's. The user receiver, employing an omni–directional antenna, receives signals from all the GPS satellites above its horizon. By means of cross correlation of the received code with a code model contained in the receiver, a search is performed through all simultaneously received signals to derive the apparent time of flight of the signals relative to the local clock in the user receiver. The user receiver also extracts the particular satellite's identity and broadcast ephemeris data to eventually locate the receiver on a sphere of radius given by the apparent time of flight once the receiver's clock synchronization has been determined. All of the GPS satellite clocks are time and frequency synchronized to the U.S. Naval

Observatory Master Clock to within parts in 10^{12} by frequent ground station monitoring and uplink radio commanding. By measuring the apparent one–way time of flight from satellite to ground station from at least four satellites, the user's clock bias is determined together with the three dimensional position of the user receiver relative to the satellite ephemerides. This scheme for position determination is accomplished entirely in a receive only mode which is an essential element of the military support mission of the GPS Project.

Series Concept

The above brief discussion of the conventional GPS mode has been given in order to contrast the proposed SERIES concept. The SERIES system operates by using pairs of simultaneously observing stations rather than one receiver at a time *(Fig. 1)*. An individual SERIES station consists of an open loop receiver connected to a high gain antenna, which for this discussion is chosen to be of a phased array type (Brejcha, 1978) pointed by a microprocessor. The antenna pointing microprocessor contains the various GPS satellite ephemerides but accurate to only one degree although automatic pointing based on received signal strength is also possible. The choice of a high gain antenna is made in order to reduce the interferometer instantaneous bandwidth requirements and to provide a method of eliminating the error introduced by multipath since a sub–centimeter instrumental system inherent accuracy is desired.

The majority of SERIES applications are of the network monitoring type, so that the a priori position of a SERIES site will probably be known to within 5 m in three dimensions. However, station geographic coordinates to within only one degree of latitude and longitude are needed for antenna pointing. Each SERIES station contains a crystal or possibly a rubidium time and frequency reference which is synchronized to UTC within at least 0.03 hours in order for the microprocessor to perform the satellite ephemeris to phased array antenna pointing coordinate conversion. More stringent time and frequency requirements occur from other subsystems to be discussed later. The antenna pointing is switched between the satellites simultaneously in view, usually four to six, at a once per second rate.

During the one second that the array is pointed at a particular satellite, the open loop L–band receiver performs a phase stable conversion of four (or possible eight) bandpass windows into a 100 Hz to 2.4 KHz baseband. Two of the four windows are at the L_2 (1.2276 GHz) channel. Each of the windows appears in the baseband output for a 0.25 second duration. The baseband signal is infinitely clipped and one bit sampled at a rate of about 5 KB/s. The sampled bit stream, appears as a random temporal sequence of ones and zeroes, because the SERIES station has no mechanism for decoding the pseudo random noise (PRN) sequence emitted by the GPS. The PRN code appears to be pure white noise within the sampled four windows in a manner identical to the usual situation in VLBI geodesy using quasars as sources (Clark, 1973). The key element here is that the identical temporal sequence of ones and zeroes is being received at all SERIES stations but at different epochs owing to their different geodetic positions and as yet unknown clock synchronizations. The random bit stream emerging from the clipper at each station is then time–formatted and stored at the station (i.e. digital cassette tape) or forwarded to a central site via a relatively narrow band communications medium (i.e. land–line or radio telephone). At the central site, a specialized computer buffers and then cross correlates the various arriving bit streams. In a four second interval, each SERIES station observes four satellites and samples four

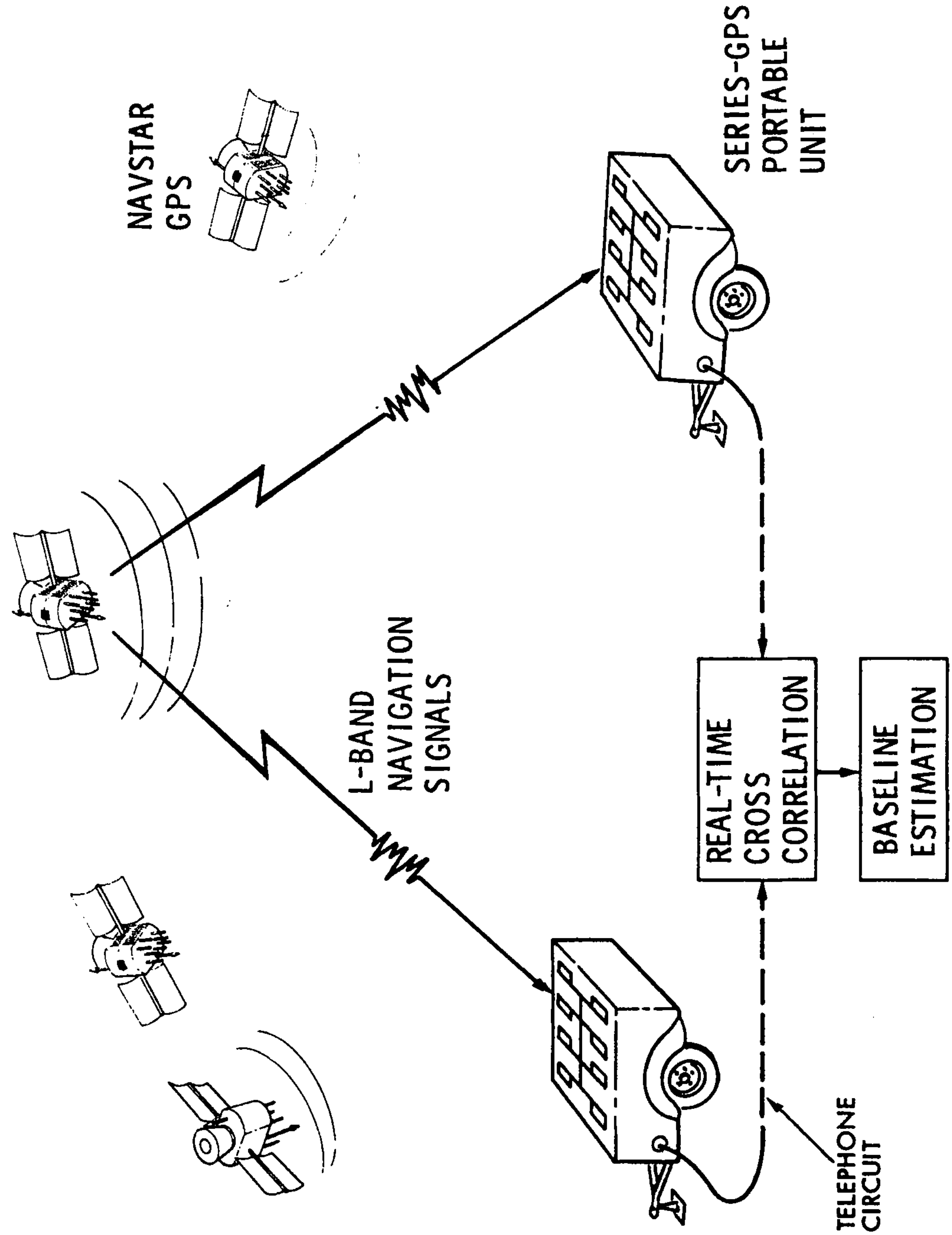

Fig. 1 – Satellite Emission Radio Interferometric Earth Surveying, SERIES concept using L–band signals from the Global Positioning System (GPS) to illuminate a pair of portable ground units. At least four GPS satellites are required in order to derive the three dimensional separation between the SERIES station and to determine a clock–like bias between the stations. The pair of portable units may be operated in real–time or record data for later processing.

windows during each satellite observation for a total of 0.25 sec per window. By cross–correlating 1200 bits from each window, a signal to noise ratio of 24 to 1 is obtained. An ambiguous interferometer phase value is extracted from each window every four seconds (**Thomas,** 1973). By combining 25 such phase values (100 seconds of operation) from two windows separated by 10 MHz and centered at L_1 and two windows separated by 10 MHz about L_2, an interferometer bandwidth synthesis of differenced phase at the L_1 channel divided by $\Delta f = 10$ MHz produces a delay precision estimate equivalent to 6 cm. A similar 6 cm precision value is obtained by bandwidth synthesis from the L_2 channel.

Since the L_1 channel is 348 MHz higher in radio frequency than the L_2 channel, the L_2 channel experiences twice the ionospheric time delay resulting at the L_1 channel, because of the frequency squared nature of electromagnetic dispersion in a charged particle medium. It is this differential delay between the dual L–band channels which allows the ionospheric calibration of the observer to satellite path for the conventional GPS mode and a calibration of the ionospheric differential delay along the two paths to the SERIES stations.

Having developed a set of 6 cm precision delay observations from four satellites with the ionospheric error removed, a simultaneous estimation is then made for the three vector components of the baseline and a bandwidth synthesis phase bias term, analogous to a clock bias, (**Thomas,** 1976). The 30 meter ambiguities of the 10 MHz bandwidth synthesis are resolved by the use of a priori information or by adding a third synthesis channel at 0.5 MHz. The 5 KB/sec digital sampling of the received PRN sequence will provide an unambiguous cross correlation bit stream alignment with a 0.4 microsecond (120 meter) precision obtained in 100 seconds which is sufficient to resolve the 600 meter ambiguities in the 0.5 MHz bandwidth synthesis. This moderately accurate ($\sim$ 6 cm) baseline vector resolution is then used to resolve the 19 cm or 24 cm full cycle phase ambiguities of the interferometer response from either the L_1 or L_2 channel observations. The full strength of the signal to noise ratio can now be used to extract the interferometer phase unambiguously from all four satellites so that the formal precision of the baseline vector estimation is equivalent to a few millimeters.

The next problem is how to become independent of the orbit determination uncertainties of the GPS and make SERIES derived baseline vectors traceable to the time invariant quasar directions. To accomplish this, additional SERIES stations are required. A total of eight stations are now considered. A mobile VLBI system, such as ARIES is assumed to exist (**Niell,** 1979). The mobile VLBI system establishes a sparse grid of primary control at approximately 200 km spacings. Four of the eight SERIES stations now occupy four ARIES sites arranged approximately at right angles *(Fig. 2).* Thus, four of the SERIES locations are now known a priori via ARIES measurements relative to the quasars. The GPS signals arriving at the SERIES / ARIES sites from at least four satellites are now treated in a manner that is the reverse of usual SERIES operations. To a first approximation, the satellite apparent positions are now adjusted such that the observed delay between the four SERIES / ARIES sites gives the same baseline vector components previously determined relative to the quasars. These GPS apparent positions are now used for determining the vector baselines between the remaining four roving SERIES stations and the semi–fixed SERIES / ARIES sites.

In actual fact the GPS satellites are not very distant as in the case of the quasars, so that the GPS signals arrive at the earth as spherical wave fronts. In order to apply the considerable body of experience gained from VLBI geodesy to the case of the GPS signal

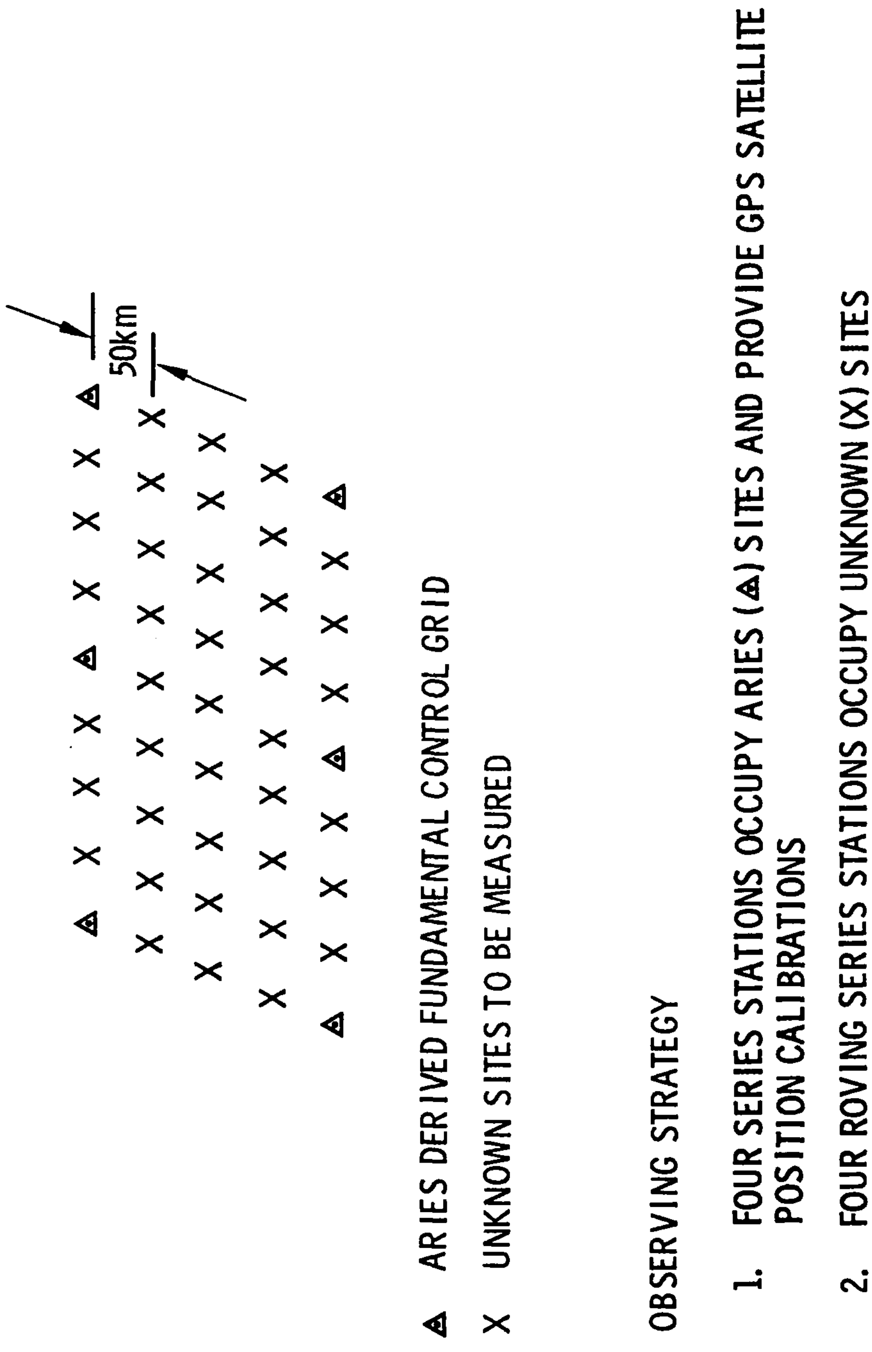

Fig. 2 — SERIES Network Densification with Quasar Traceability

sources, the actual spherical wave fronts must be reformulated into a plane wave with a correction term which requires some explicit range information. The baselines between the SERIES stations are intended to be principally regional in character ($<$ 200 km) and the GPS satellites are relatively high (20,000 km). Because the GPS wave front departures from pure plane waves are functionally dependent upon the square of baseline length divided by satellite distances, the need for satellite range accuracy is considerably attenuated. For example, on 100 km baselines, a 1 km range uncertainty contributes 1 cm of error to the baseline vector solution. A detailed analysis of the use of this range difference observable data type is in preparation with a summary given by Ong (1978).

Another option is to use the satellite ephemerides determined by the DoD either by equipping one of the SERIES stations with a complete GPS receiver or being provided precise ephemerides (2 m accuracy) by terrestrial communications. The use of a conventional GPS receiver could provide actual range and satellite positional data with approximately 10 meter accuracy but in a coordinate system which depends upon the earth's reference gravitational field. The gravity field and quasar reference frames are as yet unrelated and would bring about a complication for a geodetic monitoring mission but an opportunity to define the GPS satellite positions in a manner previously unavailable. Preliminary analysis (Ong, personal communications, 1978), indicates that interferometric angular tracking of 0.05 μ radians (plane of the sky) is possible using station locations derived by ARIES at 200 km spacings.

Radio Flux equivalent of GPS Transmissions

The quasars are continuum emitters across an enormous range of wavelengths from optical to deka meter radio with currently useful microwave radio flux in the regime of 0.1 to 40 Jy (Jy $= 10^{-26}$ W/m^2/Hz). In contrast, the GPS signals are narrow band but quite strong. The current received power performance of the first two GPS satellites (Parkinson, personal communications, 1978) is -155 dBW for the course/acquisition (C/A) channel, -158 dBW for the precise (P) L_1 channel and -158 dBW for the L_2 P channel. The transmissions are bandlimited to 2 MHz for C/A and 20 MHz for the P channel with a $\frac{\sin x}{x}$ amplitude pattern. Two bands, $L_1 = 1.575$ GHz and $L_2 = 1.227$ GHz are simultaneously transmitted.

To translate these GPS parameters into terms familiar in VLBI geodesy, the received radio intensity must be determined from the signal power and antenna gain. The definition of antenna gain (Kraus, 1966) is $G = \frac{4\pi A}{\lambda^2}$, where A is the antenna area and λ the received wavelength. For an isotropic antenna $G \equiv 1$ and for the L–band $\lambda_1 = 19$ cm and $\lambda_2 = 24$ cm, the equivalent collecting areas are 2.9×10^{-3} and 4.6×10^{-3} m^2, respectively. The P channel is of most interest because of the desire to have the largest spanned bandwidth possible to obtain greater delay measurement precision in the bandwidth synthesis process (Rogers, 1970; Thomas, 1972 b). The -158 dBW received power in the L_1 P channel corresponds to 5.5×10^{-14} W/m^2. If this signal intensity were uniformly distributed across the 20 MHz of the P channel, the flux density would be 2.8×10^{-21} W/m^2/Hz or 2.8×10^5 Jy. The L_2, P channel has a -158 dBW signal corresponding to 3.4×10^{-14} W/m^2 or 1.7×10^5 Jy over a 20 MHz band. Thus, the signal strength from a GPS satellite is 10^4 to 10^6 times stronger than signals available from quasars which affords SERIES–GPS, a vast system trade–off potential for a geodetic interferometer design in favor of system simplification and reduced costs.

The basic information content from SERIES is differential range derived from the interferometer phase delay which is synthesized rather than being obtained from a large instantaneous bandwidth. The bandwidth synthesis delay precision is inversely related to the product of spanned bandwidth (Δf) and the interferometer system signal to noise ratio. The method for obtaining the greatest delay precision then becomes the maximizing of the function $\frac{\Delta f(\sin X)}{X}$, where $X = \pi f$, f is the frequency separation in MHz from the L_1 or L_2 center frequency and $\Delta f = 2f$.

So,

$$\frac{d}{df}\left[\left(\frac{2f\sin\frac{\pi f}{10}}{\frac{\pi f}{10}}\right)\right] = 0$$

requires that $f = 5$ MHz or an optimum bandwidth synthesis of $\Delta f = 10$ MHz. At ± 5 MHz, the $\frac{\sin X}{X}$ and uniform power distribution functions are approximately equivalent at 2.8×10^5 Jy for L_1 and 1.7×10^5 Jy for L_2.

Signal to Noise Ratio

The signal to noise ratio (SNR) for an independent station interferometer is given in Shapiro (1970) and MacDoran (1974) which by applying the definition of antenna gain can be written as

$$\mathrm{SNR} = (1.4 \times 10^{-5})\, S\lambda^2 \left[\frac{G_1 G_2 RT}{T_{S_1} T_{S_2}}\right]^{1/2}$$

where

- S – Satellite radio signal flux, Jy
- λ – Received wavelength, meters
- G – Antenna gain relative to isotropic
- R – Digital recording rate (bits per sec)
- T – Signal coherent integration time, sec
- T_S – Receiver operating system temperature, Kelvin

Synthesized Delay Precision

The synthesized delay observable is used as an L–band phase ambiguity resolver.

$$\sigma \tau = \frac{1}{\sqrt{2\pi}\,(\mathrm{SNR})\,\Delta f}$$

where Δf is the synthesized bandwidth, Hz .

Intermediate Baseline Vector Precision

$$\sigma B_L\,(m) = C\,\sigma\tau\,A_{cov}\sqrt{\frac{N_p}{N_{obs}}}$$

where

C = Vacuum speed of light

A_{cov} = Covariance amplification factor

N_p = Number of parameters estimated

N_{obs} = Number of observations

The term A_{cov} accounts for the specific distribution of sources being used for the simultaneous estimation of baseline vector and clock offset terms. For an ideal distribution involving a transparent earth $A_{cov} = 1$, however, in typical situations A_{cov} will equal unity only for the local horizontal baseline components and probably will be 2 to 3 for the vertical component depending on the satellites distribution in the sky relative to the SERIES network.

Phase Differential Distance Measurement Precision

$$\sigma D_\phi = \frac{\lambda}{2\pi\,(\mathrm{SNR})}, \quad \textit{meter}$$

Inherent Baseline Precision Limit

$$\sigma B_L\,(m) = (\sigma D_\phi)\,A_{cov}\sqrt{\frac{N_p}{N_{obs}}}$$

As a specific example, consider the following configuration of instrumentation with GPS signals.

S = 1.7×10^5 Jy flux from the L_2 channel

λ = 0.24 meters , L_2 cha nnel

G = 27 db gain, phased array using design concepts originally developed for and flown aboard SEASAT (Brejcha, 1978).

R = 5 kilo–bit per second digital recording rate

T = 0.25 sec coherent integration for corss correlation signal detection

T_S = 100 Kelvin , using an ambient temperature field effect transistor amplifier

$$SNR = (1.4 \times 10^{-5})(1.7 \times 10^{5})(0.24)^2 \left[\frac{(500)(500)(5 \times 10^3)(0.25)}{(100)(100)}\right]^{1/2}$$

$$SNR = 24$$

The synthesized delay is then,

$\sigma\tau = \dfrac{1}{\sqrt{2\pi}(24)(10^7)} = 1\ \eta s$ from each 0.25 sec of observation. The 30 meter baseline vector ambiguities resulting from the 10 MHz bandwidth synthesis are assumed resolved by a priori station position information. A total of four parameters are to be estimated, three baseline components and a bandwidth synthesis bias term analogous to a clock synchronization between the two observing stations. The four satellite orbital positions are assumed provided by the four semi–fixed SERIES stations occupying ARIES provided ground positions. Short act orbit extrapolation methods can be used to adjust the satellite positions to the normal point epochs of the synthesized delay observations for the various pairs of SERIES interferometer stations. The number of observations is 4 per channel obtained at four channels from four satellites in 16 seconds. The resulting intermediate precision baseline vector will be 30 to 45 cm every 16 seconds. By averaging 60 such blocks of 16 sec. data (approximately 17 minutes), a resultant precision is obtained of 4 cm in the local horizontal and approximately 10 cm for local vertical components. Combining the L_2 and L_1 channel baseline vectors after estimating the ionospheric error will provide a 3 to 7 cm precision. This 7 cm or better precision now provides the necessary information to resolve the 24 cm full L_2 channel wavelength ambiguities to obtain a phase differential distance precision of 2 mm from each 0.25 second of observation.

In order to obtain the greater time resolution from SERIES baselines and to minimize the time and frequency stability requirements, a stand–alone solution is formed every four seconds. In four seconds, a total of 16 phase measurements are made. Each 4 second data block now stands alone and the instrumental bias term is free to change between individual 4 second data blocks. If it were not for other error sources, the instrumental precision of SERIES would approach a 0.3 mm limit in approximately 7 minutes.

Time and Frequency Subsystem Requirements

At each step of the previously cited example, a certain stability for the time and frequency subsystem was required. A more detailed analysis of time and frequency requirements for VLBI geodesy is given in MacDoran (1975) and will not be repeated here. In the first step of obtaining interferometer fringes in 0.25 sec of coherent integration time, the first local oscillator of the open–loop receiver must not deviate from purely linear phase behaviour by more than one quarter cycle of phase in 0.25 seconds which requires that

$$\frac{\Delta\phi}{\phi} = \frac{\Delta\phi}{ft} = \frac{0.25\ cycle}{(1.227 \times 10^9\ Hz)(0.25\ sec)} = 8 \times 10^{-10}$$

The next step is the intermediate precision bandwidth synthesis to resolve whole L–band cycle ambiguities. Here, only one clock synchronization term is to be estimated over the 16 second data block. The 1 nsec (30 cm) delay precision requires a $\frac{\Delta\tau}{T} = \frac{10^{-9}}{16} = 6 \times 10^{-11}$ fractional stability. The further combination of 60 data blocks is performed in an incoherent manner so that new synthesis phase biases are allowed every 16 seconds.

The final step of phase differential distance measurement requires 10^{-11} second (3 mm) stability over a 4 sec interval or $\Delta f/f = 2 \times 10^{-12}$.

The stability requirements for digital sampling and time formating of the baseband output of the SERIES receiver depends upon the sampling rate. At the rate of 5 KB/sec a sample occurs every 200 microseconds. Since cross correlation bit stream alignment techniques might be required for some baseline solutions where no a priori information is available, stability of 0.4 μs over 100 seconds requires $\Delta f/f = 4 \times 10^{-9}$.

Thus, a variety of frequency and timing subsystem stability requirements results for different averaging times which are summarized below.

Table 1

Frequency/Timing Subsystem Requirements

Averaging Time, Sec.	Fractional Stability
0.25	8×10^{-10}
4	2×10^{-12}
16	6×10^{-11}
100	4×10^{-9}

These requirements can be met by relatively inexpensive rubidium frequency systems or by crystal oscillators of modern design.

Transmission Media Errors

The nature of transmission media errors, both troposphere and ionosphere, for regional scale VLBI geodetic networks, is to cause little error in local horizontal baseline components but errors amplify in the vertical direction. A simple heuristic argument will serve to illustrate the reason for this error propagation. The radio sources, either quasars or satellites, are generally well distributed over the sky. So, pairs of sources east/west and north/south can often be formed during an observation interval. The simultaneous estimation process models simple instrumental terms, clock synchronization and rates, and terms which vary depending upon from which direction the radio source signals are arriving.

Consider a simple one dimensional baseline of only east/west extension with a source in the east and a source in the west. When both antennas are pointed east, the interferometer delay indicates the free–space time of flight of the radio wave from station 1 to station 2 plus the transmission media delay encountered between stations 1 and 2 plus the clock difference between stations. When both antennas are pointed west, the observed delay is the negative of the free–space travel time between stations but the same positive media delay plus the same relative clock error. Because only the baseline terms change algebraic sign depending upon the direction of the arriving radio waves, and the transmission media and the clock terms, to a first approximation, do not depend upon the direction of antenna pointing, the baseline components are separable in a simultaneous solution. In the simple east/west baseline case, there are two observed delays involving two unknowns, the baseline length and a constant term which actually is the combined clock synchronization and transmission media delay. So, in the absence of additional information, the baseline is separable but the clock synchronization is highly correlated with the transmission media delay between stations.

Considering now a baseline of three dimensions merely adds a north/south extension which is analogous to the east/west extent already discussed, however, the vertical component results in an entirely different behaviour. Pairing sources to correspond with sources near to vertical direction would require an unphysical situation of a transparent earth. Through a set of simulations involving actual ARIES quasar observations (G.M. Resch, unpublished data, 1977), it has been found that azimuthally symmetric transmission media errors amplify their effects upon the local vertical varying by a factor of 2 to 3, while the horizontal baseline components are substantially unaffected. Specifically, making a differential 1 cm error between the zenith delays above stations 1 and 2 results in a 2 to 3 cm error when estimating the relative vertical positions of the stations. However, if explicit calibrations are available for each of the observation directions, the zenith error will not grow as one over the sine of elevation angle and the vertical component error will remain the 1 cm of calibration accuracy. Another aspect of media errors has been implied but needs to be explicitly stated and that is the azimuthal symmetry of the error. In many cases, the troposphere is virtually plane layered above each station, however, in rapidly changing weather conditions the azimuthal symmetry will not exist. Thus, the media delay when receiving signals from the north will be different than signals arriving from the south and the degree of azimuthal asymmetry will map directly into horizontal baseline errors. Of course, as the stations are brought closer together the differential transmission media vanishes. Some bounds can be placed on these effects. In the case of connected element radio interferometry on baselines of 1 to 35 km, the baseline vector components are soluable with sub–centimeter repeatability (Ryle, 1973) using data spans of several hours. The issue of whether such repeatability actually represents the connected element interferometry accuracy cannot be independently verified because conventional geodetic methods do not allow few millimeter three dimensional geometric accuracy on 35 km baselines. The primary geodetic limitation results from the necessity to develop a differential geoid accurate to a few mm in order to translate the geopotential difference measurements of geodetic leveling into the corresponding geometric position differences (Heiskanen, 1967; Whitcomb, 1976).

Because of the temporal and spatial variability which is possible in the transmission media, it is essential for the SERIES–GPS geodetic system to incorporate explicit tropospheric and ionospheric measurement systems or the overall system will suffer a factor of 10 to 100 degradation of the inherent few millimeter instrumental precision.

Tropospheric Errors

The tropospheric delay is composed of two parts, wet and dry. The wet component tends to be variable at 10 to 20 % over periods of several hours, has a zenith delay magnitude of 2 to 25 cm depending on location and season and is not reliably calibrated from surface meteorological measurements when 1 to 2 cm accuracy is required. The dry component is more stable, less than 1 % variations in a few hours, has a zenith delay of approximately 200 cm and can be accurately calibrated by surface pressure and temperature measurements using equations of hydrostatic equilibrium (Chao, 1974). The greatest problem from this error source is thus the calibration of the wet component.

For several years the method of microwave water vapor radiometry (Schaper, 1970) have been studied to develop direct methods for measuring the water vapor delay along an arbitrary line of sight. Dual channel radiometry at 22 and 31 GHz has demonstrated (Winn, 1976) the ability to measure water vapor path delay to an accuracy of 12 to 15 mm when compared to radiosonde weather balloons and airborne meteorological sensors. The data analysis methods used for this radiometry are presented in Claflin (1978). The accuracy of the radiometry does not significantly degrade with elevation angle for angles greater than 20 degrees. Theoretical studies (Moran, 1976) indicate an accuracy limit for the technique of 3 to 5 mm.

An automatic water vapor radiometer (WVR) is now being implemented for routine field use with the ARIES mobile station. For SERIES–GPS it is proposed that an automated WVR be a part of every station when the length of the baselines are to be longer than 50 km. In mid–1979, three to five WVR devices will be available for simultaneous observations which will begin to more definitively answer the question over what baseline lengths will the troposphere be self–eliminated in differenced data types and when is a WVR required? No alternative calibration approaches (i.e. / solar hygrometers) offer the combination of flexibility, day/night operation, arbitrary directions, through clouds, and accuracy of 1 to 2 cm. While the present WVR devices are expensive ($\sim$ \$ 90 K each), much of the non–recurring engineering costs are now past. Also, several cost saving innovations are possible so that future SERIES deployed units might carry \$ 30 K WVR devices when eight or more SERIES stations are built. The increased effectiveness through a higher data yield in almost all weather conditions will more than pay the WVR costs over a several year interval when SERIES operations involve field personnel.

Ionospheric Errors

The baseline equivalent errors introduced by the ionosphere on 200 km and shorter baselines are difficult to estimate where centimeter accuracies are of interest. However, recent experience with the ARIES transportable VLBI system on a 380 km baseline observing simultaneously at S and X band can provide some reasonable bounds on the errors to be expected.

An experiment conducted in June 1977 resulted in identical baseline vectors obtained at both S and X bands within the 3 to 5 cm system noise limits (MacDoran, 1978). The X–band (8.4 GHz) data would have experienced 13 times less charged particle error than the S–band (2.3 GHz) data. Assume now that the X–band data was perfect and that a 5 cm ionospheric error was present in the S–band data.. This 5 cm S–band error can now be scaled to the L–band channels. At the L_1 channel the effect will be $5\text{ cm}\left(\frac{2.3}{1.575}\right)^2 = 10.7$ cm and at L_2 the effect will be $5\text{ cm}\left(\frac{2.3}{1.227}\right)^2 = 17.6$ cm. Thus, the individual baseline vector solutions will differ by approximately 7 cm depending upon whether L_1 and L_2 channel data is used.

The intermediate precision baseline vector solutions from the 10 MHz band-width synthesis will be approximately of 4 to 6 cm precision which is about the same magnitude as the ionospheric errors. Once the data processing reaches the individual L_1 or L_2 cycles of phase where precisions of a few millimeters exists, the 7 cm ionospheric effects will be clearly visible and correctable to the one centimeter or better level. This 1 cm effect is assumed to be both a random and systematic error and exists at 200 km baselines and diminishes to near zero as the baseline becomes very short (i.e., 1 km).

Systems Analysis

Having discussed the various system elements, it is appropriate to assemble the system analytically and examine the aggregate effects of the random and systematic error sources. The random errors are those which are capable of having their effects diminished by averaging more data together with the mean estimate improving by the square root of the number of observations. Such formal estimate improvement is ultimately limited by systematic errors which are not amenable to reduction by data averaging and merely sum quadratically to limit the accuracy. ***Tables 2*** and ***3*** summarize these errors.

Table 2

Random Error Sources

Source	Baseline Equivalent (cm)
Phase Delay Measurement Precision (4 sec. intervals)	0.2 to 0.5
Time and Frequency ($\Delta f/f = 2 \times 10^{-12}$, $\tau = 4$ s)	0.3
Troposphere *	
Dry (Surf. Met.)	1.0
Wet (Water Vapor Radiometry)	1.5
Ionosphere (residual from dual L–band calib.)	1.0
GPS Satellite Positional Uncertainties (range acc : 1 km, baseline : 100 km)	1.0

Root Sum Square Per
4 sec : 2.4 cm

1 min. average : 0.6 cm

* – The actual random variability of the troposphere on 4 sec intervals is unknown but is assumed to be the same as the several hour value.

Table 3

Systematic Error Sources

Source	Baseline Equivalent (cm)
GPS Satellite Positional Uncertainty (range acc : 1 km, baseline ; 100 km) (ARIES constrained network, 2 cm acc ; 200 km spacings)	1.0
Time and Frequency ($\Delta f/f = 6 \times 10^{-11}$, $\tau = 16$ s) (incoherent averaging of 60, 16 s data blocks)	0.3
Troposphere	
Dry (Surf. Met.)	1.0
Wet (Water Vapor Radiometry)	1.5
Ionosphere (residual from dual L–band calib)	1.0
Root Sum Squared	2.3
Combined Random and Systematic Errors :	2.4 cm

Figure 3, graphically summarized the various baseline accuracies which might be achieved for various baseline lengths. The relative networks curve illustrates the higher internal network accuracy that should be achieved by a simultaneous adjustment of the many (28) baseline vectors which result from eight simultaneously observing stations. The adjusted network need not be closely constrained to the ARIES inter–site vectors since the post–adjusted precisions will probably be better than the 2 cm accuracy at 200 km spacings.

Series Field Station Conceptual Design

Figure 4 illustrated the basic block diagram for a SERIES station. The station, in its portable configuration, would be trailer mounted and towed by a car or truck. While being transported, a battery supply will maintain D.C. power on the station's frequency and timing reference, either a rubidium or crystal oscillator, and other critical subsystem elements. When on site, the trailer is leveled to an accuracy of about one degree and a self–contained gasoline powered generator is started to recharge the batteries and supply the station's main power bus.

The antenna is then aligned in the north/south and east/west directions. The GPS signals can be used to provide this referenced. Using the station microprocessor, the program is used in an antenna non–switching mode to track a particular satellite, for example in an approximately eastward direction (i.e. 98.2 degrees). The array will be configured with a slight freedom for rotation, approximately 30 degrees . The array is manually rotated until the received satellite signal is a maximum, as indicated by a broadband (20 MHz) detector. The antenna should now be ready for its once per second switching to the various satellites in view. The eccentric offset of the antenna's electrical phase center (probably the geometric center for a symmetric phased array) is now measured with respect to the nearby geodetic mark. This eccentric offset might be determined by an optical plumb device rigidly attached to the phased–array antenna and

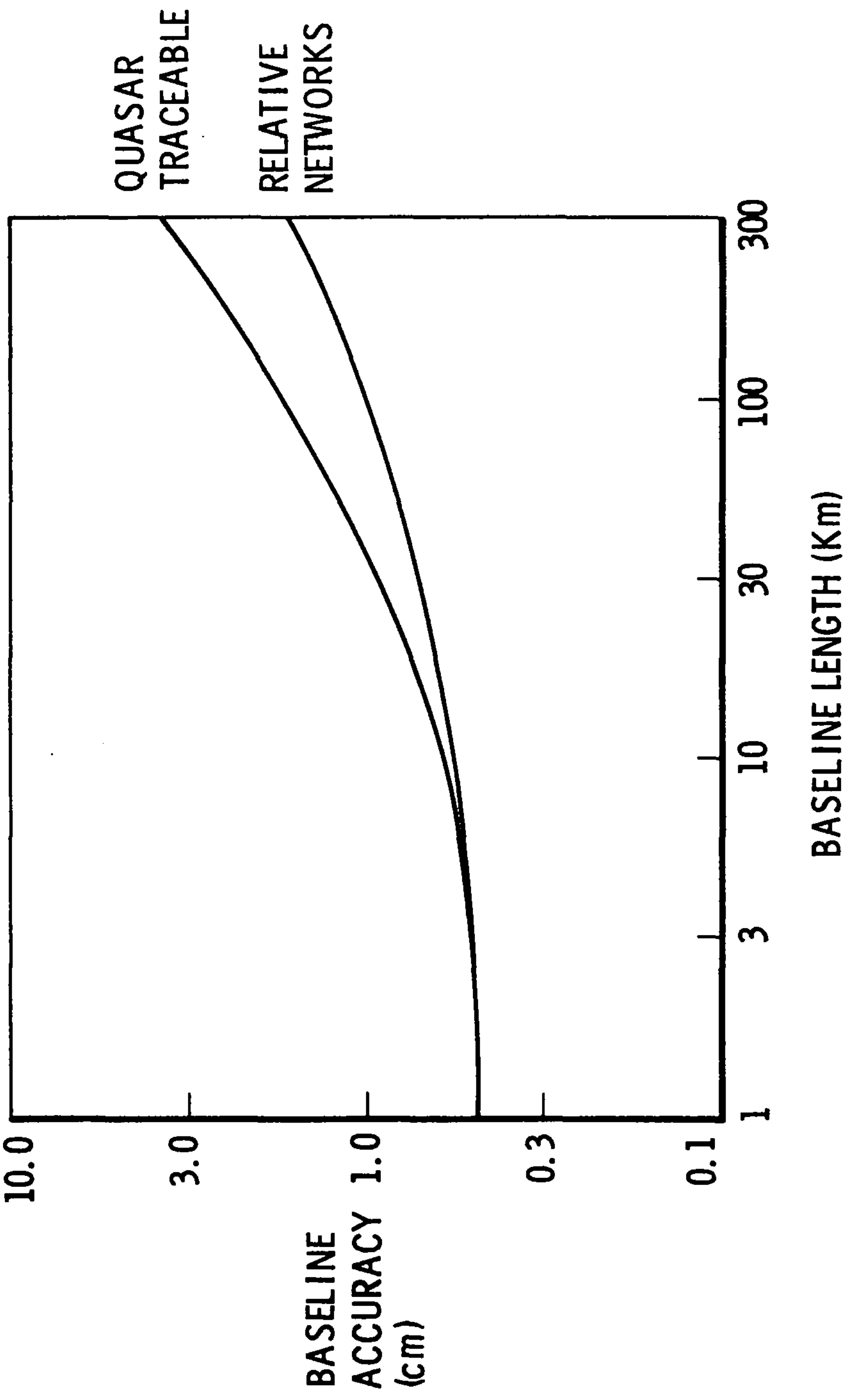

Fig. 3 – SERIES–GPS Accuracy Estimates

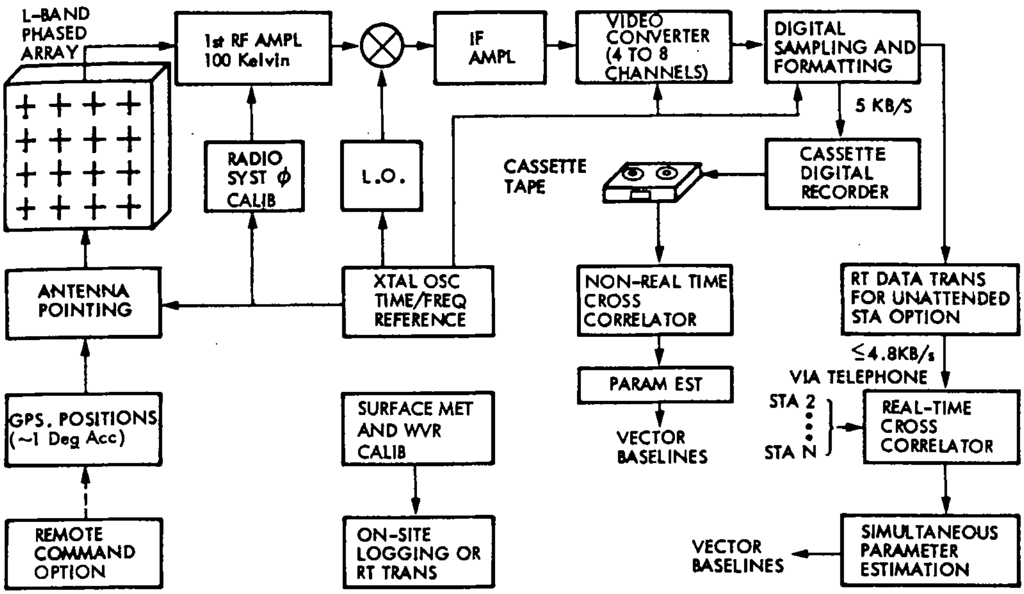

Fig. 4 – SERIES Field Station Conceptual Design

a temporary mark to establish the horizontal offset. The height of the antenna above the mark can be determined in the usual manner. The positioning of the antenna relative to the mark should be measurable to an accuracy of 2 millimeters where the offset is less than a few meters.

The microprocessor controller will probably be a disk based system into which a diskette containing the observing schedule is inserted. In an automated mode, a telephone dial–up approach can be used to load the observing strategy. The microprocessor contains a table look–up program for each of the 24 satellites . From the station's UTC clock and the approximate station location (latitude and longitude accurate to one degree), the program determines which of four to six of the satellites are in view and a pre–established protocol determines the antenna switching sequence. For example, northern most satellite on integral minutes, then east, south, west and vertical. The program determines the voltages to be applied to the active elements of the phased array to steer the beam to within one degree of the satellite's position. The program must update the array pointing voltages every 12 seconds .

The field effect transistor first RF amplifier is simultaneously coupled to the antenna and a phase calibration device (Rogers, 1975). The phase calibrator inserts continuous wave tones into each of the L–band windows which are mapped to baseband. Because the tones are present in the baseband video, it is digitally sampled and recorded as if it were the PRN signal from the GPS. As a part of the cross correlation processing, the phase of the individual tones from each of the four windows will be extracted in an analytic heterodyne manner. By substracting the corresponding phases of the windows from stations 1 and 2 , the interferometer phase differential is determined. A detailed analysis of this type of phase calibration procedure is given by Thomas (1978).

The output of the first RF amplifier is then mixed with the first local oscillator to a convenient intermediate frequency (i.e. 500 MHz) where the various synthesis windows are determined. A reasonably high IF is used because both the L_1 and L_2 signals are to be sampled. A second stage of heterodyne conversion occurs in the video converter to a baseband of 100 Hz to 2.4 KHz. The baseband signal is now infinitely clipped, one–bit sampled and formatted into a 4.8 KB/s data stream which can be either recorded onto a tape cassette or a telephone modem for transmission in real–time to a central site for cross correlation processing.

The tropospheric calibration equipment, a scanning water vapor radiometer and surface pressure/temperature instruments, will be contained together and placed a few meters from the station. An interconnecting cable will carry commands from the station microprocessor to the WVR and return WVR, pressure and temperature data to the station for either recording or real–time transmission with the interferometer data.

At the central site, a microprocessor computer separates the interferometer and tropospheric calibrations. The time formatted bit streams from each of the stations participating are buffered for an amount of time corresponding to geometric light time between stations ($<$ 1 millisecond), telephone line delays and clock differences (few milliseconds). In 10 msec, only 48 bits occur so the buffers are small. The bit streams are aligned according to the available a priori station locations usually accurate to 5 meters or better and for the GPS satellite positions derived from the four SERIES stations at known locations. The cross correlation proceeds in the usual manner (Clark, 1973) to produce correlation coefficients every 30 milliseconds which are phase tracked to produce a sinusoidally varying signal called fringes. The fringe phases from the various windows are differences to produce delays by bandwidth synthesis in a iterative fashion until the phase of the L–band signals can be measured unambiguously.

Series System Challenges

The discussion just presented has assumed that the transition from bandwidth synthesis to individual L–band cycles is in fact possible. Present VLBI geodesy experience has not yet fully dealt with these challenges. Some experiments have been performed using a fringe phase data type on a 1.2 km baseline at X–band (8 GHz) frequencies (Rogers, 1978), however, at L–band where the ionosphere has a factor of 50 greater effect, no geodetic demonstrations are available. While considerable theoretical analysis remains to be done, it appears promising to investigate an implementation that simultaneously uses all four windows to estimate the linear phase shift resulting from baseline errors and the quadratic phase shifts from the ionospheric dispersion. This approach affords, in effect, a 358 MHz bandwidth synthesis which has an 84 cm ambiguity interval. Using the 10 MHz synthesis from either L_1 or L_2 should provide the 15 cm precision necessary to resolve the 84 cm ambiguities. The 358 MHz synthesis can then be used to calibrate the ionosphere and derive 3 cm precision baseline components to resolve the 19 and 24 cm ambiguities of the L_1 and L_2 channels. Some use can also be made of the fact that the geometry of the incoming signals is changing. In two hours, the satellites will move 60 degrees and cause a linear phase versus frequency shift if a baseline error is present. So, the satellite motions can aid in the problem of L–band cycle ambiguity resolution, hopefully, without seriously impacting the time required on–site to acquire the necessary geodetic data.

Another item for further investigation has to do with the high signal levels at the SERIES stations. Because signals are strong, the data system may saturate and the signal to noise equations and experience derived from quasar experiments may not completely apply to this problem.

Applications

Geodesy – The applications of SERIES–GPS to the field of geodesy are several. Because of the virtually all–weather capability of the system, each of the field personnel used to operate the portable units will be far more productive than when using optically based instrumentation. Since baseline vector solutions can be formed in less than 15 minutes, a two hour on–site time should allow adequate time to set up, check out equipment and acquire geodetic data with a reasonable redundancy. A two site per day visitation schedule should be achievable.

Seismo–Tectonics – The ability to track the SERIES system phase, either unambiguously or with unknown multiple cycles present, on a short time scale begins to move this technique into the regime of seismology. In only 0.25 seconds a 24 to 1 signal noise ratio can be achieved at a single window. However, an SNR = 8 is suitable for cross correlation phase tracking which implies that only 0.03 seconds (150 sample bits) per window are required. Combining the phase change information from all four windows will yield an effective SNR = 16 which implies a phase differential distance measurement precision of approximately 2 mm every 30 milli–seconds but in four second intervals because of the phased array antenna switching between satellites. Whether the other elements of the system, both instrumental and transmission medium, will allow the exploitation of this high resolution mode remains an issue for actual demonstrations. It is, however, interesting to speculate on SERIES utilization as a high time resolution three dimensional strainmeter which can respond to deformation in an absolute sense since the geodetic positions at the beginning and ending of a strain event can be determined.

A 2 cm positional accuracy over a 100 km baseline corresponds to 0.2 μ strain and the ability to track short term (100 second) changes with 2 mm precision is equivalent to 0.02 μ strain. Real–time strainmeters of 100 km dimensions are not currently available even in one dimension and could prove interesting should a seismic event occur while measurements are being made.

A combination of portable units frequently (every few weeks) monitoring a dense network, at perhaps 50 km spacings, within a larger network of continuously operated stations, at 200 km spacings, could prove to be extremely useful in an earthquake prediction research program. The revisitation time for ARIES to update the fundamental control grid is not clear but may be every six months.

Marine Geodesy – Some marine geodesy applications are also possible. A buoy could be equipped with SERIES instrumentation and a low gain antenna. This marine station could be operated in combination with a high gain land–based antenna to offset the reduction in gain at the ocean station. A narrowband satellite communications circuit could be used to link the SERIES and oceanographic data back to a central site. The ocean station would do no antenna pointing and the potential meter level multipath errors will not be considered serious in this application. The large (10 m dish) land–based antenna will be pointed to the various GPS satellites in a sequential manner but at a low rate, perhaps one satellite per two minutes. The pitching and rolling motion of the ocean station will cause a data processing problem. Applications for this system might include buoy tracking, open ocean tide measurement, tsumami monitoring and sea floor tectonic monitoring in conjunction with sonar positioning of the buoy relative to bottom transponders.

Conclusions

Some very interesting possibilities exist for using the L–band transmissions from the GPS satellites as sources of illumination for a geodetic radio interferometer. The GPS signals are at least five orders of a magnitude stronger than the quasar radio sources now being used in VLBI geodesy. The added complication of the satellite's orbital motion is dealt with by using SERIES stations at known baseline positions derived relative to the quasars using ARIES mobile VLBI geodesy. Thus, the apparent positions of the GPS satellites can be developed in a manner traceable to the time–invariant quasar directions. Some a priori range information is required but only to the kilometer accuracy level.

The overall system accuracy appears very attractive at the 0.5 to 3 cm level for baselines from 1 to 200 km with only two hours of on–site data acquisition. The path delay effects imposed by the wet troposphere will be explicitly calibrated by water vapor radiometers. However, the 1.5 cm accuracy of the radiometers will probably be the limiting error source. The inherent instrumental accuracy may be 5 mm but will be difficult to exploit as accuracy because of several other systematic errors of similar magnitude. The use of cross correlation signal detection techniques nicely avoids the necessity of knowing the form of the pseudo random noise transmissions from GPS which makes the GPS a global geodetic resource. The 4.8 KB/sec data rate is low enough for real–time telephone return or to be recorded on a digital cassette device at the station.

A note of caution is appropriate because the VLBI geodesy experience gained from quasar sources is not entirely applicable to the GPS as sources because of the high signal levels from satellites. Saturation effects in the data system, RF cycle ambiguity resolution and simultaneous ionospheric calibrations at L–band are not yet fully understood and experimentally demonstrated techniques.

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