A SYSTEM FOR NEAR REAL-TIME CRUSTAL DEFORMATION MONITORING

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ABSTRACT

It is proposed to demonstrate a near real-time monitoring system for study of vertical crustal deformation such as the Palmdale Bulge. This monitoring will be achieved by independent station radio interferometry techniques with a pair of small antennas (2.5m), illuminated by ALSEP S-band signals from the moon or other artificial radio signal sources. Although the ALSEP will allow only fringe frequency observations and measurement of equatorial baseline components, 82% of vertical deformation can be sensed. This system will occupy sites previously measured in three dimensions by ARIES (Astronomical Radio Interferometric Earth Surveying) and monitored thereafter by this small antenna system. By comparing the ARIES equatorial baseline components, derived from quasar positions, with those determined by ALSEP signals it will also be possible to relate lunar motions relative to the quasar reference frame with approximately 0.1 arc sec.

INTRODUCTION

The ARIES (Astronomical Radio Interferometric Earth Surveying) technique, as presently constituted, is sophisticated and cumbersome to operate because of the quasar sources are weak signals when received at the earth. However, the quasars compose a virtually time-invariant frame of reference because of their great distances and thus are free of orbit computational challenges.

The ALSEP (Apollo Lunar Surface Experiments Package) units placed on the moon by Apollo Flights 12, 14, 15, 16 and 17 represent a valuable resource of radio illumination for earth-based interferometers. Such interferometry has been accomplished by several investigators (ref. 1, 2, and 3) although, no use has been made of the ALSEP signals for terrestrial geodesy.

Unlike the quasars which emit very wideband radio spectral noise, the ALSEP is spectrally narrow being composed of telemetry signals from lunar-based scientific instruments. The ALSEP's are not radio transponders of the type used aboard interplanetary spacecraft. The ALSEP does accept uplink commands from earth to control certain functions, however, no coherent response occurs from the device.

Although the ALSEP spectrum is narrow, about 6 KHz at 3 db, the radio flux arriving at the earth is equivalent to 50,000 Jansky (10^{-26} w/m^2/Hz). By comparison, in ARIES experiments a strong quasar is considered to be a source of 5 or more Jy. This factor of 10^4 difference in flux is then available to be traded-off to achieve a simpler radio interferometry system but at the expense of having introduced radio source dynamics into the problem. Fortunately, LURE (Lunar Ranging Experiment) ref. 4 and the ALSEP/Quasar ΔVLBI experiments, ref. 5, have been successfully dealing with such problems and now represent a valuable resource for achieving the desired radio interferometric geodesy simplifications.

FRINGE FREQUENCY OBSERVABLES AND VERTICAL COMPONENT SENSITIVITY

The RF spectral narrowness of the ALSEP's does represent a limitation relative to the extremely wide RF continuum emissions of quasars. A broad RF emission spectrum allows the interferometer to precisely measure the delay function by signal cross-correlation within 0.1 nanosecond, but a narrow spectrum allows only the time rate of delay change to be precisely measured (ref. 6). Three dimensional geodesy requires interferometry delay measurements from at least two quasars at substantially different declinations. In actual practice, ARIES experiments use ten to twenty quasars observed over periods of 8 to 26 hours because of a need for an alternate solution strategy caused by frequency system instabilities.

Having access to only delay rate data, also called fringe frequency, results in the interferometer being sensitive to only the two equatorial components (X and Y) of the baseline vector. The Z component insensitivity results in a loss of 18% of the information and some uniqueness of interpretation. More specifically, consider the effect of applying the rotation matrix (valid for latitude 35°) to transform a unit local vertical displacement into geocentric baseline components:

$$\begin{pmatrix} -.26 & .88 & -.39 \\ -.49 & -.47 & -.73 \\ -.83 & 0 & .56 \end{pmatrix} \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} = \begin{pmatrix} -.39 \\ -.73 \\ .56 \end{pmatrix}$$

Thus, a one meter increment in the local vertical appears as a 39 cm decrease in the gocentric X component (direction toward Greenwich) and a 73 cm decrease in the Y component (90° E of Greenwich). The spin axis component, which will not be sensed by this system, experiences a 56 cm increase.

REAL-TIME DATA TRANSFER

The narrow RF spectrum of ALSEP does offer an important advantage of being easily recorded or transferred via telephone. A 3 KHz information bandwidth is suitable from signal to noise ratio considerations and quite reasonable for telephone circuit transmission for real-time cross correlation signal detection processing.

The phone lines have instabilities that need frequent calibration. This can be accomplished by time-formatting the data in the usual Very Long Baseline Interferometry (VLBI) manner at each station. Each of the 2.5m antenna stations will have a cesium clock which can be synchronized to the other clock within one microsecond or better and thus the phone line delay can be determined well within the 3 KHz bandwidth restrictions of the line. Figure 1, illustrates the conceptual elements for monitoring stations 100 km apart at Pearblossom and Palos Verdes, California. The Pearblossom site is in the maximum zone of the uplift associated with the San Andreas Fault in Southern California and known as the Palmdale Bulge (ref. 7). There is reason to believe that these uplifts can occur relatively rapidly (i.e. few months) and therefore the interest in near real-time automated monitoring.

TELECOMMUNICATIONS ASPECTS

Consider two or more 2.5 meter ($\sim$ 8 ft.) diameter dish antennas with efficiencies of 50%, 200 Kelvin S-band receiver operating temperatures, 3 KHz bandwidth, 10 second coherent integration time and receiving ALSEP signals equivalent to 5×10^4 Jy. The signal to noise ratio (SNR) of the cross correlation output is then 27, (ref. 8).

By deriving the interferometer phase every 10 seconds over an 800 second interval it will be possible to extract the fringe frequency with a precision of 50 to 100 μHz of S-band. Several 800 s. samples of the fringe frequency over a wide range of sky visibility for the ALSEP's will allow the amplitude and phase of the diurnal signature to be determined along with the frequency system offset. Thus, equatorial baseline components can be measured (ref. 6 and 8). Having 50 μHz data quality every 800 sec. implies 10 cm baseline precision.

FREQUENCY SYSTEM REQUIREMENTS

The independently operated atomic frequency systems at each station introduce another error source. Ideally, a frequency system such as a hydrogen maser could be used with virtually no contribution to the error budget. However, cost aspects make it important to consider other frequency sources for this study where unattended remote station operations are highly desireable. At 800 sec. the HP 5061, option 4.5 cesium frequency system has a stability of about $\Delta f/f = 1.6 \times 10^{-13}$ which at S-band causes a 350 μHz noise level. Incoherently combining these 350 μHz observations over a 10 hour observation period allows improvement to an effective 50 μHz observation which is equivalent to about a 10 cm baseline precision.

CALIBRATIONS

A. Phase Stability

Because the equatorial baseline information is inherently diurnal in nature, special care must be taken to either stabilize the receiving system or to explicitly measure possible thermal phase variations over the tracking pass. Such phase calibration can be performed and transmitted along with the time-formatted video data (ref. 9).

B. Lunar Orbit

Based upon LURE data (ref.10) the lunar ephermerides are believed to be internally consistent to within approximately 0.01 arc sec. Considering the two small antenna stations to be deployed 100 Km apart at established ARIES sites, for example, one on the Palmdale Bulge maximum (Pearblossom) and the other near Tidal Bench Mark 8 (Palos Verdes). A 0.01 arc sec lunar position internal error causes a 0.5 cm baseline error. Possible angular rotations between the lunar frame and the quasar frame might be present and could be sensed at about the 0.1 arc sec level by this 100 Km baseline.

C. Transmission Media

1. Ionosphere - a 100 Km baseline is short enough that diurnal variation are self-cancelling in the differential measurement that is intrinsic to interferometry. Residual effects due to ionospheric clouds of scale <100 Km are estimated to be 10 cm per pass and random on a pass to pass basis.

2. Troposphere - twice daily radiosonde weather balloon flights are available to calibrate both of the proposed sites. Edwards Air Force Base can be used to calibrate the Pearblossom site 35 Km away with both in the Mojave desert environment. Los Angeles Inter-

national Airport is 15 Km away from Palos Verdes site and both are coastal locations. It is also possible to transmit surface meteorology through the phone line. The radiosonde calibrations will be accurate to 3 cm at zenith and considering that tracking data will be taken to only 20° elevation angles, the baseline will be affected at about the 10 cm level on a single pass basis. Water vapor radiometers could calibrate the wet tropospheric delay effects within 2 cm to 10° elevation angles, however, such instruments are relatively expensive and may be non-optimal for continuous monitoring on a time scale of months to years.

Figure 2, summarizes the random and systematic errors that allow about a 21 cm performance from a single 10 hour pass and about a 7 cm accuracy given the statistical combination of nine passes of ALSEP/interferometer data.

SUMMARY

A radio interferometry scheme has been proposed which uses the relatively strong S-band radio signals coming from the ALSEP stations on the moon. These strong signals have allowed several simpifications to independent station radio interferometry such as small 2.5 m antenna sizes and real-time cross correlation. The frequency system requirements of $\Delta f/f = 2 \times 10^{-13}, \tau = 800$ sec, remain fairly sophisicated but obtainable commercially. Stations of the type discussed could be implemented and operated at comparatively low cost and could make important geophysical contributions to the determination of crustal deformations.

ACKNOWLEDGEMENTS

The author gratefully acknowledges useful discussions with JPL colleagues: K. M. Ong, R. A. Preston, G. M. Resch, M. A. Slade III, D. J. Spitzmesser, J. B. Thomas, and J. G. Williams.

This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Contract No. NAS 7-100, sponsored by the National Aeronautics and Space Administration, Office of Applications, Earth and Ocean Dynamics Applications Program.

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REAL-TIME CRUSTAL DEFORMATION MONITORING

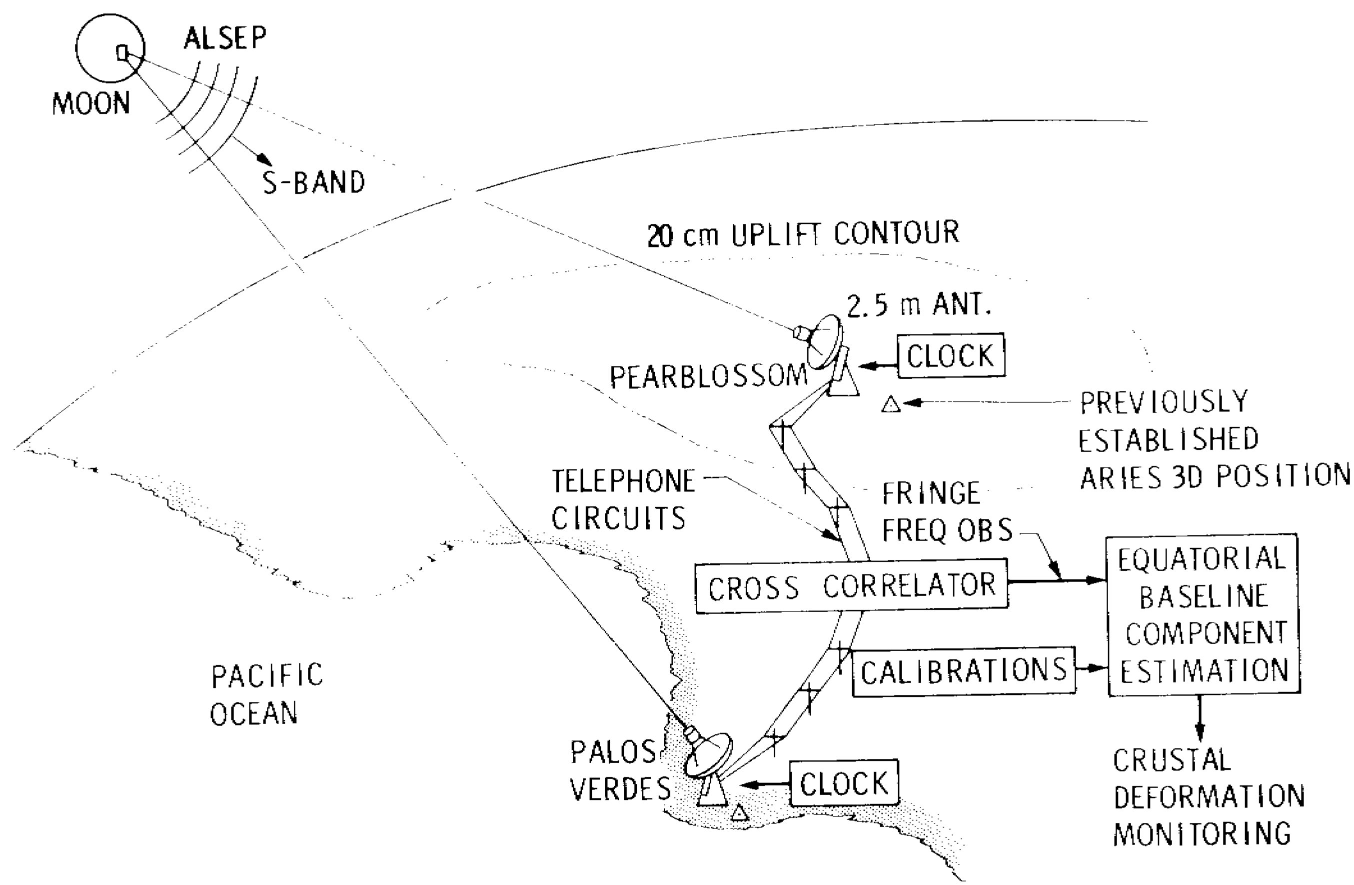

Figure 1

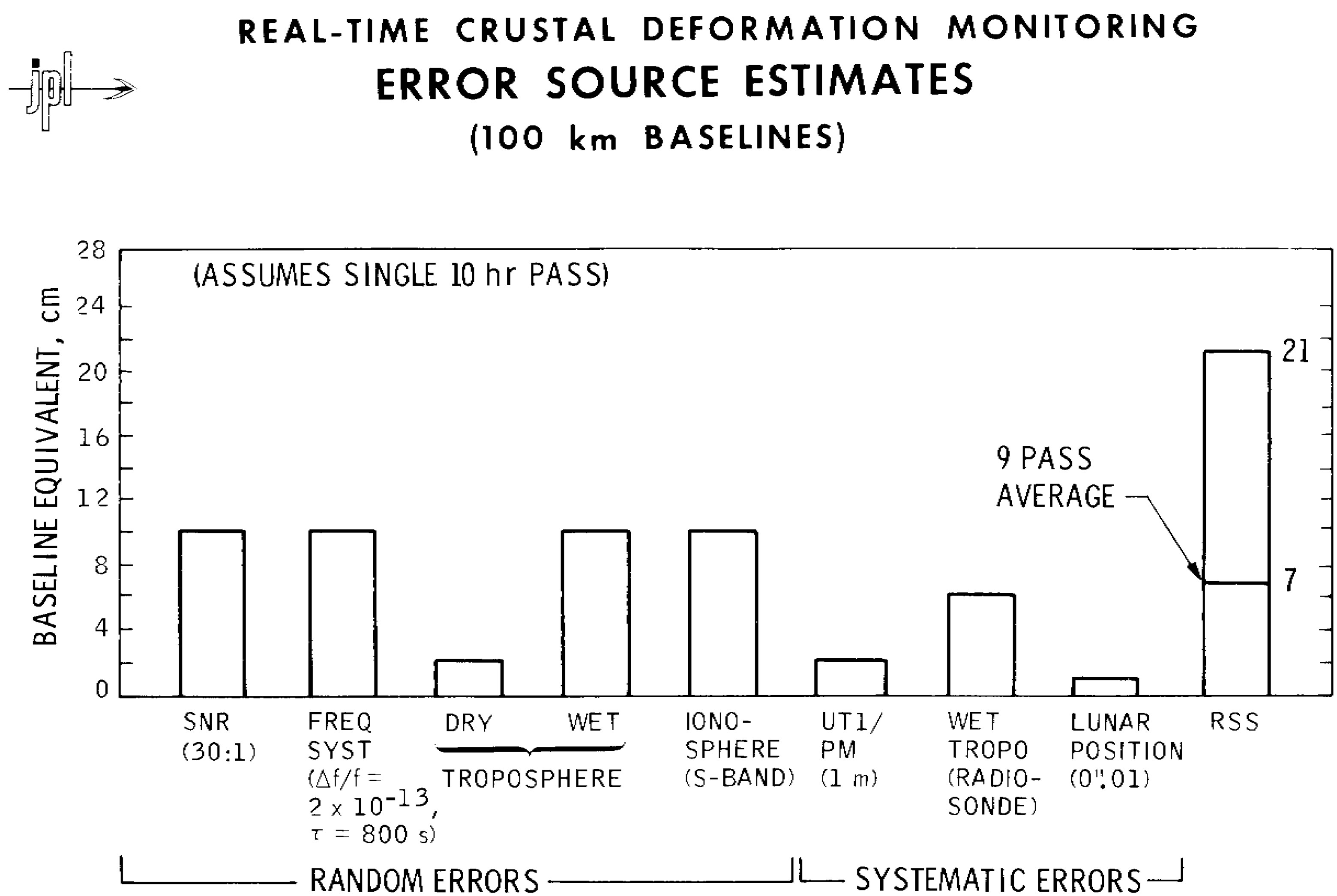
REAL-TIME CRUSTAL DEFORMATION MONITORING
ERROR SOURCE ESTIMATES
(100 km BASELINES)
(ASSUMES SINGLE 10 hr PASS)
BASELINE EQUIVALENT, cm
28
24
20
16
12
8
4
0
21
7
9 PASS AVERAGE
SNR (30:1)
FREQ SYST (Δf/f = 2 x 10-13, τ = 800 s)
DRY
WET
TROPOSPHERE
IONO-SPHERE (S-BAND)
UT1/PM (1 m)
WET TROPO (RADIO-SONDE)
LUNAR POSITION (0".01)
RSS
RANDOM ERRORS
SYSTEMATIC ERRORS

Figure 2