

Positioning with Autonomous Formation Flyer (AFF) on Space-Technology 3

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BIOGRAPHIES

Sien-Chong Wu is currently a Technical Group Leader in the Tracking Systems and Applications Section at JPL. He has been involved with the development of various tracking systems for deep-space as well as near-Earth space vehicles, and their applications to precision geodesy. His current interest is in the area of real-time wide-area differential GPS and special applications of GPS technologies. Sien received his Ph.D. degree from the University of Waterloo, Ontario, Canada.

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ABSTRACT

The NASA's Space Technology 3 mission (ST-3) will demonstrate, among others, the newly developed Autonomous Formation Flyer (AFF) technology. The multiple receiving antennas on each of the two spacecraft are capable of acquiring precise pseudorange and carrier phase signals transmitted by the other spacecraft, from which precise inter-spacecraft distance and bearing angles can be derived. A simulation/covariance analysis indicates that the inter-spacecraft distance can be determined to better than 5 mm and the bearing angles to better than 1 arc-minute. The differential phase ambiguities (between antennas on the same receiving spacecraft) can potentially be resolved after measurements over several epochs have been accumulated. With such ambiguity-free differential phases, the spacecraft bearing angles can be determined to a far better accuracy of 2 arc-seconds.

INTRODUCTION

As part of NASA's New Millennium Program, the Space Technology 3 mission (ST-3) will send two spacecraft to

a heliocentric orbit in 2005. The spacecraft will fly in formation for a period of 3 months to demonstrate various elements of technology required for space interferometry (Ref.1). One of the mission goal is to validate the Autonomous Formation Flyer (AFF) technology to a level that enables future separated (non-formation) spacecraft missions. The high-precision relative positioning capability of AFF will also support relevant sciences to be performed on ST-3.

The separation between ST-3's two spacecraft will vary between 50 and 1010 meters. The AFF system on each spacecraft will carry multiple transmitting and receiving antennas, enabling the acquisition of pseudorange and carrier phase data types. At the proposed Ka-band frequency, the expected data quality is 1 cm for pseudorange and 10 μ m for carrier phase. With the multiple receiving antennas on each spacecraft, differential phase data type can be formed and precise relative attitude can be derived. The goal is to validate that the inter-spacecraft distance be determined to 1 centimeter and the relative spacecraft bearing angles to 1 arc-minute. Since only two spacecraft are involved, AFF is unable to determine the absolute spacecraft attitudes; these attitudes will be provided by onboard star trackers.

This paper investigates the potential positioning accuracy of AFF with ST-3 configuration. Optimum tracking scenarios are searched to yield strongest parameter estimation information. A phase ambiguity resolution scheme is studied. Resolving the ambiguities would greatly strengthen the differential phase measurements and hence the spacecraft bearing angle determination. Various implementation issues are discussed.

In an early design phase of ST-3, a three-spacecraft formation was proposed, and later dropped for budgetary concern. An analysis for the three-spacecraft formation of ST-3 has been reported in Ref. 2. Some of the system issues described therein remain applicable for the two-spacecraft design currently adopted.

SPACE TECHNOLOGY 3 MISSION (ST-3)

ST-3 is one of the proposed missions under NASA's New Millennium Program. The goals of the mission are to demonstrate various elements of technology required for precise space interferometry. ST-3 will consist of two Sun orbiting spacecraft flying in formation. The two spacecraft, to be labeled "Collector" and "Combiner", will make simultaneous observations of galactic optical sources with varying baseline length and orientation for a coverage over the U-V plane. The signals collected at the Collector will be mirror reflected to the Combiner where interferometric fringes will be detected and tracked, and interferometric delay derived. The fringe amplitude will in turn yield the structure and size of the source being observed.

Interferometric fringes are detected when the total signals observed at the Collector and the Combiner have identical total delays as they are compared at the Combiner. Fixed and variable delay lines over a finite range will be used to maintain the zero differential delay. To minimize the differential delay variation, the spacecraft will stay in controlled formation. The Collector will move along a parabola whose axis is along the line-of-sight of the optical source to be observed, while the Combiner will stay at the focus, as shown in Fig. 1. The inter-spacecraft distance between 50 and 1010 m will be configured so that the baseline will vary between 40 and 200 m in length. The formation will also rotate with respect to the parabola axis to vary the baseline orientation, thus mapping out a 2-dimensional U-V plane coverage. Both spacecraft will maintain at the same orientation (attitude) while making interferometric observations.

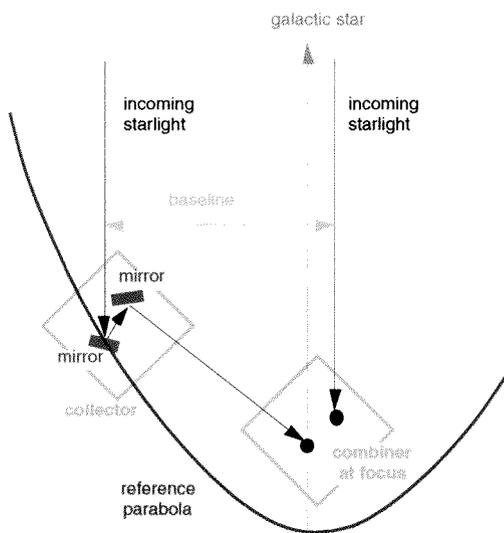


Fig. 1. ST-3 Formation

During a planned interferometric observation period of 3 months, the instrument will demonstrate its ability to point at specified targets, change baseline length and

orientation, and maintain the formation at the required accuracy, as well as to find and track the interferometric fringes and report its measurements back to Earth. In the process, the instrument will measure the correlation amplitudes of 50–100 galactic sources.

For the 2-S/C formation, the inter-spacecraft distance and bearing angles can be determined by the AFF system (to be described in the following section). However, the spacecraft absolute attitudes have to be independently provided. These attitudes will be furnished by the star trackers onboard both spacecraft. Note that, for a formation with more than two spacecraft, absolute attitude of only one spacecraft needs to be provided. The attitudes of other spacecraft can be determined from the AFF system together with the given attitude of the first spacecraft.

AUTONOMOUS FORMATION FLYER (AFF)

AFF is a newly developed technology at JPL for precise radiometric position and attitude determination. The technology is based on dual one-way pseudorange and differential phase measurements acquired by multiple onboard receiving antennas. Three receiving antennas and one transmitting antenna will be installed at the four corners on one face of the nearly cubical body of each ST-3 spacecraft. In addition, a receiving and a transmitting antenna will be installed on the opposite face of the cube to assure contact between the two spacecraft regardless of each spacecraft's individual orientation. Under the normal observing condition, the faces with multiple receiving antennas will be facing each other, although at a slant angle in general. At any epoch, six pairs of pseudorange and carrier phase measurements can be acquired, as depicted in Fig. 2, for the determination of the inter-spacecraft distance and their relative bearing angles. Clock offset can also be determined from the dual one-way

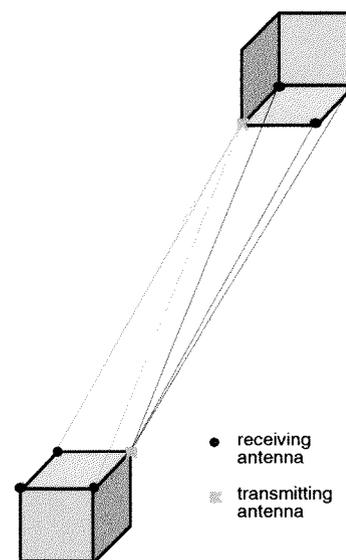


Fig. 2. ST-3 AFF radiometric measurements

pseudorange measurements and isolated from the distance and angle determination. At the Ka-band operation, the expected data qualities are 1 cm for pseudorange and 10 μm for carrier phase measurements at 1-sec interval.

AFF MEASUREMENTS AND PARAMETER ESTIMATION

A simulation/covariance analysis was carried out to assess the potential AFF positioning accuracy on ST-3. While the ultimate shape and size of the spacecraft are yet to be finalized, a geometry assuming the nominal cubical shape with 1 m in each dimension was adopted in this study. As mentioned earlier, one transmitting antenna and three receiving antennas on each spacecraft will be involved during normal observing session. These antennas were assumed located at the four corners of one face of the cube, as shown in Fig. 2. All 3 receiving antennas on a spacecraft acquired both data types from the transmitting antenna on the other spacecraft, producing a total of 6 pseudoranges and 6 carrier phases at each observing epoch. The expected data noise of 1 cm for pseudoranges and 10 μm for carrier phases was assumed.

A local coordinate frame with the origin at a reference point in the Combiner was defined as shown in Fig. 3, where the X-axis is normal to the plane where the four antennas are located. The inter-spacecraft distance R was defined as the distance between the spacecraft reference points. The two bearing angles ϕ and θ are, respectively, the azimuth and elevation angles in the local coordinates.

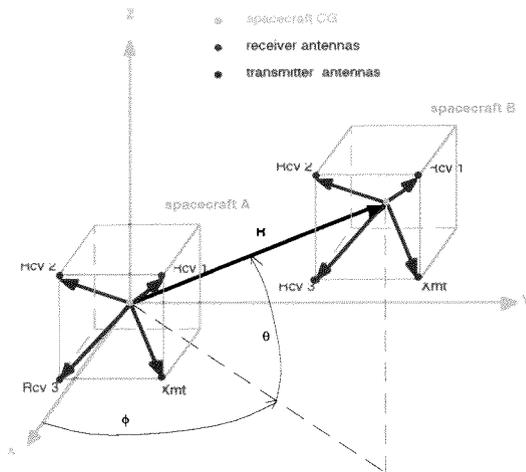


Fig. 3. AFF local coordinates

Other estimated parameters include the clock offset $\Delta\tau$, and the carrier phase biases. Spacecraft attitudes, needed to define the geometry from which correct partial derivatives can be calculated, were assumed known.

With single epoch of observations, carrier phases do not have any geometrical strength because of the unknown biases associated. Although all geometrical parameters (R , ϕ , θ and $\Delta\tau$) can still be determined, the solutions rely

solely on pseudorange measurements which are known to be weak in determining the two bearing angles. With two or more epochs of observations with varying observing geometry, carrier phases provide strong information on the bearing angles. The information strength increases with increasing relative attitude change between the two spacecraft. Since identical orientation of the two spacecraft should be maintained during interferometric observations, such relative attitude variations will be made only during AFF initialization. The initializing process will cease once carrier phase biases have been estimated with reasonable accuracy. In this analysis, different components of relative attitude variations were studied to investigate the optimal initializing AFF geometry. These relative attitude rotations are defined in Fig. 4 where the Roll-axes are defined along the line-of sight between the two spacecraft.

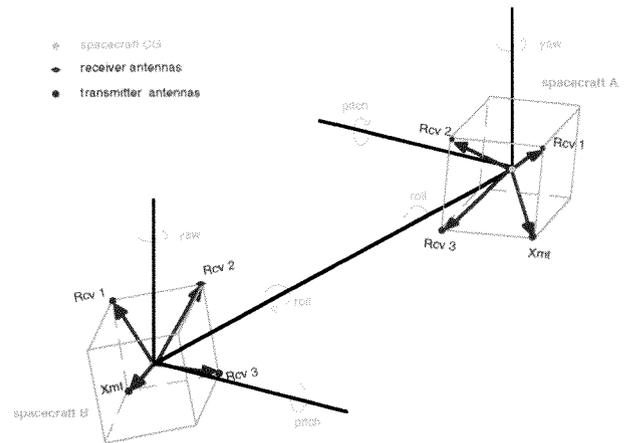


Fig. 4. Definition of relative spacecraft body rotations

For the simulation, the following truth geometry was adopted. The Combiner spacecraft was located at the origin; the Collector spacecraft was 1 km away on the X-axis ($\phi = 0$, $\theta = 0$). They were positioned such that their antennas were facing each other with the "Roll" axes coincide with the X-axis and the "Yaw" axes parallel to the Z-axis. Simulated data were generated at 1-sec interval for 20 epochs. The relative attitude was varied at a rate of 0.02 rad/sec. The nominal data noise of 1 cm for pseudoranges and 10 μm for carrier phases were added onto the simulated data.

The a priori knowledge of the inter-spacecraft distance was assumed to be $R = 2$ km (1 km truth); and those of the bearing angles were $\phi = -0.2$ rad (0 rad truth) and $\theta = 0.5$ rad (0 rad truth).

Ideally, all carrier phase biases remain constant over time. However, thermal and other physical environmental uncertainties preclude such desirable assumption. Since the carrier phase biases from the three receiving antennas on the same spacecraft can be made highly correlated, their differences can be treated as constant in time.

Therefore, the phase biases to be estimated were modeled such that only the two common biases B 's were treated as time-varying and the four differential phase biases ΔB 's were treated as constant parameters. These differential biases may potentially be *fixed* (ambiguities resolved) after processing a few epochs of data, greatly improving the bearing angle solution accuracy.

The modeling of all estimated parameters is summarized in Table 1. The clock offset and the common phase biases were allowed to vary in time freely (modeled as unconstrained white noise). The three geometrical parameters (R , ϕ and θ) were treated as loosely constrained random-walk parameters. Differential phase biases between the receiving antennas on the same spacecraft were treated as constant over time.

Table 1. Modeling of Estimated Parameters

Parameter	a priori σ	Model	Constraints
R	2 km	random-walk	100 m/sec ^{1/2}
ϕ, θ	0.5 rad	random-walk	0.05 rad/sec ^{1/2}
$\Delta\tau$	∞	white-noise	—
B (total of 2)	∞	white-noise	—
ΔB (total of 4)	∞	bias	constant

The estimation was carried out with a UD factorized filter (Ref.3). Parameter estimates and their error covariances were computed when all measurements at each data epoch have been processed. Process-noise updates were performed according to Table 1 before processing measurements for the following data epochs.

In general, the a priori knowledge of the bearing angles differs from the truth by a level large enough to render the estimation problem into nonlinearity; hence a few iterations are needed for the solution to converge. The *converged* filter UD matrix, which contains the parameter estimates and their covariances resulted from the current epoch of data alone, was combined (by an efficient UD combining algorithm) with a priori UD matrix or the *converged* filter UD matrix resulting from processing the previous epochs of data, after properly deweighted by parameter stochastic attributes. This post-filter UD combining process is necessary to assure proper weighting between the previous UD matrix and the new data batch wherever an iteration process is involved. A cheaper way of combining the information would be treating the previous UD matrix as a priori for starting the filter iteration. This a priori UD matrix is updated with measurements at current data epochs. However, this would tend to put more weight on the new data batch as the number of iterations increases.

RESULTS OF SIMULATION ANALYSIS

As pointed out in the preceding section, varying the relative attitudes between the two spacecraft is essential to strengthen the carrier phase data for the determination of bearing angles. To search for a near-optimum initializing scheme, three cases were studied, each with the relative attitude varying along only one of the relative Roll-, Yaw- and Pitch-directions. The results of the simulation analysis indicate that the best attitude variation for strengthening the geometry is in the relative Roll-direction. In the following, only the results with a relative Roll variation $\Delta\text{Roll} = 0.02$ rad/sec are reported.

Fig. 5 presents the simulation results for the inter-spacecraft distance R and the clock offset $\Delta\tau$. The upper frame shows the formal error which reflects the expected error statistics. The lower frame shows the actual solution error based on the simulated data. Since both R and $\Delta\tau$ are treated as independent from one epoch to the next (i.e., unconstrained white noise, cf. Table 1) and are insensitive to geometrical changes, their error remains essentially the same over the 20-sec period. Both parameters can be determined to 4 mm with two or more epochs of data, as shown in Fig. 5. The larger error with

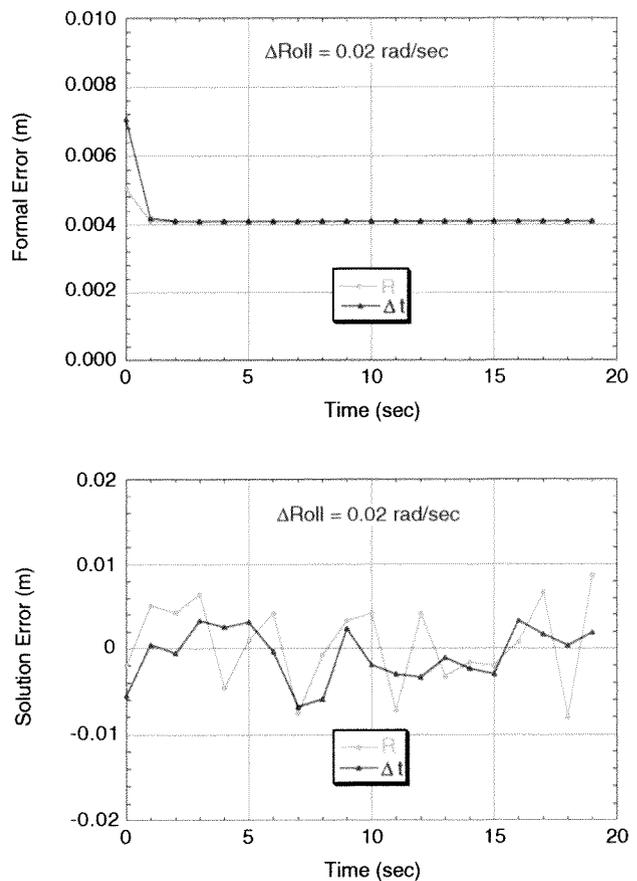


Fig. 5. Formal error and actual solution error of inter-spacecraft distance and clock offset determination

single epoch of data is due to the fact that the pseudorange data are the sole data type for the determination of all R , $\Delta\tau$, ϕ and θ . Carrier phases at a single epoch have no geometrical information.

Fig. 6 presents the results for the bearing angles (ϕ and θ). The solution improves monotonically with increasing number of epochs of carrier phase data. The 1 arc-minute (0.3 mrad) accuracy goal for ST-3 can be attained after 6 epochs of data (with a total of 0.1-rad variation in relative Roll-direction).

The solution accuracy for the differential phase biases also improves monotonically with increasing epochs of carrier phase data, as shown in Fig. 7. In this figure, ΔB_{m_n} denotes the differential phase bias between receiving antennas n and 1 on spacecraft m where $m = 0$ denotes the Combiner and $m = 1$ denotes the Collector. After 3 epochs of data (with a total of 0.04-rad variation in ΔRoll) a 1-mm accuracy can be realized. This level of accuracy will allow the fixing of the differential phase biases (resolving phase ambiguities). Such biased-fixed differential phase data are mathematically identical to high precision ($2^{1/2} \times 10 \mu\text{m}$) differential range data and possess enhanced data strength for bearing angle determination.

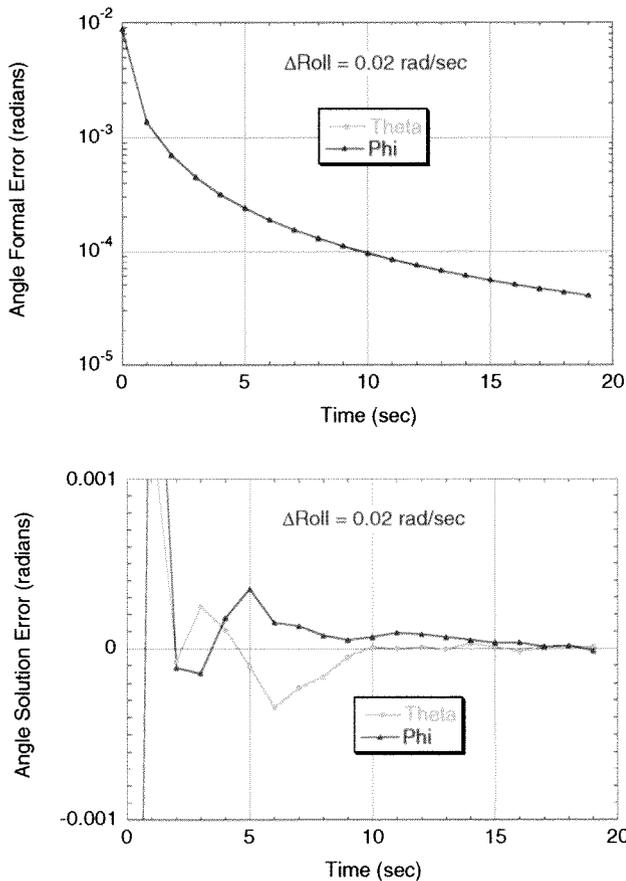


Fig. 6. Formal error and actual solution error of spacecraft bearing angles

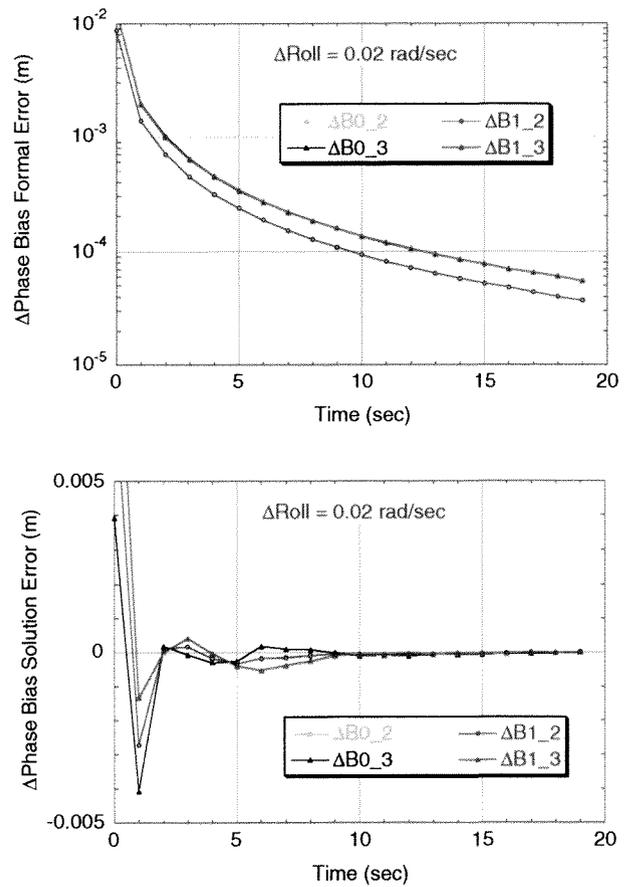


Fig. 7. Formal error and actual solution error of differential phase biases. (See text for the definition of ΔB_{m_n})

To investigate how the relative spacecraft angular position can be greatly improved with bias-fixed differential phases, the analysis was repeated without adjusting ΔB . The results, as shown in Fig. 8, indicate that ϕ and θ can be determined to 2 arc-seconds ($10 \mu\text{rad}$) with a single snapshot of data. The fixing of differential biases does not affect the accuracy of R and $\Delta\tau$.

Errors in spacecraft inertial attitudes, which will be independently determined by onboard star trackers, will affect spacecraft bearing angle determination. To study the sensitivity to these errors, the nominal values of these attitudes for the calculation the partial derivatives were intentionally deviated and the simulation analysis repeated. The results show that an attitude error in relative Roll-direction is least damaging to the determination of ϕ and θ , with a sensitivity of about 0.01. On the other hand, an attitude error in relative Yaw- and Pitch-directions will have a one-to-one effects on the determination of ϕ and θ , respectively. Therefore, it is essential that the star trackers be capable of independently determining the spacecraft attitudes to a level better than the desired spacecraft bearing angle accuracy, at least in the two directions other than the relative-Roll rotation.

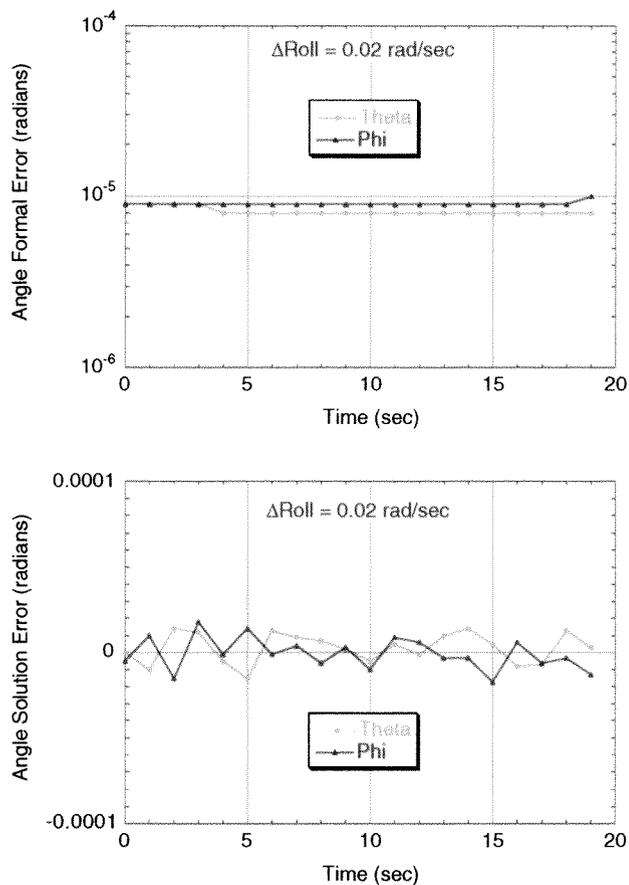


Fig. 8. Formal error and actual solution error of spacecraft bearing angle determination with bias-fixed differential phases

IMPLEMENTATION CONSIDERATIONS

A few assumptions have been made on the spacecraft body shape, data quality and signal line stability. The validity of the above analysis results depends, to a certain degree, on these assumptions. Therefore, care should be taken in designing the system to approach those assumptions. The following lists a few that will affect the AFF relative positioning performance.

The bearing angles are derived from differential phases between receiving antennas on the same spacecraft. The strength of the information is proportional to the separation between these antennas. Hence widely spaced antennas placement is desirable.

During the normal interferometric observing sessions, the distance between the two spacecraft will cover a range of 50–1010 m, the transmitted signals strength should be compromised between the longest and shortest distances so that they will not interfere with the received signals transmitted by the other spacecraft.

The assumed high data quality (1 cm pseudoranges and 10 μm phases) can be assured only with low multipath

environment. Therefore, both transmitting and receiving antenna patterns should be narrow enough to assure low multipath error and to reduce interference between receiving and transmitting antennas. On the other hand, the pattern should be wide enough to cover slant angles at shorter baselines.

The signal lines should be well controlled to maintain high stability so that differential carrier phase biases can be kept constant over the whole period of each observing session. This implies proper temperature shielding and equalizing environment impacts on the signal lines to all three operating receiving antennas on each spacecraft.

Since the bearing angles are sensitive to the relative Yaw- and Pitch-components of the spacecraft attitudes, it is imperative that these attitude components be determined to a level better than the desired spacecraft bearing angle accuracy.

SUMMARY

A simulation/covariance analysis has been carried out to assess the expected relative positioning accuracy for ST-3 spacecraft with AFF. The results of this analysis indicate that the inter-spacecraft distance can be determined to better than 5 mm and the relative spacecraft bearing angles to better than 1 arc-minute. With careful design and controlled environments, the differential phase biases between the antennas on the same spacecraft can be made invariable with time and can be resolved with a few epochs of measurements. Such bias-fixed differential phases become a far stronger data type capable of determining the bearing angles to 10 arc-second accuracy.

Several formation flying missions have been proposed for the next decade. These cover the area of planet finders, planet imagers and space interferometers. AFF can play a major role in high precision relative positioning for these missions. AFF can also contribute to the upcoming Mars infrastructure for positioning of landers, rovers and ascending sample returning canisters.

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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