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# TAOS Orbit Determination Results Using Global Positioning Satellites

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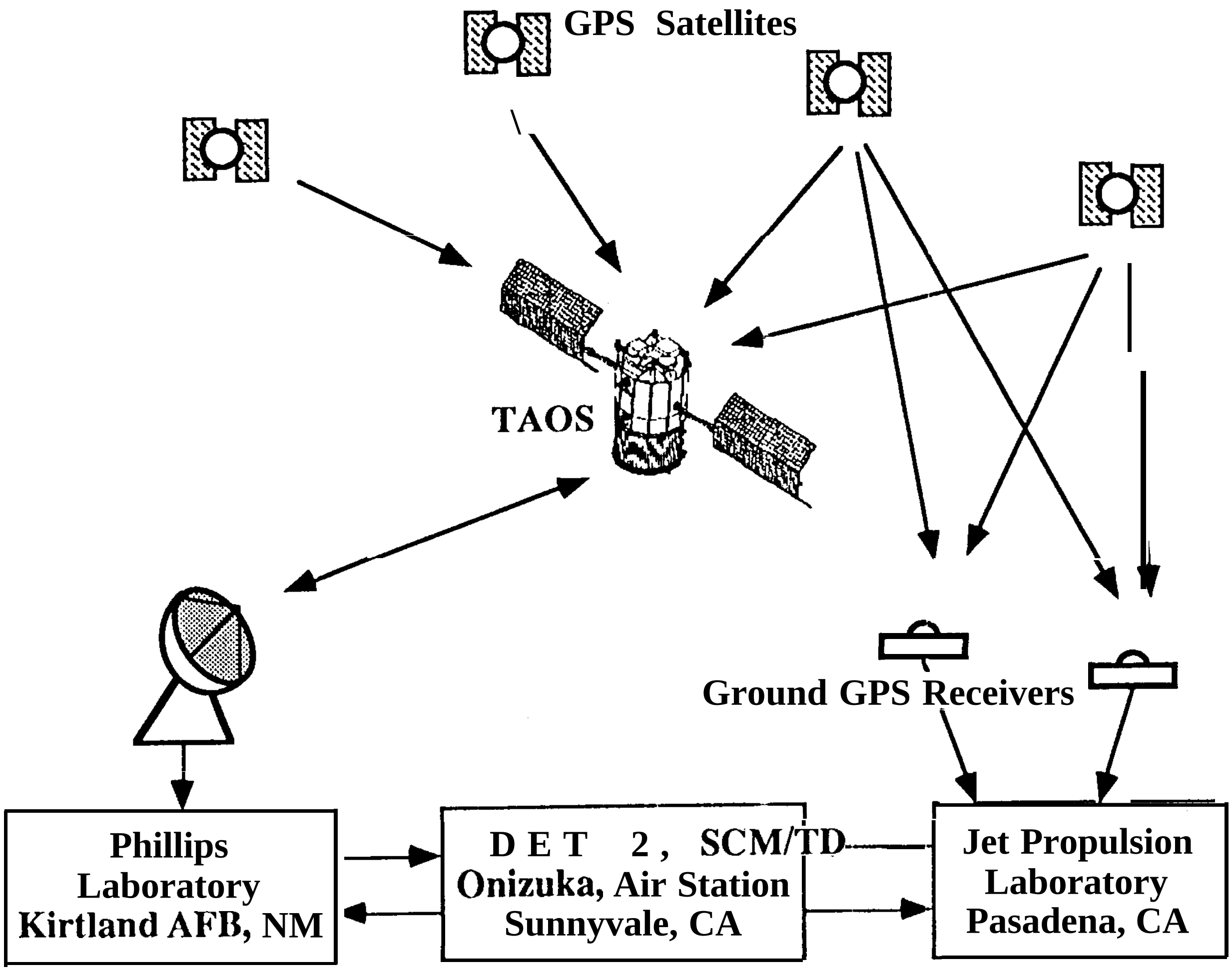
Orbit determination results for the Air Force Phillips Laboratory's Technology for Autonomous Operational Survivability (TAOS) satellite using a Rockwell AST V Global Positioning System (GPS) receiver are presented in this paper. Under a cooperative effort, GPS orbit determination technology developed at Jet Propulsion Laboratory (JPL) has been transferred to the U.S. Air Force. JPL's post processing differential GPS software MIRAGE [1] was modified to perform precise orbit determination for the TAOS satellite, Reconstructed TAOS position accuracies of 10 meters (3 sigma) are the objective. With four days of data, three-dimensional positions of less than 3 meters (1 sigma) have been achieved with overlapping orbit determination spans. Orbit determination results are also compared with those of the on-board CJPS receiver's navigation solutions and with the Air Force's Satellite Control Network SGLS processing.

## INTRODUCTION

The TAOS program, sponsored by the U.S. Air Force's Space Test Program and Phillip's Laboratory, is operated by Detachment 2, Space and Missile S ystems Center, Test Planning and Operations Division (Det 2, SMC/TD), Onizuka Air Station, Sunnyvale, California. It was launched on 13 March 1994 into a 560 km circular orbit with 105 degree inclination. Elements of TAOS/GPS orbit determinant ion system are shown in Figure 1.

**Figure 1. - TAOS/GPS Data Flow**




The TAOS/GPS receiver is not capable of removing the effects of Selective **Availability** (SA) or tracking the encrypted P-code (i.e., Y-code) [2]. However, the SA effects do not diminish the orbit solutions since the MIRAGE software employs a differential technique that effectively removes SA effects.

During Anti-Spoofing (AS) operation of the GPS constellation, only single frequency Coarse Acquisition (CA)-code pseudorange and delta range measurements are available from the GPS receiver on-board TAOS. Therefore, the ionospheric calibrations based on the linear combination of the TAOS dual frequency pseudorange measurements are unavailable. The GPS receivers used at the ground sites have an advanced hardware design that allows for the dual frequency ionospheric calibration [3-4].

Since the delta range observations of the TAOS receiver do not provide high precision information, compared to the ground station carrier phase measurements, no TAOS delta range measurements were processed. Further studies will evaluate the usefulness of the delta range.

Orbit accuracy is assessed by examination of orbit overlaps and comparisons to the kinematic GPS real-time point position solutions (or "Navigation Solutions") and Space Ground Link System (SGLS) solutions. The "Navigation Solution" is produced in real-time on-board TAOS by the Rockwell AST V receiver while the SGLS orbits are doppler based solutions from the Air Force Satellite Control Network.

## STUDY OBJECTIVE

The objective of this study is to show MIRAGE processing results of TAOS GPS observations. One of the TAOS mission objectives is to reconstruct the TAOS positions to within 10 meters (3 sigma) for designated periods of up to four revolutions [5].

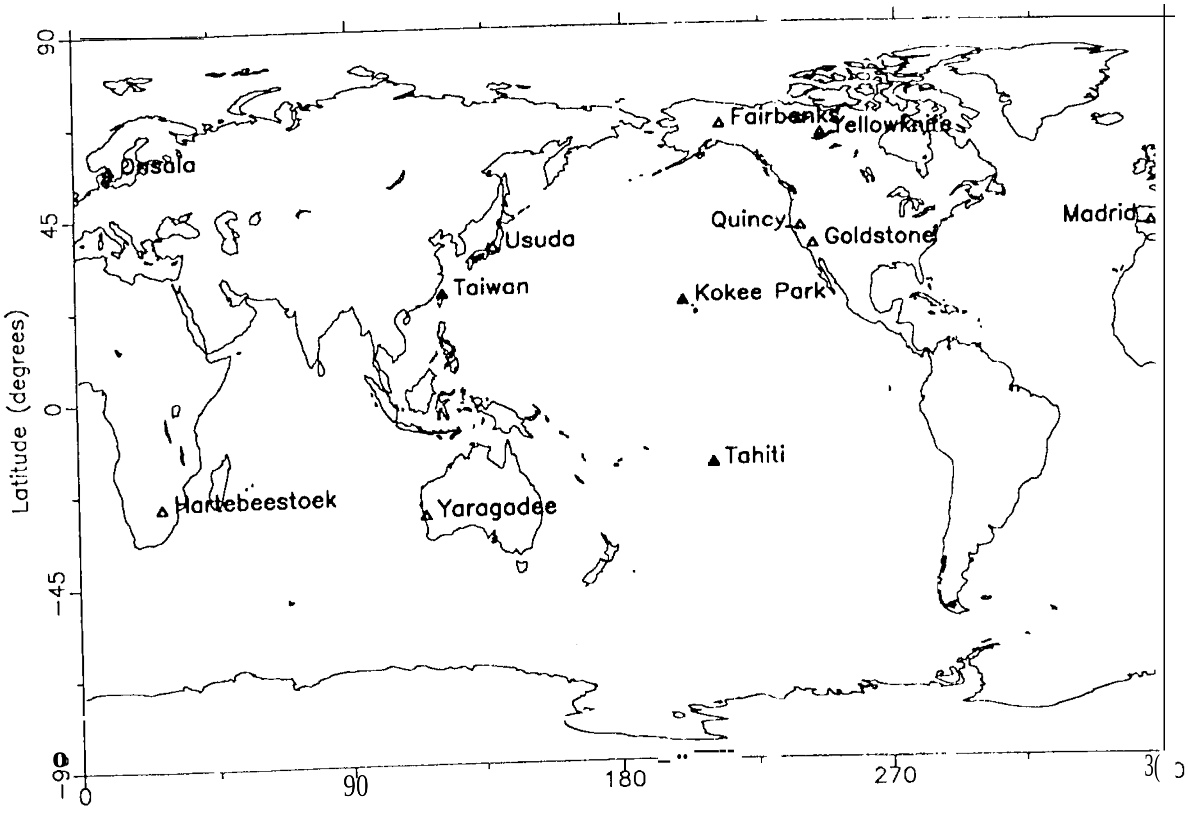
A primary use of these orbits is for assessing the performance of the Microcosm Autonomous Navigation System (MANS). In addition, this is the first satellite from which both GPS and SGLS are available. Thus, the data will be useful in calibrating the Air Force's Satellite Control Network. The Space Command Space Warfare Analysis Center has also requested precise ephemerides for calibration of the Space Surveillance Network.

## OBSERVATION PREPROCESSING

Daily TAOS GPS flight receiver data are preprocessed to remove outliers and correct for clock biases. The raw data consists of CA-code pseudorange at 1 second intervals. Robust cubic spline fits are employed to smooth the observations and provide interpolation at 2.5 minute intervals for alignment with the ground station observations.

Ground GPS receiver observations are available *from the* GPS Data Handling Facility at JPL about 36 hours after the last data were collected Both the carrier phase and pseudorange are provided in RINEX[6] format at 30 second samples. The same editing and calibration steps are performed as described above for the TAOS observations. Ground station locations are shown in Figure 2.

## Figure 2. - TAOS/GPS Ground Receiver Network

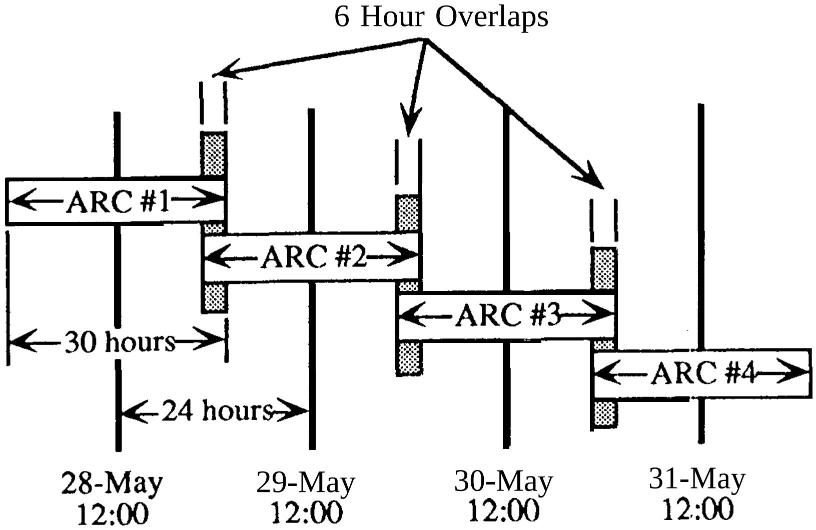



ORBIT DETERMINATION STRATEGY

Thirty hour data arcs centered at noon each day were processed (See Figure 3). The overlapping segments were used for consistency and accuracy determination. Iteration of the trajectory propagation, observation processing, and filtering steps was performed until the state solutions converged. A maximum of three iterations were required for the fits in this paper.

***Trajectory Propagation*** - To achieve meter level accuracies, several dynamic force models are required. Tables 1 and 2 summarize the force models used in the numerical integration of the TAOS and GPS satellite trajectories. Reference frame, force, and measurement model parameters are based on International Earth Rotation Service (IERS) standards [7].

## Figure 3. - Orbit Arcs with Overlaps




## Table 1. - Trajectory Models for TAOS

| Model: | Description: |
|---|---|
| N-Body: | All Planets, Sun, Moon |
| Earth Geopotential: | 50x50 truncated JGM-3† |
| Indirect Earth-Moon Oblateness: | *2x2* Lunar Model |
| Solid Eath Tides: | IERS‡ |
| Ocean Tides: | IERS‡ |
| Rotational Deformation: | IERS‡ |
| Relativity: | Point Mass Earth -t Lense-Thirring |
| Solar Radiation Pressure: | Conical Shadow Model |
| Atmospheric Drag: | DTM* Model |
| Albedo and Infrared Earth Radiation: | 2nd Degree Zonal Model |
| Empirical Accelerations: | Once/Rev and Twice/Rev Models |

† JGM = Joint Gravity Model (Joint solution from Goddard Space Flight Center, University of Texas Center for Space Research, and Centre National d'Etudes Spatiales)

‡ IERS = International Earth Rotation Service

* DTM = Drag Temperature Model

## Table 2.- Trajectory Models for GPS Satellites

| Model: | Description: |
|---|---|
| N-Body: | All Planets, Sun, Moon |
| Earth Geopotential: | 12x12 truncated JGM-3† |
| Indirect Earth-Moon Oblateness: | 2x2 Lunar Model |
| Solid Eath Tides: | IERS‡ |
| Ocean Tides: | IERS‡ |
| Rotational Deformation: | IERS‡ |
| Relativity: | Point Mass Earth + Lense-Thirring |
| Solar Radiation Pressure: | Rock4 and Rock42 Models |

† JGM = Joint Gravity Model (Joint solution from Goddard Space Flight Center, University of Texas Center for Space Research, and Centre National d'Etudes Spatiales)

‡ IERS = International Earth Rotation Service

***Observation Processing*** - Both carrier phase and P-Code pseudorange are processed. Table 3 lists the measurement models used for producing observation residuals and partials. Again, these models are adopted based largely on IERS standards.

## Table 3. - Measurement Models

| Model: | Description: |
|---|---|
| Solid Earth Tides: | 0th, 1st and 2nd Order Corrections |
| Rotational Deformation (Pole Tide): | IERS‡ |
| Ocean Loading: | IERS‡ |
| Polar Motion: | UTCSR§ |
| Plate Motion: | Linear Velocities |
| Earth Center of Mass Offset: | Currently Zero |

‡ IERS = International Earth Rotation Service

§ UTCSR = University of Texas Center for Space Research

***Filtering and Smoothing*** • The filter and smoother generate corrections to the parameters affecting the trajectory propagation and the observation processing. MIRAGE employs a numerically stable square root information filter that can compute smoothed estimates of time varying stochastic parameters. Our orbit determination strategy employs a fiducial concept where all ground receiver locations are held fixed while the filter estimates the positions and velocities of l 'AOS and the. GPS satellites along with GPS space vehicle solar pressure model and stochastic parameters. A complete list and count of all estimated parameters is provided in Table 4. Orbit accuracies will be limited by dynamic models errors. But, the geometric strength of the GPS measurement system allows *one* to obtain a high precision TAOS trajectory in the presence of these dynamic models errors.

**Table 4.- Estimated Parameters**

| Parameter(s) | Number of Parameters |
|---|---|
| TAOS State | 6 |
| GPS States (24 Satellites) | 144 |
| GPS Solar Pressure Scale Factors and Y-Bias | 72 |
| Empirical Dynamic Parameters | 9 |
| Stochastic: (30 hour arcs with 2.5 minute updates) | |
| Troposphere (12 Ground Stations) | 12 |
| TAOS and Ground Clocks (1 master clock fixed) | 36 |
| Carrier Phase Biases | -260 |
| TOTAL | ~539 |

Data Weighting: The measurement precision expected from the TAOS Rockwell AST V receiver observations were determined by examining the post fit observation residuals. Assuming that the dynamic and measurement system models errors are at the tens of centimeter level, the data weight for the TAOS pseudorange can be inferred from the meter level observation residuals. The ground receiver carrier phase and pseudorange noise characteristics have been studied extensively for prior missions such as TOPEX/Poseidon. Therefore, the ground receiver data weights were predetermined. All data weights applied during filtering are shown in 'l'able 5.

**Table 5.- Data Rates and Processing Weights**

| Data Type | Processing Rate | Weight (meters) |
|---|---|---|
| TAOS Pseudorange | 2.5 min. (decimated) | 3 |
| Ground Pseudorange | 2.5 min. (decimated) | 1 |
| Ground Carrier Phase | 2.5 min. (decimated) | .04 |

Stochastic Clock Estimation: To eliminate synchronization errors due to unstable oscillators, clock biases at the receivers and GPS transmitters are estimated at each measurement time, In the filter, one ground clock is chosen as a reference and a stochastic clock bias is estimated at each of the other receivers and GPS transmitters. A white noise stochastic process is employed with a batch length coinciding with the measurement intervals (2.5 minutes) and the estimated smoothed clock biases are fed back to the observation processing module. As with standard double differencing techniques, the stochastic clock estimation strategy eliminates common clock errors. However, the stochastic method avoids both the difficulties of selecting a set of non-redundant double difference combinations and the data noise correlations inherent in difference measurements.

Stochastic Phase Bias Estimation: Continuously tracked GPS carrier phase precisely measures the relative range change between a GPS transmitter and its receiver. However, the carrier phase is ambiguous which requires the estimation of a constant phase bias for each continuous pass between a transmitter and a receiver. In the filter, each phase bias is estimated as a white noise stochastic parameter that remains constant over a pass. At tracking discontinuities, the filter applies a white noise stochastic update for the bias parameter corresponding to an individual transmitter-receiver pair. The smoother generates a time profile of phase bias corrections that are applied during subsequent observation processing. This stochastic phase bias estimation strategy is efficient in terms of computation time and memory requirements but does not attempt to resolve the integer nature of the phase biases. These parameters relate only to the ground receiver observations since the TAOS GPS receiver is unable to produce accumulated carrier phase.

Stochastic Estimation of Tropospheric Fluctuations: The model for troposphere delay is decomposed into a wet and dry component.

$$\rho=\rho_{Z_d}R_d(\theta)+\rho_{Z_w}R_w(\theta)$$

where $\rho_z$ is the zenith delay and R is a mapping function that maps the zenith delay to the line of site at elevation 0. The fluctuations in the wet zenith delay are modeled as a stochastic random walk. The wet zenith delay is estimated at 2.5 minute intervals (coincident with the measurement interval) using an a priori sigma of 5 cm and an effective batch-to-batch sigma of 3 mm for the noise driving the random walk process. As with the phase and clock biases, the smoothed time profiles of the stochastic fluctuations are fed back into the observation processing module on subsequent iterations of the orbit determination program.

## ORBIT DETERMINATION RESULTS

Four 30 hour orbit arcs with common six hour overlaps were computed to assess the accuracy of the MIRAGE generated TAOS orbit solutions. For each day, TAOS pseudorange observation residuals are shown in Figure 4 with an average Root Mean Square (RMS) of approximately 2.3 meters. Orbit comparisons during the six hour overlapping periods yield an average 2.4 meter three-dimensional precision (Figure 5). Two independently determined orbit solutions for TAOS are available from the real-time, on-board GPS navigation solutions and the SGLS orbits from the Air Force Satellite Control Network. These orbits are expected to be of lower accuracy than the differential solutions from MIRAGE. Thus, the MIRAGE orbits serve as near truth orbits for navigation solution and SGLS orbit calibration. Figure 6 shows the RMS difference between the precise differential GPS solutions and the navigation solution and SGLS solutions respective y. The SGLS orbits show, on average, about 23 meters RMS difference with the navigation solutions differing at about 58 meters RMS.

**Figure 4.- Observation Residuals**
'TAOS **and 12 Ground** Receivers

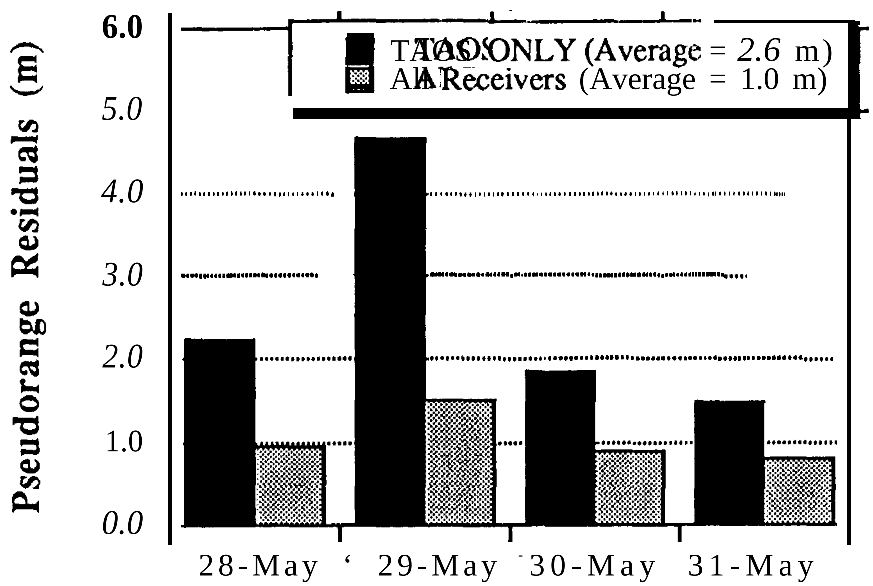


**Figure 5.- Orbit Overlap Comparisons**

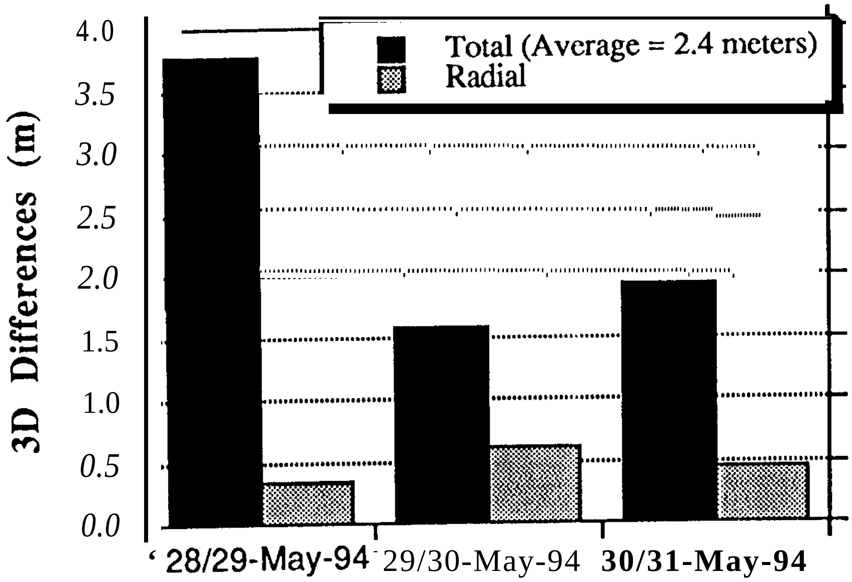
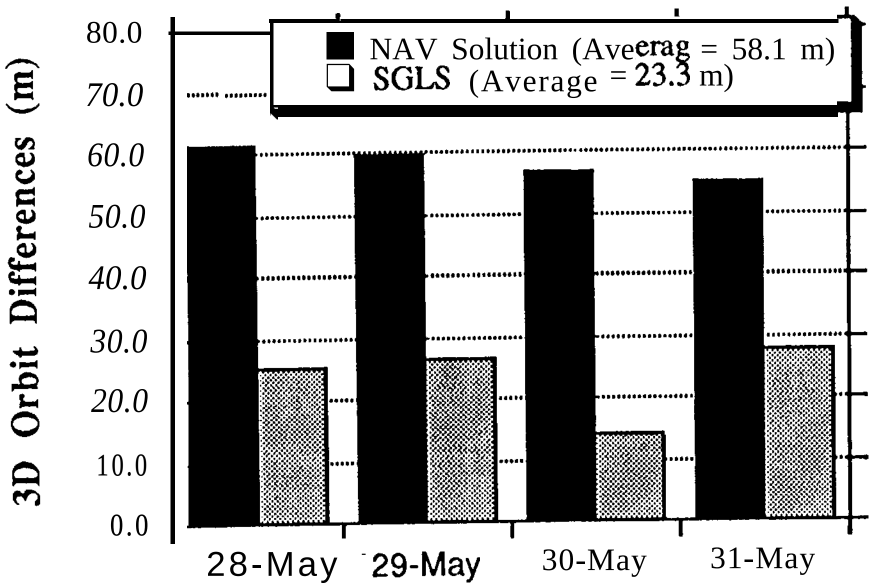



**Figure 6. - Independent Orbit Comparisons**



## SUMMARY

This paper documents results of a cooperative effort to transfer technology developed under NASA contract at the Jet propulsion Laboratory to the U.S. Air Force. Precision spacecraft orbit determination using post-processing differential GPS software called MIRAGE was modified to support the TAOS satellite. Orbit overlap comparisons show three meter precision using reduced accuracy CA-code pseudorange data from the TAOS GPS receiver. Sub-meter accuracies could be obtained, as demonstrated by TOPEX/Poseidon [1,8], by including P-code, delta range, and/or continuous carrier phase observations.

## ACKNOWLEDGEMENTS

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