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# SHUTTLE NAVIGATION STATUS

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## INTRODUCTION

Shuttle navigation, for the purpose of this report, is defined as the determination of Orbiter position, velocity, and attitude and associated effort. This, together with guidance, flight control, consumables, and systems management, is required for classical navigation - successful movement of a craft from an initial to a final destination.

Position and velocity propagation (the extrapolation in time using an initial estimate) requires the measurement or modeling of the gravitational, aerodynamic, and rocket engine forces acting on the vehicle. Position and velocity determination is performed using observations such as the distance to external features, the rate of change of such a distance, and the direction toward the feature. Onboard state propagation is more often the mode of state knowledge maintenance, as is shown in table 1, since the ability to determine position and velocity using such observations is limited. An overview of Shuttle navigation is presented in reference 1.

TABLE 1.- SHUTTLE NAVIGATION SYSTEM

| Navigation systems | Ascent | Descent | Orbit |
|---|---|---|---|
| Orbiter | State[a] propagation | Propagation and determination | State propagation, attitude determination |
| Ground | State determination | State determination | Orbit determination |

[a]State: position and velocity.

By state is meant that set of parameters which adequately describes the translational and/or rotational situation of the Orbiter. The actual state parameter set maintained onboard sometimes includes acceleration and system biases; however, most of the time, it is limited to position and velocity.

## CHALLENGING AREAS

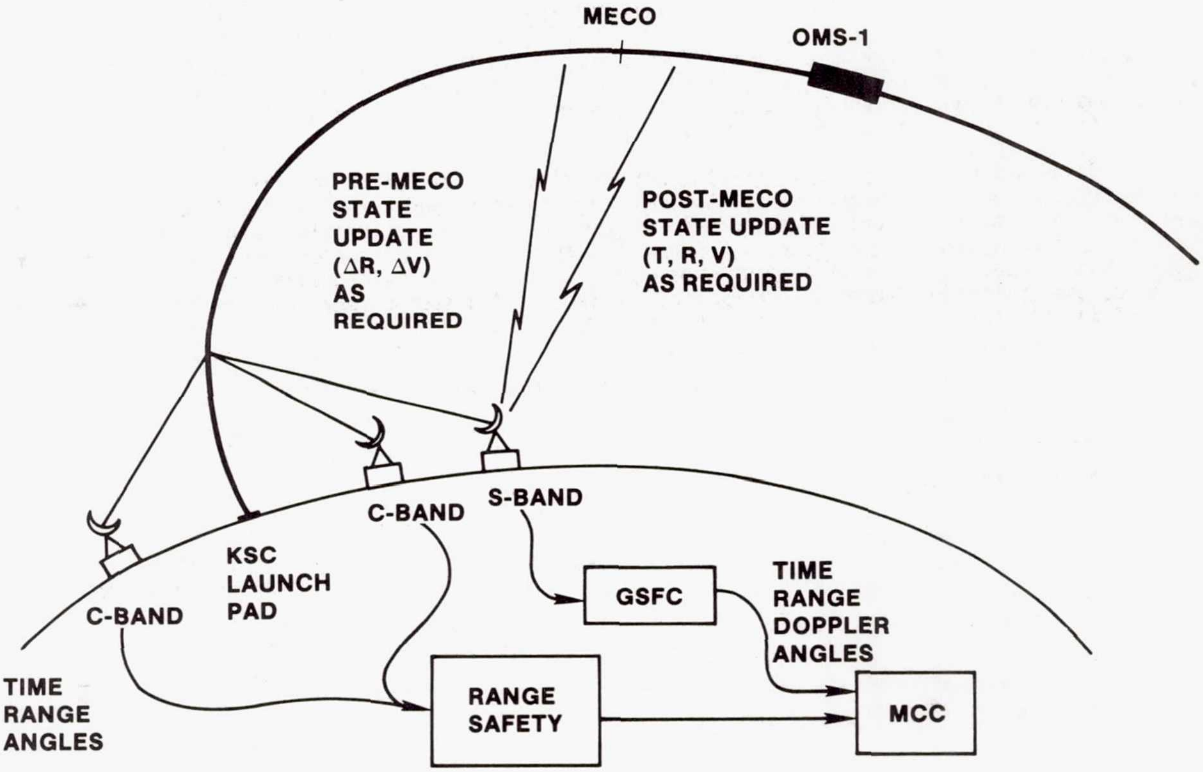
Shuttle navigation as accomplished during the initial flights was challenging in at least three respects: the use of off-the-shelf redundant conventional navigation equipment and the project goal to successfully return the vehicle and crew after two nonsimultaneous failures; the need for accurate, timely ground-determined position and velocity during ascent; and navigation during descent from orbit through rollout.

The management of redundant Inertial Measurement Units (IMU's), the use of redundant Tactical Air Navigation (TACAN) equipment, the use of triple state maintenance, and the details of descent navigation have been presented in reference 2. The following material contains a review of ascent ground state determination and selected descent navigation areas.

## ASCENT GROUND NAVIGATION

A ground-based system (state calculation performed by a ground computer) was developed to support the ascent flight phase during the interval from lift-off through about 1 minute past main engine cutoff (MECO). This system provided the ground flight control team with a capability to monitor onboard navigation system performance and to protect engine cutoff conditions as necessary with an update to the onboard position and velocity. A capability to update the onboard state after MECO was provided to protect ascent abort options - primarily the ability to return to a landing site within one revolution.

Figure 1 shows these update opportunities. Both C-band (range and angle observations) and S-band (range, Doppler, and angle observations) tracker data were used in the Houston Mission Control Center (MCC) computers to determine position and velocity. The transfer of state information to the Orbiter is done in the form of a correction using differences between onboard and ground knowledge during powered flight. The onboard state vector is replaced as necessary with ground information during free flight.



**OMS** - ORBITAL MANEUVERING SYSTEM
**KSC** - KENNEDY SPACE CENTER
**GSFC** - GODDARD SPACE FLIGHT CENTER

FIGURE 1.- ASCENT STATE UPDATE OPPORTUNITIES.

The ground pre-MECO performance is shown in table 2. Position accuracy has been 300 to 1100 feet, well below a 6000-foot goal. The critical parameters, radial and downtrack velocity components, ranged from 3 to 20 ft/sec and 2 to 5 ft/sec, respectively, compared to a required accuracy of 50 and 40 ft/sec.

Figure 2 is a sketch of the post-MECO geometry. One minute of tracking data is available from which to determine the orbit. During this time, the vehicle covers about 4° of travel. The task is to determine the orbit semimajor axis (SMA) to 1 nautical mile or the perigee altitude to approximately 2 nautical miles. The insertion altitude (post-MECO) is approximately 60 nautical miles and the Orbiter skims the Earth to reach 150 to 160 nautical miles halfway around, at which time a maneuver is performed to circularize the orbit.

An accuracy in the semimajor axis of 0.3 nautical mile or better has been achieved as shown in table 3. The position was determined to a few hundred feet on most flights. Orbit plane was determined to about 0.01°. These accuracies were achieved through the use of a Kalman filter and measurements from multiple trackers, accurate atmospheric refraction models with constants reflecting launch day conditions, and by including measurement bias and vehicle thrusting as state elements. Interactive controls and displays allowed for some inflight ground user control such as the adjustment of the filter state noise for powered versus free flight and the assessment of the quality and validity of navigation results.

TABLE 2.- STS ASCENT DELTA STATE UPDATE ERRORS
(MECO MINUS 30 SEC)

| Flight | Position errors,[a] ft | | | | Velocity errors, ft/sec | | | |
|---|---|---|---|---|---|---|---|---|
| | U | V | W | Mag | U | V | W | Mag |
| STS-1 | 300 | 100 | 100 | 330 | 3 | 2 | 2 | 5 |
| STS-2 | 100 | 50 | 50 | 120 | 5 | 3 | 2 | 7 |
| STS-3 | 500 | 100 | -300 | 590 | 10 | -5 | -5 | 13 |
| STS-4 | 1000 | 500 | 300 | 1160 | 20 | 5 | 5 | 22 |
| STS-5 | -300 | 200 | 300 | 470 | -10 | 5 | 7 | 14 |
| STS-6 | 500 | 400 | -200 | 670 | 10 | 5 | -5 | 13 |
| Predicted (3σ) | | | | | 40 | 20 | | |
| Required (3σ) | | | | | 50 | 40 | | |

[a]U = radial, V = downtrack, W = crosstrack.

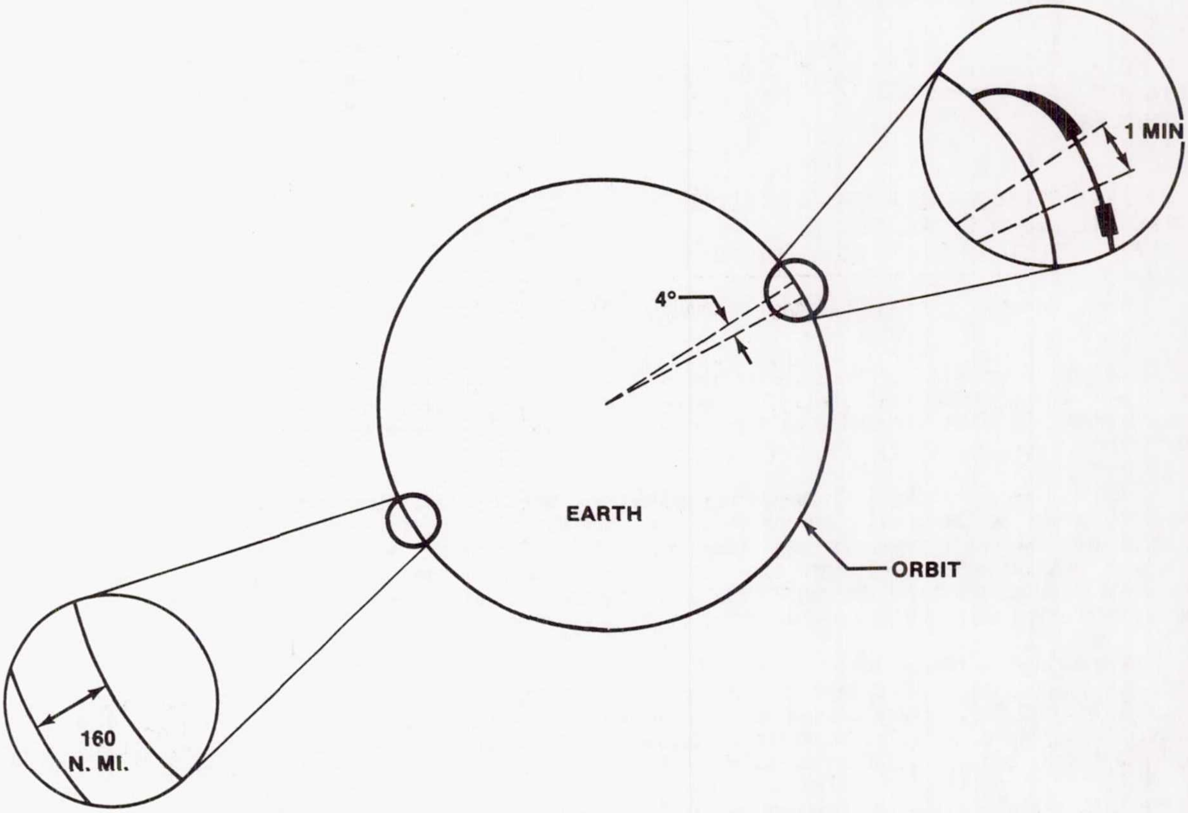


FIGURE 2.- POST-MECO ORBIT DETERMINATION.

TABLE 3.- STS ASCENT GROUND NAVIGATION ERRORS
(MECO PLUS 60 SEC)

| Flight | Position, ft | | | SMA, n. mi. | Orbital plane, deg |
|---|---|---|---|---|---|
| | U | V | W | | |
| STS-1 | -100 | 100 | 40 | 0.3 | 0.007 |
| STS-2 | 70 | 10 | -50 | -.1 | -.012 |
| STS-3 | 41 | 31 | -58 | -.2 | .005 |
| STS-4 | 220 | 65 | 30 | -.2 | .007 |
| STS-5 | -1350 | 300 | -100 | -.3 | -.012 |
| STS-6 | 40 | 50 | 40 | 0 | -.005 |
| Predicted ($3\sigma$) | | | | 0.5 | |
| Required ($3\sigma$) | | | | 1.0 | |

Onboard post-MECO errors are shown in table 4. The onboard navigation state has never been updated by the ground because the errors are small.

TABLE 4.- STS ASCENT ONBOARD NAVIGATION ERRORS
(MECO PLUS 60 SEC)

| Flight | Position, ft | | | SMA, n. mi. | Orbital plane, deg |
|---|---|---|---|---|---|
| | U | V | W | | |
| STS-1 | 700 | -300 | -4200 | 0.1 | -0.04 |
| STS-2 | 700 | -600 | -3000 | -.5 | -.03 |
| STS-3 | 600 | -200 | -3200 | 0 | -.04 |
| STS-4 | 300 | 300 | -3200 | .1 | -.04 |
| STS-5 | 200 | -300 | -1800 | -.1 | -.02 |
| STS-6 | -600 | 100 | -2100 | -.2 | -.03 |

## ENTRY NAVIGATION

The entry pre-deorbit activities include establishment of a knowledge of IMU orientation using star trackers and the transfer of an accurate state vector from the ground to the Orbiter. On some flights, there is provision for a downtrack position update between the deorbit maneuver and 400 000 feet altitude (entry interface).

Figure 3 shows events and altitudes. Use of altitude data derived from IMU measurements starts at 235 000 feet altitude and continues until barometric altimeter data are used at about 84 000 feet. TACAN range and bearing data are used from about 135 000 feet until microwave landing system data are used at 17 000 feet altitude.

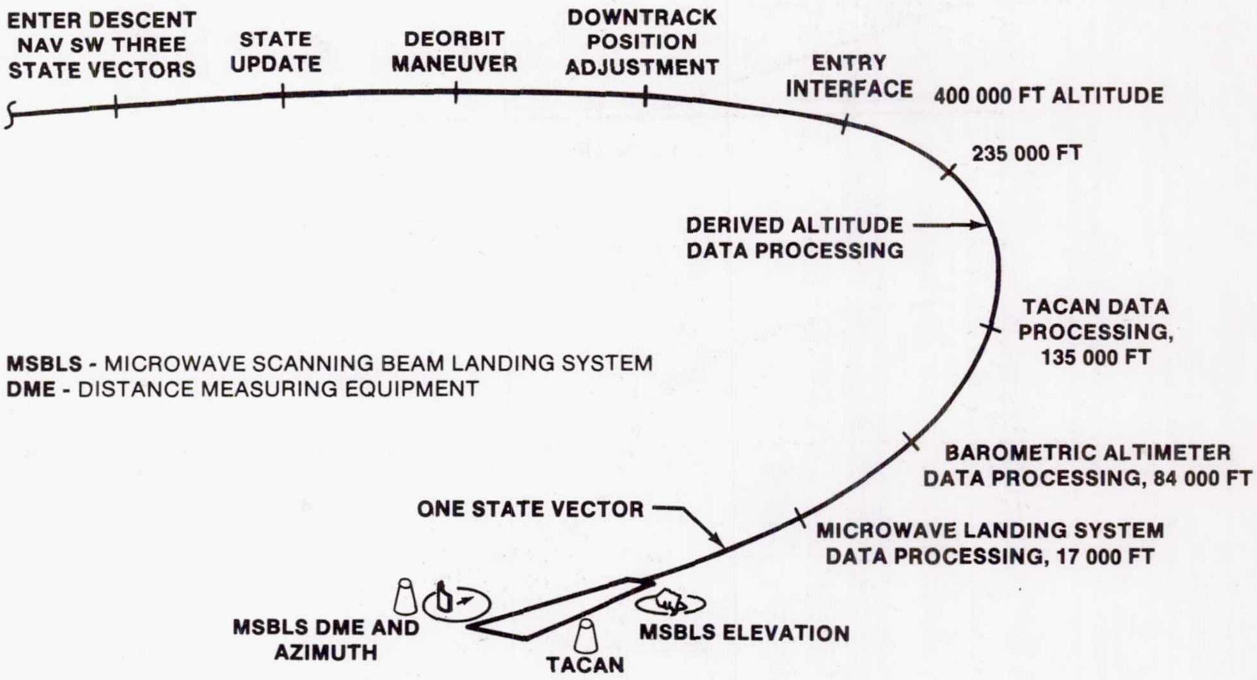


FIGURE 3.- DESCENT ONBOARD NAVIGATION.

## BASE VECTOR

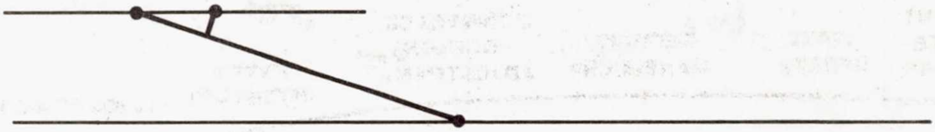
The accurate propagation of an initial state vector to entry interface is affected by translational effects from rotational maneuvers, drag, and vehicle outgassing or venting. These effects were reduced by procedures designed to minimize the time between ground state determination and entry interface, minimizing the rotational maneuvers, and use of attitude-dependent drag force models.

The position accuracy at entry interface has ranged from 0.2 to 0.8 nautical mile. This is small compared to a 5-nautical mile $3\sigma$ predicted accuracy because the propagation interval was greatly reduced from that originally expected.

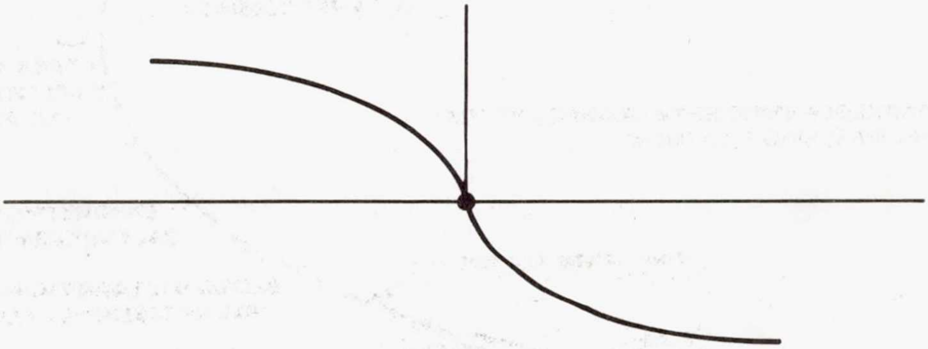
## DOWNTRACK ADJUSTMENT

A capability was developed to quickly determine downtrack position and adjust the onboard vector if necessary in the region between the deorbit maneuver and entry interface. The procedure is to use S-band range and Doppler data directly to determine the downtrack position error in the onboard state and then calculate the adjustment to the onboard vector timetag required to move the estimate of position forward or back along the orbit path. The timetag adjustment is voiced to the flightcrew for manual entry into the onboard computer.

The range measurement is used at vehicle acquisition near the horizon, at which point most of the downtrack position error is reflected in the differences between the observed range and the range computed using the onboard state vector (fig. 4).



RANGE



RANGE RATE

FIGURE 4.- DOWNTRACK POSITION ADJUSTMENT TECHNIQUE.

The Doppler measurement is zero as the vehicle passes by the site which, given good orbit shape and plane information, enables downtrack position to be easily determined. The two independent determinations of downtrack position are compared. No adjustment has been made on any of the flights to date because of the very small errors in the base vector. The adjustment technique has been accurate to at least 1000 feet (0.04 second).

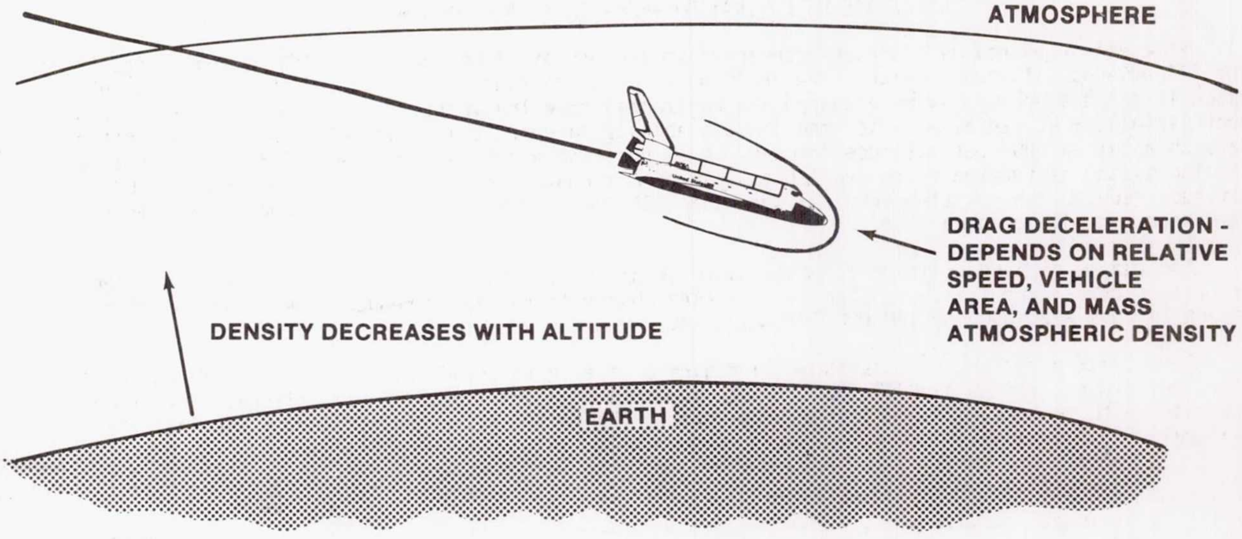
## IMU ORIENTATION

The IMU orientation accuracy requirement for descent support is $0.53^\circ$ with a design goal to provide for desired system performance margins of 0.26 deg/axis. Orientation knowledge is accurate to about 0.06 deg/axis $1\sigma$ using the star tracker for initial determination and 0.08 deg/axis $1\sigma$ using a crew optical alinement system. These accuracies allow for 3.3 hours of IMU drift from the last alinement to entry interface. IMU drifts are calibrated in flight by the ground. Typical calibrated drift rate errors are about 0.02 deg/hr/axis. IMU alinement on Apollo was performed using a manually operated sextant. Use of the automatic star tracker has also been very successful.

## DESCENT NAVIGATION

### RADIAL POSITION ERROR AND IMU MEASUREMENTS

State propagation with the use of velocity change due to contact forces measured by the IMU and gravitational acceleration models was expected to result in large errors in radial position during descent. A method for constraining the size of the radial position and velocity error was desired to minimize position transients at TACAN acquisition and to provide good radial rate information for guidance. The approach taken is shown in figure 5. Drag acceleration, measured by the IMU, is a function of vehicle speed, mass, area, and atmospheric density. Atmospheric density decreases exponentially with altitude. Altitude was computed given the other parameters and provided to a navigation filter as an observation for state determination. This approach was expected to degrade IMU altitude knowledge for normal IMU performance at higher altitudes but to improve on it at lower altitudes. This prediction can be seen in figure 6. A shift in the predicted error (mean $+3\sigma$) in radial position occurs at initial use of the derived altitude at about 230 000 feet altitude. The predicted errors apply for all of the flights shown except flight 4. Flight 4 occurred in July and the uncertainty in atmospheric density is expected to be worse than for cooler seasons. Use of derived altitude worked as predicted. The altitude error is less than 1 nautical mile throughout descent.



**DETERMINE ALTITUDE USING IMU MEASUREMENTS OF DECELERATION PROCESS ALTITUDE INFORMATION IN NAVIGATION FILTER**

FIGURE 5.- DESCENT ALTITUDE AND DOWNTRACK POSITION ERROR RESTRAINT TECHNIQUE.

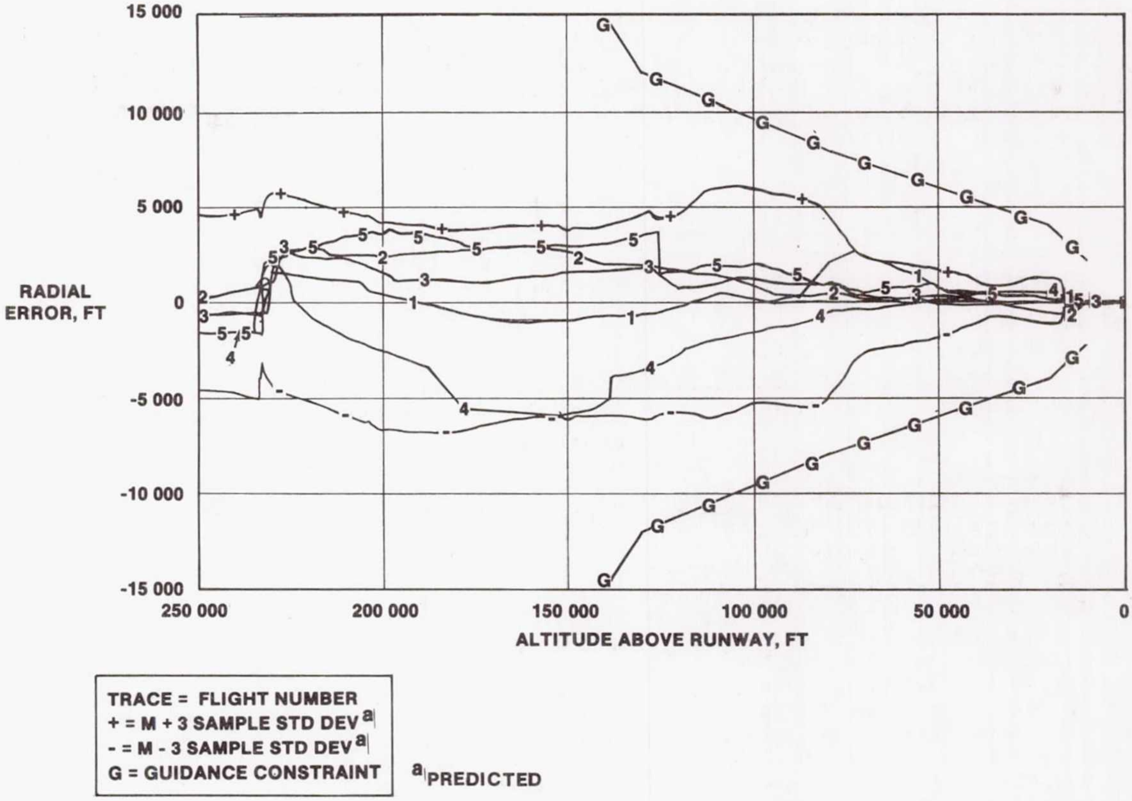


FIGURE 6.- ERROR IN RADIAL POSITION.

## DESCENT STATE DETERMINATION USING TACAN AND MICROWAVE DATA

Some effect on radial position accuracy from the use of TACAN range data can be seen (fig. 6) in the 130 000-foot-altitude region. The TACAN ground site is near the runway and the line of sight between it and the Orbiter is more toward the horizontal than the vertical. The result is limited direct visibility of radial position and limited ability to correct it. Use of barometric altimeter data at about 84 000 feet altitude reduces radial position error to less than 500 feet by the time landing system measurements are available. Use of microwave landing system data at about 17 000 feet altitude reduces the position error to less than 100 feet. Radial position guidance requirements have been met with good margins.

The use of derived altitude affects downtrack position because radial and downtrack position errors are correlated (fig. 7). The use of TACAN observations easily reduces downrange position errors to less than 3000 by 120 000 feet altitude.

Crosstrack position error is shown in figure 8 as a function of altitude. A 1.2° TACAN bearing error on flight 1 led to an 8000-foot crosstrack error at about 115 000 feet altitude. The error decreased with decreasing range to the TACAN site. Otherwise, the crosstrack error was less than 1 nautical mile throughout descent.

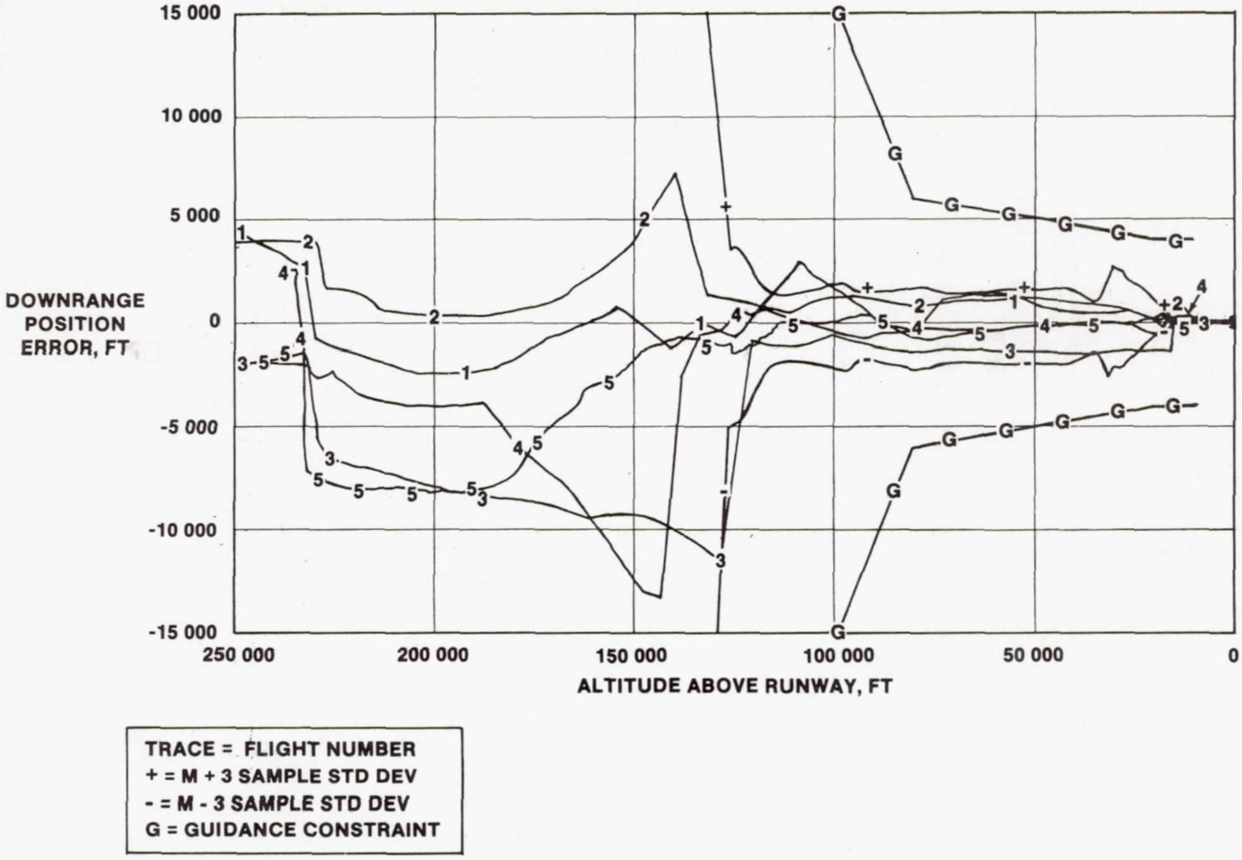


FIGURE 7.- ERROR IN DOWNRANGE POSITION.

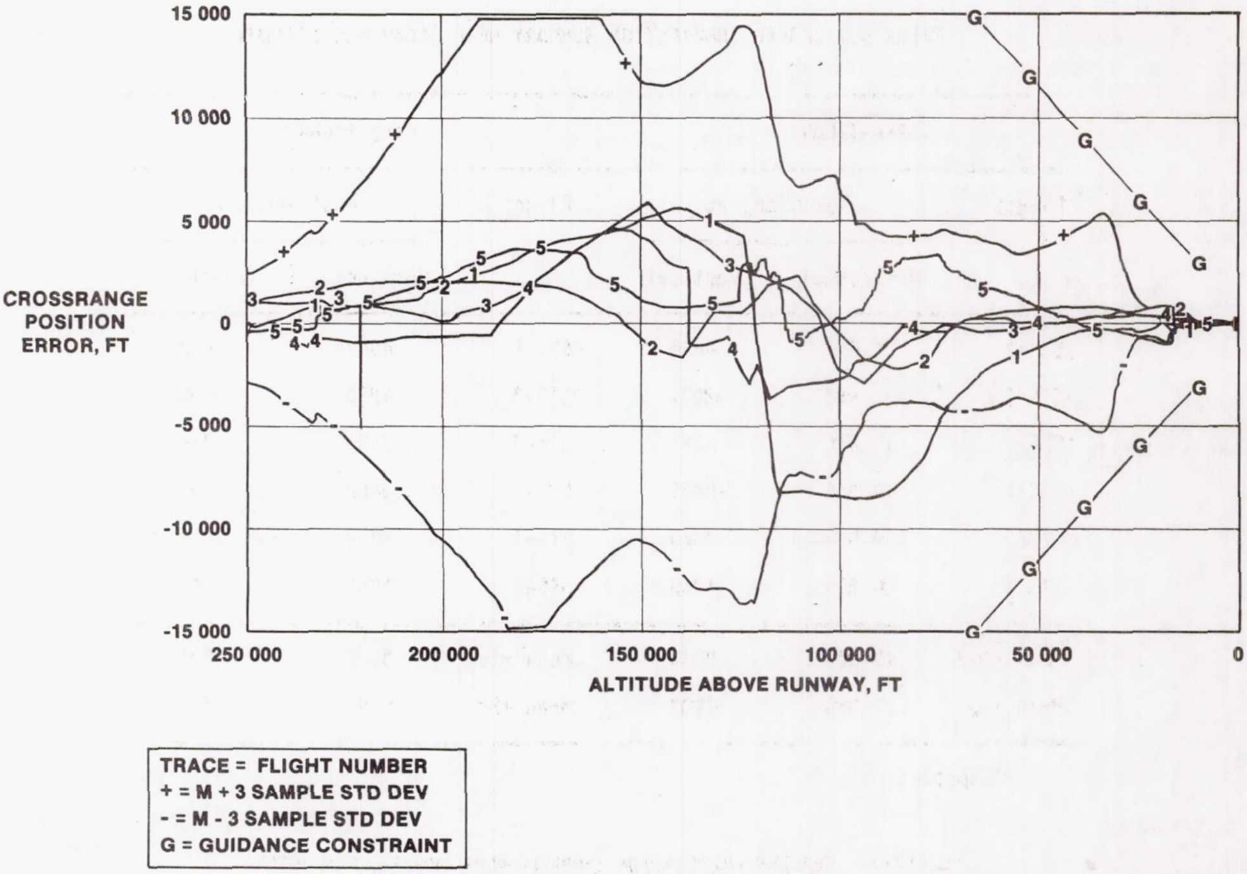


FIGURE 8.- ERROR IN CROSSRANGE POSITION.

The error information for selected times is provided in tables 5 to 7. Table 7 shows an improvement at touchdown on flight 6 due to the use of a microwave landing system ground antenna that was more compatible with the Orbiter antenna. The vertical error on flight 2 at touchdown is the result of using microwave landing system elevation data at too low an elevation so that multipath error effects deteriorated the state.

## AIR RELATIVE DATA

Air relative parameters - Mach number, angle of attack, and dynamic pressure - are required for flight control prior to air data availability at about 84 000 feet altitude. There was a desire to have the vehicle control be independent of position and velocity error. Use of drag acceleration measured by the IMU's for the computation of air relative parameters resulted in relatively accurate parameters with only second-order dependence on position and velocity.

## FUTURE NAVIGATION EFFORT

New capabilities planned include navigation for rendezvous and proximity operations and refined orbital onboard state propagation in 1984; flexibility and reduced onboard maintenance of runway, TACAN, and microwave site data in 1985; and autonomous orbital navigation by 1986. There will be three additional vehicles to check, a first KSC landing, a Vandenberg launch, a Vandenberg landing, and an automatic landing. The first use of the Tracking and Data Relay Satellite (TDRS) for ground-based orbital navigation will occur in 1983. Onboard descent autonomy requires autonomous orbital navigation, deorbit targeting, and independence from current ground management of the use of onboard descent navigation sensors.

TABLE 5.- ONBOARD NAVIGATION SUMMARY NEAR TACAN ACQUISITION

| Pre-TACAN | | | Post-TACAN | | |
|---|---|---|---|---|---|
| Flight | Position, ft | | Flight | Position, ft | |
| | Horizontal | Vertical | | Horizontal | Vertical |
| STS-1 | 5 822 | -696 | STS-1 | 4349 | -467 |
| STS-2 | 1 452 | 2021 | STS-2 | 1230 | 998 |
| STS-3 | 11 834 | 1831 | STS-3 | 2460 | 728 |
| STS-4 | 15 458 | -5858 | STS-4 | 2609 | -3903 |
| STS-5 | 4 050 | 3720 | STS-5 | 2262 | 1625 |
| STS-6 | 6 334 | -1860 | STS-6 | 1052 | -1241 |
| Mean $+1\sigma$[a] | 10 602 | 2269 | Mean $+1\sigma$ | 3326 | 2291 |
| Mean $+3\sigma$ | 27 066 | 5903 | Mean $+3\sigma$ | 9980 | 6134 |

[a] Expected.

TABLE 6.- ONBOARD NAVIGATION SUMMARY NEAR MSBLS ACQUISITION

| Pre-MSBLS | | | Post-MSBLS | | |
|---|---|---|---|---|---|
| Flight | Position, ft | | Flight | Position, ft | |
| | Horizontal | Vertical | | Horizontal | Vertical |
| STS-1 | 877 | 303 | STS-1 | 36 | 51 |
| STS-2 | 1113 | -488 | STS-2 | 120 | 51 |
| STS-3 | 1386 | -6 | STS-3 | 14 | -54 |
| STS-4 | 320 | 411 | STS-4 | 54 | 78 |
| STS-5 | 750 | 194 | STS-5 | 83 | 23 |
| STS-6 | 1220 | 440 | STS-6 | 102 | 74 |
| Mean $+1\sigma$[a] | 470 | 420 | Mean $+1\sigma$ | 67 | 43 |
| Mean $+3\sigma$ | 1230 | 1213 | Mean $+3\sigma$ | 198 | 99 |

[a] Expected.

TABLE 7.- ONBOARD NAVIGATION SUMMARY AT TOUCHDOWN

| Flight | Touchdown, ft | | |
|---|---|---|---|
| | Downtrack | Crosstrack | Vertical |
| STS-1 | -4 | 18 | 5 |
| STS-2 | 36 | 50 | 15 |
| STS-3 | 32 | 72 | 6 |
| STS-4 | 19 | 48 | 6 |
| STS-5 | 10 | 29 | 2 |
| STS-6 | 20 | 4 | 4 |
| Mean +3σ[a] | 48 | 30 | 30 |

[a] Expected.

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