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ABSTRACT

IN-FLIGHT ANGULAR ALIGNMENT OF INERTIAL NAVIGATION SYSTEMS BY MEANS OF RADIO AIDS

The principles involved in the angular alignment of the inertial reference by nondirectional data from radio aids are developed and compared with conventional methods of alignment such as gyro-compassing and pendulous vertical determination. This is followed by a discussion of the requirements imposed on the performance of the radio aid and the pertinant properties of such radio systems as AROD, SHIRAN and LORAN are examined for their applicability to the problem. Basic limitations caused by radio propagation effects such as uncertainty in the speed of propagation and multipath transmission effects are touched upon.

The report then addresses itself to the specific problem of the Space Shuttle reentry and a proposed technique for the alignment of the inertial reference system some time before landing. A description is given of the digital simulation of a transponder interrogation system and of its interaction with the inertial navigation system. It is found that the radio measurements are capable to update state vector, angular alignment and the accelerometer scale factors. The implementation of the alignment filter is illustrated with the help of logic diagrams.

Data from reentry simulations are used to demonstrate the effectiveness of in-flight inertial system alignment. Concluding remarks refer to other potential applications such as Space Shuttle orbit insertion and air navigation of conventional aircraft.

by Walter Tanner
May 1972

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1. Introduction

The objective of this report is to describe a technique of in-flight angular alignment of an inertial measurement unit (IMU) and to discuss the relevant factors which govern the successful application of the technique. The subject is the angular alignment by means of matching the inertially measured specific force vector with a corresponding external radio measurement. The technique is based on measurements which relate directly to the IMU alignment angles. It is different from parameter estimation using Kalman filters, but there are similarities with respect to weighting and smoothing of the external measurements. The conclusions regarding configuration and performance requirements for the external radio sensors are considered to apply universally.

In preparing an inertial navigation system for operational use we have three major requirements to contend with: (1) calibration of the inertial instruments, (2) angular alignment of the accelerometer package, and (3) initialization of the integration constants of velocity and position. Usually all these functions are performed on the ground. But with extended space flights it has become necessary to update most of the inertial system parameters in flight and occasionally to reinitialize the entire system. The proposed alignment technique uses nondirectional trilateration to three radio transponders and can provide complete reinitialization of the navigation system in addition to angular alignment and re-calibration of accelerometer scale-factors. The techniques can be applied to the launch and reentry of a spacecraft as well as to the flight of conventional aircraft.

A review of current angular alignment techniques will place the relative merits of in-flight radio alignment in the proper perspective. The means for angular platform alignment on the ground are (1) direct optical alignment of the accelerometer package relative to surveyed coordinates, (2) pendulous mode of platform operation for local vertical, (3) gyrocompassing for azimuth, (4) use of external angular sensor and positioning of platform gimbal angles. In flight, one has used (5) external angular sensors in an equivalent mode as in (4), or the alternative (6) a star tracking device on the inner gimbal for direct angular alignment relative to two star-lines-of-sight. More recently (Refs. 1,6,8) an effort has been made to estimate the alignment angles in flight as part of the parameter determination of the overall navigation system by using redundant external measurements such as various angles or ranges and range rates to transponders on earth or on synchronous satellites. A brief survey of the alignment techniques is given in Table 1.

Most alignment techniques consist of relating the orientation of the inner gimbal of a platform to an optical (or radar) line-of-sight. If the line-of-sight sensing is external to the platform it requires that gimbal angles be measured with high accuracy and that these angles be transferred in and out of the navigation computer. In the case of a star tracking IMU the gimbal angles are not needed, but the platform must be slewed precisely into two orientations in order to obtain three-axis alignment. The necessity for transferring a critical angle through the computer is indicated by a "yes" in the column called "Angle Transfer". Alignment optics (1) require only the nulling of two error angles rather than the accurate transfer of either gimbal angles or gyro slew angles. The more sophisticated methods of alignment sense directly the local vertical and its motion in the Earth's gravitational field. Gyrocompassing determines the North direction by using the North acceleration to null out the azimuth misalignment angle, local vertical is determined from sensing East and North acceleration errors. These two methods have the great advantage of depending only on the very basic instrumentation (acclerometers and gyros) of inertial navigation. In typical surface navigation systems the pendulous vertical alignment will place the platform in an orientation that results in automatic compensation of calibration and mounting errors of the accelerometers' sensitive axes. The in-flight alignment technique to be discussed here also does not depend on gimbal angle readout and bears, therefore, some similarity to the pendulous vertical alignment. Both methods depend on a specific force to act on the accelerometers. Alignment is obtained from determining the three components of the specific force vector in the coordinate system defined by the planes of insensitivity of the three accelerometers. Both alignment methods fail if the specific force reduces to zero as is the case in a free fall trajectory.

Table 1 also lists typical values of alignment accuracies. There is usually a wide spread depending on environmental conditions, measurement time, and sensor stability. With external tracking sensors (item 4) the bias angle between sensor coordinates and IMU coordinates is usually time varying and must be estimated from redundant measurements with changing geometry. Azimuth alignment (item 3) depends on a good estimate of gyro drift rates. The radio type in-flight alignment

Table 1. Summary of IMU Alignment Techniques.

REF	Alignment Mode	Alignment parameters	Active IMU sensors	Angle transfer	Operational Requirements	Accuracy mr (RMS)
(1)	Alignment Optics	3 axes	Mirrors on inner gimbal	no	Precisely defined IMU and optical target locations at rest; optical windows in vehicle	typical 0.05
(2)	Pendulous Mode	Local vertical	Accelero-meters	no	Vehicle at rest in gravitational field or on slow concentric trajectory	typical 0.2
(3)	Gyrocompassing	Azimuth	Accelero-meters and gyros	no	Vehicle on circular trajectory about rotation axis of gravitational body.	typical 3 to 0.4
(4)	Angle Tracking Sensors	3 axes	Gimbal angles	yes	Visibility of stars or of other well defined spatial reference points.	typical 2 to 0.2
(6)	Star Tracking IMU	3 axes	Star tracker on	yes	Visibility of stars through optical window; precisely calibrated slewing of platform.	est. 0.1
(X)	Redundant Range	3 axes,	Accelero-	no	"Visibility" or reference points; specific force on vehicle non-zero.	typical 0.4 - 0.1

in turn is highly dependent on the system angular geometry, transponder surveying accuracy, and propagation anomalies in the earth's atmosphere.

2. The Concept of In-Flight Alignment.

An inertial measurement unit feeds information into the navigation system only when a specific force is present. This force is the support force when the vehicle is at rest, or lift drag and prospulsion forces when the vehicle is in flight. The output from the accelerometer package is either an acceleration vector (a_s) or integrated acceleration (ΔV_s) over a certain time interval Δt. The subscript 's' indicates that the output is caused by specific force. The components of a_s or ΔV_s appear in the coordinate system defined by the sensitive axes of the three accelerometers. However, the true orientation of the accelerometer coordinate system is usually in error relative to the reference coordinate system used in the navigation computations. The error angles between the true and the reference system are the result of initial alignment errors and of the drift of the gyros which serve as the on-board inertial angle reference. If ΔV_{sI} of the inertial navigation system is compared with an equivalent ΔV_{sE} from some external measurement system, there will be an error in the direction between the two velocity vectors which corresponds to the angular misalignment of the true accelerometer coordinate system.

From independent external measurements of the flight trajectory the specific force ΔV_s can be determined as shown in figure 1. Subsequent velocity measurements provide a resultant ΔV for a given time interval. Since the flight trajectory is affected both by specific forces and gravitational forces, acting on the vehicle, the specific force ΔV_s is computed by subtracting a gravitational ΔV_g from the measured ΔV. The gravitational ΔV_g in figure 1 is computed by multiplying the average gravitational acceleration for the two endpoints by the time interval Δt.

Figure 2 defines the error angle ALFA between the specific force vectors obtained from the accelerometer measurements and from external (Transponder Navigation System) measurements. If the external measurements were perfect, the angle ALFA would represent the misalignment of the accelerometer package about an axis perpendicular to the plane formed by the two vectors. In general, the two vectors will be slightly different in magnitude; the difference is the result of the scale-factor and bias errors of the three accelerometers (assuming again that external measurements are perfect). Unfortunately there is ambiguity between the misalignment angle and the scale-factor errors, when the latter are not identical for all three axes. A scale factor error in a single axis causes the sensed specific force vector to be rotated in the direction of the scaling error. Figure 2 also shows the angle BETA between the specific force vector and the x-axis, which is assumed to be near the local vertical. BETA will be used later to control the weighting of azimuth and tilt angle updates.

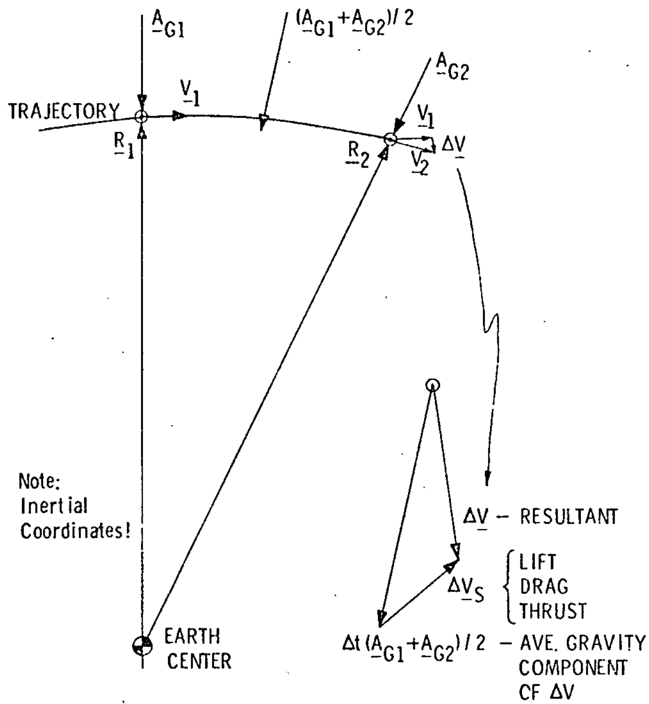


Figure 1. Definition of Specific Force Velocity Increment ΔV_S.

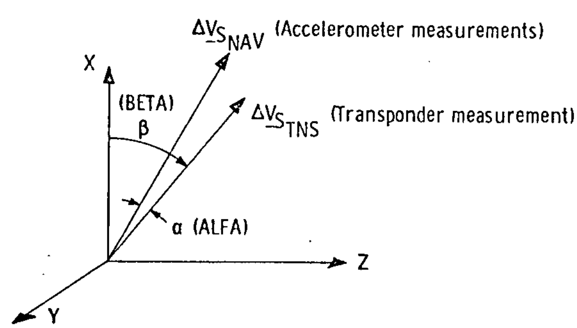


Figure 2. Specific Force Vectors from Two Measurement Sources in IMU Reference Coordinates.

Figure 3 shows how a system of three ground transponders can provide the on-board navigation system with position and velocity information. Position is determined from three simultaneous range measurements. The velocity vector is computed from three simultaneous Doppler measurements (or delta-range measurements). The trajectory data are in an Earth-fixed coordinate system. In this case an orthogonal coordinate system that has its origin at the #0 transponder was selected. The two other transponders are in the y-z plane and the y-axis is parallel to the line between the transponder sites #1 and #2. The radio ranging system under consideration here is the AROD system developed by Marshall Space Flight Center. However, there are other ways to determine position and velocity. With a hyperbolic system such as LORAN, position would be given by two surface-range differences and barometric altitude, while horizontal velocity would be derived from received phase-rates. Vertical velocity is of secondary importance for the alignment of a surface navigation system. Other three-dimensional systems such as SHIRAN and its derivatives make range and velocity measurements to a number of ground transponders in time sequence. This introduces the requirement for extrapolation of the sequentially measured quantities to a common time for which the components of the position and velocity vectors will be computed. Sequential processing of measurements tends to simplify the computation routines. The requirement for extrapolation of measurements is no imposition, since this feature is also needed to cope with measurement drop-outs or poor data.

Referring again to Figure 2 and to the problem of ambiguity between the misalignment angle and accelerometer inaccuracies one recognizes readily that a scheme is needed to isolate the individual error sources. In other words, an alignment filter is needed that will make use of a priori information to assign signed source errors on the basis of the error resultant from all sources. The distribution of the resultant error to the sources must be based on the likelihood of an error contribution and on the sensitivity of the resultant error to the contributor. In the case of angular alignment by specific force vector comparison the independent error contributors can be identified as:

Misalignment angles (3)

Accelerometer scale-factor errors (3)

Accelerometer bias uncertainty (3)

Each measurement cycle provides only 3 components of the specific force error vector to the set of the 9 unknown variables.

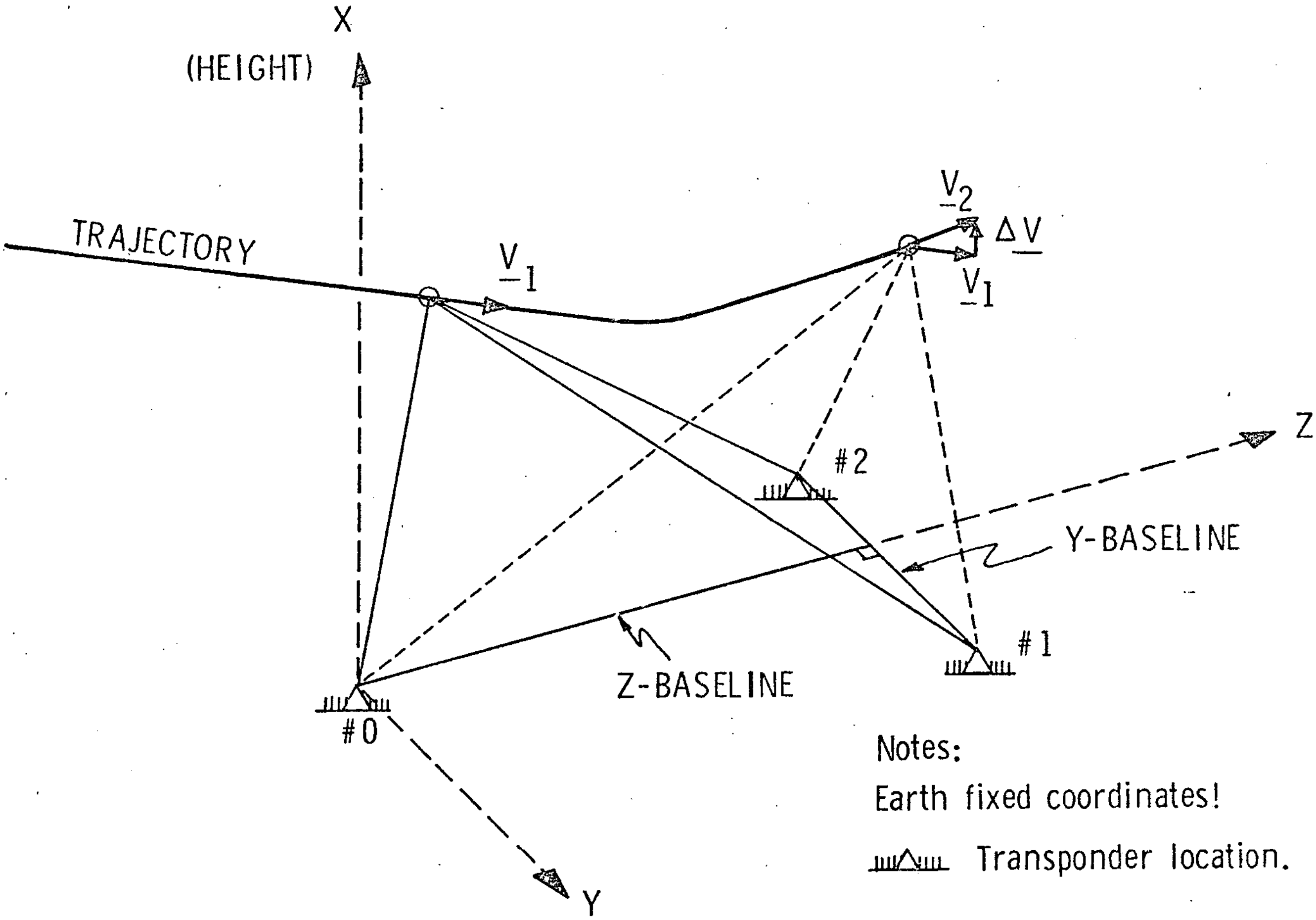
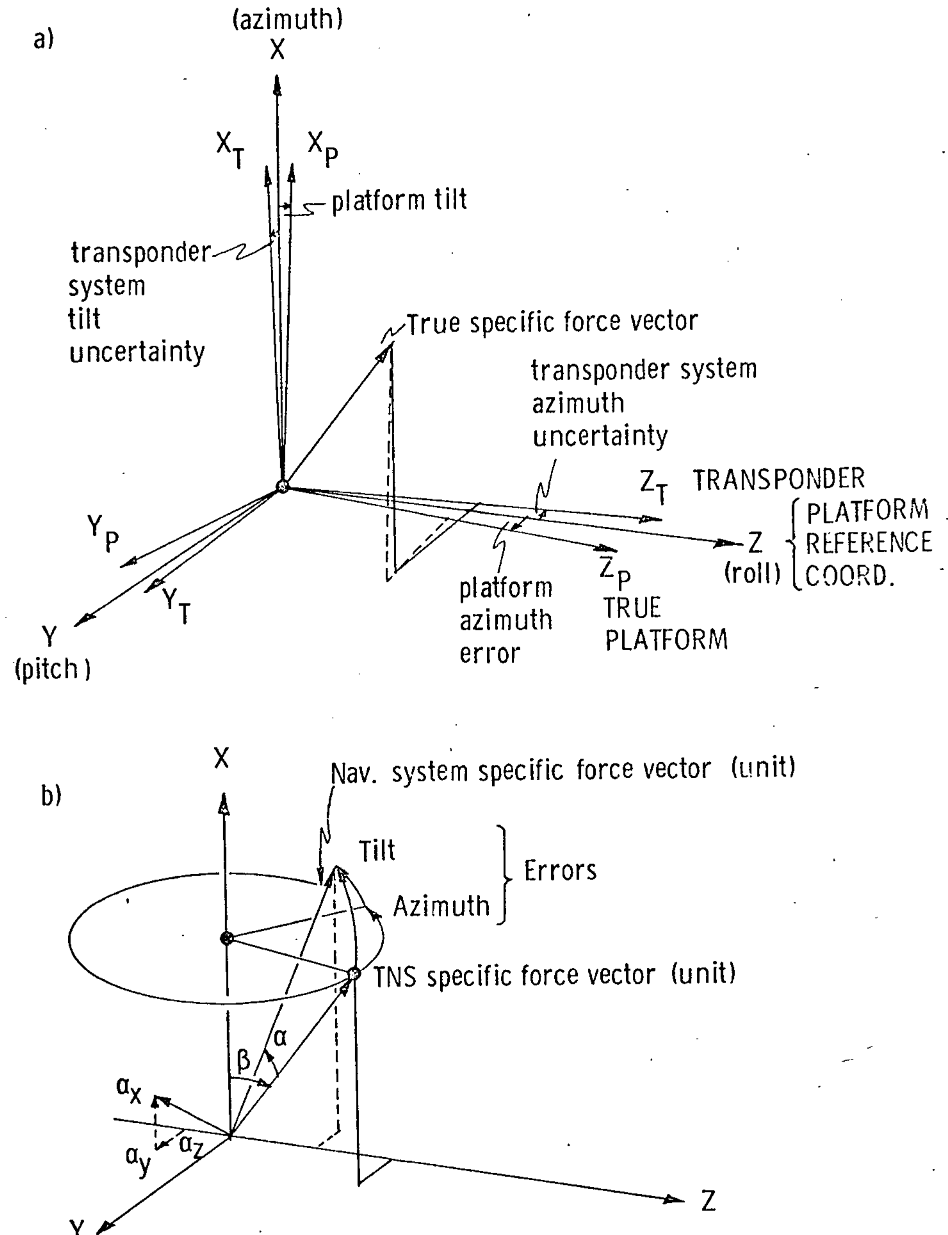


Figure 3. Transponder Coordinate System.

This discrepancy between the number of measurements and the unknown parameters is reduced by some simplifications and through the use of multiple measurement cycles. The consequences of misalignment angles and the accelerometer bias uncertainty are virtually indistinguishable in a surface navigation system, where an almost constant lift force is the dominating force acting on the IMU. In such a case one may arbitrarily assume the bias uncertainty at zero and consider it as a part of the misalignment angle. Reduction of the magnitude error of the specific force vector is achieved over a sequence of updating cycles by adjustment of the three accelerometer scale factors. As a practical routine, the weighting factors for the updates are made dependent on the cosine squared of the angles between accelerometer axes and the specific force vector. During straight and level flight only the scale factor of the vertical accelerometer should be updated. During maneuvers involving large lateral forces the North and East accelerometers are updated with additional weighting related to the angle BETA shown in Figure 2. In other words, the distribution of the error updates is made dependent on simple known characteristics of the trajectory, the navigation system, and the external measurement system.

A particular problem of error source separation is the separation of the misalignment angle into azimuth and tilt errors. The misalignment angle ALFA is a rotation vector which will cause the two independently measured specific force vectors to coincide, if the IMU reference coordinates are rotated about this vector. This is shown in Figure 4b. If the angular correction is made along a great circle, namely about the rotation vector ALFA, there is an undue crosscoupling of the azimuth correction into the tilt of the reference system. A surface navigation system is very sensitive to the tilt angle and the correction of a large initial azimuth error can easily upset the tilt alignment. Therefore it is necessary to split the alignment vector ALFA into an azimuth rotation about the local vertical and a tilt rotation in such a way that both alignment components are within estimates of respective alignment errors. Furthermore, azimuth alignment should not be attempted unless the specific force vector has a substantial horizontal component, i.e. its angle BETA relative to local vertical should be larger than 20°. For smaller values of BETA the uncertainties in the alignment vector ALFA will translate into an unreasonable uncertainty of the azimuth angle. Consequently the alignment filter must be provided with weighting of azimuth and tilt corrections which is dependent on the angle BETA.

Updating of IMU characteristics in a closed loop navigation system such as a Schuler tuned system must be coordinated with system re-initialization, if step disturbance of the system is to be avoided. Coordination is easily accomplished since the external radio measurements leading to the specific force vector are based on very precise position and velocity measurements, the only missing system initialization variables. The mechanics of re-initialization will be described later in the discussion of the filter logic.



ALFA = α = Error angle between specific force vectors measured by accelerometers and by transponders in platform reference coordinates.

BETA = β = Inclination of specific force vector.

Figure 4. Angular Alignment, Error Angle Geometry.

The last subject to be touched upon is the problem of three-axis alignment. The preceding discussion indicates that an individual external specific force measurement provides alignment information about two axes which are orthogonal to the specific force vector. Three-axis alignment depends on subsequent measurements with changing inertial orientation of the specific force vector. The principle is identical to that of gyro-compassing. However, in flight one can expect rapid changes of the specific force angle at rates much greater than the earth rotation rate. For instance during a turn maneuver the specific force angle can be tilted by as much as 30 degrees in a matter of seconds. Equally, during reentry braking of a space vehicle the specific force angle is approximately 20 degrees off local vertical and will change to approximately vertical at the time of transition into efficient glide (angle of attack transition). A space vehicle being launched into orbit undergoes even larger specific force variations. At take-off the specific force of 1g is vertical and changes to about 3g in the horizontal at insertion. The large angle variations and increased magnitude of the specific force give in-flight alignment an advantage over the gyro-compassing mode. In particular it is possible to obtain good three-axis alignment in a much shorter time.

3. Sensitivity to Environment

In-flight alignment depends on accurate external measurement of velocity increments. To put the measurement requirements into perspective, assume that alignment to 0.1 milliradians is desired. This means that both the bias and the smoothed random errors of the transverse components of the computed specific force vector must be below 10^{-4} of the vector's magnitude. While random errors can be smoothed by using a sufficient number of independent measurements, the required bias tolerance becomes a difficult system requirement. In surface navigation the magnitude of the specific force velocity increment is about 10m/s per 1 second time increment (i.e. 1g or $10 m/s^2$). To achieve the required alignment bias tolerance in a 60 second time interval, horizontal differential velocity must be determined (from external sensor alone) to an accuracy of $6 \cdot 10^{-2}$ m/s. Individual error sources such as the uncorrelated bias between measurement endpoints, the smoothed random error and the data quantization errors must all be less than that. The only radio techniques which can provide such accuracy in the measurement of differential velocity are cooperative "Delta-Range" techniques i.e. "Doppler" and precision phase measurement techniques. The delta range measurements also must be supported by occasional position or range determination from additional radio ranging circuits or from optimal range estimation using the entire navigation sensor complex.

There are two groups of environmental effects which impose basic limits on the alignment precision. The first group is made up of geometric relations between the lines along which range and Doppler measurements are made. It includes the position uncertainties of the elements of the radio system. The second group consists of the propagation anomalies of electro-magnetic waves in the atmospheric environment and includes such major factors as the uncertainty in the speed of propagation and the errors caused by multipath effects.

a. Geometric Considerations

A typical example of how sensitive alignment accuracy is to the geometric disposition of the radio system is shown in Figure 5. In this two-dimensional system it is assumed that the position and velocity of an aircraft is determined from two range measurements R_1 and R_2 relative to two ground transponders. The aircraft flies on a straight line trajectory at a constant velocity of 300 m/s at an altitude of 2000m. The transponders are separated by a baseline of 10km. If the second transponder has a relative position error of +10 m, the aircraft position computed from the range measurements will contain a height error as shown. There is also a small downrange error of -30 m or less. The computed horizontal velocity would show a constant bias of +0.3 m/s. Vertical velocity shows rapidly increasing errors as the distance from the center of the transponder array increases. There is no acceleration error of the horizontal component of motion, which is very fortunate in the case of local vertical alignment. But vertical acceleration is in error by more than 0.09 m/s^2, which is 900 ppm of earth gravitation. With this geometric uncertainty of a transponder position it would, therefore, be impossible to improve the scale-factor of the vertical accelerometer.

The sensitivity of alignment to downrange position uncertainty of one transponder relative to others is illustrated further in Figure 6. A three-dimensional simulation was made of the reentry of a space shuttle vehicle. The figure shows the angular error of the computed specific force vector relative to the true specific force vector. The simulation took into account a Doppler quantization error of "Delta-range" of ±5 cm, which accounts for the randomness of the angular error. One of the three ground transponders was assumed to be displaced in the downrange direction by 3 meters and another transponder link had an assumed range scaling error (propagation velocity) of 10^{-5}. The baselines (see Figure 3) were Z = 63 km and Y = 76 km. At 4200 seconds the space shuttle was roughly in the center of a transponder triad at an altitude of 32.7 km and its velocity was 723.7 m/s (Mach 2.2). The vehicle was in its atmospheric braking phase with a large angle of attack just prior to transition into an efficient glide.

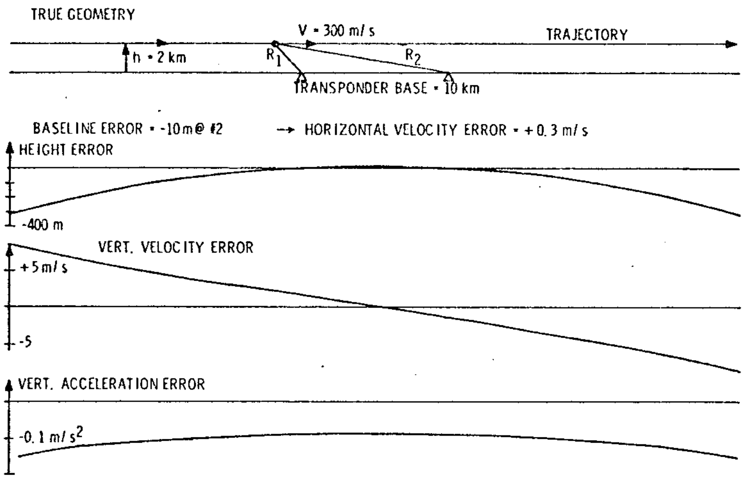


Figure 5. Bias Errors vs. Position along Baseline, for a Transponder Baseline Error of -10 m.

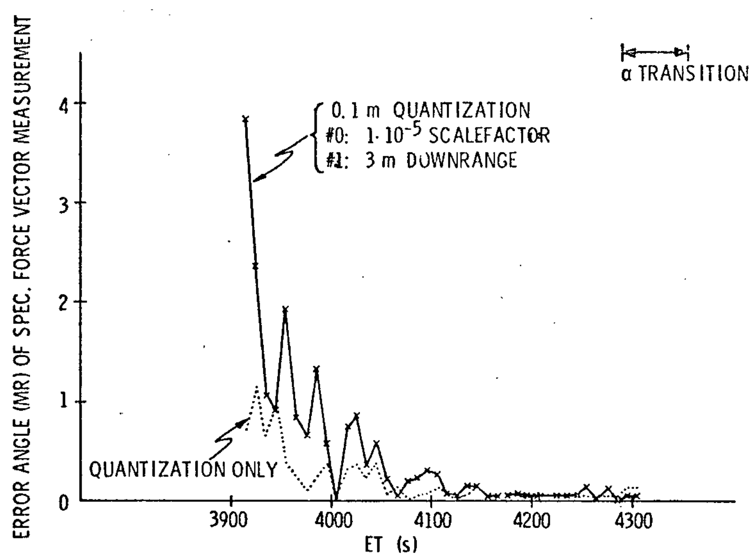


Figure 6. Angular Accuracy of Alignment Reference.

The last two figures demonstrate that the smallest angular uncertainties of the specific force vector are found in the region between the transponders, where the lines-of-sight towards the transponders encompass angles near 90^{o} (the base-lines were selected with such a geometry in mind). When the angles between lines-of-sight and the plane of the baselines become smaller than approximately 30^{o}, the angular uncertainty of the specific force vector will increase rapidly. It is easily seen that in a trilateration system such as a three-transponder system, the vehicle altitude places a limit on the operational range and on the time interval during which useful information may be obtained. Among the geometric parameters, the downrange displacement of one transponder relative to the others is found to be the most important error source, and vehicle velocity a critical modifying factor. Transponder height errors, lateral displacement and simultaneous displacement of all transponders have less of an effect on angular alignment bias. Common displacements of 200m or equivalent navigation errors were found to be tolerable.

With two-dimensional surface navigation systems (LORAN or 2 transponders), where the vertical component of the specific force vector is estimated from other system information, the restrictions on operating range or duration of measurements are less severe from the point of view of geometry, but radio propagation anomalies become more critical.

b. Radio Propagation Anomalies

Density and humidity of the earth's atmosphere lower the speed of propagation of electromagnetic waves by about 316 ppm at sea level. Since atmospheric density follows approximately an exponential law with height, it is best to describe the difference in progagation velocity by using the notion of scale-height h_o. Widnall and Morth[1] have used for the range measurement bias the following relation:

$$E_R = R \cdot N_g (1 - e^{-h/h_s}) h_s / h$$

where:

- R = slant range
- N_g = $316 \cdot 10^{-6}$, refractive modulus at ground reference
- h = Height of vehicle above ground reference
- h_s = 8100m, scale height for exponential pressure decay

This equation assumes a flat earth with horizontal stratification of atmospheric density and is good for horizontal ranges up to 300km.

Atmospheric ranging errors may be predicted on the basis of a standard atmosphere and the elevation of the ground station, leaving a rms bias uncertainty of about 50 ppm . If humidity and atmospheric density at the ground station location are also considered, the prediction error may be reduced to 10 ppm rms. Extensive data on ranging and refraction errors at radar frequencies are found in Barton[3] and in the USAF Handbook of Geophysics[2].

At horizontal ranges over 300 km precise ranging requires consideration of the earth's curvature (refer to figure 7). The bias error in this case is:

$$E_R = N_g \int_{r=q}^{R+q} e^{-h(r)/h_s} \, dr$$

with:

$$h(r) = \mathrm{SQRT}(r^2 + R_o^2 - q^2) - R_o$$

$$q = (h_i^2 + 2R_o h_i - R^2)/(2R)$$

where:

- r = Slant range variable
- R_o = Radius of ground reference from earth center
- h_i = Height of interrogator (vehicle) above ground reference
- h_s = 8100, scale height

Again it is possible to reduce the slant range bias by computed prediction to an rms uncertainty of 50 or 10 ppm.

The implication of range bias uncertainty is that the error creates an effect identical to horizontal position uncertainty of the ground reference (transponder). At line-of-sight elevation angles of less than 1^o the slant range uncertainty is over 10 or over 2 meters, depending on the type of bias prediction. If two ground transponders are separated by more than 10 km it can be assumed that the atmospheric bias uncertainties are uncorrelated and that they are equivalent to a relative position error between two transponders. The unfavorable results of such a bias on the specific force computations has been discussed already under geometrical considerations.

The next question is: How will the atmosphere affect the measurement of range rate? Typical Doppler measurements may require a counting interval of 10 to 30 seconds for the counting of phase cycles or Doppler range increments, and in order to obtain the required range rate resolution of better than 0.06 m/s. During such a

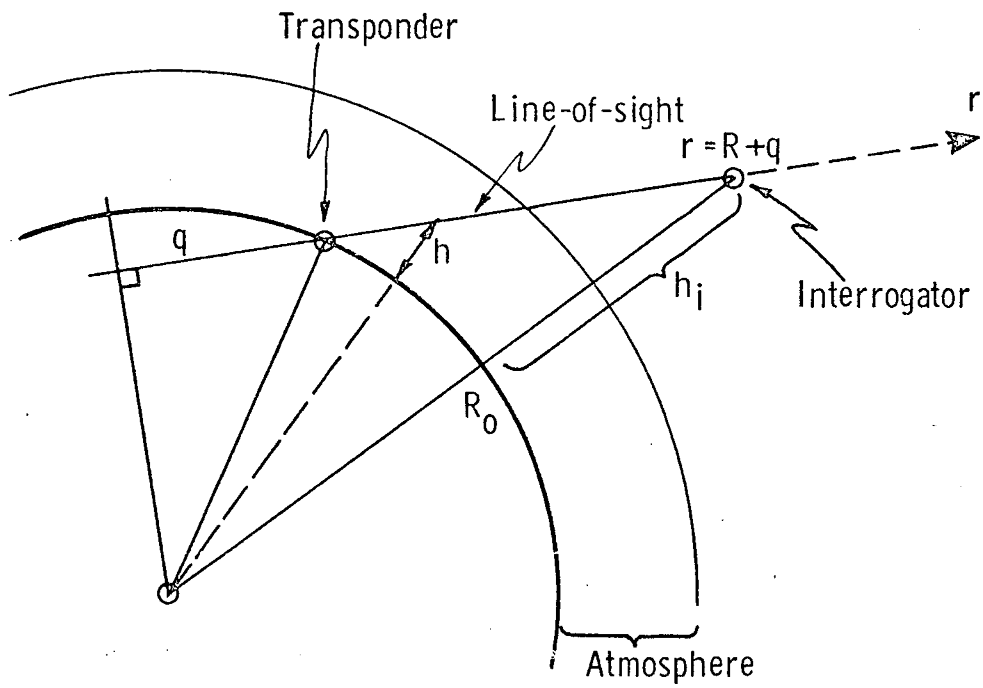


Figure 7. Curved Earth Geometry.

counting interval there is generally anegligible change in attitude or slant range. Therefore, the range rate bias caused by the atmosphere is essentially equal to the refractive modulus at the location of the moving vehicle. The deterministic bias becomes:

$$E_{\dot{R}} = \dot{R}\, N_h$$

where:

$\dot{R}$ = Range rate

N_h = Refractive modulus at vehicle altitude h.

Correspondingly, the rms range rate uncertainty after removal of the deterministic error will be:

$$\epsilon_{\dot{R}} = \dot{R} \cdot \Delta N_h$$

$$\text{where} \quad 10^{-5}\, e^{-h/h_s} < \Delta N_h < 5 \cdot 10^{-5}\, e^{-h/h_s}$$

ΔN_h RMS uncertainty of refractive modulus at vehicle altitude h

For a vehicle at an altitude of 10,000 m the uncertainty in the measurement of range rate, due to atmospheric propagation delays, is between $2.7 \cdot 10^{-6} \dot{R}$ and $13.5 \cdot 10^{-6} \dot{R}$. For a closing velocity of 2000 m/s (Mach 6) the velocity uncertainty would be 0.0054 to 0.027 m/s. Such errors would not affect the angular alignment; and since the angular alignment is based on specific force vectors, computed from velocity differences, the deterministic velocity bias will cancel out, unless the bias rate is very high. The latter may be the case at low level overflights of a transponder or during a vertical dive. But in most cases the effect of the atmosphere on the velocity measurement may be neglected.

At LORAN frequencies of 100 kHz the electromagnetic waves propagate along the surface of the earth as trapped surface waves. Surface conductivity and surface reactance tend to retard the advancing phase front and there is a dependence of the LORAN position error on ground impedance, altitude, LORAN lane number, average atmospheric temperature and pressure. At altitudes above 10,000m (33,000 ft) the effects of ground impedance become negligible.

Fortunately, since with a LORAN system the vertical component of specific force would not be obtained from radio measurements, there is in general no problem with the station geometry and no critical dependence on relative station position.

The only question is how accurate a horizontal velocity difference can be measured. In a manner similar to the preceeding discussion one may conclude that the atmosphere above 10,000m has no effect on the required accuracy of the measurement of differential velocity. However, at very low altitudes the changes in terrain conductivity may introduce appreciable uncorrelated bias errors between consecutive velocity measurements and cause excessive uncertainties of the computed specific force vector. Rapid altitude changes at low altitudes will cause similar errors.

Multipath propagation errors, the other important source of errors in precision range and range-rate measurements, fall into two categories. First, the interference between two signals traveling on two different paths causes fading or cancellation of the received radio frequency carrier. This may result in temporary loss of data or in erroneous range or range-rate information because of insufficient signal levels or modulation distortions. Secondly, the carrier modulation from two or more different transmission path distances may mix and produce in the range detection circuits an error relative to the desired shortest transmission path. The first type of multipath error can be recognized easily by signal strength detectors. The second type of error is elusive to detection, in particular if the multipath interference causes only a small but consistent bias error. Only the multipath problem of the second type will be discussed here further.

The subtle multipath ranging error obviously depends on the magnitude and the time delay of the interfering multipath signal, but the configuration of the radio ranging system determines to what extent the interfering signal is rejected and how the ranging error will manifest itself. With any radio system it is possible to suppress the interfering signal to some extent by careful selection of carrier frequency, antenna pattern and wave polarization. The remaining suppression must come from signal design and detection techniques.

Amplitude modulated ranging systems, analyzed by Epstein and Reedy[4], are particularly sensitive to multipath interference. Current techniques use pulse-code/phase modulation and high deviation FM. Representative of these two approaches are the AROD system of Motorola and the SHIRAN system of USAF/CUBIC Corp. The former system has good interference rejection for interference signals which are delayed by at least one pulse interval. The latter system rejects by filtering in the frequency domain, and the ranging error has the appearance of a fast random error with zero mean value[5]. The expected ranging errors due to multipath are on the order of a fraction of a meter to a few meters.

Concerning angular alignment of the IMU, the ranging accuracy relative to the transponders will enter only through its effect on the apparent geometry between the three lines-of-sight to the transponders. Again the error is of the nature of a transponder baseline uncertainty, which was discussed earlier. The magnitude of the error is of the same order as the relative location uncertainty. While the multipath error is expected to be of similar magnitude with either of the precision ranging systems, the FM system would provide the possibility of smoothing this error over a sequence of redundant measurements.

4. Radio System Requirements.

There are two basically different concepts to be considered. One uses three-dimensional determination of vehicle position and velocity by such means as trilateration to three ground transponders and the measurement of Doppler incremental range, also in three dimensions. Hyperbolic schemes which give the desired parameters in three dimensions have also been proposed. The advantage of the three-dimensional radio system is that it permits updating of all major parameters of an inertial measurement unit. However the determination of accurate angular data and in particular of the vertical accelerometer's sensitivity imposes very stringent requirements on measurement accuracy and, in the case of trilateration, on the baseline uncertainties.

The second concept uses radio measurements for two-dimensional surface navigation only; motion in the local vertical is measured by other sensors or is estimated by the navigation system. Such a system will still permit angular alignment, but the measured data will in general be inadequate to update the sensitivity of the vertical accelerometer. Alignment operations are restricted to altitudes and velocities where aerodynamic lift is the dominating component of specific force. Velocity measurements by the two-dimensional radio system must still be precise, but the ranging accuracy can be relaxed. The representative of such a system is LORAN, but two transponders or beacons could provide data for an equivalent alignment mode. Other surface navigation systems such as 'Airborne Doppler' do not have the accuracy in the velocity measurement or the independence from the inertial system that are required of redundant external data.

The performance requirements of a three-dimensional radio transponder system will be discussed next. It appears to be obvious that such requirements will depend on mission and flight trajectory. But the radio propagation uncertainty really dictates the upper limit of desirable hardware accuracy. Table 2 gives a typical set of

Table 2. Transponder System Parameters

A. Operational Requirements:

Number of transponders in field of view:	3
Baselines (approximate, for reference):	Y = 80 km Z = 60 km
Maximum range (>5° above horizon):	300 km +
Maximum range rate:	closing 2000 m/s opening 800 m/s
Maximum range acceleration (v^2/R_{min}):	-5 to +20 m/s^2

System input:	3 transponder identifications; timing and reset of 3 Doppler counters and of 3 range buffer registers; expected range rate on 3 channels for acquisition. Synchronization of frequency synthesizers.
System output:	Range and cumulative Doppler counts from 3 identified transponders; 3 bit performance status in terms of an error index for the 6 data channels. Range unambiguous within 100 km. Delta range unambiguous within 10 km.
Measurement cycle:	Simultaneous range <u>or</u> Doppler measurement relative to 3 identified transponders.
Data readout:	Sequential serial readout of 3 components of range <u>or</u> Doppler data.

B. Performance

Range:	Hardware Alignment, thermal effects, receiver noise, antennas.	+ System Propagation errors
resolution	0.5 m	
bias (max)(uncompensated)	0	$30 \cdot 10^{-5}$ R $\cdot$ f(h)
bias uncertainty (max)	2 m	10^{-5} R $\cdot$ f(h)
random RMS (incl. multipath and turbulence)	0.5 m	0.5 m + 10^{-5} R $\cdot$ f(h)
data rate	1 s^{-1}	
lag uncertainty (max)	1 ms	
max. acquisition time	3 s	

Incremental range:

resolution	0.05 m	
bias (max)(uncompensated velocity error)	0.5 m	$30 \cdot 10^{-5} \Delta R \cdot e^{-h/h_s}$
bias uncertainty (from Measurement to meas.)	0.1 m max. bias change over 30 sec interval	$10^{-5} \Delta R \cdot e^{-h/h_s}$
random RMS (within measurement interval)	0.02 m	$10^{-5} \Delta R \cdot e^{-h/h_s}$
counting interval for average velocity	10 s	
timing accuracy, absolute	5 ms max. lag	
timing interval error (RMS)	10^{-5} max.	

C. Surveying accuracy of transponders

Common absolute error	20 m
Relative position error	1 m

transponder system parameters suitable for inertial system alignment to 0.1 mr during the re-entry navigation of a space shuttle.

The operational parameters are conditioned by the height of the spacecraft trajectory (between 36 and 27 km) and the desire to achieve good trilateration geometry. The performance requirements are aimed at an alignment accuracy of 0.1 milliradians. The data have been separated into tolerance values for the system hardware and system error contributions expected from atmospheric propagation and multipath effects. RSS addition of the two types of errors would represent the total error delivered to a navigation computer. The hardware requirements are for interrogator and transponder units working as a system. The breakdown of the errors into bias, bias uncertainty and random errors is of great importance for the design of the alignment filter. Bias uncertainties in range and incremental range are the most critical parameters, since they cannot be smoothed or estimated. In general, the range bias uncertainty will be uncorrelated for the three transponders and is equivalent to relative displacement between transponders. It distorts the system geometry as seen earlier.

Transponder acquisition and measurement cycles are assumed to be performed simultaneously on three transponder channels. Acquisition is aided through prediction of the Doppler frequency by the computer. A measurement cycle consists of range measurements on all three channels followed by a sequence of four delta-range Doppler readings. Three cumulative Doppler counters are read simultaneously four times, and the data are transferred serially to the computer through the use of buffer registers. A readout cycle will last about 30 seconds.

5. Space Shuttle Reentry

We shall now apply the principles of in-flight alignment to the specific problem of the reentering space shuttle. The reentry trajectory typically starts with a deorbit burn at 500 km and continues with a Hohman transfer to a shallow reentry into the atmosphere at 2006 seconds after deorbit. At that time a maximum tolerable drag is produced with a high angle of attack of about 50°. A bank maneuver is initiated as early as possible to obtain the crossrange capability required for reaching the landing site. There is a brief period of radio black-out. We assume that radio measurements can begin at altitudes below 50 km; this altitude is reached at 3800 sec at a range of about 760 km from the landing site. Figure 8 shows the remaining portion of the descent. (Note that the x-coordinates denoted along the trajectory

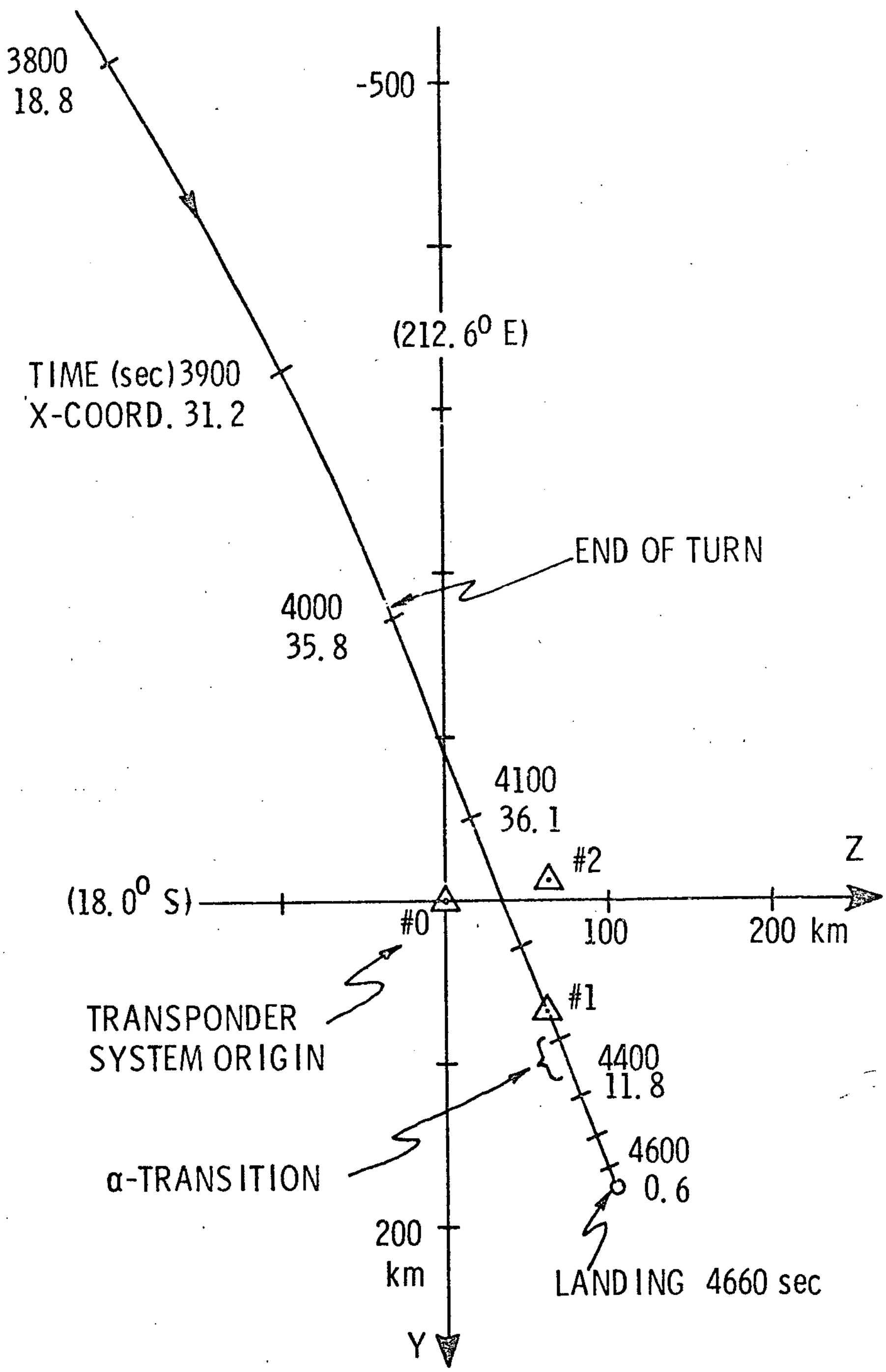


Figure 8. Approach Trajectory in Transponder Coordinate System.

refer to the plane defined by the three transponders and are not altitude above the geoid.) At about 4290 seconds there is an angle-of-attack transition from the high drag to the low drag point of the lift coefficient. The remainder of the trajectory is an efficient glide to the landing site with a glide path angle of about -14°.

The region before the ALPHA-transition is most interesting for inertial system alignment, since the high drag and possibly the end of the banked turn provide a strong horizontal component of specific force, which is needed for azimuth alignment. Also the forward velocity is rapidly dropping from about M=6 at 3950 sec to M=2 at transition. Low velocity means that the vehicle remains within the region of good measurement geometry for a relatively long time, permitting several redundant alignment measurements.

The inertial reference system for space operations uses a three-axis inertially fixed platform or strapped down inertial components. The optical star alignment before deorbit will provide an accuracy in the order of 0.5 mr RMS. Gyro drift during the next hour will augment the uncertainty per axis to about 1 mr RMS. Calibration of the accelerometers is not possible during the long period of free fall operations and scalefactor uncertainties of 200 ppm may be expected at the time of reentry. The problem of inertial system alignment consists therefore of reducing both the errors of angular alignment and of the scale factors of the accelerometers. In particular the tilt angles and vertical acceleration are important. Since in-flight alignment techniques provide only scalefactor information for the axis of the inertial force vector and since this vector is near local vertical, it is desirable to orient one inertial system axis near the vertical. A good estimate may then be obtained for the accelerometer on that axis.

The result of alignment updates can be compared in a system simulation with the true reference. However, what is more important than individual alignment errors is how the entire system will perform subsequent to such an alignment. Most likely an in-flight alignment will not be able to drive all system errors to zero, but a well-balanced state of the remaining system errors may be achieved. Testing of system alignment should, therefore, include a prolonged flight period after the alignment update, during which the navigation system is exposed to a typical acceleration environment. The position error at the end of this flight is the best measure for alignment performance. In case of the space shuttle the test is the navigation performance between the time of the last external system update and the time of arrival at the gate of the landing system.

6. Simulation of Reentry Alignment

Our reentry alignment simulation uses as controlling input data a trajectory of the space-shuttle generated by a guidance simulation. From the inertial position vector, which is considered the true reference, we compute in one branch the true specific force acting on the inertial sensors and in another branch the true ranges to the 3 transponders. This is graphically shown in Figure 9.

The inertial navigation sensors are assumed to consist of an accelerometer triad in an arbitrarily selected inertial reference orientation, which may or may not change with time. The accelerometer triad has a misalignment angle relative to the reference orientation and the triad may drift at a constant gyro drift rate. An initial bias and scale factor error can be introduced for each of the accelerometers. The inertial navigation state vector is computed from initialization and simulated accelerometer outputs. The gravity component of acceleration is based on the computed state vector.

An independent position vector is obtained in the transponder system branch by contamination of the three true ranges with Doppler quantization errors, propagation velocity errors and individual location errors of the three transponders. The position vector is then computed from the three simulated slant ranges. Inertial system state vector errors and position errors of the transponder system can be monitored relative to the true trajectory reference at any time.

Alignment computations start with an independent determination of the specific force vector from both the inertial and the transponder systems' sequence of four position vectors (in inertial reference coordinates). After the first two position measurements the inertial system state vector is updated with weighted transponder system position and velocity increments. After the fourth position measurement the difference in magnitude of the computed specific force vectors is used for weighted updating of the three accelerometer scale factors. The angle betweeen the specific force vectors is used to update the orientation of the accelerometer triad.

A number of such update sequences are used, depending on the available time. The last sequence, however, is shortened so that the final update is the one of the state vector. At this time the inertial navigation system is completely reinitialized and the on-board navigation continues without further inputs from the transponder system for the remainder of the flight trajectory. The true alignment errors are recorded after each update, and the true navigation errors are recorded before and after each update and during unassisted navigation.

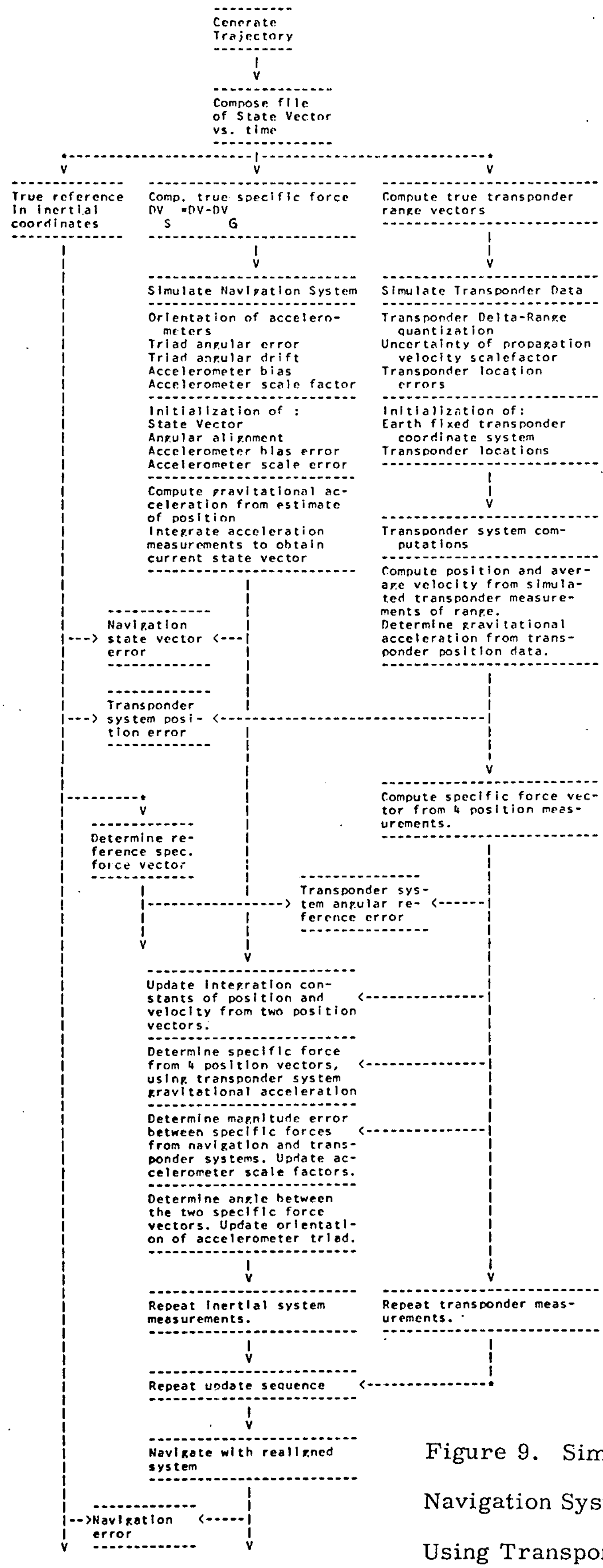


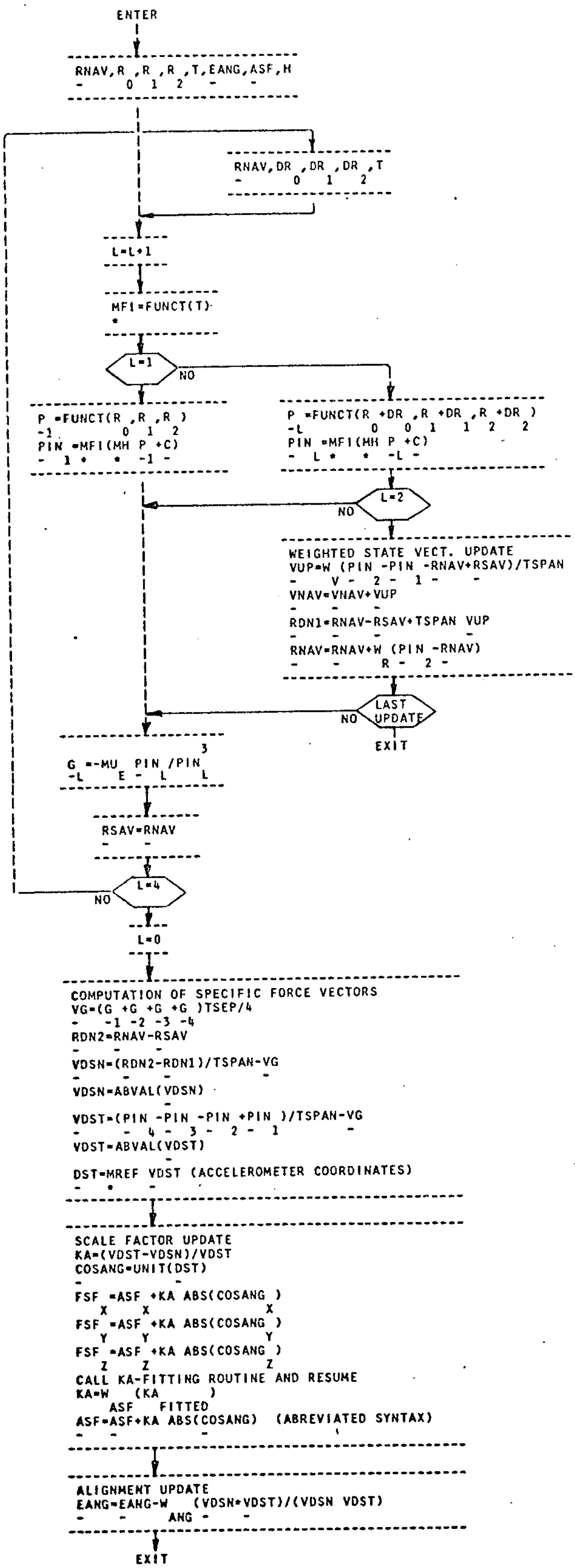
Figure 9. Simulation of Navigation System Alignment Using Transponders.

7. The Alignment Filter

The key to good in-flight alignment is the alignment filter. The external redundant measurements may be precise and relevant to the parameters which must be estimated, but there are frequently not enough diverse measurements available to resolve the resultant navigation error into its error sources. Other clues must be brought in, such as initial error estimates and the sensitivity of resultant errors to its contributors. The magnitude of the random measurement errors also must be considered. What makes matters worse is that the number of measurements and the time available for it is usually restricted by the vehicle velocity and the time the vehicle spends within a suitable transponder geometry. The alignment can never be better than the angular bias uncertainty of the externally measured specific force vector, which is very much dependent on the geometry.

The alignment filter comprises the alignment logic and the weighting functions for correction of indicated errors of the different system parameters. A flow diagram of the alignment logic selected for shuttle reentry or for atmospheric flight is given in Figure 10. Each entry into the routine results in four sets of transponder interrogations and a complete reinitialization of the inertial navigation system. The index L controls the four measurement cycles. The first transponder interrogation supplies the ranges to the three transponders. This is followed by three sets of differential range measurements. For L=2 the state vector of the navigation system is updated together with the navigation system's delta range RDN1. After the fourth measurement cycle the specific force vectors are determined from four position vectors of the navigation system and four position vectors obtained from transponder interrogation. (Note that in both computations the same gravitational Δv is subtracted, making this quantity not critical to the alignment computations.) The next operation is the updating of the accelerometer scale factors by fitting three independently weighted new scale factors to the indicated error of the magnitude of the specific force vector. The weighting of the three accelerometer scale factor updates is made dependent on the angles between the specific force vector and the accelerometer axes. The accelerometer axis nearest the vector gets heaviest weighting. The final update is that of the alignment angles. Different weighting must be applied for the three components of the rotation vector, depending on the angle BETA and on the likelihood of azimuth and tilt errors. (The angle BETA is between the specific force vector and the accelerometer x-axis, which is assumed to be near local vertical.)

Angular updating from an individual measurement of the specific force vector is ambiguous about the axis of the true specific force vector. As seen in Figure 4,



NOMENCLATURE

ASF	3 accelerometer scale factors used in navigation computations
C	Position vector of transponder #0 in earth fixed coordinates
COSANG	3 angle cosines between 3 accelerometer axes and the navigation system's specific force vector.
DR_0, DR_1, DR_2	Range difference measured to transponders
DSN	VDSN vector in accelerometer coord. system
EANG	3 error angles of accelerometer triad relative to reference coordinate system.
FSF	3 "floating" accelerometer scale factors
G	Gravitational acceleration vector
H	Index of navigation update
KA	Factor of accelerometer scale factor updating increment.
L	Index of Measurement routine
MH	Rotation matrix from transponder to earth fixed coordinates
MFI	Rotation matrix from earth fixed to inertial coordinates
MREF	Rotation matrix from inertial coordinates to accelerometer triad coordinates.
MU_E	Earth's gravitational constant
P	Position vector measured by transponder interrogation in transponder system coordinates.
PIN	Position vector measured by transponders in inertial coordinates
RDN1	Position difference for first pair of navigation measurements (updated), inertial coord.
RDN2	Position difference for second pair of navigation measurements, inertial coordinates.
R_0, R_1, R_2	Range measured to transponders.
RNAV	Position vector computed by navigation system.
RSAV	Previous navigation position vector (saved).
T	Time of measurements
TBET	Time between updates
TSEP	Time separating velocity measurements
TSPAN	Duration of Doppler counting (averaging time-span)
VDSN	Velocity difference computed from specific force measurements of navigation system.
VDST	Velocity difference computed from specific force acting on trajectory (measured by transponder system).
VNAV	Velocity vector computed by navigation system (inertial coordinates).
VSAV	Previous navigation velocity vector (saved).
VUP	Update of navigation velocity vector.
W_{ASF}	3 weighting factors for update of accelerometer scale factors
W_{ANG}	3 weighting factors for update of misalignment angles EANG
W_R	Weighting factor for position vector update
W_V	Weighting factor for velocity vector update.

NOTES: $W_R, W_V, W_{ASF}, W_{ANG}$ are functions of H.
RNAV is magnitude of RNAV, etc.
L starts at 0.

Figure 10. Navigation System Realignment During Shuttle Reentry.

there is an infinite variety of azimuth and tilt update combinations. The problem of ambiguity is overcome by using an update strategy which will cause the alignment angles to converge after a series of updates. For convergence about all three axes it is necessary that the orientation of the specific force vector changes with time. The strategy of three-axis alignment of the space-shuttle platform is shown in Figure 11. A weighting factor $\sqrt{WSQ}$ is introduced to enhance the less critical azimuth update over the two components of tilt update. The three angular updates are obtained by adding to the rotation vector ALFA a counter-rotation vector CROT in such a way, that the sum square of the three combined rotation components is a minimum. The vector CROT is parallel to the true specific force vector and represents the angular ambiguity of the update from one measurement. The minimum requirement defines the magnitude of CROT since the vector sum ALFA + CROT has only one minimum as shown in the figure. In the special case where WSQ=1, the vector CROT becomes zero and the update rotation degenerates into a three-axis rotation by ALFA. It should be noted that introduction of the ambiguous azimuth counter rotation CROT reduces the weight of the updates of both tilt angle components in a systematic way.

It is obvious that all the weighting factors are dependent on initial error estimates, number of updates, random errors of the measurements, sensitivity of the parameter to the measurement, and sensitivity of system performance to the parameter. As a practical conclusion the weighting function for velocity starts at unity and tapers to 0.1 in order to accomplish fast initial updates and good smoothing of the velocity differentials towards the end of the update sequence. Weighting of position errors is constant at 0.8 because of the high measurement accuracy and the low random errors. The angular alignment uses an initial weight of 0.8, tapering to 0.3 to provide smoothing of random errors. The weighting factor for azimuth preference was selected at WSQ=2, based on the relatively low sensitivity of the position output to azimuth errors. Weighting of accelerometer scale factor updates is a constant 0.1 in order to obtain effective smoothing of the relatively large measurement errors. All these values were determined empirically for the particular type of space shuttle trajectory discussed earlier.

This brings us to the point where a comparison with a Kalman filter cannot be avoided any longer. The Kalman filter approach is probably the most systematic analytical approach to parameter estimation from redundant data. Among others, Widnall and Morth,[1] Silver and Greenberg,[7] Hood and Buzzetti[8] have reported on alignment studies and on the optimal merging of inertial and radio type navigation information through the use of Kalman filters. There is usually a state vector of at least 10 elements required. A 10 by 10 covariance matrix must be propagated

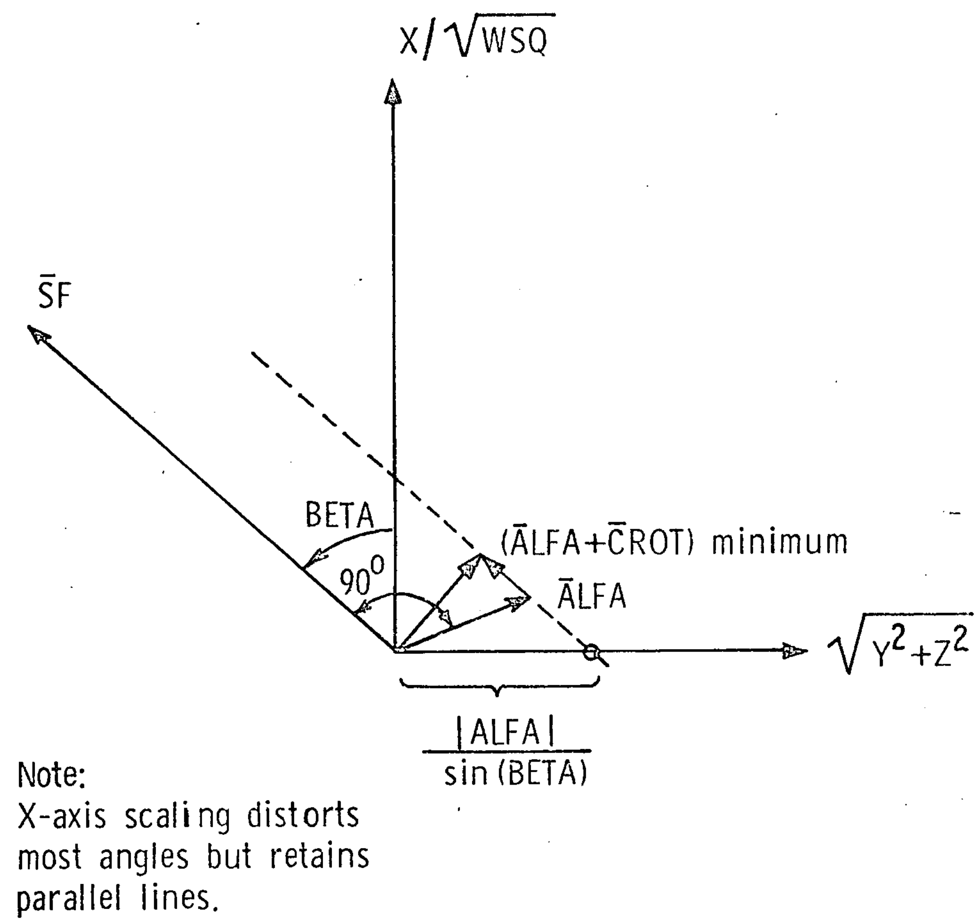


Figure 11. Geometry of 3-Axis Angular Update Weighting.

and an equivalent matrix inversion is required for the determination of the weighting matrix for the parameter updates. These computations are feasible with airborne computers and may yield the best solution to the problem, but the question is whether or not the burdens to the computer memory and the execution time requirements are justified. In particular, since the data from external sensors can provide relevant information for angular alignment only during the short time intervals for which good transponder geometry is available, it is a question whether one should not rather use a simple approximation to the optimal solution.

If we take a second look at the alignment filter just described for the space shuttle reentry, we find that actually all the elements of a Kalman filter approach are in evidence. The gradual reduction of the variance of the state vector elements is considered by the gradual reduction of the weighting of the parameter updates. The matrix inversion which establishes the sensitivity of the state vector to the measurement and the likelihood of state errors are replaced by judicial assignment of initial weighting factors, based on the experience with the effects of errors from different sources and the general properties of the flight trajectory. In effect we have considered a state vector of 12 elements and we have estimated the bias of the following parameters: 3 components of position, 3 components of velocity, 3 alignment angles and 3 accelerometer scale factors. We have not resolved the ambiguity between accelerometer biasses and misalignment angles since the type of external measurement is not suitable for this purpose. Our filter could possibly be improved, if we extended the state vector by a set of 7 elements and included estimates of the relative transponder position bias (4) and individual range measurement biasses (3). But the data rate and measurement accuracy of external data appears to be near the limit imposed by atmospheric propagation disturbances and only slight improvements could be expected.

8. Space Shuttle Simulation Data

Updating of IMU angular alignment and accelerometer scale factors with external radio data is of interest only if autonomous inertial navigation is desired past the update cycle. In the case of the space shuttle reentry we must expect that at lower altitudes the radio navigation aids may temporarily drop out or fail, and navigation will then depend on the self-contained on-board system for the remaining few minutes of the flight. Navigation during this time must be accurate enough that the landing guidance system can be reached safely. This system can be acquired by the shuttle anywhere between 30 and 8 kilometers from the runway threshold.

A typical IMU updating sequence obtained in our simulation is shown in Figure 12. The initialization of the system parameters is the same as given in Table 3 for the corresponding navigation simulation. The orientation of the accelerometer package is inertially stable and the x-axis is vertical at 4245 sec, the y axis points south, and the z-axis points east. The shuttle is at this time leaving the transponder triangle and about to commence ALPHA-transition.

One will notice that y and z-axis alignment converge gradually towards zero error, but that the x-axis or azimuth alignment is thrown off towards a 1.5 milliradian error. This divergence is the result of the angular alignment ambiguity about the measured specific force vector, and of the updating strategy used in the alignment filter. Before ALPHA-transition the specific force vector is at an almost constant inclination of 20°. After transition the vector is approximately vertical and does not provide any further information about azimuth alignment. It is important that the azimuth alignment stays within tolerable bounds for subsequent navigation.

The updating of the accelerometer scale factors is effective only for the accelerometer near the axis of the specific force vector. The scale factor of the vertical accelerometer converges readily, but there is little or no relevant input available for calibration of the two horizontal accelerometers.

The initial angular alignment errors were picked to correspond to the worst expected combination, which would result in crosscoupling into other axes. Equal RMS errors of 1 mr were assumed for each axis. The 3 mr initialization error about the y-axis represents a 3 sigma value. If the axis of a dominating misalignment is known, it is possible to reduce the error about that axis effectively with a minimum of crosscoupling into the other axes. This was demonstrated with many simulations using different alignment strategies.

The performance of the navigation system after in-flight alignment was tested by arbitrarily breaking off the alignment after eight updates. This left 400 seconds and a distance of 100 km of unaided navigation to the landing area. As seen in Figure 12, the cutoff of radio data is before ALPHA-transition. Results from three simulations with extreme sets of initializations are given in Tables 3 and 4. The first section of Table 3 lists transponder system initializations. Note that the baseline dimensions correspond to Figure 8. A relative position error of three meters of the #2 transponder was combined with a relative ranging error from the #1 transponder. This combination of errors sources dominates over other possible contributions by transponder system parameters. Initialization of the navigation

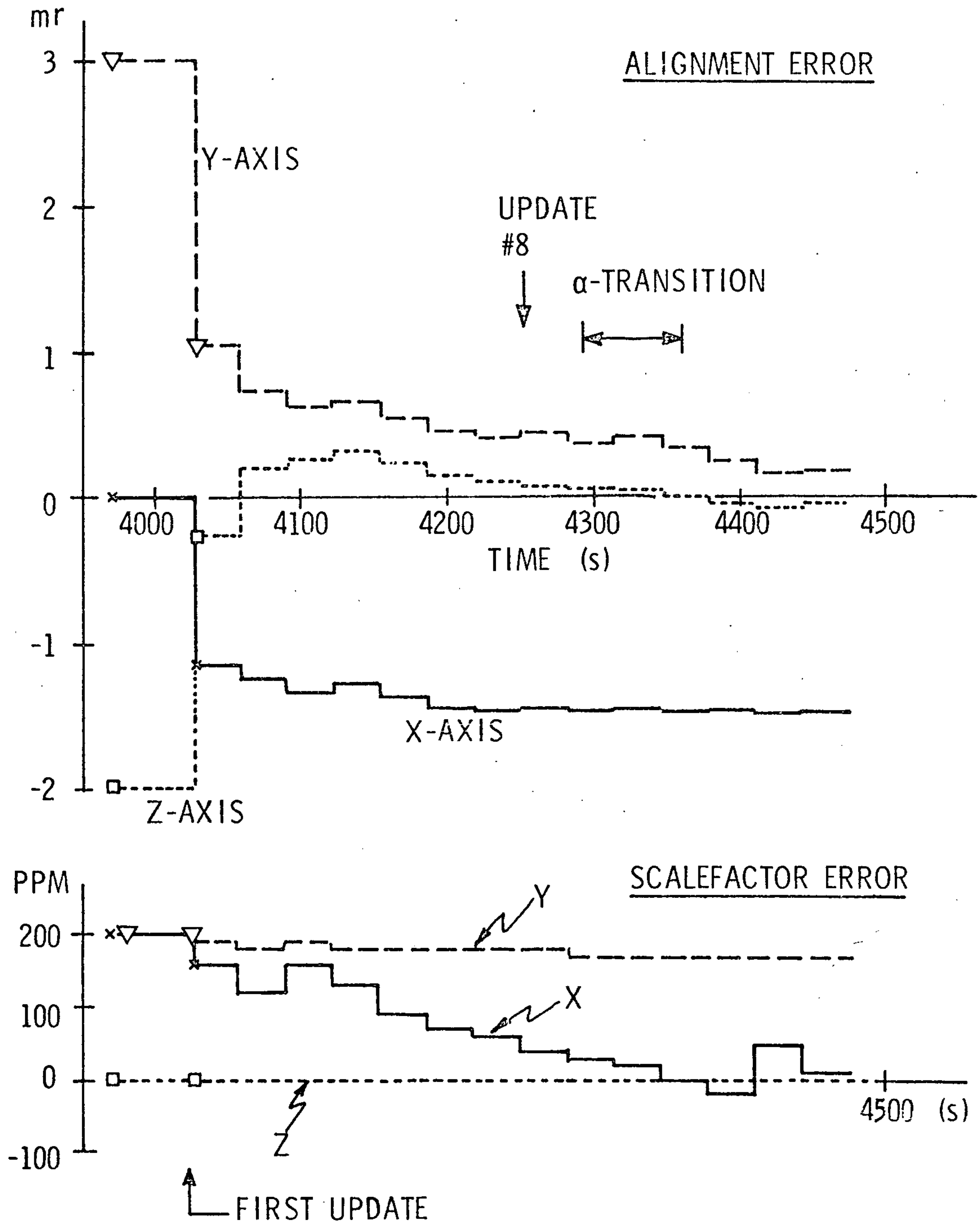


Figure 12. Space Shuttle, Updating of IMU Parameters After Reentry Blackout.

Table 3. Space Shuttle, Alignment after Reentry Blackout

Transponder system initialization

Doppler counting interval	10 sec
Separation of velocity measurements	18 sec
Separation of updates	31 sec
Doppler quantization error	0.1 m
Baselines y and z	77.922, 63.522 km
Transponder position errors	
#2 downrange	3 m
Propagation velocity bias	
#1 transponder	$+10^{-5}$

Navigation system errors

	Initialization	After 8 updates	End of flight
Time	3900 sec	4258 sec	4658 sec
Gyro drift rate	neglected		
Alignment angles	0, 3, -2 mr	-1.4, 0.41, 0.17 mr	same
Accelerometer bias	0.05, -0.05, 0(cm/s^2)	(part of angular alignment)	
Acc. scale factors	200, 200, 0 ppm	-70, 150, 0 ppm	same
Position (fixed earth coordinates)			
Height*		1 m	16 m
Crossrange	<50 km	-3 m	-290 m
Downrange		0 m	-75 m
Position without IMU updates (1 position/vel. update)			
Height*		225 m	948 m
Crossrange	<50 km	-226 m	-1795 m
Downrange		311 m	2637 m

Table 4. Space Shuttle, Alignment after Reentry Blackout

Navigation system errors (alternate initialization)

	Initialization	After 8 updates	End of flight
Time	3900 sec	4258 sec	4658 sec
Alignment angles	3, 1, -1 mr	1.7, -0.6, -0.17 mr	same
Acc. scale factors	200, 200, 0 ppm	-70, +150, 0 ppm	same
Position (fixed earth coordinates)			
Height		+2 m	-1 m
Crossrange		-1 m	316 m
Downrange		-1 m	-146 m
Position without IMU updates (1 position/vel. update)			
Height		106 m	546 m
Crossrange		-222 m	-925 m
Downrange		83 m	1111 m
Position, RMS of 3 initialization alternatives			
Height			10.5 m
Crossrange			354.0 m
Downrange			105.0 m
Position without IMU updates (1 position/vel. update)			
Height			632.5 m
Crossrange			1166.0 m
Downrange			1801.0 m

*Note: No altitude updates after last position fix.

system is indicated in the first of the three data columns under navigation system errors. After eight updates the most important alignment of pitch and roll angles (local vertical) has substantially improved, as have the scale factors of the vertical and downrange accelerometers. The most dramatic quantity is the position accuracy at the end of the updating sequence, but such accuracy (better than 3 m) is to be expected from the combined inertial and radio navigation systems for the time that precision range measurements are received.

After the inertial system is again on its own, position errors propagate mainly because of platform tilt errors, resulting in misinterpretation of the lift vector. In the vertical direction the error propagation is caused by initial velocity uncertainty and the x-axis accelerometer scalefactor. At the end of 400 seconds of unaided navigation the position error propagated to 16 m in height, -290 m crossrange and -75m downrange. It should be noted that height updates were based on transponder measurements only, and there was no input from a barometric altimeter considered. These navigation errors of the updated inertial system with in-flight angular alignment appear to be compatible with initialization requirements of typical landing guidance systems.

The bottom section in Table 3 provides comparative navigation data for the same initialization of the inertial system, but with only one position and velocity update 400 seconds before flight termination. The position error at the time of the update is substantial, because radio position data were weighted only at 80%. However, position initialization errors of a few hundred meters act as an additive component only in the propagation of position errors. The all important velocity update (not shown) was weighted at 100%, giving the system velocity initialization equal to the previous case. The propagation of horizontal position errors of the system without IMU angular alignment is about 10 times larger than the previous case and could not be tolerated by the landing guidance system.

Table 4 gives additional data on navigation performance with another set of initial alignment errors. At the bottom a comparison is made of navigation errors with and without IMU updates by averaging the errors from 3 extreme simulations. In flight IMU alignment will improve the horizontal navigation error by a factor of 6 and the altitude error down to the accuracy of a barometric altimeter. It will permit the approach to the landing guidance system (ILS, MLS) without further use of radio navigation aids for the last 400 seconds.

9. Conclusions

In flight angular alignment of an IMU (inertial measurement unit) and calibration of the accelerometer scale-factors can be accomplished with the aid of precise external range and delta-range (Doppler) measurements. Two categories of external navigation aids have been considered, a three-dimensional ground-transponder system and a two dimensional surface navigation system. The three-dimensional system has the advantage of providing relevant data for complete system reinitialization but is critical with regard to the parameters which define the measurement geometry. The two-dimensional system depends on other instrumentation for the definition of height and cannot provide updates of vertical accelerometer scale factors. Both external systems are critical with regard to the velocity (or range rate) measurements and the time correlation of the external measurements with the IMU derived acceleration data.

The application of the transponder alignment concept to the reentry of the space shuttle demonstrates that the concept works even under such adverse conditions as limited observation time of 4 minutes and with little change in the direction of the specific force vector. The concept has been found more effective during the launch of the space shuttle and in a conventional flight application, where a special alignment maneuver was flown by the aircraft. The flight trajectory in this latter application is shown in figure 13. In the region of the transponder system the aircraft flew an open triangle at standard turn rates to effect changes of the direction of the specific force vector. During this maneuver it was possible to reduce the initial azimuth misalignment of 10 mr effectively, as shown in figure 14. Crosstalk into tilt alignment was subsequently removed during the straight and level flight portion. After completing the radio update sequence, the aircraft made a 90° turn and continued with pure inertial navigation for 16 minutes. The navigation errors at the end of the flight were 124, -131, -50 meters in height, crossrange and downrange respectively (see table 5). This typical performance shows better than anything else that in conjunction with proper radio aids the operational features and accuracy of inertial navigation systems can be substantially improved.

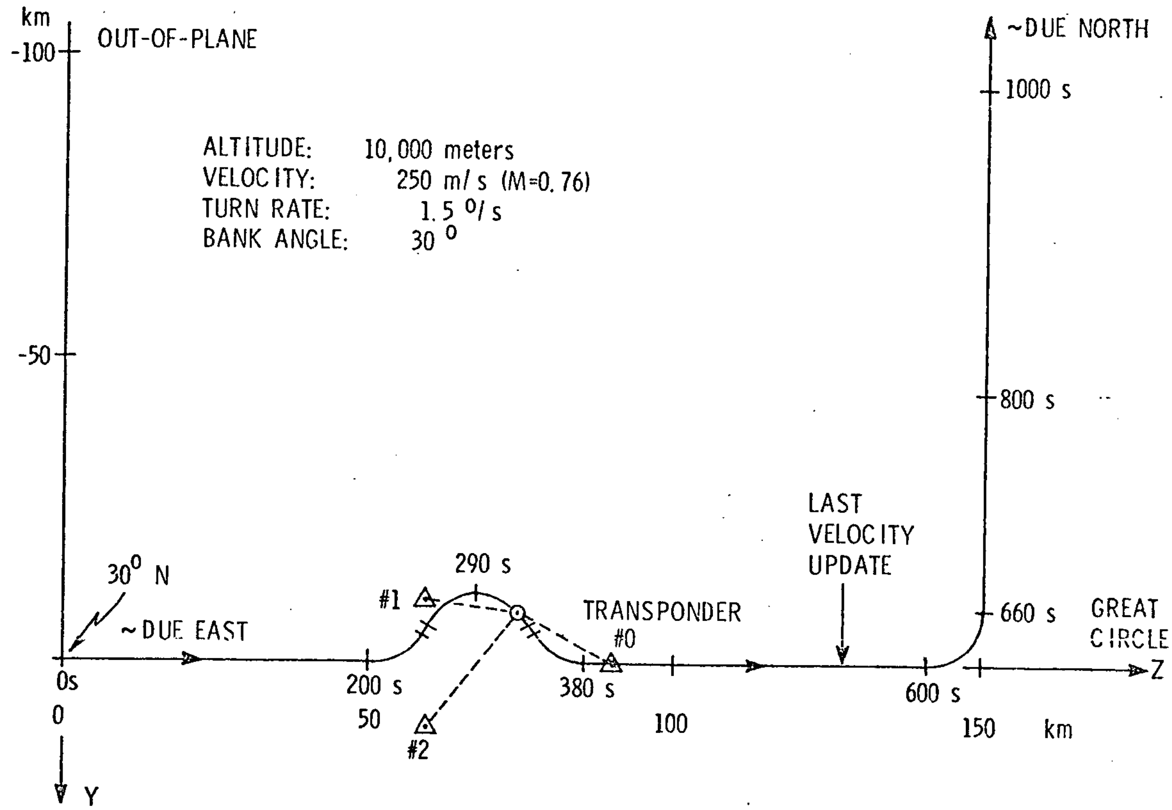


Figure 13. Test Trajectory with Open Triangle for Alignment.

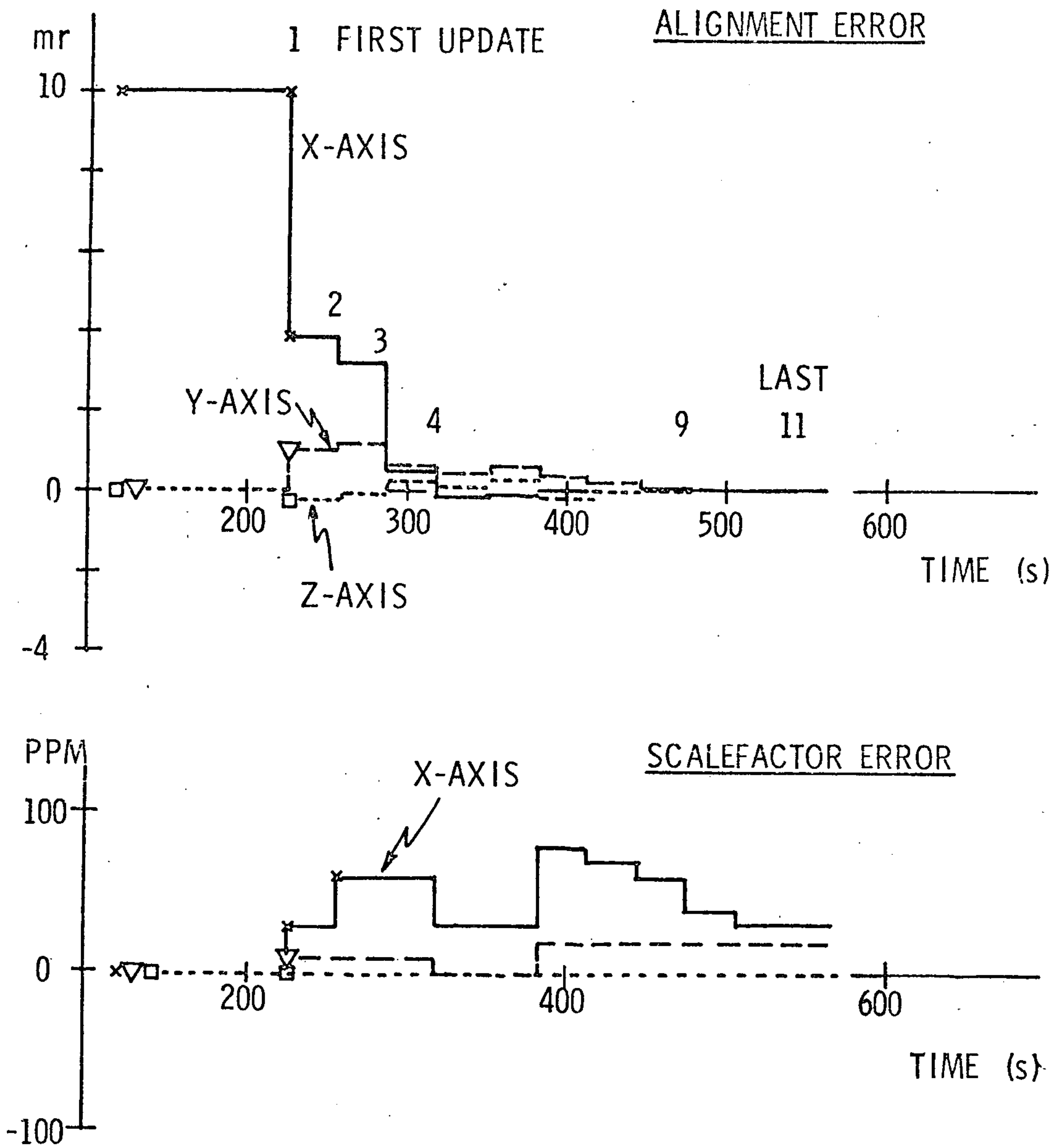


Figure 14. Atmospheric Flight. Updating of IMU Parameters with Special Alignment Maneuver.

Table 5. Atmospheric Flight, Alignment using Open Triangle Maneuver

Transponder system Initialization

Doppler counting interval	10 s
Separation of velocity measurements	20 s
Separation of updates	31 s
Doppler quantization error	0.1 m
Baselines y and z	20.5/30.8 km
Transponder position errors	
#1 downrange	2 m
Propagation velocity bias	
#0	50 ppm
#1	50 ppm
Range bias	
#1	1 m
#2	-1 m

Navigation system errors

	Initialization	After 11 updates	End of flight
Time	0 sec	536 sec	1497 sec
Gyro drift rate	neglected		
Alignment angles	10, 0, 0 mr	0.10, 0.02, 0.01 mr	same
Accelerometer bias	0, 0, 0 m/s^2		
Acc. Scale factors	0, 0, 0 ppm	30, 20, 0 ppm	same
Position (fixed earth coordinates)			
Height*	<10 km	2.6 m	124 m
Crossrange	<10 km	0.8 m	-131 m
Downrange	<10 km	-2.1 m	-50 m

*Note: No altitude updates after last position fix.

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