ARTICLE NO. 80-4118

Cruise-Missile-Carrier Navigation Requirements

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This paper addresses the modeling, simulation, and performance predictions used in determining aircraft avionics and transfer-alignment requirements for a generic aircraft that would launch cruise missiles over water, a considerable distance from a first TERCOM (terrain comparison) update area. Such would be the case for an undefended wide-body aircraft that must remain far away from an opponent's air defense system. This long standoff range presents some unique requirements that are not present in a mission where cruise missiles are launched "close" to the first fix point, as from a penetrating bomber. The methodology used and the system requirements' results are described.

I. Introduction

THIS paper describes the methodology and results of a parametric study conducted to determine the navigation requirements for cruise missile (CM) carrier aircraft (CMCA) candidates.[1] Section II of this paper describes the methodology used in allocating the allowable navigation errors between the CM guidance system and the CMCA avionics system. From this baseline error allocation, avionics and transfer-alignment tradeoff studies were conducted. These tradeoff studies are described in Secs. III and IV, respectively. In Sec. V, a total weapon-system evaluation from aircraft takeoff to CM impact is presented which validates the error allocation of Sec. II for the models assumed in the study.

II. Methodology for Baseline System Error Allocation

To initiate the CMCA avionics tradeoff portion of the study, it was necessary to define a baseline mission for both the CMCA and the CM, and to allocate the errors between each navigation system to meet the total required accuracy at the first TERCOM (terrain comparison) update area. The baseline mission is summarized in Fig. 1.

The mission begins with a fast-reaction takeoff from the U.S. with the CMCA inertial navigation system (INS) dormant and unheated at takeoff. During the next 30 min, the attitude heading and reference system and a doppler radar are used to dead-reckon to the nominal site of the first radar position fix while the CMCA INS is being powered up and thermally stabilized. Near that first radar fix, the CMCA INS is initialized from the dead-reckoning system and then begins navigating after the fix has been made. Nominally, a total of eight equally spaced radar fixes are made during the overland portion of the outbound flight so that the CMCA INS is satisfactorily aligned prior to beginning its long overwater flight to the CM launch area.

During overwater flight, the CM INS's are powered up at least 45 min before transfer alignment and calibration to allow thermal stabilization. The transfer-alignment/calibration sequence is performed within a 30-min period prior to launch of the first missile. The assumption, based on Air Force requirements, is that only one horizontal CMCA maneuver will be used during this 30-min period to aid the

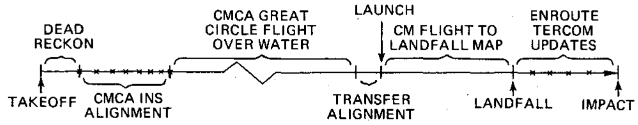

Fig. 1 Baseline mission evaluation.

alignment filter. Following completion of transfer alignment and calibration, the CM is launched while it is still a considerable distance from the first TERCOM update area. The CM, immediately after launch, descends to a low altitude and executes a maneuver to bring it to its proper course; then it proceeds to navigate to the first landfall map. A representative CM flight path is shown in Sec. V.

The calibration of the CM guidance set is a particularly important aspect of the transfer-alignment mechanization. Table 1 lists the gyro and accelerometer performance parameters for the CM guidance set after a 2½-yr dormancy period.[2] Even if the CM guidance system was provided with perfect initial conditions by the CMCA INS, these performance parameters would result both in a system error growth rate on the order of 16 n.mi/h and in a totally unacceptable position error at the nominal first update area. (A 0.01-deg/h gyro drift results in about a 1.0-n.mi./h error growth rate.) Consequently, the methodology of the study was to first evaluate how well transfer alignment and calibration might be performed; then, to allocate the errors between CMCA avionics and transfer alignment; and finally, to perform detailed studies within each allocation to determine if the allocations could be met. Then, the overall system must be evaluated to verify the error allocations.

The method of assessing the possible accuracy from transfer alignment is to perform a covariance analysis based on a complete 40-state truth model of the CM navigation-system errors, assuming an error-free CMCA navigation system. Position differences between the two systems are compared and processed in a filter to estimate the CM INS parameters. A full 40-state optimal filter would lead to optimistic results since, in practice, only about 10 important error states would be implemented in the CM computer. Consequently, a "consider-variable" appproach is used in the analysis which allows an estimate of how a well-designed reduced-order filter might perform; this approach alleviates the need to actually design a reduced-order filter.[3-5] Table 2 illustrates the consider-variable approach.‡

This technique was applied to the transfer-alignment problem. Figure 2 illustrates the results of transfer alignment and calibration performed relative to the assumed-perfect

Received Aug. 20, 1979; revision received March 5, 1980.

Index categories: Guidance and Control; LV/M Guidance; Missile Systems.

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‡Reference 6 contains a typical covariance-analysis program.

Table 1 Inertial instrument parameters

Parameter	Units	Acceptance value (1 σ)	30-month turn-on value (1 σ)
Gyro:			
Drift	deg/h	0.02	0.16
Random drift[a]	deg/h	0.005	0.005
g-sensitivity	deg/h/g	0.05	0.11
Scale-factor error	%	0.05	0.11
g^2-drift	deg/h/g^2	0.02	0.02
Misalignment	arc-sec	120	120
Accelerometer:			
Bias	μg	500	640
Scale-factor error	%	0.05	0.11
Misalignment	arc-sec	60	60

[a] $\tau = 100$ s.

Table 2 Consider-variable covariance analysis

System model:	$x(t_K) = \Phi x(t_{K-1}) + \Gamma w$
Measurements:	$z(t_K) = Hx(t_K) + v$
Statistics:	$\mathrm{cov}(x(0)) = P(0)$
	$\mathrm{cov}(w) = Q$, $\mathrm{cov}(v) = R$
Propagation:	$P^- = \Phi P^+ \Phi^T + EQ\Gamma^T$
Optimal gain:	$K = P^- H^T [HP^- H^T + R]^{-1}$
Suboptimal gain:	Appropriate rows of gain matrix, corresponding to those states that would not be estimated in the implemented filter, are zeroed. With that modified K, update $P^+ = [I - KH]P^- [I - KH]^T + KRK^T$

CMCA inertial system, while the aircraft was performing a 4-min coordinated 0.5-g horizontal S-turn maneuver 15 min into the transfer-alignment period. Cases 2, 3, and 4 correspond to different measurement noises in the position-match filter used for transfer alignment between the INS's. The measurement noise would be due to local vibrations, bending, and flexure between the INS locations. Case 3, corresponding to a noise of 1-ft rms, would probably exceed the levels to be expected in any of the aircraft considered. Consequently, case 3, a CM navigation performance of 1.0 n.mi./h (CEP) relative to the CMCA INS, was chosen as the baseline performance that should be established as a goal for transfer alignment and calibration of the CM guidance set. (The choice of position, rather than velocity, matching was based on a desire to use the same CM filter as for TERCOM position updating.)

Section IV will consider the various aspects of transfer alignment and calibration in detail in an attempt to meet the goal of a calibrated CM INS whose errors grow at a rate on the order of 1 n.mi./h with respect to the CMCA INS error growth rate. Figure 2 also illustrates that a key parameter is the azimuth-gyro bias term that exists after transfer alignment and calibration have been completed. Case 2 was rerun with a perfect azimuth gyro, and the differences in performance are quite noticeable. In fact, as illustrated in Fig. 3, a significant error growth rate appears due to the azimuth gyro alone if the gyro is uncalibrated. Consequently, for long-range air-to-ground weapons using this guidance system, adequate calibration of the azimuth gyro is required if the 1-n.mi./h (CEP) relative error growth rate is to be met.

Given the requirements on navigation accuracy ($\mathrm{CEP_{LF}}$) at the first TERCOM map, and using the expected CM INS relative navigation-error-rate performance ($\mathrm{CEPR_{CM}}$) of 1 n.mi./h and the time the CM must fly to the first map, it is then possible to determine an approximate expression [Eq. (1)] for the required CMCA navigational accuracy:

$$\mathrm{CEP_{LF}} = [\mathrm{CEPR^2_{CM}}(t_{\mathrm{LF}} - t_{\mathrm{L}})^2 + \mathrm{CEPR^2_{CMCA}}(t_{\mathrm{LF}} - t_{\mathrm{OF}})^2]^{1/2} \tag{1}$$

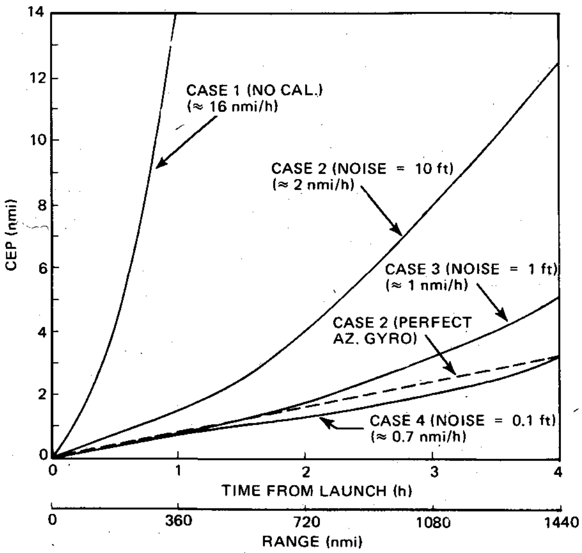

Fig. 2 Impact of transfer alignment/calibration on missile performance.

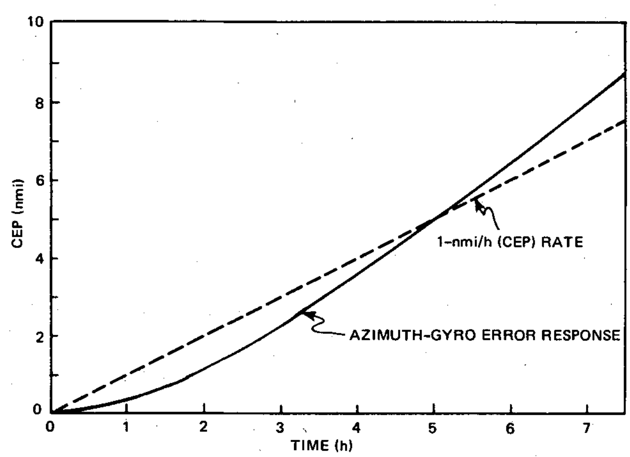

Fig. 3 Response to azimuth-gyro bias of 0.1 deg/h (1 σ) flying northwest great circle at 600 ft/s constant velocity.

where

$\mathrm{CEP_{LF}}$	= required CEP (n.mi.) at first TERCOM update area after CM launch
$\mathrm{CEPR_{CM}}$	= relative error growth rate of CM INS (nominally 1 n.mi./h)
t_{LF}	= time at first TERCOM update (h)
t_{L}	= time of CM launch (h)
$\mathrm{CEPR_{CMCA}}$	= error growth rate of CMCA INS, n.mi./h
t_{OF}	= time of last position update of CMCA INS (h) (position update is assumed perfect) and also note that
t_{OW}	= $t_{\mathrm{L}} - t_{\mathrm{OF}}$, the overwater time of the CMCA during which there are no updates to the CMCA

A covariance analysis of the complete interactive two-system transfer-alignment process was used to verify that Eq. (1) is a close approximation to the true $\mathrm{CEP_{LF}}$ if the initial CM INS uncertainties are significantly (10 times) larger than those of the CMCA INS, as is the given situation. Otherwise, significant correlations would need to be included and Eq. (1) would be invalid.

From Eq. (1), the maximum allowable range of the CM from launch to landfall fix can be traded off against CMCA INS quality for various overwater CMCA flight times (i.e., time since last CMCA position fix); see Fig. 4 for three dif-

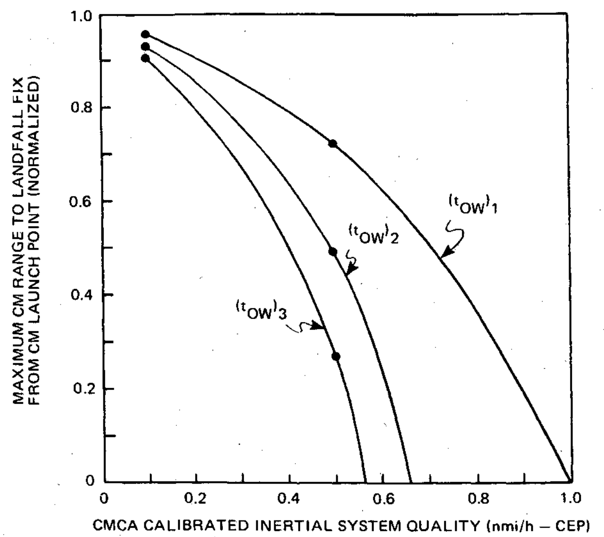

Fig. 4 CM range vs CMCA calibrated INS quality for three overwater flight times from last CMCA outbound fix.

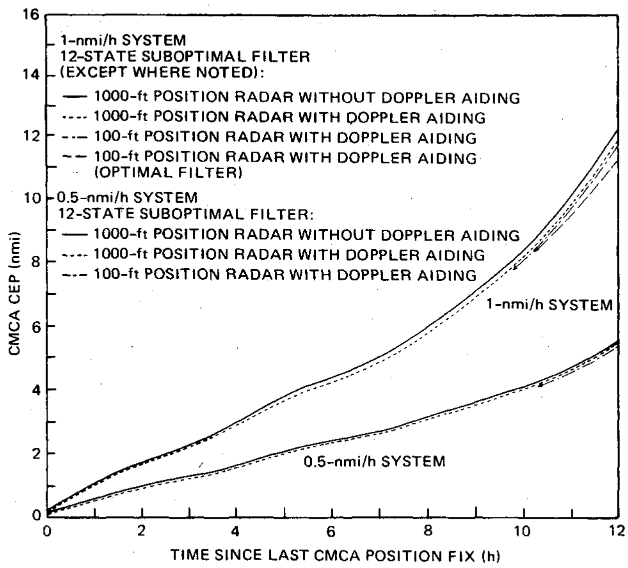

Fig. 5 Impact of performance to avionics using baseline fixes (8 fixes).

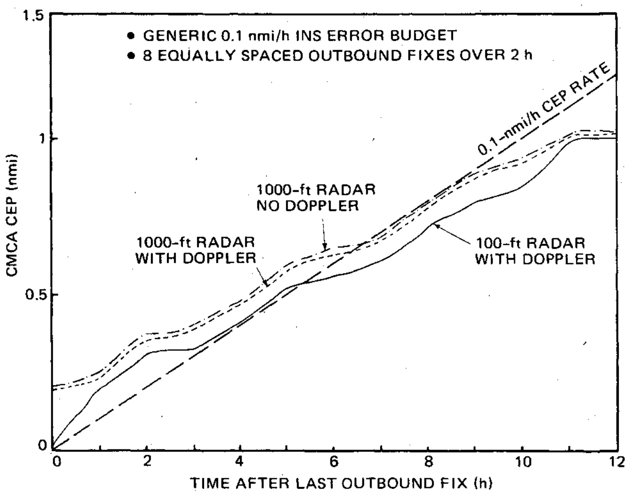

Fig. 6 Impact of avionics on baseline mission.

ferent flight times (t_{OW}). For the purposes of this paper, a nominal 0.5 n.mi./h (CEP) has been selected for the CMCA navigation system. This CMCA performance allows several missile standoff ranges as a function of the overwater flight times. In Sec. III, the avionics requirements to achieve that goal are presented.

It should be noted that this study addressed only the position error required to cross the first TERCOM map. No requirements were studied for acceptable downrange or crossrange velocity errors, azimuth errors, etc., at the first map, the assumption being that an acceptable fix could be made if the CM overflew the map.

III. Methodology of CMCA Avionics Tradeoffs

To select a set of CMCA avionics meeting the baseline error allocation of 0.5 n.mi./h (CEP) after the last CMCA outbound fix, a consider-variable approach was again used. A 12-state suboptimal filter consisting of north and east position and velocity errors, three INS attitude errors, three gyro biases, and two doppler errors was used during the outbound CMCA flight to perform CMCA in-flight alignment and calibration after the cold start of the CMCA INS.

Using the various avionics suites for the overland outbound CMCA flight, the resultant error propagation for three generic INS's has been plotted in Figs. 5 and 6. It should be noted that for the cases employing doppler aiding, doppler aiding is shut off after the last outbound fix so that for all cases the INS operates in the pure inertial mode (with the exception of altimeter aiding) during the overwater flight. This avoids having to model ocean currents, and the inaccuracy of doppler data over water makes doppler data of marginal benefit. The cases with doppler aiding refer to the use of doppler aiding up to and during the position-fixing portion of the baseline mission.

The results presented point to an obvious conclusion that the CMCA performance after the last outbound fix is practically insensitive to improvements in the position-fixing radar and doppler aiding between fixes for the baseline mission. This insensitivity is due to the fact that even with a moderately accurate position-fixing radar (1000-ft CEP), eight fixes are enough to estimate the alignment of the platform and to trim the sensor biases to the levels limited by random drifts and nonobservability.

Figures 7 and 8 show the time histories for the calibration of the azimuth error and north gyro bias, respectively, during the outbound CMCA flight using the 0.5-n.mi./h-CEP navigator and no doppler aiding. These plots show that using a higher accuracy radar allows faster calibration and alignment of the platform. However, given a reasonable number (≥ 4) of fixes over a 2-h period, the end result remains the same.

Figure 9 shows the impact of the position-fixing radar accuracy on CMCA performance when the number of equally-spaced outbound radar fixes and length of time for alignment are reduced. The figure charts the CMCA CEP 8 h after the last outbound fix for the generic 0.5 n.mi./h-CEP navigator. Figure 10 is a time history of error propagation when a 2000-ft-CEP radar is used for outbound position fixing. Note that in both Figs. 9 and 10, no doppler aiding is employed between position fixes. Both figures illustrate the need for more accurate position-fixing radars if the time and number of outbound fixes are reduced from the baseline. It does appear, however, that as long as six outbound fixes are available over a 1½-h period, adequate CMCA INS alignment can be achieved using a 2000-ft-CEP radar alone.

Figure 9 also shows that four outbound fixes in a 1-h period using a 1000- to 2000-ft-CEP radar are not adequate to align the 0.5-n.mi./h INS to the 0.5-n.mi./h (CEP) level using only radar fixes. However, Fig. 11 shows that the addition of doppler aiding between four outbound 2000-ft radar fixes permits further calibration and alignment of the CMCA INS down to the 0.5-n.mi./h (CEP) level. What doppler aiding provides is best illustrated in Fig. 12, which is a plot of azimuth misalignment estimation during the outbound fixes.

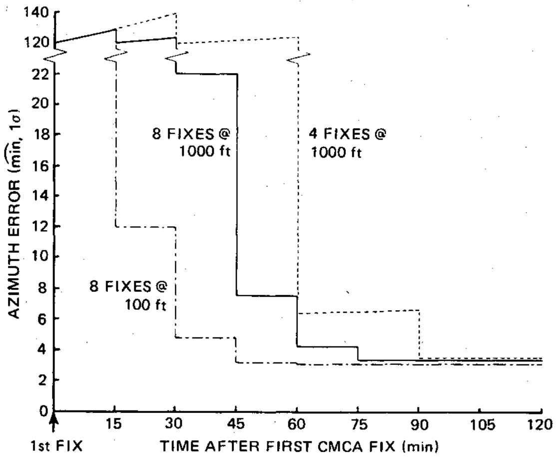

Fig. 7 CMCA azimuth error calibration (0.5-n.mi./h system).

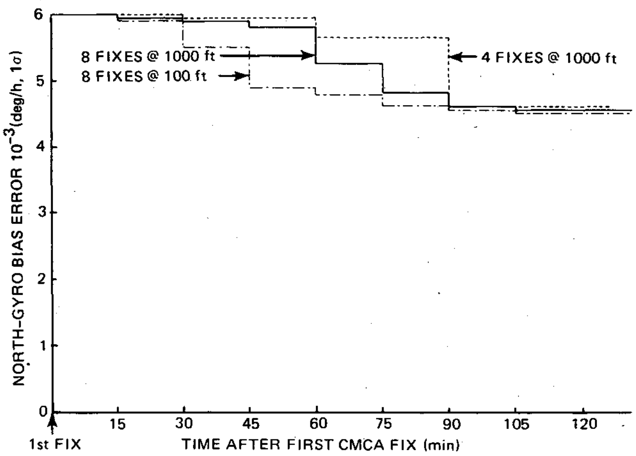

Fig. 8 CMCA north-gyro bias calibration (0.5-n.mi./h system).

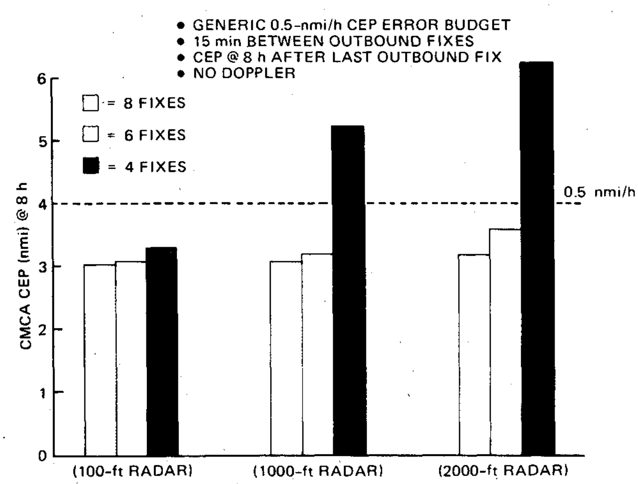

Fig. 9 Impact at 8 h of reducing the number of equally spaced outbound position fixes.

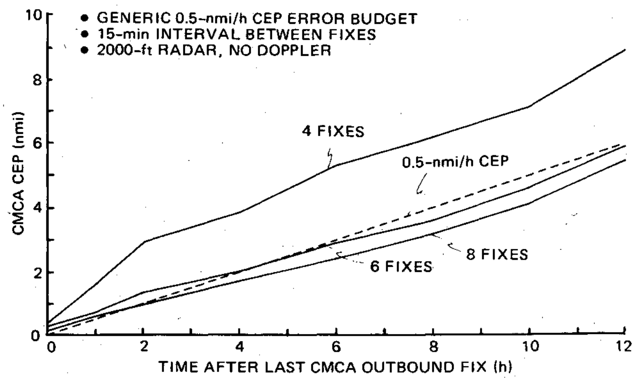

Fig. 10 Impact of reducing the number of equally spaced outbound position fixes.

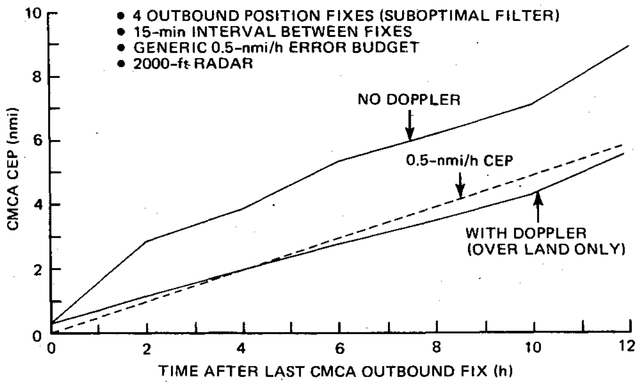

Fig. 11 Impact of doppler aiding on CMCA INS performance.

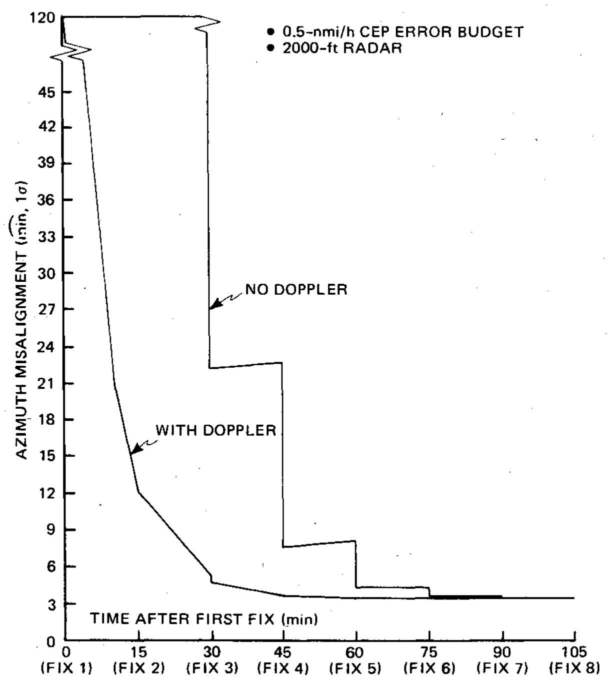

Fig. 12 CMCA azimuth misalignment calibration.

Doppler aiding enables faster azimuth estimation so that by the fourth fix, the steady-state estimation level has been reached; whereas without doppler aiding, two more fixes are required.

Similar results were observed using a better quality 0.1-n.mi./h (CEP) navigator. The impact of reducing the time and number of equally spaced outbound fixes for this navigator is shown in Fig. 13. Again, the importance of doppler aiding when the number of fixes is reduced is clearly shown. It is noteworthy, however, that by using the higher quality navigator, no doppler aiding, and a 1000-ft-CEP radar, an acceptable error growth rate of 0.5 n.mi./h (CEP) can still be achieved with four fixes in 1 h. Thus, higher quality navigators provide the flexibility of reducing TERCOM map widths or, as an alternative, may provide for reducing the number of outbound radar fixes, particularly with doppler aiding in use.

Figure 14 illustrates the required TERCOM landfall map widths vs CMCA INS quality. If the baseline map width is

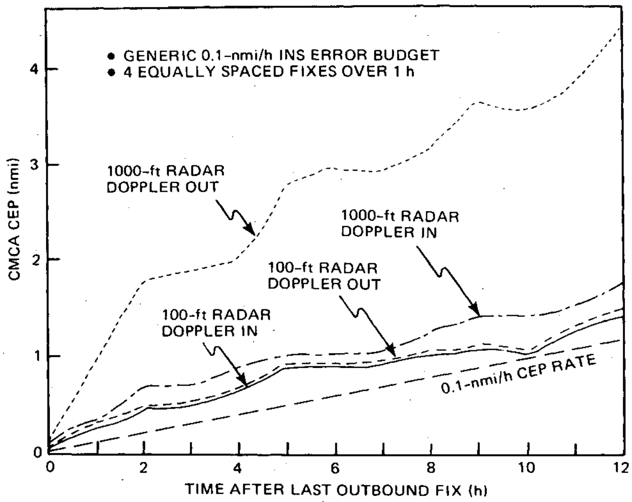

Fig. 13 Impact on avionics when the number of outbound fixes is reduced.

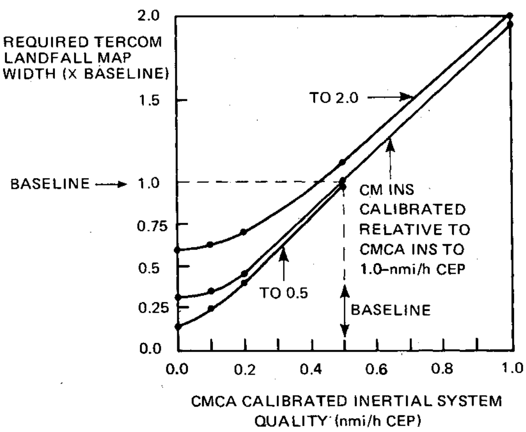

Fig. 14 Required TERCOM landfall map widths vs CMCA INS quality.

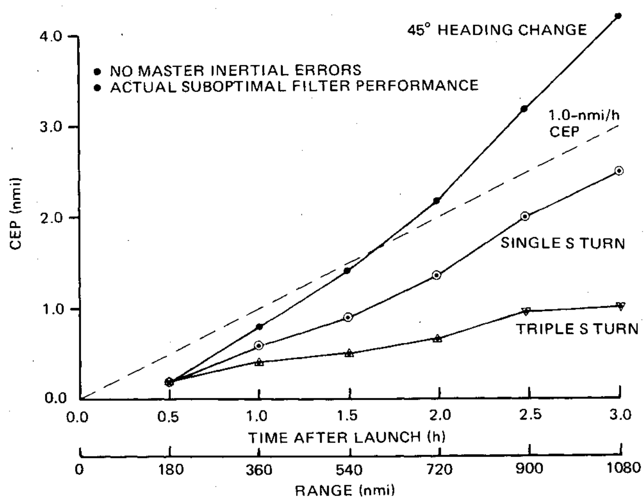

Fig. 15 CM CEP vs time (range) after launch for a 45-deg-heading change, single S-turn, and triple S-turn alignment maneuvers.

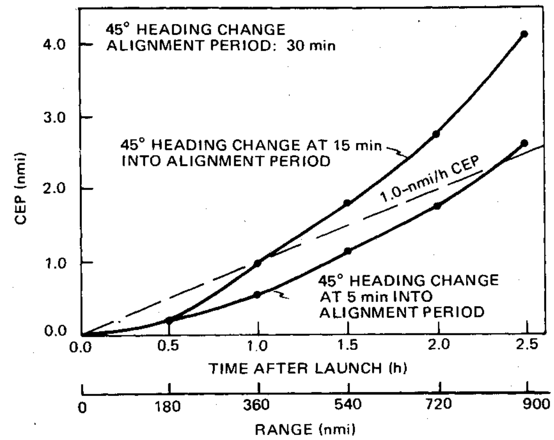

Fig. 16 CM CEP vs time (range) launch for 45-deg-heading change maneuvers executed at 15 and 5 min into a 30-min alignment period.

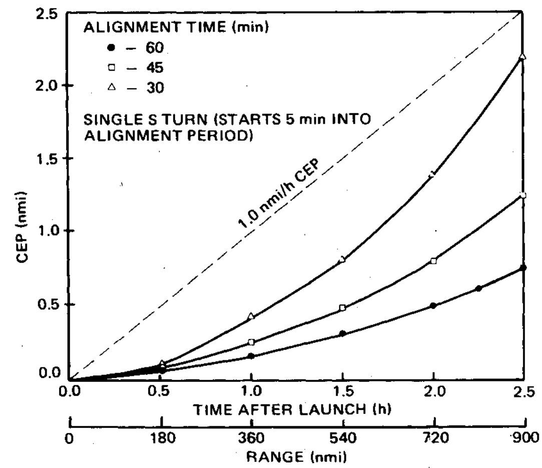

Fig. 17 CM CEP vs time (range) for 60-, 45-, and 30-min alignment periods.

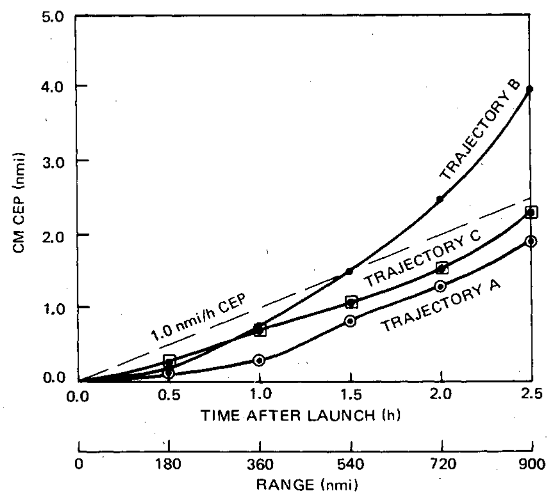

Fig. 18 CEP vs time (range) after launch for CM trajectories A, B, and C.

reduced by a factor of 2, then the requirement on the CMCA INS is on the order of 0.2-0.3, n.mi./h (CEP) if the CM INS is relatively calibrated to 1.0 n.mi./h. There is an advantage to using smaller map widths, in that onboard storage and computation is minimized for the CM, and it is also likely that many more suitable map areas with the appropriate terrain statistics over the entire TERCOM map would be available for use in updating.

For the baseline CMCA mission, the requirements for CMCA avionics can easily be met by state-of-the-art INS's, doppler radars, and position-fixing radars. Consequently, technology issues are not the key issues in selecting the CMCA avionics suite; rather, the key issues are cost, nuclear hardness, and commonality with equipment already in the inventory.

IV. Transfer-Alignment/Calibration Issues

Transfer alignment was addressed using a 10-state suboptimal position-matching filter. The states were two horizontal position errors, two horizontal velocity errors, three attitude errors, and three gyro drifts—all relative to an assumed-perfect CMCA INS. Some of the effects studied included different types of maneuvers and maneuver times within a 30-min transfer-alignment period, longer alignment times, CM heading sensitivities, and in-air "gyrocompassing."

Figure 15 shows the subsequent CEP error growth rate for three different types of maneuvers occurring in the transfer-alignment period of 30 min. It is apparent that for a 1-n.mi./h relative calibration requirement and for the imposed constraints, a 0.5-*g* 45-deg-heading change maneuver occurring 5 min prior to launch is unacceptable for subsequent CM flight times longer than about an hour. However, Fig. 16 shows that if the 45-deg-heading change occurs at the beginning of the alignment period, a near-acceptable error growth rate is achieved for slightly over 2 h. This is because subsequent to the maneuver to determine azimuth error, the filter has time to estimate azimuth-gyro drift. Figure 17 shows the results for longer alignment times up to 60 min using a single S-turn occurring 15 min into the alignment period. Here it is noted that as the alignment times are increased, the single S-turn results in significant improvement in the CEP.

Figure 18 shows the results for the case of a single S-turn in a 30-min transfer-alignment period where the CM subsequently flies straight ahead after launch. Trajectory A corresponds to CMCA and CM northwest flight; trajectory B corresponds to southwest flight. The difference in the subsequent CEP error growth rate is due primarily to the sensitivity of the inertial-system error growth rate to the trajectory heading. This is an effect commonly seen in long-term aircraft inertial-navigation problems, and it is an important effect for long-range air-to-ground missiles. The results are presented to point out the direct dependence of all simulation results on the chosen mission scenario.

Figure 18 also shows trajectory C where the CM is launched from the same southwest direction as trajectory B and then turns 90 deg and flies northwest (same final heading as trajectory A). These results again show the heading sensitivity as well as the effects of errors excited during the CM turn, the predominant error in the latter category being an initial velocity error caused by the CM initial azimuth error.

The use of either single-position or two-position in-air "gyrocompassing" for extended periods of time was also investigated. "Gyrocompassing" was simulated by simply extending the normal alignment time and filter operation to 6 h without employing any special maneuvers. In single-position "gyrocompassing," the CM INS is fixed local-level and north pointing; in two-position "gyrocompassing," the INS is rotated 90 deg in azimuth after 3 h of transfer alignment for 3 more hours of alignment in the new orientation. This has the advantage of allowing the filter to estimate the bias of the unobservable east gyro which is now pointing north. Figure 19 shows the results in terms of azimuth misalignment of the CM guidance set for the single-position and two-position in-air "gyrocompassing" cases, as well as for the S-turn transfer-alignment maneuver previously discussed. The azimuth error in the latter case is significantly less than the in-air "gyrocompassing" cases. Figure 20 shows the resultant CEP's for all three cases. The S-turn transfer-alignment maneuver is clearly superior to in-air gyrocompassing schemes.

Figure 21 presents results for the gyro-drift estimation for the three in-air alignment schemes. Note that the gyrocompass cases always result in better estimation of the gyro-drift parameters. Thus, a logical combination of the approaches would be to do in-air gyrocompassing for as long as possible during the overwater portion of the CMCA flight, and then to do a maneuver within a period of 30 min prior to launch to bring the azimuth error down even further.

In summary, various options are available for use in transfer alignment and calibration of the CM guidance set. Many of these options appear to give acceptable CEP error growth rates according to the baseline error allocation. Which option is chosen would appear to be primarily a function of operational constraints such as the power and cooling requirements of the CM INS and time available.

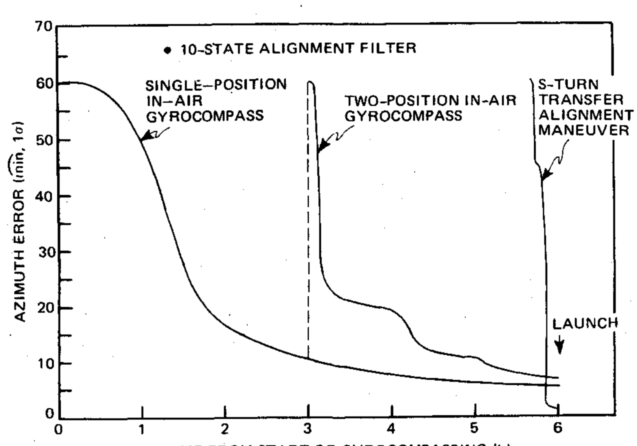

Fig. 19 Azimuth misalignment calibration.

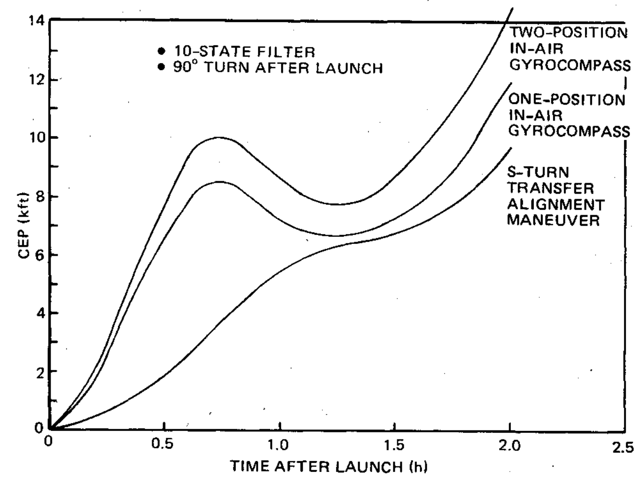

Fig. 20 CM error only after launch for various in-air alignment schemes.

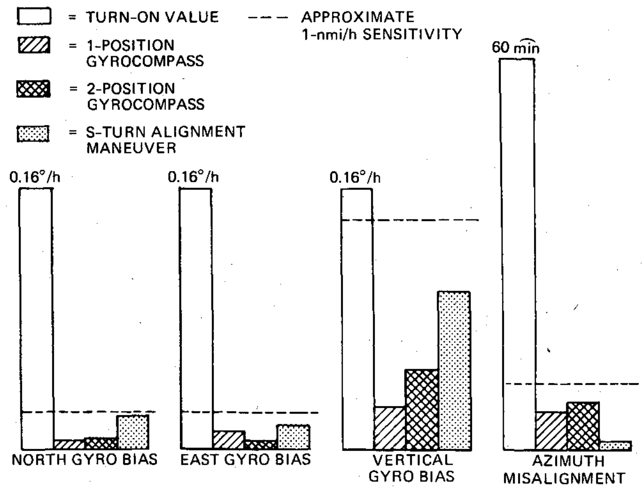

Fig. 21 CM critical parameter estimation for various in-air alignment schemes.

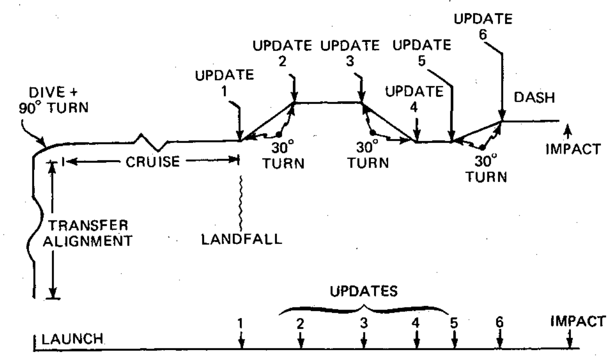

Fig. 22 CM flight profile.

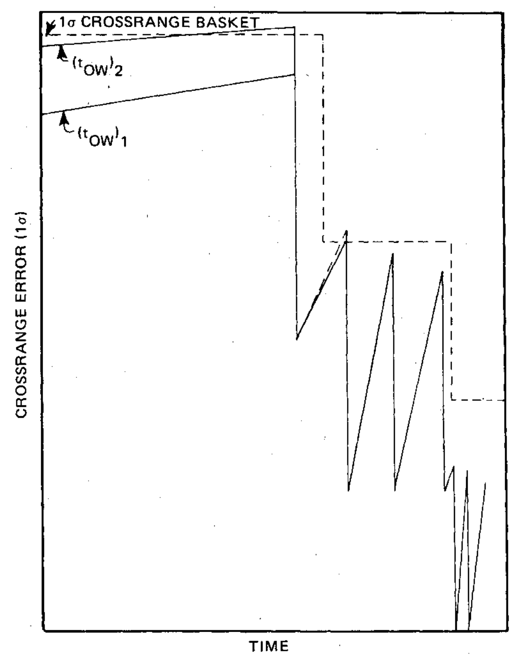

Fig. 23 CM crossrange error after launch.

V. Baseline-Mission Evaluation

The previous sections have described the tradeoffs conducted for the CMCA avionics and for transfer alignment and calibration. The intent of this section is to present some overall simulated system-level results, including both transfer-alignment and avionics errors.

The CM flight profile that was used in this study is shown in Fig. 22. An S-turn transfer-alignment maneuver is used onboard the aircraft, and is followed by launch of the CM. The CM then descends to low level, makes a 90-deg turn, and flies for a considerable distance until update 1; it subsequently makes fives more updates on its course into the target area. Each of the updates improves the CM guidance system's knowledge of position, velocity, attitude errors, and gyro-drift errors. Consequently, the required TERCOM map widths decrease as a function of the number of updates. The smaller map widths allow more accuracy at each update until at update 6, the accuracy at the update is actually much better than the accuracy on target.

Figure 23 shows the nondimensional total CM crossrange error (on a logarithmic scale) after launch for launches that occur at two different times after the last CMCA outbound fix. The dotted lines show the allowed 1-sigma crossrange error at each update location. Note that the allowed error decreases because the map widths decrease. As can be seen from this figure, the error allocation has resulted both in acceptable errors at each update time and in an acceptable on-target CEP. The final CEP is also a strong function of how far the cruise missile must fly from the last TERCOM map to the target.

VI. Concluding Remarks

A representative cruise missile (CM) carrier aircraft (CA) weapon-system mission has been used to evaluate the system-level error allocation, and it has been shown that a CMCA navigation error rate of 0.5 n.mi./h (CEP), or less, and a relative CM navigation error rate of 1 n.mi./h (CEP), or less, results in an acceptable high probability of overflying the first landfall TERCOM (terrain comparison) map, as well as the maps en route to the target. The key issues in implementing a CMCA navigation and guidance system do not appear to be performance issues since the requirements can be met by well-known state-of-the-art avionics elements.

Acknowledgments

The work presented in this paper was performed by The Charles Stark Draper Laboratory, Inc., under Contracts F33657-78-C-0473 and F33615-78-C-1563 with the Air Force Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio. Publication of this paper does not constitute approval by the U.S. Air Force of the findings or conclusions contained herein.

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