

# F-16 Flight Tests of a Rapid Transfer Alignment Procedure

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## ABSTRACT

This paper presents the results of an effort directed at developing and flight-testing an innovative rapid transfer alignment algorithm for inertially-guided air-launched munitions. The algorithm, referred to as RAP (**R**apid **A**lignment **P**rototype), employs a 17-state Kalman filter designed to accurately align a weapon-grade Inertial Measurement Unit (IMU) relative to an aircraft-grade Inertial Navigation System (INS) within five seconds. The alignment procedure requires the pilot to execute only a brief wing-rock maneuver. No time-consuming heading changes or lengthy s-turns are required. The RAP Kalman filter achieves the rapid convergence time by recursively processing both velocity-match and attitude-match measurements at a 12.5 Hz rate to estimate and correct IMU velocity, attitude, and inertial sensor errors. Following laboratory and van testing at Eglin AFB, a series of F-16 flight tests were conducted. Flight test results demonstrated that the RAP filter achieved sub-milliradian alignment accuracy in less than 10 seconds. As further confirmation of alignment accuracy, IMU position error statistics were computed over a 100-sec post-alignment captive-carry trajectory. Test results indicated that the mean radial position error after 100-sec of unaided navigation was roughly 70 ft with an associated CEP of 61 ft. RAP's unprecedented alignment accuracy and reduced launch timeline provide a rapid-response capability for time-critical targets such as mobile launchers and troop emplacements.

## 1. INTRODUCTION

The U.S. Air Force is currently pursuing several technology programs which specify precise navigation requirements for air-to-surface weapons equipped with an onboard inertial measurement unit (IMU). To exploit the benefits of an IMU-equipped weapon, the IMU's navigation equations (i.e., position, velocity, and attitude) must be accurately initialized prior to launch. Typically, these equations are initialized using a two-step transfer alignment procedure. The first step coarsely initializes the

navigation equations by transferring navigation data from the host aircraft's inertial navigation system (INS) to the weapon's navigation computer. The second step refines the coarse initialization by recursively computing the differences between selected INS and IMU navigation quantities and processing the differences as discrete measurements through a real-time Kalman filter. The Kalman filter incorporates state-variable models to characterize the most important error sources contributing to the measurement differences (e.g., attitude and sensor errors) and estimates these error sources based on the available measurements. The estimates are then used to correct the coarse initialization errors and calibrate the modeled IMU inertial sensor errors.

Transfer alignment Kalman filters have traditionally been designed to process measurements computed by differencing IMU-indicated velocity and (lever-arm compensated) INS-indicated velocity. Although these traditional "velocity-match" procedures are capable of achieving accurate alignments, the aircraft is typically required to perform lengthy horizontal plane maneuvers (e.g., s-turns). Consequently, the launch timeline is often dominated by the time required to complete these maneuvers and thus align the weapon IMU. Over the last several years, the U.S. Army, Air Force, and Navy have sponsored efforts directed at reducing the launch timeline without sacrificing IMU alignment accuracy [1-5]. Of particular interest are advanced procedures which provide rapid, accurate alignment of an IMU-equipped weapon, while not requiring significant crew interaction or any specialized hardware and/or external aiding sources.

This paper summarizes the results of an Air Force-sponsored effort directed at developing and flight-testing an innovative rapid transfer alignment algorithm for inertially-guided air-launched munitions. The algorithm, referred to as RAP (**R**apid **A**lignment **P**rototype), employs a 17-state Kalman filter designed to accurately align a weapon-grade IMU relative to an aircraft-grade INS within five seconds. The alignment procedure requires the pilot to execute only a brief wing-rock maneuver. No time-

consuming heading changes or lengthy s-turns are required. The RAP Kalman filter achieves the rapid convergence time by recursively processing both velocity-match and attitude-match measurements at a 12.5 Hz rate to estimate and correct IMU velocity, attitude, and inertial sensor errors [6].

The remainder of this paper is organized as follows. Section 2 presents the RAP equipment suite and the RAP Kalman filter design, Section 3 summarizes laboratory and van test results, and Section 4 summarizes flight test results. Finally, the overall conclusions are presented in Section 5.

## 2. RAP EQUIPMENT AND FILTER DESIGN

### 2.1 RAP EQUIPMENT

The RAP equipment suite consists of off-the-shelf hardware specifically selected to be consistent with modern precision-guided air-to-surface weapon systems. The RAP equipment suite includes a:

- Honeywell H-423 RLG strapdown INS
- Honeywell RLG strapdown Integrated Flight Management Unit (IFMU) with embedded IEC GPS receiver card
- ICS ruggedized 486/50 PC
- Termiflex controller.

The H-423 INS is an aircraft-quality (0.8 nmi/hr) strapdown navigation system designed to conform to the USAF Standard INS specification (SNU 84-1). The IFMU is a tactical-grade RLG strapdown navigation system incorporating the Honeywell HG-1700 IMU and an embedded IEC P/Y code five-channel GPS receiver card. The HG-1700 includes three Honeywell GG1308 RLGs (1 deg/hr fixed drifts) and three RBA-500 accelerometers (1 mg fixed biases). The IFMU is capable of providing either a free inertial or a GPS-aided navigation solution.

The RAP computer is a ruggedized 486DX2/50 MHz PC equipped with a MIL-STD-1553B interface card (DDC BUS-65529) and a RS-422 interface card (DDC BUS-61560). The computer hosts the RAP Kalman filter and functions as the MIL-STD-1553B bus controller. In the laboratory configuration, the computer is interfaced with a desktop monitor, keyboard, and mouse. However, in the flight configuration, these I/O devices are replaced by the Termiflex controller. The Termiflex controller is a calculator-size control display unit (CDU) employed to control and monitor RAP flight tests from the cockpit. The

RAP equipment interfaces are illustrated in Figure 2.1-1. The RAP equipment is self-contained and therefore isolated from the test aircraft's data buses.

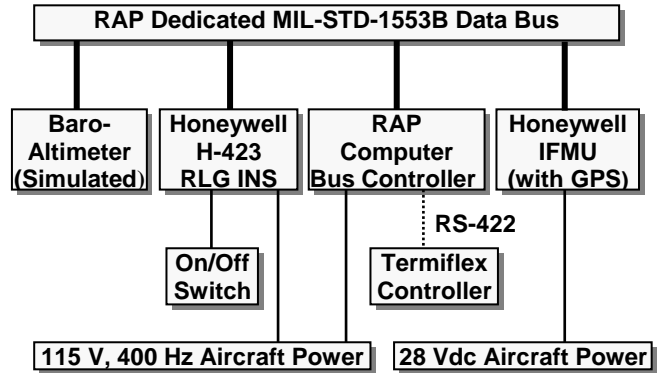


Figure 2.1-1 RAP Flight Configuration Interface

### 2.2 RAP KALMAN FILTER DESIGN

The RAP Kalman filter was designed by first developing a full-order optimal transfer alignment Kalman filter and then downsizing the optimal filter to achieve a practical reduced-order design. The optimal filter incorporates the high-fidelity truth model which precisely models (in state-space form) all significant linear error sources associated with the transfer alignment equipment and procedures. The RAP truth model (and hence, the optimal filter) included 66 state variables to characterize equipment error behavior [6, 7]. While not practical for real-time implementation (due to its large state size), the optimal filter provides the performance benchmark for the reduced-order RAP filter design.

**RAP Filter States:** The RAP filter design is summarized in Table 2.2-1. The RAP filter includes 17 states and processes both velocity-match (VM) and attitude-match (AM) transfer alignment measurements at a 12.5 Hz update rate. States 1 through 6 model IFMU velocity and attitude errors. States 7 through 12 and 16 and 17 model IFMU inertial sensor errors. Because of the short (5-sec) alignment time, inertial sensor calibration was not considered to be a primary objective of the RAP program. However, since certain sensor errors become observable during the wing-rock maneuver, and since gyro biases become observable during extended alignments, it was considered prudent to include these states. States 13 through 15 model the INS-to-IFMU rigid misalignment (i.e., boresight) errors. More detailed explanations of the RAP filter states and measurement equations can be found in [6] and [7].

Table 2.2-1 RAP Filter States

STATE	DESCRIPTION	INITIAL <sup>(1)</sup> 1σ VALUE	Q <sub>d</sub> <sup>(3)</sup> (rms)	UNITS
1-3	Velocity Errors	4	0.005	ft/sec
4-6	Attitude Errors	20 <sup>(2)</sup>	0.01	mrad
7-9	Accel Biases	0.5	0.001	mg
10-12	Gyro Fixed Drifts	1	0.0001	deg/hr
13-15	Rigid Misalignment	20	0.03	mrad
16,17	Gyro x,y Scale-Factor Errors	1	0	ppm

<sup>(1)</sup> Square-root of the diagonal elements of the P(0) matrix  
<sup>(2)</sup> Attitude errors are initially uncorrelated with misalignment errors  
<sup>(3)</sup> Q<sub>d</sub> is the discrete process noise covariance matrix

Prior to hardware testing, extensive computer simulations were conducted to assess filter performance. System Dynamics' transfer alignment covariance simulation (TRANSIM) was exercised to provide transfer alignment and navigation accuracy projections for a variety of alignment scenarios. The nominal simulation scenario involved a 5-sec alignment trajectory followed by a 100-sec post-alignment navigation trajectory. For the alignment trajectory, the aircraft maintained straight and level flight for the first two seconds, performed a 30-deg roll during the third second, returned to level during the fourth second, and maintained level flight during the fifth second. The trajectory timeline is illustrated in Figure 2.2-1. (The positive roll and return-to-level maneuver is referred to herein as a wing-rock maneuver.) The post-alignment navigation trajectory was included to propagate IFMU alignment errors into IFMU navigation errors (e.g., CEP), thereby providing a more familiar figure-of-merit. This trajectory simulated a 12-nm glide-bomb trajectory with a terminal 60-deg pitch down maneuver executed 8-sec before impact.

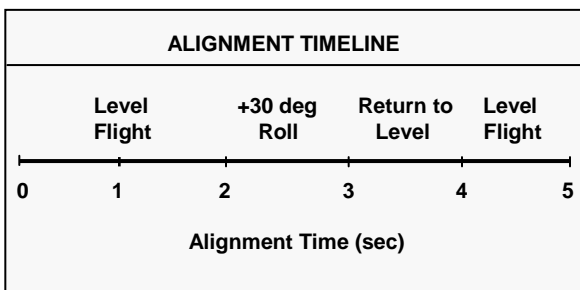


Figure 2.2-1 Simulated Alignment Trajectory

Simulation results indicated that RAP alignment errors converged to below 1 mrad (1σ) in less than three seconds. Furthermore, at steady state, the RAP and optimal-filter curves were virtually identical, indicating that the RAP filter was expected to achieve the smallest possible alignment error [6, 7].

### 3. LABORATORY AND VAN TESTS

#### 3.1 TEST PREPARATION

The primary objective of the laboratory and van tests was to assess the alignment accuracy and convergence time of the RAP filter when operating in both benign and moderate-dynamic environments. In order to properly assess filter performance, a reference configuration was first established by mounting the IFMU and INS on a slab in a known orientation. Specifically, a 17-inch square aluminum slab was fabricated so that the IFMU and INS could be mounted flush to the slab and adjacent to each other. The slab was then machined so that steel dowels could be inserted to intentionally misalign the IFMU from the INS in yaw by -2 deg (i.e., -34.9 mrad). Consequently, for all laboratory and van tests, the INS-to-IFMU misalignments were established to be 0 mrad about the roll and pitch axes and -34.9 mrad about the yaw axis. The laboratory test configuration is illustrated in Figure 3.1-1.

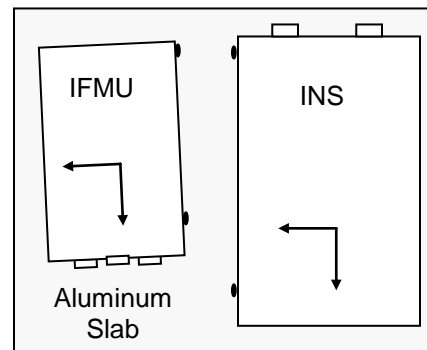


Figure 3.1-1 Laboratory and Van Test Configuration

Prior to each test, the filter's knowledge of the INS-to-IFMU misalignments was intentionally corrupted by computing the initial body-to-body transformation matrix using non-zero roll and pitch misalignment values and a zero yaw misalignment value. Specifically, the filter was initially "told" that there was a 10 mrad misalignment about the roll and pitch axes, when actually none existed, and that there was no yaw misalignment, when actually a -34.9 mrad misalignment existed. Consequently, during alignment, the RAP filter was expected to estimate and remove the artificially-induced 10 mrad roll and pitch errors and the actual -34.9 mrad yaw error.<sup>1</sup> For all laboratory and van tests, the wing-rock maneuver was performed by manually tilting one end of the slab up and then setting it back down on the test table. Laboratory tests conducted at System Dynamics' facility confirmed that the

<sup>1</sup>It can be shown that this procedure establishes the "reference" misalignments to be -10 mrad in roll and pitch and -34.9 mrad in yaw.

RAP alignment errors consistently converged to below 1 mrad ( $1\sigma$ ) in all three axes [6, 7].

Van tests were subsequently conducted with the RAP equipment installed in the AFRL/MNGN Mobile Test Vehicle (MTV) at Eglin AFB. The MTV is shown in Figure 3.1-2. Like the laboratory tests, the INS and IFMU remained bolted to the aluminum slab for all van tests. Consequently, filter performance was assessed by comparing the filter's cumulative misalignment estimates with the reference misalignments (i.e., -10 mrad and -34.9 mrad).



Figure 3.1-2 Mobile Test Vehicle (MTV)

Van tests were conducted over two, two-day intervals in February and March 1997. The February tests were performed on winding access roads at Eglin AFB using the Astro AZ survey point as a position reference for INS initialization. The March tests took place at Eglin range C3 (an abandoned runway) using the MITS1 and MITS2 survey points for position references. This site was selected to allow the van to achieve higher speeds (e.g., 60 mph) during transfer alignment.

### 3.2 VAN TEST RESULTS

A total of 46 tests were conducted to assess filter performance in the van. Figure 3.2-1 illustrates the van's trajectory and alignment results for a typical test (Test V49). For this test, the van was traveling approximately 30 mph, the wing-rock maneuver was manually initiated at the 3.5-sec point, and alignment was terminated at the 7-sec point. The results indicated that: (1) the roll and pitch misalignment estimates quickly converged to the reference values, (2) the yaw misalignment was partially estimated prior to the roll maneuver (due to small level-axis accelerations caused by van motion), and (3) the yaw estimate rapidly converged to the reference value once the maneuver was initiated.

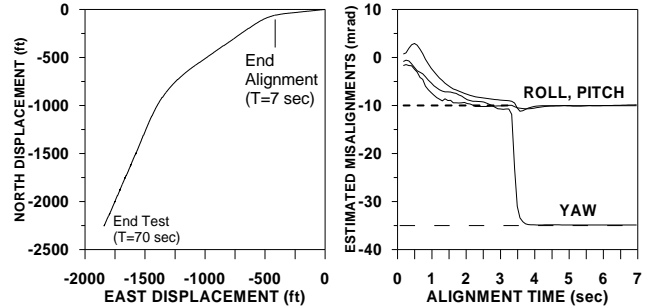


Figure 3.2-1 Typical Van Test Result (Test V49)

The alignment error statistics for the 46 van tests are summarized in Figure 3.2-2. The alignment errors represent the deviation of the RAP filter's cumulative misalignment estimates from the corresponding reference values. The histograms indicate that the RAP filter accurately estimated the misalignments in all three axes. Specifically, the mean estimation errors and standard deviations were all less than 0.3 mrad.

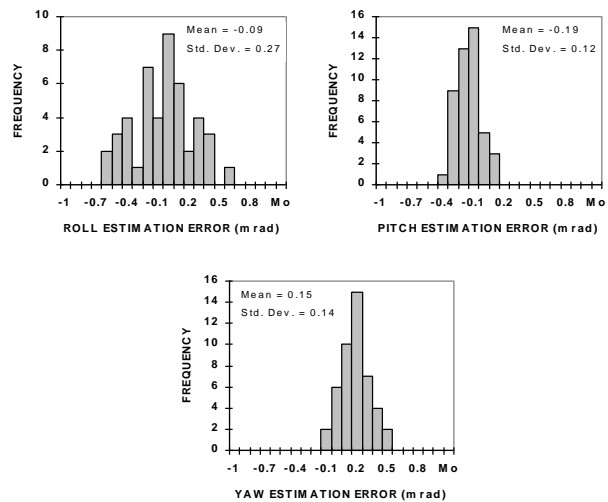


Figure 3.2-2 Van Test Summary

Post-alignment IFMU position and velocity errors were computed for selected van tests during post-test analysis. The velocity errors were computed by differencing time-synchronized IFMU- and INS-indicated velocities, compensated for lever-arm effects. The position errors were computed by numerically integrating the velocity errors. The north and east position errors for the above van test are presented in Figure 3.2-3. The figure includes the  $2\sigma$  error bounds projected by TRANSIM over the van's post-alignment trajectory. (TRANSIM assumes that the IFMU has been accurately aligned (to better than 1 mrad) and then propagates its modeled IFMU errors over the actual test trajectory.) This figure indicates that the magnitude of the (unaided) IFMU position errors remains below 20 ft, well within the projected  $2\sigma$  bounds. These

results are indicative of an accurate (better than 1 mrad) transfer alignment.

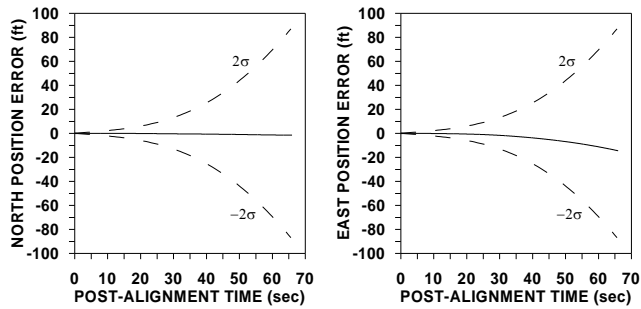


Figure 3.2-3 Post-Alignment Position Errors (Test V49)

## 4. FLIGHT TESTS

### 4.1 TEST PREPARATION

The objective of the flight tests was to assess the alignment accuracy and convergence time of the RAP filter when operating within a tactical airborne environment. All flight tests were conducted with the RAP equipment installed in a Block 25 F-16 aircraft operated by the 39<sup>th</sup> Flight Test Squadron at Eglin AFB. The IFMU and RAP computer were installed in a general instrumentation (GI) pod attached to weapon station #3 under the left wing. The INS was installed in the aircraft's aft equipment bay, and the CDU (i.e., the Termiflex controller) was installed in the cockpit. The location of the RAP equipment is shown in Figure 4.1-1. The aircraft loadout configuration for all flight tests is illustrated in Figure 4.1-2. A GPS RAJPO pod was installed on station #1 to provide GPS reference data if needed. An inert AIM-9 missile was installed on station #9 to balance the loadout configuration.



Figure 4.1-1 RAP Equipment Location on F-16 Aircraft

### 4.2 TEST PROCEDURE AND ASSESSMENT

#### 4.2.1 Test Procedure

RAP flight tests were grouped into two functional categories designated herein as alignment and navigation.

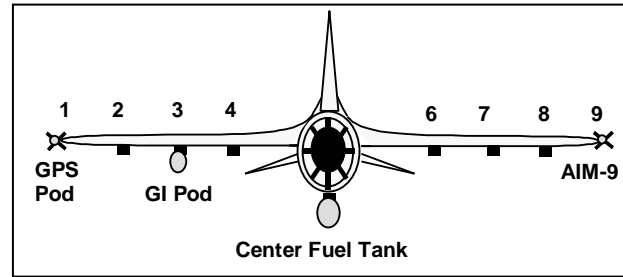


Figure 4.1-2 F-16 Loadout Configuration for Flight Tests

The alignment tests were directed specifically at assessing the alignment accuracy of the RAP filter. The majority of these tests performed a nominal 5-sec RAP alignment followed by a 60-sec post-alignment (captive-carry) flight which included a 90-deg turn. A few tests, however, replaced the nominal RAP alignment with a "one-shot" alignment. The one-shot alignment coarsely initializes the IFMU using instantaneous INS data (which is the first step in the RAP alignment), but does invoke the RAP filter. The one-shot alignment tests were conducted to facilitate the accuracy assessment of the RAP filter (see below). The navigation tests were directed primarily at assessing post-alignment IFMU navigation accuracy. These tests performed a nominal RAP alignment followed by a 100-sec (captive-carry) straight flight.

#### 4.2.2 Accuracy Assessment

The flight test performance of the RAP filter was primarily assessed using two complementary evaluation methods. The first method directly computed the filter's alignment errors by differencing the filter's cumulative misalignment estimates with the reference misalignments. Although this method is the most straightforward, its effectiveness depends entirely on the accuracy of the reference misalignments. Since the INS and IFMU were not bolted to the aluminum slab for flight tests, the laboratory and van test reference misalignments could not be used. Rather, a new set of "flight-test" reference misalignments were required.

Two candidate procedures were developed to measure the flight-test reference misalignments. The first procedure was developed to measure the misalignments while the aircraft was stationary on the ground. The second procedure was developed to measure the misalignments while the aircraft was airborne at the test altitude and velocity. Although both procedures were shown via simulation to yield accurate reference misalignments, the airborne procedure was ultimately selected in favor of the ground-based procedure. The ground-based procedure was rejected primarily because the actual ground-based misalignments were expected to shift to new steady-state (airborne) values (especially about the roll axis) when the

aircraft becomes airborne. The shift is caused primarily by aerodynamic forces which deflect the wings upward during flight, thereby changing the orientation of the IFMU (which is attached to the wing) relative to the INS (which is mounted in the fuselage). (Details are provided in [6].)

In the airborne procedure, a fixed-point Kalman-smoother algorithm was employed during post-test analysis to compute the reference misalignments. In general, a fixed-point Kalman smoother processes data available before and after a fixed point in time in order to estimate its state vector at the fixed point. For this effort, relative IFMU velocity errors were first computed over the 60-sec post-alignment trajectory for each one-shot alignment test. (The velocity errors were computed by differencing INS- and IFMU-indicated velocities.) The post-alignment velocity errors were then processed by the smoother to "back-out" the residual misalignment errors existing at the end of the alignment. Since by definition the one-shot alignment does not attempt to estimate the misalignments, the residual misalignment errors equal the actual INS-to-IFMU misalignments, i.e., the reference misalignments. During post-test analysis, the reference misalignments were estimated by the smoother to be approximately 19 mrad in roll, -50 mrad in pitch, and 8 mrad in yaw.

A second evaluation method infers RAP alignment accuracy by comparing IFMU position errors incurred during the post-alignment trajectory with IFMU position error bounds generated by TRANSIM. The simulation is initialized to characterize an accurate (better than 1 mrad) RAP alignment and then executed over the actual post-alignment trajectory flown for a particular flight test. An accurate alignment is inferred if the position error traces remain within the simulated ( $2\sigma$ ) error bounds.

### 4.3 FLIGHT TEST RESULTS

Five one-hour flight-test missions were conducted at Eglin AFB during April and May 1997. The missions were conducted at an altitude of 5000 ft at 320 kt (Mach 0.5). During each mission, multiple RAP tests were performed. Valid data were recorded for 67 individual tests comprising 45 RAP alignment tests, 2 one-shot alignment tests, and 20 unaided navigation tests. The test results are summarized below.

#### 4.3.1 Alignment Tests

Figure 4.3.1-1 presents the wing-rock maneuver and trajectory flown for a typical RAP alignment test (Flight Test F206). For this test, RAP alignment occurred during the first 10 sec followed by a 40-sec post-alignment (90-deg turn) trajectory. Note that for this test, RAP alignment was actually performed over an interval which exceeded the specified 5 seconds. This timeline deviation was due

primarily to pilot unfamiliarity with the RAP CDU and procedure. It is anticipated, however, that for an operational system, the alignment procedure would be automated to eliminate the pilot interaction required during flight tests.

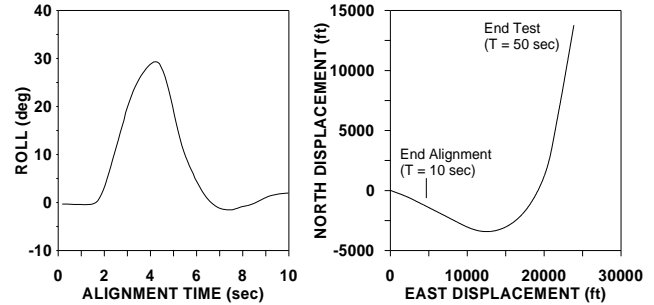


Figure 4.3.1-1 Alignment Maneuver and Flight Trajectory

Figure 4.3.1-2 contrasts the RAP filter's cumulative estimates for Test F206 with the reference misalignments. The results indicate that: (1) the RAP filter's roll and pitch misalignment estimates quickly converged to the reference misalignment values, (2) the filter partially estimated the yaw misalignment prior to the wing-rock maneuver due to level-axis accelerations caused by aircraft motion, and (3) during the maneuver, the filter's yaw misalignment estimate rapidly converged to the reference value.

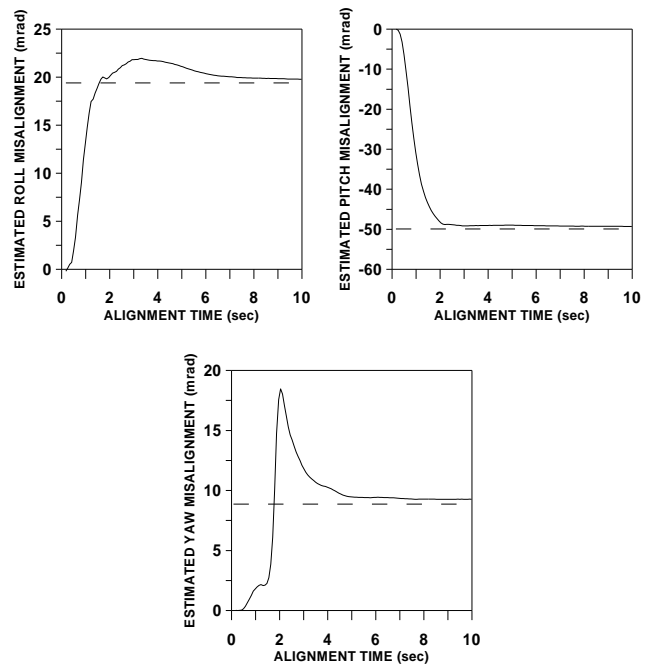


Figure 4.3.1-2 Alignment Test Results for Test F206

Figure 4.3.1-3 contrasts IFMU position error growth during the 40-sec post-alignment trajectory with the  $2\sigma$  position

error bounds generated by TRANSIM. The figure illustrates that the magnitude of the IFMU position errors remained below 40 ft, well within the predicted  $2\sigma$  error bounds. These results further indicate that an accurate transfer alignment was performed.

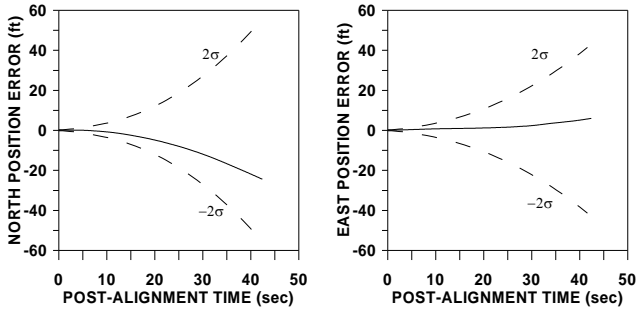


Figure 4.3.1-3 Post-Alignment Position Errors for F206

Figure 4.3.1-4 presents the alignment results for a second RAP alignment test (Flight Test F307). For this test, RAP alignment occurred during the first 11 sec followed by a 40-sec post-alignment trajectory. The figure indicates that, as for Test F206, the RAP filter's misalignment estimates rapidly converged to the reference misalignment values during the wing-rock maneuver.

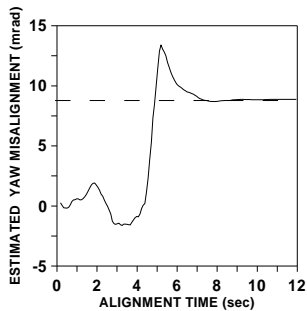
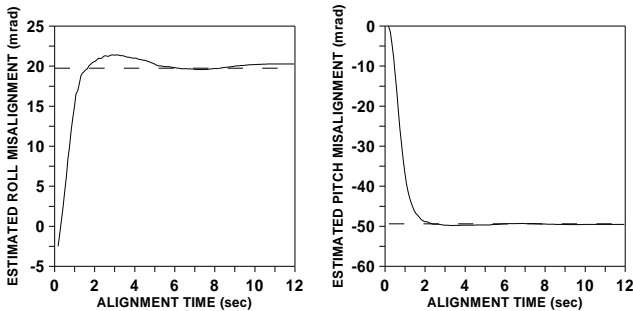


Figure 4.3.1-4 Alignment Test Results for Test F307

Figure 4.3.1-5 contrasts IFMU position error growth during the 40-sec post-alignment trajectory with the  $2\sigma$  position error bounds generated by TRANSIM. The figure illustrates that the magnitude of the IFMU position errors remains below 25 ft, again well within the  $2\sigma$  error bounds.

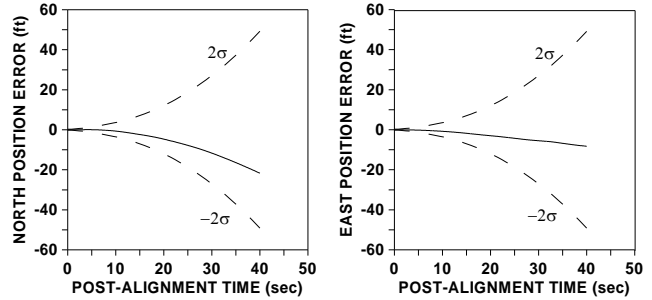


Figure 4.3.1-5 Post-Alignment Position Errors for F307

The results of the 45 RAP alignment tests are summarized in Figure 4.3.1-6. The histograms indicate that the RAP alignment errors were small on the average and consistent across the set of tests, as evidenced by the tight distribution of the data.

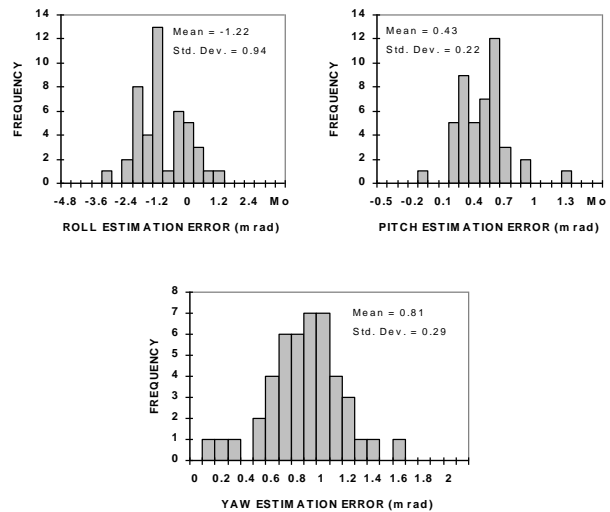


Figure 4.3.1-6 Flight Test Summary (Alignment Tests)

### 4.3.2 Navigation Tests

The primary objective of the navigation tests was to quantify post-alignment IFMU navigation accuracy over a lengthy captive-carry flight. Recall that these tests involved a nominal RAP alignment followed by 100 sec of straight-and-level flight. A total of 20 valid tests were performed. Figure 4.3.2-1 presents IFMU position error growth during the post-alignment flight for a typical navigation test (Flight Test F406). The  $2\sigma$  position error bounds projected by TRANSIM are also shown. The figure illustrates that for this test, the magnitude of the IFMU position errors remains below 60 ft, well within the predicted error bounds.

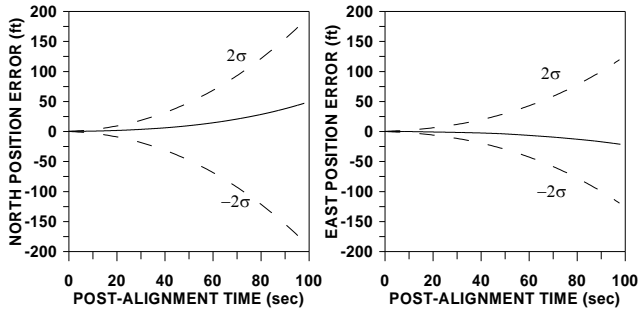


Figure 4.3.2-1 Post-Alignment Position Errors for F406

Figures 4.3.2-2 and 4.3.2-3 summarize the results for the 20 navigation tests. The mean radial position error after 100-sec of unaided flight was roughly 70 ft with an associated CEP of 61 ft. These results are consistent with accurate (better than 1 mrad per axis) transfer alignments.

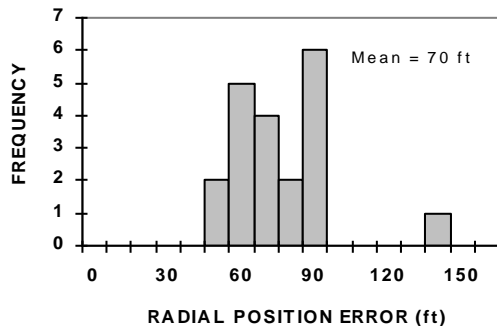


Figure 4.3.2-2 Radial Position Error After 100-sec of Free-Inertial Flight

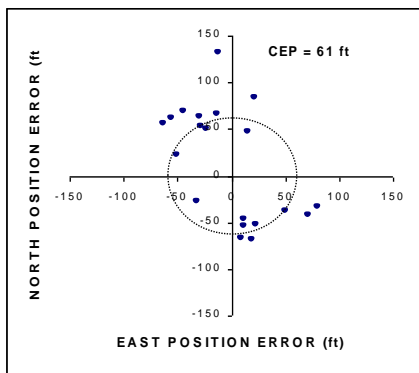


Figure 4.3.2-3 CEP After 100-sec of Free-Inertial Flight

## 5. CONCLUSIONS

The RAP flight test program successfully demonstrated that the RAP procedure is capable of achieving a rapid, accurate alignment of a weapon-grade IMU in an airborne environment. By processing both velocity-match and attitude-match measurements at a 12.5 Hz rate, the RAP

Kalman filter was shown to achieve sub-milliradian alignment accuracy in less than 10 sec. The RAP filter was designed to be consistent with the throughput rate, memory capacity, and computation capabilities of current-generation weapon-grade processors, while maintaining near-optimal accuracy and robust performance. Furthermore, the filter's architecture was structured with enhanced modularity to facilitate implementation into a wide range of weapon systems. The RAP procedure provides the Air Force with a rapid-response capability for time-critical targets such as mobile launchers and troop emplacements.

## ACKNOWLEDGMENTS

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## REFERENCES

- [1] Graham, W.R. and Shortelle, K.J., "Advanced Transfer Alignment for Helicopter-Launched Fire-and-Forget Missiles", System Dynamics International, Report No. ISG 91-01, 31 March 1991.
- [2] Graham, W.R. and Shortelle, K.J., "Advanced Transfer Alignment for Inertial Navigators (A-TRAIN)", System Dynamics International, Report No. ISG 94-02, 30 September 1994.
- [3] Graham, W.R. and Shortelle, K.J., "Advanced Transfer Alignment for Inertial Navigators (A-TRAIN)", Proceedings of the Institute of Navigation (ION) National Technical Meeting, January 1995.
- [4] Shortelle, K.J. and Graham, W.R., "Advanced Alignment Concepts for Precision Guided Weapons", System Dynamics International, Report No. ISG 94-01, 24 June 1994.
- [5] Shortelle, K.J. and Graham, W.R., "Advanced Alignment Concepts for Precision Guided Weapons", Proceedings of the Institute of Navigation (ION) National Technical Meeting, January 1995.
- [6] Graham, W.R. and Shortelle, K.J., "Rapid Alignment Prototype (RAP) Flight Test Demonstration", System Dynamics International, Report No. ISG 97-01, 30 August 1997.
- [7] Graham, W.R. et al, "Rapid Alignment Prototype (RAP) Flight Test Demonstration", Proceedings of the Institute of Navigation (ION) National Technical Meeting, Long Beach, CA, January 1998.