GPS Align in Motion of Civilian Strapdown INS

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BIOGRAPHIES

Doug Weed is a Navigation Analyst with Honeywell Commercial Aviation Products. He has been developing navigation algorithms and system architectures for Honeywell since 1985. Doug holds a B.S. in Aerospace Engineering and Mechanics (1987) and a M.S. in Electrical Engineering, Control Sciences, (1988) from the University of Minnesota.

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ABSTRACT

Strapdown inertial navigation systems require an initialization process that establishes the relationship between the aircraft body frame and the local geographic reference. This process, called alignment, generally requires the device to remain stationary for some period of time in order to establish this initial state. This paper describes an alignment process where the initialization occurs while the device is moving. This is possible because an accurate determination of the aircraft motion is available based on measurements obtained from GPS.

Align In Motion allows initialization of a Strapdown Inertial Navigation System while an aircraft is moving, in the air or on the ground. This is accomplished using Civilian grade GPS and an inertial reasonableness test, thereby allowing commercial data integrity requirements to be met. Align In Motion has been FAA certified to recover pure INS performance equivalent to stationary align procedures for civilian flight times up to 18 hours.

This Align In Motion capability allows the removal of dedicated backup batteries on aircraft resulting in weight, cost, and reliability improvements. Align In Motion also has benefits for aircraft operations on the ground, on board ship, and in the air such as reduced turn backs, quicker dispatch, and world-wide alignment including polar regions.

This paper will describe an avionics architecture using Align In Motion. It will cover INS warm start and cold start following a power interrupt with recovery to full inertial navigation capability without pilot interaction. Successful flight test results will also be presented.

KEY DESIGN CONSIDERATIONS

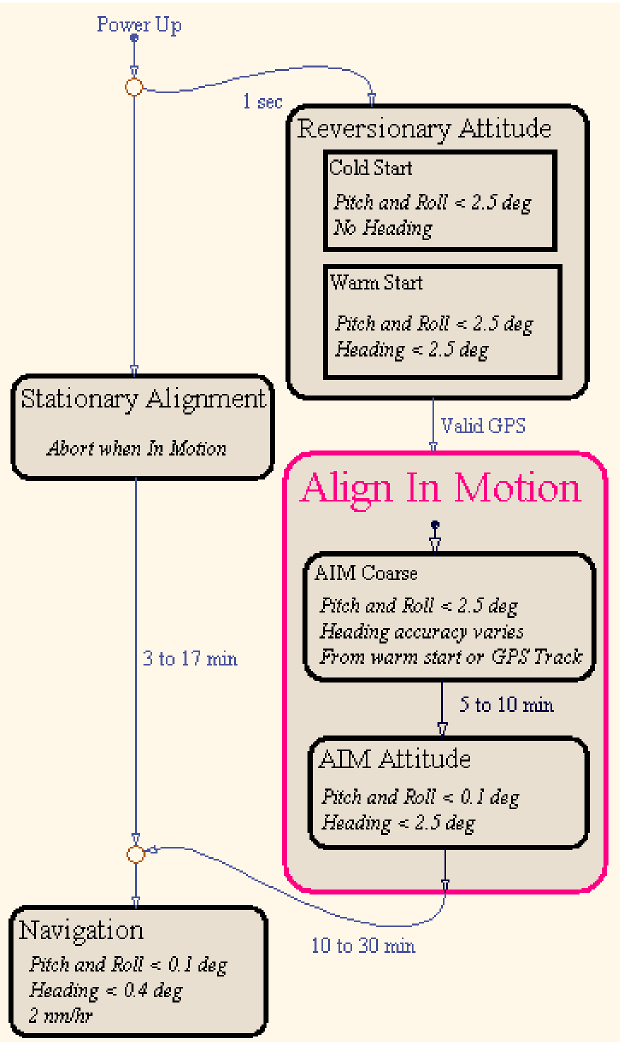
- Commercial Aircraft Safety and Reliability Requirements
- Commercial grade inertial sensors
- Commercial grade GPS with and without SA on
- No initial knowledge of heading (±180°)

KEY DESIGN FEATURES

- Automatic, no pilot interaction needed
- No special constraints or demands place upon the aircraft flight path
- World wide alignment capability
- Warm Start initialization following 200 msec power outages

ALIGN IN MOTION OVERVIEW

The Honeywell Laseref™ V Micro IRS™ device provides an Align In Motion capability in addition to the classical Stationary Alignment mode. This Align In Motion function provides for recovery to full IRS navigational capability in the event of a total interruption of power in flight.



Modes – Timing and Accuracy

NOTES:

No Motion scenario

1. ARINC Outputs provided by Reversionary Attitude and Nav Modes
2. Align In Motion is active in background only

Motion scenario

Align In Motion is active in foreground

4. ARINC Outputs provided by Reversionary Attitude, AIM Attitude, and Nav Modes

Inertial navigation is the process of calculating the position and velocity of a body (such as an aircraft) from self-contained accelerometers and gyroscopes. Before navigation can commence, the IRS goes through a self-alignment process to align the vertical axis of the local level coordinate frame with sensed acceleration (leveling) and to measure the horizontal earth rate to determine the initial azimuth (gyrocompassing).

Like previous IRS products, the Micro IRS™ provides an on ground alignment mode, called Stationary Alignment, where the alignment is performed while the aircraft is stationary. This is the primary alignment mode, and is performed each time power is initially applied to the device.

Unlike past IRS products in commercial markets, the Micro IRS™ also provides an additional reversionary alignment mode while in motion called Align In Motion (AIM). Align In Motion is used to recover IRS navigational capability due to a total interruption of power in flight. Per the installation manual, the Micro IRS™ requires two sources of power. Both power sources must be interrupted for a period greater than 20 msec before the device is reset. Consequently, the probability of alignments in air is remote.

In addition to these alignment and navigation modes, IRS products provide a Reversionary Attitude mode to allow quick recovery of attitudes, body rates, and body accelerations in the event of an interruption of power in flight.

In past IRS products, the IRS was either in the Stationary Alignment mode, the Navigation mode, or the Reversionary Attitude mode depending upon the state of a Mode Select Unit. The Micro IRS™ does not use a Mode Select Unit, and instead implements automatic mode control logic in which several modes may be operating simultaneously. An example of this is following power up initialization, the Micro IRS™ immediately transitions to the Reversionary Attitude mode. If on the ground, the Micro IRS™ also concurrently executes the Stationary Alignment mode to allow the IRS to transition from the Reversionary Attitude mode to the Navigation mode. If a power interrupt should occur while in flight, the Micro IRS™ again immediately transitions to the Reversionary Attitude mode at power up. The device then concurrently executes the Align In Motion mode to allow transition back to the Navigation mode. At some point during the Align In Motion mode, the ARINC output data being provided by Reversionary Attitude is replaced by data from the AIM Attitude mode. AIM Attitude mode provides improved pitch and roll attitude performance and gyro compassed azimuth data (true and magnetic heading) to within TSO C-5e and C-6d performance levels prior to recovering to full navigation capability.

Since Align In Motion is dependent upon the availability of ARINC 743A GPS data, the unavailability or loss of this data during an alignment while in flight will cause the device to remain in or revert to the Reversionary Attitude mode. GPS integrity concerns are addressed by executing both Reversionary Attitude and AIM Attitude modes concurrently and using the pure inertially derived Reversionary Attitudes as an integrity check against the GPS based AIM Attitudes. The device will revert back to the Reversionary Attitude mode from the AIM Attitude mode in the event of an attitude integrity miscompare.

In summary, on the ground the Micro IRS™ initially enters the Reversionary Attitude mode and requires a successful completion of the Stationary Alignment mode to achieve full navigation capability. In the air the Micro IRS™ initially enters the Reversionary Attitude mode, and if AIM is active, transitions to the AIM Attitude mode, and requires a successful completion of the Align In Motion mode to once again achieve full navigation capability.

2.0 ALIGN IN MOTION DETAILS

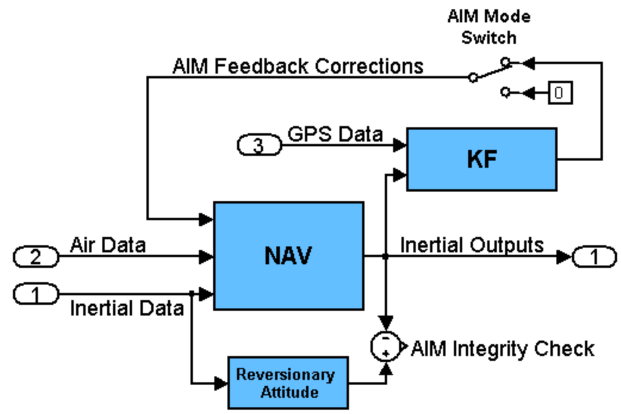
A more detailed description of the Align In Motion function and how it relates to the Stationary Alignment, Attitude, and Navigation modes of the device is presented here.

The Micro IRS™ Align In Motion capability is not intended to be used as the primary means of aligning the inertial reference system when on ground. Prior to aircraft departure, the device typically achieves full navigational capability by first completing a Stationary Alignment. Hence in the primary mode of operation, the attitudes and navigation parameters are not dependent upon the availability and integrity of GPS data. If the aircraft begins to move before Stationary Alignment is complete, then Stationary Alignment is aborted and the device behaves the same as if it had been an in air power up. Thus a transition to the Align In Motion mode will occur in either case if all of the following conditions are true, otherwise the device simply remains in the Reversionary Attitude mode:

- ARINC 743A compliant GPS data is received and is valid (includes autonomous and satellite measurement blocks).
- GPS Horizontal Integrity Limit is less than 2.0 nautical miles.
- Aircraft is in motion
- Successful entry into Reversionary Attitude mode has occurred.

2.1 PITCH, ROLL, AND HEADING DETERMINATION

A Kalman filter is used to resolve pitch, roll, and true heading to the required accuracy.



AIM Mode Computations

At the start of Align in Motion, pitch and roll are initially provided to the AIM mode computations by the Reversionary Attitude mode and are known to within 2.5° or better, where as heading may be completely unknown (±180°). The time required to resolve heading down to <2.5° prior to AIM Attitude mode and down to < 0.4° for AIM complete is dependent upon aircraft maneuvers. Aircraft accelerations and maneuvers will shorten the time to complete the Align In Motion mode. A worst case estimate of the time to complete AIM is provided as an ARINC output. Resolving the initial ±180° heading uncertainty down to < 0.4° is the primary Align In Motion technical challenge given commercial grade GPS and commercial grade inertial sensors, especially considering that the commercial GPS measurement noise exceeds the Stationary Alignment measurement noise induced by passenger loading and wind buffeting. For the power up in air scenario, the GPS track angle is used to initialize heading with an uncertainty that decreases as ground speed goes up, thereby shortening the time to complete Align In Motion. There is another technique that is implemented in the Micro IRS™ known as Warm Start which is used to shorten the time to complete Align In Motion as well.

2.2 WARM START

For the Micro IRS™ installation, a total interruption of power in flight occurs if both power sources are interrupted for a period greater than 20 msec. If the power interruption continues for more than 200 msec, then a cold start will occur, else a warm start will occur. In the warm start case, the navigation processor and Ring Laser Gyros were specifically designed to quickly restart and provide pitch, roll, heading, body rates, and body accelerations again in less than 1 second. This is accomplished by continuously storing data in the navigation processor non-volatile memory prior to the loss of power. Appropriate data integrity checks are performed to assure the integrity of this stored data. The pitch, roll, and heading parameters are then extrapolated across the power outage period using this stored data along with the body rates that are present when power is recovered. The following 1st order attitude extrapolation algorithm is used which assumes constant aircraft angular rates during the power outage (< 1 sec).

Attitude(n) = Attitude(n-1) + (Attitude Rate(n-1) + Body Rate(n)) * Δt / 2.0

Ideally, the new attitude rates would be used rather than the new body rates in order to correctly extrapolate the attitude. However, body rates and attitude are needed to compute the new attitude rates, and the new attitude has not yet been re-established. Thus the new body rates are used in place of new attitude rates. This approximation works fine at typical aircraft roll and pitch angles.

Warm start accuracy is < 2.5° for pitch, roll and heading. The accuracy budget for the warm start design accounts for typical variations in the aircraft angular acceleration, aircraft attitude, and knowledge of the power outage time. The power outage time is measured outside the navigation processor using hardware circuitry held up via capacitors during the power outage.

2.3 COLD START

During a cold start, the total sensed acceleration (aircraft and gravity) is used to determine pitch and roll to TSO C-4c performance levels (i.e. to within 2.5°). Normally, if the aircraft is operating unaccelerated (i.e. constant velocity, heading, and pitch), a Cold Start will complete in less than 1.0 second. In an accelerating flight condition, the Cold Start time period will be extended due to either total acceleration, yaw rate, or pitch rate that is beyond reasonableness thresholds.

2.4 REVERSIONARY ATTITUDE

Reversionary Attitude mode is initialized on the ground and in the air either via a Cold Start or a Warm Start. The Reversionary Attitude mode implements a second order control loop used to maintain a leveled platform from which pitch and roll attitudes and platform heading are derived. The pitch and roll attitudes computed during Reversionary Attitude mode meet the pitch and roll attitude performance levels specified in TSO C-4c (i.e. 2.5°). In Reversionary Attitude mode, an initial magnetic heading input (called set heading) is required to reference the computed platform heading. The ARINC 429 magnetic heading output is set to No Computed Data until an initial set heading input is received. In Reversionary Attitude mode, the device does not transmit a valid true heading output.

The second order control loop does not compensate for vertical earth rate and therefore drifts at this rate (i.e. maximum of 15.04°/hr and varies as a function of latitude). Consequently, while the device is in the Reversionary Attitude mode, periodically a set heading input may be necessary to maintain an accurate magnetic heading output. Generally this will not be required in the Micro IRS™ product. On ground, the Micro IRS™ will reach navigation mode after a Stationary Alignment duration of between 3 and 17 minutes (varies as a function of latitude); and, a valid IRS magnetic heading is not likely to be required during the Stationary Alignment phase of operation. In air, the Align In Motion function allows the IRS to self compute azimuth (gyrocompass). Thus normally, the amount of time the IRS is in Reversionary Attitude mode in flight is short (approximately 5 to 10 minutes) before the AIM Attitude mode is available. The only likely scenario where the Micro IRS™ will remain in Reversionary Attitude mode for an extended period of time while in flight is when GPS data is not available due to a GPS failure.

2.5 AIM ATTITUDE MODE

In air, while the Micro IRS™ is in Reversionary Attitude mode, it is also executing the Align In Motion mode in parallel. Once pitch and roll attitudes have reached an accuracy of 0.1°, and true heading has reached an accuracy to support TSOs C-5e and C-6d performance levels, the Micro IRS™ will transition from Reversionary Attitude mode to the AIM Attitude mode. AIM Attitude provides the following advantages compared with Reversionary Attitude mode:

- Improved accuracy for the pitch and roll attitudes.
- Self determined true and magnetic heading outputs that are not subject to vertical earth rate drifts.

A five second linear smoothing function is implemented between the transition from Reversionary Attitude mode to AIM Attitude mode to minimize the step potential resulting from the difference in computed attitudes.

While in AIM Attitude mode, the attitudes being transmitted are dependent upon the availability and integrity of GPS. However, GPS alone does not provide adequate integrity to meet the integrity requirements for IRS computed attitudes. Consequently the Micro IRS™ incorporates an attitude comparison monitor by continuing to run pure inertial Reversionary Attitude computations in the background while AIM Attitude is active and comparing the computed attitudes between the two modes.

The AIM Attitude pitch and roll outputs will not be used unless they are better than the TSO level of Reversionary Attitude Mode. This ensures that any GPS failures will not affect the "integrity" of the attitudes. It is understood that the 10^{-7} integrity provided by the RAIM algorithm would be a common mode failure source to a dual Micro IRS™ installation, and would not ensure the aircraft would meet the 10^{-9} criticality for attitudes with a common mode failure. Thus, the AIM Attitude internal continuous checks ensure that the attitudes are independent (from all other installed device(s)) and allow the aircraft system to meet the attitude criticality requirements as in all traditional systems and installations.

Once AIM Attitude mode has been entered, the Micro IRS™ will revert back to the Reversionary Attitude Mode if a miscomparison exists in pitch and roll attitudes between AIM Attitude mode and Reversionary Attitude mode. Therefore, in addition to a GPS Receiver HIL of 2.0 nautical miles or better being continuously required for AIM to operate, attitudes from the pure inertial sensor based Reversionary Attitude mode are used to ensure the integrity of the attitudes derived from the GPS based AIM Attitude mode.

If a transition from AIM Attitude mode to Reversionary Attitude mode should occur, the initial magnetic heading output will equal the last computed magnetic heading output from the AIM Attitude mode which passed the attitude comparison integrity check. A five second linear smoothing function is implemented between the transition from AIM Attitude mode to Reversionary Attitude mode to minimize the step potential resulting from the difference in computed attitudes.

2.6 EXTENDED ALIGN IN MOTION

The time period to complete Stationary Alignment is precisely deterministic and varies as a function of latitude from 3 to 17 minutes. The time period to complete Align In Motion is not deterministic and varies as a function of latitude and aircraft maneuvers. Generally, Align In Motion will complete in 10 to 30 minutes.

The Align In Motion function converges faster when the aircraft performs a maneuver such as a heading change or a velocity change (acceleration). When the aircraft is stationary on the ground, the Align In Motion function will work in the same manner as the Stationary Alignment function and use the horizontal component of earth rate to find north via gyrocompassing. This condition can only occur if the aircraft was moved during a Stationary Alignment such that Align In Motion was activated (in violation of the current installation manual procedures), and then became stationary again. The circumstances that cause the Align In Motion function to converge slowly are:

- no change in the aircraft flight conditions.
- no net horizontal earth rate and transport rate.

One realizable flight scenario does exist in which Align In Motion will not complete and the device will remain in Align In Motion for an extended period of time. This is a steady high-speed westbound cruise from middle to upper latitudes. A steady flight would mean that there are no aircraft heading or velocity changes. High-speed westbound flight means that the aircraft transport rate cancels the horizontal earth rate component at that latitude. At 60° of latitude, the horizontal earth rate is about 7.5°/hr which can be offset by a 450 knot west bound cruise. At lower latitudes it takes higher westbound cruise velocities to offset the horizontal earth rate. For example, it would require 900 knots at the equator, which is not a reasonable commercial aircraft velocity. Also consider that at very high latitudes west/east bound flight would imply that the aircraft is flying circles around the pole.

The extended Align In Motion condition is what prompted the AIM Attitude feature. If the Micro IRS™ could assure the AIM Attitude mode completes quickly, then the benefits of the Align In Motion capability could always be realized

3.0 NAVIGATION PERFORMANCE

Upon successful completion of Align In Motion, the device transitions to the pure inertial Navigation mode. The Align In Motion mode completion criteria is the same as the Stationary Alignment mode, such that the navigation performance after an Align In Motion would be the same as after a normal Stationary Alignment. This means full ARINC 704 navigation capability (i.e. no degraded outputs).

4.0 HARDWARE DESCRIPTION

The Laseref V Micro IRS is the first commercial IRS to be certified with Align in Motion capability. This IRS is used in a wide variety of applications including:

Business Jets:

- Gulfstream G100 Retrofit , G350, G450, G500, and G550
- Raytheon Hawker Horizon
- Dassault Falcon 900EX, 2000EX, and 7X
- Beechcraft King Air Retrofit

Air Transport & Regional:

- Embraer 170/175/190/195
- Boeing 7E7
- ATR-42 Retrofit

Tankers & Transports:

- C5-AMP Retrofit
- C-130 Retrofit
- B-707 Retrofit

High Performance Aerobatic Trainers

- T-38N Trainer Retrofit
- Pilatus PC-21, PC-7, and PC-9 Trainers

Helicopters

- Eurocopter AS-365

CHARACTERISTICS

- Weight 9.8 lbs
- Size 260 cubic inches
- Dimensions (W x L x H) 6.5”x6.4”x6.4”
- Digital Ring Laser Gyros
- Quartz Accelerometers

- Power Consumption 25 watts
- 40,000 MTBF Reliability
- Automatic Mode Control Logic and Automatic Initialization for reduced crew workload
- Alignment In Motion software allows dispatch even while IRU is in alignment mode. This feature eliminates delays while waiting for the IRU to align.
- Passive Cooling eliminates the weight and cost of cooling fans
- Electronic mounting tray alignment for reduced installation cost
- ARINC-615-3 Interface for simple software updates
- Enhanced Automatic Realignment to refine the alignment between flights
- Hybrid GPS provides 100% Availability of RNP Navigation and extended coasting through GPS outages
- Partitioned Operating System provides Pure Inertial and separate Hybrid Outputs

CERTIFICATIONS

The following certification are either complete or pending for this device.

- Software Certification DO178B Level A
- Hardware Certification DO160D
- TSO & JTSO C-3d, C-4c, C-5e, and C-6d
- TSO & JTSO C-129a Class B1/C1 (with ARINC 734A GPS Receiver)
- FAR 121 Appendix G (Federal Aviation Regulations) – Operating Requirements: Domestic, Flag, and Supplemental Operations
- Advisory Circular 25-4 Inertial Navigation Systems (INS) -- Certified applications up to 22 hours flight time
- AC 120-33 - Operational approval of airborne long-range navigation systems for flight within the North Atlantic minimum navigation performance specifications airspace.
- FAA Order 8400.12A, Required Navigation Performance 10 (RNP-10) Operational Approval, for 12 hours unaided
- AC 90-96, Approval of u.s. operators and aircraft to operate under instrument flight rules (IFR) in European airspace designated for basic area navigation (BRNAV/RNP-5), for 2 ½ hours unaided

LASEREF® V

MICRO IRS ™

5.0 HONEYWELL FLIGHT TEST RESULTS

The flight test setup consisted of three Micro IRS™ devices and one GPS source being received by each unit. Device #1 was aligned normally and was used as the inertial truth reference providing the pitch, roll, and heading reference. The other two units were aligned in motion three separate times throughout the flight test. These two AIM units were powered on at different times and during various dynamics when possible in order to evaluate the effects on unit operation and performance. After an Align in Motion was completed in each of the three test phases, the units were allowed to navigate for a period of time in order to evaluate the quality of the alignment in motion. The expectation was that the attitude outputs for both AIM units would compare to the reference unit within the accuracy of the reference. Also the velocity performance for the AIM units were compared to the GPS velocity reference. It was also expected that with both AIM units seeing similar vehicle dynamics and the same GPS data that they would show equivalent Align in Motion timing and performance.

Ground Test - Baseline

Description - In this test all three units performed a normal stationary alignment and navigated for a period of time with no aircraft maneuvers. The main objective of this test was to establish the static offsets in roll, pitch, and heading angles between the three units.

Results - The nominal device performance levels were:
Device #1 – peak ground speed error = 0.6 knots
Device #2 – peak ground speed error = 3.4 knots
Device #3 – peak ground speed error = 1.0 knots

The offsets relative to the Device #1 reference were:
Device #2 to Device #1:

- Roll offset = -0.07°
- Pitch offset = -0.02°
- Heading offset = +0.64°

Device #3 to Device #1:

- Roll offset = -0.10°
- Pitch offset = -0.21°
- Heading offset = +1.54°

Flight Test Phase 1 - Takeoff

Description - Prior to departure the reference Device #1 had completed a normal stationary ground alignment. During takeoff both AIM units were turned on at slightly different times in order to determine the ability to coarsely initialize pitch and roll angles during periods of aircraft acceleration (Cold Start). After takeoff the aircraft proceeded to its cruise altitude at which point it flew straight and steady until Align in Motion and the following navigation period was complete.

Results - Device #2 was powered on during ground taxi and self-initialized during a pause between taxi and takeoff. Device #3 was powered on during the takeoff rollout and self-initialization sometime during climb out (due to pitch rate and acceleration cut-outs) with larger, but acceptable, pitch and roll errors. This was due to sustained longitudinal acceleration providing a false vertical. The total time to complete align in motion for this flight phase was less than 29 minutes for the two AIM devices. See the table and figures below for further performance details.

Flight Test Phase 2 – Loiter

Description - Following the completion of the phase 1 navigation period Device #2 and Device #3 were powered off. Device #1 continued to navigate and provide the inertial reference for the entire flight test. Device #2 was then powered on while the aircraft continued in steady cruise. Device #3 was powered on after the aircraft entered the loiter pattern. This loiter pattern was chosen to provide optimal align in motion conditions.

Results - Device #2 initialized immediately during the steady cruise segment. Device #3 waited for the turn segment of the loiter pattern to end (yaw rate cut-out) and initialized during the straight segment of the loiter pattern. Given the optimal flight conditions of a loiter pattern, the total time to complete align in motion for this flight phase was about 11 minutes for the two AIM devices.

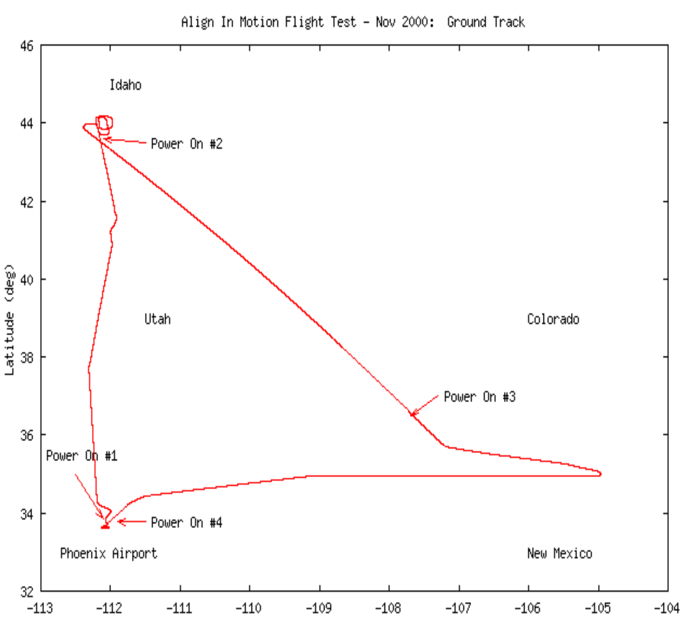
Flight Test Phase 3 – Steady

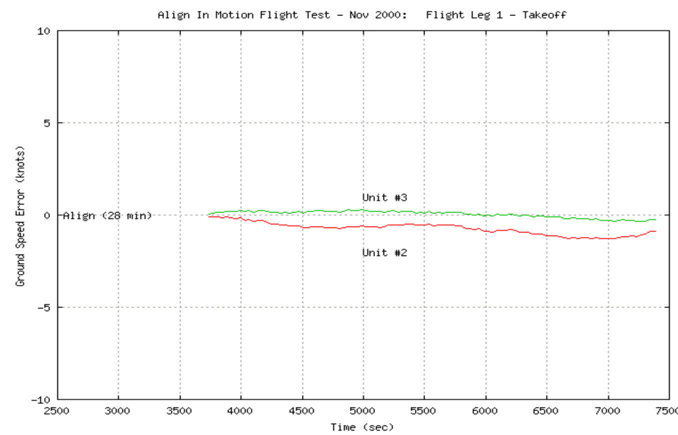
Description - Following the completion of the phase 2 navigation period Device #2 and Device #3 were powered off. Both Device #2 and #3 were then powered on while the aircraft continued in steady cruise. The following flight phase was intended to be straight and steady so as to provide near worst case align in motion conditions. However, the aircraft made a small heading change near the start of the align in motion period and another 180 degree heading change at the end of the align in motion period. Also the cruise direction was mostly east where the absolute worst case direction would have been west (earth rate and transport rate cancellation). Therefore this flight phase was more representative of typical conditions.

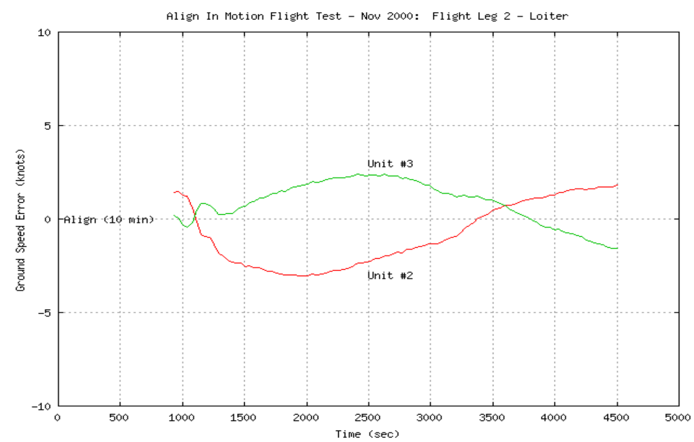
Results - Both units were powered on during cruise conditions and self-initialized immediately. The align in motion timing (about 25 minutes) and performance between the two units were nearly identical.

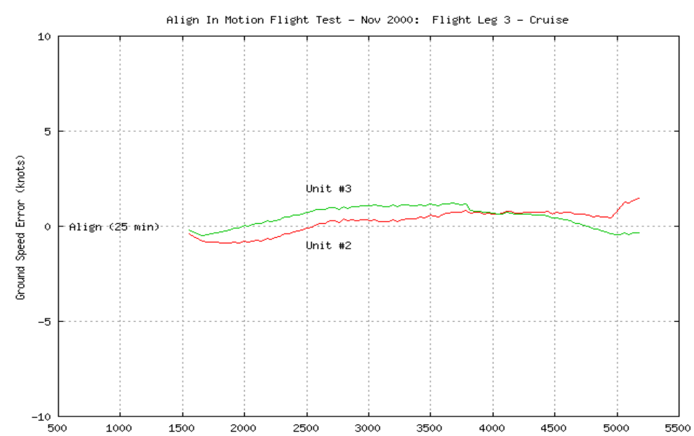
Flight Test Performance						
Test Phase	Power up Pitch/Roll Error	**AIM Attitude Time**	AIM Attitude Pitch/Roll Error	AIM Attitude Heading Error	**Total AIM Time**	**Navigation Ground Speed Error**
	Rqmt 2.5° 2σ		Rqmt 0.1° 2σ	Rqmt 0.4° 2σ		Rqmt 12 kts R95
Takeoff Device 2	0.0°	**5.9 min**	0.0°	0.4°	**28.8 min**	**1.3 kts**
Takeoff Device 3	2.3°	**5.4 min**	0.1°	0.0°	**28.4 min**	**0.4 kts**
Loiter Device 2	0.1°	**5.2 min**	0.0°	0.2°	**10.6 min**	**3.0 kts**
Loiter Device 3	2.5°	**5.3 min**	0.1°	0.0°	**11.3 min**	**2.3 kts**
Steady Device 2	0.5°	**9.0 min**	0.1°	0.3°	**25.3 min**	**1.5 kts**
Steady Device 3	0.7°	**9.0 min**	0.1°	0.1°	**25.3 min**	**1.1 kts**

Flight Test Aircraft









6.0 CONCLUSION

The FAA has approved AIM in August of 2003 on a Gulfstream G550 Ultra-Long Range business jet via a Type Certificate with no limitations. JAA and EASA certifications have also been received on the Embraer 170 and Dassault Falcon 900EX with no limitations. The AIM recovery of full performance navigation mode has been successfully demonstrated at all latitudes and longitudes. Flight tests of Align in motion have also been successfully demonstrated to the FAA while flying directly over the North Pole. Aircraft types successfully demonstrating AIM include turbo-prop trainers, ultra-long range and long range business jets, mid-size business jets, and regional jets.

GPS Align in Motion of Civilian Strapdown INS will provide many benefits to Commercial Aviation including:

- Improved dispatch reliability
- Reduced gate delays while waiting for IRS alignment
- Reduced turn-backs or diversions due to in-flight power interrupts resulting in loss of IRS
- Improved high latitude alignments

Future software enhancements are planned to take advantage of C/A code GPS SA off to significantly shorten alignment times.