PRECISION ATTITUDE DETERMINATION USING A LOW GRADE GPS-AIDED INERTIAL MEASUREMENT UNIT

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BIOGRAPHIES

Ian Longstaff
Ian Longstaff joined NAVSYS Corporation as the Integrated Product Team Leader for GPS/Inertial products and services in July 1996. He has over 25 years experience in developing inertial systems and inertial measurement units. He was most recently Lead System Engineer at Litton Space Systems, Goleta, Ca., on their Precision Hemispherical Resonant Gyro program, for space-based applications. Previous to this he was Systems Engineer for the Litton ZLG™ based LN100 systems from 1986-1994 at Litton Guidance and Control Systems in Woodland Hills, Ca. Prior to this Mr. Longstaff was a Systems Engineer at Litton Italia in Rome, on the LISA 2000 and Tornado Nav HARS. Mr. Longstaff started his professional career as an Assessment Engineer at British Aerospaces' Precision Products Group working on testing and designing gyroscopes for tactical applications.

Alison Brown
Alison Brown is the president of NAVSYS Corporation, which specializes in developing GPS customized products and services. Dr. Brown has more than 15 years experience in GPS receiver design and has seven GPS related patents. She has published numerous papers on GPS applications and is on the editorial board for *GPS World* and *GIS World* magazines. She is currently a member of the USAF Scientific Advisory Board and the GPS III independent review team. Dr. Brown received her BA in Engineering from Cambridge University, a MS from MIT, and a PhD from UCLA.

ABSTRACT

Precision attitude determination is a key requirement for precision targeting. Current targeting systems use range and bearing to target (relative to the Forward Observer's GPS coordinates) to derive the target coordinates. The accuracy of these coordinates is currently limited by the accuracy to which the bearing to target can be observed. Conventional methods of determining attitude include gyrocompassing, GPS interferometry and magnetic sensors. Existing portable targeting systems provide bearing to an accuracy of 10 mrad which introduces 10 m of position error in target coordinates at a range of 1 km.

NAVSYS have developed a precision GPS/inertial attitude determination method that enables 1 mrad pointing accuracy to be provided using low cost (missile-grade) inertial instruments. Test data presented in this paper shows that this method provides better than 30 times improvement in accuracy over conventional gyrocompassing methods.

INTRODUCTION

Battlespace awareness is a core requirement for current and future military operations. Awareness in this context means a global capability to precisely, comprehensively and continuously define the battlespace. This includes both the location and status of friendly and enemy forces.

Both commercial and military surveillance systems are expected to proliferate over the next several decades. Digital video is expected to be the most widely available data type, although multi-spectral and hyper-spectral sensor and Synthetic Aperture Radar (SAR) data will also be available.

The challenge is to develop an image-based Battlespace Awareness system that can support real-time integration of intelligence, surveillance and reconnaissance (ISR) data from a variety of different platforms. This "system of systems" must achieve the following core requirements:

- sensors need to be digital and capable of deriving precise target coordinates
- sensor products need geospatial, temporal referencing for electronic integration, archival and retrieval actions
- precision 3-D geolocation of images (i.e. "every pixel a coordinate")

GPS-guided munitions have enabled low cost, "seeker-less", precision weapon delivery which is anticipated to dramatically improve kill probability and sortie effectiveness. However, precision delivery requires precision target location. The Global Positioning System (GPS) will be the backbone of all geospatial referencing systems. Planned improvements to the system will enable global 3-D positioning to a precision of 1 meter. However, in order to fix, track and target any object from image or sensor data, the precise range, elevation and azimuth to that target from the sensor platform must be known.

Both the Target Location, Designation and Hand-Off System (TLDHS) and the Motorola TAMER are examples of existing targeting systems that exploit GPS to derive the precise location of the sensor. These use a laser range-finder to determine the range to the target and include tilt sensors for elevation and a magnetic sensor for heading. They have been shown to deliver coordinates to an accuracy of 50 m at 5 km. The dominant error contribution to the target location is from the azimuth error. Magnetic sensors can provide heading to at best 10 mrad (0.57 deg).

Unmanned Air Vehicles (UAVs) are anticipated to be widely used for collection geospatial referenced image data. NAVSYS is currently supporting DARPA's Warfighter program and is developing a precision targeting system to process UAV imagery data called GI-EYE (See **Figure 1**). This system relies on triangulation from multiple images to precisely locate targets ("every pixel a coordinate"). The precision of the target coordinates with this approach is primarily a function of the attitude accuracy of the UAV's reference system.

The Warfighter targeting system includes a digital video camera for collecting the image data. A GPS receiver provides the 3-D coordinates of the camera for each image captured and an inertial measurement unit (IMU) is integrated with the video camera to enable the precise camera attitude to be derived. A precision inertial alignment algorithm has been developed by NAVSYS that provides the camera attitude to an accuracy of 1 mrad (0.057 deg). This enables location of target coordinates to an accuracy of 1 meter at distances of 1 km from the UAV.

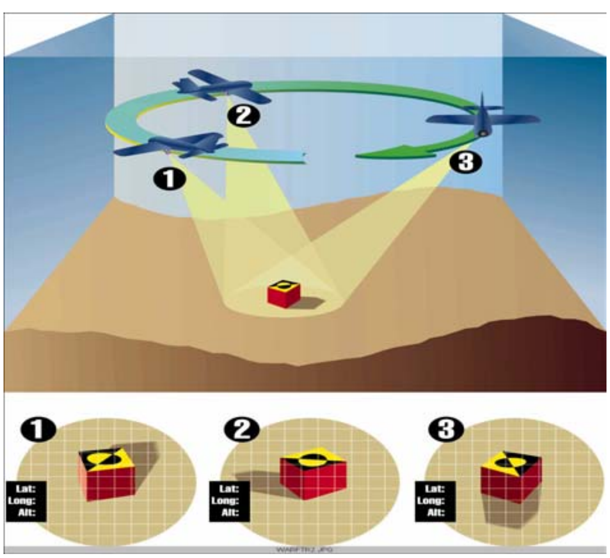

Figure 1 NAVSYS GI-EYE Targeting System

2. CONVENTIONAL ATTITUDE DETERMINATION TECHNIQUES

The dominant error source in existing targeting systems is the attitude error. A 10 mrad (0.57 deg) heading error will result in a 10 meters error at 1 km. In order to achieve the precision desired for targeting, a 1 mrad (0.057 deg) pointing accuracy is required (see **Figure 2**).

To illustrate the benefits of the NAVSYS precision inertial alignment approach, an explanation is first provided of state-of-the-art techniques and their limitations. These are subdivided into conventional inertial alignment and GPS interferometric approaches.

Inertial Attitude Determination

Standard high and medium accuracy Inertial Navigation Systems (INS) use the accelerometers to determine pitch and roll of the system and the gyroscopes to observe earth rate (15.04 deg/hr) to determine heading. This process is known as gyrocompassing. Using conventional gyrocompassing for an inertial system to observe heading, causes the resulting heading error to be directly proportional to the uncalibrated east gyroscope bias. For example, a 1 deg/hr uncalibrated gyro bias will result in roughly 4-6 degrees of heading error,

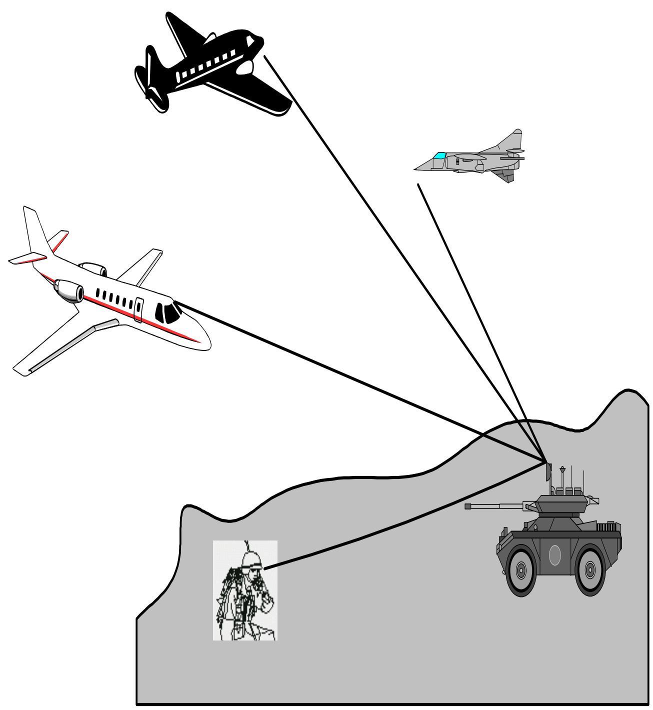

Figure 2 Precision Delivery Requires Precise Target Location

depending on system latitude. This puts a bias repeatability requirement on medium accuracy aircraft navigation systems of 1nm/hr performance of .01deg/hr to obtain a heading accuracy of 1 mrad. This instrument accuracy requirement results in a system cost of the order of $100k. Also, gyrocompassing relies on precise knowledge of system latitude (for precise knowledge of local level earth rate), and the system to be stationary. In order to meet the precision attitude requirements for targeting, expensive, high grade IMUs are required when conventional alignment methods are used. Instead, the low cost methods of precision targeting currently use magnetic heading systems and unreliable gimbals for attitude determination, which give at best a 10 mrad pointing accuracy.

GPS Interferometric Attitude Determination

GPS interferometry operates by observing the relative location of two or more antennas to a fixed baseline. Dr. Brown received a patent award while at the Draper Labs for some of the pioneering work on this technique[1]. The accuracy of this approach is dictated by the accuracy of the carrier phase measurements (σ_{CPH}^2 = E[$n^2(t)$]) and the separation between antennas (L).

$$\sigma_H \approx \frac{\sigma_{CPH}}{L}$$

From previous test results, multipath errors on the carrier phase observation are the dominant error sources in using interferometry. Testing with multiple antenna configurations demonstrated that the best performance was achieved using a choke ring antenna assembly which minimizes the received multipath[2]. With a conventional microstrip antenna and no ground plane (such as is used on the TLDHS system), the observed carrier phase noise was 6 mm. With a choke ring, this was reduced to around 2 mm. Using a choke ring antenna and a 1 meter baseline, heading could be determined to 2 mrad (0.1 deg). When the antenna separation was reduced to 0.25 meters, the heading error grew to 58 mrad (3.35 deg) which would result in over 50 meters of target error at a range of 1 km. The size and weight of the antenna choke rings eliminates this option for a man-portable system. With miniaturized antennas and a reduced baseline, the test results demonstrate that the susceptibility from multipath eliminates this method as a candidate for a man-portable targeting system.

3. INTERNAV PRECISION ALIGNMENT ALGORITHMS

The NAVSYS' INTERNAV GPS/Inertial software package was designed to facilitate integration of different types of GPS receivers with inertial measurement units (IMUs). This software computes the inertial navigation solution from the IMU data ($\Delta\theta$, ΔV) and aligns and calibrates the inertial errors using updates from the GPS receiver (either PR/CPH or P/V). (**Figure 3**) The INTERNAV software includes the capability to perform a precision "transfer alignment" from a GPS derived "pseudo-baseline". This capability enables significantly enhanced alignment performance over that provided by conventional inertial gyrocompassing.

The concept of the "pseudo-baseline" is illustrated in **Figure 4**. As described in the previous section, GPS can derive precise coordinates for two points in space, which in turn describes the precise attitude of a baseline between these coordinates. This principle is used with GPS interferometric attitude determination to derive the relative baseline coordinates between two antennas. The inertial navigation solution can derive the precise relative position of these two points in space in a "body-frame" coordinate system. This "pseudo-baseline" derived from the inertial solution substitutes for the fixed-baseline used in a GPS interferometric attitude determination system. From a comparison of the "pseudo-baseline" coordinates in the body frame at point 2 (Δx^B) and the "pseudo-baseline" coordinates derived in the navigation frame from the GPS data ($\Delta x^N = x_2 - x_1$), the error in the inertial body-to-navigation direction cosine transformation can be observed (C_B^N).

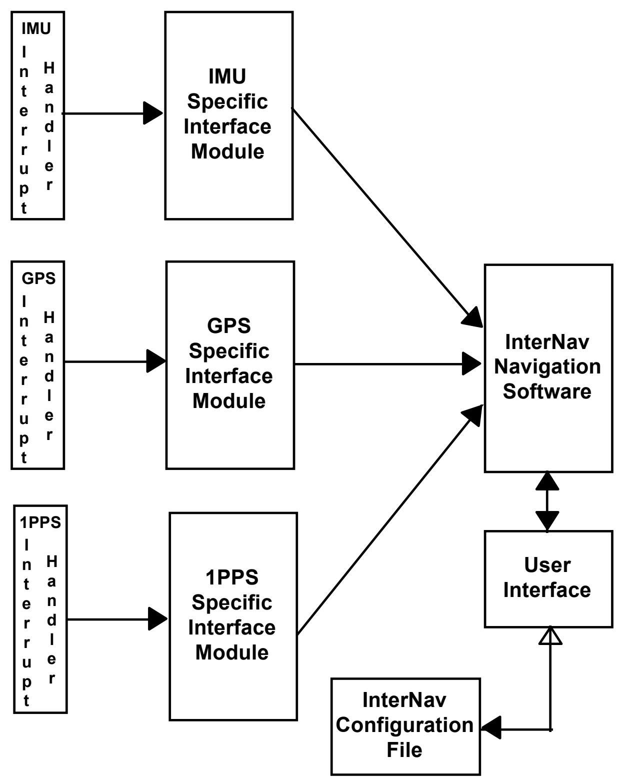

Figure 3 INTERNAV Software Structure

This precision alignment technique can be considered to employ the best features (or observability) of GPS interferometry, while only requiring a single antenna to determine precision attitude. Moreover, the "smoothing" provided by the inertial data significantly reduces the impact of multipath errors which to date have severely limited the use of GPS interferometers. The precision alignment method employed is also analogous to transfer alignment

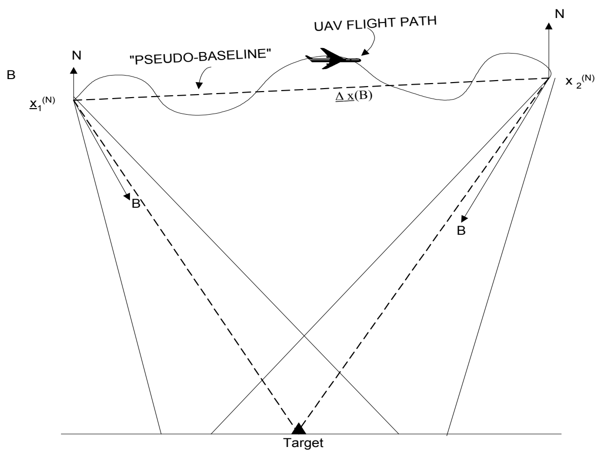

Figure 4 Pseudo Baseline Transfer Alignment Concept

techniques previously used to transfer alignment from one INS to another. Transfer alignment accuracies of 1.75 mrad (.1 deg) are now state of the art with low grade inertial instruments.

The accuracy of the INTERNAV precision alignment mechanism is a function of the accuracy to which the coordinates of the "pseudo-baseline" end points are determined (GPS accuracy), the length of the baseline (for example, the distance between the georeferenced images) and the errors in the IMU instruments. In the following section, test data taken with a prototype targeting system is shown that demonstrates this capability.

4. GPS/INERTIAL VIDEO (GI-EYE) SYSTEM

Under the DARPA Warfighter Visualization program NAVSYS is currently under contract to provide a GPS/Inertial/Video targeting system for UAVs' to exploit this targeting accuracy, and further expand the capabilities of the INTERNAV software. This program is called GI-EYE. The system concept is illustrated in **Figure 1** and the system components are shown in **Figure 2.**.

This system uses GPS position and the INTERNAV precision alignment algorithm to allow precise target location via video. The GPS provides long term aiding to the inertial system, while the inertial provides pointing accuracy for the camera, simplifying the video processing of the camera data to precisely locate targets in the image.

For the NAVSYS GI-EYE program the INTERNAV software was modified to allow the video data to be taken synchronously with the inertial updates. The INTERNAV

- **UAV Hardware**
  - **Miniature Camera**
  - **MEMS IMU (µSCIRAS Brassboard System or Litton Multi-Sensor)**
  - **Rockwell PLGR GPS**
  - **Rockwell Soldier Phone Brassboard or SCM data link**
  - **Custom Power / CPU**
  - **Video / Inertial Calibration algorithms**

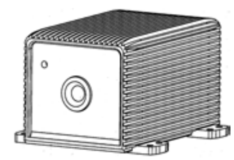

Figure 5 GI-Eye UAV System Hardware

position and attitude data was recorded for each digital image to allow for precision targeting based upon target pixel position and camera location and attitude.

5. GI-EYE PROTOTYPE TARGETING ACCURACY DEMONSTRATIONS

To evaluate the attitude performance of the INTERNAV precision alignment system a targeting test fixture was built (**Figure 6**). This included a precision 25X rifle scope precisely aligned to the mounting pins of the IMU. This was developed to provide a method for prototyping and test and evaluation of the GI-EYE targeting system. In the UAV GI-EYE system (**Figure 5**), the rifle scope test fixture is replaced by a video camera which is also precisely aligned to the IMU mounting pins.

To test the targeting accuracy, several reference points around the NAVSYS facility were kinematically surveyed to an accuracy of better than 10 cms. and visual targets were mounted at these points. The rifle scope test fixture was mounted on a pallet on a test vehicle and a test pattern was driven to align the navigation system using the INTERNAV precision alignment algorithm. After 20 minutes of driving the test pattern the vehicle was stopped and the three-axis fixture was leveled to within 20 arc seconds using a bubble level. The indicated reading of the INTERNAV pitch and roll was then taken. The three-axis table was then rotated to align the rifle scope's cross hairs with the reference targets, which were each at least 200 meters distant. Each observation was then marked be pressing a softkey on the

PC to time stamp the INTERNAV attitude and position data with GPS time. The postion of the test vehicle was derived post-test using kinematic data processing from the GPS and reference station data. The target coordinates derived from

Table 1 TANS III/LN200 INTERNAV system test data

Position Number	Heading Error #1	Heading Error #2
1	0.136 deg	0.164 deg
2	-0.229 deg	-0.173 deg
3	0.255 deg	0.281 deg
4	-0.142 deg	0.041 deg
5	0.093 deg	0.130 deg
6	0.033 deg	0.028 deg
7	0.277 deg	0.224 deg
8	-0.134 deg	-0.094 deg
9	-0.024 deg	-0.021 deg
10	-0.206 deg	-0.206 deg

the INTERNAV attitude and position data were compared with the known target coordinates to determine the targeting accuracy and inertial alignment errors. This test demonstrated the elements of battlefield targeting, as the location of each target was known and the attitude errors of the designation system were not. This precision targeting range at the NAVSYS facility provides a very cost effective and accurate method of determining the alignment accuracy of targeting system.

The tests were performed with two different configurations of the INTERNAV system. In the first configuration, a Trimble TANS III GPS receiver was used with a Litton LN200 IMU configured to give 100 Hz data. In the second configuration a Rockwell MPE 1 GPS receiver and a standard Litton LN200 IMU configured to give 400 Hz data were used. The LN200 is the Litton standard core missile system which has the performance characteristics shown in **Table 2**. The testing was performed using the C/A code Standard Positioning Service (SPS) updates which were not differentially corrected. The test results showing the heading accuracy are in **Table 1**.

Table 2 TANS III/LN200 INTERNAV system test data

Time Bearing	Measurement	Error
39.2080	39.347643	-.13964
39.2080	39.02549	.18250
55.6382	55.7585	-.14766
55.6382	55.53341	.10479
235.64	236.65	-.01
267.79	267.90	-.11
277.40	277.25	.15

The standard deviation of heading error from the first set of test data was 3.03 mrad (0.174 deg) and for the pitch and roll data 0.76 mrad (0.044 deg) and 0.78 mrad (0.045 deg), respectively. The standard deviation of the second set of test data was 2.4 mrad (0.142 deg) and the standard deviations for roll and pitch errors were 0.59 mrad (0.034 deg) and 0.61 mrad (0.035 deg), respectively. The combined heading error standard deviation across the two different systems was 2.78 mrad (0.159 deg).This shows that even with the inaccuracies (due to Selective Availability) with the SPS GPS data and with the low dynamic "pseudo-baseline" generated by the slow-moving test vehicle, the INTERNAV precision alignment algorithm was capable of providing heading

Figure 6 Rifle Scope Test Fxture

accuracies to 2.78 mrad (0.159 deg). This would provide target coordinates to an accuracy of 3 m at 1 km. Using conventional gyrocompassing techniques, the LN200 would only be able to provide 100 mrad (5 deg) which would result in 100 m of error at the same target range.

When a Precise Positioning Service (PPS) receiver is substituted for the SPS receiver in the next phase of testing, and a UAV test vehicle is used in place of the slow-moving land test vehicle, the targeting accuracy can be expected to improve to better than 1 mrad based on our simulation results.

CONCLUSION

The prototype testing performed on the INTERNAV precision alignment algorithms has shown a factor of 30x improvement over conventional gyrocompassing techniques. The GI-EYE targeting system being developed by NAVSYS Corporation under the DARPA Warfighter Visualization Program is designed for installation on a UAV to provide an airborne precision targeting capability from precisely georeferenced (position and attitude) video images. Under the next generation of the GI-EYE system, a man-portable targeting system using the same architecture is being developed using a Micro Electro Mechanical (MEMs) IMU. The MEMs technology advances have made possible a truly miniaturized personal inertial navigation system with very low power requirements. For example, the AlliedSignal : SCIRAS system, illustrated in **Figure 7** is projected to be 1.7" x .75 “, consume less than 1 watt, and to have 1 deg/hr turn-on-to-turn-on bias repeatability.

The UAV-based and man-portable GI-EYE systems being developed under the Warfighter Visualization Program, will provide the military with an order of magnitude improvement over current targeting systems using the INTERNAV precision alignment algorithms described in this paper. The GI-EYE system will be available for use in UAVs' in early 98 and a man portable version will be ready in prototype form in late 98.

6. REFERENCES

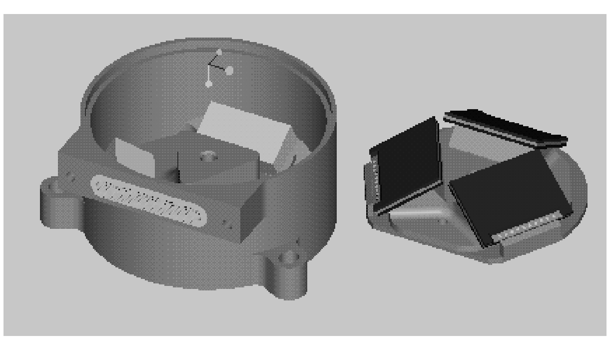

Figure 7 : SCIRAS Sensor Assembly

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