PRECISION NAVIGATION FOR UAS CRITICAL OPERATIONS

Alison K. Brown, Dien Nguyen and Paige Felker, *NAVSYS Corporation*
Glenn Colby and Frank Allen, *PMA-268 NAVAIR*

BIOGRAPHY

Alison Brown is the President and Chief Executive Officer of NAVSYS Corporation, which she founded in 1986. NAVSYS Corporation specializes in developing next generation Global Positioning System (GPS) technology. Dr. Brown has a PhD in Mechanics, Aerospace, and Nuclear Engineering from UCLA, an MS in Aeronautics and Astronautics from MIT, and an MA and BA in Engineering from Cambridge University. She is a fellow of the Institute of Navigation and an Honorary Fellow of Sidney Sussex College, Cambridge.

Dien Nguyen works for NAVSYS Corporation as a research engineer specializing in Kalman filtering estimations, kinematic positioning, and related navigational optimization techniques. He holds a BS in Electrical Engineering from Mercer University and a MS in Electrical Engineering from Clemson University

Paige Felker is a research engineer in the Algorithms and Analysis group at NAVSYS Corporation. She holds a BS and MS in Aerospace Engineering from the University of Texas at Austin.

Glenn Colby is the Chief Architect for the Navy Unmanned Combat Air System at the Naval Air Systems Command in Patuxent River, Maryland. Glenn has led the research, development, and testing of advanced aircraft, navigation and communications systems for over 26 years. Glenn received his B.S. in Aerospace Engineering with honors at the University of Virginia in 1984.

Frank Allen is the Technology Manager for the Navy Unmanned Combat Air System at the Naval Air Systems Command at Patuxent River, Maryland. In the last 16 years he has worked in management of research and development of advanced aircraft navigation and communications systems. Frank received his B.S. in Physics form the University of Massachusetts and M.S. in Physics from Northeastern University.

ABSTRACT

The Navy Unmanned Combat Air System (N-UCAS) is a carrier-based, autonomous combat air vehicle designed to conduct long-endurance strike and ISR operational missions. Due to its very nature, the N-UCAS requires the ability to perform precision navigation in a variety of roles. The current precision approach to support Autonomous Aerial Refueling (AAR) relies on a Precision GPS (PGPS) technique utilizing relative kinematic GPS positioning, coupled to an inertial navigation solution. This method depends on the tanker and the Unmanned Aerial System (UAS) tracking common GPS satellites, and then using relative pseudorange and carrier-phase differences to resolve the relative carrier cycle ambiguities between the aircraft's observations and thus determine their precise relative positioning to update the INS solution.

Under contract to the Navy, NAVSYS is developing an alternative PGPS architecture, termed Precision RELNAV (P-RELNAV) where the tanker and the N-UCAS are able to independently navigate to a high degree of precision without requiring carrier cycle ambiguity resolution using Precision GPS Ephemeris (PGE) updates to a tightly coupled GPS/inertial solution onboard each aircraft.

In this paper, we present test results that show how the PGE-enhanced navigation solution rivals that of conventional relative kinematic techniques while providing a more robust positioning solution that reduces message traffic between aircraft and does not require a long filtering time to obtain carrier cycle ambiguity resolution.

INTRODUCTION

N-UCAS (Naval Unmanned Combat Air System) is the Navy's program to demonstrate technologies and reduce risk for unmanned, carrier based strike and surveillance aircraft. The Unmanned Combat Air System Carrier Demonstration (UCAS-D) program is specifically maturing technologies for unmanned carrier operations and Autonomous Aerial Refueling (AAR). Successful demonstration of UCAS-D technologies provides for transition and risk reduction to future unmanned and manned programs.

A key enabler for N-UCAS is the ability to perform AAR so that the N-UCAS can support long duration missions. As shown in Figure 1, the intent is for AAR operations to mirror current manned Aerial Refueling operations as much as possible and to operate using existing Navy probe and drogue and US Air Force boom receptacle refueling methods.

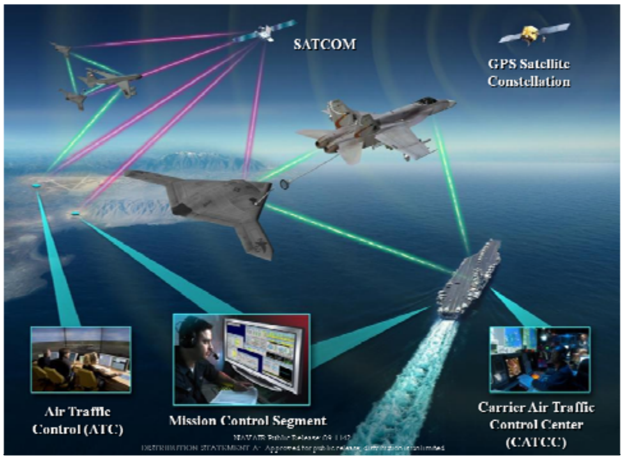

Figure 1 AAR Operational View

The planned refueling architecture for probe and drogue and boom-receptacle refueling developed by PMA-268 is shown in Figure 2 and Figure 3. For both of these architectures, the GPS/inertial navigation system on the UAS and tanker are used to calculate a precise relative position to be used by the UAS to approach the tanker from astern. For drogue systems, the final connection to the basket is performed using aiding from a laser-based drogue positioning system. In addition, an optional machine vision system is used to aid both methods of refueling from the receiver. Under the UCAS-D demonstration program testing is being conducted with surrogate aircraft to verify the CONOPS procedures and performance of the precision GPS/inertial navigation solution alternatives being evaluated. NAVSYS is supporting this program through a Small Business Innovation Research (SBIR) contract and is demonstrating a Precision-RELNAV (P-RELNAV) tightly coupled GPS/inertial solution that improves the robustness of the relative navigation solution as described in the following sections.

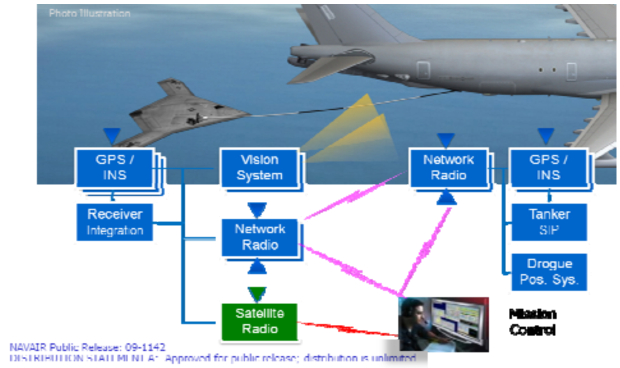

Figure 2 Probe and Drogue Refueling Architecture

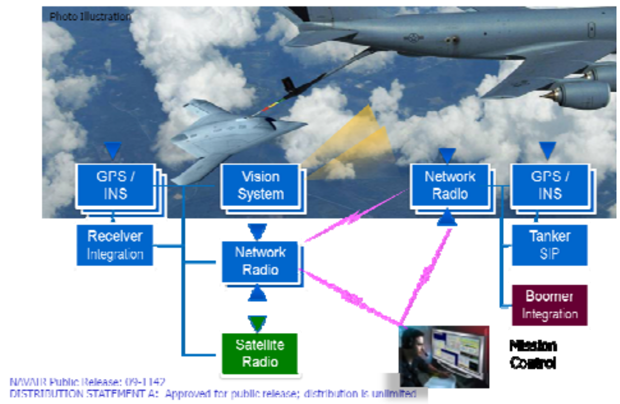

Figure 3 Boom Receptacle Refueling Architecture

PRECISION RELNAV ALGORITHM

The first method that PMA-268 implemented for computing a relative GPS solution used the GPS/inertial integration approach illustrated in Figure 4. The inertial navigation solution from both aircraft was used to calculate the relative inertial vector e that is used for the real-time AAR guidance. The tanker's raw GPS observations are also passed over the data link to the UAS where a relative kinematic solution is calculated to derive the carrier-phase based relative position between the aircraft, a. This approach relies on solving for the integer carrier cycle ambiguities on the observations from the two aircraft using the same algorithms that were previously developed for use in performing GPS precision approach and landings on the carrier. The precise GPS relative position is then applied to calibrate the inertial derived relative position and the resulting GPS/inertial solution is used to calculate an offset to the center of the refueling envelope (u) for guidance of the UAS to connect to the receptacle.

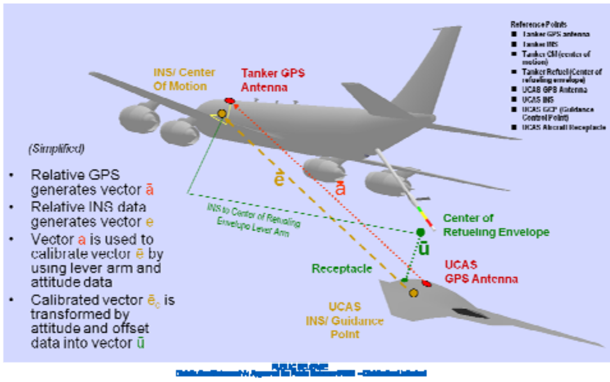

Figure 4 PGPS Relative GPS Positioning

With the P-RELNAV approach shown in Figure 5, Precision GPS Ephemeris data is provided to both aircraft across the tactical data links using the NAMATH system. As shown in Figure 6, NAMATH provides global services across military tactical data links through the Joint Range Extension (JRE) to provide real-time corrections to the GPS system errors using Zero-Age Precision GPS Ephemeris data, which is refreshed by the GPS Control Segment every 15 minutes. The NAMATH system is currently being used operationally by the US military to improve navigation accuracy and also precision weapons delivery.

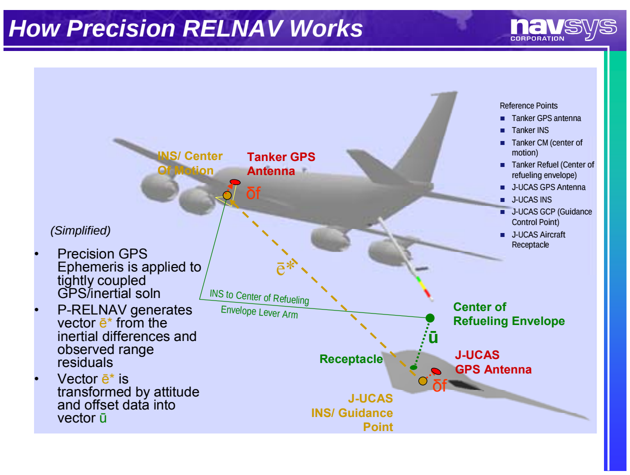

Figure 5 Tightly-coupled P-RELNAV Solution

Using the PGE corrections significantly reduces the errors on the GPS observations allowing the GPS/inertial solution to rapidly converge and not exhibit step changes during satellite transitions from the GPS system bias errors. The GPS/inertial Kalman Filter on the tanker is used to observe the residual errors from the GPS satellites being tracked, and these residuals ($\underline{\delta f}$) are sent from the tanker to the UAS which applies these as an update to its internal GPS/inertial Kalman Filter. As shown below, this final correction sets both the tanker and the UAS on a precise common reference frame resulting in a high accuracy relative position being derived from the vector difference of the two tightly-coupled GPS/inertial solutions ($\underline{e}^*$).

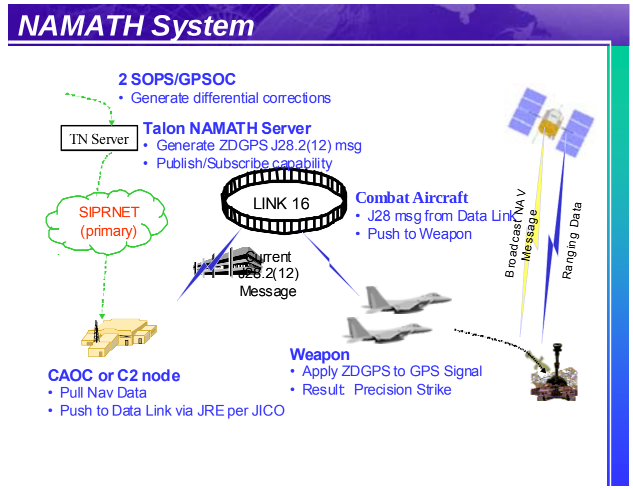

Figure 6 NAMATH Precision Ephemeris Delivery

Figure 7 shows the difference in the GPS position that is calculated using the Precision GPS Ephemeris as opposed to the Broadcast Ephemeris. This shows that over a month, there can be peak position excursions as high as 5 meters in the horizontal and 10 meters in the vertical based on the GPS broadcast ephemeris. With a GPS/inertial solution, these bias offsets will cause the solution to "trend" between different position bias offsets whenever the satellite selected set changes. This trending introduces significant errors into the relative inertial vector between two aircraft ($\underline{e}$).

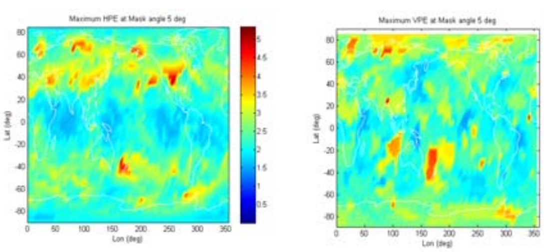

Figure 7 GPS Peak Position Errors from Broadcast Ephemeris Offsets (March 2010)

P-RELNAV FLIGHT TEST SET-UP

The P-RELNAV performance was tested using data collected on a UH-1 helicopter at Eglin AFB (Figure 8). Two independent GPS/inertial systems were mounted on the equipment plate below the aircraft (Figure 9) and a GPS reference receiver on the ground was used to calculate a kinematic position post-test using a Magellan ZXW receiver on the aircraft as a truth system. The PGE corrections were uplinked to the aircraft through EPLRS for use in calculating a PGE-corrected navigation solution. NAVSYS used recorded GPS and inertial data from a Kearfott KN4073 and a NovAtel/LN-200 inertial system provided by Dahlgren NSWC. The raw GPS (Pseudo-range and carrier phase) and IMU (high rate acceleration and angular rate) data was processed using our InterNav solution and also recorded for post-processing. This data was then played back through InterNav to calculate independent GPS/inertial tightly coupled solutions from the two inertial systems with and without the PGE corrections and to compare the performance of the absolute and relative solutions against the kinematic positioning truth data.

Figure 8 Flight Test at Eglin AFB 9-12 Aug 2010

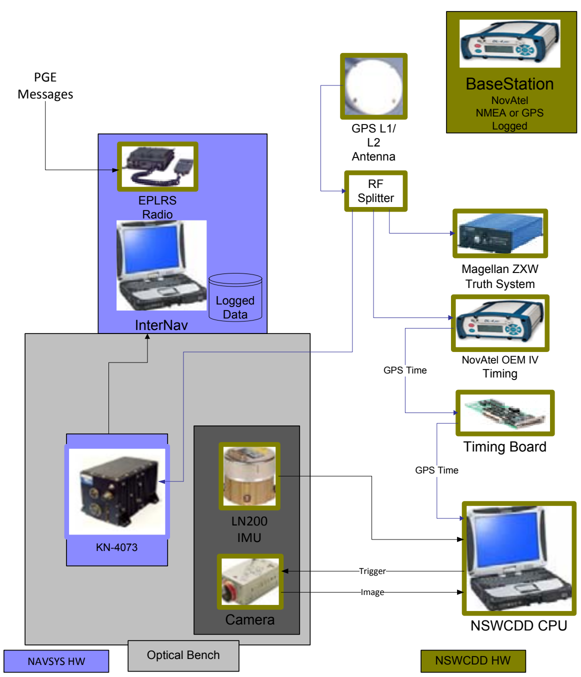

Figure 9 Flight Test Equipment

P-RELNAV FLIGHT TEST RESULTS

The P-RELNAV algorithms were implemented in our InterNav software[1] package. This has been previously used to generate very high accuracy relative kinematic solutions for providing high-rate Time Space Position Information (TSPI) for instrumenting F-16 aircraft[2]. The InterNav software was upgraded to apply the tightly-coupled GPS updates to the inertial solution using the PGE Zero-Age Differential GPS (ZDGPS) corrections, and also to apply the GPS residual updates ($\underline{\delta f}$) in the UAS Kalman Filter to compute the P-RELNAV relative position solution. Dual-frequency observations from the GPS receivers were used to correct for the ionospheric group delays in the solution.

The performance of the P-RELNAV solution was evaluated by comparing the results from the two independent inertial solutions for the same location on the UH-1 aircraft. Tests were conducted over multiple flights with the GPS antennas at different locations on the UH-1, as shown in Figure 8.

The results from the first flight test are shown in Figure 10 through Figure 14. Figure 10 shows the GPS/inertial results during the flight with a tightly-coupled solution but without PGE corrections. Figure 11 shows the GPS/inertial results during the flight with a tightly-coupled solution but with PGE enabled. Figure 12 shows the satellite visibility during the flight test. These plots show that the satellite geometry changes, dramatically affecting the inertial position covariance, whenever the satellites used in the solution change. The inertial filters these errors, but the relative solution is biased and drifts resulting in over 2 meter errors. In Figure 13 the same plot is shown when the PGE corrections are applied. This shows that the relative position error has been reduced to better than 1 m per axis and 35 cm 1-sigma. For flight critical operations, such as AAR, minimizing position excursions is essential. Figure 14 and Figure 15 shows a statistical measure of the percentage of time that the data exceeds a horizontal or vertical threshold. This shows the benefit of the PGE corrections in removing GPS excursions caused by satellite ephemeris errors from the navigation solution. (See the Appendix for a definition of the Inverse Circular Error Probable (ICEP) metric and its comparison with other statistical measures).

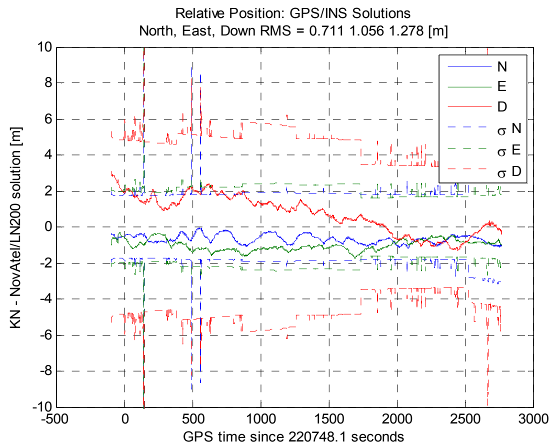

Figure 10 Flight 1: Relative position of KN and NovAtel/LN200 GPS/INS solutions

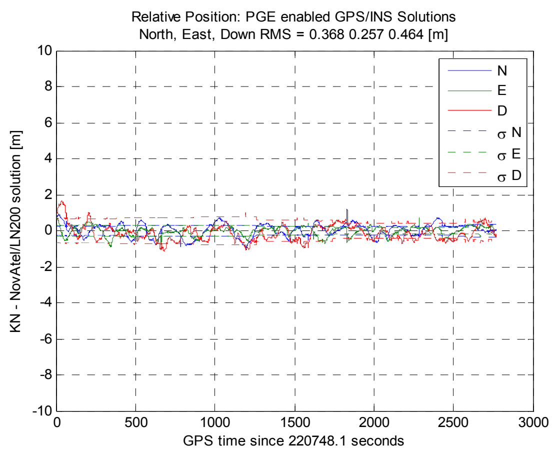

Figure 11 Flight 1: Relative position of KN and NovAtel/LN200 PGE enabled GPS/INS solutions

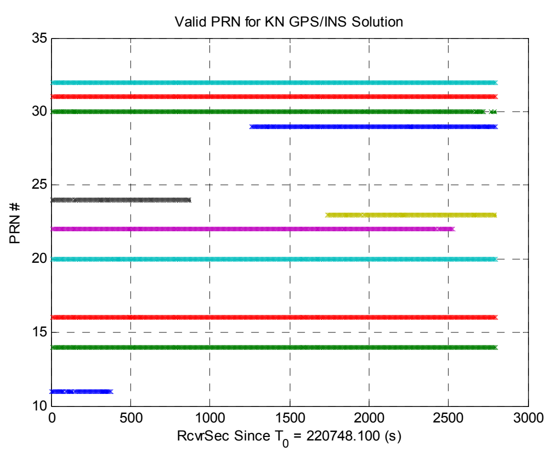

Figure 12 Flight 1: Valid PRNs used in KN GPS/INS solution

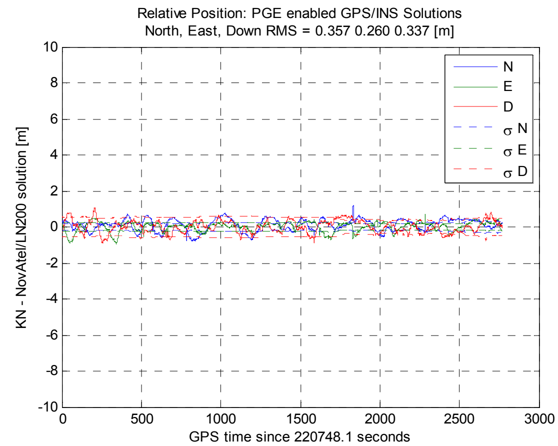

Figure 13 Flight 1: Relative Position of KN and NovAtel/LN200 PGE enabled GPS/INS solutions

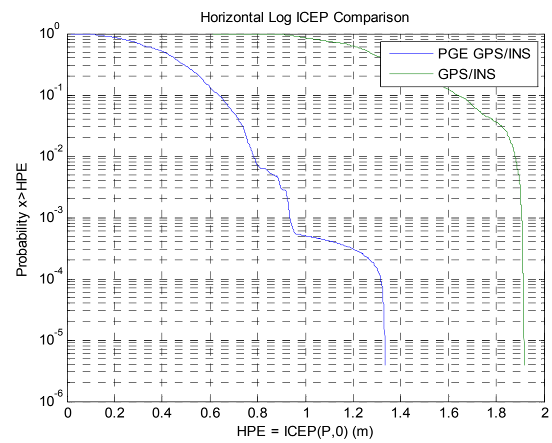

Figure 14 Flight 1: Horizontal ICEP comparison for PGE enabled GPS/INS and GPS/INS solutions

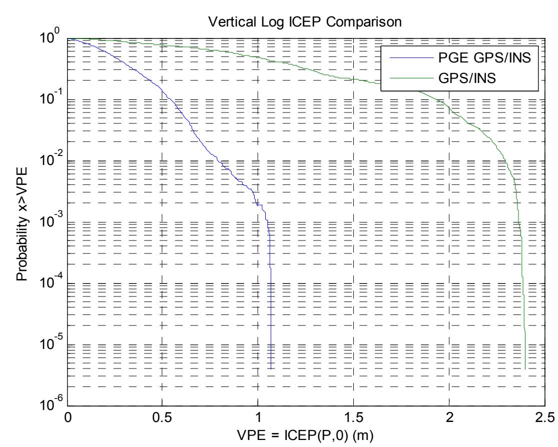

Figure 15 Flight 1: Vertical ICEP comparison for PGE enabled GPS/INS and GPS/INS solutions

Since both GPS receivers used in the test had a reasonably clear view of the sky, they were both tracking the same satellites. In the AAR CONOPS, the UAS approaches the tanker from below and so will have some satellites obscured from view by the tanker (see Figure 4). In this case, the use of different satellites can significantly increase the relative position error when PGE corrections are not available. In the case shown where one satellite was forced as a drop-out, the non PGE corrected vertical error grew to 4 meters for the relative solution.

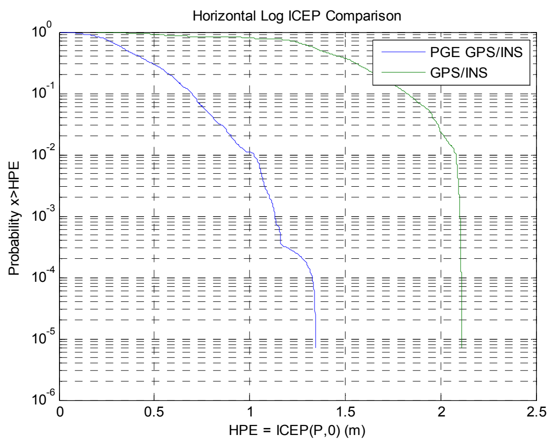

Figure 16 Flight 1: Horizontal ICEP plot for PGE enabled GPS/INS and GPS/INS solutions. Different satellites tracked by the receivers

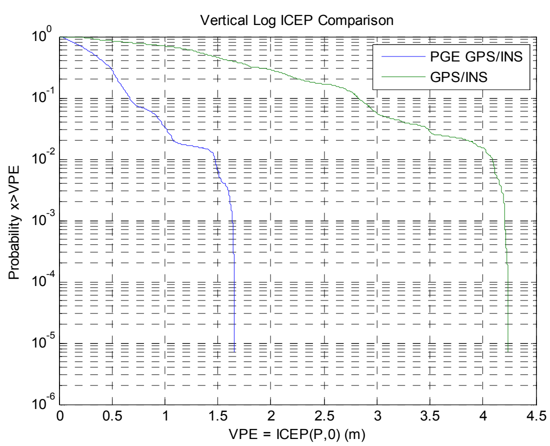

Figure 17 Flight 1: Vertical ICEP comparison for PGE enabled GPS/INS and GPS/INS solutions. Different satellites tracked by the receivers.

Further improvements in the P-RELNAV performance will be achieved using the residual (δf) update mode in the InterNav Kalman Filter to set the estimated observation residuals for the common satellites to the same values for the UAS and Tanker GPS/inertial filters. This mode is currently being tested and the results will be presented in a follow-on paper.

CONCLUSION

The P-RELNAV solution has the following advantages over using a conventional relative kinematic positioning solution in meeting the Automated Aerial Refueling precision positioning requirements.

- Fast initialization – does not require time for carrier ambiguity cycles to be resolved.
- Robust operation during satellite obscuration by the tanker – is not dependent on common satellites being maintained in view between platforms.
- Insensitive to loss of carrier lock – does not require cycle ambiguity reinitialization if carrier lock is lost during the UAS approach to the tanker.

Work is proceeding on testing the P-RELNAV solution. Additional test data is being collected for performance evaluation under the UCAS-D demonstration program using dual aircraft as surrogates to demonstrate the P-RELNAV performance and compare the benefits of the P-RELNAV tightly coupled approach with the PGPS kinematic solution.

This work was sponsored under NAVAIR contract N68335-10-C-0094. The authors gratefully acknowledge the support of PMA-268 and the assistance of NSWC Dahlgren in collecting the flight test data and providing the truth reference for the P-RELNAV analysis.

REFERENCES

[1] InterNav Modular GPS/Inertial Software, http://www.navsys.com/brochures/NAVSYS_InterNav.pdf

[2] M. Nylund, A. Brown and JJ Clark, “Kinematic GPS-Inertial Navigation on a Tactical Fighter”, Proceedings of ION GPS/GNSS 2003, Portland, OR, 9-12 Sept 2003, http://www.navsys.com/Papers/0309004.pdf

APPENDIX: INVERSE CIRCULAR ERROR PROBABLE (ICEP) DEFINITION

For safety of life applications, the statistic of the excursion events, for example when a horizontal error is outside the safe error bound, is often more important than the knowledge of the percentage of points that are within a smaller error bound, such as CEP or DRMS. These excursion, or low probability, statistics can be examined with the Inverse Circular Error Probability (ICEP) function. The ICEP provides the horizontal position error (HPE) with a specified probability that a result could be outside this value. An optional input to the function is a filtering time constant, with the filter applied to the time-series horizontal error data before calculating the ICEP. This separates the effect of bias errors from short term noise errors that could be filtered (for example with an inertial unit) from the HPE.

$$HPE = ICEP(P\%, \tau)$$

Where
HPE= Horizontal Position Error value [m]
P% = Percent of total horizontal errors (x) that are larger than HPE
τ = filter time constant to reduce short term white noise

Note that the Circular Error Probable (CEP) which is the radial value that encloses 50% of the positioning results is closely related to ICEP, with
CEP = ICEP(50%, 0)
Also the R95 which is the radial value that encloses 95% of the positioning results is related to ICEP, with
R95=ICEP(5%,0)

Other common statistics used are the DRMS and 2DRMS values which are defined below, are also related to ICEP through the following equations.

$$DRMS = \sqrt{E(x^2 + y^2)} = \sqrt{\sigma_x^2 + \sigma_y^2}$$
$$= 1.414\sigma = 1.2CEP = ICEP(P, \tau)$$

Accuracy Measure	**Probability (%)**	
DRMS (Distance Root Mean Square)	63 to 68	
CEP (Circular Error Probable)	50	ICEP(50%,0)
2DRMS (Twice the Distance Root Mean Square)	95 to 98	
R95 (95% Radius)	95	ICEP(5%,0)

From/To	**CEP**	**DRMS**	**R95**	**2DRMS**
CEP	-	1.2	2.1	2.4
DRMS	0.83	-	1.7	2.0
R95	0.48	0.59	-	1.2
2DRMS	0.42	0.5	0.83	-
1-sigma	1.177	1.414	2.47	2.828

For a Gaussian, uncorrelated error distributions with sigma of one meter in the range and azimuth axes, the ICEP is shown in Figure A-1 in blue[2]. For each horizontal position error value, the ICEP gives the percentage of the distribution that has larger errors. Also shown on this plot are the CEP, DRMS, 2DRMS and R95 values which match the 1-sigma scale factors shown in the table above. Figure A-2 is the same data with a $\log_{10}$ plot. In this plot the y-axis is probability rather than percent. This plot is useful for examination of outlier behavior, as it shows low probability events more clearly.

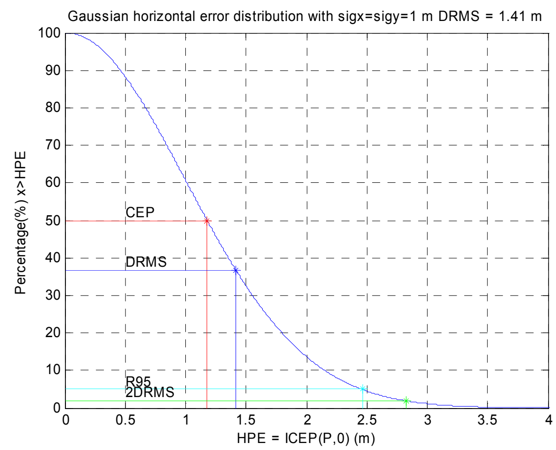

Figure A-1 ICEP(P,0) for a Gaussian Distribution with 1 m 1-sigma

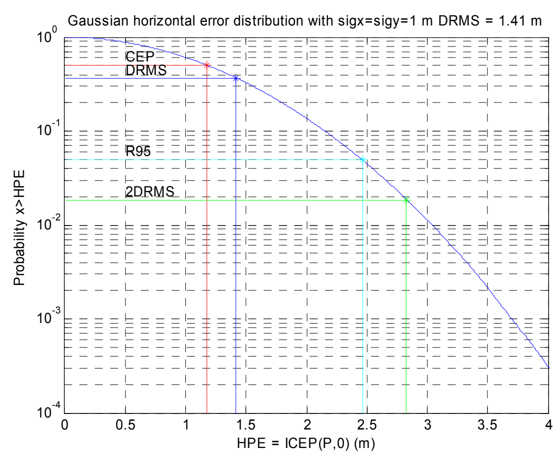

Figure A-2 Log Scale ICEP(P,0) for a Gaussian Distribution with 1 m 1-sigma