Development of Navigation and Automated Flight Control System Solutions for Maritime VTOL UAS Operations

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Since first flight on September 8th, 2004, The Boeing Unmanned Little Bird (ULB) program has served as a company owned low cost rapid prototyping platform to examine all aspects of vertical takeoff and landing unmanned aerial system operations. Designed with an optionally manned capability, the program has conducted most developmental flight test activity in civil airspace just north of the Boeing Facility in Mesa, Arizona. In 2005 and 2006, fully autonomous integration and firing of a prototype 50 cal machine gun, 2.75" rockets, and Hellfire missiles, as well as flight without a safety pilot on board were demonstrated at the U.S. Army's Yuma Proving Ground. Autonomous resupply concepts of operations, with both slung load and cargo pods have been flight tested, along with casualty evacuation. For several years now the ULB program has been examining various methods for precisely navigating to a moving vessel for vertical takeoff and landing unmanned aerial system launch and recovery operations. This paper describes a recent company sponsored flight test effort to integrate and demonstrate a novel and highly precise navigation system for use in a maritime environment. Included are modifications to the test helicopter, flight crew and engineering test crew training and qualification, and operational theory and an evaluation of the precision navigation solution. The result is a method to guide the Boeing H-6U vertical takeoff and landing unmanned aerial system to a predetermined precision landing anywhere on a ship deck, regardless of deck dimensions.

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INTRODUCTION

The Boeing Unmanned Little Bird (ULB) program was initiated in the fall of 2003 as an optionally manned vertical takeoff and landing unmanned aerial vehicle (VTOL UAV) developmental platform. Initial flight test activity was conducted using a modified MD530FF helicopter. First flight occurred on September 8th, 2004, with a fully autonomous multiple waypoint demonstration flight from takeoff through landing achieved six weeks later. After several hundred flight hours of simulated autonomous flight with a safety pilot on board, an unmanned flight was performed at the U.S. Army's Yuma Proving Ground on June 30th, 2006. The ULB team succeeded in creating a powerful VTOL UAV technology development and demonstration aircraft, assisting in the rapid development and understanding of operational concepts and requirements. The platform's autonomous capabilities continue to be expanded through low risk testing in support of UAV subsystems development.

A second highly upgraded developmental and demonstration test helicopter (H-6U) was built to support continuing VTOL UAV concepts of operation (CONOPS). This platform more closely resembles the Mission Enhanced Little Bird operated by the U.S. Army's 160th Special Operations Aviation Regiment, based at Fort Campbell, Kentucky. The H-6U offers a large increase in performance and payload over the original MD530FF technology demonstrator. The design approach and integrated test capability that the ULB program provides supports rapid development and cost avoidance in the growing VTOL UAV market.

Federal Aviation Administration (FAA) policy regarding civil UAS operations with a safety pilot on board forced flight test procedural changes in 2009. Flight test validation and verification of the trajectory control portions of Boeing's proprietary COMC2 ground control station software is now executed in cooperation with New Mexico State University's Physical Science Laboratory facility adjacent to Las Cruces, New Mexico.

When trajectory control of the H-6U by the ground control station is not required to accomplish the test objectives, flight testing can be conducted in civil airspace. In this environment, the automated flight control system (AFCS) is programmed to behave as a full authority autopilot. Navigation routes are pre-programmed and briefed, and the safety pilot uses a simple button push to allow the H-6U to progress between programmed waypoints. This button push emulates the command that would otherwise be provided by the ground control station operator, and this simple technique allows the ULB team to comply with current FAA policy.

The ULB program has realized tremendous value by employing the safety pilot approach. Flight control software can be evaluated in flight, updated and re-flown in a single day. Gains governing aircraft behavior can be modified in flight and fine tuned for optimal system performance. The safety pilot can allow the AFCS to misbehave long enough to insure data is collected that will define the system problem, allowing the engineering staff to gain a quicker understanding of malfunctions, and thus correct issues faster. Ultimately, the safety pilot is tasked with insuring that the H-6U does not depart to an attitude or situation where the helicopter cannot be recovered without damage or injury.

The Boeing Unmanned Little Bird H-6U program is currently partnered with French companies Thales and DCNS to develop and demonstrate a radio frequency (RF) based navigation system, a ship "green deck window" safe landing period predictor, and a deck lock aircraft capture device, all intended for VTOL UAV ship board terminal operations. The terminal area navigation system, known by the French acronym DAA, is designed to minimize ship

emissions and to be independent of satellite based navigation solutions such as GPS or GLONASS. The "green deck window" predictor and the deck lock system are designed to minimize human error and the risk of airframe or ship damage during decking operations in a variety of weather and sea state conditions.

The test program has been broken into several phases. Initial trials of the navigation system included the use of a 6 degree-of-freedom motion platform to examine the ability of the navigation system to compensate for ship motion. Concurrently, the "green deck window" predictor was evaluated. The mechanical deck lock (Figure 1, 2) testing began with static lab testing and progressed to manual then automatic engagements while landing to a platform that was underway.
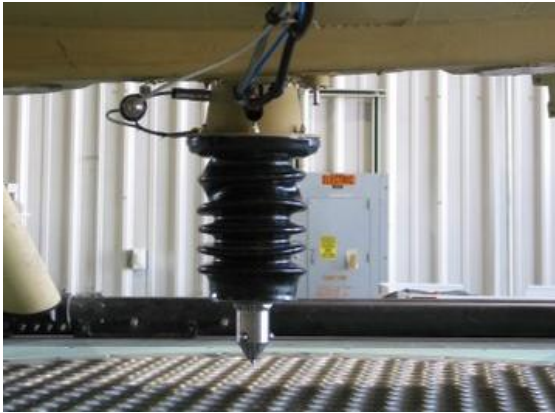

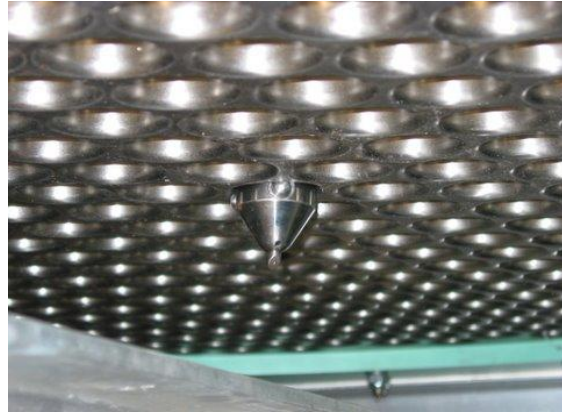Figure 1. Deck lock mechanism   Figure 2. Deck lock engaged in grid

Cost, safety, and logistical constraints demanded a unique developmental facility to support the intermediate phase of the test program. A tractor trailer rig was highly modified to emulate the landing deck of a frigate (Figure 3, 4). The trailer deck was extended to 16 feet wide with an aft load bearing helipad measuring 16' x 16'. The helipad was equipped with a NATO standard harpoon grid. The forward deck of the trailer was equipped with the RF navigation system, a tactical common data link (TCDL) for VTOL UAV command and control, a NovAtel OEM-4 SPAN differential GPS / inertial measurement unit truth data system, and various video cameras. The rig was towed by a specially modified command and control vehicle precisely maintained speed from 5 to 25 miles-per-hour. The test method allowed the accurate and rapid evaluation of the RF navigation and harpoon deck lock system to successfully navigate to a landing and secure the H-6U to the heli-deck. The in-motion test activity was accomplished using the vast runway facility at Spaceport America in New Mexico, which is under Restricted Airspace controlled by White Sands Missile Range.

During flight testing at Spaceport America, the OEM-4 SPAN system was flown in a real-time kinematic (RTK) mode with a local reference station; the baseline never exceeded 10,000 feet. Figure 5 demonstrates the level of accuracy in each dimension, comparing the RTK solution versus the post processed solution provided by Waypoint's Inertial Explorer software. This test vetted the NovAtel OEM-4 SPAN RTK solution for use as a "truth" source to evaluate the performance of the DAA radio navigation landing system.

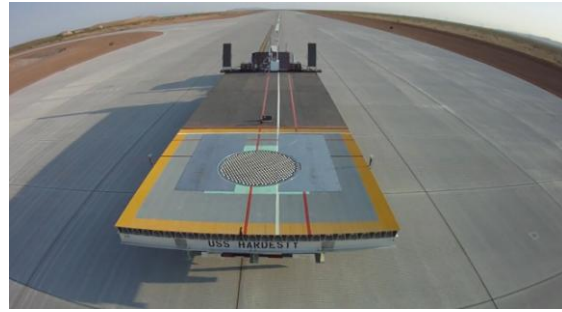**Figure 3. H-6U landing to the trailer helipad**

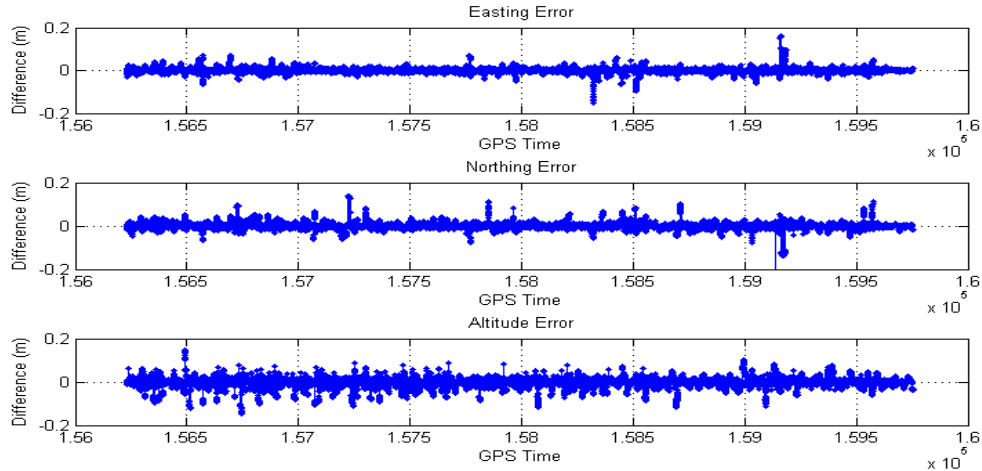**Figure 4. Pilot's view of the trailer helipad**

Figure 5. H-6U mounted OEM-4 SPAN RTK vs. post processed accuracy plot from Spaceport America flight test

PREPARATIONS FOR MARITIME FLIGHT OPERATIONS

H-6U Cockpit Instrument Panel Upgrades

The H-6U cockpit instrument panel was originally equipped for VFR flight in a non-visually degraded environment. This cockpit instrumentation was considered adequate for flight visibility conditions that almost always exist in the desert southwest of the United States, where most flight test activity has occurred. Visibility conditions that can be expected in a maritime environment such as the western Mediterranean demanded a complete cockpit instrument panel redesign.

Boeing Flight Operations in Mesa, Arizona utilizes a Eurocopter AS-350B3 helicopter for chase and crash rescue duties. This helicopter is equipped with a Garmin G500H glass cockpit display system. The expense of training pilots on different cockpit designs and the complexities of operating various avionics suites made common cockpit avionics architecture a logical decision.

The H-6U was also in need of a new RADAR altimeter for terminal and near-Earth flight operations. Research suggested that Garmin was in the process of developing a device that would

be integrated into the G500H cockpit display system, and whose output could also provide data to the H-6U AFCS where it could be integrated into the flight control laws. Boeing and Garmin agreed to work together to evaluate the performance of the new device, with antennas mounted on the tail boom of the H-6U. Often, RADAR altimeter antennas are mounted on the belly of a helicopter, an installation that can render the device useless when interference below the helicopter exists. The tail boom antenna placement allows use of the RADAR altimeter data during slung load operations, as well as while landing to a NATO standard deck lock grid (Figure 6, 7). The Garmin cockpit avionics suite (Figure 8) consists of:

- GMA350H communications control panel
- GTN635 VHF / GPS nav/com panel
- GTS800 traffic collision avoidance system (TCAS)
- GTX33H Mode S transponder
- G500H integrated primary flight display (PFD) and multifunction display (MFD)
- GRA5500 RADAR altimeter

Figure 6. H-6U RADAR altimeter antennas

Figure 7. Prototype antenna installation

Figure 8. H-6U instrument panel

Test Crew Training For Maritime Operations

Flight test operations involving the trailer equipped helipad resulted in over 100 landings to the moving rig. While a challenging landing deck at only 16' x 16' (the H-6U landing gear width is a bit over 8 feet), the only motion environment the heli-deck presented to the safety pilot was linear translation down the Spaceport America runway. Ships at sea exhibit the following heli-deck motion: pitch; roll; yaw; heave; sway, and surge. Conducting terminal flight operations in this environment, which also includes the wind turbulence generated by the ship super structure created a requirement for safety pilot training in a maritime environment. As four Boeing engineers and technicians will also be required to reside and conduct the flight test on the French frigate for a period of two weeks, both a suitable training vessel and qualified trainers were investigated. After an extensive search, a helipad equipped yacht (Figure 9) that was available on a weekly lease basis was located in Fort Lauderdale, Florida.

Figure 9. Allure Shadow

The Squadron, a company that specializes in training both flight crews and deck hands in the super yacht industry, was engaged to provide maritime environment training to the test team (Figure 10). Staffed by helicopter pilots formerly of both the US Department of Defense and the United Kingdom's Ministry of Defense, The Squadron was able to provide deck qualification pilot training to a standard equal or exceeding US and UK military requirements. Interestingly, there is no Federal Aviation Administration certification similar to deck qualification training common to a military training program. An additional safety requirement for the flight crew was helicopter dunk tank training, which was completed prior to the flight test program at Louisiana State University's facility in Lafayette, Louisiana.

Figure 10. The Squadron conducting various crew training

The Shadow Marine Allure Shadow is equipped with a helipad that measures 34 feet wide by 50 feet long. Around three sides of the helipad are safety nets that are raised about 5 inches above the helipad surface. At the forward edge of the helipad is an overhang from the pool deck above. This overhang presents a contact hazard for the helicopter main rotor system. The safety net system around the other 3 sides of the helipad presents a contact hazard for the helicopter's tail structure (Figure 11).

Figure 11. Structural clearances

The dimensions of the H-6U are: main rotor diameter - 27.5', tail rotor diameter – 4.75'; total helicopter length rotor tip to rotor tip – 32.06'. The stinger, the lowest part of the vertical stabilizer is approximately 2.5' above the landing surface. The Squadron advised a minimum of 3' lateral clearance from the stinger to the edge of the helipad where the safety net frames protruded upwards, and a minimum of 10' lateral clearance between the main rotor blades and the closest ship structure. A careful survey of the helipad yielded a zone of approximately 5' fore and aft in which the safety pilot could allow the H-6U to land and insure safe structural clearance. Simple but highly effective markers were installed to create a visual cue environment which would enhance the flight crew's judgment regarding a safe landing zone (Figure 12). The proximity of the helicopter rotors to the yacht structure, while fairly tight compared to dimensions generally found on US DOD vessels, is common in the super yacht world.

Risk mitigation dictated that Boeing provide H-6U trained fire/crash rescue personnel and firefighting equipment (Figures 13, 14) independent of the Allure Shadow crew. The Squadron conducted a review of all yacht safety equipment and emergency procedures, provided maritime environment training to Boeing fire/crash rescue personnel, and trained the flight test engineering staff in ship board flight operations procedures.

Figure 12. Safe landing zone visual cues (orange lines)

Figure 13. Boeing fire/ crash rescue crew

Figure 14. Portable fire suppression system

Ship State Monitoring

Knowledge of the ship motion while underway is crucial to insuring the limitations of the test helicopter are respected during landing and takeoff operations. A system developed for the US Navy by Hoffman Engineering Associates, the "Landing Period Designator" or LPD, was installed and operated by the developer during the flight test program. This system provided trend information, absolute deck motion data, and a green, yellow, or red deck condition indication, insuring terminal operations were conducted within the limitations of the test helicopter (Figure 15). Of particular interest was the ship motion in the sway axis (lateral back and forth motion), which could contribute to a dynamic rollover event if limits were exceeded.
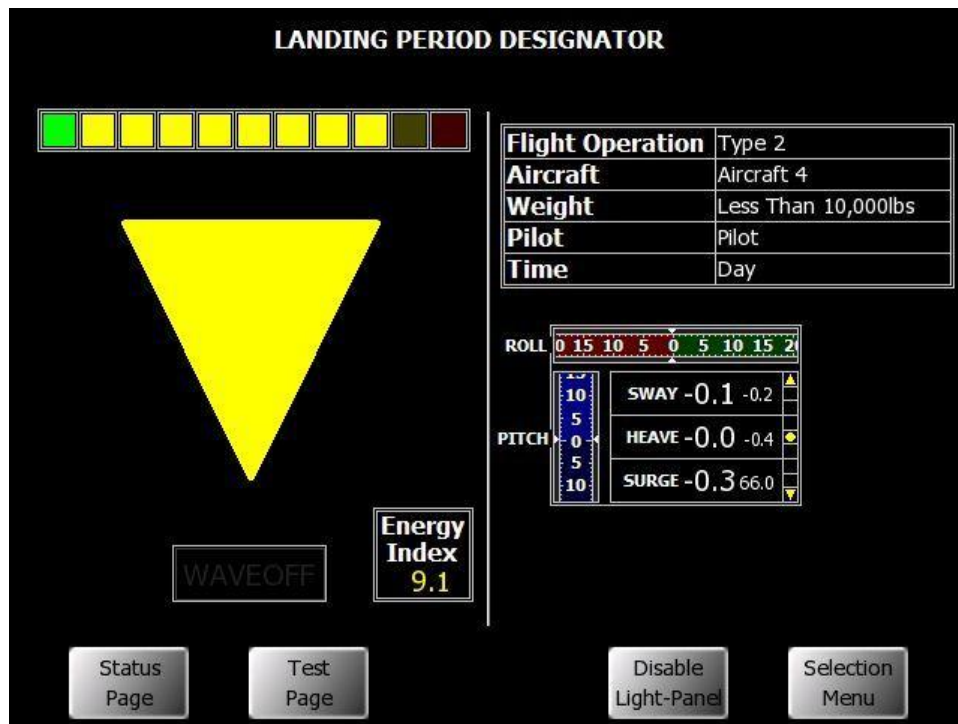
Figure 15. LPD indicating a "yellow deck" condition

Relative Navigation System Methodology

This application requires continuously precise and accurate relative positioning of the helicopter and the ship. The solution implemented by NovAtel uses global navigation satellite system (GNSS) positioning and inertial navigation, and is a modernization of the system previously demonstrated in 2005.[7]

The conventional way to achieve precise positioning with GNSS is to transmit code and carrier phase corrections from a stationary base station at a known coordinate to the rover receiver. The position of the rover receiver is computed with respect to the base station, with typical accuracies of 1 centimeter (cm) plus 1 part per million (ppm) of distance between the base and the rover (baseline) when a fixed integer solution is possible. In order to achieve fixed integer accuracies a set of minimum criteria must first be met. A minimum of 5 common satellites must be tracked between the base and rover combination. Furthermore, a continuous and robust radio link must be maintained at all times. The failure of either of these criteria, albeit to environmental masking or intermittent radio link, will result in the inability to achieve the highly accurate differential solution.

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[7] Tom Ford, Mike Bobye, and Mark Hardesty, "Helicopter Shipboard Landing System", Institute of Navigation GPS 2005 International Conference, Long Beach, California, September, 2005.

When landing a helicopter onto a ship, a number of difficulties with the conventional approach to precise GNSS positioning arise. Due to the mobility of the ship and its ability to operate in remote locations, establishing a stationary base station becomes highly impractical if not impossible. Additionally, varying dynamics of the ship and helicopter can result in highly variable constellations with respect to a stationary base station. If the changes in the satellite constellation become too poor, the geometric strength determined by the geometry of the available observations can become too weak and may result in the loss of the GNSS solution altogether.

Real time kinematic (RTK) algorithms solve for the position offset vector from the base to the rover receiver. The base receiver does not have to be stationary, and it does not need a highly accurate known coordinate if the only quantity of interest is the relative displacement of the rover with respect to the base. NovAtel's ALIGN™ algorithm provides a relative RTK solution. It can be used with two receivers that do not move with respect to each other – a fixed baseline implementation – to solve for the heading and pitch of the fixed baseline. It can also be used with two receivers that are moving with respect to each other – a moving baseline implementation. In this case, the base receiver has a single point (autonomous) GNSS position solution, and transmits code and carrier phase corrections to the rover based on that position. The rover then uses those corrections to compute the vector from the base to itself, resulting in a RTK quality solution between the two receivers, but a single point quality absolute position solution for both receivers.

The moving baseline RTK solution has the same benefits and drawbacks as a fixed baseline RTK solution. The main benefit is a very precise relative solution because the distance between the base and rover is quite short. The drawbacks are the usual challenges of requiring constant communication between the rover and the base, as well as maintaining enough common satellites during the landing maneuvers as the helicopter approaches the ship deck.

Inertial navigation system (INS) is typically added to a GNSS solution to address issues like these. With a GNSS/INS system, the INS can coast through periods of GNSS signal blockage or degraded GNSS solution quality. INS provides good relative accuracy over time, allowing it to "hang on" to a high accuracy solution. For very precise relative positioning between two systems, there are a few limitations to the accuracy the INS can provide during GNSS blockages or communication failures.

The INS relative accuracy is with respect to itself and both the ship and helicopter GNSS/INS solution will start to drift without GNSS aiding. Their drifts will depend on their respective residual inertial errors, which are not dependent on each other and could be drifting in opposite directions, maximizing the relative ship to helicopter solution disparity. The IMU quality will dictate how quickly the free inertial solution will drift. For a tactical grade IMU used in a synchronized position attitude navigation (SPAN) system, the position will drift 10-15 cm over 10 seconds without any external aiding. A navigation grade IMU would reduce this drift to 5-8 cm over the same time interval.

Another usually beneficial aspect of GPS/INS is that the integration filter used to combine the two systems results in a smoother solution than GNSS alone. A GNSS single point position will have a fair amount of variation due to multipath, atmospheric errors, and especially changes in satellite constellation. A typical single point GNSS position standard deviation is approximately 3 meters (m), while a typical single point GNSS/INS position standard deviation is <1 m. Figure 16 provides an illustration of this.
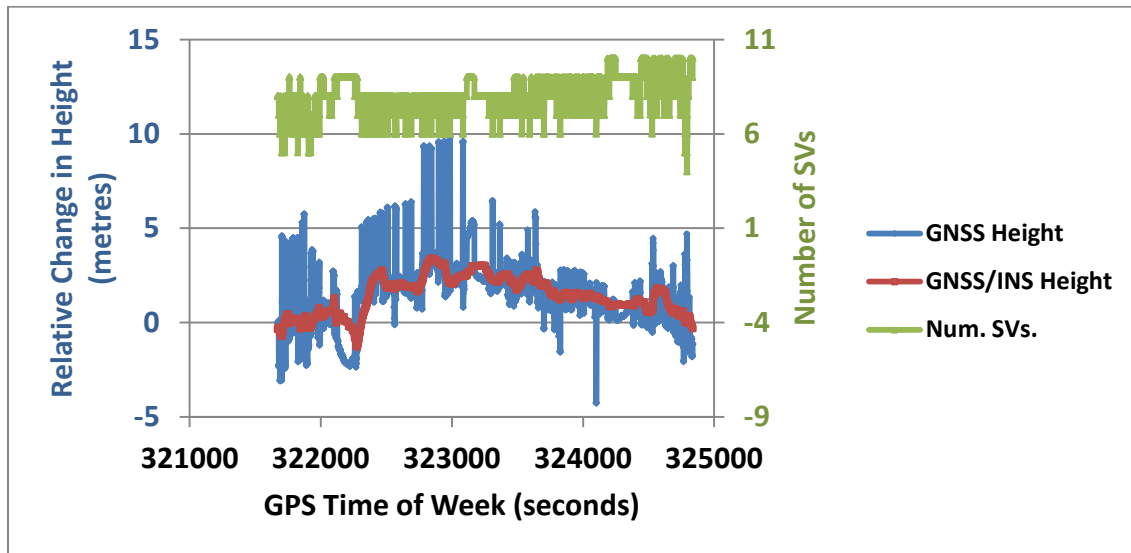
Figure 16. Single Point GNSS Height vs Single Point GNSS/INS Height

The difficulty this poses in the inertial moving baseline case is that the ship and helicopter INS may not smooth out the GNSS variations in the same way. Just as the drift of both INS systems are not related to each other, the smoothing that both INS's do is also not directly tied to the other. The rover GNSS/INS needs an absolute coordinate to update the INS. The coordinate used to update the rover INS is computed by adding the estimated relative RTK vector to the base receiver's single point position. Both the ship and helicopter systems are using coordinate updates that have single point absolute accuracy, and the rover's update coordinate error follows the base's coordinate error. Since the rover and base single point GNSS solution errors could vary significantly, due to different constellation views or multipath, this approach minimizes the difference in errors in the coordinate updates used on the base and rover.

To further strengthen the relative accuracy of the INS solutions, delta phase updates are continually applied as well. The delta phase update computes a precise position displacement from carrier phase measurements differenced between satellites and over time. This position displacement update is accurate to the several millimeter level (cycle slip detection is in place) and is available whenever 2 or more satellites are available. The delta phase updates will constrain the drift of the INS solutions if there is a partial GNSS outage (<4 satellites), and also help to further smooth out discontinuities from GNSS position jumps, usually due to constellation changes.

The differential corrections are sent from the base to the rover at 10 Hz. (The rate limit on this is imposed by the data link capacity not the GNSS receiver.) The INS is updated at 1 Hz. While the relative RTK solution is available (ie data link is working properly and an RTK solution is possible), a position correction is applied to make the output GNSS/INS position match the RTK position exactly. The update coordinate approach described above seeks to minimize the size of the position correction. In the event the RTK solution is no longer available, this post-update correction is only applied for 10 seconds. After approximately 10 seconds, the error from the inertial drift becomes larger than the GNSS to GNSS/INS offset and applying the position correction no longer has a benefit.

The relative attitude measurement between the ship and helicopter does not benefit from the moving baseline RTK implementation. It is computed by differencing the ship and helicopter GNSS/INS attitude solutions. The variance of the relative attitude solution is effectively the combined variance of the ship and helicopter attitude solutions.

In this helicopter landing aboard ship application, the quality of the attitude solution on the ship's system plays the most significant role in determining the overall relative accuracy. The ship's GNSS/INS system is mounted in a convenient location away from the landing pad, but the landing pad is the true point of interest. Similarly, the landing gear is the point of interest on the helicopter, not the location of the inertial measurement unit (IMU). Both SPAN systems must project the GNSS/INS solution from the IMU to the point of interest. To do this coordinate projection, the offset vector from the IMU must be measured in the IMU frame and the rotation matrix between the IMU frame and the ECEF frame must be known. The accuracy of the solution at the point of interest therefore depends on the quality of the measured offset as well the quality of the rotation matrix from the IMU frame to ECEF frame. This rotation matrix is maintained as part of the INS solution. The quality of the rotation matrix is very dependent on the quality of the initial INS alignment (i.e. finding the IMU's orientation with respect to gravity and north), and the overall convergence of the GNSS/INS solution. The longer the offset vector is to the landing pad, the larger the impact of the rotation matrix errors (i.e. a classic pointing error in survey terminology). Attitude errors in GNSS/INS are best observed with vehicle dynamics. In particular, horizontal accelerations allow the azimuth error to be observed, and controlled.

Depending on the size of the vessel, the dynamics observed aboard a ship can be very low leading to degradation in the azimuth solution. The initial alignment poses another challenge as well. A stationary coarse alignment can be performed with tactical grade IMUs, but only when the system is truly stationary. A transfer alignment can be performed with the GNSS course over ground azimuth and pitch, but only when the vehicle's forward direction of travel is aligned to the IMU's forward axis (or there is a fixed known offset between them). With a ship or helicopter, this condition cannot be assured due to crab angles. For the ship's system, it will often be moving enough to prevent a stationary alignment, it is not guaranteed to be moving without any crab angle, and even if an alignment is achieved, the dynamics will likely be too low for good GNSS/INS convergence. This will degrade the quality of the projected coordinate at the landing pad, which is what the helicopter is aiming for.

The helicopter system suffers a similar challenge in initial alignment. Helicopters are not an ideal platform to use a transfer alignment from GNSS course over ground measurements, due to their maneuverability.

To solve the initial alignment problem (on ship and helicopter), and to address the attitude error convergence/observability problem (on the ship), the GNSS/INS was augmented with a second GNSS receiver and antenna, using the fixed baseline implementation of the ALIGN™ relative RTK algorithm. The ship's GNSS/INS has two GNSS antennas associated with it, as does the helicopter's GNSS/INS. The offset vector from the IMU to both antennas must be measured and input. The pitch and heading of the baseline between the two antennas is used for the initial INS alignment. Since it is unobservable with just two antennas, the roll angle is assumed to be zero in the initial alignment. After alignment, the GNSS azimuth is used as a heading update to the INS. This is critical for the ship system, since it will be experience low dynamics making the attitude errors less observable. For the helicopter system, the GNSS

azimuth updates are not as vital since the helicopter maneuvers much more and its attitude errors are generally observable via the vehicle dynamics.

Equipment Description

Both the ship and the helicopter were outfitted with SPAN-SE-D™ dual antenna GNSS/INS receivers. The ship system used two NovAtel 702GL antennas. The ship system used a Northrop Grumman LN200 IMU, while the helicopter system used a Honeywell HG1700 AG58 IMU.

The data links used between the SPAN-SE-D receivers were Microhard 2.4 GHz IP2421 frequency hopping spread spectrum RF modem radios. The data links transmitted differential correction data between the ship and the helicopter as well as transmitting the navigation solution back to "command center" (Figure 17).

Test Setup and Description

The lever arms (offset vector from IMU to GNSS antenna) and point of interest offset vectors were measured with survey instruments while the ship was docked. During the survey, it was exceptional windy, leading to ship motion and lower accuracy lever arm determinations than desired (Figures 18 – 20).

Figure 17. Command center view

Figure 18. GPS antenna installations

Figure 19. SPAN IMU installation

Figure 20. Total station survey

The H-6U was equipped with the primary antenna on the "T" tail, secondary antenna on the nose, and a LASER micrometer mounted on the belly center to measure absolute displacement of the belly above the heli-deck on initial touchdown, and the final height after the landing gear had settled (Figures 21 – 23).

Figure 21. Primary and nose GPS antennas

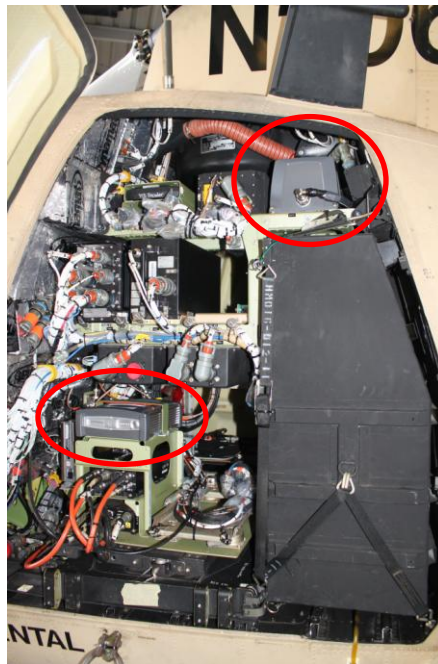**Figure 22. LASER micrometer installation**

Figure 23. NovAtel SPAN-SE-D processor & LN200 inertial measurement unit installations

Tables 1 and 2 show the measured offset vectors. Since the lever arm quality was suspect during the test, a specific set of figure-eight maneuvers was executed to allow for lever arm estimation in post-processing with NovAtel's Waypoint Inertial Explorer ™ software. When the primary lever arm for the ship system was estimated in post-processing, a significant error in the height component was determined.   Table 3 gives the post-processed ship offset vector sum, which are accurate to approximately 10cm.

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Table 1. Surveyed lever arms

System	Lever Arm	X (m)	Y (m)	Z (m)
SPAN LN200 on ship	Starboard Antenna (Primary)	2.80	-0.36	5.44
	Port Antenna	-2.61	-0.36	5.44
SPAN HG1700-AG58 on helicopter	Starboard Antenna (Primary)	0.42	-4.74	1.20
	Port Antenna	0.28	2.13	-0.39

Table 2. Surveyed IMU to point of interest offsets

From	To	X (m)	Y (m)	Z (m)
SPAN LN200	Helipad Target	0.09	-12.52	-0.13
SPAN HG1700	Aircraft Belly	0.28	0.31	-1.32

Table 3. Post-processed ship system offset vectors

Lever Arm	X (m)	Y (m)	Z (m)
Starboard Antenna (Primary)	2.80	-0.36	5.08
Offset to Helipad Target	0.09	-12.52	-0.09

The real-time relative ship to helicopter solution was output in the log RELINSPVA, which was transmitted back to the "command center" via radio link. The raw inertial and GNSS data was logged onboard the SPAN-SE-D receivers, to be able to post-process the ship and helicopter conventional RTK trajectories, using continually operating reference station (CORS) base station 'LAUD' located about 25 km from the test area, and the Inertial Explorer™. The accuracy of each post-processed trajectory was ~3cm. For performance analysis, the real-time ship to helicopter relative position vector was compared to the post-processed ship to helicopter relative position vector. The real test of the performance came in the real-time testing and was evidenced through several successful autonomous landings. Tests were undertaken on July 4th and 5th, 2012 off the coast of Ft. Lauderdale, Florida.

Test Results from Morning July 4

For most of the morning, the aircraft performed maneuvers behind the boat, following its movement, and was also allowed to approach the landing pad and hover over the landing point to provide a sufficient confidence level that the system was functioning as expected. The aircraft

performed a single automated landing before returning to the airport for fuel. The trajectory of the boat (green) and the aircraft (red) are shown in Figure 24.

Figure 24. July 4 morning test trajectory

The aircraft autonomously landed on the helipad at time 316350s to 316772s. The SPAN system on the helicopter reported a real time relative position of 0.024m North, -0.028m East, and 1.09m Up to the helipad center. The helicopter belly height measured was approximately 64cm, so the real-time results seem to have about 40cm of vertical error. This vertical error matches the vertical lever arm error. In post-processing, the new lever arm was used and the average relative position values of the helicopter on the landing pad were -0.383m North, -0.298 East, and 0.771 Up, which agrees much better to the known helicopter belly height. Figure 25 shows the real-time relative solution of the helicopter landing gear to the landing pad. Figure 26 shows the difference between the real-time and post-processed relative position solutions while the helicopter was landed. Recall that the real-time solution has ~35cm of height error due to the lever arm used in real-time.

The nature of the test program did not allow for extensive tuning of the automated flight control system to respond in an optimal fashion to the navigation data input. Nevertheless, the results from the initial test program were impressive. Table 4 presents the difference between H-6U position at 10' above the helipad, and after landing to the helipad for one sortie.

Table 4. Ship landing guidance and control errors

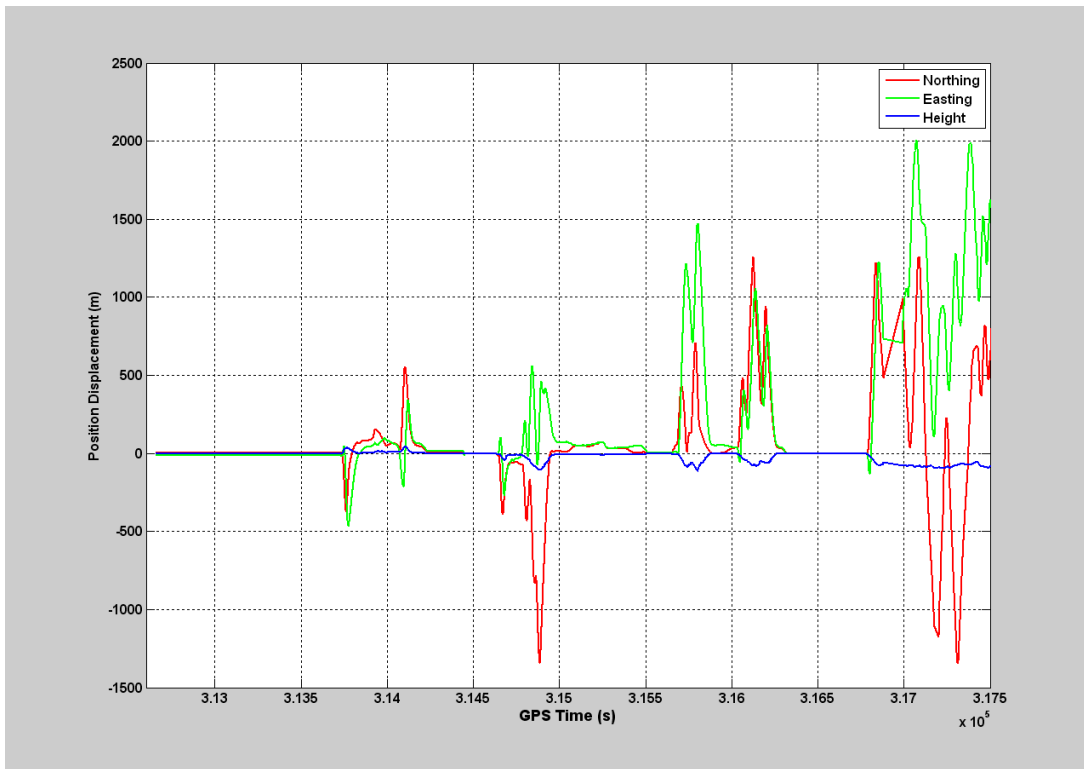| Landing	10' over the pad		On the pad	
	Longitudinal (ft)	Lateral (ft)	Longitudinal (ft)	Lateral (ft)
1	0.5 Aft	0.1 Right	1.5 Fwd	0.1 Right
2	1.2 Aft	0.7 Right	0.5 Aft	0.8 Right
3	1.0 Aft	0.2 Right	0.3 Fwd	0.6 Left
4	0.7 Fwd	0.1 Left	2.6 Fwd	0.1 Left
5	0.2 Fwd	0.5 Left	0.5 Fwd	0.3 Right
6	1.0 Fwd	0.4 Right	1.5 Fwd	0.7 Left

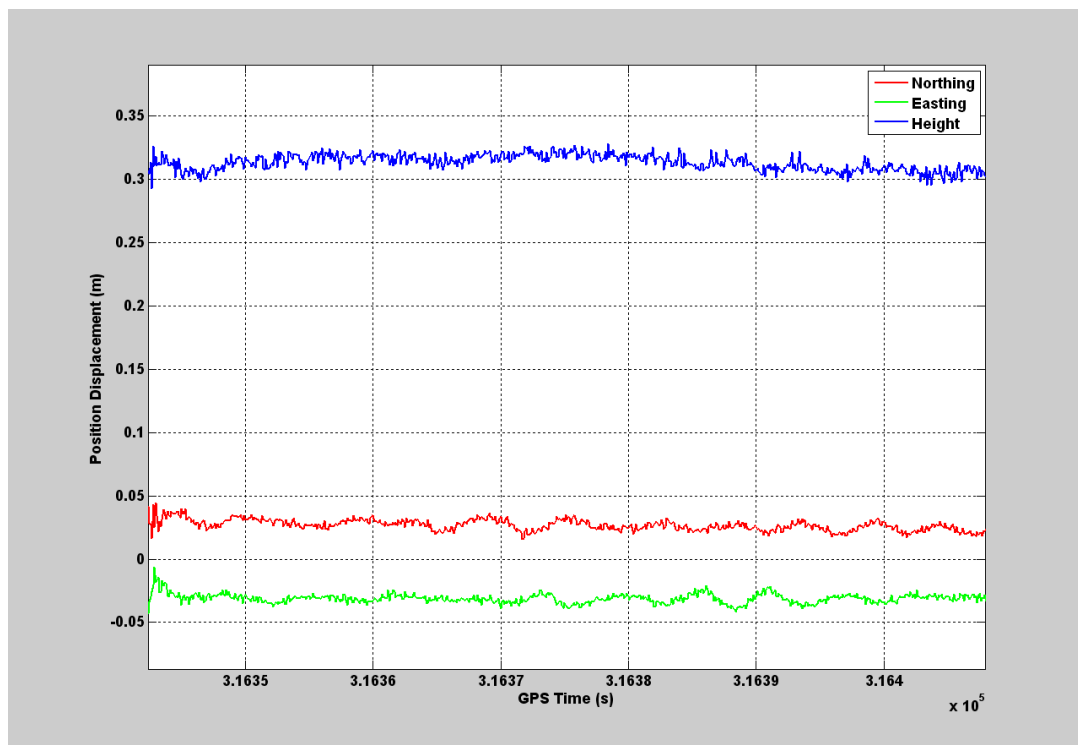**Figure 25. Real-time relative position solution**

Figure 26. Real-time to post-processed relative vector differences

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The Garmin GRA5500 RADAR altimeter output compared very favorably with the NovAtel RTK solution (Figure 27). The tail boom antenna installation should offer excellent functionality for slung load operations where the load interferes with the radio wave returns, or landing to a deck lock grid equipped deck where multi-path below the mechanical grid surface will render the output completely unreliable. Incorporation of reliable RADAR altimeter data into the terminal operations solution enhances the reliability and redundancy of the navigation method.
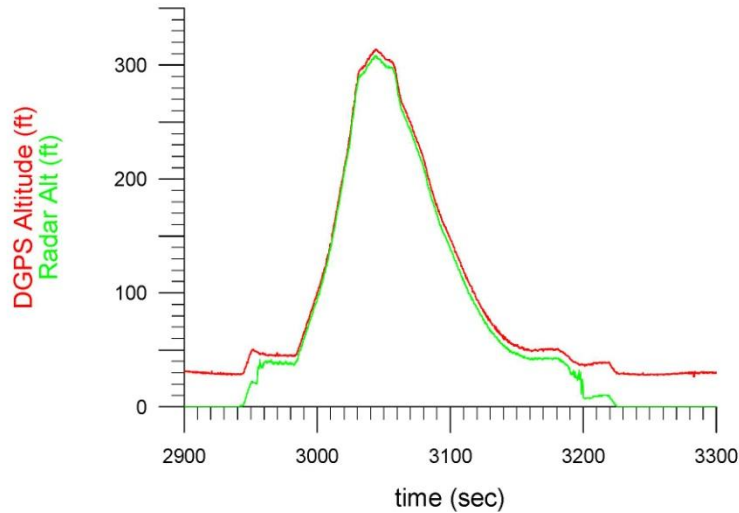
Figure 27. GRA5500 RADAR altimeter compared to NovAtel SPAN-SE-D

Conclusion

Flight tests performed in 2005 and 2006 provided encouraging results for the initial development of a moving baseline relative navigation system. Extensive flight test activity at Spaceport America vetted the integrity of the NovAtel OEM-4 SPAN system as a performance evaluation tool for navigation systems such as the Thales DAA radio navigation system.

Flight test activity in 2011 at Spaceport America demonstrated the integrity and accuracy of the NovAtel OEM-4 SPAN solution, certifying that system for TSPI applications. Over 100 landings were made to the moving trailer helipad. This most recent maritime flight test effort demonstrated the accuracy of the navigation solution, as well as the integration of the navigation solution with the automated flight control system on the Boeing H-6U Unmanned Little Bird. A total of 16 fully autonomous landings and 13 fully autonomous takeoff/departures were performed with the flight crew closely monitoring the controls and the aircraft position when in close proximity to the deck. In the process, the project test pilot responsible for the French frigate landing test experienced 84 landings to and takeoffs from the yacht. Seven sequential days were consumed to accomplish the deck qualifications of 2 Boeing test pilots, complete the integration and debug of all systems and software, and complete maritime terminal operations until the operation became routine. The on-board safety pilot was able to allow the autonomous systems to misbehave enough that a good understanding of system malfunctions was rapidly gained and corrected. Once again, the value of the Unmanned Little Bird program's optionally manned system architecture has been demonstrated.

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