Evolution Leads To Revolution – Helicopter Flight Testing Using RTK DGPS Technology

Mark Hardesty, Flight Test Engineer
Greg Ashe, Senior Experimental Test Pilot
The Boeing Company
Mesa, Arizona USA

BIOGRAPHY

Mark Hardesty is a Flight Test Engineer and FAA Designated Engineering Representative at The Boeing Company. He has a Master's Degree in Mechanical Engineering from North Carolina State University. For the last 13 years, he has been directing helicopter test programs, while developing acoustic, spacial position, and atmospheric data systems for a variety of research and FAA certification flight tests.

Greg Ashe is a Senior Experimental Test Pilot and FAA Designated Engineering Representative at The Boeing Company. He attended Western States College of Engineering, graduated from the U.S. Army Helicopter Flight Training Center at Ft. Rucker and served as an Army helicopter pilot. He has over 30 years and 12,000 hours of flying experience and has been involved in engineering flight test at Hughes / McDonnell Douglas / Boeing for the last 21 years.

ABSTRACT

With the availability of high-accuracy RTK DGPS, a major revolution in helicopter flight test techniques has taken place. RTK DGPS based tools have been developed specifically to support flight test activities, resulting in tremendous increases in the efficiency and safety of experimental flight test operations. FAA related flight test efforts such as Category A, fly-over noise, and low speed controllability benefit tremendously from the precision 3-dimensional position and velocity data available. Handling qualities maneuvers described by Military Aeronautical Design Standard 33D are quickly and accurately scored using similar techniques. Additional applications being developed for the technology include climbing and descending airspeed calibration and flight loads survey maneuver cueing.

INTRODUCTION

The Boeing Company in Mesa, Arizona - formerly McDonnell Douglas Helicopter Systems, has been continuously developing an RTK DGPS based "Portable Test Range" since 1994, when NovAtel, Inc. introduced the RT-20™; capable of sub-meter accuracy processed position output at 5 hz with latency rates approaching 70 milliseconds. Initial flight test applications involved simple on-board archiving of 3-dimensional position and velocity. On-board real-time data processing using a hardened personal computer soon followed; allowing vertical and lateral guidance with respect to ground based microphone arrays. Integration of airspeed transducers and standard cockpit indicators with analog/digital and digital/analog boards in the computer added a capability to perform dynamic, precision four-dimensional landing approaches (X, Y, Z, and velocity) for noise research flight testing.

Cues have been developed to increase the safety and repeatability of a variety of FAA certification flight test programs including height-velocity, Category A, and fly-over noise. Applications such as aircraft handling qualities evaluation for maneuvers described in Aeronautical Design Standard 33D are being developed. The efficiency of all test applications has been greatly enhanced by the real-time display of critical data to both the flight crew and the ground-based test director. New flight test locations, typically selected for wind, temperature, terrain obstruction, or density altitude environmental considerations can be made completely operational for use with the Portable Test Range within a day of arrival at a test site.

Presented at Institute of Navigation GPS '99 Annual Conference in Nashville, Tennessee, September 14 – 17, 1999.

RTK DGPS FUNDAMENTALS

RTK DGPS requires that a high integrity data link be maintained between the reference and rover GPS receivers during system operation. This requirement can easily become the biggest challenge in taking maximum advantage of the technology. In urban environments or areas with heavy industrial operations, radio frequency (RF) clutter can drastically affect the ability of the system operator to maintain a reliable data link.

A variety of data link choices are available - selection of the data link method appropriate to the environment and operational constraints requires care and deliberation. This data link may be provided by cellular telephone, VHF, UHF, 900-megahertz spread spectrum, or other high frequency, highly directional radio systems. RF modems that can reliably transmit this type of data are often equipped with forward error correction (FEC), an error checking technique that insures the correction data message is received just as it was broadcast. Higher frequency signals are more quickly attenuated by the atmosphere, and have more stringent line-of-sight requirements. Some radio frequency bands, such as 900 megahertz, are restricted in transmit power so that the reliable radio range is severely limited.

Integration of DGPS capable receivers with a particular RF modem system is often left to the end user, hence it is important to discuss with the receiver manufacturer the particular requirements of a modem system for such features as FEC. For users that desire to down link data from an air vehicle to a ground based test director, cellular telephone data links are not an option due to Federal Communications Commission (FCC) regulations.

FCC licences for discrete radio frequencies suitable for broadcast of differential corrections can be difficult or impossible to obtain. Large corporations often own several radio frequency licenses for their regional operating areas. Small companies and individuals, especially located in RF rich environments typically found around metropolitan areas, are at a distinct disadvantage for obtaining radio frequency licenses. In some areas, surveying groups have pooled their resources to obtain a single licensed frequency, and installed a DGPS reference station that broadcasts corrections to be used by all subscribers in the area. Because differential correction logs are not always standardized between manufacturers, groups sharing a reference station may need to compromise on a particular manufacturer's equipment line. In some areas, subscription services may be available for precision differential corrections. Used at low power levels, 900 megahertz band spread spectrum modems do not require FCC licensing, however broadcast range may be severely limited.

The baseline – the distance between the DGPS reference station and any rover station, must be controlled to maintain the system accuracy claimed by the manufacturer. Assuming the differential correction data link can operate over the baseline, the accuracy of the DGPS can still degrade due to unpredictable elements of the processing algorithm. Manufacturers of DGPS capable receivers create ionospheric propagation delay models that are only reliable over specified baselines.

In the flight test business, the time that it takes for the DGPS to initialize and arrive at an acceptable level of accuracy is a serious operational consideration when selecting a manufacturer's equipment. Single frequency, L1 only receivers typically require substantial dynamic initialization times; static initialization times are typically much faster. Initialization begins only after the differential correction data link is established. Given the limitations of whatever RF modem is in use, operations must be planned which accommodate the initialization requirements of the DGPS in use.

Dual frequency, L1/L2 receivers are typically able to more quickly initialize in dynamic situations. Dual frequency systems greatly reduce the errors induced by unpredictable ionospheric propagation delay, however this advantage is minimized as the baseline increases. The dual frequency receiver systems also offer greatly increased accuracies. As might be expected, the cost of an L1/L2 system is much greater than an L1 only system, and some operational limitations may arise due to the less robust L2 signal strength.

TEST RANGE SELECTION AND LAYOUT

Historically, systems such as microwave trisponders, grid cameras, or encoding optical theodolites have been used for flight test programs when accurate 3-dimensional position data referenced to ground objects was required. The use of these now antiquated systems required large open areas for proper system setup and operation, severely limiting the selection of test range locations. RTK DGPS operations are much less restrictive with regards to test range selection. The reference station GPS antenna should have an unobstructed view of the sky from horizon-to-horizon, as much as buildings or natural obstacles permit. The RF antenna for the differential correction data link should be located so that the radio system in use can maintain good line-of-sight between the air vehicle and the reference system. Cellular telephone modems can be used in up-link only applications, but must be used such that the air vehicle will always be in range of a broadcasting station.

In some cases it is necessary to establish the RTK DGPS reference station relative to a regional geodetic coordinate system. This situation might occur when working on an instrumented test range such as NASA Crow's Landing or the Army's Yuma Proving Ground. Often, the DGPS position data needs to be correlated with other range assets such as laser tracking system data or target locations. Once the reference station antenna is located, all RTK DGPS data should match the test range coordinates within the system's stated performance.

In the case where a locally established coordinate system is adequate for the test program, the reference station GPS antenna should be situated so that the installation can be precisely repeated. Afterwards, the reference station GPS receiver should be allowed to acquire its position. Typically, the latitude and longitude will be more accurate if the vertical position of the GPS antenna is fixed in the GPS receiver. This vertical information can usually be adequately derived from local topographical maps or airport facilities directories. After the reference station GPS receiver has acquired a position, the latitude, longitude, and elevation can be fixed in the receiver as a known location. Once established, the reference station can begin broadcasting differential corrections to rover units. Other items on the test range, such as microphone locations, landing pad locations, runway ends, etc. are best surveyed using RTK DGPS operating with the newly established reference station. This will insure that all critical locations on the test range relate properly to the newly established local coordinate system.

Most GPS receivers provide waypoint navigation functions that will allow the user to establish "From" and "To" waypoints. The receiver will then output such information as distance from the "To" waypoint, lateral deviation from the line between the "From" and "To" waypoints, vertical and horizontal velocities, ground track, etc. This Cartesian coordinate data in familiar units allows the typical engineer (non-surveyor) to design software that will archive and manipulate this data to meet the needs of the test program.

SYSTEM EVOLUTION

There are a large number of manufacturers of commercially available GPS equipment. Many GPS receivers now available, even small hand-held units, offer a variety of features including parallel twelve channel satellite receivers and serial interfaces for input of differential corrections and output of various position and velocity data. Depending upon the needs of the user, these devices, some only costing several hundred dollars, might be quite adequate for many applications. However, because the designers of these GPS receivers intended to meet the needs of a certain market segment, the usefulness of these devices is limited in developmental flight test applications. Even sophisticated RTK DGPS equipment designed for precision land surveying applications may lack the robustness necessary to be successfully applied in dynamic flight test applications.

The Boeing Company – Mesa, formerly McDonnell Douglas Helicopter Systems (MDHS), researched the GPS equipment market extensively in 1994, focusing on the offerings at the Institute of Navigation GPS conference in Salt Lake City. The objective of the market survey was to locate a RTK DGPS designed for dynamic machine control and tracking applications with adequate accuracy, latency, and update rate. A position update rate of at least 4 hertz, data latency time of less than 100 milliseconds, position accuracy of better than 0.5 meter in all 3 dimensions, and flexibility in use were major goals of the search. At that time, only NovAtel Communications, Limited**,** of Calgary, Canada offered an OEM product that met the requirements. That product was designated "RT-20™", an L1 only receiver.

The RT-20™ system specifications included a 5-hertz data update rate, 70 milliseconds data latency time, and a one-sigma standard deviation in 3-dimensional position of 20 centimeters. The RT-20™ system was sold, as a pair of differential capable receivers with accessories such as antennas, cables, power supplies, and a simple interface for system familiarization, however no integrated differential data link equipment was offered. NovAtel did recommend 9600-baud rate radio data linking equipment that included forward error correction (FEC) because of the complexity of their proprietary differential correction messages.

MDHS was left with researching the RF data modem market for suitable equipment. Long range plans for the system included not only up-linking differential correction messages from the reference station to the rover, but also down-linking processed aircraft position and velocity data for immediate archiving, plotting and review by a ground-based test director. This led to the requirement for extremely flexible radio modems with the capability of very high duty cycles. A market search turned up only one company, G.L.B. Electronics that offered a product that would fulfill the requirement. After researching available licensed radio frequencies within the McDonnell Douglas Corporation, a pair of UHF radio modems, programmable in 12.5-kilohertz steps between 460 and 470 megahertz was selected. These radios were equipped with 9600-baud rate, forward error correction, and a 99% data throughput rate (since upgraded to 19200 baud).

System integration was relatively trouble free, with most difficulties involving simple cabling and power supply problems. Software to control data archiving and display was created using National Instruments Labview for Windows, a graphical users interface programming language offering a multitude of analog and digital control and display options for the computer screen. As the software development progressed, a digital to analog output card was added to the aircraft computer. This was used to drive an analog cockpit indicator to guide the flight crew over a microphone array as required by FAA FAR Part 36 noise certification testing. Eventually, downlinking of critical aircraft position and velocity data for real-time plotting at the ground-based test director’s station was added.

The Boeing Company in Mesa, Arizona currently operates the RT-20™, RT-2®, and Beeline™ systems at a position update rate of 4 hertz, which is processed, archived, and decimated on board the aircraft, and then downlinked to the ground station at a 2-hertz rate. This update rate has proven adequate and highly effective for flight crew guidance as well as for all certification and developmental testing attempted.

Several GPS antenna locations have been used with great success. The most desirable location is above and centered on the rotor head. This location requires the installation of a special standpipe through the center of the main rotor drive shaft, something usually available only to helicopter manufacturers. When the instrumented rotor head hardware has not allowed for this installation, a tail boom location for the GPS receiver antenna has been used. Both antenna locations offer distinct advantages and disadvantages. The main rotor head location most nearly approximates the aircraft center-of-gravity (C.G.) and is generally not influenced by yawing of the tail in gusty conditions or pitching motions during acceleration and deceleration maneuvers. The main rotor head location also allows for a completely unobstructed view of the sky, thus optimizing the reception of GPS satellite signals while minimizing multipath and signal blockage difficulties.

The tail boom location for the GPS receiver antenna is subject to obstructions such as the upper forward fuselage and rotor head, as well as the tail empennage. Reception of GPS satellite signals passing through the rotor disk causes no particular problems for NovAtel receivers, however some precision RTK DGPS surveying systems have demonstrated an inability to function under helicopter rotors. This appears to be a function of blade number, chord length, and rotor RPM. Disadvantages of the tail boom location include artificially induced accelerations due to pitching and yawing motion of the aircraft that are not indicative of the aircraft C.G. One particular advantage, however, is that when examining maneuvers such as low speed controllability, this information can be related to pilot workload and ability to control the aircraft.

Figure 1 is a right side view of the MD902, a twin engine civil helicopter with a certified gross weight of 6250 pounds. The GPS antenna is located above a rotating pulse code modulation (PCM) package installed on the main rotor head. The differential data link antenna is located on the aircraft belly, towards the nose. Note the laser reflector installed on the right cabin step.

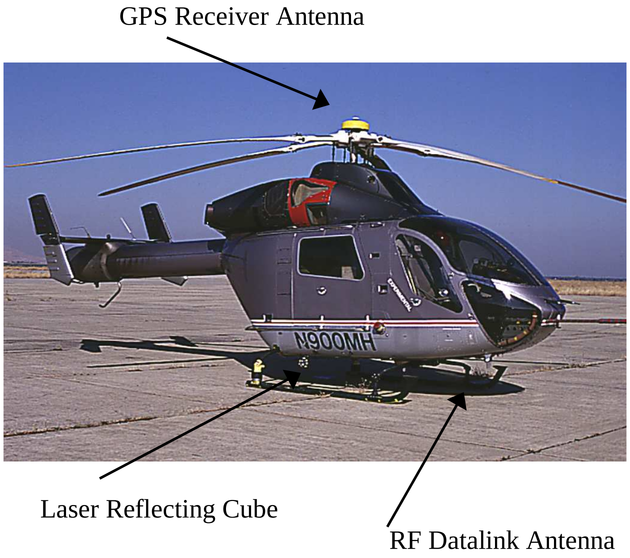

Figure 1. MD900 Explorer

A crash-worthy RTK DGPS installation for internal or external (pod) mounting on helicopters allows stand-alone operation from any other aircraft instrumentation that might be installed. This installation includes a twelve-volt sealed lead-acid battery to power the GPS receiver and radio modem. The battery power to the GPS receiver and radio modem facilitates system initialization without requiring aircraft power, notorious for power transients when switching from external power to aircraft battery and generators. A static inverter is included to power the hardened computer required by the system. A sunlight readable color display (Figure 2) is mounted in the front cockpit to display data to the flight crew. Analog indicators to provide guidance and velocity cues are installed in the direct view of the pilot. System software is designed so that control of all software functions is done using a track ball device.

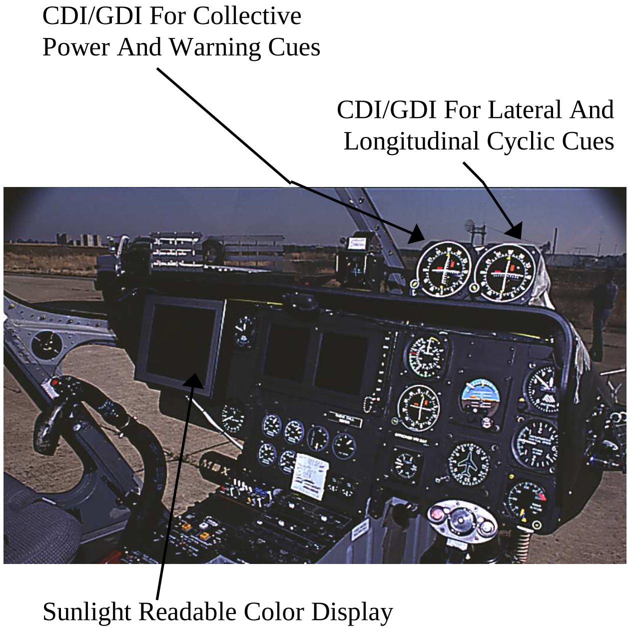

Figure 2. Cockpit Display And CDI/GDI

SYSTEM CERTIFICATION WITH FAA AND DOT

Initial performance verification of the MDHS Portable Test Range was conducted to satisfy the FAA Los Angeles Aircraft Certification Office (LAACO). Time encoded, vertically oriented video, and vertical and horizontal photo-scaling techniques were used to demonstrate the time versus position accuracy in three-dimensions of the Portable Test Range system. FAA officials reviewed test range survey techniques and verified the accuracy of the aircraft position data with respect to the microphone locations.

Evolution of the Portable Test Range continued to facilitate developmental and certification flight testing for height-velocity and Category A. Because these test programs involved flight safety related issues, not just fly-over noise (environmental), FAA scrutiny of the position data accuracy became more extreme. To satisfy FAA and Department of Transportation (DOT) requirements, a completely documented and approved Portable Test Range operating procedure was developed. This document included a standardized procedure for hardware installation on the aircraft and the test range as well as methods for surveying the test range for relevant monuments and waypoints. Techniques were outlined to demonstrate proper system operation and performance for whatever vehicle the system was to be installed on.

Per DOT guidelines relating to flyover noise testing, the Portable Test Range operating software was designed to access relevant navigation information from documented data files, and to regurgitate this same information into the test data file. Manipulation of the DGPS data prior to archiving was documented and raw data demonstrating performance of the system was recorded. DOT guidelines required that the software version be completely documented and controlled, and an executable version of the software be evaluated and approved by engineers at the Volpe National Transportation Systems Center.

COMPLEX APPROACH PROFILES

In the Fall of 1996, MDHS participated in a flight test program involving a variety of complex landing approaches. The purpose of the program was to develop quiet landing approach techniques that fell within the normal operating envelope of the MD902 Explorer. A variety of landing approaches were designed, varying from constant angle-constant speed to varying rates-of-descent with varying rates of deceleration. The approaches began with a transition from steady state level flight 10,000 feet from a helipad, and terminated with a 30-second in-ground-effect (IGE) hover at the landing point. An array of over 40 microphones was installed beneath the flight path, and the noise data were used to develop noise contour maps for the various landing approach techniques. The objective of the flight test program was to develop ways to minimize the noise impact that terminal area operations have on a surrounding community.

The flight test program was executed at NASA Crow’s Landing, a test range instrumented for aircraft, atmospheric, and laser tracking data. The laser tracker is equipped with a data link and aircraft guidance system, allowing pre-programmed landing approaches to be compared to aircraft position. The difference data is generated at the ground station and transmitted back to the aircraft, then used to drive a course and glideslope deviation indicator installed in view of the aircraft pilot.

Rather than take advantage of this system, the test team chose to further develop the Portable Test Range to provide the complex landing approach guidance to the flight crew. The flight profiles required constant and varied airspeed deceleration schedules as well as constant and varied rates of descent schedules for the different landing approaches. To use the output of the on-board airspeed transducer, an analog-to-digital (A/D) card was installed in the hardened computer. A digital-to-analog board was installed and used to drive two King 206 analog course and glide-slope deviation indicators, installed directly above the standard flight instruments in the pilot’s direct view (Figure 2).

To provide precision glide path and velocity guidance, the lateral deviation bar and airspeed deviation bar were collocated on the right indicator, and the vertical deviation bar and warning needle were collocated on the left indicator (Figure 2). This method of information presentation provided the pilot with a simple but effective flight director. The right side indicator provided cues for the pilot's right hand on the cyclic (roll and pitch), while the left side indicator provided cues for the pilot's hand on the collective (power). Test pilots commented that the only instrument interpretation required was the amount of control deflection required to keep the needles centered. Lateral and vertical deviation needle sensitivities were initially set at a needle centered to full-scale value of ±50 feet. After some practice, it was determined that an increased sensitivity of ±25 feet reduced pilot workload. The airspeed deviation was set at a needle centered to full-scale deviation value of ±10 knots indicated airspeed. This relatively low sensitivity compensated for the high noise floor of the inexpensive A/D card installed in the airborne computer.

To ease inbound course intercept, the sensitivity of the lateral and vertical deviation needles was reduced at a linear rate farther out than 12,000 feet from the landing pad. It should be noted that the pilot's workload was limited to flying the aircraft with reference to the instruments. Distractions such as radio communications were virtually eliminated during the test runs. The flight test engineer provided the pilot with verbal and indicator warnings of upcoming changes in the flight profile, so the pilot's eyes could remain focused on the instruments. Obviously, for a single crew cockpit, this situation in real instrument flight rules (IFR) conditions is not the norm, and any full scale excursions of the deviation needles would make executing a missed approach mandatory. However, in the interest of repeatable noise data, the philosophy was to fly the most precise approach possible.

The pilot noted that regardless of the deviation needle sensitivity, the amount of deviation from needles centered remained the same, however the looser the deviation needle tolerances, the higher the magnitude of the control input and amplitude of oscillations about the reference flight path. With a very high sensitivity of ±25 feet in effect, the pilot was typically able to keep the aircraft within 10 feet of the reference flight path. It is important to note that the Portable Test Range was configured to acquire the true aircraft position at a 4-hertz rate. However, due to the high precision of the position data, no smoothing was necessary, and no noise in the deviation needle was noted.

Laser tracking data was acquired at 100-hertz rate and decimated to 4 hertz for comparison. The laser cube was mounted on the right side step to the passenger compartment (Figure 2), and the data was translated to the same position as the GPS antenna (top center of the rotor head) for comparison. Data translation did not take into consideration aircraft heading, hence in strong cross winds the simple X-Z translation from the laser cube to the GPS antenna would generate some degree of error due to aircraft crab angle. Figure 3 offers a comparison of NovAtel RT-20 based Portable Test Range versus an autonomous laser tracking system. Figure 4 depicts a typical flight test profile.

CATEGORY A PROFILE DEVELOPMENT

Category A certification is required for transport category multi-engine helicopters. The manufacturer is required to demonstrate the ability of the aircraft to abort or continue takeoffs and landings following an engine failure.

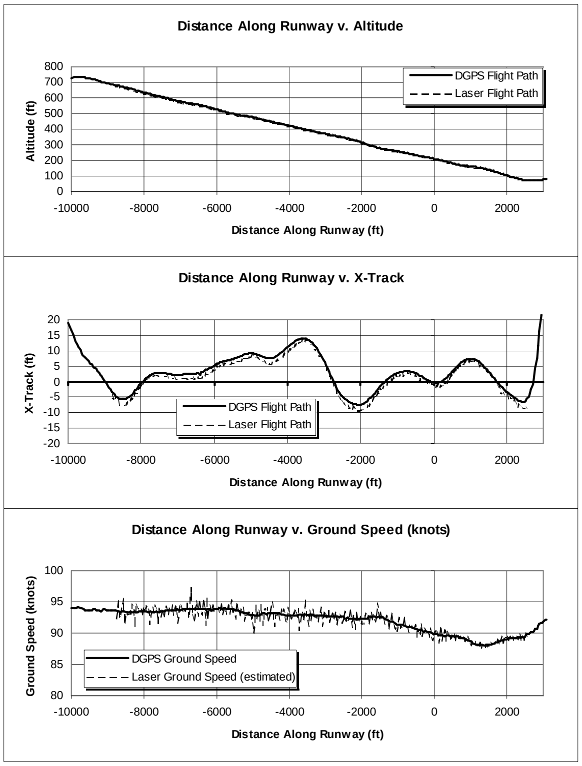

Figure 3. DGPS Versus Laser Tracking Data

Through 1997 and 1998, developmental and FAA certification flight testing was conducted on the MD902 Explorer to demonstrate Category A capabilities. Documentation of the helicopter's flight path relative to a designated helipad was required for this test program.

The Portable Test Range allowed the flight crew to precisely place the helicopter for the initiation of each test point, and to record the exact flight path of each take-off or landing attempt. Three-dimensional position and velocity profile plots were immediately available to the test director between take-off and landing runs. Slight differences in altitude, acceleration, airspeed and climb rate were highlighted to the cockpit crew between data points, allowing very fine tuning of pilot techniques.

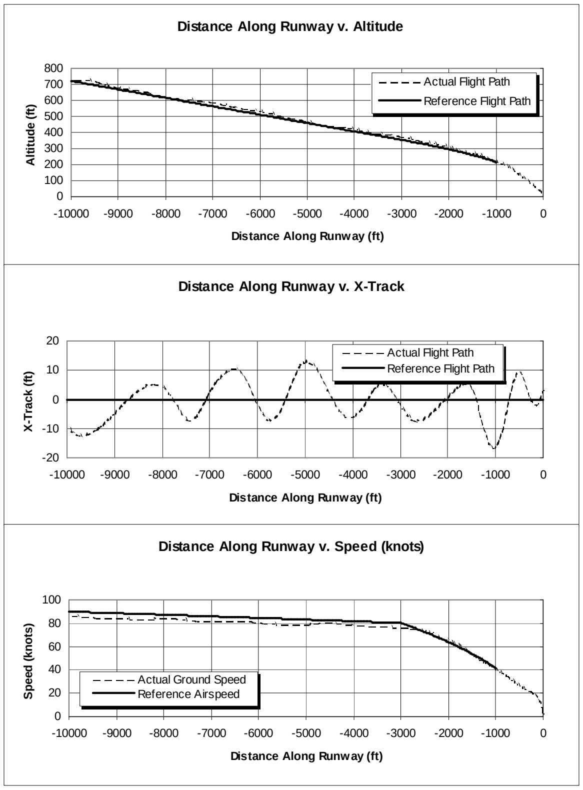

Figure 4. Complex Flight Test Profile

Typically, during the execution of ground referenced flight test activity, local winds are measured within several hundred feet of the flight operations area. It is not uncommon for wind indicators at each end of a runway to contradict one another. Because atmospheric conditions can be extremely localized, the Portable Test Range facilitates direct comparison of the test aircraft's horizontal and vertical speed with the aircraft's true airspeed to develop a detailed profile of the winds aloft. Knowledge of this wind profile gives the flight test team a greater understanding of the variation in flight profiles from one data point to the next. Typical Category A takeoff and landing profiles for an elevated helipad are depicted in Figures 5 and 6.

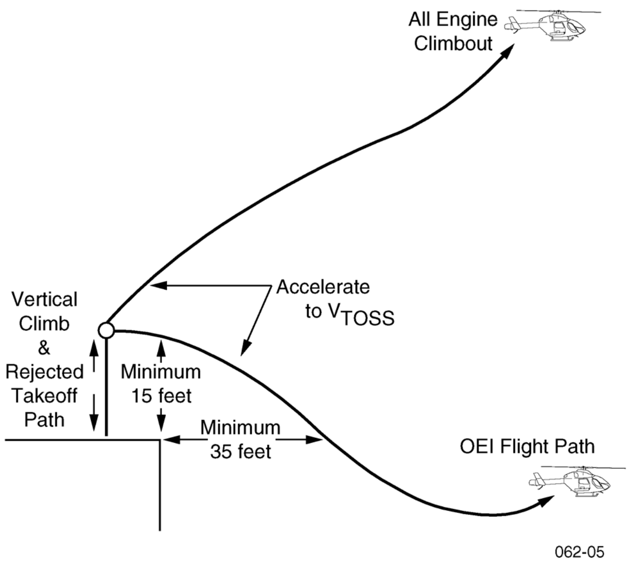

Figure 5. Category A Vertical Takeoff Profile From A Pinnacle

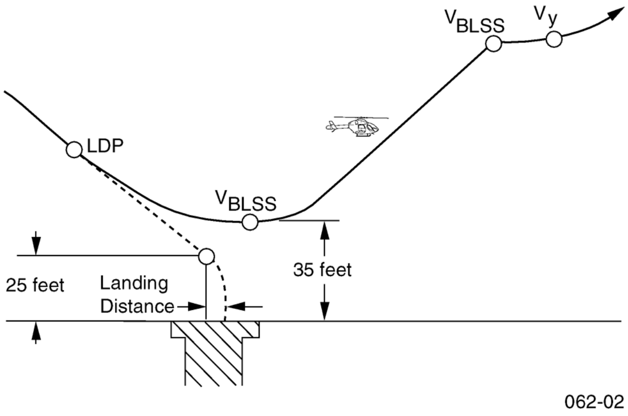

Figure 6. Category A Vertical Landing

NOTATION

LDP	Landing Decision Point
OEI	One Engine Inoperative
V_{BLSS}	Balked Landing Safety Speed
V_{TOSS}	Takeoff Safety Speed
V_Y	Best Rate-of-Climb Speed

AERONAUTICAL DESIGN STANDARD 33D MANEUVER GRADING AND CUEING

Aeronautical Design Standard 33D (ADS-33D) is a criteria developed by the U.S. military to evaluate the ease of helicopter control. Helicopters must be designed so that a pilot of average ability is able to successfully fly the precision maneuvers required in routine helicopter operations.

ADS-33D describes a series of mostly ground referenced maneuvers that are to be executed and scored per the outlined criteria. Typically, a surveyed and carefully marked runway surface is prepared to provide good visual cues. The pilot then flies the helicopter through the series of maneuvers by referencing the ground markers. Historically, judges in strategic positions have been used to evaluate how well the pilot maintained horizontal and vertical position relative to the ground markers. The judges score the maneuvers using their best visual judgement. A subjective rating system known as the Cooper-Harper scale is used by the pilot to subjectively evaluate the ease of maneuver execution. Helicopters that are found to be difficult to control precisely may be instrumented to monitor control activity.

Considering how much is resting on the qualitative opinion of the evaluator, an objective method of documenting the aircraft performance is imperative. The Portable Test Range allows the test team to immediately provide feedback to the crew regarding the true performance level actually achieved. The data can be used by the to assist in rating the handling qualities using the standard Cooper Harper Scale.

Figure 7 shows the cross track and altitude error incurred while performing a pirouette maneuver. The pirouette maneuver requires that the pilot hover at a specified altitude. The pilot points the nose of the helicopter towards a point defining the center of a circle of a specified radius. The pilot then maneuvers the aircraft around the circle defined by this radius, keeping the nose pointed at the center marker, and holding a constant altitude above ground level. The pilot completing this maneuver in an MD900 helicopter rated the task as easy requiring small, infrequent collective, cyclic and pedal inputs. Immediate capability to plot the maneuver on the cockpit display proved invaluable in producing accurate handling qualities ratings. Furthermore, no judges were required to participate in the exercise. The PTR assists greatly in shifting handling qualities ratings from subjective to more objective rating criteria.

LOW SPEED CONTROLLABILITY

FAA certification of helicopters requires that the hover controllability envelope be defined for gross weight versus density altitude up to a limiting altitude of 7000 feet. The ability of the helicopter to control heading with wind from any direction to a minimum of 17 knots must be demonstrated. Testing may be done both in ground effect (IGE, typically defined as a landing gear height of 3-6 feet above ground level) or out of ground effect (OGE, typically defined as 1.5 times the main rotor diameter.

Because even The Boeing Company cannot control the wind, a procedure has been created to incrementally map the helicopter controllability by flying along a runway centerline. Headwind, tailwind, and crosswind components are artificially created by flying up and down the runway at various headings relative to the direction of travel. Normal helicopter airspeed indicating systems are only accurate for straight ahead flight, and even then only begin to indicate accurately at perhaps 30 knots. Another method of velocity measurement must be found.

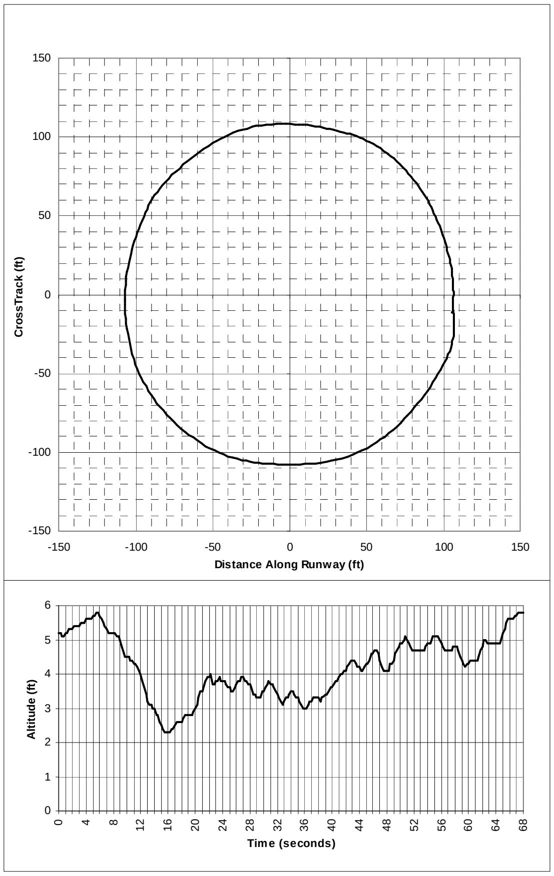

Figure 7. Pirouette Maneuver

Traditional low speed controllability testing involves coordinating the motion of the test helicopter with a pace vehicle equipped with a calibrated speed measurement system. The test is conducted over a runway surface with the pace vehicle driving along the edge and the helicopter maintaining a position along the middle of the runway, and matching speed with the pace car. Data is typically collected in five knot ground speed increments up to a maximum speed that defines the helicopter's capability to maintain constant heading relative to the direction of travel down the runway. Testing is typically conducted at various density altitudes using a gross weight build-up approach until control limit margins are reached. Alternatively, a gross weight build-down approach can be used until controllability is achieved at what is believed to be the critical azimuth. Once the weight is arrived upon for the target density altitude, the full azimuth is documented, typically in 10-degree increments versus velocity, using the pace vehicle as a reference.

Some of the variables that can be introduced into the results gained using the pace car method are: drivers ability to hold speed while driving next to a virtual tornado; quality of the calibration of the pace vehicle speed measurement system; and the flight crew's ability to judge their speed relative to that of the pace vehicle. Furthermore a large safety element is introduced when the pilot's attention is divided between performing the helicopter control task and avoiding a collision with the pace vehicle, as well as to communicate with the pace vehicle driver. The pace vehicle driver must attempt to avoid running through fences at the end of the runway, which does occasionally occur. Helicopters with gross weights in the neighborhood of 15,000 pounds or more tend to blow gravel and other debris, which occasionally shatter pace vehicle windows. At the conclusion of this sometimes terrifying experience, the result is data of an almost anecdotal nature, since no time history data is recorded. Coordination between the test team, the flight crew, and the pace vehicle driver is so critical to the success of this test that even with an experienced test team, controllability data that is collected is only considered reliable to within perhaps 2-3 knots.

A technique has been developed by The Boeing Company to tremendously increase the efficiency of low speed controllability testing. Due to the extreme accuracy of the velocity acquired using the Portable Test Range, the pace vehicle can be eliminated from the equation. Using the Portable Test Range combined with a precision portable wind measurement system, controllability data can be collected that is considered accurate to tenths of a knot. The importance of this is realized when the critical azimuth capability is less than that required by FAA regulations, and a limitation will have to be published in the operator's handbook. In that case, every tenth of a knot is important in establishing the certified maximum gross weight of the helicopter. Immediately upon conclusion of the flight, the digitally archived aircraft velocity and heading data are combined with the measured wind vector obtained at the portable met station and the controllability azimuth plot can be quickly generated and presented to the FAA (Figure 8).

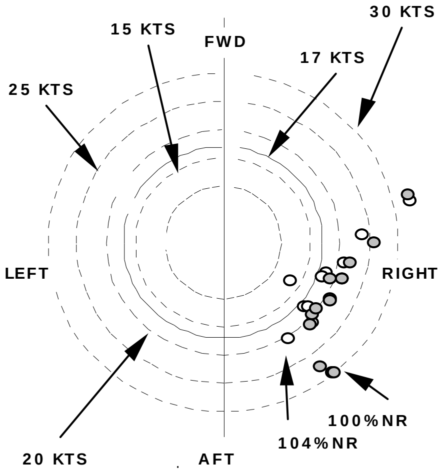

Figure 8. Low Speed IGE Controllability Diagram – 100% Versus 104% Main Rotor RPM

HEIGHT-VELOCITY TESTING

The last flight test to be completed prior to FAA certification is height-velocity. This test is designed to demonstrate the autorotation envelope of the helicopter. It is required test for single engine helicopters, and involves engine throttle chops at various altitudes above ground level and indicated airspeeds, as slow as hover. The results of this test are published in the operators handbook in the form of an "avoid region", depicted in Figure 9.

Height-velocity is usually done at the conclusion of the test program due to the extreme risk associated with the data collection process. It is not uncommon to severely damage the airframe finding the end points of the envelope. Due to the risk to equipment and flight crew, it is imperative to provide cross checks for helicopter altitude above ground level. As well, wind shear between the helicopter and the landing zone can dramatically affect the success of the sportier data points. The Portable Test Range allows the pilot and ground crew to know his exact altitude above ground level, and to evaluate winds aloft for shear conditions, contributing greatly to the overall safety of the flight test exercise.

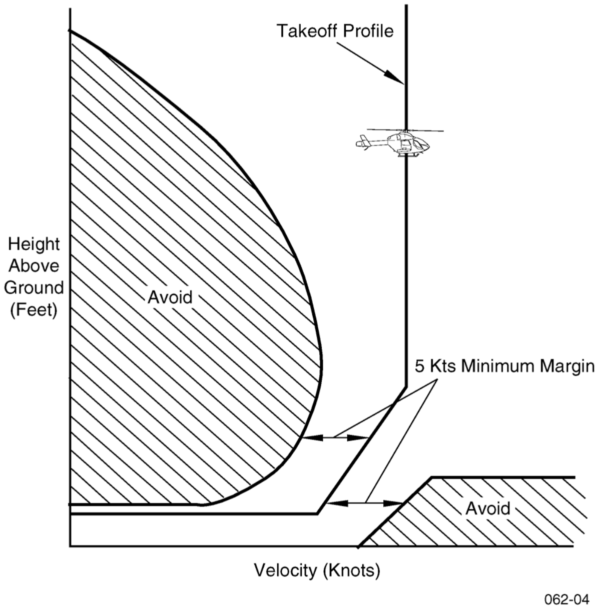

Figure 9. Typical Height-Velocity Envelope

CONCLUSION

Precision flight tests involving control margins, performance, or airspeed system calibration require that winds be very light or calm, and vertical air movement be virtually non-existent. In Arizona, conditions that will satisfy these requirements are typically only found during a small time window each day, typically in the early morning hours after dawn, until solar heating begins to cause convective turbulence or localized winds. It is imperative that this critical window for satisfactory atmospheric conditions be used with great efficiency. Highly trained test teams working with reliable instrumentation and data systems produce optimum results. Just a few minutes lost due to poor crew coordination, equipment malfunction, or air traffic interruptions can result in an entire test team being on location for an additional day.

In the increasingly competitive aerospace business environment, more has to be accomplished with less, i.e. less individuals have to produce more results. The Portable Test Range, developed with the highest quality hardware available, helps flight test teams at The Boeing Company in Mesa, Arizona work smarter and faster. The Portable Test Range developer/programmer only works part-time on the system software and is occasionally interrupted for many months with other responsibilities. Due to the graphical nature of the system programming language, this individual has been able to very quickly re-familiarize himself with the program code and make modifications required to support new flight test programs. This has contributed to an unexpected increase in productivity.

The development and use of RTK DGPS as a truth source has contributed greatly to the success and safety of a variety of flight test programs. The accuracy of the position and velocity data provided by this technology has improved the fidelity of computer models used to design new products, speeding development and certification of new aircraft models. Aircraft manufacturers that are first to the market with a product that fills a niche and offers good value are destined to succeed.

ACKNOWLEDGMENTS

The authors would like to thank the following individuals and organizations for their support in the development of the “Portable Test Range”.

Francis Yuen, and Tom Ford of NovAtel, Inc. Ron Wilson Sr., Ron Wilson, Jr., Jamie Wilson, and Ron Kostorowski of G.L.B. Electronics. Neil Toso of NFT Ventures, Inc. Gregg Fleming of the Volpe National Transportation Systems Center, U.S. DOT Research and Special Programs Administration. Bruce Conze of the Propulsion Department, FAA LAACO. Joe Flint of The Boeing Company-Mesa, Engineering Flight Test. Al Lehman and Ken Watterson of Allen Instruments, Scottsdale, Arizona. Jay Zimmerman of GPS Neatly Done, Phoenix, Arizona.

REFERENCES

United States Department of Transportation, Federal Aviation Administration, “Certification of Transport Category Rotorcraft, Advisory Circular 29-2A, September 16, 1987.

AVSCOM, ADS-33D, ”Aeronautical Design Standard, Handling Qualities Requirements for Military Rotorcraft”, July, 1994.

John A. Volpe National Transportation Systems Center Acoustics Facility and Landing Systems Laboratory, “Requirements For DGPS-Based TSPI Systems Used In Aircraft Noise Certification Tests”, April 14, 1997.

Hardesty, Mark, Metzger, Mark, Flint, Joe, and Fredrickson, Daphne, “Developmental Test And Evaluation Of Helicopters Using A Precision Differential Global Positioning System,” American Helicopter Society 53rd Annual Forum, Virginia Beach, Virginia, May 1997.