THE USE OF GPS TRACKING AND GUIDANCE SYSTEMS FOR THE CHICKEN LITTLE JOINT PROJECT'S "ACOUSTIC WEEK" FLIGHT TEST PROGRAM

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ABSTRACT

A two-week flight test effort was conducted in September 2003 at a remote location at Eglin Air Force Base in Florida. Dubbed "Acoustic Week", the test was sponsored by the Chicken Little Program Office and the National Ground Intelligence Center. The test was designed to examine the effectiveness of data collection techniques for a variety of sensors, while simultaneously collecting signature data for a variety of aircraft. Eight aircraft were tested including two rotorcraft from the United States Army Lead The Fleet program, a Navy fixed wing unmanned air vehicle (UAV), a prototype rotary wing UAV, and four civil helicopters. Sensors included acoustic and seismic arrays, infra-red measurement devices, and a human sound jury. Essential vehicle position data were acquired by five different organizations using five different systems of varying accuracy and quality. The focus of this paper is the GPS tracking system used by an Army/NASA/Boeing test team to provide flight path guidance cues, as well as to acquire precise vehicle position data, for two of the test vehicles. The measurement technique used to obtain vehicle source noise hemispheres and the use of these noise hemispheres to predict ground noise footprints is discussed and the need for precise vehicle position data and precision flight tracks is investigated. A detailed description of GPS tracking systems, sources of analysis errors and data accuracy degradation, and the criticality of instrumentation installation on system performance are provided. Flight track results document the improvement in deviations from the desired flight track when guidance cues are provided by course and glide slope deviation indicators rather than the typical ground reference cues.

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NOTATION

The following symbols, used in this paper, are identified for quick reference:

ADAM	Acoustic Detection of Aircraft Model
CDI	Course Deviation Indicator
CORS	Continuously Operating Reference System
DGPS	Differential Global Positioning System
DoD	Department of Defense
GDI	Glideslope Deviation Indicator
GOES	Geostationary Operational Environmental Satellite
GPS	Global Positioning System
L1	GPS carrier frequency at 1575.42 MHz
L2	GPS carrier frequency at 1227.60 MHz
MMW	Millimeter Wave
NAD	North American Datum
NOAA	National Oceanic & Atmospheric Administration
RNM	Rotorcraft Noise Model
RTK	Real Time Kinematic
SAM	Surface to Air Missile
UAV	Unmanned Air Vehicle
UTC	Universal Coordinated Time
WAAS	Wide Area Augmentation System
WGS	World Geodetic System

INTRODUCTION

The Chicken Little Program Office test organization was developed specifically for the purpose of foreign threat system exploitation to aid Department of Defense (DoD) organizations in the development of seeker/sensor systems. Exploitation consists of Surface to Air Missile (SAM), Millimeter Wave (MMW), infra-red, hyper-spectral, visual, automotive, and more.

Acoustic Week was conducted to provide DOD, US intelligence organizations and industry the opportunity to collect various signatures of numerous aircraft. An open dialog was also provided to allow the acoustics community to advance signature collection capabilities. A primary program motivation was to increase the rotary wing signature data available through the Defense Intelligence Agency's National Signatures Program data base for future seeker/sensor development. During this test program relatively short-range acoustic data were collected for source noise hemisphere development. After collection of the short-range acoustic data, long-range acoustic data and aural detection (sound jury) data were collected simultaneously for validation of acoustic detection prediction models. Finally, data were collected for a number of non-acoustic sensors for system validation purposes.

Participants in the exercise included (in part):

- Army Aeroflightdynamics Directorate
- Army Aviation Applied Technology Directorate
- Army Aviation Technical Test Center
- Army Research Labs
- Bell
- Boeing
- Draper Labs
- L3 Communications
- MILTECH Research Group
- NASA Langley
- NAVAIR
- Night Vision Labs
- Sandia National Labs
- Sikorsky
- Southwest Research

The U.S. Army's Joint Research Program Office, Aeroflightdynamics Directorate (JRPO-AFDD), Aviation Applied Technology Directorate (AATD), and the NASA Langley Research Center (LaRC) participated in the Acoustics Week Flight Test Program with the primary purpose of obtaining a benchmark rotorcraft acoustic database for (1) validation of acoustic detection prediction programs and (2) acquisition of a database of acoustic source noise characteristics for a variety of rotorcraft. More specifically, it is planned to use this database to validate a new acoustic detection prediction code called the Acoustic Detection of Aircraft Model (ADAM) that is currently under development by a NASA LaRC/AFDD/AATD/Wyle Laboratories team. At the heart of ADAM is the Rotorcraft Noise Model (RNM), which is an environmental noise prediction program developed by Wyle Laboratories under contract to NASA LaRC (Refs. 1-3). RNM estimates the noise footprint for rotorcraft (or any air vehicle) operations and thus provides a tool to aid in the development of low noise operations. Source noise hemispheres are required as input to the RNM. This paper will focus on the use of a Differential Global Positioning System (DGPS) based tracking and guidance system for the collection of measured source noise hemispheres.

ROTORCRAFT NOISE MODEL (RNM)

To understand the criticality of accurate aircraft position data and precision flight tracks necessary to obtain high quality source noise measurements, it is helpful to have at least a basic understanding of RNM. RNM is a computer program that simulates sound propagation through the atmosphere. As a noise source, rotorcraft are far more complex than fixed-wing aircraft, with a high degree of noise directionality that is not present for fixed-wing aircraft. While a single engine operating state parameter (a generalization not applicable to rotorcraft) is typically used to characterize fixed wing noise emissions, rotorcraft sources are three dimensional in nature and the directivity and spectral content vary with flight condition, namely flight speed and flight path angle. At its core, RNM utilizes single or multiple sound hemispheres (broadband and pure tone with phase) for a given flight condition to define the three-dimensional spectral source characteristics of a flight vehicle.

RNM calculates the noise levels, in a variety of metrics, at receiver positions on the ground either at points of interest or on a uniform grid. Rotorcraft operations are defined as either single flight tracks or as multiple flight tracks with varying vehicle types and flight profiles. Acoustic properties of the noise source(s) are defined in terms of either broadband or pure-tone (with phase information) sound hemispheres and may be obtained from theoretical predictions, wind tunnel experimentation, flight test measurements or a combination of the three. RNM has been recently expanded to include atmospheric sound propagation effects over varying terrain, including hills and mountainous regions, as well as regions of varying acoustical impedance such as coastal regions. Modifications are currently under development to include the effects of winds and temperature for a two-dimensional stratified atmosphere. The United States Department of Defense and the North Atlantic Treaty Organization (NATO) have adopted RNM as the standard prediction tool for Environmental Impact Assessments of military rotorcraft operations noise.

The major computational and physical elements of the RNM are the sound propagation module and the input and output modules. As input, RNM requires source noise hemispheres, vehicle flight track, flight profile orientation and operating state. Vehicle operations are quantified along a set of user defined vectored flight tracks (Figure 1). The vehicle flight is simulated in a time based domain along a prescribed flight track and the sound is analytically propagated through the atmosphere to the specified receiver locations. The propagation model currently assumes that the acoustic ray paths are straight lines and that there is no wind present. Program plans are to incorporate the current state-of-the-art atmospheric propagation methodology for wind and temperature effects into RNM in the near future. RNM currently accounts for spherical spreading, atmospheric absorption, ground reflection and attenuation, Doppler shifts and the difference in phase between the direct and reflected rays. The most recent upgrade to the RNM (version 3.0) allows for the prediction of noise over varying ground terrain using an implementation of the Geometrical Theory of Diffraction, which includes extensions for diffraction as developed by Rasmussen (Ref. 4). Prior versions of RNM (Ref. 5) simulated propagation over flat terrain only, and are applicable only where physical properties of the surrounding area are not significant. RNM performs the acoustical atmospheric propagation for a given vehicle and creates ground noise predictions and detailed metric time history. RNM is also capable of providing information that can be imported into a Geographical Information System (GIS). The noise contours can then be overlaid to scale on a background map, which is ideal for performing noise abatement studies, airport and vertiport noise impact evaluations and land-use planning studies. Ground mesh time history data may be post processed into acoustic simulation animations, which is useful for understanding propagation over varying terrain.

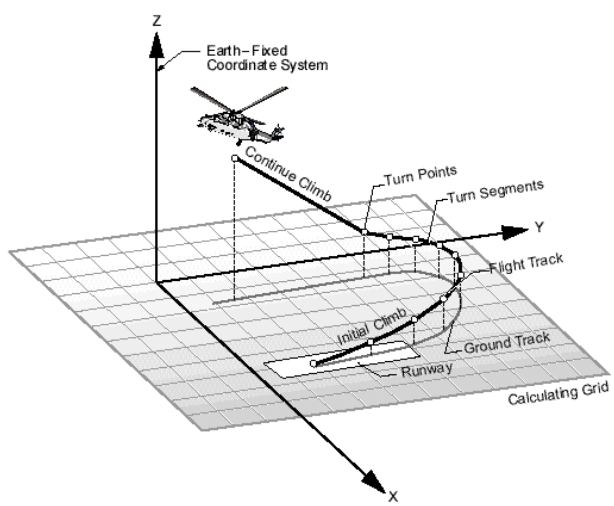


Figure 1. RNM single flight track definition.

Sound Hemispheres

RNM has the capability to accept either analytically or experimentally generated sound hemispheres for multiple sources, both broadband and pure tone with phase. The analytical data may be created using computational fluid dynamics or other techniques and interfaced with RNM. One-third octave band and narrowband sound hemispheres may be created from experimental flight test data using the Acoustic Repropagation Technique (ART2) that is included with the RNM distribution (Ref. 6). RNM will perform the atmospheric propagation for up to ten independently defined sound sources for a given vehicle. Source level noise data are defined on the surface of a sound hemisphere (Figure 2) and contain one-third octave or pure-tone sound levels. Points on the hemisphere are described in terms of a fixed radius and two spherical angles.

The sound hemisphere contains noise data for a single aircraft flight condition. Each file contains a set of attributes defining a quasi-steady flight condition, using three independent variables: airspeed, flight path angle, and nacelle pylon angle (for tiltrotor). For conventional helicopters, the nacelle pylon angle is fixed at 90 degrees. There may be multiple sound hemispheres, each describing a different noise source (e.g. main rotor, tail rotor, engine, etc.), for each flight condition.

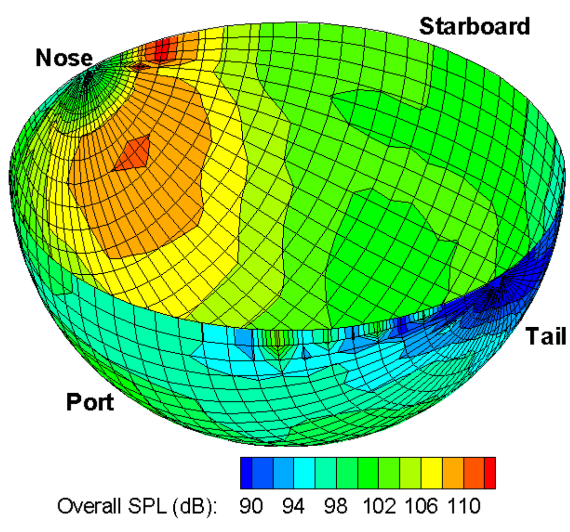
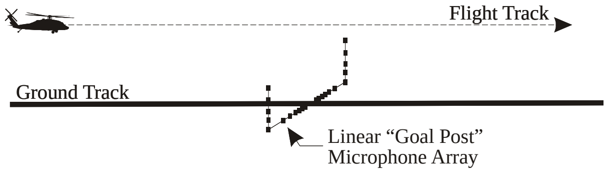


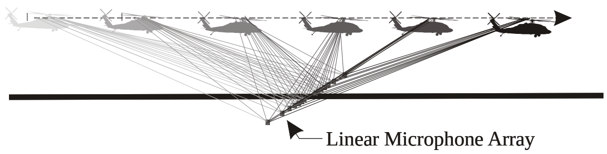
Figure 2. CH-46 sound hemisphere.

Acoustic Repropagation Technique (ART)

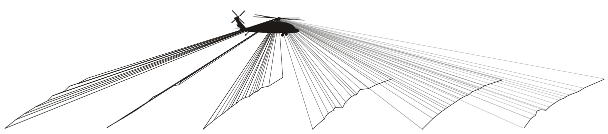
Source noise hemispheres such as the one shown in Figure 2 are experimentally measured and created using the technique described in Reference 7. This is referred to as the Acoustic Repropagation Technique (ART) and is depicted graphically in Figure 3. The aircraft flies through a linear microphone array that is perpendicular to the ground track (projection of the flight track on the ground) at a constant operating condition as shown in Figure 3a. Noise spectra are computed at a selected time interval (typically every 0.5 seconds) over the duration of the flyover and each noise spectrum is related to the aircraft position relative to each microphone (Figure 3b) thus providing noise levels as a function of the emission angles. By freezing the aircraft at a point in space, these noise directivity data can be projected onto the ground, as shown in Figure 3c, producing a detailed, high-resolution effective noise contour that is moving with the vehicle. The ground noise levels are then de-propagated, using the same propagation algorithms contained in RNM, to a hemisphere of selected radius (Figure 3d and Figure 2). While the example shown in Figure 3 is for level flight, the same technique can also be used for ascending or descending flight. It should be noted that this measurement technique does not always provide measured data to populate the noise hemisphere all the way up to the rotor tip-path-plane. In this case ART assumes that the level from the nearest angle below the rotor tip-path-plane for which data were measured up to the rotor tip-path-plane is constant. This source noise measurement technique can be compared to the typical fixed-wing measurement technique that uses a centerline microphone and a single sideline microphone, from which all acoustic directivity characteristics are derived.



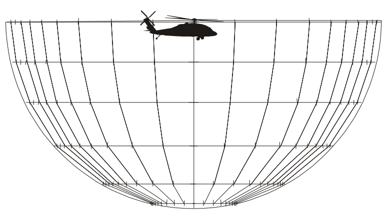
a) Source flyover of a linear microphone array.



b) Acoustic data measured during flyover.



c) Single source location transformation.



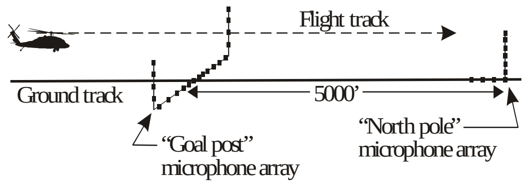
d) Source noise hemisphere.

Figure 3. Source noise measurement procedure.

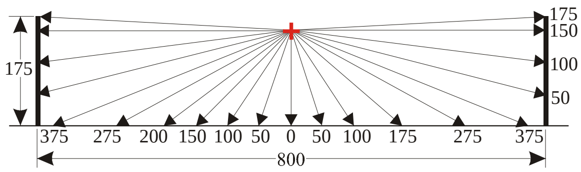
EXPERIMENTAL SETUP

Microphone Array

A 30-microphone array was used during this test to measure RNM-type source noise hemispheres for each vehicle. Due to the emphasis on acoustic detection, the microphone array shown in Figure 3a was modified for the Eglin test to provide improved in-plane noise measurements directly forward of the rotorcraft, where first acoustic detection typically occurs. The modified microphone array is shown in Figure 4. Figure 4a is a 3-dimensional sketch of the overall microphone array, and shows the addition of a "north-pole" microphone array to measure the critical in-plane noise directly in front of the vehicle. The microphone array consisted of 16 ground board mounted microphones and 14 above ground microphones deployed in three vertical arrays, with the highest microphones located 175 feet above ground level (AGL). A "goal-post" array was created by suspending four microphones from each of two cranes and deploying 12 microphones across the ground between the two vertical arrays, as shown in Figure 4b. The distance between vertical arrays was 800 feet. This provided approximately equal angular resolution acoustic measurements, up to and even slightly above the rotor plane, when the aircraft flew along the intended flight track between the vertical arrays at 150 feet altitude as indicated by the red "+" sign in the figure. The north-pole tower was deployed on the flight track centerline, 5000 feet down range from the goal-post array. To capture noise levels for the forward portion of the noise hemisphere, six microphones were suspended from the north-pole crane at heights of 30, 60, 90, 120, 150, and 175 feet above ground level and four microphones were deployed on the ground along the flight track in front of the north-pole array. The objective was to fly the aircraft at a prescribed steady state flight condition for a distance of about 8000 feet, 4000 feet before to 4000 feet past the goal-post array. A straight and level flight path was flown between the goal-post array and directly toward the north-pole array as shown in Figure 4a. This flight condition was held until the aircraft approached to within approximately 1000 feet of the north-pole array, at which point the pilot turned to the right to go around and set up for the next run. The run was considered complete when the right turn was initiated. Data runs were conducted at 150 feet and 250 feet altitude. White target cloth was placed at regular intervals along the ground track to provide visual guidance cues to the pilots. A photograph of the MD520N flying through the goal-post array is presented in Figure 5.



a) 3-dimensional sketch.



b) Goal-post array details.

Figure 4. Eglin microphone array.

Figure 5. MD520N flying through goal-post array.

Test Matrix

Data flights were conducted for a number of flight conditions as indicated in Table 1. All runs were level flyovers at 150 or 250 feet altitude and velocities of 60, 80, 100, and 120 knots or Vmax, as shown in the table. The maximum airspeed tested was vehicle dependent. If the vehicle could achieve at least 120 knots, then 120 knots was the maximum airspeed tested. If a vehicle was incapable of reaching 120 knots, then the maximum airspeed tested was the maximum airspeed that vehicle was capable of flying, Vmax. Multiple runs at each flight condition were desirable to improve the statistical confidence in the measured data. This test matrix equated to a total of 20 runs per vehicle.

Table 1. Test matrix.

Alt.\Vel.	60 kts	80 kts	100 kts	120 kts / Vmax
150 feet	2	3	3	4
250 feet	2	3	3	

Test Aircraft

A total of eight vehicles were tested during this program. Table 2 provides a list of the vehicles tested, the date each vehicle was tested, and the organizations that were instrumental in securing participation of each vehicle.

Table 2. Test vehicles.

Date Tested	**Vehicle**	**Organization**
9/8/03	Bell 206	Chicken Little
9/10/03	AH-64A	Ft. Rucker, Lead The Fleet, Chicken Little
9/11/03	K-Max	LaRC, Kaman, Northrop-Grumman
9/12/03	Schweizer 333 (FireScout prototype 2)	LaRC, Schweizer, Northrop-Grumman
9/15/03	Aerostar UAV	NAVAIR
9/16/03	Bo105	LaRC, Boeing-Mesa
9/17/03	UH-60L	Ft. Rucker, Lead The Fleet, Chicken Little
9/18/03	MD520N	LaRC, Boeing-Mesa

Aircraft Position Data

Accurate vehicle position data during these acoustic measurements are essential to the generation of high-quality noise hemispheres. Vehicle position data were acquired by five different organizations during this test program. Table 3 lists each organization, the vehicles for which they were responsible, and whether the data were differentially corrected. Differential corrections generally improve position data accuracy from several meters to sub-meter accuracy.

Table 3. Organizations providing vehicle position data.

Organization	Vehicle(s)	Differential GPS
Chicken Little	Bell 206	Yes
Ft. Rucker, Lead The Fleet	AH-64A, UH-60L	No
LaRC, Boeing-Mesa	K-Max, Bo105, MD520N	Yes
Northrop-Grumman	Schweizer333	Yes
NAVAIR	Aerostar	No

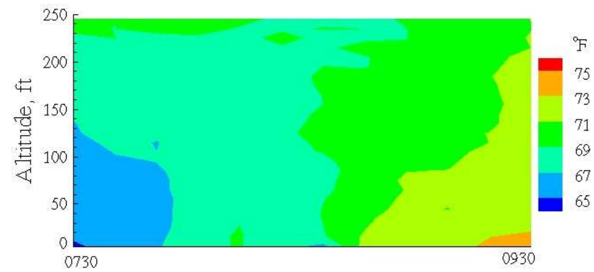
Weather Data

A tethered weather balloon system was used to acquire research weather profiles during each day's flight testing period. This system consisted of an electric winch-controlled, tethered, helium-filled balloon, an instrument/telemetry pod, a ground-based receiver/data-controller, and a ground-based support computer. Profiles of temperature, relative humidity, wind speed, and wind direction were acquired up to 500-ft altitude before, during, and after each test flight. An example of the weather data profiles for a typical test period is presented in Figure 6.

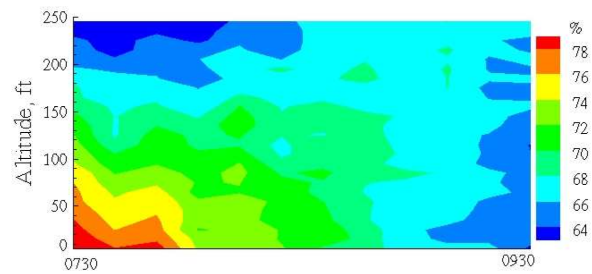
FLIGHT TEST PLANNING AND EXECUTION

Daily Operations

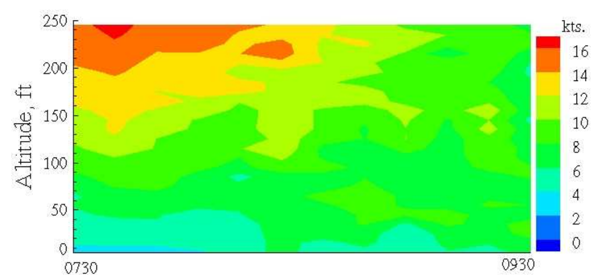
Acoustic Week was executed with limited resources. A remote test area on the Eglin AFB reservation was designated for the exercise, and a limited airspace window was made available from dawn to 1:00 p.m. to provide safe separation from other aircraft, and to help insure a minimally disturbed ambient noise environment. The multi-purpose range space was off limits during several weapons firing tests, limiting the time Acoustic Week test personnel could be on site. Due to the variety of restrictions driving the schedule, each test aircraft was allowed only one day for all flight and data collection activities. Fuel was available at the Crestview civil airport, approximately 7 minutes flight time from the test site. With an average endurance of about two hours per fuel load, this arrangement limited most vehicles to 2 sorties.



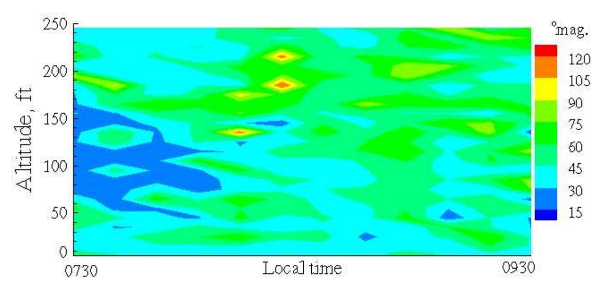
a) Temperature.



b) Humidity.



c) Wind speed.



d) Wind direction.

Figure 6. Weather profiles for the MD530N test period.

Several hours before dawn each morning, data collection personnel conducted their sensor deployment and calibration activities. The test aircraft was cleared into the airspace around 7:00 a.m. and recovered at the site headquarters so that the test director could brief the flight crew on flight profiles, range safety, and communication procedures. The first sortie of the each day was spent performing the flight profiles through the 3-dimensional microphone array. After a refueling stop at Crestview Airport, the second sortie was generally devoted to performing cloverleaf patterned flight paths over a human sound jury and a seismic array. Several minutes were also allocated near the conclusion of the second sortie to collect infra-red and various other data on the aircraft at a variety of azimuth and elevation angles.

Efficiency and Accuracy

Accurate vehicle position data and flight path accuracy, relative to the microphone array, is necessary for the collection of a high quality acoustics data set. Because of the variety of flight profiles required to be flown during the limited test time, few repeat flights were possible. Therefore, it was important that every data pass be performed as precisely as possible.

Efficient flight test execution requires substantial advanced planning and coordination. Matters such as range time coordination, minimum acceptable data accuracy (for all type data sets), calibration procedures, aircraft support logistics, aircraft data system recording methods and media, data archiving and control, etc. must be carefully considered. However trivial or mundane this may seem, the post-test realization that errors in information exist could call into question the validity of data that required significant resources to collect. The combined daily cost of range assets and personnel easily exceeded $50,000.00 per day. One lost day of testing due to poor planning, communication, or equipment failure would not only have wasted the day's resources, but also might have eliminated a test aircraft from the database.

The ability of various sensor data to be collected and quantified accurately is controlled in part by:

- Sensor accuracy and stability
- Proper calibration procedures
- Recording system dynamic range
- Electrical noise floors
- Ambient environment
- Correct deployment and operating procedures

The ideal test organization trains their personnel and fields the best sensor suite that technology offers. Next, the variables that can influence the quality of the data sets are considered. Local ambient weather conditions, particularly variable wind conditions, are beyond the control of the test team. Typically, maximum allowable levels of steady wind velocity, gust spread, and turbulence will be defined. Even when the atmospheric sensor equipment is installed at an optimized location, only the conditions at that measurement location are known for certain. Accelerations and attitudes experienced by an inertial measurement unit on the test aircraft, combined with subjective assessment of the conditions by the aircraft crew provide further guidance on flight test data quality. Aircraft control activity can also be used as a tool to evaluate air quality and the stability of maneuvers intended to be steady state.

Since the Acoustic Week test program budgeted only one day per vehicle, atmospheric conditions were simply accepted as nature provided them. However, testing was initiated as early each day as possible as this is typically the time of day when atmospheric conditions most suitable for acoustic testing. Only in the event of non-VFR conditions or precipitation that would damage sensor arrays were operations to be delayed or cancelled. Remarkably, no flight test operations were delayed or cancelled due to atmospheric conditions through the course of the test. However, the effects of atmospheric turbulence, both horizontal and vertical wind gust conditions, are evident in the data.

Once all sensor data has been optimized and atmospheric constraints met, it is imperative to accurately record the test aircraft position relative to the sensors, as a function of time. During this test, circumstances dictated that the Lead the Fleet military test aircraft were limited to on-board mux data recording of autonomous GPS aided inertial position data. The remainder of the test aircraft had some variation of differential GPS installed. Three of the test aircraft (K-Max, BO-105, and MD520N) were instrumented for precise real-time kinematic

(RTK) 3-dimensional position and velocity data. This system has been described in detail in earlier publications (Ref. 8, 9, 10), and is an exploitation of differential GPS using either RTK or post-processing techniques. Data from these 3 test aircraft were generally accurate to better than 2 inches in 3-dimensions. For both the MD520N and the BO-105, the system also provided real-time 3-dimensional guidance cueing to keep the flight crew on a pre-planned flight path. Real-time cues improved flight path accuracy, thus minimizing lost profiles due to gross altimeter errors or lack of familiarity of the flight crew with the environment. Naturally this level of accuracy ultimately improves the fidelity of the data set, which is used to validate or fine tune analytical and prediction models. As well, this system provided a defined data stream that could be merged the same day with the acoustic data so that the effectiveness and meaningfulness of the test procedures and flight profiles could be evaluated without delay.

Common Range Time

A variety of sensor recording systems must be precisely synchronized to a common time base for the data to be merged and evaluated. Misunderstandings still exist among testers regarding timing device errors, IRIG timing formats, and different time synchronization sources. This observation was reinforced during analysis of the Acoustic Week data sets as much time and effort was required to correctly identify the synchronization source for all the data sets provided by all the different organizations.

Historically, remote test operations synchronized their time databases among various assets using either (WWV) radio receivers or Geostationary Operational Environmental Satellite (GOES) constellation receivers. When properly employed, these methods offered the potential for time synchronization between locations of better than one millisecond.

If a tester is using a WWV receiver, a correction must be manually inserted based on the great circle distance from the WWV broadcast station in Ft. Collins, Colorado. At Eglin Air Force Base this is approximately 7 milliseconds. At 120 knots ground speed, an aircraft position will change approximately 1.4 feet in 7 milliseconds. However, if the same individual is using a GOES timecode receiver, an estimated propagation delay must be entered as a correction based on the geographical location of the receiver relative to the satellites. At Eglin AFB, this can result in corrections in the neighborhood of 53 milliseconds. Failure to enter this correction can cause an aircraft position error of 10.6 feet at 120 knots.

In the last few years, many test organizations have begun procuring and operating time code translator/generator devices that synchronize time to the GPS satellite constellation. The raw time broadcast by the GPS satellite constellation differs from Universal Coordinated Time (UTC) by a value known as leap seconds, which is explained in detail in the next section. GPS based timecode devices may automatically insert the leap second correction, or a manual or menu selection may be required for the device to produce UTC.

Manufacturer’s quote time accuracy values based upon whether the time sources (WWV, GOES, or GPS) are constantly monitored or whether the time code devices are initially synchronized then operated autonomously without further regard to the master source timing transmissions. Older timecode devices tend to exhibit excessive drift rates: regardless frequent synchronization of any timecode device with a master source is imperative if errors due to drift are to be minimized.

Leap Seconds

Civil time is occasionally adjusted by 1-second increments to ensure that the difference between a uniform time scale defined by atomic clocks does not differ from the Earth's rotational time by more than 0.9 seconds (Ref. 11). UTC, an atomic time, is the basis for civil time. Historically, the second was defined in terms of the rotation of the Earth as 1/86,400 of a mean solar day. The Earth is constantly undergoing a deceleration caused by the braking action of the tides. Through the use of ancient observations of eclipses, it is possible to determine the average deceleration of the Earth to be roughly 1.4 milliseconds per day per century. This deceleration causes the Earth's rotational time to slow with respect to the atomic clock time. Other factors also affect the Earth’s rotational speed, some in unpredictable ways, so that it is necessary to monitor the Earth's rotation continuously.

Currently the Earth runs slow at roughly 2 milliseconds per day. After 500 days, the difference between the Earth rotation time and the atomic time would be 1 second. Instead of allowing this to happen, a leap second is inserted to bring the two times closer together. This leap second can be either positive or negative depending on the Earth's rotation. The GPS constellation was made active on January 6, 1980 and was synchronized to UTC at that time. GPS time is not adjusted for leap seconds, and as of 1 January 1999 GPS was ahead of UTC by 13 seconds.

TEST RANGE SURVEY

Flight test activities performed relative to ground based sensors or geographical features require a high order survey of all relevant objects. The test plan typically describes how a variety of sensors must be located relative to a planned aircraft flight path, while local terrain features might force modification of planned sensor array locations. Such surveying tools as autonomous military or Wide Area Augmentation System (WAAS) enabled civil GPS receivers might be adequate for initial test range rough layout, however once final data processing is underway, analysis tools often demand position information of much higher accuracy.

Geoids And Ellipsoids

The ellipsoid is a mathematical model of the earth that defines the shape as a somewhat flattened sphere that is fatter in the horizontal than the vertical dimension. The geoid is defined as the difference between the ellipsoidal elevation and local sea level. Variations in the local gravity field contribute to the separation between the ellipsoid and the geoid. This variation is commonly referred to as the undulation. Most modern maps and differential GPS surveying and navigation use an ellipsoid model known as World Geodetic System 1984 (WGS-84).

Differential Global Positioning Systems have been demonstrated to be highly efficient and accurate surveying tools. However, different manufacturer’s equipment, or even different generations of equipment from the same manufacturer are often found to use different geoid databases. These databases exist in memory in the GPS receivers in the form of look up tables. Due to processor speed or memory constraints (i.e. GPS receiver competitive cost goals) these GPS receivers might use entirely different geoid data sets, or they might use the same basic geoid set that may have been severely decimated. Because the GPS manufacturers might not always provide clear information regarding their geoid correction table, the surveyor would be prudent to collect data relative to the ellipsoid. Even then the surveyor must be careful to insure that all assets are surveyed using the same ellipsoidal model. If using local terrain maps that present data relative to North American Datum 1927 (NAD ’27) significant conversions between datum reference frames will be required. NAD ’83 and WGS ’84 are virtually identical – the tiny differences that do exist are generally not an issue for flight test work (Ref. 12, 13).

Differential GPS Corrections

Differential GPS corrections remove systematic errors caused by:

- ionospheric group delays
- tropospheric refraction delays
- ephemeris errors
- satellite clock errors
- receiver clock errors
- multipath signal reception

Ultimately, the accuracy and precision of the DGPS solution will be dictated by:

- quality of the aircraft GPS antenna installation
- quality of the reference GPS antenna installation
- reliability of the differential correction data link
- particular GPS equipment manufacturer’s technology that is enabled on the GPS receiver
- satellite geometry
- resistance of the receivers and the installation to EMI/EMC, destructive interference of GPS signals by rotor blade modulation, and intentional and unintentional jamming and interference

Differential GPS corrections can be accomplished either real-time using a method referred to as Real Time Kinematic (RTK) or in a post-processed fashion. In the event that a highly accurate local reference station coordinate is not available, a method now exists for establishing one without hiring a land surveyor. The National Oceanic and Atmospheric Administration (NOAA) offers a free service to post-process static GPS survey data relative to the Continuously Operating Reference System (CORS) network. For test range survey planning purposes, the CORS network data processing service can be used to determine the level of accuracy that a local reference station can be established. Once that task is accomplished, the local reference station should be used to collect GPS range and ephemeris data for post processing, or to use for generating and transmitting RTK corrections. In some cases the CORS data can be used to adequately process dynamic GPS receiver data from the test vehicle if the range data is properly acquired and archived. Use of CORS data for this purpose requires the employment of a commercially available GPS data post processing software package, such as GrafNav from Waypoint Consulting, Inc. of Calgary, Canada.

In the event that the tester wishes to use RTK differential Global Positioning System (DGPS) techniques for position and guidance cueing, a reliable data link must be maintained between the DGPS reference station and the test vehicle. Generally, packet data radios - UHF simplex modem radios, typically 9600 or 19,200 baud rate, or 900 MHz spread spectrum radios are used to broadcast and receive differential corrections. These radios are susceptible to interference, and require that an acceptable antenna installation be created both on the test vehicle and at the ground station.

AIRCRAFT PRECISION DIFFERENTIAL GPS

Antenna Installation

The location of the GPS antenna on the test vehicle is of critical importance on a helicopter. Many GPS antenna locations that would be considered completely acceptable for an autonomous code based GPS receiver contribute to extremely poor performance on a precision carrier based DGPS installation. Typically what suffers the most is the RTK solution quality, however the post-processed data may be of unacceptable or disappointing quality as well.

The next several figures and accompanying text provide instrumentation installation descriptions during Acoustic Week. Figures 7 and 8 depict the installation of the GPS antenna on the BO-105 test aircraft. This was an FAA (337) certified installation that provided extremely variable results in RTK mode. Three dimensional solution accuracy varied from 1 inch to 8 feet, depending on aircraft attitude and GPS constellation orientation and availability. Figure 9 depicts two GPS antenna locations used on the K-Max test aircraft. The tail location provided excellent RTK system performance. Due to a sudden failure of the tail GPS antenna during the test, a temporary GPS antenna installation was created on the cockpit glare shield, which provided very poor RTK performance. Because raw GPS range and ephemeris data was recorded during the flights, it was possible to post process the aircraft position data. Using the GrafNav software tools, 3-dimensional data accuracy of better than 1 meter was obtained for the glare-shield antenna location. Figure 10 shows the GPS cycle slips – losses of GPS direct ranging information – that were experienced during the flight test period using the glare shield antenna location.

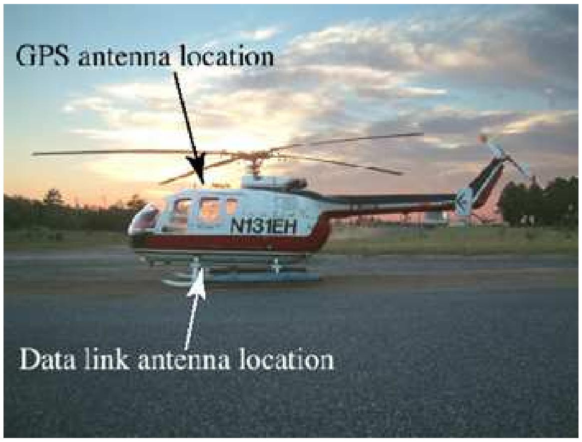


Figure 7. BO-105 Flight Test Vehicle

Figure 8. BO-105 GPS antenna detail.

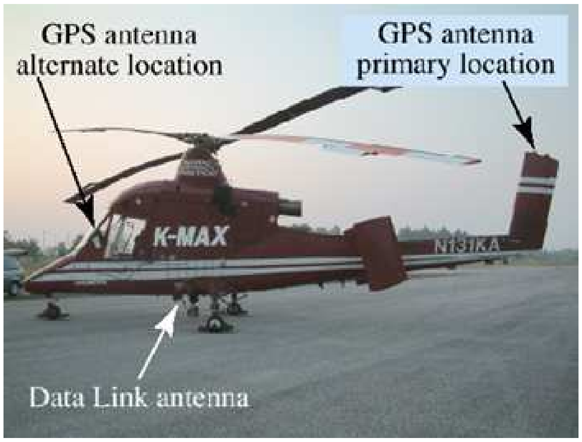


Figure 9. K-Max test aircraft antenna locations.

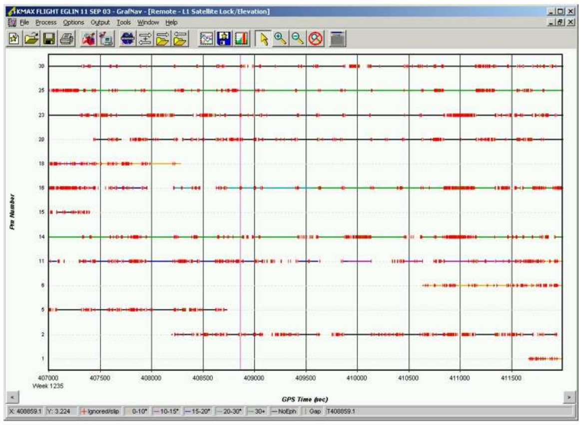


Figure 10. GPS satellite lock breaks (cycle slips in red) caused by poor GPS antenna location.

Figures 11 and 12 demonstrate the installation of the RTK radio data link antenna, tuned for 414.1375 MHz, and the installation of the cockpit command/control touch screen and course deviation indicator / glideslope deviation indicator (CDI/GDI) used to cue the pilot for the precision flight profiles.

Figure 11. BO-105 RF data link antenna installation, left side of airframe.

Figure 13 depicts the RTK DGPS package that was installed in each of the precision test aircraft. Figure 14 depicts the GPS antenna installation on the MD520N. Note that this location is between two fiberglass vertical stabilizers, which are transparent to RF. Also note that the location is at the edge of the rotor disk, so that the incidence of blade passage isn't a factor in GPS satellite signal reception. The BO-105 antenna installation suffered both from the GPS satellite signal blockage due to the rotor head, upper controls, and fairing structure, as well as the much higher frequency of rotor blade passage. Rotor blade effects can be estimated by considering the rotor RPM, along with the blade chord length and the distance the GPS antenna is from the rotor center.

Figure 12. BO-105 modified instrument panel.

Figure 13. PTR airborne package installation in the BO-105.

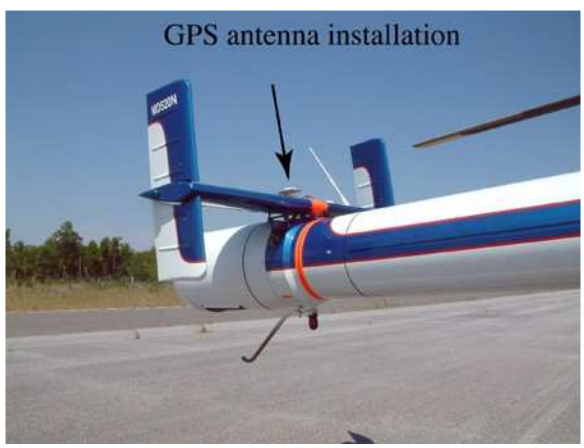


Figure 14. L1/L2 GPS antenna installation on the MD520N.

The Merits of Real Time Guidance

Figure 15 plots the flight track for a data run from the Bell 206 helicopter, which was flown through the microphone array using only ground objects to reference the desired flight track. The vehicle altitude and ground track are plotted as a function of distance from the goal-post microphone array for a 60 knot level flyover. The ideal desired flight path is indicated by the dashed lines. Figure 16 plots a similar data run from the MD520N, which was configured with a cockpit indicator providing both lateral and vertical guidance provided by the DGPS derived position solution. These plots are the first data run for each aircraft. Note the MD520N maintained altitude and centerline with much greater accuracy than for the Bell 206, so that even the very first data point is a quality run. This level of efficiency and accuracy provides for a high level of data repeatability and an opportunity to average data sets with very low scatter.

Figure 15 presents a good example of the bias that is present in an aircraft when a pilot has to fly relative to ground references. While this is position data from the first data run, Figure 17 demonstrates that the bias is present over virtually all data runs. The horizontal bias from centerline is due to the pilot's sense of which way "straight down" is, and the ability to line up an instrument panel or canopy frame reference with the available ground markers. The vertical bias is typically a result of static system error or barometric altimeter instrument error.

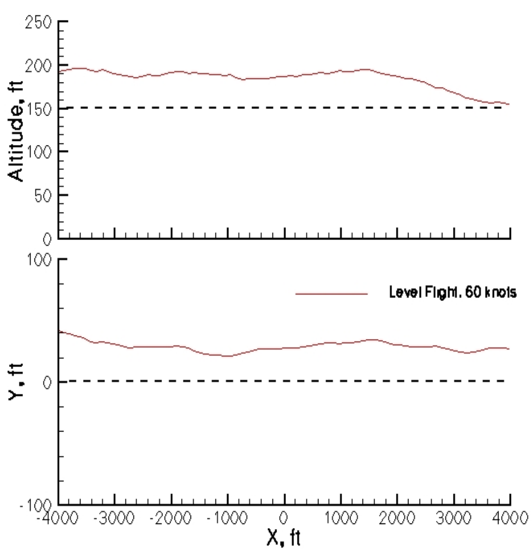


Figure 15. Bell 206 first data run, 60 KIAS.

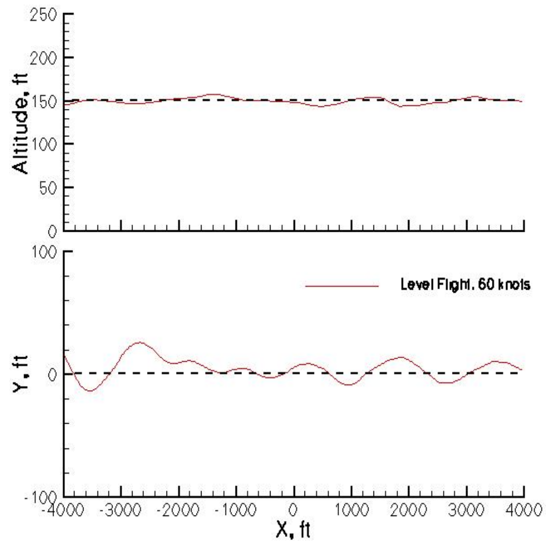


Figure 16. MD520N first data run, 60 KIAS.

When the pilot is familiar and proficient at the use of the CDI/GDI, anything other than a cursory familiarization run through the sensor array is unnecessary. Since the pilot is not navigating with reference to outside objects, the pilot's attention can remain focused on the course line guidance, airspeed indicator, and any other required reference instruments. However, proper arrangement of the required reference instruments so that they can be rapidly scanned and interpreted is also crucial to obtaining precision flight tracks.

When the above conditions are met, the tolerances for the CDI/GDI can be minimized. During the Eglin flight test, the MD520N pilot flew a CDI/GDI with gains of +/- 25 feet from course line center (horizontal and vertical) to full-scale needle deviation. This high level of sensitivity allowed the test pilot to rapidly detect a trend away from the desired horizontal or vertical centerline, and make a very slight course correction using extremely small control movements. Obviously large abrupt control movements to effect course corrections will result in a much larger anomaly in the acoustic data, and some other sensor data sets due to the larger change in aircraft attitude. MD520N flight tracks for all the 150 foot altitude runs is presented in Figure 18.

If pilot's control activity, as well as rates, attitudes, and accelerations available in the data set, one could determine the contribution that horizontal and vertical gusts played in the flight path oscillations. Although a major effort was made during this test program to profile the atmosphere, the winds aloft measurements were only made from one ground location. Atmospheric disturbances are often extremely localized. Subjective assessment regarding horizontal wind gust conditions during several of the MD520N data runs correlated well with some of the excursions from the 3-dimensional centerline. A comparison of vertical and horizontal position scatter for all runs for both the Bell 206 (no cockpit guidance) and the MD520N (3-dimensional cockpit guidance) is presented in Figures 19 and 20. The average sideline distance from the desired flight track and the altitude, including 150 and 250 foot altitude flyovers, during a run are indicated by a dot, with the error bars indicating ± one standard deviation. The Bell 206 data are shown in black while the MD520N data are shown in red. Desired ideal flight tracks are indicated by the solid black lines.

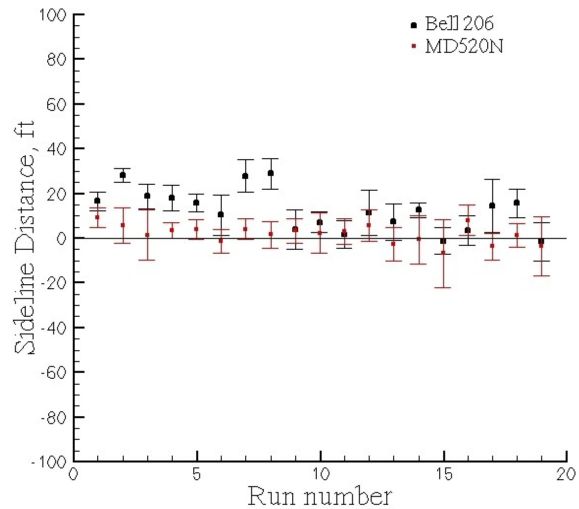


Figure 19. Horizontal centerline data scatter for two civil test aircraft.

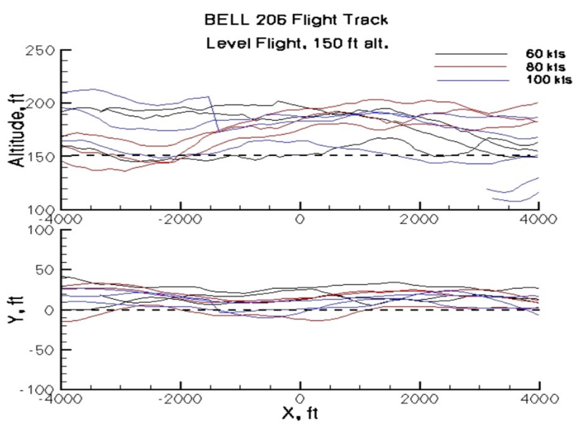


Figure 17. Bell 206 150 foot altitude data runs.

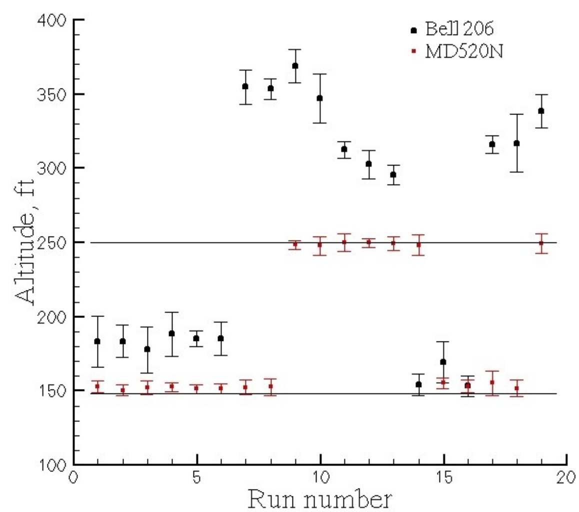


Figure 20. True altitude data scatter for two civil test aircraft.

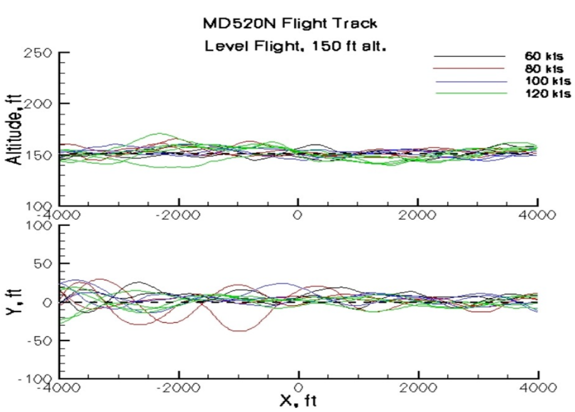


Figure 18. MD520N 150 foot altitude data runs.

ACOUSTIC DATA RESULTS

This section is intended to provide examples of acoustic results that can be provided by RNM using high quality measured noise hemispheres.

Figure 21 is a MD520N noise hemisphere, developed using the Acoustic Repropagation Technique and measured data from the Eglin test, for a level flight condition at 80 knots airspeed. The hemisphere radius is 100 feet. The A-weighted overall sound pressure level, L_A, is indicated by the contour color. All acoustic data presented in this section are based upon this noise hemisphere.

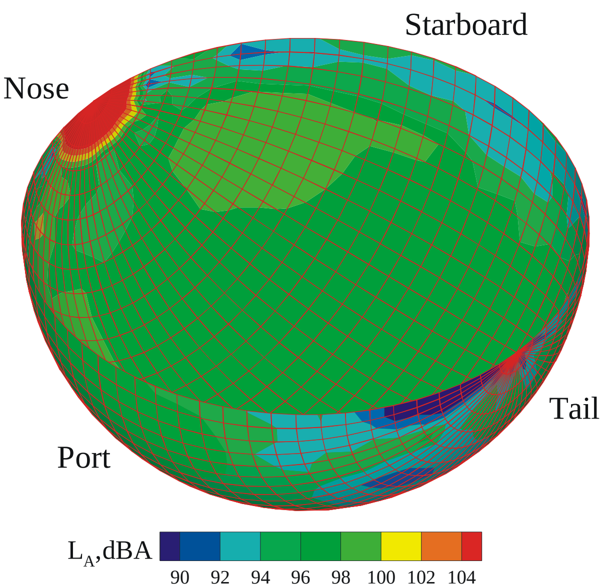


Figure 21. MD520N measured LA noise hemisphere, 80 knot level flight condition.

Figure 22 shows a comparison of the measured and RNM predicted L_A time histories for the centerline ground microphone position in the goal-post array. The vehicle flight condition was a 150 foot AGL level flyover at 80 knots airspeed. The noise hemisphere of Figure 21 was used by RNM to simulate an 80 knot level flyover and predict the noise levels at the centerline microphone location. The aircraft is approaching the microphone location for negative times, directly overhead of the microphone at time equal zero, and departing the microphone location for positive times. As would be expected, the maximum noise levels occur when the aircraft is directly overhead of the microphone and fall off steadily with increasing distance from the microphone. Predicted and measured noise levels compare nearly identically at the higher levels (65 to 90 dBA), thus validating the propagation algorithms in RNM and ART for relatively short ranges. Below 65 dBA the mean levels are approximately equal, however, the measured data has some variability that is not accounted for in the predicted data. One contributor to this variability could be variations in the actual flight track from the ideal flight track, or frequent control inputs made in an attempt to maintain the ideal flight track and requested airspeed, and variations in the vehicle attitudes (roll pitch and yaw) caused by these control inputs. Another contributor to this variability is probably atmospheric effects on the acoustic propagation of the measured signal that are not currently (or properly) accounted for in RNM. The current version of RNM used for these predictions does not model excess attenuation due to non-homogeneous temperature profiles, winds, atmospheric turbulence, etc.

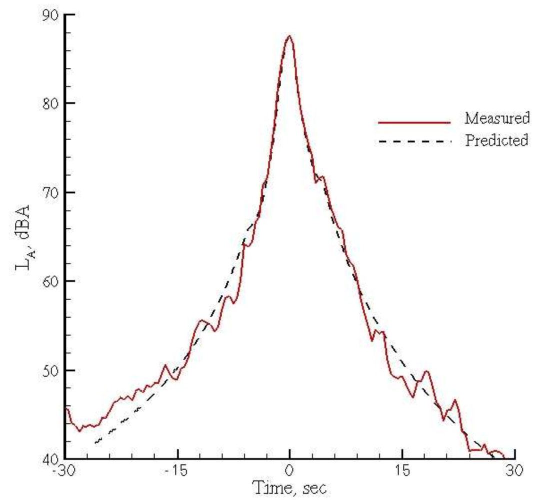


Figure 22. Comparison of measured and RNM predicted LA time history for centerline ground microphone, 80 knot level flight condition at 150 foot AGL.

Figure 23 shows a comparison of the measured and RNM predicted L_A time histories for a microphone location 400 feet to the starboard side of the aircraft, 50 feet above the ground. The vehicle flight condition was the same as for Figure 22 and again, the noise hemisphere of Figure 21 was used by RNM to simulate the 80 knot level flyover and predict the noise levels at this microphone location. Just as for Figure 8, the predicted and measured noise levels compare nearly identically at the higher levels (>65 dBA) and the mean levels are approximately equal at the lower levels. The same variability can be seen in the measured data at the lower levels that is not accounted for in the predicted data. Compared to the ground microphone of Figure 22, ambient noise levels appear to be higher on this elevated microphone, at about 48 dBA, due to increased wind noise on the microphone.

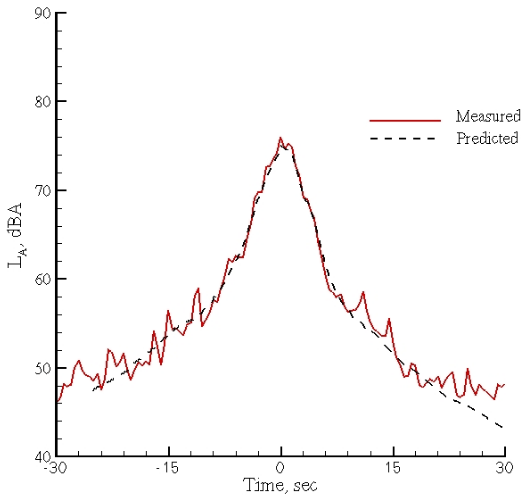


Figure 23. Comparison of measured and RNM predicted L_A time history for elevated microphone located 400 feet to the starboard sideline and 50 feet above ground level, 80 knot level flight condition.

RNM predicted Sound Exposure Level (SEL) noise footprints for MD520N 80 knot level flyovers at 150 feet and 1000 feet altitudes are presented in Figures 24 and 25, respectively. The noise hemisphere of Figure 21 was used by RNM to predict the SEL at a grid of points on a ground plane. A commercially available software package was then used to curve fit between the discrete prediction points and generate smooth contour plots. In these figures, the aircraft was simulated to fly a straight and level flight path, from left to right in the figures, at a sideline distance of 0 feet and the prescribed altitudes of 150 and 1000 feet AGL. The footprints are shown for an area that is 4000 feet long in the direction of flight and 2000 feet to either side of the vehicle flight track. As expected, the noise levels are greatest directly beneath the flight track and decrease continuously with increasing distance from the flight track. Note that these two plots have different SEL contour scales. Increasing the flyover altitude from 150 to 1000 feet decreased the noise levels directly beneath the flight track by 10 SEL, dB, from about 91 to 81 SEL, dB. However, noise levels 2000 feet to either sideline were greater for the 1000 foot AGL flyover than for the 150 foot AGL flyover, with a 2 SEL, dB noise increase observed on the port side (very top of the figures, at a sideline distance or Y = 2000) and a 6 SEL, dB increase on the starboard side (very bottom of the figures, at Y = -2000). The cause of the noise increase on the starboard sideline can be easily explained by looking at the source noise hemisphere of Figure 21. On the starboard side of the noise hemisphere, noise levels 27° below the rotor tip-path-plane (gridlines are at 5° increments), which corresponds to the directivity angle for the 1000 foot flyover, are significantly higher (about 4 dBA) than the noise levels 4° below the rotor tip-path-planethat corresponds to the directivity angle for the 150 foot flyover.

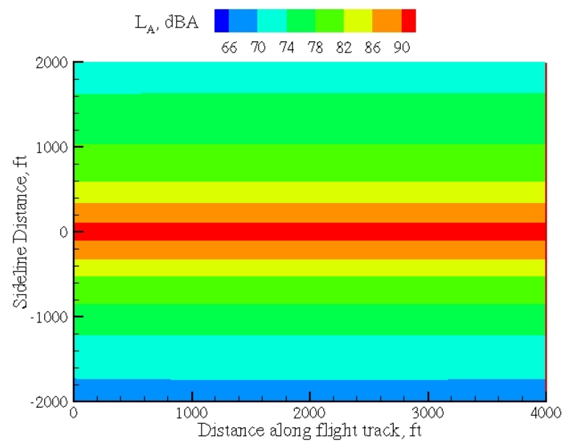


Figure 24. RNM predicted SEL noise footprint for MD520N 80 knot level flyover at 150 feet altitude.

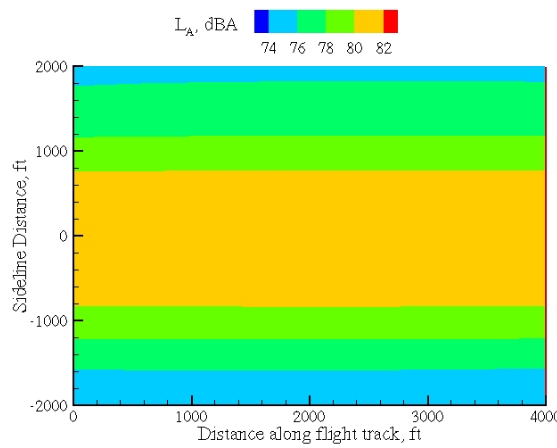


Figure 25. RNM predicted SEL noise footprint for MD520N 80 knot level flyover at 1000 feet altitude.

Differences in propagation losses will be small between the two flyover altitudes since the source to receiver propagation distance increases by only 11%, from 2006 to 2236 feet, for the 1000 foot flyover compared to the 150 foot flyover. These noise footprints show the atypical effect on the ground noise footprint, compared to fixed wing aircraft, of the highly directional source noise characteristics of rotorcraft, and emphasize the criticality of accurately measuring the entire noise hemisphere for rotorcraft.

CONCLUDING REMARKS

A synopsis of the Acoustic Week test program has been provided. The need for accurate vehicle position data was established through a discussion of the noise hemisphere measurement technique. The requirement to accurately measure the relationship between the source and receiver, as a function of time, is fundamental to defining the vehicle acoustic characteristics and directivity. A detailed description of GPS tracking systems and a discussion of the sources of analysis errors and tracking accuracy degradation underscores the need for system operators that possess a thorough understanding of their specific GPS system. Ultimately, the precision and reliability of a differential GPS solution was found to be strongly dictated by the quality of the aircraft and reference GPS antenna installations, as well as the reliability of the differential correction data link, the enabled technology in a particular GPS system make and model, the satellite geometry, and resistance of the receivers and the installation to EMI/EMC and intentional or unintentional jamming and interference.

All Acoustic Week sensor-recording systems were required to be precisely synchronized to a common time base to facilitate merging of data sets to meet program goals. Analysis of the Acoustic Week data sets required significant time and effort to correctly identify synchronization sources for all the data sets provided by all the different organizations, indicating that misunderstandings still exist among testers regarding timing device errors, IRIG time formats, and different time synchronization sources. Standardization of the time base used for data synchronization during flight tests would significantly reduce processing time and effort.

The high costs inherent to flight testing demand experimental efficiency. The Acoustic Week test program budget allowed for only about four flight hours (during a single day) per vehicle; therefore it was imperative that every data run be of maximum quality. Improved run quality was anticipated and realized through the use of a DGPS based flight track guidance system that was installed on two of the test aircraft by the Army/NASA/Boeing test team. Real-time vehicle position data (DGPS) were compared against desired vehicle position information and the results were used to drive course and glide slope deviation indicators (CDI/GDI). A comparison of all flight tracks flown by a vehicle using only ground references and a pressure altimeter for guidance cues and a vehicle using CDI/GDI instrumentation for guidance cues shows dramatic improvements in flight track accuracy and repeatability with the CDI/GDI guidance cues. The effect of vehicle flight track variations, and the control inputs required to precisely maintain the desired flight track, on the measured noise hemispheres should be investigated. However, results from this paper indicate that the collection of accurate source noise hemispheres for rotorcraft does require accurate vehicle position data and precision flight tracks.

FUTURE EFFORTS

Overall, the objectives of the Chicken Little Acoustic Week test were completed, and the exercise was considered a great success. A variety of lessons learned will be applied to the next planned test, which is tentatively scheduled for 2005. The focus of the 2005 test effort is expected to include a combination of heavy lift rotary wing and UAV aircraft. Coordination is on-going with the DoD/INTEL government community as well as key industry players.

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