Rotorcraft Visual Situational Awareness

Solving the Pilotage Problem for Landing in Degraded Visual Environments

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ABSTRACT
Rotorcraft experience landing accidents caused by loss of visual situational awareness and spatial disorientation due to brownout or whiteout conditions from obscurant clouds created by the downwash of the rotor blades. BAE Systems is developing a solution that provides the pilot with intuitive, eyes-out landing guidance augmented with a dynamic, cognitive head-down synthetic view of the ground and obstacles around the landing zone, or LZ. A pilot-designated landing point produces a geographically referenced 3-D landing symbol projected on a helmet-mounted display, which provides perspective of where to land as indicated by the dynamic size and orientation of the symbol. A scanning 94-GHz monopulse radar that penetrates obscurant clouds provides continuous updates of the terrain and objects in the LZ. The radar feeds a synthetic 3-D scene terrain-morphing display algorithm that continuously augments a 3-D terrain model to generate a real-time synthetic image of the LZ on a head-down display.

INTRODUCTION

Rotorcraft have long experienced accidents caused by loss of visual situational awareness and spatial disorientation due to brownout or whiteout in dusty, sandy, or snowy areas as the downwash of the rotor blades creates obscurant clouds that engulf the helicopter. In addition, rotary-wing aircraft continue to be susceptible to controlled flight into terrain and impact with objects, such as wires. These problems cannot be solved by pilot training alone. No optimal technical solution for brownout or whiteout conditions is currently available.

As part of an overall degraded visual environment (DVE) solution for rotorcraft, BAE Systems is developing Brownout Landing Aid System Technology, or BLAST, that provides the pilot with intuitive eyes-out landing guidance on a helmet-mounted display augmented with a dynamic, cognitive 3-D synthetic view of the LZ on a multifunction display generated from active scanning millimeter-wave radar.

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A pilot-designated landing point produces a geographically referenced 3-D landing symbol projected on a helmet-mounted display, providing perspective of where to land as indicated by the dynamic size and orientation of the symbol. A 94-GHz monopulse radar that penetrates obscurant clouds provides continuous updates of the terrain and objects in the LZ. The radar feeds a synthetic 3-D terrain-morphing display algorithm that continuously augments a terrain model to generate a real-time image of the LZ on a multifunction display.

The LZ designation with conformal landing point symbology on a helmet mounted display has been successfully evaluated by operational pilots and test pilots. The System has been evaluated in a simulator environment in the U.K. and plans for flight trials in 2009.

Field tests conducted by BAE Systems at Yuma Proving Grounds (YPG) of an active-terrain scanning system using a declassified production radar missile-seeker head from MBDA Missile Systems, a world leader in missiles and missile systems, have demonstrated the capability of the 94-GHz based radar/display system to scan the designated terrain and accurately depict objects of interest in the landing zone and confirmed the ability to see through dust and generate comprehensive 3-D synthetic images of the illuminated area. Follow-on flight testing is planned in 2009.

Pilot evaluations of the combined passive/active system solution in a static flight simulator in conjunction with the Army Aeroflightdynamics Directorate (AFDD) at NASA Ames Research Center under a Cooperative Research and Development Agreement (CRADA) are being performed to validate the system's effectiveness and refine its operational concepts.

This paper describes BAE Systems' approach to solving the pilotage problem by providing the pilot with intuitive actionable information to maintain situational awareness and safely land in a degraded visual environment. This approach, in conjunction with a low-cost inertial reference and navigation system such as an embedded GPS, can be readily installed on most types of rotorcraft platforms to satisfy the urgent need for a brownout landing capability.

MAIN BODY

Brownouts are caused by excessive dust and dirt thrown up by aircraft taking off or landing – or, as is often the case with helicopters, just idling. They can turn piloting from a challenge to a nightmare in seconds, brownout conditions, as shown in Figure 1, can cause pilots to lose situational awareness or encounter spatial disorientation, resulting in flight into terrain during landing, hard landings, landing on or running into undetected obstacles, wire or cable strikes, obstacle strikes during ground roll, or dynamic rollover during touchdown from lateral drift or uneven or sloping terrain.

Figure 1: Flying into brownout condition

The problem can occur anywhere there are dusty conditions. It is a particular issue in Iraq and Afghanistan, currently affecting operations by the U.S., U.K., and NATO partners.

Limitations on rotorcraft operation caused by degraded visual environments (DVEs) are a current operational concern. Although DVEs encompass effects due to snow, very low light, and dust, it is predominantly dust that is considered here. For the purposes of this note, the "brownout" problem is defined as a rotorcraft landing (single or multi-ship) that commences in satisfactory day or night visibility. At some point close to the desired ground land-on point, dust raised by the aircraft rotors obscures the outside view, effectively divorcing the pilot from ground contact. Some air vehicles also lose returns from the radar altimeter at this time. During these conditions, there is a danger of pilot disorientation and subsequent contact with the ground with sufficient lateral drift to induce the aircraft to topple. Additionally, visual contact with ground obstructions and other co-operating helicopters is lost, resulting in risk of collision. Less-serious risks are hard landing and contact with minor obstructions, which cause non-catastrophic damage to the aircraft. To an extent, the pilot is able to control the onset and severity of vision loss by selection of a landing profile, balancing speed, height, and approach track against the current tactical situation.

Consequently, there is a need to find a way to allow pilots to land safely in these conditions. The solution should be intuitive and easy to use, preferably without needing to change current flying rules and operational procedures. Pilot workload must be kept to a minimum. This, in turn, implies that minimal training in how to use the solution is needed. To keep costs as low as possible, integration of any solution should be simple and must be suitable for retrofit to existing platforms, and for any new-build platforms.

Figure 2 is an initial definition of the zero-visibility zone produced by brownout conditions. Any solution has to allow the pilot to safely land the aircraft at the required point in this volume or to safely extract himself during an approach and to take off again once landed. Safe operation with under-slung loads also is required. These operations are to be performed in the presence of adjacent aircraft and land vehicles infringing on the zero-visibility zone, day or night.

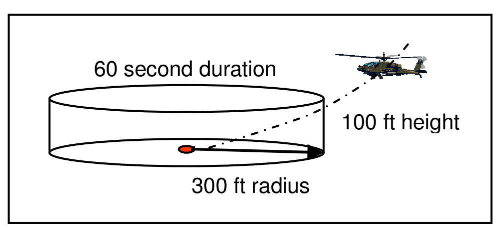

Figure 2: Zero-visibility design box

Improved operation in brownout conditions is the current operational objective, but there also are visible long-term trends. Shifts in warfare to asymmetrical conflicts and expeditionary forces, operating outside of northern Europe, pose challenges of fast-tempo operations in close contact with non-combatants conducted in difficult natural environments. This means helicopter forces will be expected to conduct more operations under increasingly difficult conditions. BAE Systems' view is that a shift in cockpit operation from eyes-in to eyes-out operation will greatly assist in meeting these objectives.

The brownout problem can therefore be viewed as an initial stage in this long process of transition, with implications beyond the immediate need. For example, eyes-out technology developed for brownout operations will have application in fog and high-moisture environments and operation during day and night transit. Additionally, other mission functions, such as targeting, can easily be added to the helmet system. Crews may demand different information to deal with different environments and phases of flight, but fundamentally, it must be possible to grow and add onto the baseline brownout solution to gain advantage over the whole flight regime. A solid understanding of these longer-term needs and seamless integration of these into the specific brownout DVE solution is essential for the efficient operation of the helicopter force.

Operational concept

To perform a safe landing, the pilot needs visual cues as follows:

- Visual cue of intended touchdown point
- Location and size of obstacles for collision avoidance
- Geographic fixed point(s) of reference for drift velocity estimation
- Geographic fixed point(s) of reference for maintaining orientation
- Topography (smoothness and slope)

The following factors must be considered in defining system capabilities:

- Ground mapping and sensor imaging becomes important below 500 feet above ground level (AGL) for rotorcraft operations, and significantly more important below 100 feet AGL for brownout
- Pilot's active surveillance of LZ starts at 100 feet AGL, looking for obstructions and suitability of LZ for landing
- Brownout begins at or below 75 feet AGL and persists down to zero feet AGL for a Blackhawk helicopter
- Descent to zero occurs with a continually variable approach profile
- Nominal descent flight path angle can vary from 3 to 15 degrees
- Changing aerodynamic and handling qualities due to wind changes causing drift
- Variable deceleration rates
- Clearing for landing must be a minimum 150 feet wide and 250 feet long for safe landing
- Pilot needs to "see" and avoid an object that is minimum one foot in diameter and two feet high
- Dangerous obstacles such as cables, fence posts, or poles may be in flight path
- Stationary obstructions such as buildings may be close by
- Moving vehicles may cause hazardous situations if driven into path of rotorcraft
- Landing surface not surveyed
- Slope of landing site must not exceed 9 degrees for some rotorcraft
- Pilot loses ground point of reference in zero visibility
- Pilot becomes disoriented in brownout
- System required to provide cognitive input to pilot to restore spatial awareness

BLAST overview

BAE Systems has developed Brownout Landing Aid System Technology, or BLAST, based on the concept of operation for landing a rotorcraft in brownout conditions. The solution takes into account an operational concept that will provide pilots with enhanced situational awareness from the point where the descent to the LZ already has been initiated.

The BAE Systems solution provides the pilot with intuitive landing guidance augmented with a dynamic cognitive view of the ground in and around the LZ. The System is in two integrated parts — an eyes-out symbol set to maintain situational awareness combined with a heads down synthetic view of the LZ to detect moving and stationary obstacles. The system emulates normal flying operations where the pilot chooses the desired landing point and then visually flies the helicopter to that position using flight instruments and internal and external references. The solution uses this constant aspect procedure to allow a landing in brownout or whiteout conditions.

The system, as depicted in Figure 3, consists of a forward-looking 94GHz sensor, an embedded computer with proprietary monopulse radar-processing algorithm and synthetic terrain morphing display engine, a multi-function display, a landing zone designation switch, and a tracked helmet-mounted display for each pilot.

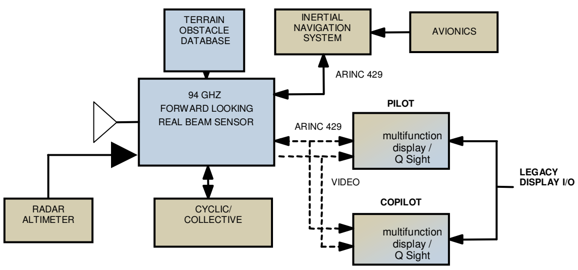

Figure 3: BLAST system diagram

Prior to entering brownout conditions, the handling pilot assigns the desired landing point by simply looking at it and then designating it using a pointing indicator head-tracked helmet mounted display and a button on the collective. A geographically referenced 3-D landing symbol is then projected on the helmet display. This conformal symbology provides the pilot with perspective and situational awareness of the landing point, indicated by the change in size and orientation of the symbol. The helmet mounted display also displays the flight instrumentation required to fly the helicopter with eyes out of the cockpit. This passive solution provides the pilot with an intuitive method for landing to synthetically generated reference points, but provides no information on the suitability of the landing area or any real-time updates once the visual references are obscured.

To provide the pilot with real-time situational awareness of the objects in and around the LZ, a low-power, high-resolution, 94-GHz frequency-modulated continuous wave radar from MBDA actively scans the designated LZ. The detected radar signal is digitized and processed using innovative BAE Systems monopulse processing techniques to provide terrain details, including the height of objects, to augment a detailed 3-D terrain model of the LZ. A terrain-morphing display algorithm uses the sensor data along with the stored terrain database and vehicle state data to continuously update and synthetically render a real-time image on a head-down display to portray the LZ features as depicted in Figure 4. The resultant terrain model is of high-enough resolution that objects of interest such as boulders, fences, poles, vehicles, and personnel, will be distinguishable from terrain features. The pilot also can select a 2-D horizontal situational view to improve awareness of horizontal position and velocity during hover mode.

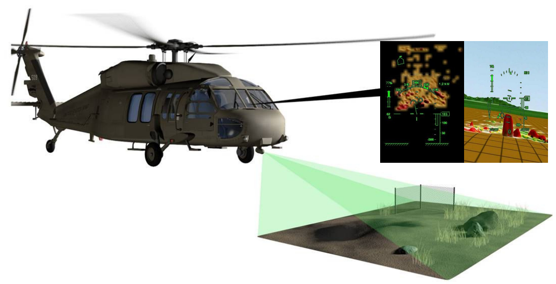

Figure 4: Terrain scanning and display on head-down display

The enhanced Brown-Out Symbology Set (BOSS) developed by the Army Aeroflightdynamics Directorate (AFDD)[1] is optionally overlaid on the head-down display, providing cueing to guide the pilot to a designated landing point in the absence of a helmet mounted display with conformal landing symbology.

The BLAST architecture provides a scalable, low-cost capability that can offer the pilot passive flight guidance via conformal symbology on a helmet mounted display with the option to add active scanning to provide a dynamic cognitive view of the ground in and around the LZ on a multi-function display during landing.

Key discriminators of the BAE Systems BLAST landing solution:

- Total system solution from sensor to display
- Intuitive and simple to use, so training costs are minimal
- Scalable capability from passive conformal symbology to active sensor technology
- Low-cost, head-tracked, helmet mounted display
- Eyes-out intuitive landing guidance on the helmet mounted display
- Conformal symbology design reflecting years of experience in conformal development
- MBDA 94-GHz GHz monopulse radar sensor with “see-through” capability
- BAE Systems unique monopulse radar data processing algorithms (patent pending)
- Novel terrain-morphing algorithm to produce real-time 3-D terrain display
- Rendered display image is simple for pilots to interpret

- Brown-Out Symbology Set (BOSS) developed by the Army Aeroflightdynamics Directorate (AFDD) provided for head-down guidance
- Radar adapted from mature production design
- Small radar size
- Low Radar weight
- Radar provides excellent range resolution
- Narrow pencil beam with monopulse processing achieves high angular accuracy
- Adaptive scanning technique minimizes latency
- Army-conducted simulator pilot evaluations assess pilot-vehicle interface effectiveness
- Production systems can easily be fitted to new aircraft or retrofitted to existing helicopters

Passive approach

BAE Systems has developed a passive solution for helicopter landing in degraded visual conditions. In normal flying operations, the pilot chooses the desired landing point and then visually flies the helicopter to that position. The BAE Systems solution emulates this procedure to allow landings in brownout or whiteout conditions.

The components used for the passive capability consist of a low-cost tracked helmet mounted display such as the BAE Systems Q-Sight™ 150, shown in Figure 5; terrain database; processor; and human-machine input device(s), preferably hands on throttle-and-stick, which the operator uses to control the system.

Figure 5: The BAE Systems Q-Sight™ 150 helmet mounted display

Prior to entering brownout conditions, the pilot positions the designation marker (an open cross symbol shown on the helmet display) over the desired landing position and presses the designate button on the collective. Once designated, the symbol changes to the landing symbol (shown in Figure 6), which is a circle of markers centered about the landing position. The size of the circle is based on the helicopter rotor disc and the height of the markers on the size of the helicopter. Using a combination of the aircraft position and attitude and the pilot's head position and attitude, the geographical position is determined and the landing point symbol is geographically referenced and remains at that position on the Earth's surface. The displayed symbol's size is drawn relative to the aircraft's distance from the landing point. The symbol provides the pilot with situational awareness of the landing point's location, how far away it is, and the attitude of the aircraft relative to the landing point. In addition, the rate of closure to the landing point can be determined and displayed. Other geo-referenced symbols also can be used to augment the basic landing circle. For example, the standard NATO landing "T" or "Y" can be displayed so that glide slope angle and approach heading awareness can be maintained in a familiar and intuitive manner. These landing symbols are displayed on the helmet in addition to the normal flight instrument symbols such as altitude, height above terrain, airspeed, ground speed, and heading displays.

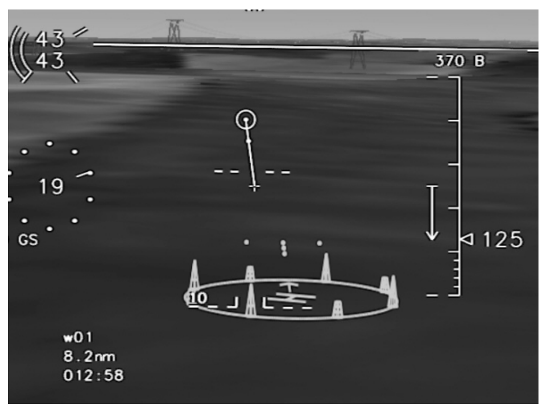

Figure 6: Conformal landing symbology on the helmet mounted display

The designated landing point also can be viewed on the head-down displays, including a moving map if available.

This passive approach uses inputs from the aircraft's inertial navigation systems (INS) and GPS to provide position and attitude information. As the INS is subject to offset and drift errors, this could result in errors in the positioning of the landing symbol. However, these effects can be ameliorated by taking multiple designations of the landing point. This will help to calibrate errors in the designation process and provides feedback of current system errors to the pilot. The pilot can constantly verify that the landing symbol remains correctly positioned at the desired landing site prior to entering the brownout, which provides valuable feedback and confidence in the performance of the system as a whole. Once the aircraft has entered the brownout zone, which typically is one-and-a-half times the rotor blade diameter, the helicopter is landed using the landing point symbol. As the symbol is synthetically generated, it is always visible and locked to the geographical location of the landing point. In addition, as it is a 3-D symbol, it provides feedback on approach angle, attitude, and distance. Further details showing the height of lines drawn on the individual cones composing the landing point symbol also provide information about height above the ground. Once satisfied with the location of the landing point, the pilot flies the vehicle through the low-visibility condition using the conformal symbology until touchdown.

If the symbology appears to drift off the intended landing point on approach, or the pilot wishes to refine the position of the landing point, the hands on throttle-and-stick controls are used to adjust its geographic position. At any time, the pilot may clear the designation, removing the conformal landing zone symbology and recalling the pointing reference, and designate a new landing point.

This passive approach to providing situational awareness during brownout conditions is based on the concept that the pilot selects a landing point under normal visual flying conditions, checking the landing zone for suitability, obstructions, slope, etc. The pilot continues to fly to that position as under normal visual flight without brownout conditions. This means that the pilot is always in control with the symbology being used to provide a reference to where the landing position is. As there are no sensors being used, it is not dependent on the pilot having to interpret sensor imagery or on the ability of the sensor to see through the dust or other obscurants. However, the system can be used with a sensor system to update the position of aircraft and other obstacles. When used in conjunction with the active capability, sensor-generated range data can be used to help determine the landing zone's geographical position.

Although the prime mode of operation is expected to be landing at previously undesignated landing points, the system can be used to land at pre-designated landing points for which a latitude, longitude, and elevation are known, or the position can be designated from other sources such as the mission planning system, the digital map, or a forward air controller at the landing site.

Landing point designation and symbology generation has been demonstrated in fixed-base simulators using a helmet-mounted display. The symbol set has been updated and refined based on pilot feedback and objective experimental measurements. Resulting changes ensure that information required during the final stages of landing is available for all landing scenarios without display clutter. BAE Systems has addressed issues affecting the ability to produce a stable, low-latency display and designation point. The company also conducted an error and sensitivity analysis to enable definition of error budgets for system components and completed a draft safety case. BLAST passive system software has been written to production standard, and the system is being qualified for flight test in 2009.

Active approach

The BAE Systems BLAST active approach is based on the premise that a 94-GHz millimeter-wave sensor's ability to "see through" the type of brownout dust particles encountered in the Middle East is already proven and accepted. Industry participants, government agencies, and universities have performed extensive dust phenomenology studies on dust particles encountered in the geographic regions in and around Afghanistan and Iraq. Much of this work was directed by government agencies such as Defense Advanced Research Projects Agency (DARPA) and the Air Force Research Laboratory (AFRL). The scientific community has concluded that 94-GHz radar will penetrate dust clouds encountered in this global region, and furthermore is the preferred sensor frequency and technology to use in this type of obscurant condition for see-through capability. It is not the intent of this paper to provide supporting evidence of this capability, but dust-testing results with the BLAST radar will be presented that support these conclusions.

The active sensing portion of the BLAST solution adapts a 94-GHz seeker radar from MBDA that is used on an air-to-surface missile application. The maturity, small size, and light weight of the MBDA sensor is a key discriminator of the BAE Systems BLAST active approach.

In its production-seeker configuration with built-in monopulse capabilities, the radar is designed to scan terrain and search for and track ground targets. This application is similar in principle to the sensor function in a brownout landing, where the active sensor is used to scan the designated landing area forward of the vehicle during the approach to landing. The active sensor can detect terrain and obstacles in low-visibility conditions caused by sand, dust, fog, or other visual obscurants.

This seeker radar is being adapted to the BLAST system solution that includes the associated BAE Systems patent-pending monopulse radar data processing. The system will be able to extract terrain details, including the range and angle from the vehicle, which in turn is used to derive the height of the terrain and objects within the LZ in conjunction with the navigation solution from an INS and GPS.

A terrain-morphing algorithm updates a Digital Terrain Elevation Data (DTED) database with the derived height information for the scanned area and renders it as a real-time 3-D image on a head-down display. The resultant terrain model is of high-enough resolution that objects of interest such as boulders, fences, vehicles, and personnel, will be distinguishable from the terrain. This image can be rendered in an egocentric view as part of a vertical situation display (VSD) or as a plan view as part of a horizontal situation display (HSD), as shown in Figure 7.

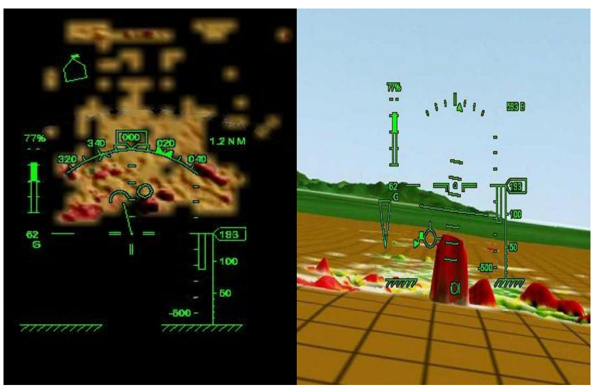

Figure 7: BLAST synthetic vision image in plan view (HSD) and egocentric 3-D view (VSD) with BOSS overlay

It is not the intent to identify objects in the landing zone, but simply to detect their presence and location and modify the terrain display accordingly so the pilot can deduce that there is something at or near the LZ to be avoided.

Typical landing scenario with the active approach

When the aircraft approaches the LZ, the radar begins scanning the zone and the synthetic vision display starts to morph the terrain based on the obstacles detected in the scan area. As the aircraft continues its approach into the LZ, the radar will continue scanning the zone. The scanned area will either remain fixed or decrease, based on the aircraft's slant range to the center of the landing zone, and depending on the selected radar scan control mode. The system will continue to update the synthetic vision image based on radar returns that are continually being processed. The right side of Figure 7 is an example of what the morphed terrain image looks like in the egocentric 3-D view with BOSS overlaid.

As the aircraft gets closer to the LZ and prepares for landing, it is normal procedure for the pilot to pitch the nose of the aircraft up in order to reduce forward airspeed and prepare for the landing. When the aircraft performs this maneuver, the sensor will lose view of the LZ and will not be able to further update the landing zone during this terminal phase of the approach.

In order to accommodate this maneuver, the system will change the synthetic image view when the aircraft reaches airspeeds of less than 15 knots. The normal forward-looking view (as shown in the right side of Figure 7), which has been displayed up to this point, then changes to an overhead plan view (as shown in the left side of Figure 7). The overhead plan view still will provide the situational awareness the operator needs to avoid any obstacles or hazards that are present in the landing zone. The latest radar data captured prior to triggering the changed view will be used to generate the overhead synthetic view of the obstacles to the operator. If sufficient display "real estate" exists in the cockpit, both display views may be presented simultaneously.

The major components of the BLAST active system architecture are:

- MBDA 94-GHz millimeter-wave radar
- BAE Systems monopulse radar signal processing
- Antenna scan control processing
- Terrain-morphing display processing
- DTED level-1 terrain elevation database
- Navigation sensor unit with integrated GPS
- Head-down display

MBDA 94-GHz millimeter-wave radar

The MBDA 94-GHz millimeter-wave radar, depicted in Figure 8, has the following features:

- Adapted from an existing air-to-surface missile application
- Qualified for airborne environment

- Small and lightweight
- Excellent all-weather performance
- Dual-circular polarization
- Dual-axis monopulse (elevation and azimuth)
- High-angle measurement accuracy
- Low transmitter output power (mWatts)
- Narrow 1-degree beam width in azimuth and elevation
- Low side lobes
- Frequency-modulated continuous wave modulation
- One-meter range accuracy
- Inherent low probability of intercept
- Scan range of > +/- 30 degrees in azimuth and elevation
- Adaptive scan pattern control
- Space-stabilized scan control

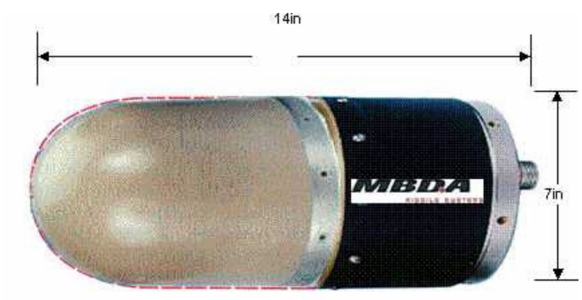

Figure 8: MBDA 94-GHz millimeter-wave radar

To evaluate the accuracy of the monopulse angle measurements of the radar, the elevation monopulse angle-tracking slope of the radar was analyzed and observed to be within a range of +/- half-beam width.. Similar results were obtained for the azimuth monopulse performance. This capability forms the basis of the monopulse radar signal processing algorithm used to determine provide more accurate depiction of terrain and object height in the synthetically generated image.

With advanced signal processing, BLAST can achieve highly accurate elevation angular measurements with sufficient target SNR.

Radar signal processing

BAE Systems' unique, patent-pending[2], radar signal processing algorithm processes the raw radar data to generate an output data vector consisting of azimuth and elevation angles, range, and intensity.

The algorithm improves angular measurement accuracy for resolved targets. This technique measures the angular errors of targets away from the beam center for all radar returns at each range bin. An adaptive signal-to-noise ratio (SNR) threshold is applied to filter out range bins with weak radar returns and reduce false target detection.

An adaptive-elevation angular-binning approach is used to take into account the number of range bins within the radar beam's ground coverage (assuming a flat earth).

Doppler motion compensation is applied to the radar range data to compensate for relative motion between the aircraft and the illuminated targets due to the aircraft velocity.

The object or terrain height is determined relative to the terrain database by making use of the object elevation angle and range from the radar relative to the instantaneous location and attitude of the aircraft. Any object above or below the normal terrain (based on DTED and the navigation solution) with sufficient height (or depth) and radar SNR would cause the terrain to be morphed to that new height (or depth) at that location to generate a synthetic 3-D view of the illuminated terrain.

The ability to detect and resolve objects in the LZ improves as the range to the LZ decreases due to the inherent increase in signal strength and narrowing of the area painted by the radar's pencil beam. The capability of the sensor and radar data processor to resolve objects in the scanned area is dependent on the range to the objects. The closer the range, the smaller the area scanned by the radar beam, and the better the ability to resolve objects within the scene.

Antenna scan control processing

The radar antenna produces a pencil beam that is scanned in a unique raster pattern to cover the specified scan extent. Figure 9 illustrates the elevation coverage of the scanning, which detects the height of objects and the length of the ground coverage of the LZ; Figure 10 illustrates the azimuth scanning, which detects the breadth of objects and the width of the ground coverage of the LZ. Together they produce the overall 3-D scan coverage of the landing area and the space above the ground.

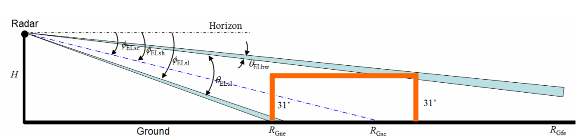

Figure 9: Elevation scan coverage

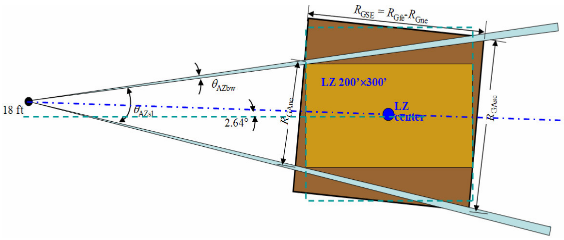

Figure 10: Azimuth scan coverage

A typical raster scan pattern for an AZ and EL scan frame is depicted in Figure 11. The scan step size is programmable in azimuth and elevation to provide overlap of the beams and ensure full coverage of the landing area.

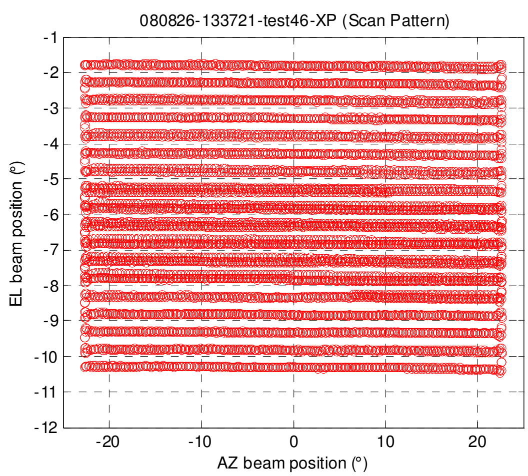

Figure 11: Typical antenna raster scan pattern

BLAST implements a unique scan control mode called "LZ track" to focus the radar scan on the ground around the LZ. When the latitude and longitude of the LZ is entered into the system, the tracking algorithm will dynamically adjust the azimuth and elevation scan angles such that the scan is always centered on the designated LZ. If the LZ coordinates are not known, or if the LZ location is beyond the angular scanning limits of the antenna, then the control will revert to a mode called "heading track" where the elevation angular scan is set to a predetermined fixed value and the azimuth angular scan is set to fixed value in the direction of the aircraft's true heading.

The sensor's refresh rate (or latency) for detecting objects and terrain is primarily dependent on the antenna scan frame rate. The rate of the scan is a function of the chirp rate, the scan step size, and the scan frame size. The resultant frame rate affects the refresh of objects on the head-down display. For static objects this is not critical, and subsequent scans of the same object will simply refine the details of the object as the range to the LZ decreases. For moving objects the frame rate becomes more important to be able to see the change in the display as the object moves through the LZ.

It is important to separate the frame update rate and resultant object detection latency from the video image refresh rate on the head-down display with respect to the motion of the rotorcraft, which is a function of the graphic display driver monitor refresh rate (typically 60 Hz) and the INS/GPS data update rate (typically 100 Hz) needed to drive the orientation of the database-derived display. Generally, the display update of the landing zone image will be consistent with the aircraft motion, with no noticeable lag. Conversely, the rate at which the radar scans an entire frame to update the displayed terrain database is significantly slower.

To maximize the radar scan frame refresh rate, minimize moving object latency, and obtain maximum coverage of the desired landing area, BAE Systems has adopted three main concepts for controlling the radar scan parameters. The first is to track the designated landing point at the center of the radar scan pattern to avoid scanning areas of little or no interest. The second is to have a separate scan field of view (FOV) in azimuth and elevation to take advantage of the fact that for low approach angles, the elevation scan angles can be much smaller than the azimuth scan angles to achieve the same ground coverage. The third is to fix the desired landing area ground coverage at the onset of the approach and allow the ground coverage to naturally shrink as the vehicle gets closer to the landing point. The typical scan coverage of a landing area from the initial approach at a 1000-foot slant range is 500 feet by 500 feet of ground area centered on the designated LZ coordinates. This area gradually reduces as the rotorcraft approaches the touchdown point.

The BLAST radar scanning mechanism supports an adaptive AZ and EL angular scan FOV derived from the approach angle to the LZ to achieve the desired ground coverage at the start of the approach. This method of scanning results in uniform ground coverage regardless of the approach angle to the LZ. The scan angles are further modified by a space-stabilization algorithm to account for changes in pitch, roll, and yaw attitudes during flight to maintain the fixed look-angle to the LZ.

To further explain the adaptive nature of the scan pattern, as the azimuth and elevation pointing angles to the LZ change relative to the aircraft position, the AZ and EL angular limits within the scan frame change to accommodate the specified ground coverage. As the elevation angle gets steeper, the angular extent of the EL scan FOV must increase to achieve the specified ground coverage, and as the angle gets shallower, it takes fewer elevation scans to cover the same area on the ground, therefore a smaller EL FOV is needed. Similarly, as the elevation angle increases, the range to the ground decreases and the AZ angular FOV to cover the specified ground coverage must increase. Similarly, as the elevation angle gets shallower, the distance to the ground increases geometrically, resulting in much-reduced AZ scan angles to achieve the same amount of ground coverage. This feature results in optimized scan frame rates that adapt to the approach angle and range to the landing zone.

Terrain-morphing display algorithm

The terrain display uses patented dynamic morphing terrain engine technology[3]. The DTED-level-one-based terrain database is updated in real time in response to data obtained by the radar sensor. As long as the sensor beam's pointing direction is known, the sensor range returns can be geo-registered (using a transformation from the vehicle body-axis position and attitude to earth coordinates) to create a 3-D measurement in earth-referenced coordinates. In the absence of DTED, a flat earth is assumed and the sensor alone will provide the real-time 3-D image of the terrain. In that case, or if the DTED database does not include the geographical area being sensed, the peripheral view outside the sensor field of regard will be shown as a flat earth. However, it is assumed that this would be an abnormal scenario.

The DTED-based synthetic view displays terrain in the same position, orientation, and perspective in which it would appear to the pilot on a bright, clear day. The synthetic view can therefore be used in darkness or degraded visual conditions to replace one's normal vision with this enhanced synthetic display. The synthetic terrain database provides default contours for the FOV display that may extend beyond the area scanned by the sensor, providing the pilot with some situational awareness of the areas surrounding the landing zone and aiding with orientation of the display with the outside view or known landmarks. The display view can be selected to represent an egocentric (pilot) view, exocentric (external) view from above or behind the helicopter, or an overhead plan view, supporting various modes of operation.

The display resolution is primarily limited by the sensor information provided to the display processor, up to the limits of the programmed terrain resolution. The terrain database resolution is nominally one meter square for the BLAST configuration. However, height resolution is continuous based on the calculated height from the sensor data and smoothing of the area between grid points. Higher grid resolutions are possible but involve a trade-off of processing throughput, memory capacity, sensor capabilities, and operational effectiveness.

A combination of pre-existing and sensed data is illustrated in Figure 12, which shows a 3-D perspective image of a terrain grid. Part of the image has been "painted" by the 3-D terrain sensor. The plain grid represents data that has not been painted, while the textured grid represents sensed data. It is intuitively clear that something is different about the validated area compared to the plain area, and operators are trained to understand that the textured area represents detailed terrain and obstacles painted by the sensor.

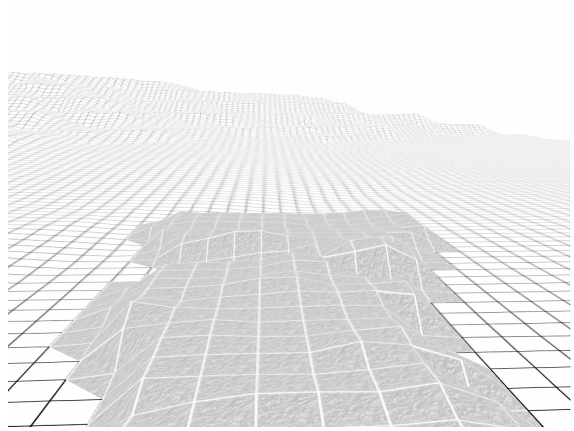

Figure 12: Database and sensed terrain fused into one synthetic vision scene

BLAST tower testing at Yuma Proving Ground

In an important step to validate the BLAST solution concept, BAE Systems, with support from DARPA and AFRL, conducted static field tests and data collection in September 2008 at YPG to characterize the performance of the 94-GHz radar-based obstacle detection, monopulse processing, and synthetic visualization system in clear and brownout conditions. Elements such as dust density, range, and object types associated with helicopter brownout landings under realistic field conditions were considered.

The on-site demonstration at Yuma Proving Ground and post-processing analysis have verified the system's capability to accurately depict objects of interest in the landing zone and to see through dust and generate comprehensive 3-D synthetic images of the illuminated area. Figure 13 shows the image generated by the BLAST test bed for the Yuma Proving Ground "La Posa Oasis" test site. Highlights include the successful demonstration of the following performance factors:

- Real-time radar data processing, terrain morphing, and synthetic 3-D imaging of the LZ
- Range performance sufficient for helicopter landing functions
- Reasonable frame update rate reflecting obstacles within the LZ
- Imperceptible false alarm rate
- Ability of the monopulse mode to provide effective obstacle height information
- Similar performance obtained in clear and dusty conditions
- Promising cable-detection performance

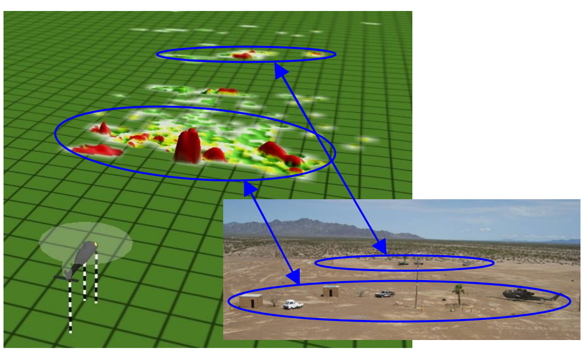

Figure 13: BLAST test bed image of Yuma Proving Ground test site

The Yuma Proving Ground test site is 300 feet wide and 500 feet long, with various obstacles and poles as tall as 31 feet. The sensor is set on a 44-foot tower 240 feet from the south edge of the LZ. The radar was programmed to scan the entire LZ volume of 300 feet by 500 feet by 31 feet for ground-mapping and surface-obstacle imaging. Figure 14 shows the LZ site zone distribution with the tower position on the far left (south end) and Figure 15 depicts the LZ site obstacle layout at each zone.

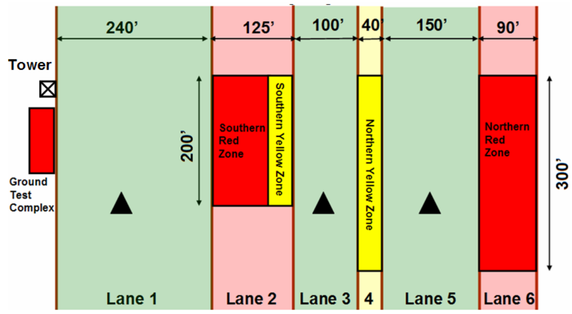

Figure 14: Test site LZ zone distribution (Courtesy of YPG)

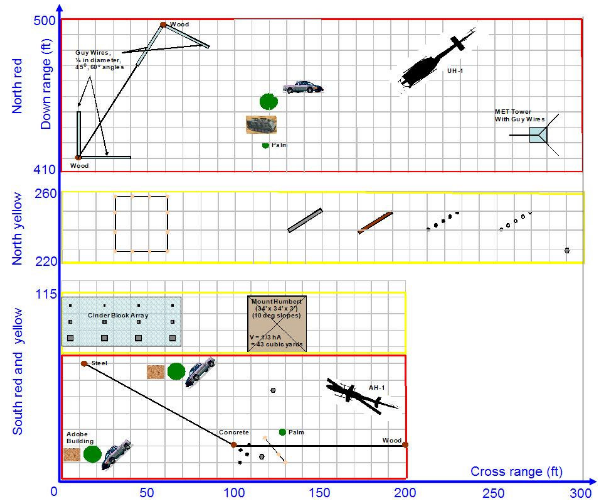

Figure 15: LZ site obstacle layout (Courtesy of YPG)

Pictures of the sensor platform, sensor tower and connex box, and the LZ site as seen from the tower are shown in Figure 16, Figure 17, and Figure 18, respectively.

Figure 16: Sensor, sensor mounting tube, gimbal, and ambient forced air

Figure 17: Sensor tower and connex box (LZ in the background)

Figure 18: LZ site as seen from tower

Post-processing Data analysis was mainly focused on evaluating the sensor performance. The performance metrics include SNR measurement, height estimation, visual quality of the image, and false alarm rate.

Using a set of monopulse data as an example for obstacle detection, Figure 19 shows the correspondence of the 3-D height images of the detected obstacles at south red and yellow zones and the LZ site photo, while Figure 20 presents the 3-D obstacle height images at north red zone. These results further demonstrate the obstacle detection capability of the BLAST system. Visual evaluation and comparison with the photo of the illuminated area indicate the monopulse mode shows distinct image features of various targets, including tall poles, vehicles, rotorcrafts, trees, and buildings.

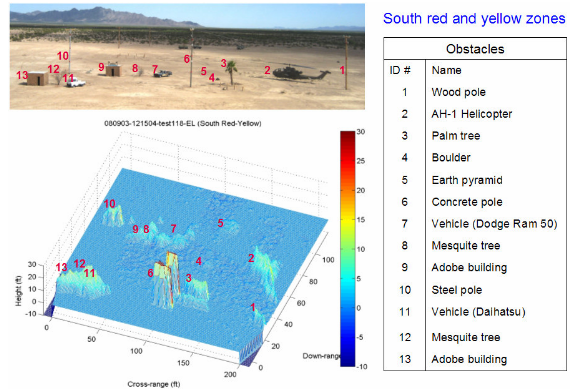

Figure 19: Correspondence of detected obstacle images and LZ site photo (south red and yellow zones)

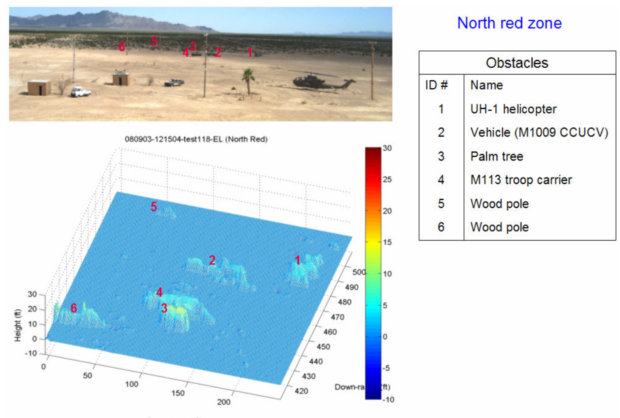

Figure 20: Correspondence of detected obstacle images and LZ site photo (north red zone)

Data was collected in dust conditions to evaluate the ability of the sensor to "see through" the dust cloud. A UH-1 was flown low to the ground between the sensor tower and the LZ site to generate the dust cloud as shown in Figure 21. To illustrate the BLAST performance in dust, 2D height maps are shown in Figure 22 and Figure 23 for height estimation comparison between clear air and dust conditions. These height color maps show very similar visual effects for both clear air and dust conditions.

Figure 21: UH-1 fly-by generating dust cloud

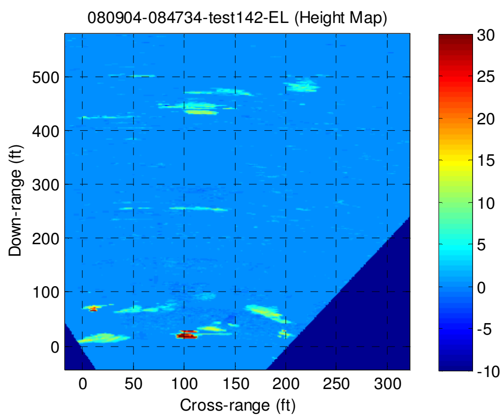

Figure 22: 2D height map of LZ in clear air

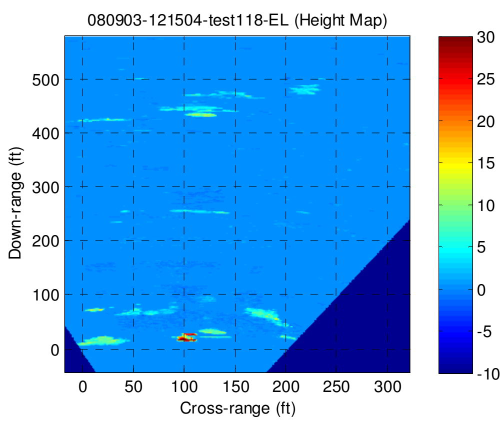

Figure 23: 2D height map of LZ in dust

The wave propagation attenuation in dust is determined by comparing the magnitude of the point target (a corner reflector placed inside the LZ site) response before and during the dust data collection. For the dust data sets, the point target responses were determined from the range profiles that were generated for the first 80 seconds after the dust generation. The difference in the overall peak response magnitude between the clear air and dust data collection conditions is about 0.8 dB and the difference in the average response magnitude is about 0.5 dB. These results indicate that the 94-GHz radar signal is virtually unaffected by dust.

BLAST simulator system evaluation

A collaborative effort between BAE Systems and the U.S. Army Aeroflightdynamics Directorate (AFDD) is under way to perform a metric pilot vehicle interface (PVI) evaluation of the BLAST passive and active solutions for brownout landing. A fully integrated BLAST simulator, shown in Figure 24, has been developed for that purpose. The piloted simulated landing scenarios will include various combinations of helmet mounted display, panel mounted presentations, and pilot flight techniques to compare and contrast which features result in consistent, safe, and repeatable brown-out landings.

Figure 24: BLAST Simulator for PVI evaluation (Courtesy of AFDD)

<u>Simulator description</u>
The BLAST piloted simulation includes a fully integrated cockpit, appropriate flight controls, flight simulation with realistic rotorcraft flight models and out-the-window displays, and a visual situational awareness system that includes the following:

- Simulation of the active 94-GHz millimeter-wave radar sensor image
- Terrain display with morphed terrain radar image on the head down display
- Brown-out Symbology Set (BOSS) image that overlays the radar image
- BAE Systems helmet-mounted display with BAE Systems conformal flight symbology

There are three panel-mounted displays in the simulation cockpit that simulate multifunction head-down displays on a cockpit instrument panel. Only two displays are used for the BLAST simulation. These 12" flat screen monitors present the vertical situation display (VSD) in the center and optionally the horizontal situation display (HSD) on the left. AFDD BOSS flight symbology overlays the BAE Systems generated radar morphed terrain image with aircraft primary flight information for viewing on the center panel mounted cockpit display. Symbology similar to that in Figure 25 below will appear sequentially on the center display with optional simultaneous HSD BOSS only (no radar terrain image) on the left display. The information presented on the VSD will be used during the approach phase of the brown-out landing. The HSD symbology will be used during the terminal landing phase of the approach.

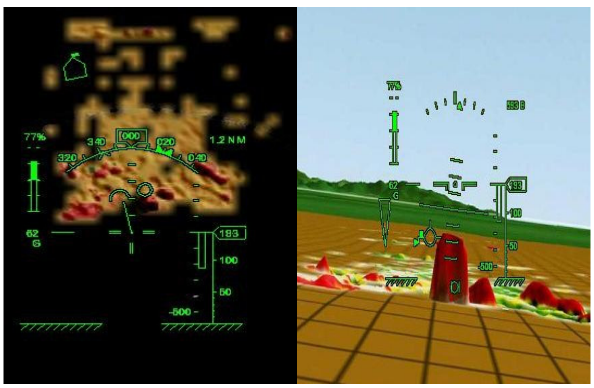

Figure 25: BOSS HSD and VSD displays with morphed terrain image

The passive conformal landing zone symbology as shown in Figure 26 is displayed on the helmet mounted display. The helmet is head tracked to facilitate the display and use of a flight path marker and the BAE Systems conformal ground reference symbols.

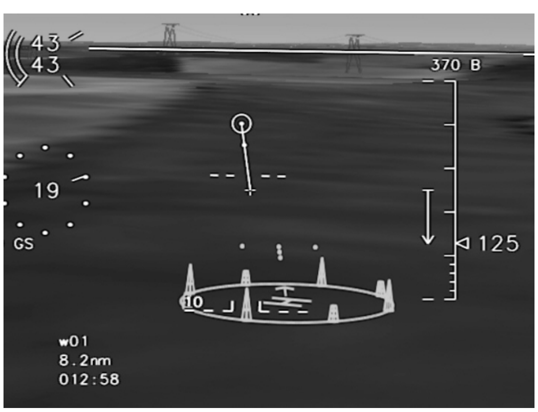

Figure 26: Conformal landing symbology on helmet mounted display

The Yuma Proving Grounds terrain database is used as the flight environment for the simulation. Graphic models of buildings, poles and various objects populate the LZ area of the database for the visual out the window scene. An identical model is also used by the radar simulator to provide the simulated radar returns used to generate the radar range profiles.

Selected system parameters are recorded for use in data collection and analysis. Examples of variables recorded are aircraft vertical speed at touchdown, lateral speed at touchdown, longitudinal speed at touchdown, landing heading deviation, distance from intended landing point, and many others.

Video cameras are used to capture up to four different visual images simultaneously to visually record pilot performance during the simulation test. Examples of recorded images are the out-the-window view, the VSD and HSD views with radar image and symbology overlaid, and the helmet display image.

<u>Test description</u>
The test conditions to be evaluated are summarized in the test matrix diagram in Figure 27.

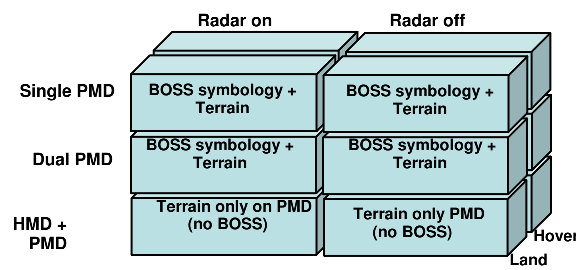

Figure 27: Pilot evaluation test matrix

There are two primary test conditions for the radar and terrain modes. They are radar ON with morphed terrain database and radar off but terrain database turned on to provide head down visual cues of the terrain. These radar and terrain modes are independent variables.

There are three primary display conditions for presenting the display images of radar, terrain, and symbology to the pilot. One condition is with a single panel-mounted display with BOSS overlay as the only pilot reference. The second condition is a dual panel-mounted display configuration with separate VSD and HSD displays. The third is a combination of panel-mounted and helmet-mounted display images. These display modes are independent variables.

Within those data sets there are combinations of symbology, terrain and radar images that the pilot will use to execute the brown-out approach and landing. Two approach modes will be evaluated for each combination of conditions. One is an approach to land and another is an approach to hover.

Pre-designated LZ locations are used for the purpose of the pilot evaluations to eliminate variability associated with pilots designating their own landing points. The pilot will set up an approach to that pre-designated LZ. As the pilot approaches the LZ and begins to scan the obstacles with the radar, the pilot will have the ability to move the LZ symbol using a 4-axis switch on the collective.

Measures of performance are the standards that the pilot attempts to achieve while executing the test maneuvers. This experiment will collect both objective and subjective data. The objective measures of performance for this test are shown in Table 1.

Table 1: Maneuver performance standards

Variable	Desired	Adequate
Vertical Velocity	≤ 100 fpm	≤ 300 fpm
Longitudinal Speed	≤ 5kts	≤ 10kts
Lateral Speed	≤ 1kt	≤ 3kts
Heading Deviation	≤ 5°	≤ 10°
Position Error from LZ Center	≤ 25ft	≤ 50ft
Obstacle Contact	None	None

Experienced pilots selected for the evaluation process will be briefed in the following areas prior to flying the simulation.

- Purpose of the simulation
- Experimental design – define all variables
- Data collection – what is being collected and measured
- Controls, displays, switch logic – location, input action/reaction
- Flight symbology functionality and control strategies
- Approach and brownout landing maneuvers
- Performance evaluation tools – objective and subjective
- Schedule

Pilots will then be given a simulation cockpit briefing and hands-on training to cover the following areas:

- Hands on use of cockpit controls and displays
- Fly simulated brownout landings in all combinations of display (helmet-mounted and head-down) symbology, and sensor combinations that will be flown during the test
- Complete a flight evaluation task that will ensure the pilot has mastered the cockpit and maneuvers and can execute them within the performance standards to ensure the test will produce good data

Flight scenarios

There is one basic maneuver with minor variations that will be flown during the experiment. The maneuver is a 45-degree entry to a straight-in approach to land at the designated LZ. On short final the aircraft will enter brownout conditions and the pilot will attempt to land in the center of the designated LZ on the approach heading, with zero forward airspeed, no lateral drift, and with a minimal vertical rate. The only variables to this maneuver will be the lead-in turn direction (Left/Right), and the approach direction to the LZ. A normal 4-degree approach angle will be flown. There will be a variety of LZs laid out in different obstacle arrays. These variables are intended to vary pilot workload and landing strategies.

There will be several LZ obstacle field configurations. Each LZ will be arrayed with a variety of obstacles and barriers similar to the types of obstacles shown at the Yuma test site. Each LZ will have a different layout of the same obstacles.

Approximately 10 to 12 pilots will be assessed as part of the evaluation process. Data for each will be compiled, analyzed and a report generated. The effort is expected to complete in the first half of 2009. Conclusions drawn from these results will be considered for design upgrades to the BLAST approach.

CONCLUDING REMARKS

Developing a solution to help rotorcraft pilots land safely in brownout is addressing an urgent need. The BAE Systems Brownout Landing Aid System Technology (BLAST) is a unique approach to solve this problem. Using intuitive eyes out conformal landing symbology on a helmet mounted display combined with mature 94-GHz radar sensor technology and monopulse radar data processing algorithms specifically adapted for brownout landings driving real time updates to a high-resolution head down display of the terrain in and around the landing zone overlaid with BOSS landing guidance symbology gives the pilot the means to maintain situational awareness and avoid impact with objects and terrain when the outside view is obscured.

Test results of the active portion of BLAST at the Yuma Proving Grounds verified the system's capability to see through dust and accurately depict objects of interest in the landing zone and generate comprehensive 3-D synthetic images of the illuminated area. Highlights of the system performance include:

- Real-time radar data processing, terrain morphing, and synthetic 3-D imaging of the LZ
- Range performance sufficient for helicopter landing functions
- Reasonable latency of imaging obstacles within the LZ
- Imperceptible false alarm rate
- Ability of the monopulse mode to provide effective obstacle height information
- Insignificant difference in clear and dusty conditions
- Promising cable-detection performance

With continued support from government agencies and potential users to perform simulated and real system flight evaluations and refine the system requirements, the BLAST will be a significant step forward to supporting this urgent need.

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