Synthetic Vision System Flight Test
Results and Lessons Learned

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ABSTRACT

Honeywell Systems and Research Center developed and demonstrated an active 35 GHz Radar Imaging system as part of the FAA/USAF/Industry sponsored Synthetic Vision System Technology Demonstration (SVSTD) Program. The objectives of this presentation are to provide a general overview of flight test results, a system level perspective that encompasses the efforts of the SVSTD and Augmented VIsual Display (AVID) programs, and more importantly, provide the AVID workshop participants with Honeywell's perspective on the lessons that were learned from the SVS flight tests.

One objective of the SVSTD program was to explore several known system issues concerning radar imaging technology. The program ultimately resolved some of these issues, left others open, and in fact created several new concerns. In some instances, the interested community has drawn improper conclusions from the program by globally attributing implementation specific issues to radar imaging technology in general. The motivation for this presentation is therefore to provide AVID researchers with a better understanding of the issues that truly remain open, and to identify the perceived issues that are either resolved or were specific to Honeywell's implementation.

CHART 1: Synthetic Vision System Flight Test

The SVSTD program was motivated by an existing "catch-22" situation, in which the avionics user community was unaware of the capabilities and benefits of an adverse weather (fog, rain, snow, haze) imaging system, while potential manufacturers of such a product did not perceive an existing marketplace. The program focused on demonstrating this technical capability, as well as on a first step toward resolution of the many issues associated with the system's certification.

A Gulfstream 2 was used as the flight test aircraft. Honeywell developed an active 35 GHz imaging radar and integrated it with the Gulfstream 2 avionics system. A scanning antenna and the radar transmit/receive unit were mounted behind the radome. A real-time display processing unit, housed within a single, ruggedized VME chassis, was mounted in the aircraft cabin. The Honeywell display processor provided

pilot-perspective radar video to a Head Up Display (HUD) mounted in the cockpit. The HUD electronics projected a holographic image onto the HUD combining glass, effectively overlaying the radar image on the pilot's real world scene.

The test aircraft was outfitted with a host of related sensors and instrumentation. In addition to Honeywell's 35 GHz radar, the Gulfstream 2 was equipped with a 3-5 micron-band forward looking infrared (FLIR) camera and a visible-band camera. Separate flight tests were briefly flown using a Lear 94 GHz radar imager in place of the 35 GHz radar. The aircraft cabin was equipped with recording equipment, allowing radar, FLIR, and visible-band imagery to be simultaneously recorded. In order to support accurate analysis of the performance of each sensor as a function of weather conditions, the aircraft was also equipped with wing-mounted pods that measured atmospheric liquid content (both water density and droplet size).

Hundreds of approaches were flown into more than 25 airports across the US, encountering a wide variety of weather conditions. The program executed a flight test matrix, involving both instrumented and non-precision approaches with several test pilots, under varying weather conditions. The Honeywell 35 GHz radar demonstrated clear pilot advantages in most situations. Pilot performance across the flight test matrix was well documented, but will not be addressed in detail within this presentation.

CHART 2:   Autonomous Airplane Technology - System Concept

Honeywell envisions an overall system concept that is much broader in scope than the fundamental Synthetic Vision System previously described. Ultimately, an aircraft can achieve greater autonomy through the integration of advanced cockpit decision aids and display technology, high-precision navigation aids, forward visibility sensors, and hazard detection sensors. Honeywell is actively involved with Boeing in the development of an Enhanced Situational Awareness System (ESAS) that could potentially take advantage of such technology capabilities.

CHART 3:   Autonomous Airplane Technology - System Functions

A strawman block diagram could potentially include display electronics, forward visibility sensors, navigation and landing aides, and advanced processor systems. High precision guidance and navigation can be achieved using one or more of several candidate navigation/landing aides. A digital terrain map registered with a radar altimeter can also be used for increased accuracy. A millimeter wave (radar) imager, a FLIR, and/or digitally stored imagery are potential sources of images that can be presented to the pilot on some type of display. These image sources could be used in several ways, including selection of

the sensor with the best image at some time instance, fusion of multiple sensor images, or registration of a digitally stored image to one or more of the sensors. Other variations upon these themes can be constructed.

CHART 4: Honeywell 35 GHz Radar Imaging System Hardware

The major components that were flight tested include a 34"x4"x8" electro-mechanically scanned antenna, a radar receiver/transmitter (R/T) unit, an R/T Controller unit, and the Display Processor. The antenna and RT unit were both mounted behind the aircraft radome. The R/T Controller and Display Processor were mounted in the aircraft cabin. The majority of processing was housed within the Display Processor, implemented primarily with commercially available hardware mounted within a ruggedized VME chassis.

CHART 5: Honeywell SVS Function Block Diagram

A custom RF Interface card within the VME chassis is responsible for controlling the radar and antenna, as well as digitizing range samples. All range samples are then passed through the display processing pipeline, implemented with TI TMS320C30 digital signal processors. The display processing pipeline is controlled by a system processor. The system processor is also responsible for communicating with avionics bus interface cards, as well as storing raw radar data for post-flight analysis.

CHART 6: SVS Image Beam Sharpening

The display processing pipeline contains hardware allocated for optional execution of image enhancement functions. Honeywell has developed several algorithms for image contrast enhancement, noise reduction, and beam sharpening. Although the image enhancement algorithm suite was not part of the SVSTD flight test baseline configuration, Honeywell's beam sharpening algorithm has shown promising results.

The beamsharpening algorithm operates across the image, attempting to improve azimuthal resolution. Azimuthal resolution is most critical, in that runway acquisition range is typically driven by the ability of the sensor to fully contain one beamwidth between the runway edges, and thus provide the necessary contrast between the runway and the surrounding terrain. Honeywell's beamsharpening algorithm can be executed with real-time, flight-worthy hardware, to produce approximately a 2.5:1 improvement in azimuthal resolution.

CHART 7:   A Honeywell SVS Image

An example of a pilot's perspective radar image is shown to include the flight director and navigational symbology that is overlaid by the GEC HUD. One issue that was identified by the SVSTD program concerns the tendency of HUD symbology to obstruct the runway at far ranges, or hide obstacles on the runway from the pilot's view.

CHART 8:   SVS Lessons Learned

Several issues were studied or brought about by the SVSTD program. This presentation addresses those that are more of a concern from a radar imaging perspective, and represent only Honeywell's point of view. Other issues, perhaps at a higher system level, were addressed by the SVS Certification Issues Study Team, as presented at their January 1993 conference in Williamsburg, VA. An attempt is made to classify the issues according to the radar subsystem from which they are derived. Some issues are truly introduced at the system level, while others that have been related to a particular subsystem are indeed a system issue.

Minimum Range is an issue that concerns the inability of the radar system to sense near range signal returns. This "blind spot" is necessary to allow time for the saturated radar receiver to "settle" after each 1 kW pulse is transmitted. The visual effect is an absence of image in the near range. The Honeywell configuration that was tested began sampling radar returns at 150 feet. As shown in Chart 9, a 75 foot minimum range is more tolerable, and can be achieved within the current implementation with only minor adjustments.

Resolution at 35 GHz was a concern. The program demonstrated that 35 GHz resolution is marginally acceptable. As discussed earlier, beamsharpening can be applied to the imagery to provide image resolution which would approach that inherent in a 94 GHz radar with equivalent antenna aperture. A beamsharpened 94 GHz image would offer excellent resolution. Similarly, a 10 GHz (X-band) system using beamsharpening would at best be marginally acceptable (about equivalent to 35 GHz without beamsharpening).

Intrusion Detection was an operational capability tested by the SVSTD program. Pilots could usually detect foreign obstacles on the runway after some exposure to a "normal" runway radar scene. The few occasions when the pilot failed to detect intrusions may be attributed to one or more problems. The tendency for overlaid HUD symbology to obstruct obstacles shown in the radar image was evident on some occasions. Additionally, the radar image itself contained secondary artifacts, that with further radar

development work may be resolved, but tended to cause problems for pilots in discerning obstacles from the artifacts.

Motion Compensation with a low scan rate antenna is an approach that may or may not be viable as an alternative to expensive high scan rate antennas. Honeywell did not study this approach, opting instead to use a relatively high scan rate antenna (>10 Hz). It is still an open issue as to whether a slow antenna with motion compensation will allow adequate pilot performance based on only the radar image.

Antenna Performance Requirements were fairly well determined by the flight test program, as well as previous research. Prior research had shown that frame rates in excess of 17 - 18 fps provided diminishing return in terms of pilot performance. The 10 Hz Honeywell system was marginally acceptable. The 30 degree antenna field of view (fov) was driven primarily by inherent limitations in the HUD. It was established that a 40 degree fov would be desirable, especially for high crab-angle approaches.

Achieving high scan rate and wide fov is very challenging for antenna designs. The approach taken by Malibu Research in developing Honeywell's antenna was effectively to piece two antennas side-by-side. One resulting effect was a dark line in the center of the image, caused by a gain imbalance between the two antenna halves. This imbalance may have been resolved with extensive antenna tuning, or with addition processing downstream. System designers should note this problem as an artifact of the Malibu antenna design, and not necessarily a characteristic of all radar imaging systems.

Antenna Pitch Stabilization was a debated requirement until flight testing proved its necessity. The Honeywell flight test configuration did not pitch stabilize the antenna. Since the antenna vertical beamwidth is relatively narrow, even slight changes in the aircraft pitch attitude tended to produce dynamic intensity variations across the runway scene. The most notable problem, however, was the inability to optimize the pitch angle for both approach and taxi. Nominally, a look-down angle of 3 degrees was optimal for approach on typical glidepaths. For ground operations, however, the antenna fixed at 3 degrees down was very inefficient since the scene ahead was nominal at 0 degrees. For purposes of the flight test, a compromise configuration was used (without pitch stabilization) as shown in Chart 10. Ultimately, the imaging radar should use a pitch stabilized antenna.

Antenna Sidelobe Suppression is critical to the radar imaging system implementation. The Malibu antenna implementation had fairly low sidelobes, however runway artifacts observed during flight testing may be attributed to the sidelobe returns. Although the sidelobe returns would be relatively low in amplitude, they would still tend to stand out against the extremely low runway returns onto which the sidelobe returns

would be mapped. It may be possible to remove sidelobe returns with additional signal processing, however this issue remains open.

Radome Effects were negligible for Honeywell's 35 GHz implementation. The development of radomes with high transmissivity at 94 GHz is still a problem, as witnessed by the 94 GHz Lear system tests. The difficulty at 94 GHz is in developing radome materials that are thin enough to allow 94 GHz transmission, yet strong enough to tolerate bird strikes and other stresses.

"Ground Rush" is a phenomena in which the motion in the radar image tends to convey increasing aircraft ground speed as altitude is decreased through the last few hundred feet. This effect is attributed to the fact that the Honeywell implementation used linear range samples (ie. one sample every 25 feet). Linear sampling produces too few samples per display pixel in the near range, and too many samples per display pixel in the far range. In the Honeywell implementation, this produced very blocky imagery in the near range. A more sophisticated approach would either use non-linear sampling, providing more samples in the near range, or would perform more processing intensive interpolation on near range pixels with a linear sampling approach.

Power vs Backscatter is a relationship that requires further study. The issue concerns the ability of a radar signal to penetrate weather. First instincts would suggest that more transmit power would result in better weather penetration. The reality is that at some point, the atmospheric backscatter begins to blind the radar, much like car headlights in fog. The point where this occurs can be theoretically derived, but was not verified by the flight test program.

Snow and Rain Performance was not adequately documented by the flight test program. More data needs to be collected and analyzed in this area. Of specific concern is the fact that radar cross sections from snow cover tend to vary widely depending upon several factors associated with the snow itself. This coupled with many potential runway states (snow covered, icy, freshly plowed, etc.) will not allow very accurate modelling or prediction of system performance in many situations.

Processing Latency: The processing latency, observed as the time from start of an aircraft maneuver until the radar image showed correlated effects, was about 0.4 seconds for Honeywell's prototype SVS system. Contrary to what some have purveyed, the system frame rate (> 10 Hz) is unaffected by processing latency. Latency through the image processing pipeline was actually only about 0.2 seconds. An implementation problem with the servicing of avionics bus interrupts accounted for the additional latency. Since aircraft orientation parameters were not being efficiently updated, image perspective was substantially (0.5 sec) lagging real world orientation changes (roll, pitch, yaw), even though the data

presented was relatively current. Display processing hardware used within the prototype primarily consisted of commercially available boards selected to enable rapid system development. Latency could be improved to about 0.2 seconds using this hardware, with minor changes to system control software. Ultimately, a more custom hardware approach would have substantial latency improvement.

Beamsharpening: Image enhancement that can be accomplished through antenna beam sharpening techniques is a well understood issue, and has been discussed in previous charts.

Image Enhancement: Other image enhancement techniques for noise reduction and contrast enhancement to the radar image are actively being developed at Honeywell. Image enhancement is a very open area of research if one begins to consider the potential impact of fusion with other image sources such as FLIR, terrain databases, or computer graphics.

Display Registration: Registration of the radar image on the HUD with the true world scene was a concern at the onset of the SVS flight test. Several techniques were used to accomplish radar image registration, resolving the issue. An interesting artifact of registering the radar scene to the real world relates to the fact that the radar has limited range. Since the radar doesn't "see" to the horizon, the radar horizon line in the image usually appears lower than the true world horizon if the remainder of the radar image is registered. This is at first misleading, however the pilots seemed to become comfortable with the artifact. Future implementations may wish to artificially extend the radar horizon if the image is to be displayed in original (not fused) format.

Taxi Display: Due to the fact that the radar has a limited vertical ranging angle, the resulting perspective transform image at low altitudes becomes vary "short" vertically. This made taxi and ground operations very difficult for pilots during the flight test program. Some experimentation was performed in which the perspective altitude was artificially increased by 50 to 75 feet, giving more of a "god's eye" view while at low altitude or on the ground. Although this lead to a slightly, generally mis-registered image, the pilots found it was a much more useful than the true perspective during ground operations. An extension to this concept would be to present the radar "plan" view as an augmentation to the C-scope image.

Fusion: Clearly sensor fusion is an open area of research, and is one of the main topics for the AVID workshop.

Synthetic Vision System Flight Test

Antenna Mount

Cockpit/HUD

Test Aircraft
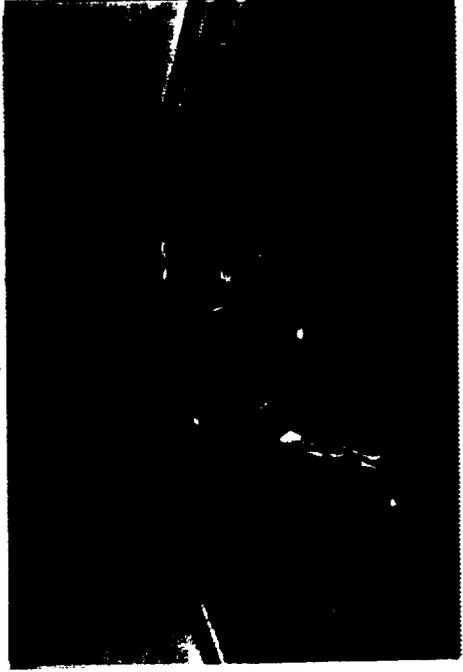
Flight Instrumentation

CHART 1

System Concept

Autonomous Airplane Technology

- WAKE VORTEX DETECTION
- WINDSHEAR ANNUNCIATOR
- HAIL DETECTION
- CLEAR AIR TURBULENCE DETECTION
- CONTROLLED FLIGHT INTO TERRAIN AVOIDANCE
- VISUAL LANDING AID
- GUIDANCE SYMBOLOGY
- WEATHER RADAR SYMBOLOGY

VORTEX WINDSHEAR HAIL TURB TERR

100
1000
1237
QNH

GPS

Complex Approach

Digital Map

ILS MLS

CHART 2

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Autonomous Airplane Technology

System Functions

NAV / LANDING AIDES

- GPS
- INS
- ILS
- MLS

PROCESSING

Guidance & Navigation

Digital Map

Display Processing

Sensor Processing
- Selection
- Registration
- Fusion

DISPLAY
- HUD
- HMD
- HDD

SENSORS
- MMW Imager
- FLIR Camera

CHART 3

SVS Flight Demo Hardware

Labels visible in image: PROCESSOR, SYNTHETIC VISION SYSTEM, RECEIVER - TRANSMITTER

CHART 4

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SVS Technology Demonstration

Sensor Description

SYNTHETIC VISION SYSTEM FUNCTION BLOCK DIAGRAM

Beamsharpening
Noise Reduction
Contrast Enhancement

H, Ø

Roll, Pitch

R/T

Radar Control

Antenna

RF Interface

Pulse Integration

Image Enhancement (Optional)

Perspective Transform

Rendering: Interpolation/ Decimation

Video

RS-170

INS

ARINC 429

Radar Altimeter

VME A/D

Time Code Generator

Time Code Interface

Processor

Control

Sun Workstation

Disk

Mag Tape

Raw Data
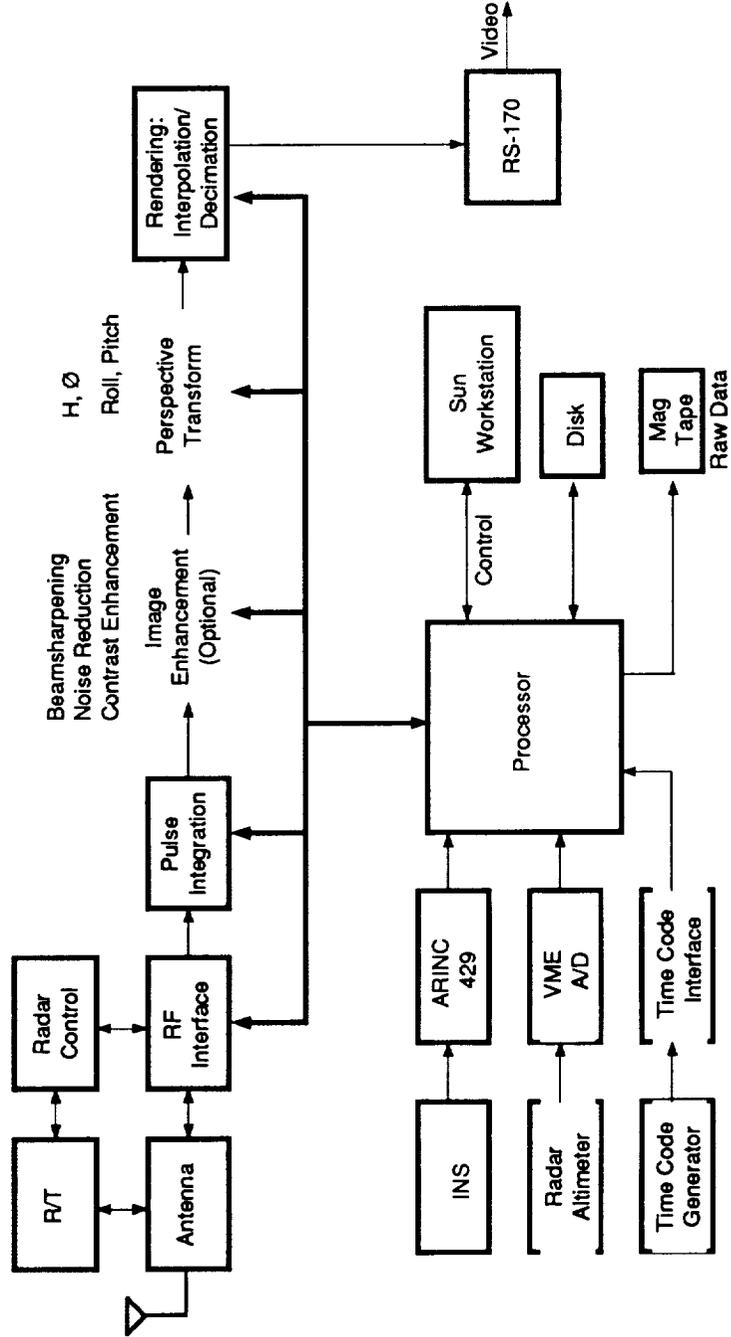
Chart 5

Synthetic Vision Radar Image

Path: 2drübp4

go | quit | zoom = 1 | [292, 380] = 165

Unenhanced Image

Path: 2denhrübp4.sig

go | quit | zoom = 1 | [273, 167] = 32
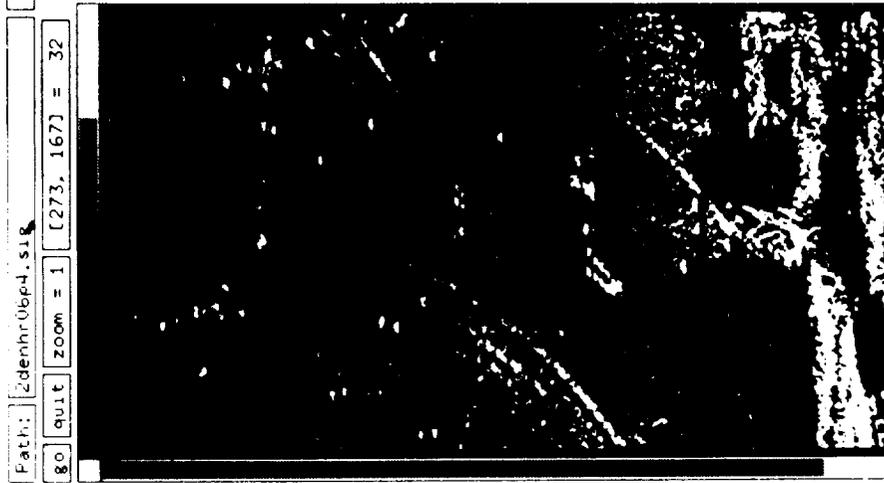
Image After Beam Sharpening

CHART 6
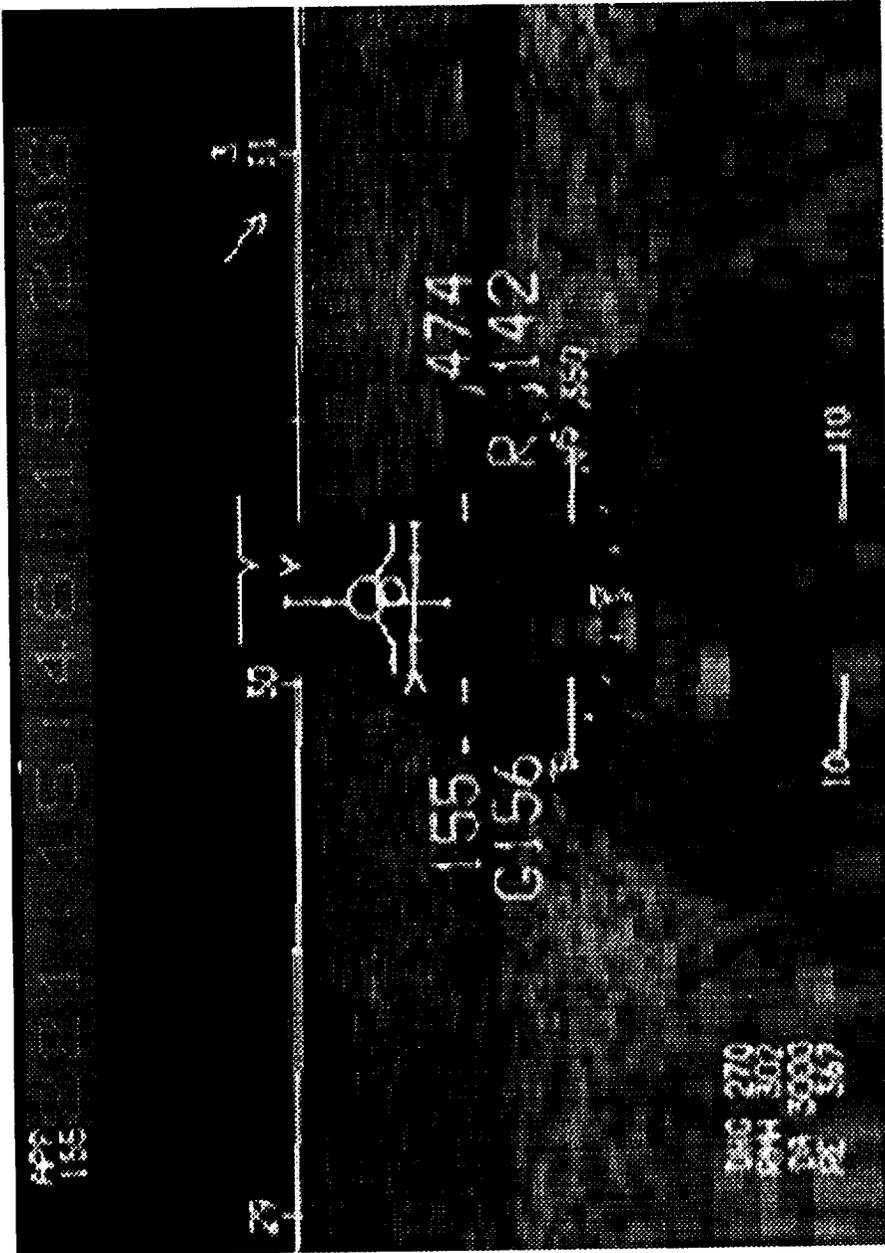
CHART 7

SVS Technology Demonstration

Imaging Radar
Issues and Lessons Learned

System
- Minimum Range
- Resolution
- Intrusion Detection
- Motion Compensation

Antenna
- Performance Requirements
- Pitch Stabilization
- Sidelobe Suppression

Radar Phenomenology
- Radome Effects
- "Ground Rush"
- Power vs Backscatter
- Snow & Rain Performance

Processing
- Latency
- Beamsharpening
- Image Enhancement

Display
- Registration
- Taxi Display
- Fusion
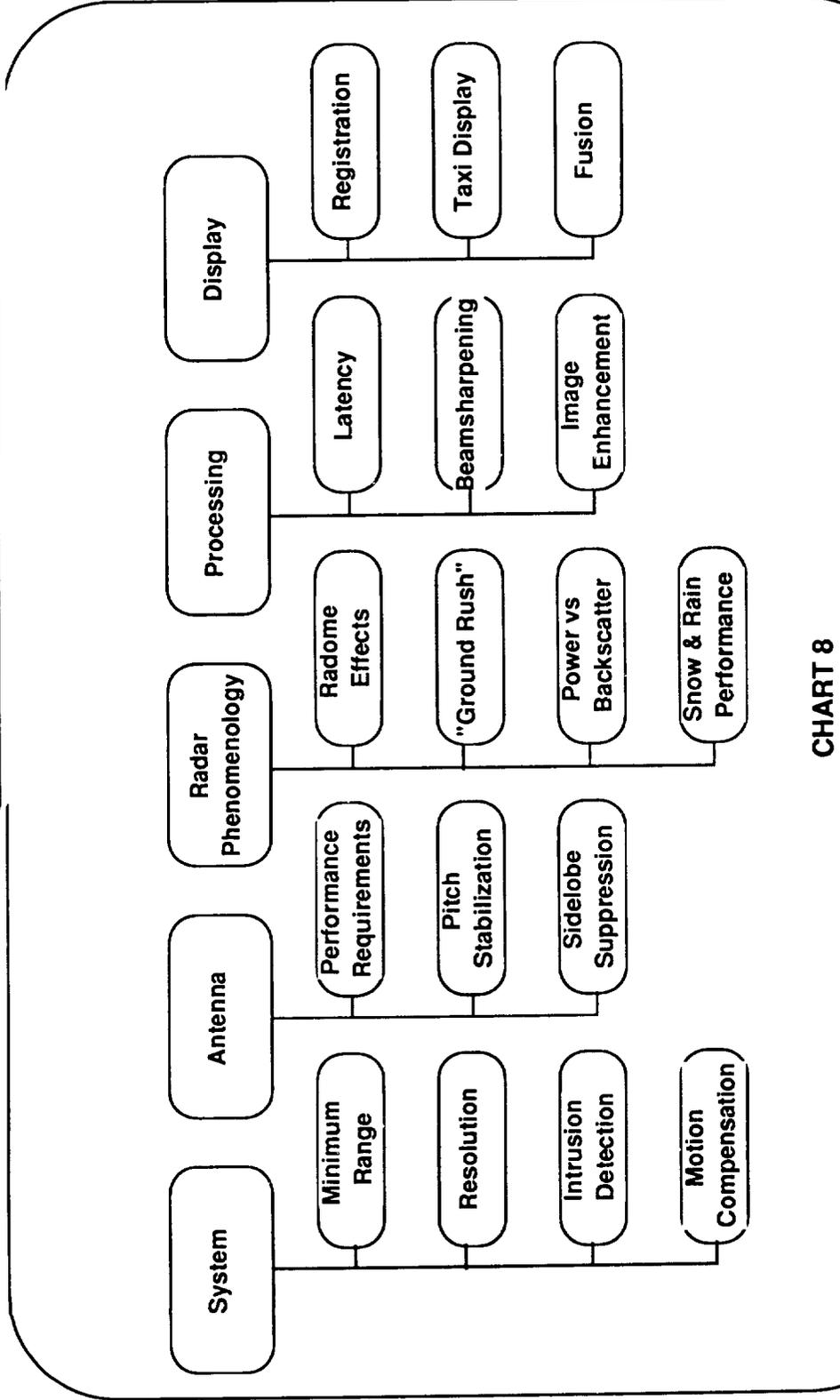
CHART 8

HUD View During Taxi
with Minimum Radar Range of 150 ft and 75 ft

12,000 ft

150 ft.

12,000 ft

75 ft.
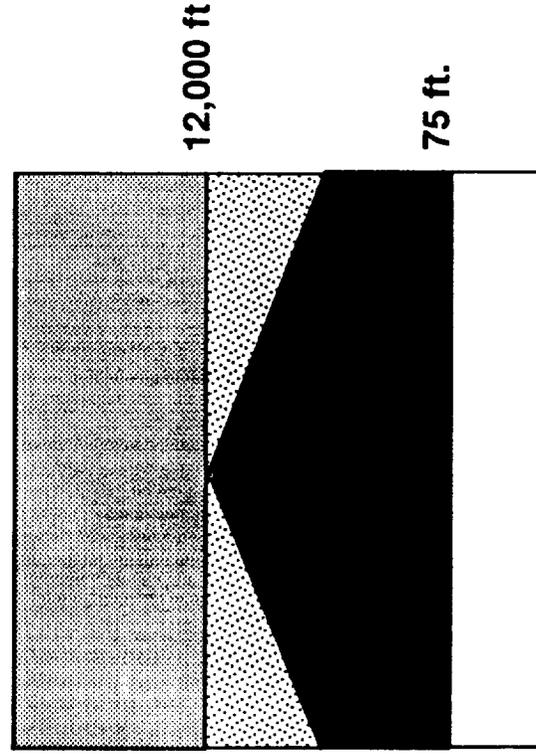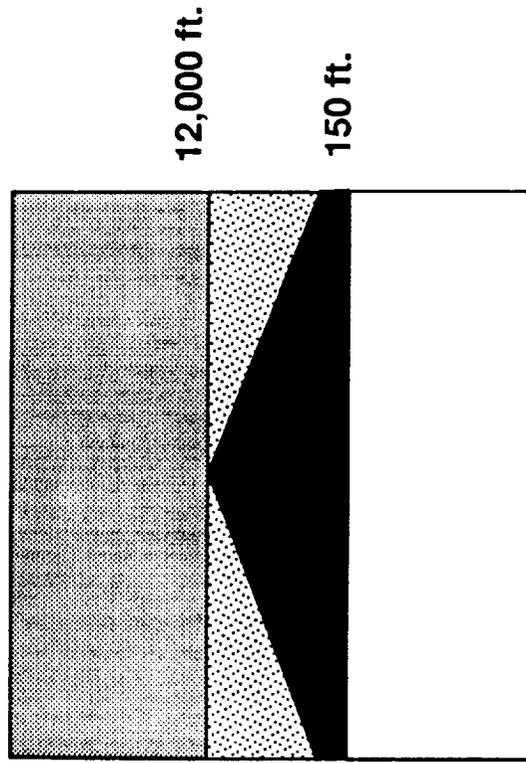
Taxi strip width: 100 ft.
HUD FOV: ±15° Azimuth; 26° Elevation
Perspective View Elevation: 12 ft.

CHART 9

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Flight Test Antenna Configuration

Antenna Mounting Surface

Ref Normal to W.L.

Ref Normal to Antenna Mount

9° Antenna Depression Angle

Antenna Tilt Back
6.6° Compromise Position
5.6° Optimum Approach Position
7.6° Optimum Ground Position

2.4°

Water Line and Horizon (40° Flaps)

Antenna Radiation

3° Glide Slope

CHART 10

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