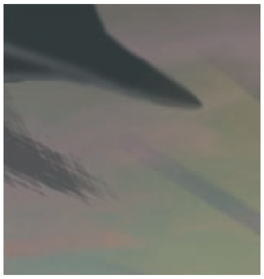

An Airborne Captive Seeker with Real-Time Analysis Capability

Frank J. Marcotte and James M. Hanson

The development of modern air defense missile systems requires robust simulations to adequately place margins on hardware and software design. Coupled with this is the need to accurately model surface reflections that constitute clutter to the missile system. A thorough understanding of these reflections is becoming increasingly important as the air defense threat evolves from large, high-altitude aircraft into small sea- or land-skimming aircraft, making the radar echo difficult to detect in the resulting surface clutter. The Applied Physics Laboratory has developed an airborne captive seeker, carried by a specially instrumented aircraft, that incorporates production Standard Missile system hardware to collect surface scattering data for clutter model development. The Captive Seeker System has a significant spectral processing capability that allows the received signals to be analyzed while still in the air. It has been used on various missile and radar programs over the last decade and is continually being upgraded to maintain its utility to missile system design at APL.

(Keywords: Captive Seeker, Radar clutter, Standard Missile.)

INTRODUCTION

The Combat Systems Development Group of APL has developed the airborne Captive Seeker System to aid in the ongoing development of Standard Missile programs. The Captive Seeker, carried by a specially instrumented Learjet 36 aircraft (Fig. 1), was originally developed in 1987 to measure land scattering of X-band RF signals. Since then it has been used for other land- and sea-scattering experiments, including a testing period for the Canadian Navy, and more recently as a risk-reduction tool for the Cooperative Engagement Capability (CEC) program. The CEC used the Standard Missile in an unconventional manner, i.e., its target was illuminated by an elevated radar. Planned upgrades to the Seeker will provide a multiband capability and allow system testing of new target illumination schemes being developed by U.S. allies.

The Captive Seeker System uses the Standard Missile ultralow-noise illuminator signal to collect bistatic

Figure 1. The Captive Seeker wing pod is shown mounted on a Flight International Learjet. This photograph was taken during initial testing to characterize land backscatter in Vestfjord, Norway.

RF scattering data. Although not a fully coherent bistatic radar system, modulations introduced by radar targets (whether due to aircraft or distributed targets such as land or sea) far exceed the inherent low noise of the system, allowing conventional coherent signal analysis of received signals.

The primary objective of the Captive Seeker System is to closely simulate a semiactive missile to enable collection of target and clutter data for both real-time and off-line analysis. Information gained during an experiment is used in missile design upgrades. A large portion of the data collected is also used to refine RF scattering models, which are important in robust missile simulations.

PAST USE OF THE CAPTIVE SEEKER

As previously noted, the Captive Seeker was originally used in 1987 to characterize the land backscatter from a Norwegian fjord during Ocean Safari '87. The Safari series of exercises represented some of the first attempts by the Navy to investigate the possible use of Standard Missile in littoral regions. The huge amount of scattering from fjord faces tested the original design margins of Standard Missile 2. Test results were used in the redesign of its receiver.

The success of that test and the need to improve scattering modeling in sophisticated missile simulations resulted in another testing phase in 1992: land scattering from a desert environment was investigated at White Sands Missile Range, New Mexico, and sea reflectivity over a wide range of transmitter and receiver depression angles was studied at Wallops Island, Virginia.[1,2] The tests at Wallops Island were the first to closely monitor atmospheric and surface conditions (e.g., surface reflectivity and propagation) that could affect the Captive Seeker. Atmospheric monitoring has become a staple of Captive Seeker tests since then.[3,4]

In 1993, the Canadian Navy asked APL to help determine the cause of missed uplinks in the Standard Missile 2 integration into their Tribal Class Update and Modernization Programme (TRUMP). (Uplink is the term used to describe communications between a ship and an in-flight missile. These communications update target information to ensure acquisition in terminal homing.) For this experiment, Standard Missile uplink decoder hardware was mounted in the Captive Seeker to monitor uplinks sent by the shipboard radar. During the successful 3-day testing period, the Captive Seeker helped identify the problem, and APL has worked closely with the TRUMP Office ever since to improve engagement system performance.

The proliferation of high-speed, low-altitude "sea-skimming" cruise missiles jeopardizes the security of U.S. surface ships. The growth of the CEC and the need to counter the sea-skimmer threat resulted in the Mountain Top Program. Mountain Top design centered on the ability of a ship to perform a Standard Missile engagement of a sea-skimming target beyond the ship's radar horizon using an elevated illuminator. The geometry of such an engagement differs greatly from that typically encountered by Standard Missile, and the Captive Seeker was employed as a risk-reduction tool to test system design prior to any live Mountain Top engagements.[5] Using target information from ground-based radars, designation data linked to the system were adequate to enable the Seeker to acquire and track a target drone in all four attempts, thus demonstrating the Mountain Top design concept. Several successful Mountain Top engagements by Standard Missile in early 1996 have allowed the next phases of an over-the-horizon capability program to be initiated.

CAPTIVE SEEKER FEATURES

Seeker Pointing and Tracking

The utility of the Captive Seeker System has grown considerably since the 1987 experiment when the RF antenna was manually pointed and received signals were recorded for later analysis.[6] The system can now perform multimode pointing, which gives the operators several options to acquire and track a target. The most basic option is the original manual pointing, which is accomplished using a joystick aided by a boresighted video camera. In 1992, pointing information obtained from the Global Positioning System (GPS) was incorporated. This development allowed the Captive Seeker to point the antenna at a target GPS position on the basis of knowledge of its present location. This feature was expanded during a 1995 testing phase when the coordinates of a target drone were linked to the Captive Seeker using information derived from ground-based radars. Monopulse angle tracking, the most recently developed pointing aid, used this linked information as designation data.

Doppler Spectral Processing

The Captive Seeker possesses considerable spectral processing capability in its cabin-mounted VME rack. The rack contains several high-speed digital signal processors operated by general-purpose controllers that process the signal to facilitate real-time analysis and antenna pointing. Raw and processed signals are recorded in both analog and digital formats to provide redundancy in case of equipment failure and to make data easily transportable for off-line analysis.

Real-Time Processing and Display Capabilities

Two important attributes of the Captive Seeker System, clearly demonstrated during the 1995 experiments, are its ability to perform real-time processing and to effectively display processed data for the operators. Many people in APL's Combat Systems Development Group expended considerable effort to design a system that could process, display, and record data so that initial results could be generated in flight and then be made available for analysis within hours of landing.[7] The effectiveness of the displays helped pinpoint setup errors (e.g., improper transmitter or receiver pointing) in time to abort a test and make corrections while the craft were still airborne. This capability contributes to a very efficient and cost-effective data collection period with minimal downtime. In the past, setup errors such as these would have gone unnoticed for months, possibly after much time and effort had been wasted on corrupted data.

Standard Missile Antenna and Front End

The Captive Seeker System incorporates production Standard Missile hardware, taking advantage of years of development of a low sidelobe slot array antenna, low-noise front-end monopulse receiver electronics, and a responsive gimbal assembly. Monopulse data collection enables the study of land- and sea-clutter effects on angle tracking. The use of this hardware also gives authenticity to the data collected and increases data utility to the Standard Missile community.

SYSTEM DESIGN

Figure 2 is a close-up view of the Captive Seeker pod mounted on a Flight International Learjet, and Fig. 3 shows the Seeker's cabin-mounted electronics. The Standard Missile 2 Seeker head is mounted in a modified AN/ALE-2 wing pod along with a steerable video camera, analog and digital control electronics, microwave and video electronics, and power supplies. The antenna is protected by an APL-fabricated radome that provides less distortion of the RF signal than conformal or more aerodynamic designs. A reference antenna is positioned on the underside of the pod along with a second video camera that can image the surface directly beneath the aircraft. Equipment to control the Seeker and camera and to process, monitor, and record data is

Figure 2. Close-up of the Captive Seeker wing pod. The steerable RF antenna is mounted behind the radome. A boresighted video camera is mounted in the smaller, slightly slanted tube.

installed in custom racks that were tailored to the Learjet 36 interior.

A simplified block diagram of the system is shown in Fig. 4. Inputs from an Ashtech GPS satellite receiver, Airborne Tracking and Recording System inertial navigation instruments, and the very-high-frequency digital radio link are used by the VME-based processors to generate the proper antenna and camera-pointing commands. The special four-channel Ashtech GPS receiver measures aircraft attitude as well as position. A joystick and boresighted video camera allow an operator to adjust or override the computed pointing command while in flight. Two Sun Voyager workstations provide most of the display and user input functions, with two small custom control panels accounting for the rest. These workstations communicate with the VME processing subsystem via Ethernet onboard the Learjet.

All control and status information is passed between the wing pod and the VME subsystem via a serial digital interface. The design allows up to 10 signals to be passed in each direction on the multiplexed link; 8 of these signals can be analog values that are converted to or from 12-bit digital values once inside the pod. This link was designed for reliability and noise immunity; the bit rate is therefore a relatively low 5 kHz. APL designed and built the VME interface card and the multiplexer inside the pod. Because of their higher bandwidths, the three monopulse receiver channels (Σ, ΔAz, and ΔEl), the video channel, and the local oscillator signals are passed between the pod and the interior using semirigid coaxial cable to minimize signal interference. Two phases of 120-V/400-Hz aircraft power are connected to the pod to feed the 10 direct-current power supplies necessary for the Seeker, camera, and control electronics.

The three monopulse channels from the receiver are processed

Figure 3. Captive Seeker cabin-mounted electronics. These racks were designed at APL to conform to the Learjet interior while providing standard rack-mounting surfaces for commercial and APL-designed equipment.

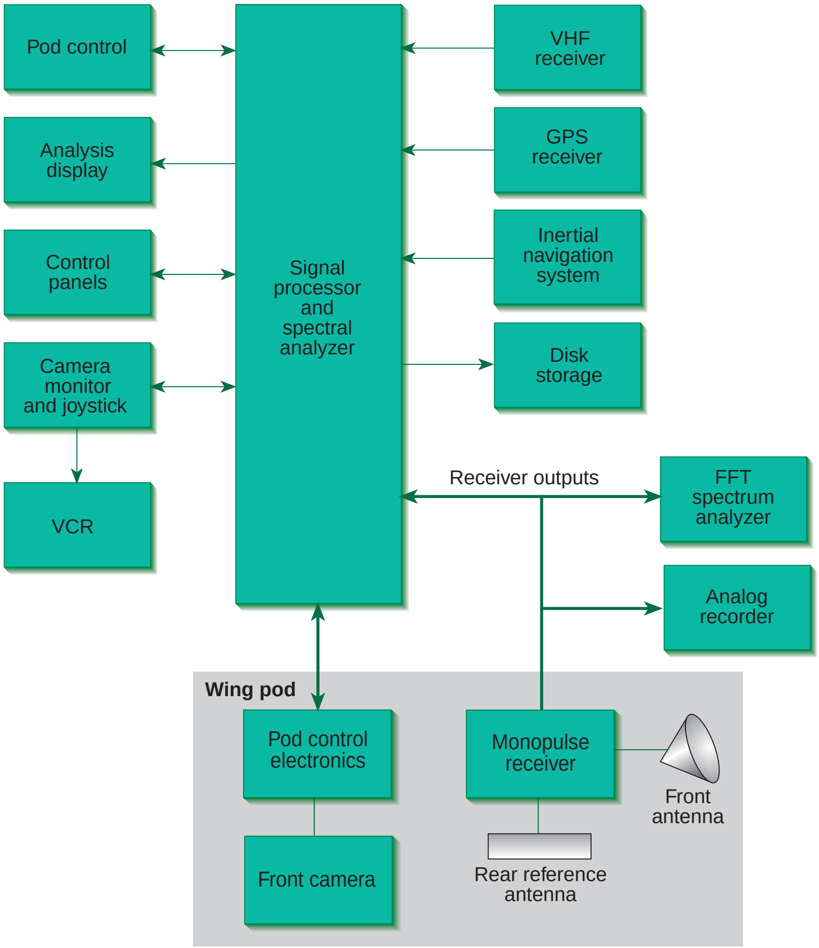

Figure 4. Captive Seeker System block diagram (FFT = fast Fourier transform).

inside the VME chassis using programmable four-pole Chebychev anti-aliasing filters. Raw signals are input to a digital signal processor for real-time display and to a Metrum tape recorder to allow for post-processing. These signals are also digitized and input to the Captive Seeker tracking algorithms.

CAPTIVE SEEKER SOFTWARE

The Captive Seeker System has evolved from a simple monitor of received signals via commercial test equipment to a complex VME-based system with custom software that controls Seeker functions and processes many of the signals for in-flight analysis.

Human Interface

The human interface design of the Captive Seeker was also developed for efficient operation and the clear display of real-time spectral processing and data analysis. Control and display are accomplished using the two portable Sun Voyager workstations mounted in two cabin consoles. The first workstation is primarily used for Captive Seeker control (Fig. 5). The operator can select the type of Seeker tracking (GPS, joystick, or monopulse), monitor GPS and Seeker status, and initiate data recording. A PPI (plan position indicator) type display plots GPS track history and user-entered waypoints.

The second Sun Voyager serves as a spectral analysis tool (Fig. 6). Displayed on this console monitor are low- and high-resolution power spectra, which are selectable from one of the three received monopulse channels (Σ, ΔAz, and ΔEl). The operator can position a cursor on a signal and designate a speedgate (frequency) tracker with the push of a button. Once a speedgate track is initiated, the operator can enable angle tracking, overriding manual or GPS pointing. Coast modes are incorporated into both speedgate and angle trackers to facilitate regaining of track following signal fades. The operator can choose from several types of signal trackers depending on the type of target, e.g., a narrowband tracker for point-type targets like aircraft or drones and medium- or wideband trackers for distributed targets such as land or sea clutter. In addition, since Doppler clutter signals can have very well-defined leading or trailing edges depending on geometry, the operator can select an edge tracker.

The display presents azimuth and elevation angle errors as a function of frequency. This feature comple-

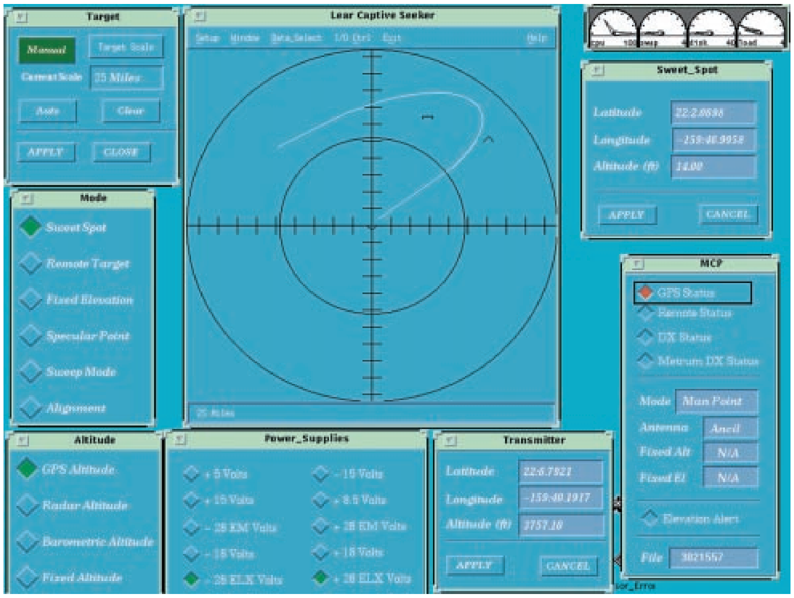

Figure 5. Captive Seeker System control display. Information on this monitor provides the operator with Seeker status and facilitates control of the system using window-based input.

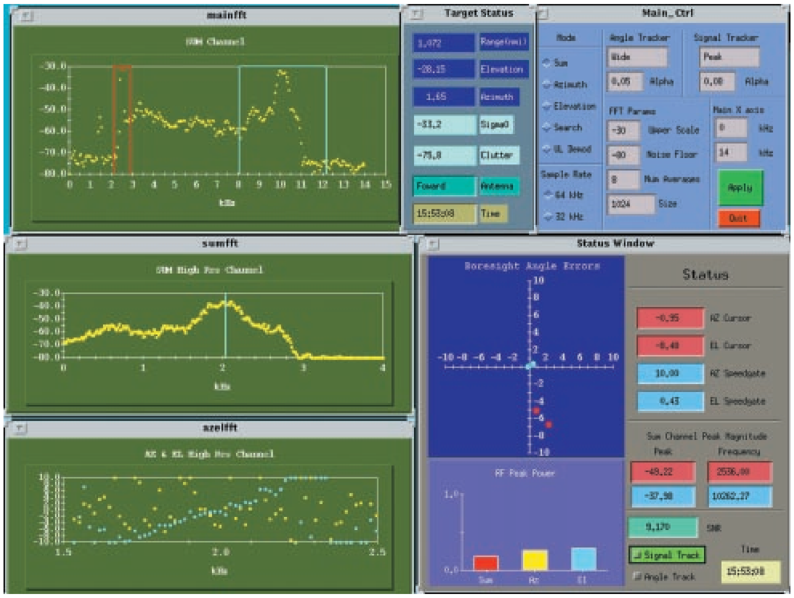

Figure 6. Captive Seeker System spectral analysis display. Doppler frequency spectra allow the operator to see what a Standard Missile will process in terminal homing. The display also serves as the means to input signal and angle track parameters.

ments the more traditional angle-error display on the monitor. Angle error versus frequency is extremely useful when tracking distributed targets. Several times during the Mountain Top test this display revealed setup errors in transmitter or receiver pointing early enough to prevent serious loss of time. Again, such setup errors would have gone unnoticed in the past until revealed by post-processing.

The peak power in each receiver channel is displayed as a bar chart. This information can be used by a stepped automatic gain control function, if enabled by the operator, to avoid receiver saturation.

Much thought even went into the design of the cursor used to designate a speedgate. Following track initiation, the cursor and the speedgate are unlocked, and the cursor can be used to measure the frequency and amplitude of other signals of interest. The azimuth and elevation angle errors of the cursor position are plotted on the angle-error display as well.

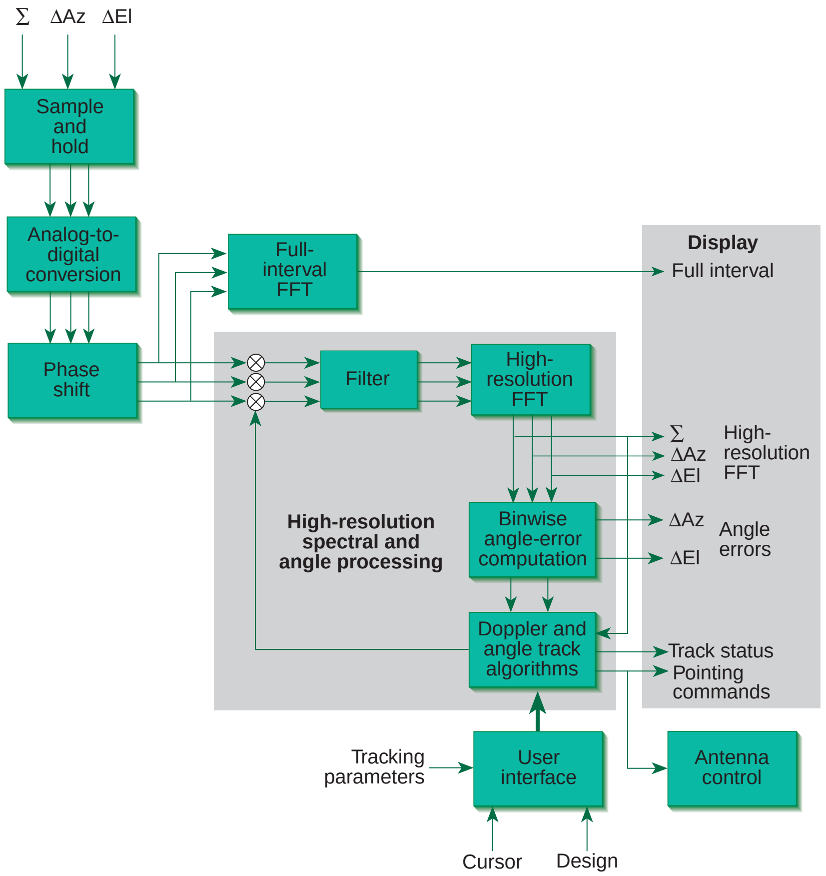

Figure 7. The Captive Seeker Doppler and angle tracker. Several points in the signal flow are extracted and displayed to the operators. Operators also can change tracker parameters in real time.

Tracker Design

A block diagram of the tracker incorporated into the VME system is shown in Fig. 7. The input monopulse channels are simultaneously sampled before being digitized by a 12-bit analog-to-digital converter. The ΔAz and ΔEl channels are shifted in phase to account for delay differences among the three channels and to ensure that the Δ channels are orthogonal to the Σ channel for optimum monopulse sensitivity. A fast Fourier transform (FFT) is computed for each phase-shifted signal, one of which is selected for full-interval display. Each signal is digitally mixed with the tracker frequency (speedgate position) and filtered to generate the high-resolution FFT, which is also displayed. A binwise angle-error computation is performed on each bin of the high-resolution data; this process then generates the ΔAz and ΔEl versus frequency data for display.

This information, along with user-supplied inputs such as track parameters and cursor position, is input into the alpha/beta tracking algorithms, thereby generating a new speedgate position and closing the track loop. Similarly, the angle-error information and current Seeker antenna position are used to close the angle track loop. Digital recording of all data displayed in real time is impractical; therefore, amplitude and angle-error data from a segment of the spectrum surrounding the speedgate position are recorded. This provides limited off-line analysis of the spectrum and eliminates the need to replay the raw data into the system during quick-look analysis.

Real-Time Analysis Description

Software developed at APL calculates and displays in real time the received signal spectrum, monopulse angle errors versus frequency, measured sea or land reflectivity, average clutter value, and other useful information. These data are also recorded on Bernoulli disks to facilitate report preparation and further analysis. As noted previously, the wealth of data products available to the operators in real time has proved invaluable in conducting an efficient, successful set of tests.

During in-flight data collection, sufficient data (ranges, angles, transmitter/receiver geometry) exist in the VME system to calculate surface reflectivity. Although an entire test can be recreated later, it is often a difficult and time-consuming task since the complete data package is recorded on separate storage media that require synchronization for playback. We therefore added an extra processing capability to the system to calculate reflectivity in real time.

Figure 8 is a flow diagram of the real-time signal processing. The VME data acquisition system samples the received signals and processes them using conventional spectral analysis techniques. Significant data reduction occurs here by using the tracker to highlight the pertinent cells or frequencies of interest. Experiment geometry is calculated in real time using current Captive Seeker parameters (location, speed, etc.). Reflectivity models employ the geometric information and user-defined target type (aircraft, land, sea) to calculate a received power using a fixed reflectivity value, which is subtracted from the actual received power in a normalization process to obtain measured target reflectivity. The information is displayed and recorded digitally along with the input parameters to provide immediate quick-look–quality information for the operator. In-depth off-line processing is used to factor in other variables such as atmospheric effects.

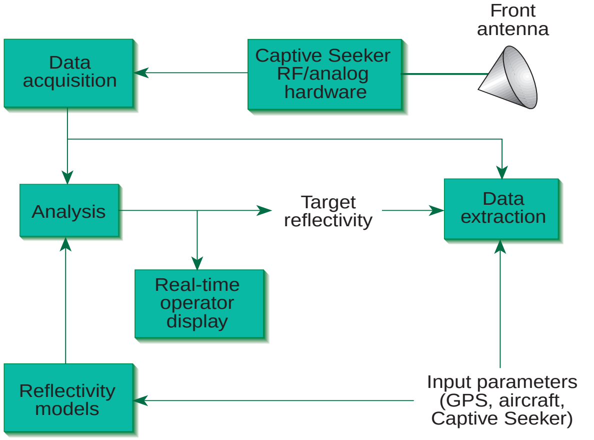

Figure 8. Signal flow for the real-time analysis capability of the Captive Seeker. Extra processing power was added to the system to provide a true quick-look capability.

TYPICAL CAPTIVE SEEKER EXPERIMENT

A typical Captive Seeker experiment is shown in Fig. 9. The system, simulating a missile in terminal homing, is flying toward a target drone that is being illuminated by a shipboard radar. The target echo received by the Seeker is corrupted by signals reflected from the surface. "Front multipath" denotes target energy reflected off the surface that enters the primary missile antenna along with the target signal. This interference can corrupt tracking and guidance. "Rear multipath" denotes surface-reflected signals that enter the missile's aft-looking rear receiver, which is used for maintaining coherency with the shipboard radar. The missile mixes this rear reference signal with the front signal to estimate the target's Doppler velocity. Corruption of this signal can slow or prevent the acquisition of the target signal.

Front and rear multipath are extensions of the third type of signal interference shown in Fig. 9, i.e., clutter. Clutter can be either land- or sea-reflected signals. Most of the radar energy incident on a surface is reflected away from the illuminating radar as if the surface were a mirror (specular reflection). Clutter received by the missile in this fashion is called forward-scatter clutter; backscatter clutter is the small amount of energy reflected back toward the radar. If the surface becomes sufficiently rough, backscatter can become a major contributor to the overall clutter signal received by the missile. In a typical engagement, the missile is flying away from forward-scatter clutter sources, which appear at lower Doppler frequencies. Similarly, backscatter clutter is apparent at higher Doppler frequencies since the missile is flying in the general direction of the clutter source.

The spectral shape of the received signals is influenced by many factors (e.g., transmitter and receiver antenna patterns, sea reflectivity and roughness, geometry of the received scattering signals). Animation of the spectra would show low-frequency activity produced by the movement of sea swells. A thorough understanding of forward and backscatter clutter and

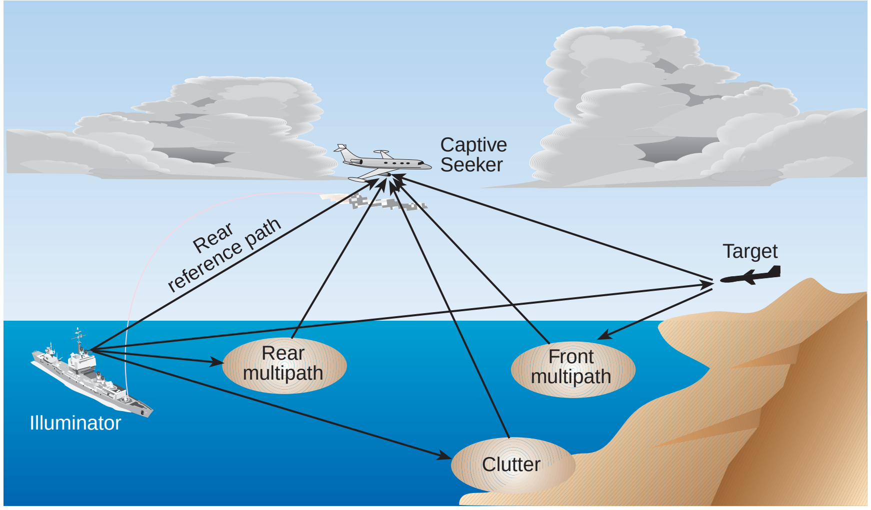

Figure 9. The primary objective of the Captive Seeker is to simulate a missile shown as a "phantom" in terminal homing. Various surface reflections that interfere with target acquisition and tracking are also represented.

their accurate modeling can enhance missile design and performance. Since clutter signals are affected by environmental factors, a well-planned exercise should include aircraft to profile atmospheric conditions and surface vessels to measure waveheight and other surface conditions.

Figure 10 contains examples of data gathered during a drone experiment. In the spectra, the "spillover" signal is the rear reference signal that spills over into the primary antenna. The binary time signal labeled SGT is the status signal speedgate track, which indicates that adequate target energy is received to maintain a Doppler and angle track of the target. During the "break engagement" interval, the system is returned to standby before the target acquisition process is reinitiated.

CLUTTER MODELING

APL's Standard Missile six-degree-of-freedom (DOF) programs comprise a very robust family of simulations. The programs model the boost, guidance, and terminal homing phases of the Standard Missile engagement. Algorithms simulate a target's motion and signal fluctuations. An important attribute of these programs is the surface reflectivity models.[8,9] Captive Seeker data are being furnished to six-DOF engineers to refine the reflectivity models used in the simulation.

Figure 11 shows a six-DOF rear receiver spectral simulation for an instant during the drone experiment mentioned previously. Overlaid on the spectrum are actual rear receiver data collected by the Captive Seeker. Because the coverage of the rear receiver antenna

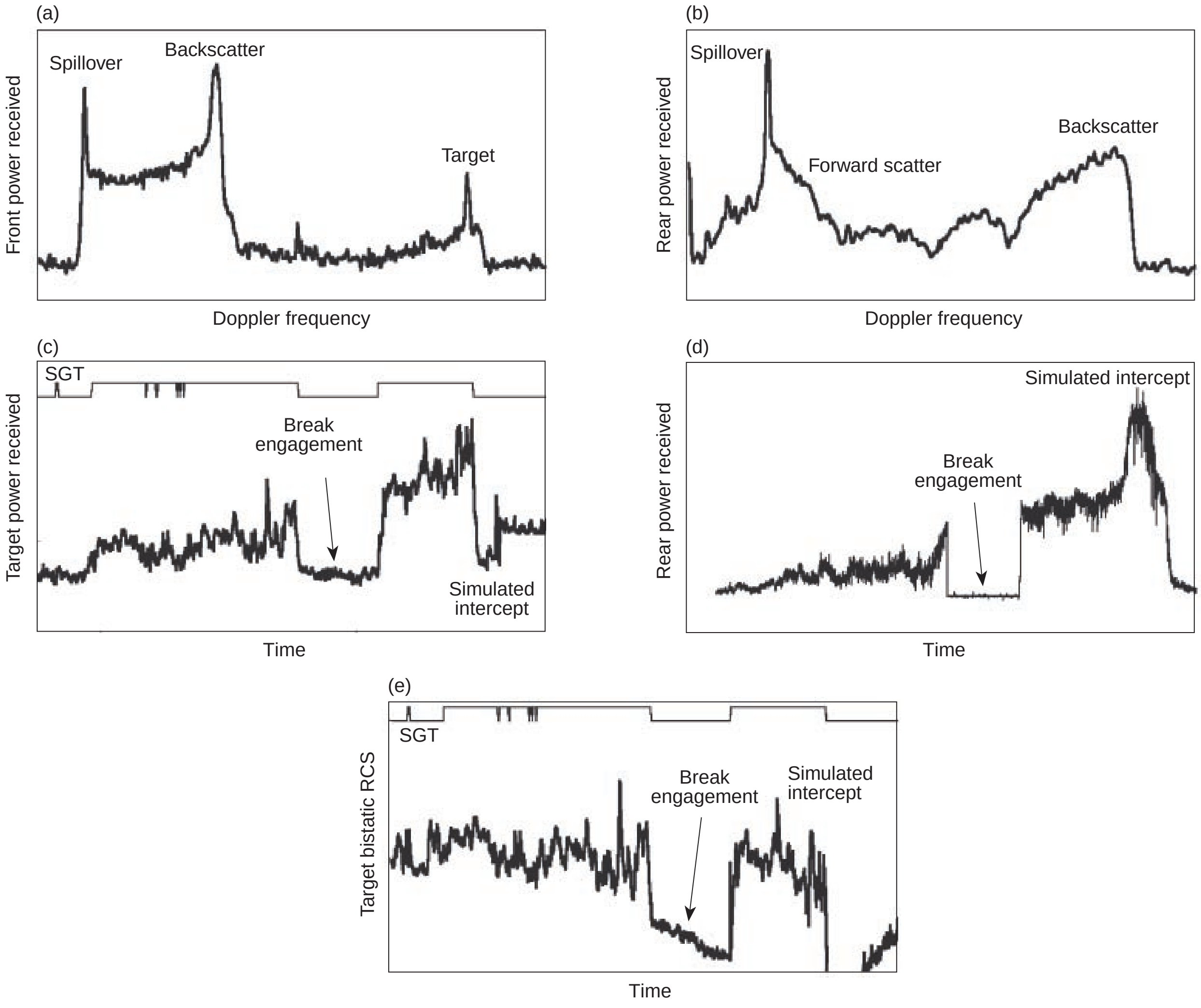

Figure 10. Examples of data taken from a recent Captive Seeker experiment. The system extracts information from received Doppler spectra to calculate target reflectivity and displays the results in real time to the operators. (a) Front-received power spectra. (b) Rear-received power spectra. (c) Time series plot of target power received (SGT = speedgate track). (d) Time series plot of rear reference power received. (e) Target bistatic radar cross section (RCS).

is wide, it receives signals from both forward- and backscatter-clutter sources, thus explaining the wide spectral extent of the rear receiver signal. Furthermore, because the spillover signal originates from behind the missile, it is typically near the lower end of the Doppler clutter frequencies.

Figure 11 shows good correlation between the simulated and real spillover and forward-scatter signals of the rear receiver. Good correlation is also seen in the shape and size of the backscatter region; however, the simulated data have less Doppler extent. A slight difference between the actual and simulated geometries and Seeker speeds could explain this difference in backscatter spectral extent.

Six-DOF estimates and Captive Seeker backscatter into the front receiver are shown in Fig. 12, which is an expanded view of the backscatter region of Fig. 10a. Here again, there is excellent correlation in the peak magnitude of the surface-reflected signal. The simulation does show less diffuse scattering into the antenna sidelobes, which becomes apparent as wideband noise 30 dB below the peak backscatter signal.

PLANNED UPGRADES

As high-power transmitters become smaller and more efficient, the feasibility of developing an active missile for air defense increases. In future programs, Captive Seeker will likely be configured with a transmitter to collect the types of data that have been successfully collected for the semiactive Standard Missile program. If such a transmitter is installed, it will probably be able to transmit in several RF bands to study the consequences of active operation in those frequency bands.

Several U.S. allies are teaming to develop a variant of Standard Missile that can operate in an interrupted continuous wave (ICW) mode. In this program, short bursts of RF energy are directed toward a target by a phased-array illumination radar. The pairing of a phased-array illuminator with an ICW waveform will greatly enhance the fire power of the engagement system by allowing the system to support many engagements concurrently. New synchronization schemes must be developed and tested for the shipboard radar to reliably communicate with the missile, and plans are under way to modify Captive Seeker hardware and software to test an ICW system design in 1998.

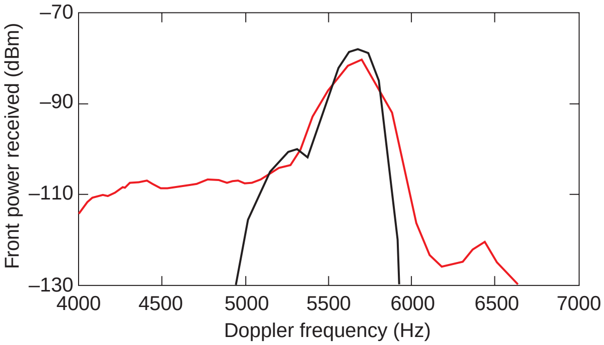

Figure 12. Captive Seeker (red curve) and six-DOF front receiver spectra (black curve) comparison. The Captive Seeker, the illuminator's antenna pattern, as well as sea reflectivity greatly influence the shape of the received clutter spectra. Diffuse scattering into the far Captive Seeker sidelobes accounts for the wide spectral extent of the real signal.

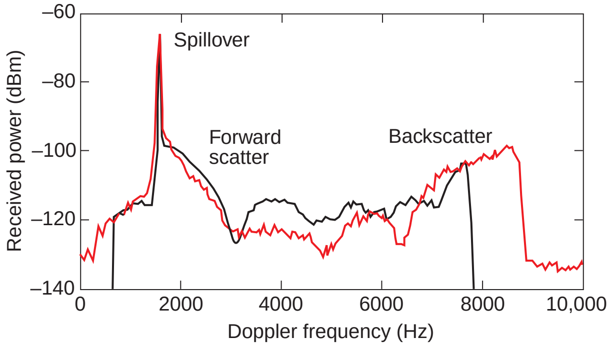

Figure 11. Comparison of data obtained from APL's Standard Missile six-DOF simulations (black curve) and real Captive Seeker rear receiver spectra (red curve).

CONCLUSION

The versatility and utility of the Captive Seeker has been demonstrated many times since initial development more than 10 years ago. Data from several experiments have been used to refine clutter model development for the Standard Missile program. The system has also been used to test new fire control system designs and evaluate existing designs. Recent modifications that incorporate high-speed signal processing have provided the Captive Seeker with in-flight analysis tools that yield a true quick-look capability. These modifications have provided the operators with effective displays for efficient data collection experiments.

REFERENCES

[1] Konstanzer, G. C., Munjal, R. L., and Dobson, E. B., *Techniques Developed for Analysis of Data from the 1991 Wallops Island Captive Seeker Bistatic Sea Clutter Experiment*, F2F-94-U-2-001, JHU/APL, Laurel, MD (1994).

[2] McDonald, R. L., *A Look at Backscatter Measurement Data from the JHU/APL 1992 Captive Seeker Clutter Experiment*, F1A(0)-94U-027, JHU/APL, Laurel, MD (1994).

[3] Babin, S. M., "A Case Study of Sub-Refractive Conditions at Wallops Island, Virginia, 1985–1994," *J. Appl. Meteorol.* **34**(5), 1028–1038 (1995).

[4] Babin, S. M., "Surface Duct Height Distributions for Wallops Island, Virginia, 1985–1994," *J. Appl. Meteorol.* **35**(1), 86–93 (1996).

[5] Hughes, A. S., "Quick Look Data from Mountain Top Captive Seeker," F2B-95-U-0-155, JHU/APL, Laurel, MD (1995).

[6] Marcotte, F. J., Hanson, J. M., and Beseke, R. A., *Standard Missile Captive Seeker Upgrade*, F2B-94-U-3-051, JHU/APL, Laurel, MD (1994).

[7] Bric, A. J., *Description of DSP Display and Control Software for the Captive Seeker Project*, F2B-95-U-1-090, JHU/APL, Laurel, MD (1995).

[8] Smalley, M. A., *Multi-Centroid SM-2 Multipath Model*, F1B-2-89U-041, JHU/APL, Laurel, MD (1989).

[9] McDonald, R. L., *A Sea Clutter Model for Standard Missile Performance Evaluations*, F1A(0)-94U-015, JHU/APL, Laurel, MD (1994).

THE AUTHORS

FRANK J. MARCOTTE joined APL in 1983 after graduating from Kansas State University with a B.S.E.E. In 1988 he obtained a master's degree in the same discipline from The Johns Hopkins University. Early in his career, Mr. Marcotte was a test and analysis engineer for many Terrier Fire Control System upgrades and used this hardware background to benefit Standard Missile and Aegis programs. He has helped design and develop several coherent instrumentation radars over the years, including radars for antisubmarine warfare and wing-tip vortex detection. Mr. Marcotte is a member of the Air Defense Systems Department's Combat Systems Development Group. His e-mail address is Frank.Marcotte@jhuapl.edu.

JAMES M. HANSON received a B.S. in electrical engineering from the Georgia Institute of Technology in 1981 and an M.S. degree in the same field from The Johns Hopkins University in 1986. He joined APL in 1981 and is a member of the Senior Professional Staff in the Air Defense Systems Department's Combat Systems Development Group. Since 1994, he has been the supervisor of the Hardware Design Section of that group. Mr. Hanson has designed data acquisition and signal processing hardware for programs including Standard Missile, Cooperative Engagement Capability, Noncooperative Target Identification, and the U.S./Norway Ocean Radar Program.. His e-mail address is James.M.Hanson@jhuapl.edu.