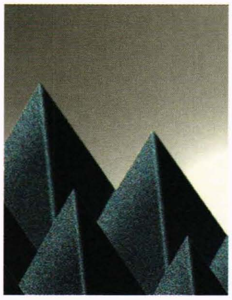

Measuring and Modeling Scan Modulation of an Infrared Seeker

Linda M. Howser

A recently developed model of a spin-scanning infrared seeker increases the accuracy of signal processing evaluations and seeker performance predictions compared with previous models. The simulation includes the effects of targets and backgrounds, seeker scanning and detector signals, gyroscope dynamics, signal processing, and acquisition and tracking. The model also incorporates realistic representations of noise, look-angle-dependent optical blur, gyroscope errors, and scan modulation. The model of scan modulation was derived from laboratory measurements and has been refined using data from aerothermal and laser-heating tests on the seeker.

INTRODUCTION

Infrared (IR) seekers are used in many defense systems for locating and identifying targets. Because of this vital function, weapons designers must ensure that the seekers operate reliably, especially in the face of changing algorithms or environmental conditions. A validated simulation reduces the need for extensive field tests of the seeker and allows algorithm changes to be assessed before their implementation in seeker hardware and firmware.[1]

To fill this need, we have developed a detailed model of a spin-scanning IR seeker. This type of seeker contains optics mounted on the seeker gimbals and an array of detectors fixed to the seeker body. As the seeker spins and precesses, it scans the background scene across the detectors' fields of view. The digitized signal from each detector is a measure of the radiance of a curved line in the background scene, and these detector waveforms are processed by the associated electronics to detect targets and reject backgrounds.

Of particular interest to the weapons designer is performance degradation caused by scan modulation, which is a spin-related artifact produced by magnetic coupling from the gyroscope and by nonuniform radiation from the seeker dome and internal components.

Figure 1 shows the geometry of the seeker. All components shown, except the coils, are mounted on a gimbal and spun. For optical scanning, the optical axis is offset with respect to the spin axis. The seeker dome and the optical baffles are the primary contributors to the optical scan modulation. The principal baffles are the sunshade, which covers the secondary mirror; the center baffle, which shields the detectors from off-axis energy; and the edge guard on the primary mirror, which limits the optical aperture. The primary mirror is a permanent magnet with a horizontal spinning field. The spin coils produce a rotating horizontal magnetic dipole moment, which maintains spin by repelling the field of the rotating magnet. The precession coils produce a vertical sinusoidal magnetic dipole moment, which interacts with the field of the rotating magnet to produce torque (hence precession).

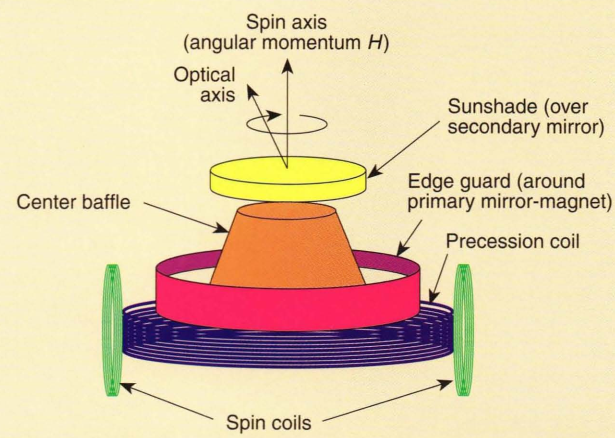

Figure 1. The geometry of the seeker. All components except the coils are mounted on a gimbal and spun to stabilize the seeker. Magnetic and optical anomalies, caused by spinning magnets and nonuniform heating of the dome and internal parts, respectively, produce artifacts and errors in the waveforms from the seeker detectors, called scan modulation.

SIMULATION OVERVIEW

The IR seeker simulation is a tool for investigating the acquisition and tracking performance of an IR seeker in a wide variety of environments and conditions. The simulation contains models of targets, scene, optics, electronics, gimbals, and gyroscope dynamics, and complete signal processing and logic for detection, track, and countercountermeasures. All features of the seeker are replicated in realistic, high-fidelity models that include seeker artifacts and errors in addition to the ideal seeker implementation. Full missile homing (i.e., missile response to track signals) is not included in this simulation but can be added as a future option.

The simulation comprises three basic computational modules: dynamics, waveform generation, and digital signal processing (DSP). The main program contains the DSP module, controls the flow of data, and produces most of the output. Embedded in the main simulation are the two modules that produce the seeker waveforms and compute the seeker dynamics. Figure 2 shows a simplified block diagram of the simulation structure. Under the control of the main program, the dynamics module executes all motions of the seeker, producing precession commands (commanded seeker rates) and the resulting gimbal angles (pointing directions). Directional information from the dynamics module is fed to the waveform module, which calculates target and countermeasure parameters, implants the targets and countermeasures in the scene, generates the detector waveforms (including noise, clutter, and scan modulation), and simulates the analog electronics up to the input to the digital signal processor. The digital signal processor subset of the main program does the full signal processing, including provisions for target acquisition and processing,

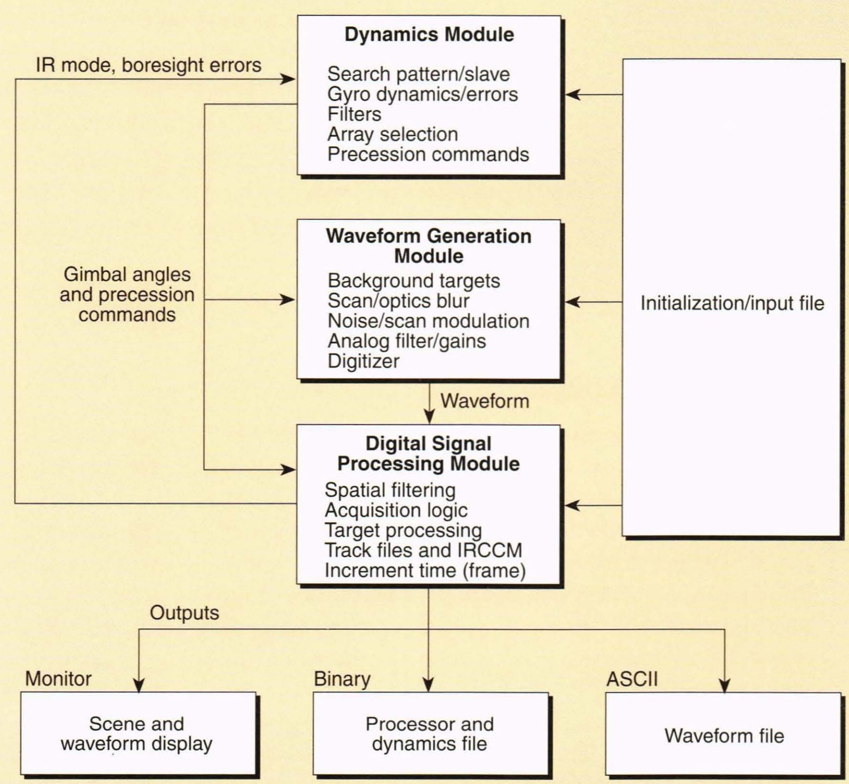

Figure 2. Overview of the simulation architecture. The simulation consists of a dynamics module, which executes all required seeker motions; a waveform generation module, which produces the seeker waveforms; and a digital signal processing module, which computes the seeker dynamics (IRCCM = infrared countercountermeasures).

track files, and countercountermeasures. The DSP calculates boresight errors, which are either target position (during acquisition) or tracking errors, and changes the seeker operating mode (IR mode). Boresight errors and IR mode are the principal inputs to the dynamics module. This computational loop—dynamics to waveforms to signal processing—is executed once per frame (seeker optical scan period), although the time step within some subprograms is equivalent to the detector sample rate.

One output of the simulation is a graphic display that is useful for visualizing the seeker actions in dynamic situations and in various clutter, countermeasures, and multiple-target scenarios. Figure 3 shows a stylized graphic display for a calibrated IR image from a Mitsubishi platinum–silicide IR camera. The green box outlines the current frame's field of view (note the target at the box's center), and the jagged line shows the seeker pointing history. The simulation starts its search of the image at the lower left corner, switching from search to track mode when it detects the target. The display on the right shows waveforms from selected detectors; the bottom two waveforms indicate the target signal as negative-going pulses. The display text shows significant parameters from the simulation.

SCAN MODULATION

The focus of the work described here was to model scan modulation, which is a spin-related artifact appearing in the detector waveforms. The seeker we investigated is a "free gyroscope," where most of the on-gimbal optical components spin to stabilize the seeker (and provide an inertial line-of-sight reference for guidance). Spinning is also used to generate the optical scan; the optical axis is canted with respect to the spin axis, producing a conical scan pattern. Scan modulation arises from the seeker spin scan and is composed of spin frequency harmonics.

Magnetic and optical effects are the two main components of scan modulation in the seeker. The magnetic component is proportional to the magnetic fields of the spinning permanent magnet and the magnets used to precess the seeker's gyroscope. The optical component is proportional to the optical radiance (brightness) of the scene and seeker parts. When the seeker flies at high speed, the temperatures of its dome and interior components rise, greatly increasing their radiance and the resulting scan modulation. (See the boxed insert for a detailed explanation of the origin of scan modulation.) The waveforms displayed in Fig. 3 do not exhibit significant scan modulation because the seeker was simulated at room temperature, eliminating optical scan modulation, and, once locked onto the target, the seeker was moving too slowly for magnetic effects to come into play.

Scan modulation is currently modeled by the linear superposition of four terms whose values are determined from seeker measurements:

1. Precession-induced magnetic modulation
2. Look-angle-dependent magnetic modulation
3. Uniformly heated dome optical modulation
4. Uniformly heated sunshade optical modulation

The first three are well-known and characterized; we recently discovered and added the fourth to the simulation.

Magnetic Scan Modulation

The precession-induced modulation changes amplitude and phase depending on the required pitch and yaw precession rates and direction. This modulation is highest in the search mode, where precession rates are high, and lowest during acquisition and track, where the precession rates are greatly reduced. The amplitude and phase of look-angle-dependent modulation depends on pitch and yaw gimbal angles. We implemented several processing changes to reduce the effects of magnetic scan modulation, and an electronics redesign

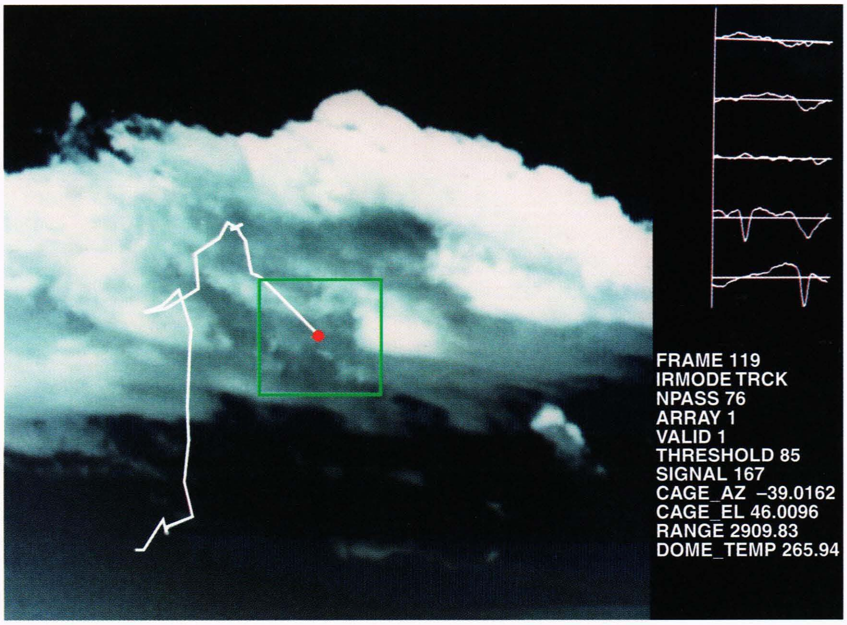

Figure 3. Video display of a simulation output from an IR camera. The jagged line is the track of the target and seeker pointing history. When the seeker detects the target (center of green box), it switches from search to track mode and follows target motion. Associated waveforms from the seeker's detectors are displayed to the right of the photo. The target signal appears as a negative pulse in the lower two waveforms.

THE ORIGIN OF SCAN MODULATION IN A SPIN-SCANNING IR SEEKER

A free-gyroscope seeker spins most of its on-gimbal mass to maintain stabilization, thus providing a spatial reference for measuring target motion for guidance. In a free-gyroscope optical seeker, the spinning mass is principally the telescope, which usually uses folded-mirror optics. The substrate of the telescope's primary mirror, the most massive element of the gyroscope, is also a powerful permanent magnet. The gyroscope is spun using current loops fixed to the seeker case. The magnetic dipole moment μ produced by these spin coils interacts with the flux density of the permanent magnet $\mathbf{B}$ to produce a torque τ about the seeker (case) axis:

$$\tau = \mu \times \mathbf{B} . \tag{1}$$

As the magnet spins, additional (spin reference) coils sense its position. The spin reference is used to properly phase the sinusoidal current through the spin coils to continuously produce the appropriate torque and control the spin speed. The spin speed is held constant after the initial spin-up.

In addition, the gyroscope is moved magnetically (i.e., for search or target tracking). A precession coil, also mounted in the case but perpendicular to the spin coils, torques the gyroscope about the gimbal axes (perpendicular to the seeker axis). The precession torque (Eq. 1) is perpendicular to the seeker axis, resulting in a precession rate Ω that is a function of the angular momentum $\mathbf{H}$ of the gyroscope:

$$\tau = \Omega \times \mathbf{H} . \tag{2}$$

To maintain torque as the gyroscope spins, a sinusoidal current (at the spin frequency) is applied to the precession coils.

In the seeker we measured, magnetic scan modulation is caused principally by the magnetic field component along the seeker axis (the detectors and their electronics are not on the gimbal). Therefore, magnetic scan modulation consists primarily of contributions from two components:

1. Precession, since the magnetic dipole moment field is always along the seeker axis. For a constant precession velocity, the scan modulation is a sinusoid at the spin frequency. Its magnitude is proportional to the precession rate, and its phase depends on precession direction.
2. Look-angle (or spin), caused by the tilt of the permanent magnet with respect to the seeker axis. For a constant gimbal angle, the scan modulation is a sinusoid at the spin frequency. Its magnitude is proportional to the angle between the look direction and the seeker axis, and its phase depends on the direction of the tilt.

Higher harmonics of magnetic scan modulation are generated by nonconstant look-angles or precession rates, especially during the rapid precession direction changes that occur in search mode.

Optical scan modulation is produced by a nonuniform irradiance (energy density) on the detector focal plane. As this energy distribution spins, its nonuniformities affect the waveforms of the off-gimbal, nonspinning detectors. The focal plane energy distribution is a function of physical tolerances, optics quality, and the temperature distribution on the principal contributors (e.g., dome and outer optical baffles). The optical scan modulation contains all the harmonics of the spin frequency, where the magnitude of the harmonic components decreases with increasing frequency.

The higher harmonics of scan modulation are targetlike, i.e., they readily pass through the electronic and digital spatial filters, producing "hits." Scan modulation hits from many detectors act to raise the detection threshold (reduce sensitivity). They can also produce false targets. Optical scan modulation increases as seeker components heat.

is under way to further reduce the magnetic field-to-detector coupling. The magnetic-induced modulation models will then be updated (or removed) from the simulation to reflect the new design.

Optical Scan Modulation

Optical scan modulation increases as seeker components heat, where heating rate is a strong function of flight speed and altitude. At low speed or high altitude, heating rate is low and optical scan modulation is also low, at least initially. For flight speeds above Mach 2, seeker heating becomes significant, and the resulting optical scan modulation can reduce performance. Thus, for optical scan modulation predictions, we must calculate the radiance, and hence temperature and emissivity, of contributing components.

As the dome of the IR seeker heats in high-speed flight, dome emission becomes the dominant contributor to total background radiance and therefore controls the optical modulation and background noise of the seeker waveforms. Dome heating is simulated using a calculated equilibrium temperature and approximations of the heating time constant from a complete aerothermal heat transfer model that includes radiation and thermal conduction effects. These two values are determined as functions of speed and altitude and include the transition from fully laminar to partially turbulent flow conditions on the seeker. The equilibrium temperature and heating time constant for any simulated condition are found by interpolation between tabular values.

The IR emissivity of the dome is calculated as a function of temperature and wavelength using a quantum mechanical model of the multiphonon absorption edge that was recently validated up to 2000 K for several materials.[2] Temperature and emissivity are integrated across the seeker spectral band and combined with optical parameters to determine the dome radiance seen by the detectors. The simulation also determines an "equivalent scene temperature" that would create the same radiance, so that we can experimentally verify calculated radiance effects on seeker noise and waveforms in the laboratory. For laboratory testing, an extended-area blackbody is heated to the equivalent scene temperature and placed in front of the seeker. (We can also use an optical beam splitter to combine the hot-dome-simulating blackbody with projected targets and scene. In this case, the blackbody temperature must be set higher than the equivalent scene temperature to account for optical loss.)

The laboratory tests show that the optical modulation of the background radiance increases linearly with the in-band radiance. This empirically determined optical scan modulation is incorporated in the simulation as a radiance-dependent contribution to the detector waveforms based on the calculated dome radiance. Optical modulation from the heated sunshade (and other components) is a newly discovered factor discussed later in this article.

VALIDATION TESTS FOR OPTICAL SCAN MODULATION

Aerothermal Tests

To validate the optical scan modulation model in the simulation, we conducted an aerothermal test on an IR seeker in cell 4 of the Avery Propulsion Research Laboratory (APRL). The heating rate was equivalent to that for a sea-level flight at maximum speed. The seeker was injected into the flow, emulating seeker cover removal, and heated for 10.5 s. During this time, the seeker was commanded to move between three gimbal angles, perform a search, and acquire a target. Seeker telemetry data were collected before, during, and after exposure to the flow. Measurements before injection established an ambient-temperature baseline, and data after retraction from the flow showed the effects of seeker cooling.

The detector waveforms collected from these tests showed an optical scan modulation 4 to 5 times higher than that predicted by the current hot-dome model, and the shape of the waveforms did not match those obtained in the laboratory tests. However, the amplitude of the measured waveforms increased as the seeker was heated, and the heated seeker waveform shapes were stable after the initial transient, as expected from optical scan modulation. Unfortunately, the seeker failed before additional tests could be conducted to investigate the cause and character of the modulation.

Laser-Heating Tests

One explanation for the larger-than-expected optical scan modulation during the aerothermal tests was additional radiance contributions from heated seeker internal components near the optical path. The seeker optical baffles, in particular, were prime suspects as sources of additional optical scan modulation. The baffles lie at the periphery of the optical rays and are made of thin, blackened metal. Hence, they have a low heat capacity and a high emissivity. We investigated this possibility by heating the seeker dome and internal components (separately) with lasers while collecting seeker telemetry data.

Figure 4 shows the test configuration. Two lasers were used: a visible-wavelength argon laser to heat the seeker internal components and a long-wavelength CO_2 laser to heat the seeker dome (and the interior via heat transfer). A mid-IR video camera and a mid-IR pyrometer were aligned to monitor the temperatures of the seeker internal components during the tests; a long-wave pyrometer monitored the dome temperature.

During the first test series, the argon laser was aligned to heat three internal components of the seeker that limit the optical field of view: the primary mirror baffle (edge guard), the secondary mirror baffle (sunshade), and the center conical baffle. Heating of any of these components during flight will add scan modulation to the detector waveforms. The test protocol consisted of heating the target internal component to a steady-state temperature, collecting data, turning the laser off, and collecting data while the component cooled. The data collected included component temperature, raw detector waveforms, and seeker performance data. The test was repeated for various seeker gimbal angles.

Waveforms collected during the argon tests showed that radiance from even moderately heated internal components significantly increased scan modulation. This modulation was stable, i.e., the optical scan modulation signal was

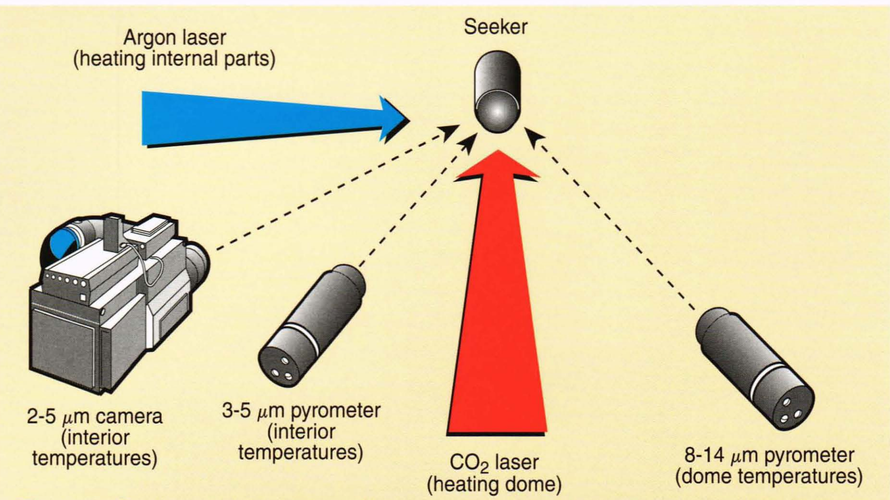

Figure 4. Configuration for the laser-heating tests to characterize the contribution of heated seeker components to optical scan modulation. Argon and CO_2 lasers heat the seeker internal components and the seeker dome, respectively. Moderate direct heating of internal components significantly increases scan modulation, whether the components are heated directly by the argon laser or indirectly by transference from the heated dome.

proportional to the change in in-band radiance above ambient.

In the second test series, the CO_2 laser was aligned to uniformly heat the seeker dome, which then transferred heat to the internal components. (The dome is opaque and almost a perfect absorber at the CO_2 laser wavelength.) We used the same test procedure for the dome-heating tests as in the argon tests, collecting temperature and telemetry data for various gimbal angles and seeker configurations. Figure 5 shows an IR photograph of the seeker in the 3- to 5-μm region during cooling. The colors indicate apparent temperature. The seeker dome, indicated by purple, appears relatively cool because it is nearly transparent in this spectral region. The sunshade at the top of the seeker is the hottest component, as indicated by its bright gold color. During this test, the sunshade and dome temperatures reached 250°F and 300°F, respectively.

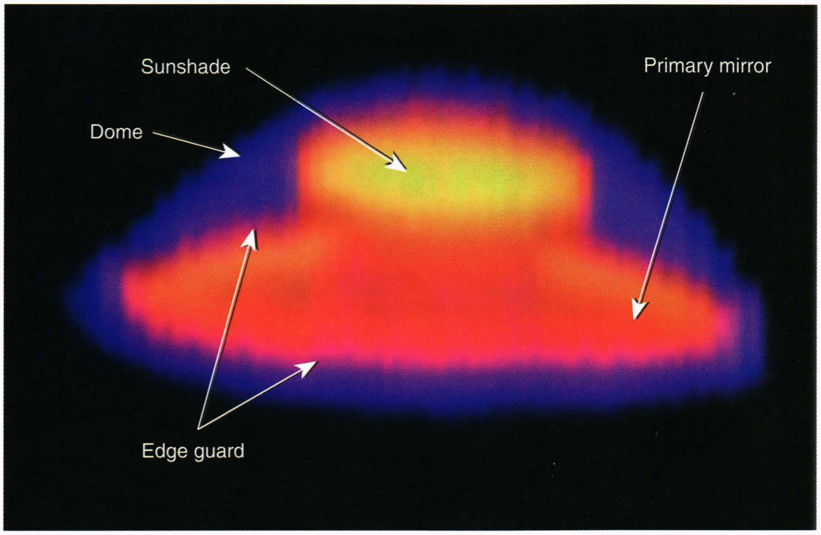

Figure 5. An IR picture of the seeker during cooling after CO_2 laser heating indicates the temperature of the components. The seeker dome (purple), which is nearly transparent in this spectral region, reached 300°F, while the sunshade (bright gold) reached 250°F.

THE IMPROVED SCAN MODULATION MODEL

On the basis of these results, we developed a new scan modulation model to account for the heating of the seeker components. Figure 6 compares the scan modulation for a heated seeker measured in the laboratory, the scan modulation of the individually measured components, and the total scan modulation of the seeker predicted by the model. The black curve represents the measured results from a detector subjected to the CO_2 laser-heating tests. The optical modulation is about 400 counts peak to peak (counts are a measure of scene radiance). The modulation caused by the heated sunshade alone (cyan curve) closely matches the total heated seeker measured modulation, indicating that the sunshade contributed the dominant modulation component in the laboratory tests. Also shown in the figure are the modulation effects due to the heated edge guard, the uniformly heated dome, and the look-angle, which are very small compared with the sunshade contribution. The additive effects of all the modeled individual modulation components (magenta curve) closely match the total measured seeker modulation.

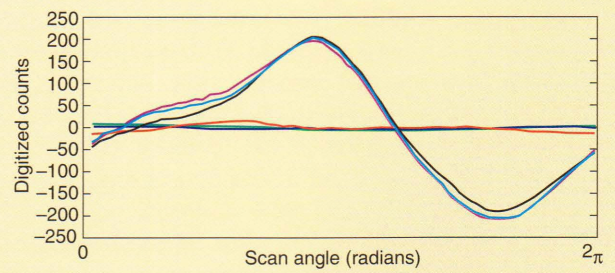

Figure 6. Scan modulation measured on a heated seeker in the laboratory agrees well with the cumulative scan modulation of the individually measured components and the model based on these data. The waveform for the heated sunshade (cyan) is similar in amplitude and shape to the waveform for the total measured heated seeker (black), indicating that the sunshade is the largest contributor to the optical scan modulation. In contrast, the contributions of the heated edge guard (red), the dome (dark blue), and the look-angle (green) are very small. The model output (magenta) closely matches the total measured heated seeker modulation.

The laser-heating tests showed that the dome transfers heat to the internal components and that the scan modulation increases as these components heat. However, since the aerothermal tests (corresponding to flight conditions) heated the dome to 300°F in seconds whereas the laser tests required several minutes, it is still unclear whether the internal components heat significantly in the brief exposure time in the wind tunnel or in flight. Recent APRL tests of a seeker instrumented with thermocouples showed that the sunshade temperature increased quickly during simulated flight conditions. Figure 7 shows measured dome and sunshade temperatures as a function of exposure time during the test. In this example, the sunshade heating time constant was 9.5 s. The increase in sunshade and dome temperatures would decrease the system performance during the flight. (Note that in flight, the dome is also a significant contributor to scan modulation because its temperature is much greater than that of the sunshade.)

As scan modulation increases, the seeker's ability to detect targets (i.e., its performance) decreases. The sensitivity of the seeker to targets is expressed as the minimum detectable irradiance (MDI), the target radiance required for detection. Thus, the seeker performance decreases and the MDI increases as aerothermal

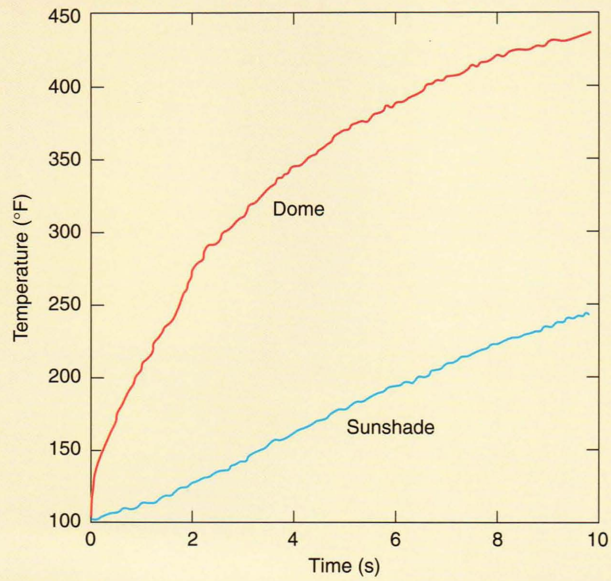

Figure 7. Instrumented seeker testing at the Avery Propulsion Research Laboratory under simulated flight conditions confirms that the sunshade and dome can reach high enough temperatures to decrease seeker performance (e.g., cause scan modulation), even over the very short times expected in actual flight. Also, unlike the results for the laser-heating tests, the dome becomes hot enough in flight to significantly contrbute to scan modulation.

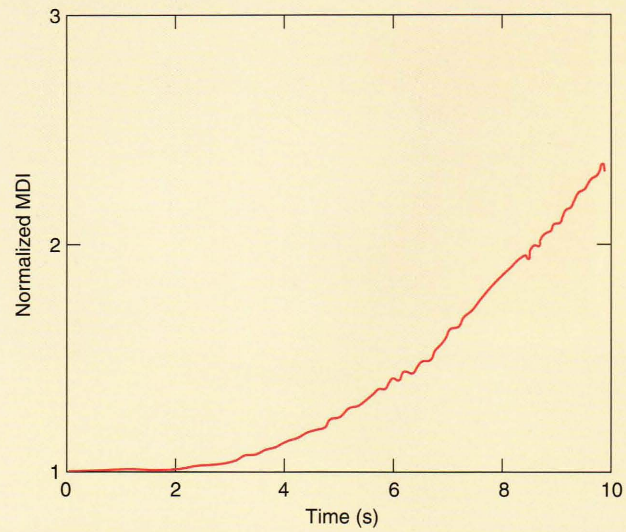

Figure 8. Modeled seeker performance as a function of aerothermal exposure time. As the seeker performance decreases owing to heating, its minimum detectable irradiance (MDI) increases, i.e., its sensitivity declines. For the modeled conditions, seeker sensitivity falls by a factor of 1.3 after 6 s.

exposure increases. Figure 8 shows the predicted seeker detection performance as a function of exposure time (performance is in normalized units), from the APRL temperature results and the modulation models in the simulation. Under the specified flight conditions, the seeker sensitivity degrades by a factor of 1.3 after a 6-s exposure.

CONCLUSION

Laboratory hot-dome experiments and wind tunnel and laser-heating tests provide valid data for formulating models of magnetic and optical scan modulation in seeker waveforms. A seeker simulation incorporating these models accurately predicted the performance of an IR seeker under flight conditions. Further laser-heating tests are planned to refine the data on the heating rates of several internal components contributing to optical scan modulation.

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