Simulation of a fast framing staring sensor

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ABSTRACT

A sensor system simulation has been developed which aids in the evaluation of a proposed fast framing staring sensor as it will perform in its operational environment. Beginning with a high resolution input image, a sequence of frames at the target sensor resolution are produced using the assumed platform motion and the contribution of various noise sources as input data. The resulting frame sequence can then be used to help define system requirements, to aid algorithm development, and to predict system performance. In order to assess the performance of a sensor system, the radiance measured by the system is modeled using a variety of scenarios. For performance prediction, the modeling effort is directed toward providing the ability to determine the minimum Noise Equivalent Target (NET) intensities for each band of the sensor system. The NET is calculated at the entrance pupil of the instrument in such a way that the results can be applied to a variety of point source targets and collection conditions. The intent is to facilitate further study within the user community as new mission areas and/or targets of interest develop that are not addressed explicitly during sensor conceptual design.

Keywords: simulation, modeling, noise equivalent target, sensor performance, clutter, jitter, staring sensors

1. INTRODUCTION

Significant work has been performed in the field of staring sensor simulation and performance determination^{1,2,3}. This paper describes a high fidelity, time-domain method of sensor simulation with application to performance prediction. In general, simulation of any type begins with the identification of the dominant simulation inputs and the development of models for each of the primary system components. Understanding the relationship of these input parameters to the system components allows the development of reasonable and accurate models. A number of system specific parameters must be considered for high fidelity modeling of a staring sensor system. A typical sensor consists of an optical system, a mosaic focal plane array and associated electronics. For this modeling effort, the specific parameters such as focal plane array size, aperture, and IFOV are left variable so that various trades studies can be performed. Reasonable values for these parameters have been chosen for the examples in this paper. While the detection algorithms used have a great impact on the performance of the system, this simulation attempts to separate the performance metric from the particular algorithm used for target detection.

One dominant parameter that profoundly affects a sensor's behavior is the scene background. Earth staring sensors will see a background that can be very bright compared to the targets of interest for the sensor. In addition, line of sight (LOS) sensor motion (due to platform motion such as orbital motion and spacecraft jitter in the case of satellite systems) can cause high spatial gradients in the earth scene to move across pixel boundaries on the detector causing changes in radiant intensity as measured by a pixel. Thus, elements of the background scene can compete with targets for detection, especially when modulated by LOS motion. This characteristic of the background (sometimes called "clutter") impacts sensor performance and drives the development of algorithms that are insensitive to background effects. A variety of background features that can affect performance can be found in any earth scene, and are discussed in section 2. For this simulation, a variety of widely differing scenes are chosen in order to determine the resulting sensor behavior. The mechanics of the simulation start by convolving the high resolution input scene with the optical point spread function of the system. Then a sequence of scene to focal plane transformation matrices are calculated using the sensor system's predicted orbital motion and residual line-of-sight jitter, along with other system parameters. These transformation matrices are applied to the input scene, simulating the scaling, shifting, and rotation that would occur frame to frame as the sensor moves. Each resulting frame is decimated to the resolution of the system being analyzed. Target radiance and sensor noise is added to each frame, resulting in a sequence of synthetic frames that simulate the output of the sensor.

The resulting sequence of frames can then be used to help define system requirements, both for the space segment and the ground segment (e.g., a clutter analysis for determining the requirements for a pointing control system, and a compression analysis to help define the ground station throughput requirements). In addition, the frame sequence can be used for target detection algorithm development and testing, as well as end-to-end ground station simulation. Another important use for

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the synthetic frames of data is to predict the system performance. Use of the simulation to determine the system performance in terms of the NET is discussed in the last section. The simulation of synthetic data allows the analyst to predict the sensitivity of the system including saturation point and minimum detectability.

2. SIMULATION INPUTS

Before a system can be modeled, the dominant factors that affect the system must be identified. The attributes described below enumerate these contributors.

Earth Background: The earth background provides a radiometric description of the scene being observed. Examples range from high-contrast backgrounds, such as sea/cloud or sea/land interfaces, to low contrast scenes, such as sandy deserts or open ocean. The spatial statistics of the scene have a direct impact on some components of system noise.

For systems that include bands in which the atmospheric transmission is high, the earth background can have a profound effect on the system performance, particularly when line of sight jitter is considered. Backgrounds in these bands can exhibit high contrast and therefore large spatial intensity gradients. In order to capture the desired background characteristics, earth scenes must be modeled in detail.

Scene illumination: Scene illumination is used to describe background lighting conditions. Point source targets which occur above a brightly lit background are much more difficult to detect than targets which occur at night. This fact is determined by three major contributors. First, brighter backgrounds cause more photons to impinge on the detector, which in turn causes higher levels of shot noise. Second, if the background is bright enough, the detector integration time may need to be reduced in order to avoid well saturation, resulting in less sensitivity. Finally, day-lit scenes have higher contrast in many bands than do the corresponding scenes at night. The higher contrast levels result in higher levels of LOS-induced noise (which is described later in this document).

Atmospheric effect: The atmosphere will cause wide variations in the operational effectiveness of the system. Aerosol content and clouds, are major factors affecting atmospheric transmission. This is primarily due to water vapor, but is also affected by dust, pollution, and other particulates.

Look Angle: The look angle, described here as the angle which is formed by the intersection of the scene surface normal and the vector which points from the target to the sensor, determines the amount of atmosphere in the line of sight. Large look angles can result in severe atmospheric attenuation, which significantly affects collected target radiance.

Orbital Position and Tracking: The orbit of a satellite affects target detection in two ways; the amount of collected target energy and the effect of LOS motion. For example, for low orbits more target energy is collected, raising the signal to noise ratio. In this example, orbital motion has a greater effect, but the effect of LOS jitter is mitigated.

LOS-induced Noise: LOS-induced noise ("clutter") results from the effect of platform motion with respect to a static input scene. Small changes in the vehicle attitude modulate the intensity of pixels that are illuminated by portions of the input scene that have non-zero spatial gradients. In general, increases in motion or greater spatial gradients produce higher noise levels. The temporal spectrum of the noise is driven by both scene statistics and the spectrum of the attitude disturbances.

LOS-induced noise can be divided into two classes: deterministic LOS-induced noise and stochastic LOS-induced noise. In general, the deterministic component of LOS-induced noise contributes low-frequency noise (or "pixel drift"), while the stochastic component contributes noise that is broadband and is dependent on the spectrum of the attitude disturbance.

Deterministic LOS-induced Noise: The deterministic LOS-induced noise is produced from the pixel intensity modulation that results from the slowly changing orbit position. As the platform moves through its orbit, its orientation with respect to the target or Point Of Interest (POI) changes. For an ideal system that stares perfectly at the POI (the center pixel of the focal plane array (FPA) is maintained exactly on the center of the POI), the effects of deterministic LOS-induced noise are primarily manifested as rotation and scaling changes of the image on the FPA. Of the two effects, rotation is typically the dominant contributor, and pixels towards the edge of the scene are affected more than pixels towards the center of the scene.

The noise which occurs from this orbital motion is typically manifested as slow changes in each pixel's amplitude. These slow changes have a minor effect on target detection (for algorithms which have been optimized to detect targets with moderate to high rates of intensity change). However, they can have a significant impact on the shape of an extracted target intensity history, and consequently target discrimination or characterization.

Stochastic LOS-induced Noise: The stochastic portion of the LOS-induced noise can have a direct impact on target detection if the platform LOS attitude jitter spectrum contains high frequency components. This high frequency jitter induces high frequency amplitude fluctuations on pixels which occur on background gradients. These fluctuations directly compete with target signatures and can cause false alarms or missed events.

Because the effect of LOS induced noise on target detection is directly related to the spectral content of the LOS jitter, having accurately modeled spacecraft attitude data is crucial to assessing the effect of this disturbance on detection. In cases where the spectrum of the attitude motion is predominately low frequency, the magnitude of the NET for LOS induced jitter noise is a function of the observation duration. Longer durations consider more of the low frequency energy in the attitude spectrum and produce higher NET values. Since selection of an appropriate analysis duration is application specific, NET values for LOS-induced jitter are also application specific and are related to the algorithm chosen.

Because not all pixels have the same LOS-induced noise level due to spatially varying scene gradients, a metric must be defined. To determine the LOS-induced noise level, a sequence of frames is produced at the selected output frame rate. From these, a vector of temporal standard deviations is calculated, containing one value for each pixel in the sequence. For studies where detectability of point source targets is of interest, pixels that exhibit high LOS-induced noise levels will limit the system's level of performance, since they determine the minimum detection threshold (for a given false alarm rate). Consequently, a histogram of the pixel standard deviations is computed, and the value of the 90th percentile is used here as the LOS-induced noise metric.

Optical Efficiency: As optical energy travels down the optical path, it passes through a number of elements. Each of these optical elements has an associated transmission efficiency, which is in general wavelength dependent and can be lumped with the filter spectral response.

Point Spread Function (PSF) Effects: The blurring due to system optics has two primary effects. First, blurring the image has the effect of "smoothing" out spatial gradients in the scene, which can significantly reduce the magnitude of LOS-induced jitter noise. Second, it has the effect of "smearing" the energy from a point source target across multiple pixels, effectively reducing the signal to noise ratio of each pixel. The effect is minimized when the target is perfectly centered on a pixel, and is worse when the target falls on the corner of a pixel.

Sensor Noise: All other major noise sources (photon noise, shot noise, detector and electronic noise)⁴ have been lumped into a single noise specification called sensor noise. Shot noise results from the generation of electrons in the detector which are due to incident photons from background radiance and the self-emission of the optical system and its enclosure. The magnitude of this noise is a function of the square root of the number of electrons which result from each source (which is related to the quantum efficiency of the detector). The self-emission sources manifest themselves as both a spatially varying offset and a random distribution. While both the offset and AC components of these noise sources are modeled, the offset component is not considered in the NET calculations, since it has little effect on target detection.

Detector and electronic noise results from quantum noise inherent in the semiconductor material and readout noise, which is produced by electronics that convert charge into voltage.

3. OVERVIEW OF SIMULATION MECHANICS

The diagram shown in Figure 1 provides an overview of the sensor simulation. The simulation accepts a number of inputs and produces a sequence of output frames that accurately model the sensor output.

The simulation process can be broken into two major areas: motion modeling and noise addition. Motion modeling is required to capture the effects of sensor motion with respect to the target or scene. During target viewing the sensor is normally pointed and staring at a particular POI. However due to proper vehicle motion, random vehicle motion, and earth rotational effects, the attitude vectors are a function of time. The second major area, noise addition, is required to model the effects of sensor noise. A brief overview of each of these areas is now presented.

3.1 Motion Modeling

The primary input to the motion modeling process is a high spatial resolution scene that has been modeled by the Synthetic Scene Generation Model (SSGM). The SSGM is a widely used modeling tool developed by the Naval Research Lab, originally for use by the SDIO. It consists of a variety of models developed by the defense community at large, including

Figure 1 Simulation flow diagram

computer software and input databases which provide the capability to generate two dimensional scenes and data in chosen wavebands. The scenes and data thus generated are intended for the use in design, development, and test of surveillance and weapon systems, and for engagement simulations. Scenes include terrain, clouds, horizon, earth limb, and aurora, as well as various military targets of interest. Using specified passbands for the optical filter, the apparent radiance of the scene at the focal plane can be modeled. The SSGM terrain model begins with a set of imagery and a data base describing the pixel content for every pixel in each image (e.g., 20% broad leaf forest, 10% asphalt, etc.). Then, using a data base which describes the spectral characteristics of each material type, SSGM calculates the radiance for every pixel in the scene in the chosen waveband using the specified sun-earth-observer geometry. The scene radiance is then propagated through the atmosphere and clouds to the observer altitude at the specified spatial resolution.

An example of typical SSGM modeled scenes are shown in Figures 2 and 3. The average radiance of the two scenes roughly correspond to a 0.4 albedo earth. High contrast areas producing high spatial frequencies are more stressing for target detection because low frequency sensor motion (e.g. orbital motion, tracking) and high frequency sensor motion (i.e. uncompensated line-of-sight jitter) can cause the high contrast areas to move across pixel boundaries, modulating the radiance on the detector. Thus, elements of the scene itself compete with targets for detection. Because of this, the derived statistics of high contrast areas as well as the mean radiance and correlation length of the scene are of concern.

The motion modeling process hinges on the requirement that the spatial resolution of the input scene be higher than that of the simulated output frames. A increase in spatial resolution by at least a factor of 5 was used for a recent study at Sandia National Labs. In general, the minimum required factor is a function of a number of parameters including the viewing geometry, optical system attributes and required fidelity. In practice, the required factor can be determined empirically by raising the input scene resolution and observing the statistics of the output frames.

To model blurring by the optical system, the high resolution input scene is numerically convolved with the PSF for the optical system. A wavelength-dependent PSF is created which considers both the diffraction limited PSF and a PSF which accounts for geometric aberrations in the optical system. The PSF is sampled at the same resolution as the input scene, and is normalized to provide unity gain. The blur kernel is also used to determine the amount of energy from a point-source target which falls on a single pixel of the FPA. For a point source target which is perfectly centered on a pixel in the FPA, the PSF causes a spreading of the target's energy which causes some percentage of the energy to fall on neighboring pixels. This effect reduces the target signal on a pixel, and is accounted for in the NET analysis. It should also be noted that the apparent PSF size can be increased by high frequency LOS jitter occurring during temporal integration. This effect has been modeled by synthesizing frames at a high frame rate and then down-sampling to the desired rate by summing frames.

Figure 2: Lakebed in Iran

Figure 3: Port Scene in North Korea

If targets are required in the simulation, they can be modeled using the system PSF and inserted into the input scene, or modeled in the original SSGM simulation. When the modeled targets are above the atmosphere or when the atmosphere can be modeled as an attenuation of the target energy, the former technique is applied because it can be much more computationally efficient, especially in the case of moving targets.

Simulated or actual attitude data must be obtained in order to model the effects of LOS motion. If a LOS stabilization system is implemented, the attitude data can be processed by a model of the stabilization system to determine the residual attitude motion. With this approach, trade studies can be performed to assess the requirements for the stabilization system.

A series of calculations is required that takes as input orbital data (ephemeris), the residual LOS jitter, and sensor specifications (e.g., FOV), to produce a sequence of time-varying transformation matrices. The time-varying transformation matrix contains information to map points in the input scene to pixels on the detector array. It considers the effects of the optical system (i.e., scaling and rotation), and viewing effects (i.e., shear, rotation, scaling and translation).

The sequence of transformation matrices is input to a motion modeling engine that performs the actual mapping⁵ and spatial integration required for each output pixel. To perform the spatial integrations as accurately as possible, the code considers not only whole pixels but also the fractional parts of input pixels that contribute energy to any given output pixel.

The output of the motion modeling process is a sequence of frames that consider all of the LOS motion effects but none of the other sensor noise sources. For LOS-induced noise studies, the statistics derived from this sequence may be sufficient. For a more comprehensive data sequence further modeling is applied.

3.2 Sensor Noise Modeling

In order to comprehensively model the system output data, sensor noises must be added (as defined in section 2). Models for the focal planes, on-board emission sources, and background are used to quantify the magnitude of each of these noise sources. Each of the noise sources is modeled as white gaussian noise (spatially and temporally), and the noise is added numerically to the motion model output. This noise model, while accurate in the magnitude sense, is simplistic in the spectral sense. Of course, the level of detail required for noise modeling is application dependent.

Other simplifications have been made in the noise modeling. No fixed pattern noise is included in the simulation. While the modeling and addition of this noise is trivial, it is intrinsically DC in nature and for many applications has little effect. Also, noise which results from self emission of the optical system and its enclosure is temperature dependent, and nominal temperatures are used as determined by system thermal studies.

4. PERFORMANCE DETERMINATION METHODOLOGY

To predict the performance of the system, a large parameter space must be explored. The parameter space considered includes the background scene, atmospheric variations, look angle and the resulting atmospheric path length, orbital position, illumination (day/night), cloud coverage, platform motion, LOS jitter, optical PSF, optical efficiency, quantum efficiency of the FPA, sensor gain, sensor and optics noise and frame rate.

In most cases it is not practical to perform an exhaustive parametric study. Rather, a nominal scenario which embodies the notion of typical system operation under expected conditions can be considered. A nominal value can be chosen for each parameter and, if reasonable, a more optimistic as well as a more stressing value can be considered. To evaluate the effect of each parameter, its variations are examined while the other parameters are held constant at the nominal value. This approach allows the parameter space to be explored efficiently and produces data in a way that can be presented in a natural and intuitive manner. The results produced by this kind of study can be considered representative of system performance. Moreover, implementing this methodology provides insight into the system parameters that most profoundly affect system performance.

5. APPLICATION OF SIMULATED DATA TO SENSOR PERFORMANCE PREDICTION

A primary use of the simulation is to quantify the effect that each of the parameters discussed in section 2 has on system performance. For each parameter, a value is chosen which is considered to be nominal; the chosen value is intended to represent the most typical mode of operation. In addition, one or more additional values are chosen for each parameter. In some cases these additional values are chosen to represent an extreme condition or an opposite condition (e.g., Day/Night).

The metric used for performance determination is the NET, which is defined as the apparent target intensity that is required to produce a signal at the FPA that is equivalent to the system rms noise level for the particular conditions. The NET metric, which has units of W/sr (in-band), is comprehensive in that it considers all elements that affect target energy reaching the detector. Attributes such as atmospheric attenuation, pixel footprint size, system optical efficiency, and optical blurring are considered in the calculation of NET.

The NET metric is particularly intuitive because it allows direct comparison of the system noise to target intensities. While it is tempting to make the simplifying assumption that any target which exceeds the NET is *detectable*, this statement is a great oversimplification. Ultimately, target detection is intimately coupled to the actual detection algorithm used and the nature of the noise sources involved.

For the application of determining sensor performance, the NET metric must be determined. The diagram shown in Figure 4 illustrates this idea. Various scaling factors are used throughout the diagram to convert to common units or to account for other scaling factors. The $1/\sqrt{N}$ term is used to model the noise reduction achieved by frame summing, where N is the number of input frames that produce a single output frame. Once all of the noise sources are converted to common units, a single output NET is produced by adding the individual noise powers.

Figure 4 Flow diagram for sensor noise modeling.

As described above, each scenario produces an NET value. The data shown in Figure 5 represent one method of displaying NET values for the scene background parameter. As previously described, all other parameters are held constant and the sequence of frames are produced for each scene background under study. The plot illustrates that some bands exhibit a higher sensitivity to background type than do others. This can be caused by the spectral content of the scenes or by the

Figure 5: Effect of scene background parameter on NET

atmospheric transmission within the band.

As another example, the data shown in Figure 6 illustrate a way of presenting the relative magnitudes of the various noise sources for a particular scenario. For each band, the first bar represents the equivalent NET value for the least significant bit of the A/D converter. The following four bars correspond to the noise contribution of the background, optical system emission, detector noise, and LOS induced noise, respectively. The last bar represents the total NET for the particular band.

Figure 6: Noise source contribution to NET

6. SUMMARY

This paper describes the high-fidelity simulation of data for a fast-framing staring sensor. The primary input parameters that affect the simulation process are enumerated and described. A high level description of the mechanics of the modeling process is presented, with special emphasis on the motion modeling aspect of the problem. The output of the simulation is a sequence of frames that accurately depicts the sensor output. These frames can be used for a number of applications including performance assessment, system requirement determination, and detector algorithm development.

In addition, a methodology for applying the simulation to the prediction of sensor performance (as defined by the NET metric) is presented. This approach attempts to make tractable the large parameter space that must be investigated for a typical performance analysis. Finally, a few suggested methods of presenting the data in a concise and intuitive manner are given.

This simulation work focussed on the aspects of the modeling process that were most germane to the application at hand. To make the work more generally applicable, the simulation could be enhanced in several ways. Among these enhancements is the incorporation of a more realistic sensor noise model. In addition, a more flexible method of adding targets is currently being investigated.

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