Model-based Exploration of HSI Spaceborne Sensor Requirements with Application Performance as the Metric

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Abstract—**As an aid to the requirements analysis of future spaceborne hyperspectral imaging systems, an example study is presented which uses an analytical performance prediction model to study application performance as a function of system parameters. In particular, the Forecasting and Analysis of Spectroradiometric System Performance (FASSP) model is used to refine requirements for spatial resolution, spectral resolution, and aperture size in an unresolved road detection application. Results show roads as small as 5 meters could be detected with a system having 5 meter ground resolution, 10 nm spectral resolution, and a 0.25 meter aperture operating from 450 km altitude.**

Keywords-spectral imaging system modeling, spaceborne hyperspectral, target detection, classification

I. Introduction

Enabled by advances in detector focal plane array technology the extension of multispectral imaging to the hyperspectral realm has led to improved capabilities for passive optical earth remote sensing. The characteristics of high spectral ($\lambda/\Delta\lambda$ ~ 100) and high spatial (order of meters) resolution that define hyperspectral imagers have led to demonstrations of improved land cover classification, atmospheric characterization, unresolved object detection and geologic mineral identification. While the majority of hyperspectral data collected and analyzed have been from airborne platforms, the Hyperion instrument on NASA's EO-1 satellite has demonstrated the advantages of hyperspectral sensing from space. The remote sensing community looks forward to the eventual operational availability of spaceborne hyperspectral imagery for land and coastal earth science applications similar to the multitude of uses of data collected by the venerable U.S. Landsat program.

With the successful demonstration of Hyperion proving the readiness of spaceborne hyperspectral technology, a limiting factor in the deployment of an operational hyperspectral imager has been the cost of the system. While instrument costs are certainly an important part of the overall system cost, the launch costs are perhaps the most significant portion and they can be nearly directly tied to the weight of the instrument. Rules of thumb couple the weight of the instrument to the size of aperture raised to a power around 2.5, making the aperture size a driving system parameter in determining the overall cost.

The size of the optical aperture limits sensor performance in two general ways. First, it defines the maximum achievable spatial resolution through the wavelength-dependent diffraction criteria. Second, it determines the total photon flux collected and ultimately the achievable radiometric resolution, or signal-to-noise ratio (SNR). The required spatial resolution, SNR and the spectral resolution (coupled together with other parameters) generally are specified early in the sensor design process and lead to a minimum size aperture and resulting system cost.

Traditionally, the hardware requirements are finalized through an iterative design process between the initial science requirements and achievable system metrics (resolution, SNR) of a given design. The science requirements are usually specified based on performance of airborne systems and user experience looking at the quality of products achieved with various instrument designs. This loose coupling between hardware performance and application product quality limits the ability of the design team to optimize the design for lowest cost, but maximum performance.

As an aid to this design process, the Forecasting and Analysis of Spectroradiometric System Performance (FASSP) model was originally developed at MIT Lincoln Laboratory to help provide, among other uses, a unified model for studying the tradeoff in application performance with sensor hardware specifications for a given analysis task [1]. FASSP models the full remote sensing process as a system including the scene, the sensor and processing algorithms. It propagates statistical descriptions of land surface classes through the atmosphere, the sensor, and analysis algorithms and predicts a metric of performance for a given application such as classification accuracy or probability of detection at a specified false alarm rate.

In this paper we explore the use of the FASSP analysis model to refine and optimize the primary hardware specifications of a spaceborne hyperspectral instrument in the context of a specific remote sensing analysis task.

II. Analytical End-to-End System Model

The analytical end-to-end performance prediction tool FASSP has been developed in support of hyperspectral imaging system design and analysis studies. Through the use of statistical descriptions for the target and background, and linear transformations to model the effects of the observing system and processing, the performance can be predicted analytically, rather than through a physics-based simulation. This approach runs very quickly and can efficiently support large numbers of trade studies.

The underlying premises of the FASSP model are 1) that the various surface classes and subclasses of interest can be represented by first- and second-order spectral statistics (and other parameters) and 2) that the effects of various processes in the end-to-end spectral imaging system can be modeled as transformations and functions of those statistics and parameters. The model propagates the spectral statistics through the effects of the atmosphere, the sensor, atmospheric compensation, feature extraction techniques, and then applies a detection algorithm to convert the high dimensional statistics to a scalar test statistic (matched filter output) to which a threshold can be applied and detection performance computed.

One application of the model is unresolved, or subpixel, target detection scenarios. Here the linear mixing model is used and the pixel of interest containing the target is assumed to be a sample from random process described by the area-weighted mixture of the target and the background classes. The rest of the analytically-described scene (no simulated "image" is generated by the model) is comprised of a number of homogeneous background classes, each covering an area percentage of the scene. The scene false alarm rate at a given threshold is then computed as the area-weighted total of false alarms from each individual background class.

III. REQUIREMENTS ANALYSIS

The following sections describe a process to use the FASSP model in refining and justifying top-level spaceborne hyperspectral sensor system parameters.

A. *System Constraints and Assumptions*

We began our example by selecting a candidate focal plane array. The analysis has to start somewhere, and this is a reasonable starting point since it will base the analysis on available technology. For this study, we selected an extended InGaAs FPA with characteristics similar to that described in a recent paper [2]. It is a single 320 x 256 pixel array with spectral response from 400 to 1700 nm.

With this focal plane, we analyzed a pushbroom hyperspectral system with a dispersive spectrometer. We selected the FPA axis with 256 pixels for the spectral direction and 320 for the spatial direction. We also assumed a platform velocity of 7 km/sec and set the integration time per pixel to equal the ground resolution divided by this velocity. This turns out to require a faster readout speed than the reference array could handle, but this could be handled through adjusting the spacecraft pointing, or by improving the design, so this minor inconsistency was ignored in the subsequent analysis.

Since we did not perform detailed optical or electrical designs, we have assumed shot-noise limited performance for all cases considered. While this may be a bit unrealistic for the low signal cases (narrow bandwidth, small IFOV and small aperture) it nonetheless provides a baseline for the analysis.

B. *Trade Space Considered*

We considered designs with spectral resolutions of 5, 10, 20, and 40 nm, corresponding to one, two, four, and eight FPA pixels per spectral sample. We considered sensor instantaneous fields-of-view that lead to 5, 10 or 20 meter ground resolution from a nominal 450 km altitude. We also considered optical apertures 0.125, 0.25, 0.5, and 1.0 meters. (We also ignore the minor problem that 5 meter ground resolution is just beyond the diffraction limited resolution of a 0.125 m aperture at 450 km altitude for $\lambda = 1700$ nm.)

C. *Analysis Scenario*

Table I presents the parameters used in the model analyses. It corresponds to a task of detecting sub-pixel gravel roads in a forest-type background. This application can be of interest in both civilian and military situations by helping map road networks in undeveloped areas. Fig. 1 shows the mean spectral reflectance for the gravel road and the five background classes.

TABLE I. SCENARIO PARAMETERS

Parameter	Value(s)
Target	Gravel road
Backgrounds	30% Trees, 20% grass 1, 20% grass 2, 20% grass 3, 10% bushes
Visibility	23 km with rural aerosol model
Solar zenith angle	30°
Atmospheric model	Summer mid-latitude
Sensor altitude	450 km
Sensor	Dispersive pushbroom
Atmospheric compensation	Physics-based code
Detection algorithm	Spectral matched filter

One assumption listed in this scenario is the use of a physics-based atmospheric code to convert the measured data to surface reflectance for comparison with the gravel road library spectrum. Since these codes rely on resolving atmospheric water vapor absorption lines, their accuracy will vary with the spectral resolution. Previous work has shown these codes to have an approximate error of 1% for 10 nm typical bandwidths [3]. While it is unclear how this error may vary with sensor spectral resolution, reasonable estimates of its magnitude were made based on experience. This varying amount of additional error was added to the instrument photon noise before computing detection performance. Table II shows the amounts assumed for this error as well as the spectral regions and channels used for the varying bandwidth cases.

TABLE II. SPECTRAL BANDWIDTH CASE PARAMETERS

Parameter	$\Delta\lambda = 5$ nm	$\Delta\lambda = 10$ nm	$\Delta\lambda = 20$ nm	$\Delta\lambda = 40$ nm
Channels in				
0.45 - 0.89 µm	89	45	23	11
0.97 - 1.07 µm	21	11	6	3
1.17 - 1.31 µm	28	15	8	4
1.50 - 1.65 µm	31	16	8	4
Total # of channels	169	87	45	22
Atmospheric compensation error (% of signal)	0.5%	1.0%	2.0%	5.0%

It is important to note that this additional error due to inaccuracy in the atmospheric compensation may significantly affect the detection probability for the wider spectral bandwidth cases. While this appears to be unfair, it is realistic in object detection scenarios using library spectra.

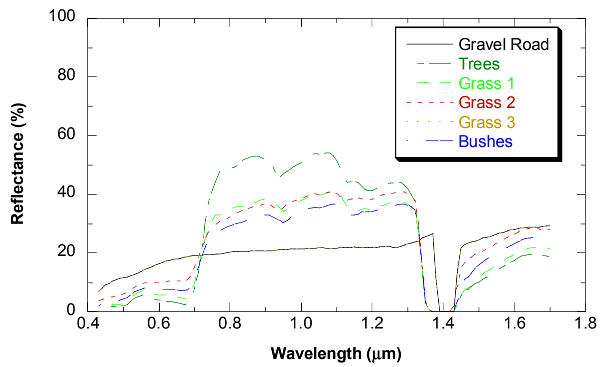

Figure 1. Scene class mean reflectance.

D. Results

The first parameter examined was the signal-to-noise ratio (SNR) for a 20% surface with the sun at 30° zenith angle and a 1976 US Standard Atmosphere. Fig. 2 shows how three main sensor parameters affect the SNR. Recall this analysis assumes no fixed noise and thus the SNR is just the square root of the signal level (in detected electrons).

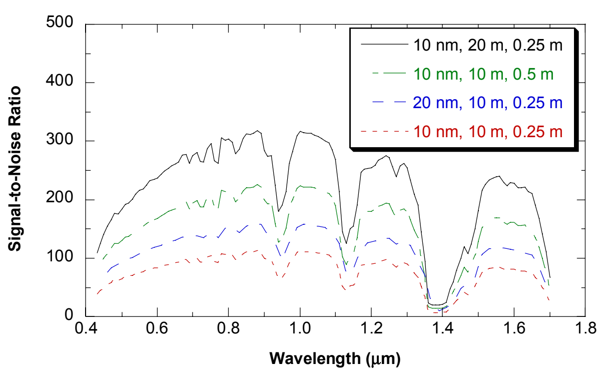

Figure 2. SNR for variou parameter combinations.

The bottom curve shows a base line SNR for the 10 nm bandwidth, 10 meter ground resolution and 0.25 m aperture case. The next curve up shows the effect of doubling the spectral bandwidth which improves the SNR by √2. The second curve from the top shows the effect of doubling the aperture which increases the signal by a factor of four, but also increases the noise by a factor of two, leading to a net doubling of the SNR. The top curve shows the effect of doubling the ground resolution. Note here we also doubled the integration time leading to an improvement in the SNR of 2√2.

Next, the various cases were considered in the subpixel detection scenario outlined earlier. Here, the metric of interest was how small of a fraction of a pixel could the road occupy yet still yield a probability of detection (P_D) ≥ 0.8 at a probability of false alarm (P_{FA}) ≤ 10^{-5}. This subpixel fraction was then converted to a linear width of road that met the P_D / P_{FA} requirement. This was done with the simple relationship:

$$\begin{aligned} &Mimimum\ road\ width\ (m) = \\ &\quad Min.\ pixel\ \ frac. \times Ground\ Resolution\ (m) \times 2 \end{aligned} \tag{1}$$

This relationship assumes the road extends greater than the ground pixel in length and that the conditions are met for the worse case of the road centered across two pixels. Given this definition, and numerous FASSP model runs, the results in Table III are obtained.

TABLE III. MINIMUM DETECTABLE ROAD WIDTH

Ground Resolution (m)	Spectral Bandwidth (nm)	Aperture Diameter (m)	Minimum Detectable Road Width (m)
5	5	0.125 0.250 0.500 1.000	5.6 4.7 3.9 3.4
5	10	0.125 0.250 0.500 1.000	5.6 4.8 4.3 4.1
5	20	0.125 0.250 0.500 1.000	6.0 5.5 5.4 5.4
5	40	0.125 0.250 0.500 1.000	7.8 7.7 7.7 7.7
10	5	0.125 0.250 0.500 1.000	8.6 7.2 6.6 6.4
10	10	0.125 0.250 0.500 1.000	9.0 8.4 8.2 8.2
10	20	0.125 0.250 0.500 1.000	10.8 10.8 10.8 10.8
10	40	0.125 0.250 0.500 1.000	15.4 15.4 15.4 15.4
20	5	0.125 0.250 0.500 1.000	13.6 12.8 12.8 12.8
20	10	0.125 0.250 0.500 1.000	16.2 16.2 16.2 16.2
20	20	0.125 0.250 0.500 1.000	21.6 21.6 21.6 21.6
20	40	0.125 0.250 0.500 1.000	30.8 30.8 30.8 30.8

The first thing to notice in Table III is that the minimum detectable road width changes very little (if at all) with aperture diameter, particularly for the broader spectral resolution cases. This is due to the "handicapping" of spectral resolution from the error modeled in the physics-based atmospheric compensation step. This added error overwhelms any SNR gain due to the larger apertures except for cases which start with low SNR (narrow bandwidth, small ground resolution, and small aperture diameter).

At the narrower spectral bandwidth's, we see a clear trend that the smaller the ground resolution and the larger the aperture, the smaller a road can be detected. In fact, the smallest road detectable at 3.4 m wide is predicted for the 5 m ground resolution case with the largest aperture (1 m) and narrowest spectral bandwidth (5 nm). Again, this may be partially due to the lower atmospheric compensation error modeled for the 5 nm spectral bandwidth case, but this result clearly shows the value of higher SNR.

However, the ability to detect smaller roads comes at the cost of increased weight (and launch costs) for the larger apertures. This is where an analysis like this can help determine if the added capability is worth the cost.

Based on experience and given the tradeoffs in launch costs, data rates and the potential to support other applications, these results support the selection of the following system requirements: 5 m ground resolution, 10 nm spectral bandwidth and a 0.25 m aperture. This supports detection of roads smaller than 5 meters across, but without the high costs associated with a larger aperture or increased data rates with the narrower spectral resolution.

Of course, other sets of parameters may serve the needs of other applications and indeed this approach should be duplicated and results considered across all potential applications of a proposed system. The analysis presented here is meant as an illustrative example of this process, and should not be considered an optimal design point across all applications.

IV. SUMMARY AND DISCUSSION

This paper has presented an analytical modeling approach and results for the selection of top-level requirements for a spaceborne hyperspectral imaging system with application performance as a metric. In particular, the analysis considered the tradeoffs in the ability of the system to detect unresolved (subpixel) roads as a function of spatial resolution, spectral resolution and optical aperture. The design was constrained using an extended-InGaAs focal plane array described in the literature and made a number of simplifying assumptions.

A significant conclusion observed in this analysis is the dominant effect of spatial resolution on the ability to detect small roads. This parameter is much more significant than narrow spectral resolution or signal-to-noise enhancement through larger apertures. Obviously, this type of analysis should be repeated for other applications of interest for a proposed system, but example analysis presented here illustrates a quantifiable approach to justifying the selection of requirements for a variety of top-level system parameters of a spaceborne hyperspectral imaging system using predicted application performance as the metric.

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