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DESIGN AND ANALYSIS APPROACH FOR A RAPID RESPONSE HYPERSPECTRAL IMAGING MISSION

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ABSTRACT

The Air Force has expressed interest in a tactically effective hyperspectral imaging payload for use in a rapid response demonstration program. The goals set for a high quality imaging spectrometer payload includes radiometric performance (sensitivity, saturation range, quantization level, and absolute radiometry accuracy), spectral performance (spectral range, resolution, sampling, and spectral calibration accuracy), spatial performance (image swath width, image length, spatial resolution, ground sample distance, and geolocation accuracy) as well as mission constraints related to payload weight, volume, power, and data rate. Raytheon has developed a number of design tools needed to balance these requirements using real-world hyperspectral detection case studies that relate directly to military tactical effectiveness. These techniques make use of high quality imaging spectrometer data sets from airborne collects to enable evaluation of probability of detection versus probability of false alarm for arbitrary spectral target sets. In this way, reasonable surrogate metrics for tactical military utility may be examined as a function of payload performance requirements in order to perform meaningful cost-as-an-independent-variable (CAIV) analysis.

INTRODUCTION

Recent Responsive Space Missions call for achieving 80% of mission performance for 20% of the cost. Applying this challenge to development of a hyperspectral imaging payload for a responsive space mission demands a more quantitative means to relate cost-performance trades to measures of effectiveness directly related to military utility. This paper presents a simulation strategy that leverages existing high quality airborne data sets and hyperspectral design and simulation tools to meet this challenge.

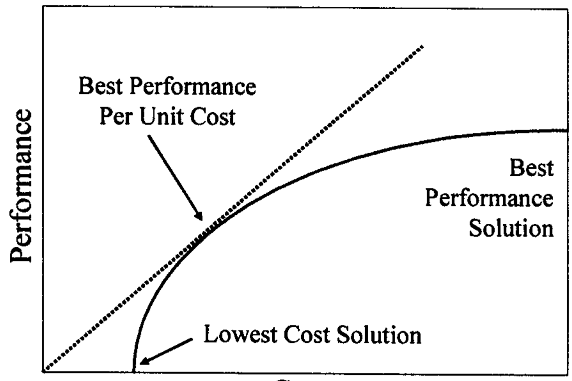

Figure 1. Notional plot of performance versus cost (Adapted from Wertz, 1999)

The notional plot of performance versus cost, shown in Figure 1., is a simple and effective way to illustrate the idea of an optimum point along the curve[1]. Best performance solutions

[1] Wertz, James R., Wiley J. Larson, eds. 1999, Space Mission Analysis and Design, El Segundo CA, Microcosm Press

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are typically not affordable for Responsive Space missions, while lowest cost missions have little military utility. Some where between the two there should exist an optimum point, either in the sense of best performance per unit cost, or in a Pareto sense with a utility near 80% of the best performance solution at 20% of the cost. To find the optimum cost-performance point it is necessary to understand how dimensions of payload performance relate to quantitative measures of military utility, and how costs are estimated for those levels of aggregate performance.

Feasible combinations of payload cost and performance can be obtained from competing payload suppliers or by one of several cost estimating techniques. Analogy-based methods compare the new mission to historical cost data for recent similar missions. Adjustments in cost are made for the relative complexity or performance required by the new payload as compared to the historical examples. Parametric methods also make use of historical data in the form of a multiple regression against cost-driving payload parameters. One challenge with using these methods to estimate cost for a Responsive Space Payload is the lack of suitable historical data. Comparisons to historical data are limited to just a few attributes such as weight, aperture size, and spectral range (visible or infrared). It is difficult to explore meaningful trades in payload performance attributes using analogy-based and parametric-based methods. A bottoms-up detailed cost estimate, likely to be the method used by payload suppliers responding to an RFP, provides good cost insight for a point design solution. The point design may or may not be the desired Pareto solution.

Comparing between different point designs with different sets of performance attributes requires a means to assess aggregate performance as it relates to military utility. The dimensions of performance for a hyperspectral payload apply to the spectral, spatial, and radiometric dimensions of the output data product. For each dimension of the data cube, the performance specifies the range, resolution, sampling, and knowledge accuracy of the resultant data. Any single element in the output data cube exhibits spectral and spatial resolution attributes and the distance between adjacent imaging cube data elements defines the spectral and spatial sampling. The radiometric sampling is defined by the data quantization level, while the Noise Equivalent Spectral Radiance (NESR) defines the radiometric resolution. The outside dimensions of the data cube define the spectral range and spatial range relates to image swath width and down-track image length. Radiometric range is set by the maximum radiance at which the sensor is still below saturation. Calibration performance parameters define the accuracy with which absolution values may be placed on any of the performance dimensions and specifically includes spectral calibration, geolocation accuracy, and radiometric accuracy. Other performance parameters limit non-linearity in response to single performance dimensions and non-orthogonal interactions between performance dimensions, and include temporal slew effects, stray-light, electronic cross-talk, and control of spectral/spatial non-uniformities. Finally, other performance dimensions relate to payload constraints such as weight, volume, power, data rate, and data volume.

The traditional trade study is one way to evaluate overall utility between point designs with differing sets of performance attributes. Ideally, a trade study compares just a few candidate options. Go/no go criteria are established along performance dimensions, and a qualitative weighting is developed for each dimension, and another weighting is developed between dimensions. A second method evaluating overall utility is to form the product of scaled performance dimensions. An example of a scaled dimension is the ratio between the achieved Swath width and a goal or threshold swath width. In a case such NESR, where higher performance comes from a smaller value, the ratio is inverted. Each performance dimension requires a goal or threshold value, and the overall performance metric is the product of the scaled performance dimensions.

While both these techniques are effective for selecting a design option, they depend on qualitative weighting factors and goal performance values with only indirect linkage to mission military utility. Many performance dimensions are highly non-linear in utility. For example, Swayze shows that finer spectral resolution improves overall utility up to the point, and then flattens[2]. Passing this point of optimum spectral resolution may then have an adverse impact on NESR. It is difficult to capture all these subtle effects using trade studies and product of scaled performance metrics. This insight has led Raytheon to develop a more direct means by which to assess complex interactions between performance dimensions in a way that can be directly linked to military utility.

UTILITY ANALYSIS SIMULATION

The spectral radiance that enters a hyperspectral sensor can be decomposed into elements of target and background spectral reflectance, atmospheric radiative transfer processes and solar illumination and viewing geometry. The response to that input radiance results in a raw output signal. The sensor response function may be decomposed into the performance dimensions that are the topic of this discussion. The output signal is calibrated, atmospherically corrected, and then processed by algorithms to produce information potentially useful to a military need. These process steps are depicted in Figure 2. By simulating this chain of events it is possible to form the relationship between the performance dimensions that describe the sensor response function and end measures of military utility.

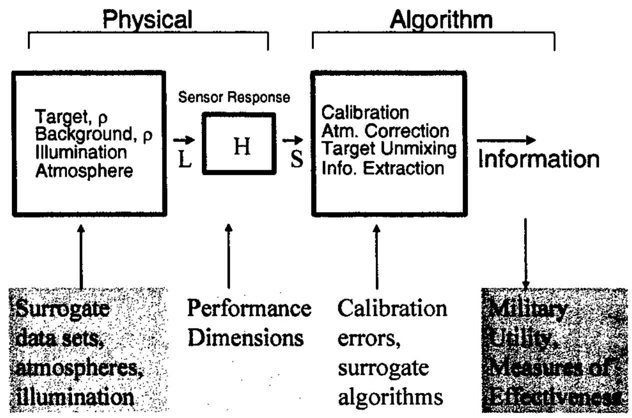

Figure 2. Process steps used to relate sensor performance to military utility

Most of the process steps described above are simulated with available modeling tools. The Modtran code is employed to simulate at-sensor input radiance from input reflectance, viewing and illumination geometries, and atmospheric parameters. Detail sensor response models have been written which simulate the manner by which the sensor degrades the input radiance spectrally and spatially, and adds noise and the effects of pixel-by-pixel variations in gain and offset. Calibration, atmospheric correction and information algorithms exist and are well understood. Metrics of military utility, such as the probability of false alarm given a required probability of detection are also well established.

The new innovation is to form a sequence of these models in order to investigate the direct

[2] Swayze,G. A., R. N. Clark, A. F. H. Goetz, T. G. Chrien, and N. S. Gorelick, Effects of spectrometer band pass, sampling, and signal-to-noise ratio on spectral identification using the Tetracorder algorithm, J. Geoph. Research (Planets), vol. 108, No. E9, 5105, doi: 10.1029/2002JE001975, 2003.

military utility of different combinations of performance dimensions. High quality airborne hyperspectral image data is available to serve as realistic scene backgrounds. By inverting this data to surface reflectance using commercially-available atmospheric inversion codes, a large set of real background spectra are made available. Targets of military interest may be inserted into these backgrounds with a perfect knowledge of ground truth location, and may be mixed with background spectra at fractions between zero and one. MODTRAN is used to simulate at-sensor radiance at very high spectral resolution and sampling.

The next step is to process the simulated input radiance with sensor response models based on the attributes of performance under study. Ideally the airborne data is collected at higher spatial resolution than is envisioned for the mission under study so the full spatial and spectral effects from the sensor response function are captured. An optical ray trace model generates the point spread functions including the impact of aberrations and diffraction from the optical design and wave front error to account for manufacturing and alignment tolerance. The effects of spectrometer entrance slit and detector width are combined with detector diffusion effects and scattering models in order to estimate system spectral and spatial response blurring kernels. The estimates are made for a sampling of points over the spatial and spectral range of response of the sensor, and interpolations of these responses are used for points in between.

First order area-solid angle product and transmittances are included to capture the details of the radiometric throughput. Detector noise, gain, and offset variations are modeled or input from detector measurement, if available. High resolution input radiance is convolved with the sensor response functions, and a simulated output signal data set with noise and calibration variations is generated.

The simulated output signal from the sensor response model is then calibrated back to units of spectral radiance using standard calibration equations. Since the calibration parameters are used in the conversion from input radiance to output signal, it is easy to simulate the effect of small errors in the calibration process used to reverse the effect. The simulated output radiance thereby contains all the effects of the sensor performance attributes including the spectral spatial, and radiometric range, resolution, sampling, and calibration inaccuracies.

The next step in the process is to implement a standard atmospheric correction. This results in a data set of the targets and backgrounds in reflectance space, similar to input reflectance used in the first step, but degraded by sensor resolution and containing all the noise and calibration errors of the sensor response model. This data is input to standard target detection algorithms. Performance metrics such as the probabilities of detecting a target or of false alarm detection are easy to compute since the ground truth is perfectly controlled in the simulation. These detection metrics may be directly related to issues of military utility.

Baseline results for the simulation are made by comparing the metric result for simulated targets in background prior to and after application of the sensor response model. This determines the impact to the military utility metric by the set of performance parameters captured in the sensor response model. The baseline represents the best the sensor can achieve and occupies the right-most point on the performance-versus-cost curve.

APPLICATION OF THE SIMULATION

The end purpose of the simulation is to fill in points along the performance-versus-cost curve so that an optimum solution may be identified and selected. In order to properly tie results to pertinent military utility it is important to understand and document the customer's unique definition of utility and to select a suitable set of targets, background, atmospheres, and illumination/viewing geometries. Also, it is important to adopt detection (information extraction) algorithms that are the same of similar to what the customer expects to employ. Once this is completed, it is important to examine the baseline case (ideal sensor response, no noise, no calibration errors) to ensure that this case provides the desired utility without regard to cost. Then it is possible to examine real point design options (sets of performance attributes) using the utility simulation and cost estimating techniques to place these point of the performance-versus-cost curve.

Raytheon is working with a local college to develop the military utility metric analysis tool set using a very simple spectral angle mapper algorithm[3] and surrogate targets and backgrounds. The work is being conducted as a senior year Engineering Clinic by a team of five students. Initial results of this effort have been used to examine the utility based performance-versus-cost for spectral band range trades, and to examine the benefits of atmospheric correction.

SUMMARY

This paper presents a simulation strategy for relating cost/performance trades to military utility. The aggregate impact of multiple dimensions of sensor performance in a given point-design may be assessed and compared against any other point design. The performance impact is easy to baseline against an idealized "highest cost" sensor solution by using an ideal or error-free sensor response function. Performance impact may be parameterized along any given performance dimension and related to a military utility metric. It is important to involve all stake holders in the defining the military utility metrics to be used, and to agree on the range of targets, backgrounds, atmospheres, illumination/viewing geometries, and algorithms to be used.

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[3] Kruse, F.A., Boardman, J.W., Lefkoff, A.B., Heidebrecht, K.B., Shapiro, A.T., Barloon, P.J., and Goetz, A.F.H. (1993). The Spectral Image Processing System (SIPS) Interactive Visualization and Analysis of Imaging Spectrometer Data. Remote Sensing of Environment, Vol. 44, p.145-163.

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