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END-TO-END PERFORMANCE MODELING OF PASSIVE REMOTE SENSING SYSTEMS

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End-to-end performance modeling of passive remote sensing systems

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ABSTRACT

The ultimate goal of end-to-end system modeling is to simulate all known physical effects which determine the content of the data, before flying an instrument system. In practice we approach this ideal but do not attain it.

In remote sensing, one begins with a scene, viewed either statically or dynamically, computes the radiance in each spectral band, renders the scene, transfers it through representative atmospheres to create the radiance field at an aperture, and integrates over sensor pixels. We have simulated a comprehensive sequence of realistic instrument hardware elements and the transfer of simulated data to an analysis system. This analysis package is the same as that intended for use on data collections from the real system. By comparing the analyzed image to the original scene, the net effect of nonideal system components can be understood. Iteration yields the optimum values of system parameters to achieve performance targets.

We have used simulation to develop and test improved multispectral algorithms for: 1) the robust retrieval of water surface temperature, water vapor column, and other quantities; 2) the preservation of radiometric accuracy during atmospheric correction and pixel registration on the ground; and 3) exploitation of on-board multispectral measurements to assess the atmosphere between ground and aperture. We have evaluated the errors in these retrievals for a variety of target types due to: telescope OTF, calibration bias, system noise, spacecraft motion and jitter, atmospheric effects, telescope distortions, and co-registration during processing of multispectral images with offset pixels.

Keywords: Remote sensing, simulation, optical systems, image processing, science retrievals

INTRODUCTION

Many models that one sees in presentation are not truly end-to-end. If a model is restricted to one component of a system, it is impossible to evaluate the effect of changes to its design on the net performance of the system. For Earth-looking, passive remote sensing systems, whether airborne or satellite-borne, it is crucial to carefully assess the expected content of flight data years before flight, when performance estimates can still be used to suggest improvements to the design. No more information can be gleaned from flight data than what is contained in on-board storage or telemetry.

Characteristics of a true end-to-end model for a remote sensing system are as follows:

- It employs realistic physics to describe the behavior of system components.
- It includes all subsystems and their real specifications wherever available.
- It is initialized with a representative natural target scene, in an appropriate physical quantity, e.g. radiance.
- It always traces information flow to the relevant bottom-line physical quantity whose measurement is the justification for the experiment.
- It computes a final scene in the same physical units as the initial scene, so that the two scenes can be directly compared, allowing measurement of net throughput and statistical analysis of residuals, root-mean-square (RMS) errors, etc.

Modeling packages lacking one or more of the above characteristics may be useful for subsystem design, and the choice of when to use them and when to use an end-to-end model should be made as follows:

- If changes to the subsystem design cannot impact the content of the flight data set, e.g. detailed digital electronics layout, then an isolated subsystem model is acceptable.

- If changes to subsystem design can impact the content of the flight data set, e.g. in telescope design, analog preamplifier design, or readout electronics design, then the effect of system trades should be evaluated within an end-to-end model. This can be accomplished by transferring results from an isolated subsystem model for insertion at the proper point in the information flow of the end-to-end model, rather than by running the subsystem model within the full end-to-end code system.

Global perspective is the *sine qua non.* As an example, consider telescope design for an IR imager, clearly a subsystem whose performance affects flight data. One might wish for a perfect optical system, with diffraction-limited imaging at all wavelengths, and try to procure one in the belief that it must be the best choice for the instrument system. However, if other contributions to the optical transfer function (e.g. motion blur or irreducible errors in data analysis) will be more debilitating, *when evaluated against an imaged scene in the bottom-line physical quantity,* than those caused by optical aberrations or imperfect optical surfaces, then striving for a perfect optical system is wasteful. Avoidance of waste requires coordination of subsystem design efforts through a central end-to-end modeling effort. This case demonstrates the interplay between subsystem and end-to-end models.

An overall error budget cannot be sanely established without end-to-end modeling. We do not wish to assign error fractions to subsystem teams without a complete understanding of their significance to the bottom line product.

The components of an adequate modeling package for passive remote sensing systems include:

- scene generation, or substitution of a scene acquired by a previously flown instrument system;
- rendering of the scene in physical quantities, at the angle of observation and in appropriate illumination for the time of observation;
- transfer of scene radiance through the atmosphere to the instrument, including all significant atmospheric effects; and
- simulation of optical system performance, sensor system performance, and front-end electronics performance.

This brings one to the end of the first half of an end-to-end model, that which will be replaced by the flight instrument system. The data set at this point consists of no more information than would be available from flight, except for test purposes. The second half includes whatever analysis package will be applied to flight data to derive a final scene. An ancillary benefit of developing an end-to-end model is that the data analysis software will be developed long before flight. Two important components of the analysis package are the science retrieval algorithms and the method of image deblurring, if any, used. Each of these analysis components must be optimized on realistic simulated data sets to estimate the effective, potential throughput and performance of the system under valid assumptions.

THERMAL IMAGING

We describe now the results of Los Alamos development of an end-to-end model for satellite-borne multispectral thermal imagers. In this case the initial and final scenes are defined in surface temperature and emissivity, pixel by pixel. The model contains all components listed above. Currently scenes are adapted from other thermal imagers (e.g. airborne) or from computed images of surface configurations defined as truth for the purpose of performance estimation for the instrument system.

Atmospheric radiative transfer is performed with MODTRAN2, for a selection of atmospheric types determined by more than 10,000 runs of the computer code. Those runs were classified into 480 types that span a range of ground surface temperature, atmospheric water vapor content, clear sky conditions, cirrus cloud conditions, and aerosol loadings. Many and various choices of observation angles and limiting band wavelengths can be quickly evaluated within the end-to-end model to predict accuracies for various algorithms for the retrieval of surface temperature from the payload data. Our model incorporated the surface temperature retrieval algorithm developed by Tornow et al.[1]

For the temperature retrieval problem, it turns out to be essential that one model the entire system. Analysis of results shows that the driving parameters for retrieval accuracy are radiometric calibration accuracy, signal-to-noise ratio (SNR), and obtaining multiple observations of the scene from widely separated angles in the same pass over the target scene. Ultimate optical performance is of secondary importance. Careful coregistration of multispectral band images (discussed below) is essential for peak spatial resolution of surface temperature scenes, as well as for temperature retrieval accuracy in each scene pixel.

WATER VAPOR

A number of multi- and hyperspectral algorithms have been suggested for the retrieval of total water vapor column from manipulation of measurements in and around the water absorption feature at 940 nm (see for example, Gao and Goetz[2]). Recently a new one, APDA (for atmophseric pre-corrected differential absorption), has been derived by Borel and Schläpfer[3]; see also Borel et al.[4] in the proceedings of this Symposium. This method is being incorporated into the end-to-end model as a subsystem.

MULTIBAND COREGISTRATION

If different bands of multi- or hyperspectral data are not coregistered, one cannot confidently use multiband algorithms for retrieval of science quantities. Misregistration can be caused by misalignment in instruments with beamsplitters and multiple sensor assemblies. The issue for end-to-end modeling is to predict the effect of misregistration if left uncorrected, and how much damaging effect can be alleviated by careful correction methods.

We consider here the special case of pushbroom multiband imagery, in which different-band linear sensor arrays view a given patch of the ground surface through a common optical path at different times in the target scan. An example would be a dispersive hyperspectral imager in which one dimension of a two-dimensional sensor array is devoted to spectral dispersion while the other is devoted to imaging with cylindrical optical elements. Another would be a multispectral imager in which separate linear arrays and filters are employed for each spectral band, but all sensor arrays are mounted parallel to each other on a common focal plane substrate.

For the latter case, we have derived a method for determining, *a posteriori,* the motion of the field of view (FOV) using in-scene information only. Once motion of the FOV is known, optimum parametric interpolation methods (Park and Schowengerdt[5]) can be employed to transform displaced band images onto a common pixel grid.

The method proceeds as follows. We take advantage of the fact that the focal plane is a rigid body. Therefore, when the FOV moves, all array footprints projected on the ground move together. Although different spectral bands do not view the same patch of ground at the same time, their images should be correlated after time delays are taken into account. It is possible to write a set of coupled, over-determined equations for the global time history of FOV motion. The system of equations, written in matrix form, looks like this:

$$\mathbf{W}\,\mathbf{D}\,\mathbf{u} = \mathbf{W}\,\mathbf{z},$$

where $\mathbf{u}$ is the vector of FOV displacements indexed by frame number (i.e. time—it is assumed that the framing interval is selected as the along-track width of the array footprint, divided by the ground scan speed); $\mathbf{D}$ is a matrix that depends only on focal plane geometry, focal length, and ground scan speed; $\mathbf{z}$ is a vector of lags that maximize the cross-correlations between each pair of spectral band radiance images with appropriate time delays; and $\mathbf{W}$ is a diagonal matrix of weights for the equations, reflecting the expected correlation (positive entries), anticorrelation (negative entries), or lack of it (zeroes) between pairs of bands. The matrix $\mathbf{D}$ is the same for a given system of optics and focal plane, as long as the ground scan speed does not vary from observation to observation. If scan speed varies, a different matrix $\mathbf{D}$ must be computed for each step in speed. If sensor arrays for different spectral bands are separated in the along-track direction by more than the array width, $\mathbf{D}$ is approximately a Toeplitz matrix, which says that is is sparse with multiple nonzero diagonals, although $\mathbf{D}$ is modified by different entries at the matrix boundaries. Obviously the vector $\mathbf{z}$ is different for each scene. The matrix of weights $\mathbf{W}$ is empirically derived from analysis of typical multiband scenes.

Since the matrices are not necessarily square, and since **D** is singular due to overdetermination of the FOV motion history (in particular if u(t) is a solution, so is u(t) + C, where C is a constant), solution of the equation system involves squaring up both sides by multiplying by $(\mathbf{WD})^T$ and inverting the matrix on the left side. An arbitrarily precise inverse can be computed by singular value decomposition. For further mathematical details see Theiler[6]. See also the related paper by Henderson et al.[7] at this Symposium.

Results of a study of reconstruction of cross-track jitter history, from simulations of pushbroom multispectral imagery of a natural ground scene, are given in Figure 1. In the upper panel only cross-track jitter was imposed, with the exact time history, in pixel units, shown by the solid line. The above interband cross-correlation method gave a reconstructed time history shown by the dashed line. The RMS error in jitter-induced displacement of the FOV was 0.07 pixels over 200 frames (the abscissa). When both along-track and cross-track jitter are imposed, the lower panel shows the somewhat degraded jitter reconstruction (cross-track component only). The RMS error in jitter determination in this case was 0.13 pixels. Incidentally, as another example of the end-to-end paradigm, these simulations were accomplished using imposed jitter histories that were realizations of the expected power spectrum of residual vibration for an appropriate satellite bus.

An important advantage of this method is that it uses in-scene information only. When viewed within the end-to-end system model for a pushbroom thermal imager, the above results show that (*a priori* unknown) jitter of the FOV amounting to several pixels will have a negligible effect on the accuracy of ground surface temperature, because they can be reconstructed and compensated for, leaving a net RMS error of less than 0.2 pixels. Uncompensated errors in reconstruction of FOV motion greater than about 0.5 pixels cause significant degradation in the accuracy of temperature retrieval at single-pixel spatial resolution. Thus realistic simulation and end-to-end analysis could result in significant cost-savings during the system design phase.

Note that the success of any cross-correlation method depends on the presence of sufficient contrast in the scene to give the cross-correlation sensitivity to lag. If this contrast does not exist, the method fails, but in this event adjacent pixels are similar on the average, and one is not so concerned with precise coregistration. Note also that the full scene need not be analyzed; a subscene of sufficient size to encompass more than the instantaneous footprint of the sensor array will yield a reconstruction of the global FOV motion history.

ON-BOARD CHARACTERIZATION OF THE ATMOSPHERE

It is advantageous for multiband remote sensing instruments to characterize the atmosphere intervening between the scene and the aperture using on-board instrumentation. Here a distinction must be made between daytime and nighttime observations, and between multi- and hyperspectral IR instruments. Using our end-to-end model, we have investigated the utility of various options for band selection from the standpoint of accurate retrieval of ground surface temperature.

In the daytime, solar reflected radiance contaminates the critical mid-wave IR band (MWIR) up to about 4 microns, where Planckian radiance of the ground surface first rises above reflected solar radiance. Therefore we recommend splitting the MWIR atmospheric window into at least two spectral channels, for example making use of the lower half between 3.5 and 4 μm, and the narrower part just below 5 μm to create two spectral bands. This conclusion is supported by extensive analysis of the effect of changes in band limits on RMS retrieval error. Moreover, thin cirrus is a threat to accurate determination of ground surface temperature, since one may effectively measure the temperature of the cirrus rather than that of the ground. A narrow band centered at 1.375 μm, as suggested by B.-C. Gao, works well in screening multiband imagery for pixels with a damaging thickness of subvisual cirrus. Similarly, for daylight observations it is profitable to employ three spectral bands around 0.94 μm to exploit the water vapor column measurement discussed above.

At night all bands below 3 μm are useless for normal ground conditions, while the band from 3.5 to 4 μm reaches maximum utility and sensitivity. Without independent meaurement of water vapor column and cirrus thickness, we must rely on subtler variations in sensitivity to water vapor and cirrus in the MWIR and long-wave IR (LWIR) bands. Bands just below 5 μm and just above 8 μm are more sensitive to water vapor column than the more comman MWIR and LWIR band choices of 3-4 and 10-12 μm. The results of end-to-end modeling shows that judicious choice of band boundaries provides enough sensitivity to atmospheric conditions to allow accurate temperature and other retrievals under the wide range of atmospheric water vapor, cirrus, and aerosol loadings described in an earlier section.

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Figure 1. Examples of jitter reconstruction using the interband cross-correlation method. The solid curves show an imposed jitter time history in pixel units as a function of time in frames. The dashed curves show reconstructed jitter history. In general the reconstructed history is offset from the imposed history by an arbitrary fraction of a pixel. Since this offset does not affect the utility of the reconstruction at all, it has been removed in the plots to show residual departures.