Scene Statistics Based Calibration of Remote Sensing Instruments

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***Abstract*—A variety of spaceborne remote sensing instruments achieve wide-area coverage with only a small number of detectors, by using a cross-track scanning mechanism and satellite motion to provide extended coverage. Errors in the detectors' relative calibrations result in stripes in the images acquired by these instruments. This letter presents a general approach for equalizing the detector responses, based on scene statistics. For the case where the detector response functions are predominantly linear, with a small quadratic component, a complete set of equations for implementing the statistics-based calibration is also presented. The resulting algorithm has been tested with application to a few select Earth scenes from the Moderate Resolution Imaging Spectroradiometer, and the quality of the resulting calibration functions is discussed. Based on the mathematical formulation and intuitive reasoning, recommendations are offered for selecting scenes that are suitable for determining the detectors' relative calibrations with validity across the full dynamic range of the instrument.**

***Index Terms*—Calibration, image sensors, remote sensing, statistics.**

I. Introduction

A VARIETY of spaceborne Earth remote sensing instruments perform cross-track scanning with a small column of detectors to achieve rectangular strips of imagery. Proper synchronization of the scan cycle with the satellite motion makes the successively scanned strips (scans for short) to be contiguous, resulting in extended two-dimensional coverage. For these whiskbroom type instruments, errors in the detectors' relative calibrations result in stripes or streaks in the imagery, particularly over flat radiance fields. Since the observations from each detector represent statistical sampling of the same Earth scene, they are expected to have the same statistical properties. Several papers and reports [1]–[6] have been published that utilize the comparison of detector radiance histograms (frequency of occurrence of various radiance values) to improve the relative calibration of detectors. However, a systematic approach that utilizes robust statistical measures (mean, standard deviation, and higher level moments) to obtain an optimal fit for detector calibrations, has not been attempted. In Section II, we define a generalized scene-content-based statistical method for tracking and updating the relative calibration of the detectors of the whiskbroom instruments.[1] For the case of detectors with a quadratic term in their calibration function, a full-fledged algorithm for relative detector calibration is presented in Section III. Based on the mathematical formulation and intuitive reasoning, we offer recommendations for scene selections that are suitable for determining the detector relative calibration functions valid across the full dynamic range of the instrument. The approach for testing of the algorithm implementation and the discussion of the results from its application to a few select Earth scenes from the Moderate Resolution Imaging Spectroradiometer (MODIS) is also presented.

II. Generic Statistical Calibration

For whiskbroom instruments, all the detectors of a given spectral band sample the same Earth radiance field, with sampling grids of individual detectors being slightly offset from each other. Therefore, for scenes involving a large enough number of scans, the individual detectors are expected to see the same distribution of radiance levels. Thus, for detectors with stable calibrations over the entire data span, the differences in the computed scene statistics can be ascribed to the errors in the calibration coefficients. Determination of detectors' relative calibration via the equalization of computed scene statistics, therefore, presents a powerful approach for tracking the slowly varying[2] aspects of detector calibration coefficients.

When the needed corrections to the initial calibration of the detectors are small, one can assume a linear relationship between the errors in the detector calibration coefficients and corresponding error in the computed statistics (statistical defect). Thus, for any given detector j ($j = 1, 2, \ldots, n_d$) of a given spectral band

$$s_k^j = \mathrm{Sum}_i \left(\frac{dS_k^j}{dC_i^j} \right) c_i^j. \tag{1a}$$

Here s_k^j is the defect in the kth statistic, S_k^j ($k = 1, 2, \ldots, n_s$), that results from the errors c_i^j in the calibration coefficient C_i^j ($i = 0, 1, \ldots, n_c - 1$), and $\left(dS_k^j / dC_i^j \right)$ are the partial derivatives of S_k^j with respect to C_i^j. Suppressing the detector

Manuscript received August 8, 2005; revised October 18, 2005. This work was supported by the National Aeronautics and Space Administration (NASA) under Contract NAS5-02041. The results and conclusions expressed here have not been reviewed or endorsed by NASA.

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Digital Object Identifier 10.1109/LGRS.2005.861544

[1]The statistical calibration approach described here is also applicable to a lesser extent (for a small number of neighboring detectors at a time) to the pushbroom type instruments that employ a large cross-track linear array of detectors in conjunction with satellite motion to obtain two-dimensional imaging. By applying the algorithm to successive overlapping subsets of detectors, equalization across all detectors can be achieved.

[2]This approach cannot remove striping arising from local or high-frequency detector response artifacts, as the equalization of radiance statistics does not imply equalization at the scan-to-scan time scale.

index, and using the matrix notation (using bold typeface for vectors and matrices) (1a) may be expressed as

$$\mathbf{s} = \mathbf{H}\mathbf{c} \quad H_{ki} = \left(\frac{dS_k}{dC_i}\right). \tag{1b}$$

Here, the statistical defect vector $\mathbf{s}$ for detector j is defined as

$$\mathbf{s}^j = (\mathbf{S})^j - \mathbf{S} \tag{2}$$

with $\mathbf{S} = S_k$, $k = 1, 2, \ldots, n_s$, being the true values of the scene statistics.

The above equations are valid for any arbitrarily defined set of scene statistics

$$S_k = \mathrm{Sum}_p f_k \frac{(Xp)}{(\text{number of pixels, } p)}.$$

Here X_p are the pixel radiance values.

We treat $\mathbf{s}$ as the derived observations that are functions of the detector calibration[3] state vector $\mathbf{C}$. The unweighted optimal solution to the set of linear equations (1b) for the case of n_s greater than or equal to n_c is given by [7, pp. 448–453]

$$\mathbf{c} = (\mathbf{H^T H})^{-1}(\mathbf{H^T})\mathbf{s}. \tag{3}$$

The solution exists when the matrix $\mathbf{H^T H}$ does have an inverse. One must also express the elements of the measurement matrix $\mathbf{H}$ in terms of available data and determine the Defect vector $\mathbf{s}$. In (2), $(\mathbf{S})^j$ can be computed from the detector observations and its calibration coefficients. A practical realization of $\mathbf{S}$, the true scene statistics, is the average of the statistics for all detectors in a given band. Thus,

$$\mathbf{S} = \mathbf{S_{avg}} = \frac{(\mathrm{Sum}_j(\mathbf{S})^j)}{n_d}. \tag{4a}$$

If the errors, $(\mathbf{c})^j$, $j = 1, 2, \ldots, n_d$, in the calibration coefficients of the individual detectors are randomly distributed, then the band averaged scene statistics are indeed the best estimates of $\mathbf{S}$. However, in general, using band averages as the true statistics runs the risk of introducing a bias that moves all detectors away from their baseline absolute calibration. Thus, in some cases, it may be desirable to use the computed statistics of a stable and well-calibrated detector as the "truth" reference, i.e.,

$$\mathbf{S} = (\mathbf{S})^{j0}. \tag{4b}$$

In this approach the corrections to detector $j0$, $\mathbf{c}^{j0}$, will be a null vector.

Equations (1)–(4) provide a complete framework for statistics-based corrections to detector calibration coefficients. Any implementation of this approach must guard against the violation of the two key assumptions, namely, that the errors in the original calibration are small ($\mathbf{c} \ll \mathbf{C}$)[4] and that the matrix $\mathbf{H^T H}$ is not ill-conditioned.

III. Application to Nonlnear Detectors

The most common case of interest is that of detectors with predominantly linear response functions with a small nonlinear component, i.e., the calibration state vector has a minimum dimensionality of three. A scene with only one significant feature has primarily two independent pieces of information—feature location and width. Therefore, the ideal scene for applying this algorithm to detectors with nonlinearity, would be the one that contains two or more significant features (peaks or valleys) that are well spaced over the detectors' dynamic range. The resulting calibration then will be portable from the sample scene to neighboring scenes, limited only by the stability (i.e., variability in time) of the detector response functions. For scene samples with only one significant feature only a linear fit is advisable and the resulting fit has limited portability to other scenes, as discussed in the paragraph that follows (9), below. However, such local linear fits can be combined, via regression analysis (e.g., a polynomial curve fitting) to obtain the detector response functions across the full dynamic range, when the detector calibrations are stable across the time frame that covers all samples involved in the process. Thus, by judiciously choosing the sample scenes for statistical calibrations, one can easily track the variation in the relative response functions of the detectors.

In the following we present a set of detailed equations for relative statistical calibration of a set of detectors with nonlinear response functions.

A. *Selection of Calibration Equation and Statistical Measures*

Assuming, a quadratic term is sufficient to model detector's nonlinearity, the detector digital read out number N, corresponding to input radiance X is given by

$$N = a_0 + a_1 X + a_2 X^2.$$

Solving this quadratic equation in X (neglecting terms $\sim \{a_2/a_1\}^2$ in the process and retaining the positive solution), the corresponding detector calibration equation is

$$X_N = X(N) = C_0 + C_1 N + C_2 N^2 \tag{5}$$

where $C0 = -(a_0/a_1)[1 + (a_0/a_1)(a_2/a_1)]$, $C1 = (1/a_1)[1 + 2(a_0/a_1)(a_2/a_1)]$, and $C2 = -(1/a_1^2)(a_2/a_1)$. We use (5) as the calibration equation for our fitting procedure that attempts to equalize the standard statistics, namely, the ensemble average and the second and higher level moments. These robust statistics can be easily computed from the histograms of the detector observations and the calibration coefficients.

[3]It is assumed that pixels that are outside the dynamic range covered by the instrument calibration are not included in compiling the scene radiance statistics. This can be accomplished by excluding from the computations an equal number of pixels for all detectors, at one or both of the extreme ends of the dynamic range (saturated pixels or below threshold/noise level pixels).

[4]If the condition $\mathbf{c} \ll \mathbf{C}$, is not satisfied, one can apply the correction process iteratively, using corrected $\mathbf{C}$ from one iteration as the initial $\mathbf{C}$ for the next iteration, until the process converges or the number of iteration exceeds a judicially selected count.