This paper examines the methodology of detecting targets in airborne or satellite hyperspectral imagery using physics-based models. More specifically, the radiative transfer inherently coupled to various physical models is considered. In fact, taking into account atmospheric effects is crucial in target detection applications, especially when dealing with targets that are particularly difficult to detect. Many tools have been developed independently which incorporate physical models that simulate atmospheric radiation transfer. Some (e.g. DIRSIG) predict sensor-reaching radiance while others (e.g. FLAASH, ATREM) retrieve ground-leaving reflectance by removing atmospheric effects. With the final aim of performing forward modeling target detection on a particularly challenging scenario, this paper illustrates the preliminary study carried out in order to assess the physical model employed and achieve a better data understanding before proceeding to detection. A cross-comparison between some well-known and established models, in addition to forward modeling, is examined. Results reveal the need for better understanding of real data by identifying the major sources of uncertainty. The strong impact of atmospheric condition uncertainty and adjacency effects, along with, though to a lesser extent, further inaccuracy introduced by possible calibration and spectral library measurement errors, are all factors that will be investigated in future work.

Index Terms—Target detection, radiative transfer, physics-based model, forward modeling, FLAASH, DIRSIG

1. INTRODUCTION

When dealing with hyperspectral imagery, atmospheric effects play an important role and have to be taken into account in order to efficiently exploit information provided by the data. In physics based target detection applications, detection of targets relies on radiance imagery and spectral reflectance signatures of the target. Therefore, radiative transfer (RT) within the atmosphere, along with viewing and illumination effects, needs to be accounted for, especially when this involves targets that are particularly hard to detect (e.g. partially concealed, in shadow, very sub-pixel, in a very complex background environment, etc.). Over the years, many tools have been developed that simulate the atmospheric RT based on a physics-based model (PBM). Some (e.g. the Digital Imaging Remote Sensing Image Generation, DIRSIG [1]), predict sensor-reaching radiance starting from first principles, whereas others (e.g. Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes, FLAASH [2] and Atmospheric REMoval program, ATREM [3]) derive ground-leaving reflectance by removing atmospheric effects from radiance imagery. These well-known and established tools have been developed independently, and the PBMs they rely upon can be slightly different, depending on the details accounted for.

In this work, real hyperspectral imagery, acquired over a complex scene with targets particularly difficult to detect, is considered. With the final aim of performing forward modeling target detection, this paper illustrates the preliminary study carried out in order to assess the PBM employed and achieve a better data understanding before proceeding to target detection. Thus, a comparison between some of the aforementioned established models in addition to a more recent forward modeling method [4], to be used for detection, is shown. The employment of both simulated and real data allows for implementation of experiments at the mere physical-level and subsequently introducing all the variability that arises in reality. Results obtained also identify the major sources of uncertainty that deserve further analysis.

The paper is organized as follows: Section 2 briefly introduces the RT tools analyzed, the data employed are described in Section 3, Section 4 deals with the design of the experiments, results are shown and discussed in Section 5, and Section 6 includes a summary and conclusions.

2. RADIATIVE TRANSFER MODELING

The RT modeling techniques considered here basically follow the physical model [5] shown in equation (1), though each RT modeling technique uses a slightly different version accounting for different details:

\[ L_s(\lambda) = [E_s(\lambda) \tau(\lambda) \cos(\theta) + E_s(\lambda) \tau(\lambda) \frac{\lambda}{\pi} + L_s(\lambda) \]

where the surface is assumed Lambertian and
$E_s(\lambda)$ exoatmospheric solar spectral irradiance;
$\tau_{1}(\lambda)$ spectral Sun-target path atmospheric transmission;
$\vartheta$ Sun zenith angle;
$E_d(\lambda)$ spectral downwelled irradiance from the sky;
$\tau_{2}(\lambda)$ spectral target-sensor path atmospheric transmission;
r($\lambda$) spectral reflectance of the target;
$L_s(\lambda)$ spectral path radiance.

All these techniques rely upon MODTRAN (MODerate resolution TRAnsmission, [6]), which makes use of user-supplied parameters (metadata related to atmospheric/illumination/viewing conditions at acquisition time) in order to simulate the radiometric terms in equation (1). These techniques typically access a Look-Up-Table, which is precomputed using MODTRAN over a variety of conditions taking into account additional parameters such as sensor response.

2.1. DIRSIG
DIRSIG [1] is a sophisticated synthetic image generation tool able to accurately model: (i) physical properties of 3D surfaces in a scene (ii) atmospheric properties, and (iii) spectral/spatial properties of a hyperspectral sensor. Sensor-reaching radiance imagery is provided through equation (1), which can be enriched with Bidirectional Reflectance Distribution Function (BRDF), adjacency effect, and other parameters of interest.

2.2. FLAASH
FLAASH [2] is a hybrid technique, both image-derived and RT modeling-based, that allows for ground-leaving reflectance derivation. It can account for adjacency effects and provide water vapor (WV) and cloud masks.

2.3. Forward Modeling Techniques
Physics-based forward modeling (PBFM) techniques have been developed to be employed in target detection applications [7, 4]. They allow for lack of knowledge about acquisition conditions by generating, for a given reflectance, a set of possible sensor-reaching radiance spectra through equation (1). The formulation adopted here [4] allows also shape factor and orientation effects to be introduced.

3. DATA SET DESCRIPTION
The data used in this analysis consist of a radiance image acquired over Cooke City, MT, by the HyMap sensor [8], operating in the Visible Near InfraRed to Short Wave InfraRed (VNIR-SWIR) range. The main characteristics of the image are reported in Table I. During acquisition, several fabrics were placed in the scene, and their spectral reflectances were measured and collected in a spectral library. The fabric panels have sizes comparable to, and sometimes smaller than, the Ground Sampling Distance (GSD), thus resulting in sub-pixel targets. This strong sub-pixel situation, along with the complexity of the background characterized by many objects and classes, makes the target detection process quite challenging. Furthermore, during acquisition, small sparse clouds in the atmosphere were observed, whose effects on the downwelling irradiation are time varying, highly unpredictable, and difficult to model.

<table>
<thead>
<tr>
<th>SENSOR</th>
<th>HyMap</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPECTRAL RANGE</td>
<td>0.4 - 2.5 $\mu$m (VNIR-SWIR)</td>
</tr>
<tr>
<td>SPECTRAL SAMPLING</td>
<td>16 nm (average)</td>
</tr>
<tr>
<td># PIXELS</td>
<td>280 x 800</td>
</tr>
<tr>
<td># BANDS</td>
<td>126</td>
</tr>
<tr>
<td>GSD</td>
<td>3 m</td>
</tr>
</tbody>
</table>

4. EXPERIMENTAL DESIGN
As part of our research into the use of physics-based forward modeling for target detection with these data, it was important to assess the validity of the model through comparison to the data and other modeling approaches. In the initial phase, depicted in Figure 1 (a), real data, related to a measured target reflectance, are employed. The target considered here is a red cotton 3m x 3m fabric, which was placed in a patch of grass, close to other fabric targets. The radiance imagery is, in this phase, replaced by a synthetic image, generated by DIRSIG, involving a much simpler scenario with full-pixel targets. The simulated environment, obtained through a reliable and recognized tool such as DIRSIG, assures the imagery generated is at the physical level, thus disregarding other issues that can arise when using real data (e.g. sub-pixel contamination, calibration errors). The target reflectance is propagated through a loop that involves subsequent propagations through the atmosphere, from ground to sensor and vice versa, by means of the aforementioned RT modeling techniques, i.e. DIRSIG, FLAASH, and the PBFM in [4]. As is evident from Figure 1 (a), all these MODTRAN-based tools are supplied with the same metadata describing acquisition conditions. The outcomes to be examined are three sensor-reaching radiance spectra, and two ground-leaving reflectances. It is anticipated that these will match, except for minimal differences due to model implementation and processing artifacts (e.g. the spurious molecular absorption residuals introduced by FLAASH).

In Phase 2, illustrated in Figure 1 (b), the same loop, as Phase 1, is repeated, this time using the real HyMap radiance cube instead of the DIRSIG image. This introduces into the experiments all the variability that arises in reality, such as uncertainty about atmospheric conditions, mixed pixels, possible calibration errors, etc. Accurate analysis of these
plotted in Figure 2 identified and isolated for further investigation.

These results show that the PBFM employed acts, at the spectra. Additionally, partial transmission through the fabric artifacts introduced from the correction, and aside from outcomes will allow the major sources of variability to be identified and isolated for further investigation.

5. RESULTS

Radiance and reflectance output spectra from Phase 1 are plotted in Figure 2 (a) and (b), respectively. Except for the water vapor (WV) and O₂ absorption bands, some spurious artifacts introduced from the correction, and aside from slight differences due to diversity in the models, these spectra exhibit a good match. The spectra are approximately within an average of 7% (radiance) and 12% (reflectance) of relative difference, computed neglecting absorption bands. These results show that the PBFM employed acts, at the physical level, in the same manner as the two independently developed and established models DIRSIG and FLAASH.

Results from Phase 2 are reported in Figure 2 (c) and (d), which refer to the radiance and reflectance domain, respectively. As is evident, a strong mismatch can be observed in both domains. Since results obtained in Phase 1 prove that no significant difference exist among the PBFMs employed, the origin of this discrepancy has to be examined and may be due to the sources of variability and uncertainty already mentioned. Factors to be considered are mainly related to cloud effects and to the (very) sub-pixel condition, both mentioned in Section 3. As to the latter, adjacency effects from neighboring materials can deeply alter spectra shape, as is observable in Figure 2 (c-d), where the red-edge effect due to grass contamination is undoubtedly visible in the spectra. Additionally, partial transmission through the fabric due to its non-perfect opacity could have lead to enhanced contamination effects from the vegetation below. Furthermore, by examining these plots along with the loop in Figure 1 (b), additional sources of the observed inconsistency can also be linked, though to a lesser extent, to calibration and spectral library measurement errors, which are two common weak links in the remote sensing chain, on which the user usually has no control. Specifically, given the typically high quality of HyMap products, supplementary sources of error may likely reside in the spectral library measurements. In fact, a non-perfect calibration of the spectroradiometer, material aging, and BRDF effects (i.e., many real materials do not respect the Lambertian assumption made in equation (1)) can have contributed to introduce inaccuracy and imperfections in the lab-measurements. Some of these aspects are currently being investigated, such as the impact of BRDF effects on physics-based modeling [9], and more known materials in the Cooke City scene will be analyzed as future work. Lastly, it is worth noting that, regardless of the actual sources of error, this seems to affect, in the same way, both reflectance and radiance domain data. This can be confirmed through a supplementary and more detailed analysis, which is not presented in this work.

6. CONCLUSION

An analysis has been carried out that involves real hyperspectral data related to a particularly challenging target detection scenario. This preliminary study, involving a comparison of radiative transfer modeling techniques, has proven to be essential in achieving a better understanding of the da-
ta used. The first phase, performed using DIRSIG, has shown similarity, at the physical level, of the PBFM to be used in target detection and the two independently developed and established models, DIRSIG and FLAASH. The second phase, accounting for both radiance imagery and target spectra, has allowed us to verify the impact of all the variability that arises in real imagery, such as atmospheric condition uncertainty and, to a greater extent, adjacency effects, due to the significant sub-pixel nature of the imagery. Furthermore, two additional weak links in the chain have been identified that can have contributed to inaccuracy in the results obtained: calibration errors and, more likely, spectral library measurement errors. All these major sources of uncertainty identified deserve further investigation, and can be isolated for additional processing. These insights will allow for a better data understanding with the final aim of improving target detection performance.

7. REFERENCES


