ITERATIVE SIGNATURE SUPPRESSION FOR DETECTION AND IDENTIFICATION OF GAS PLUME CONSTITUENTS

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ABSTRACT

In the case of long-wave infrared (LWIR) hyperspectral images, the detection and identification of all gas constituents in a plume is not well achieved by common detectors such as the Adaptive Cosine Estimator (ACE) and the structural background Generalized Likelihood Ratio Test (GLRT). This paper proposes a new approach for hyperspectral imaging called "Iterative Signature Suppression (ISS)" based on the iterative use of the structural background GLRT to detect all gaseous mixture components. The idea behind this method, is to add a previously identified gas signature to the background subspace in order to "subtract" this signal by applying the GLRT again. The results have shown that the ISS method can improve the detection of gas plume constituents hidden under the strongest gas in the plume.

Index Terms— Gas, plume, Scharf GLRT, Generalized Likelihood Ratio Test, Detection, Iterative Signature Suppression

1. INTRODUCTION

In some situations involving gas mixture, the results from the Adaptive Cosine Estimator (ACE) and the structural background Generalized Likelihood Ratio Test (GLRT) detectors have shown that these algorithms are not able to detect all plume constituents, simply because the combined signature of the mixture never induces a strong response from any of the individual target detectors.

This paper proposes and explores a new approach based on the iterative use of the GLRT also referred to as Scharf's GLRT [1, 2]. This new method is called "Iterative Signature Suppression". The idea of this innovative use of the GLRT is to add a previously identified gas to the structural background model in order to "subtract" this signal by applying the GLRT a second time. From this iterative process other gas mixture constituents blinded by the first gas may be found. The proposed algorithm is similar to the successive or serial interference cancellation technique commonly used in code division multiple access[3].

Section 2 presents the ISS method. Section 3 presents the detailed results for an HSI with mixture of multiple-band overlapping absorption signatures. Section 4 concludes the analysis with discussions and recommendations regarding the use of ISS method for the application to gas detection.

2. ITERATIVE SIGNATURE SUPPRESSION METHOD

The structural background Generalized Likelihood Ratio Test (GLRT) [1, 2, 4] basically projects the measured spectrum out of the background subspace and compares it with the projection of the measured spectrum out of the background-plus-signature subspace. This detector can be written ([5, 4]) as:

$$T_{GLRT} = \frac{\mathbf{m}^\top \mathsf{P}_B^\perp \mathbf{m}}{\mathbf{m}^\top \mathsf{P}_{BS}^\perp \mathbf{m}}, \tag{1}$$

where $\mathbf{m}$ is a measured spectrum, $\mathsf{P}_B^\perp$ is the projector out of the background subspace and $\mathsf{P}_{BS}^\perp$ is the projector out of the background-plus-signature subspace.

In the ISS method, the measured spectrum is projected out of the background **plus the target previously identified**, and compared with the measured spectrum projected out of the background, **target** and signature subspace. By doing this, the previously identified target is "suppressed" from the measurement and other plume constituents can then be identified. With the ISS method, the detector (T_{ISS}) becomes:

$$T_{ISS} = \frac{\mathbf{m}^\top \mathsf{P}_{BT}^\perp \mathbf{m}}{\mathbf{m}^\top \mathsf{P}_{BTS}^\perp \mathbf{m}}, \tag{2}$$

where $\mathsf{P}_{BT}^\perp$ is

$$\mathsf{P}_{BT}^\perp = \mathsf{P}_B^\perp \left[I - \frac{(\mathsf{P}_B^\perp t)(\mathsf{P}_B^\perp t)^T}{\left|\mathsf{P}_B^\perp t\right|^2} \right] \mathsf{P}_B^\perp \tag{3}$$

with t being the target signature to be removed, and $\mathsf{P}_{BTS}^\perp$ is

$$\mathsf{P}_{BTS}^\perp = \mathsf{P}_{BS}^\perp \left[I - \frac{(\mathsf{P}_{BS}^\perp t)(\mathsf{P}_{BS}^\perp t)^T}{\left|\mathsf{P}_{BS}^\perp t\right|^2} \right] \mathsf{P}_{BS}^\perp. \tag{4}$$

2.1. Efficiency of the method

Figure 1 shows the efficiency of the method for the case with a mixture with multi-absorption bands with some overlap. The gas mixture released in this image was composed of a ratio of 10 times of Freon 12 and of three times of Freon 22. The part A of Figure 1 shows the gas signatures of Freon 12 and Freon 22. The parts B and C of Figure 1 show the out-of-the-background projection of a measurement and the out-of-the-background signature of Freon 22 before (B of Figure

1) and after (C of Figure 1) adding the Freon 12 signature to the background projector, i.e. removing Freon 12 with the ISS method. Comparing these two Figures shows that the correspondence between the out-of-the-background projection and the out-of-the-background signature is much better when the Freon 12 signature is added to the background and, thus, suppressed with the ISS method. In this case, the detection of Freon 22 is much better and has a much better detection score. Freon 12 has a high absorption line around 10.7 μm in the measurement projected out-of-the-background (blue curve) of the part B of Figure 1. This absorption line reduces the fit of the projected measurement to the projected Freon 22 signature. After ISS method is being applied to the data removing Freon 12 signature, this feature is suppressed from the projected measurement and the projected measurement has now a much better agreement with the projected Freon 22 signature.

3. EXAMPLE: MIXTURE COMPOSED OF MULTI-ABSORPTION BANDS WITH SOME OVERLAP CASE

This section presents a case where the absorption gas signatures in the mixture have with multi-absorption bands and some overlap between the absorption bands. In this example, the mixture is composed of gas signatures with overlapping multiple absorption bands. Figure 2 depicts the different signature combinations associated with this hyperspectral image.

To illustrate the performances of ISS method, we will show the results of a hyperspectral image containing a gas plume with a mixture of three gases: Freon 114 (10), ethylene (5) and Freon 134a (3). The number between parenthesis is related to the proportion of the gas in the mixture. These three gases should be detected relatively easily when individually measure. But with the plume being a mixture of these three gases, only Freon 114 and ethylene are easily detected with the standard GLRT as shown in the Figure 3. They present the Receiver Operating Characteristic (ROC) curves of the GLRT detector using different number of vectors characterizing the background for, respectively, Freon 114, ethylene and Freon 134a and the minimum theoretical limit (dotted line) as defined in [5]. P_d is the number of detections of the specified gas divided by the total number of pixels inside the plume delimited by a mask[5]. P_e is the number of detections outside the mask for all gases in the database, plus the number of detections inside the mask for any gas not present in the gas mixture, normalized by the total number of pixels. From these ROC curves, it is evident that Freon 114 has the strongest detection, ethylene has a good detection but not as good as Freon 114, and Freon 134a is not detected. This can also be shown by plotting the GLRT output for the strongest detection on the image for each gas. Figure 4 presents these results considering the best number of vectors for each gas. The chosen threshold for all the results in this document is 10 times the standard deviation calculated from the background. Again, clearly from these figures, Freon 114 and ethylene are detected in the plume but not Freon 134a.

The first time the ISS method is applied, removing Freon 114, ethylene detection is improved, as shown in Figures 5 and 6 when compared with the previous results. But Freon 134a still does not appear clearly, as shown in Figure 7.

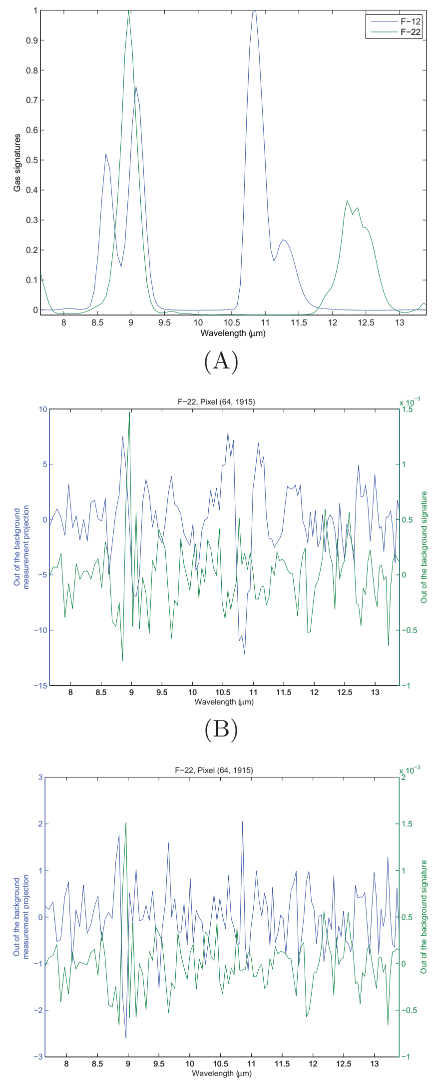


Fig. 1. A: Freon 12 and Freon 22 signatures. B: Out-of-the-background radiance of a measurement (blue) and out-of-the-background Freon 22 signature (green). C: Same as B but this time the ISS method is used removing Freon 12.

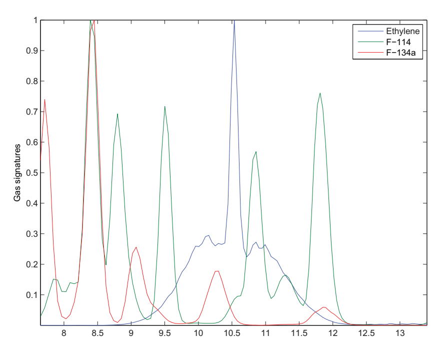
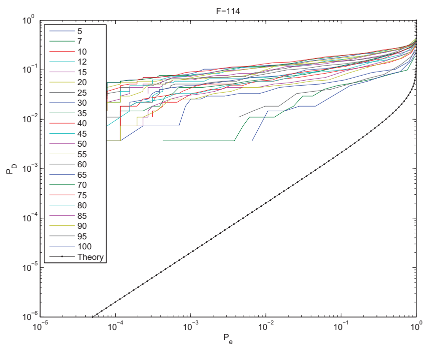
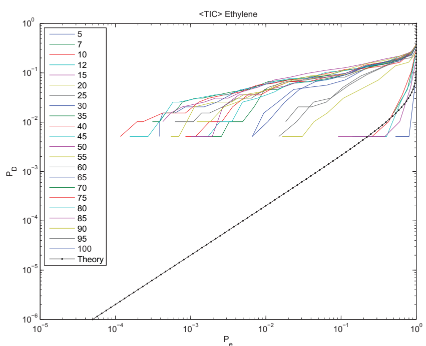


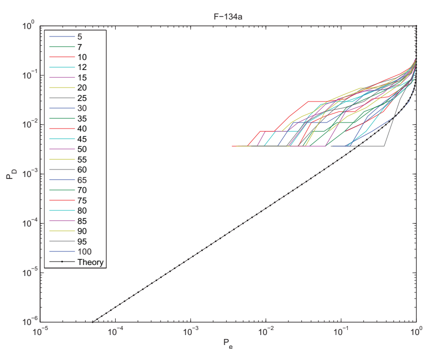
Fig. 2. Ethylene, Freon 114 and Freon 134a signatures of the hyperspectral image



(a) Freon 114

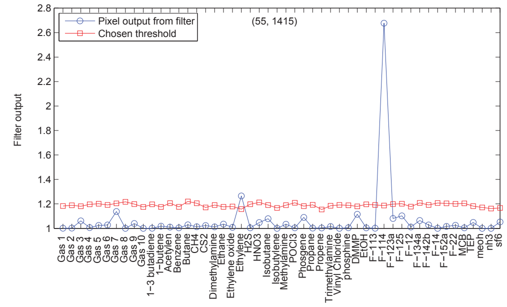


(b) Ethylene

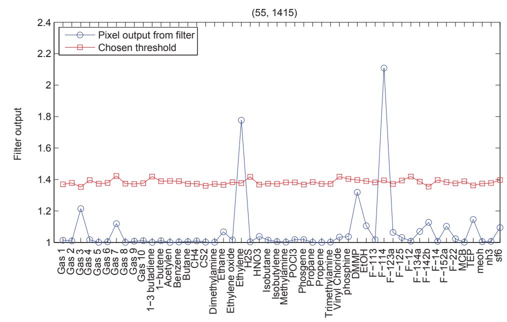


(c) Freon 134a

Fig. 3. ROC curves calculated with the GLRT detector on HSI for different number of vectors characterizing the background.



(a) Optimized for F114



(b) Optimized for Ethylene

Fig. 4. GLRT scores of 50 gases on HSI at the pixel specified at the top

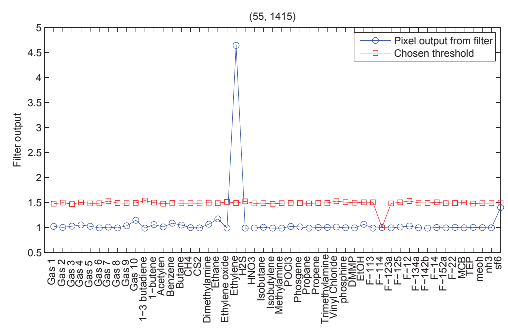


Fig. 5. GLRT scores of 50 gases after ISS removing Freon114 on the HSI at the pixel specified at the top. Optimized for ethylene.

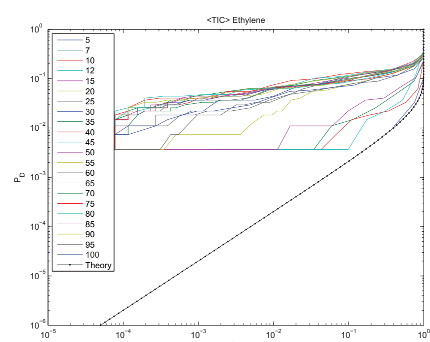


Fig. 6. ROC curves for ethylene calculated with ISS removing Freon 114 on HSI for different number of vectors

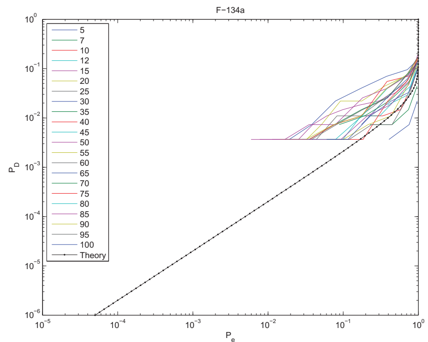


Fig. 7. ROC curves for Freon 134a calculated with ISS removing Freon 114 on HSI for different number of vectors

Applying the ISS method for the second time, including Freon 114 and Ethylene in the filter, enhances the detection of Freon 134a, as shown in Figure 8. The output of the ISS method for Freon 134a is now above the threshold and is detected, as shown in Figure 9.

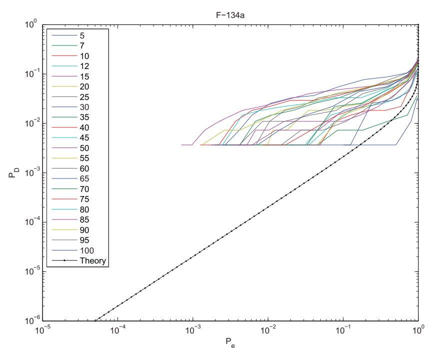


Fig. 8. ROC curves for Freon 134a calculated with ISS removing Freon 114 and ethylene on HSI for different number of vectors

4. CONCLUSION

This paper was to show the efficiency of the new ISS method. This innovative method basically removes a previously identified gas constituent to enhance the detection of other plume elements. This step is achieved by combining the previously identified gas signature in the background subspace. The results have shown that the ISS method can improve the detection of gas plume constituents when their spectral features are hidden under the strongest gas in the plume. However, in the case of single overlapping absorption bands, the method is expected to show less impressive results. The identification of plume constituents with the ISS method represents a significant advantage compared to employing only the standard GLRT detector. The knowledge obtained from the use of this ISS method combined with the results from the GLRT detector could easily feed a physics-based model such as GASEM[6] and then reduce the calculation time by selecting the appropriate gas candidates.

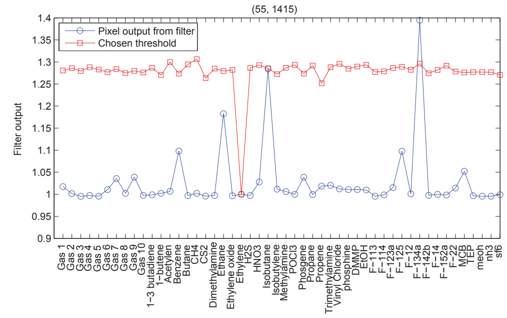


Fig. 9. GLRT scores of 50 gases after ISS removing Freon 114 and ethylene on HSI at the pixel specified at the top. Optimized for Freon 134a.

5. REFERENCES

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