Passive Infrared Hyperspectral Imaging for Standoff Detection of Tetryl Explosive Residue on a Steel Surface Using GLS and ELS-GLS

Neal B. Gallagher

Eigenvector Research, Inc.

James F. Kelly, Thomas A. Blake

Pacific Northwest National Laboratory

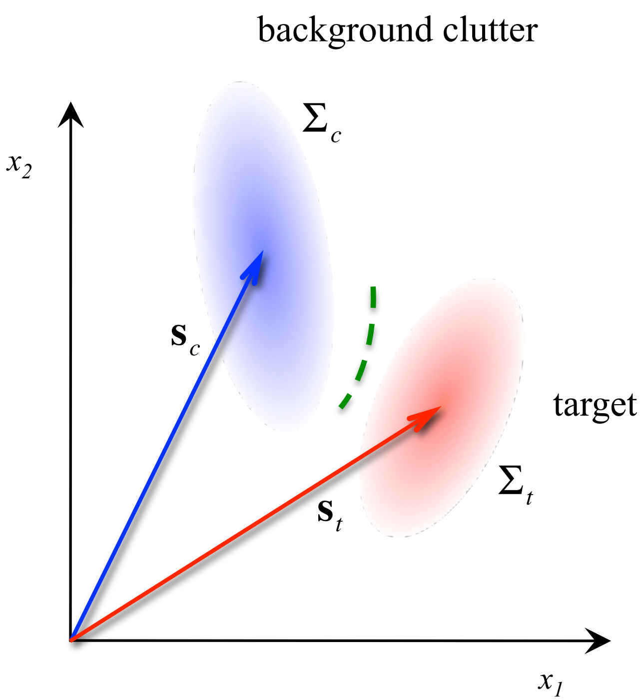
nealg@eigenvector.com

EIGENVECTOR RESEARCH INCORPORATED

Anomaly and Target Detection

- Anomaly detection (e.g., PCA, MAF, MDF) finds pixels that are unusual wrt the general trends in an image
  - but, it doesn't tell the cause of the difference
- Target detection (e.g., LDA, GLS) finds pixels that have an unusual contribution of a specific target direction (e.g., spectrum)
  - detection and classification

Target Detection

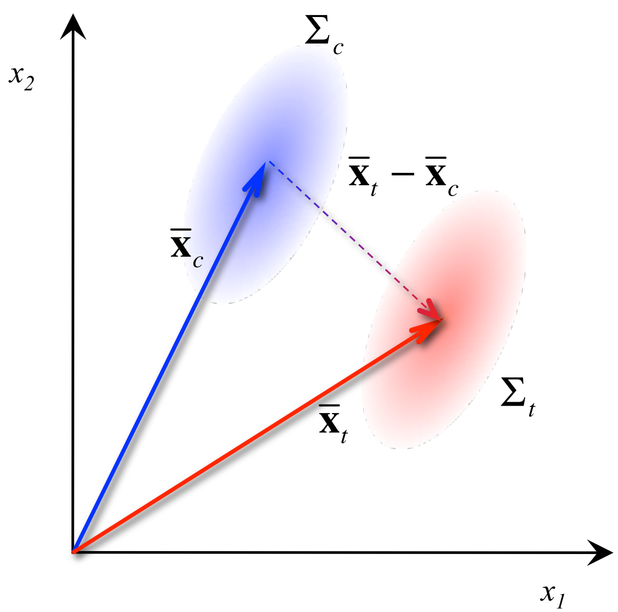


- The objective is to detect target in the presence of a cluttered background
- Clutter includes signal not related to the target and includes
    - interferences (variable background) and noise
- For this example, the boundary between classes might be represented by a non-linear surface between the clutter and target classes

EIGENVECTOR RESEARCH INCORPORATED

Fisher's Linear Discriminant

- The clutter and targets are treated as two classes with means $\bar{\mathbf{x}}_c$ and $\bar{\mathbf{x}}_t$, and covariances Σ_c and Σ_t where $\Sigma_c = \Sigma_t$



- The discriminant function is defined as the distance between classes to variance within classes

$$w_{cal}^2 = (\bar{\mathbf{x}}_t - \bar{\mathbf{x}}_c)\Sigma_c^{-1}(\bar{\mathbf{x}}_t - \bar{\mathbf{x}}_c)^T$$

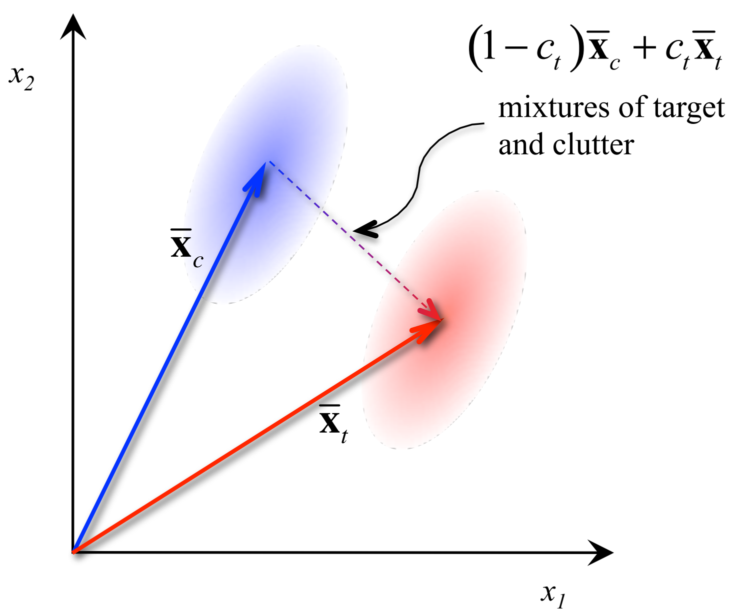
Mixed Pixels

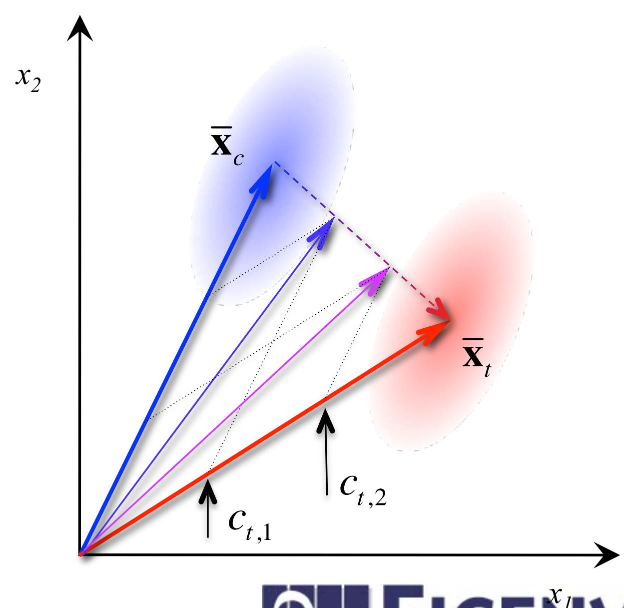
- Mixed pixels lie on the line between the mean responses

$$\mathbf{x} = (1 - c_t)\bar{\mathbf{x}}_c + c_t\bar{\mathbf{x}}_t + \mathbf{e}$$

where c_t is the contribution of target and c_c =(1-c_t) is the contribution of clutter

- Implicitly assumes closure





EIGENVECTOR RESEARCH INCORPORATED

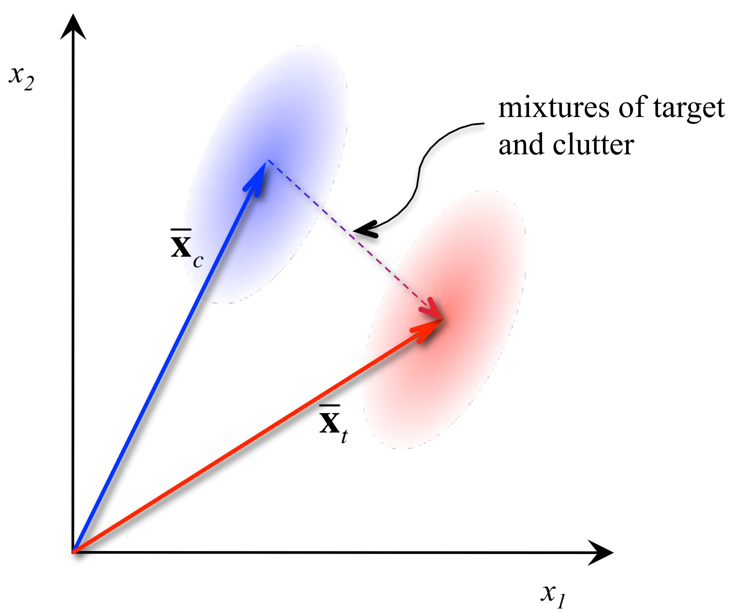
Inverse Clutter Covariance → Whitening

$$\mathbf{x} = (1 - c_t)\bar{\mathbf{x}}_c + c_t\bar{\mathbf{x}}_t + \mathbf{e}$$

$$w^2 = (\mathbf{x} - \bar{\mathbf{x}}_c)\Sigma_c^{-1}(\bar{\mathbf{x}}_t - \bar{\mathbf{x}}_c)^T$$

$$w^2 = (\tilde{\mathbf{x}} - \tilde{\bar{\mathbf{x}}}_c)(\tilde{\bar{\mathbf{x}}}_t - \tilde{\bar{\mathbf{x}}}_c)^T$$

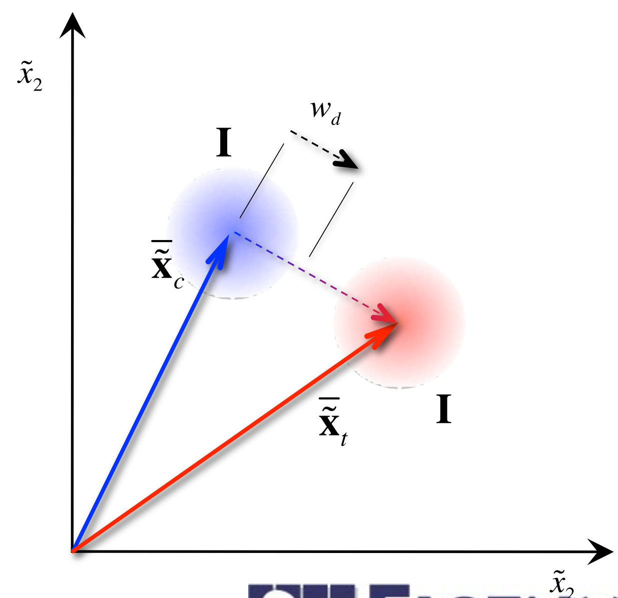
$w > w_d$ new measurements with distances greater than a threshold are considered detections



whiten

$$\tilde{\bar{\mathbf{x}}}_c = \bar{\mathbf{x}}_c\Sigma_c^{-1/2}$$

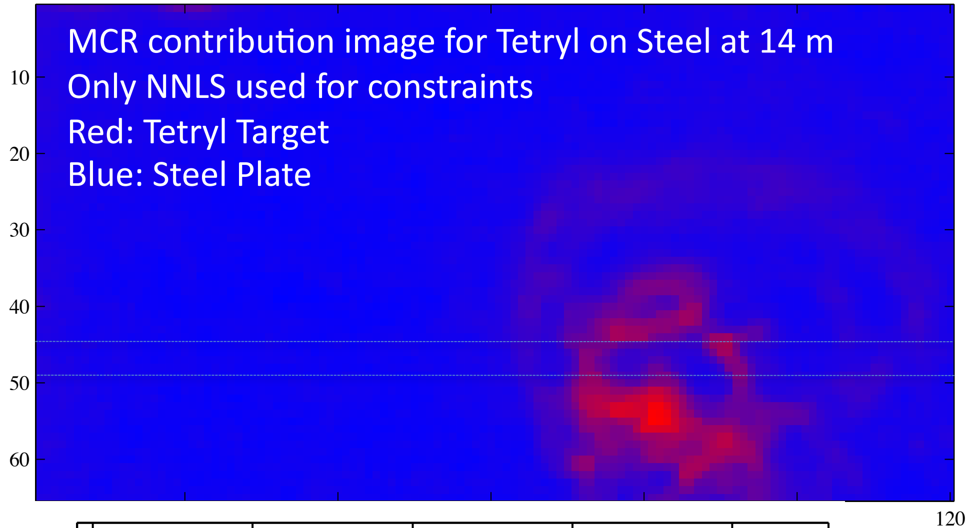
$$\tilde{\mathbf{x}} = \mathbf{x}\Sigma_c^{-1/2}$$

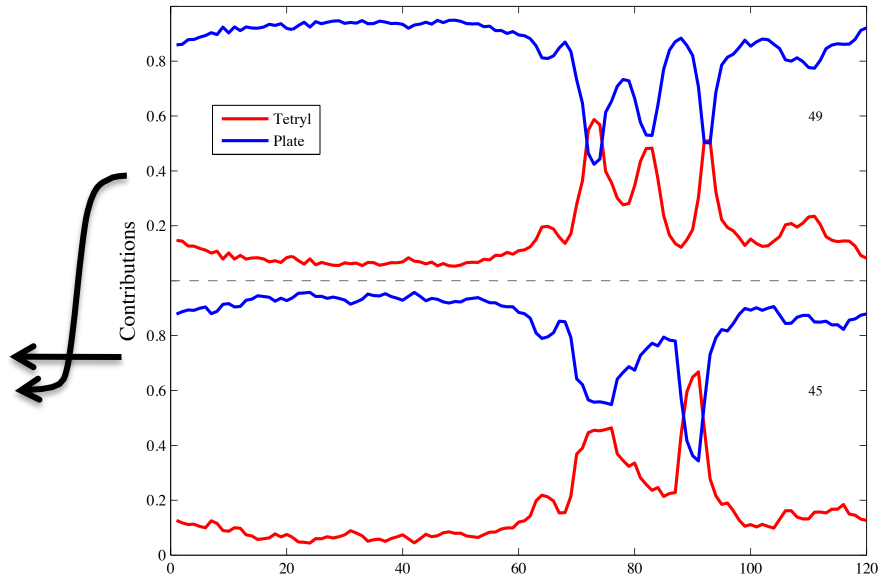


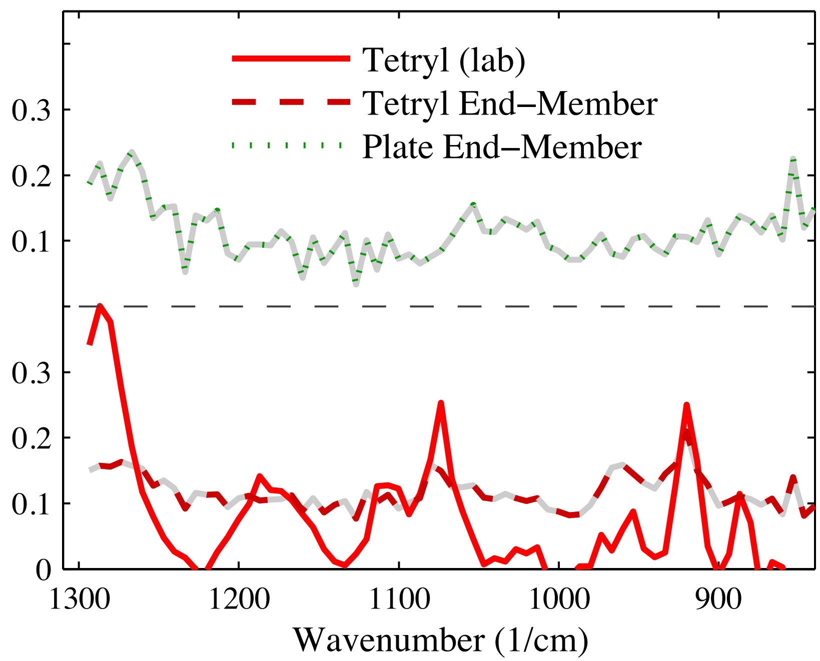
Gallagher, IDRC July 31-Aug 6, 2010

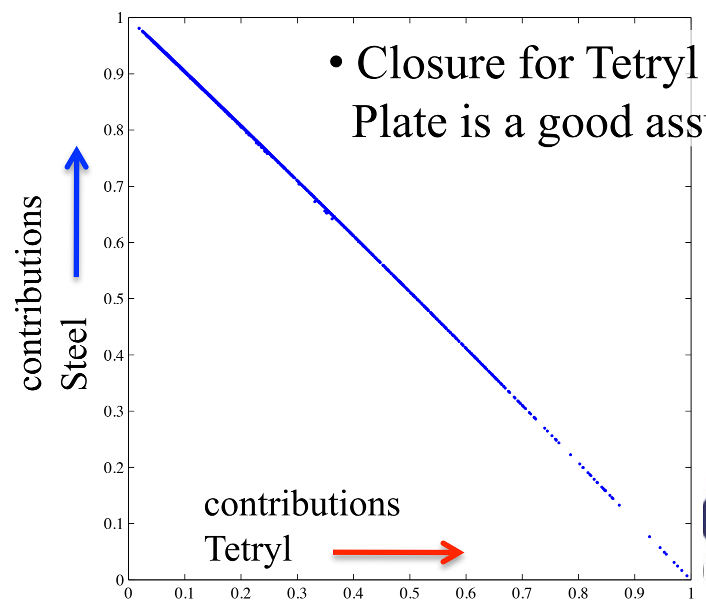
EIGENVECTOR RESEARCH INCORPORATED

Closure for Tetryl on Steel









- Closure for Tetryl on a Steel Plate is a good assumption

LD Analysis for target detection

- LDA classes are represented by their means
  - stationary spectral shape and magnitude

$$\mathbf{x} = \bar{\mathbf{x}}_c + \mathbf{e} \quad \text{off-target pixel}$$

$$\mathbf{x} = \bar{\mathbf{x}}_t + \mathbf{e} \quad \text{on-target pixel}$$

- the model of the sensor response is

$$w^2 = \left(\mathbf{x} - \bar{\mathbf{x}}_c\right)^T \Sigma_c^{-1} \left(\bar{\mathbf{x}}_t - \bar{\mathbf{x}}_c\right)$$

$$\Sigma_c = \tfrac{1}{M_c}\left(\mathbf{X}_c - \mathbf{1}\bar{\mathbf{x}}_c^T\right)^T \left(\mathbf{X}_c - \mathbf{1}\bar{\mathbf{x}}_c^T\right)$$

- how is $\bar{\mathbf{x}}_t$ obtained a priori?
  - it's likely a scalar multiple of the pure component spectrum $c_t\mathbf{s}_t$

Generalized Least Squares (GLS)

- Generalized least squares (GLS) is a weighted / whitened version of the CLS model

$$\hat{c}_t = \left(\mathbf{s}_t^T \Sigma_c^{-1} \mathbf{s}_t\right)^{-1} \mathbf{s}_t^T \Sigma_c^{-1} \left(\mathbf{x} - \bar{\mathbf{x}}_c\right)$$

$$\hat{c}_t = \left(\tilde{\mathbf{s}}_t^T \tilde{\mathbf{s}}_t\right)^{-1} \tilde{\mathbf{s}}_t^T \left(\tilde{\mathbf{x}} - \tilde{\bar{\mathbf{x}}}_c\right)$$

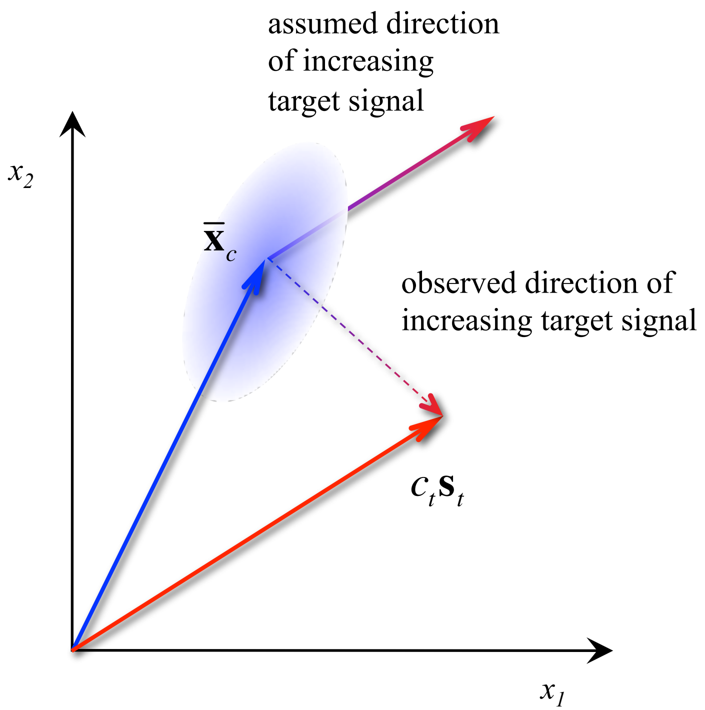
  - Aitken Estimator, Matched Filter, Adaptive Matched Filter, et. al
- GLS allows the use of $\mathbf{s}_t$ as the target
  - don't need to define mean of target class
  - assumes the target shape doesn't vary but the magnitude can

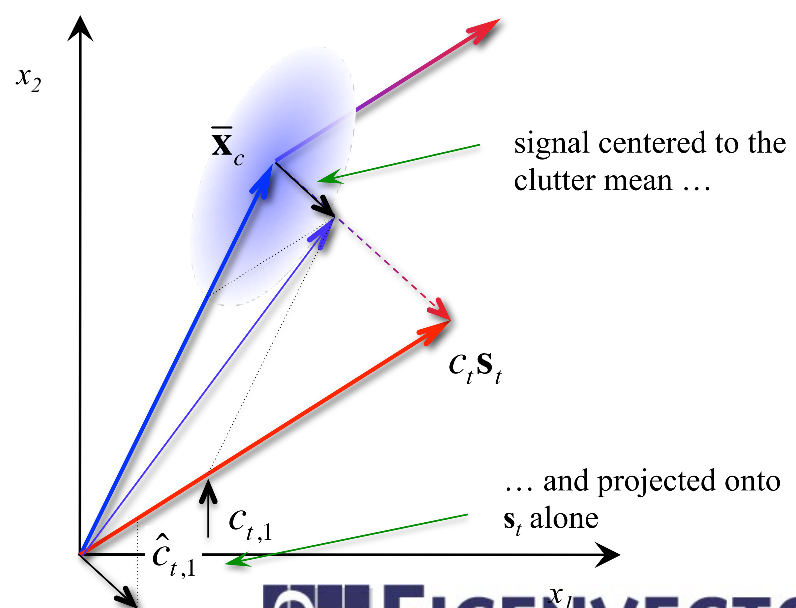
GLS References

- Aitken A, "On Least Squares and Linear Combinations of Observations", *Proceedings of the Royal Society of Edinburgh*, **55**, 42-48 (1935).
- Turin GL, "An Introduction to Matched Filters." *IRE Transactions on Information Theory*, **6**(3), 311-329 (1960). {special issue on matched filters}
- Burr T, Hengartner N, "Overview of Physical Models and Statistical Approaches for Weak Gaseous Plume Detection using Passive Infrared Hyperspectral Imaging," Sensors **6**, 1721-1750 (2006).
- Martens, H. and Næs, T., “Multivariate Calibration”, John Wiley & Sons, New York, NY (1989). "sample based"
- Marbach R, "New method for multivariate calibration," *J. Near Infrared Spectrosc.*, **13**, 241-254 (2005)
- T.A. Blake, J.F. Kelly, N.B. Gallagher, P.L. Gassman and T.J. Johnson, "Passive detection of solid explosives in Mid-IR hyperspectral images," *Anal Bioanal Chem*, **395**, 337-348 (2009).
- N.B. Gallagher, "Detection, Classification and Quantification in Hyperspectral Images using Classical Least Squares Models," in *Techniques and Applications of Hyperspectral Image Analysis*, H. F. Grahn and P. Geladi, eds. (John Wiley & Sons, West Sussex, England), 181-201 (2007).
- H. Martens, M. Høy, B.M. Wise, R. Bro and P.B. Brockhoff, "Pre-whitening of data by covariance-weighted pre-processing," *J. Chemo.*, **17**(3), 153-165 (2003).

GLS Centered to Clutter Mean

- Centering the signal to the clutter mean $\mathbf{x} - \bar{\mathbf{x}}_c$ implicitly assumes that $\mathbf{x} = \bar{\mathbf{x}}_c + c_t \mathbf{s}_t$





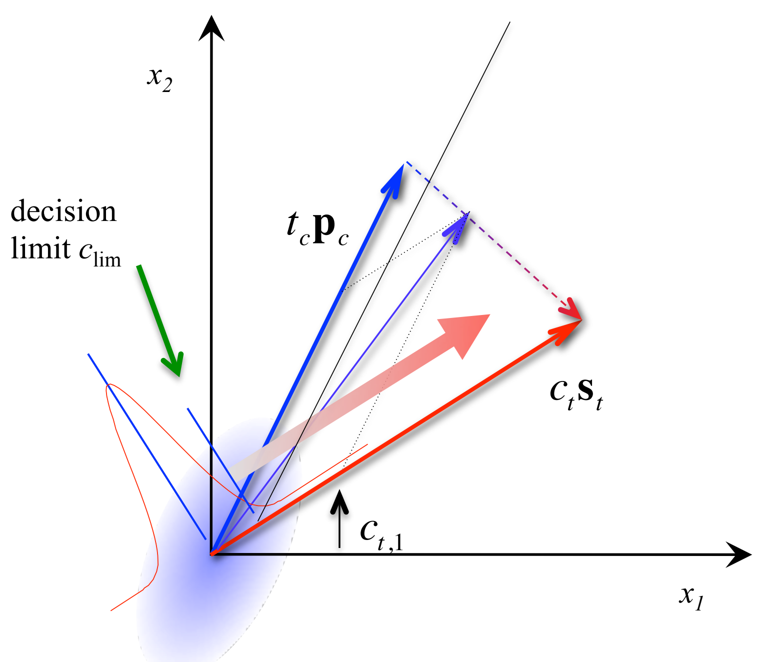
EIGENVECTOR RESEARCH INCORPORATED

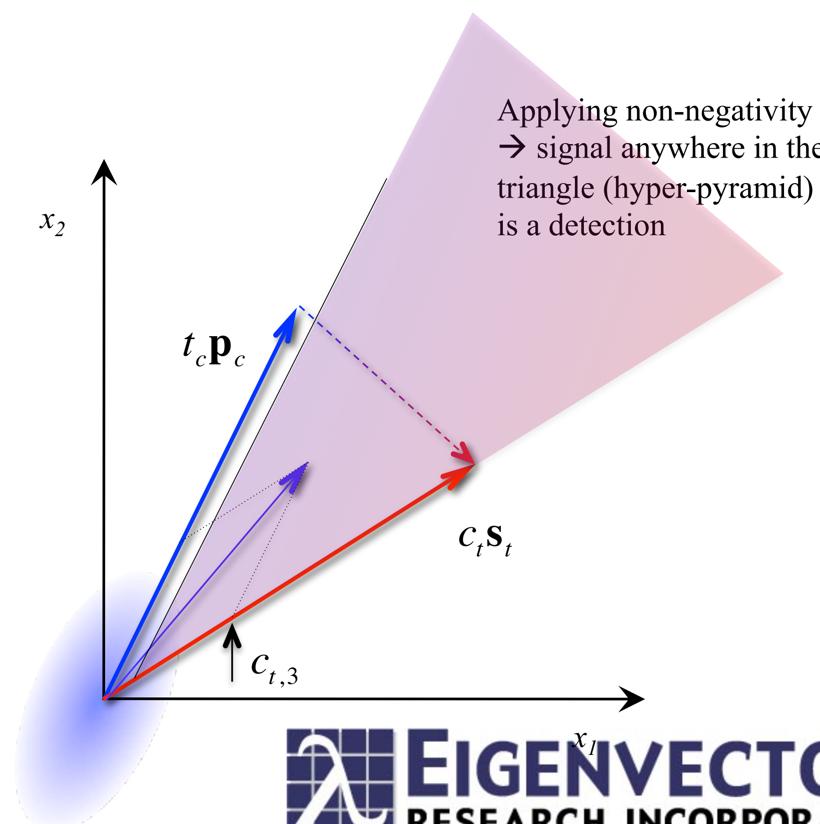
GLS Projected onto "Mean"

- Use first PC of clutter as a "target"
  - model center is zero
  - extended least squares

$$\begin{bmatrix}\hat{c}_t & \hat{t}_c\end{bmatrix} = \left(\mathbf{S}^T\Sigma_c^{-1}\mathbf{S}\right)^{-1}\mathbf{S}^T\Sigma_c^{-1}\mathbf{x}$$

$$\mathbf{S} = \begin{bmatrix}\mathbf{s}_t & \mathbf{p}_c\end{bmatrix}$$



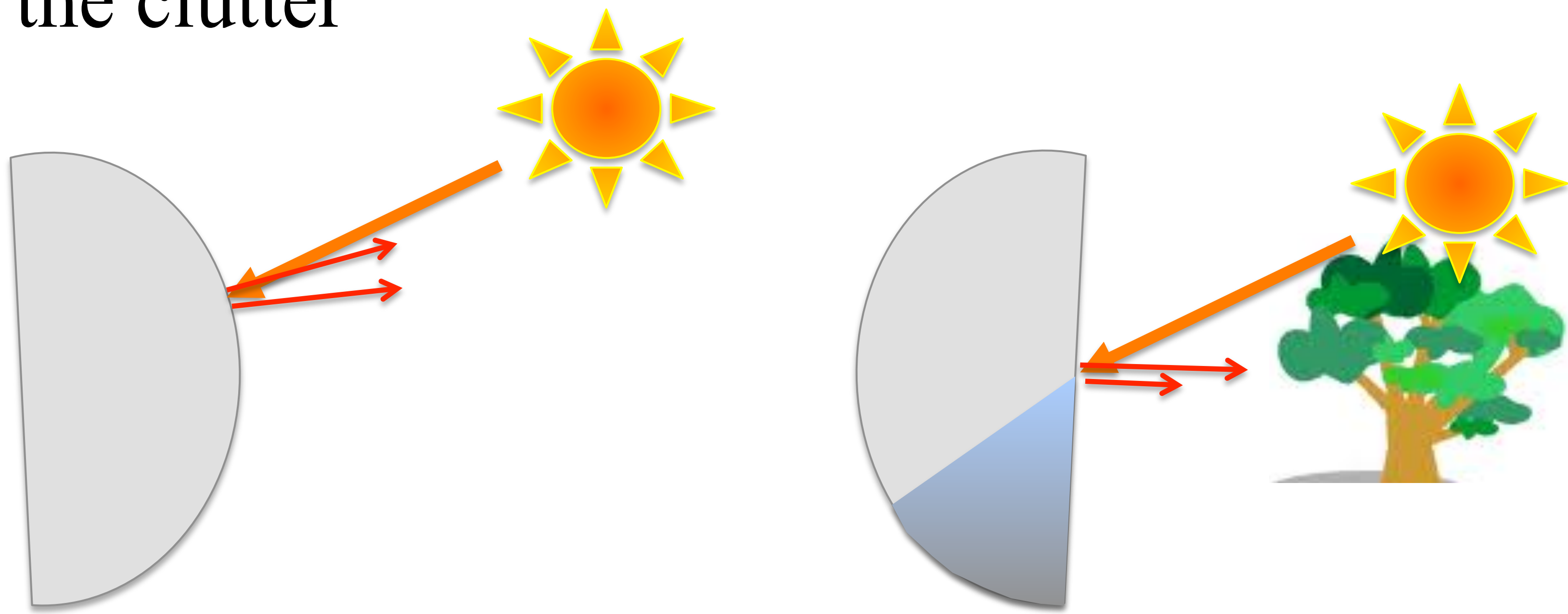


GLS For Target Detection

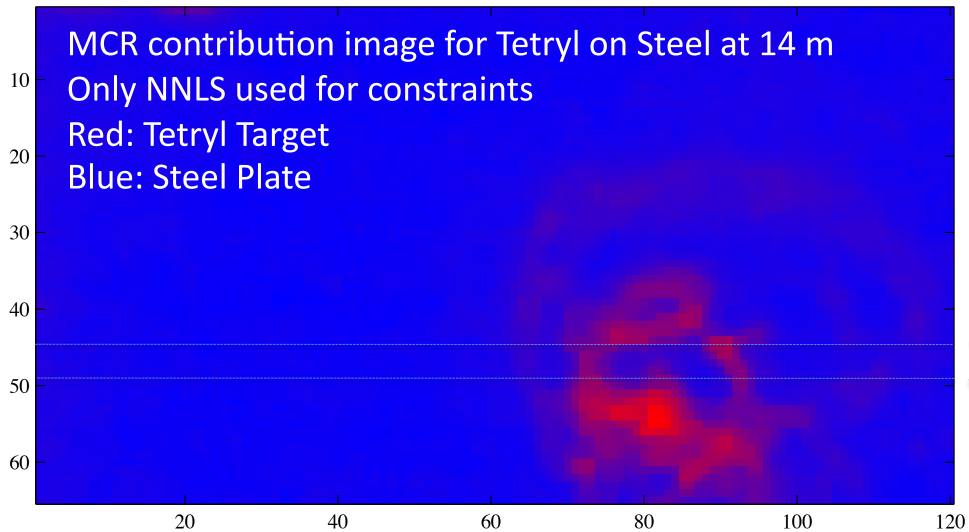
- The GLS model form
  - allows the target and clutter magnitude to vary
  - can easily impose non-negativity
    - physics suggests this constraint
  - can easily impose closure
    - but, what if the signal changes due to lighting or shading?
    - even if closure is appropriate shading suggests relaxing the strict equality
    - $c_t + c_c = 1 \quad \rightarrow \quad c_t + c_c < 1$

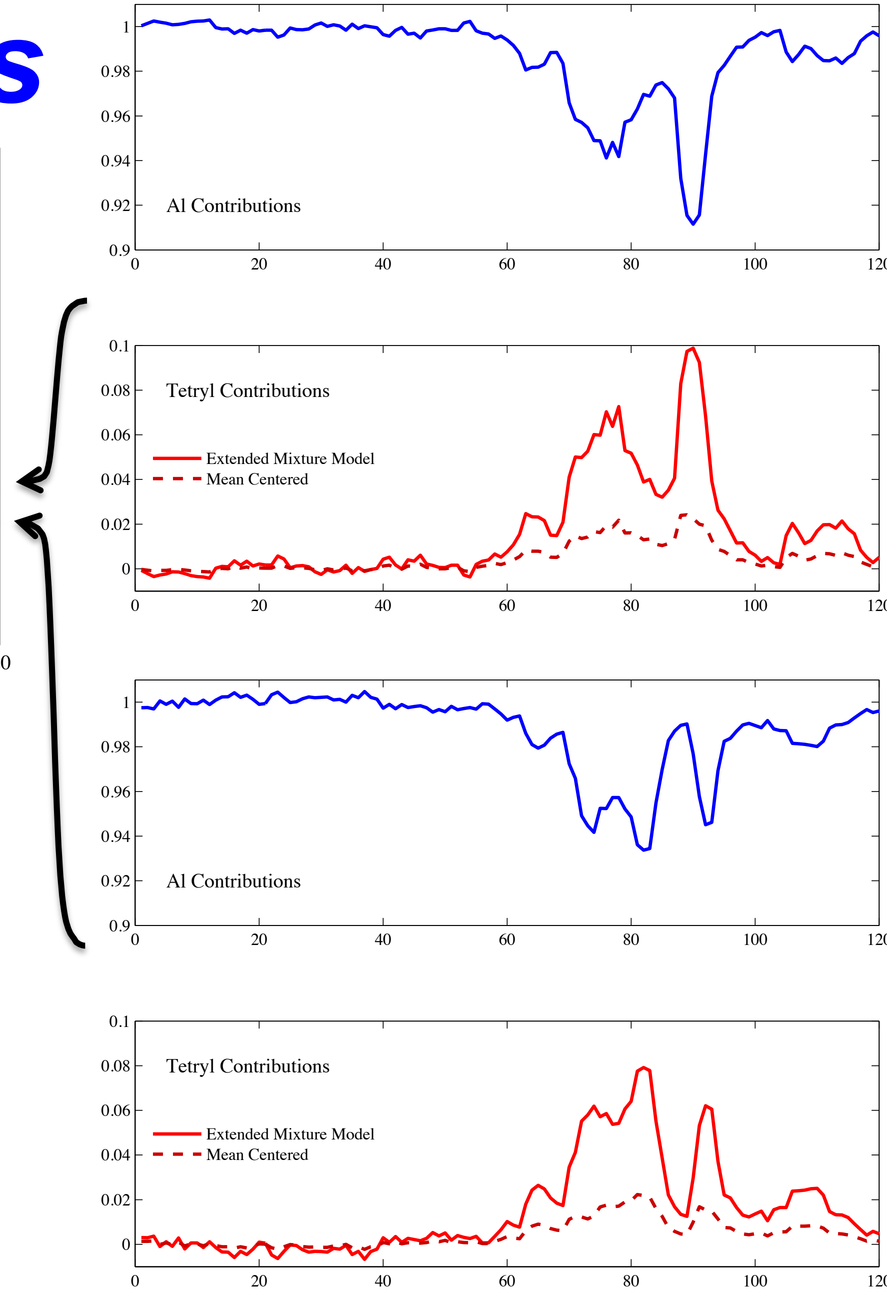
Lighting Changes

- lighting changes can change the magnitude of the clutter



Compare GLSs





- Contributions for the mean-centered model tend to be lower and show less contrast w/ the null than for the extended mixture model (ELS)
- Additionally, contributions on the background (steel plate) are available for the ELS model and provide an additional piece of information in target detection

GLS-ELS Conclusions

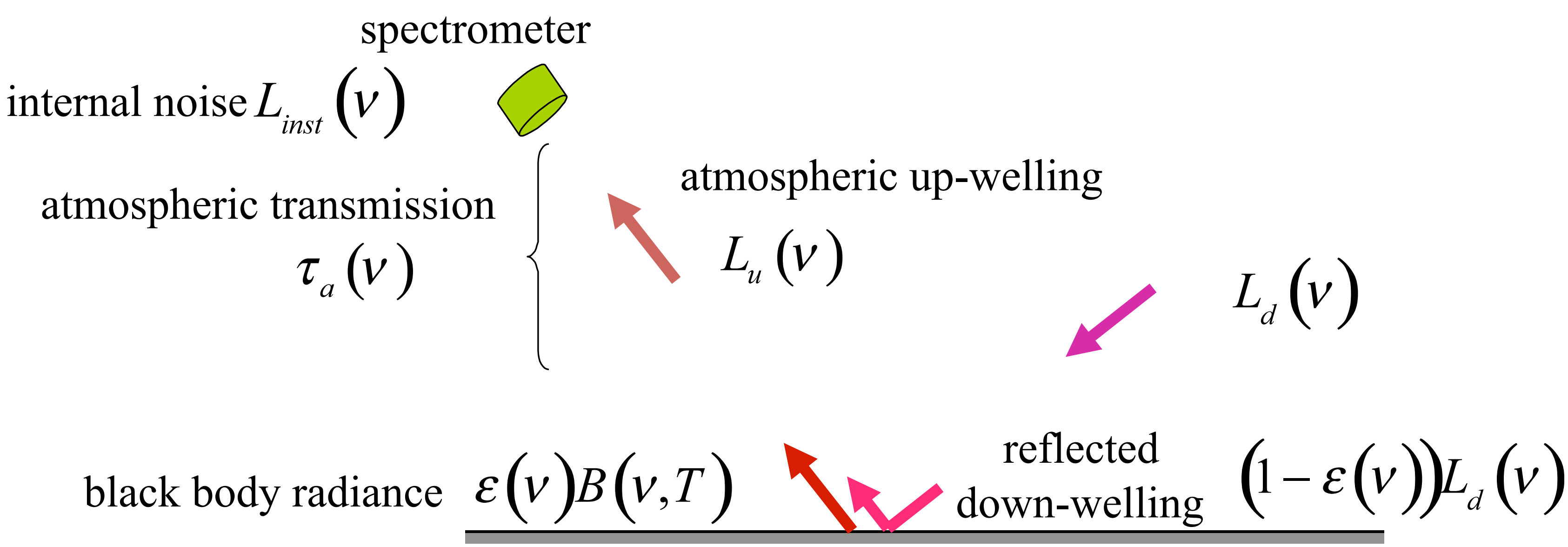
- The GLS-ELS version of the target detection algorithm shows distinct promise over the traditional approach to mean-centering of the signal
  - it is more of a 'chemistry / physics' view of the signal
- However, …

Simple Radiance Model for Standoff Detection

measured radiance

$$L(\nu) = L_u + \left[\varepsilon(\nu)B(\nu,T) + (1-\varepsilon(\nu))L_d(\nu)\right]\tau_a(\nu)$$

$$L - L_u - B\tau_a = (1-\varepsilon)\left(L_d - B\right)\tau_a$$



EIGENVECTOR RESEARCH INCORPORATED