Satellite Retrieval Assimilation
(a modified observation operator)

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Overview

- Introduction
- Derivation of retrieval equations
- Modified Assimilation observation operator based upon retrieval equations
- Results from retrieval assimilation
- Conclusions
Introduction

- **(Level 0)** Satellite instrument sensors unprocessed measurements.
- **(Level 1)** Unprocessed measurements are converted into radiances using instrument calibrated algorithms.
- **(Level 2)** Retrieval profiles of desired geophysical quantities \((T,q,O_3,CO \ldots)\) are calculated from radiances using retrieval algorithms based upon atmospheric physics and a priori info.
- **(Level 3)** Space time averaged products like fields

Artist depiction of NASA terra Satellite with MOPITT instrument
Introduction

- There are two different possibilities in satellite measurement assimilation:
  1. Radiance: Direct use of the radiance observations (level 1)
  2. Retrieval: Externally generated retrievals -- profiles typically deduced from a set of radiances through a regression (level 2)
Radiance Assimilation

• Advantages:
  – A1) Avoiding contamination by the external regression for which error characteristics may be poorly known
  – A2) Raw radiance observations exhibit less spatially correlated errors than processed retrieved information.

• Disadvantages:
  – D1) Increased computational cost of the observational operator which maps from the model state to the measurement space
  – D2) Quality control falls often to DA community
Retrieval Assimilation

• Advantages:
  – A1) Observations are expressed in the form of geophysical fields so that observation operators are less computationally expensive
  – A2) Organizations handling retrievals handle quality control which is carefully and continuously monitored producing a high quality product

• Disadvantages:
  – D1) Contamination by external regression error characteristics
  – D2) Spatially correlated errors
Assimilation Method Usage

• In the NWP community the radiance assimilation has progressively replaced retrieval assimilation for variables such as winds, temperatures and humidity (Thepaut 2003).

• In the chemical modeling community, and for trace gasses in the NWP community, retrieval assimilation is still prevalent.

• Since my dissertation experiments deal with the assimilation of satellite trace gas measurements of ozone and CO I have pursued the path of retrieval assimilation
Dissertation

• My experiments concentrate on assimilating
  – ozone retrievals from the Solar Backscatter Ultraviolet (SBUV/2) satellite instrument (version 8)
  – carbon monoxide (CO) retrievals from the Measurements Of Pollution In The Troposphere (MOPITT) instrument (version 3)
• Using the Local Ensemble Transform Kalman Filter (LETKF) data assimilation technique
• With a modified version of the NCEP GFS model
  – reduced resolution
  – incorporation of ozone and CO modeling)
SBUV/2 v8 Ozone (Bhartia et al., 2004)
6 hour period ~300 profiles

• Profiles: retrieval (black), retrieval error (red), and a priori profile (green), Abscissa log pressure 1000hPa to 0.1hPa, Ordinate 0 to 80DU

• Each profile has approx 12 retrievals in integrated Dobson Units

• Error reported do not include covariances
Profiles: retrieval (black), retrieval error (red), and a priori profile (green), Abscissa log pressure 1000hPa to 100hPa, Ordinate 0 to 600ppb

Each profile has up to 6 retrievals in point measurement mixing ratio

Fixed global climatological a priori profile
Derivation of Retrieval Method

Method is based upon C. Rodgers 2000

1. Derivation of relationship between the retrieval (\( \hat{x} \)) and the radiances (\( y \)).

2. Derivation of relationship between the retrieval (\( \hat{x} \)) and the true state of the atmosphere (\( x \)).

3. Development of an modified observation operator taking into account of the above relationship.

4. Difference between the “innovation” using a conventional versus modified observation operator.
Derivation of Retrieval Method

• Begin with the forward model \( F \) which relates the geophysical quantities to be retrieved \( x \) to the radiances \( y \):

\[
y = F(x) + \varepsilon
\]

• We assume forward model is linear:

\[
y = Kx + \varepsilon
\]

• \( K \) is the linearization of the forward model (can be thought of as an observation operator) and \( \varepsilon \) noise in radiances and error in forward model
Retrieval

• To calculate a satellite retrieval profile given observed satellite radiances is an ill posed inverse problem
• Using a Bayesian approach we can derive a Kalman Filter type relationship:

\[ \hat{x} = x_a + G_y(y - Kx_a) \]

• Where \( x_a \) is the a priori (or background or first guess), and \( G_y \) is the retrieval gain matrix (or Kalman gain matrix).
Retrieval Gain Matrix

- The expression for the retrieval gain:
  \[ G_y = S_a K^T (K S_a K^T + S_\varepsilon)^{-1} \]

- Where \( S_a \) is the a priori error covariance (or background error covariance), and \( S_\varepsilon \) is the radiance error covariance (or observation error covariance).
a Priori Profile

• The a priori may be thought of as an independent estimate of the state obtained from sources other than the direct measurement.

• The a priori represents knowledge of the state before the measurement is made. If the measurement were not made the a priori would be our only knowledge.

• For SBUV/2 ozone and MOPITT CO a priori profiles are climatologically calculated and temporally (if not spatially -- like MOPITT) invariant.
Retrieval Equation

- Combine: \( y = Kx + \varepsilon \)  \( \hat{x} = x_a + G_y(y - Kx_a) \)

\[
\hat{x} = x_a + G_y(Kx + \varepsilon - Kx_a)
\]

\[
\hat{x} = x_a + G_y(Kx - Kx_a) + G_y \varepsilon
\]

\[
\hat{x} = x_a + G_y K(x - x_a) + G_y \varepsilon
\]

- The retrieval gain matrix \( G_y \) can be combined with the linearized forward model \( K \) to form the averaging kernel matrix \( A \). And the retrieval gain matrix combined with the error term to form the retrieval error \( \hat{\varepsilon} \).
Retrieval Equation

\[ \hat{x} = x_a + A(x - x_a) + \hat{\epsilon} \]

• From this relationship it is obvious that the true state of the atmosphere is not directly comparable to the retrieval unless the averaging kernel matrix is the identity matrix (bad assumption).
• Smoothing by the averaging kernel matrix along with information from the a priori profile is also included.
Observation Operator

- In general, observation locations and model grid points do not match up in either horizontal or vertical directions.
- Shown to the left is the horizontal distribution of SBUV/2 and vertical distribution of SBUV/2 ozone observations.
- Leading to a conventional retrieval observation operator based on interpolation:

$$H(x^f)$$
Observation Operator

• The conventional observation operator however does not take into account the information used in the retrieval algorithm i.e. the a priori profile and averaging kernel smoothing.

• I propose a modified observation operator which includes this information:

\[
\dot{H}(x_f) = x_a + A(H(x_f) - x_a)
\]
Assimilation Innovation

\[ d = y^0 - H(x^f) \]

\begin{align*}
\text{Conventional} \\
\hat{d} &= \hat{x} - H(x^f) \\
\hat{d} &= x_a + A(x - x_a) + \hat{\varepsilon} - H(x^f)
\end{align*}

\begin{align*}
\text{Modified} \\
\hat{d} &= \hat{x} - \dot{H}(x^f) \\
\hat{d} &= x_a + A(x - x_a) + \hat{\varepsilon} - (x_a + A(H(x^f) - x_a)) \\
\hat{d} &= Ax - AH(x^f) + \hat{\varepsilon}
\end{align*}
Assimilation Innovation

\[ d = x_a + A(x - x_a) - H(x^f) + \hat{e} \quad \text{Conventional} \]

\[ d = Ax - AH(x^f) + \hat{e} \quad \text{Modified} \]

- When little to no radiance information is measured by the satellite for a retrieval then the averaging kernel will tend towards 0 and the retrieval tends toward the a priori.
- In this situation in conventional assimilation we would assimilate to the a priori where as in the modified assimilation the innovation would tend towards 0.
Results of Ozone Assimilation
Results of CO Assimilation
Conclusion

- Using conventional observation operators for retrieval assimilation you are effectively assimilating a priori information into your model if your averaging kernel is anything other than the identity matrix.
- Using a modified observation operator, based upon the averaging kernel and a priori profile you can remove the a priori information and reduce the contamination by the retrieval algorithm.