Optical Path Transmittance: OPTRAN. Forward and Adjoint Modeling

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Traditional Fast Transmittance Model

- Interpolate $T(P)$, $q(P)$ to fixed pressure levels
- Predictors $T$, $q$
- Include zenith angle as a predictor
- Predictand is transmittance departure or optical depth, multiple linear regression
Optical Path Transmittance (OPTRAN) approach

- Regression on levels of absorber amount
- Predictors are a function of T, P, q
- Zenith angle implicit in absorber amount
- Arbitrary pressure profile permitted
- Predictand is absorption coefficient for H2O, O3, mixed gases
- Permits changes to ‘mixed gas’ amounts as well
Heritage

- McMillin, Fleming and Hill (AO,1979)
- McMillin, Crone, Goldberg, Kleespies (AO,1995)
- McMillin, Crone, Kleespies (AO,1995)
- Three papers in the works
OPTRAN performance

• Water vapor channel much better than RTTOV
• Temperature channels generally not quite as good as RTTOV (before McMillin improvements)
What’s this adjoint stuff it all about?

1DVAR / maximum probability solution is that which minimizes a ‘cost’ or ‘penalty function:

\[ J(x) = (x - x^b)^T B^{-1} (x - x^b) + (y^o - y(x))^T O^{-1} (y^o - y(x)) \]

where \( x^b \) is an initial estimate given by the model state vector, \( x \) is the model state for which the solution is desired, \( y^o \) is the vector of observations, \( y(x) \) is an operator which transforms the model state vector into the same parameters as the observations, and \( B \) and \( O \) are the background and observational error covariance matrices respectively. For our purposes, \( y(x) \) is the radiative transfer operator. Note that \( O \) is a combination of observational errors and radiative transfer errors. (This is just a least squares problem)
What’s it all about: part deux

How do we find the minimum? From first quarter Calculus: Take the first derivative and set it equal to zero.

$$\nabla J(x) = B^{-1}(x - x^b) - K(x)^T \ O^{-1}(y^o - y(x)) = 0$$

where $K(x)$ is the matrix of partial derivatives of $y(x)$ with respect to the elements of $x$. (factor of 2 divides out)
What’s it all about: part trois

It is evident that the solution requires both the forward radiative transfer operator $y(x)$, and the transpose of its derivative, $K(x)^T$. $K(x)^T$ is called the adjoint, or Jacobian.

$x = \{ T_1, T_2, T_3, \ldots, T_n, q_1, q_2, q_3, \ldots, q_n, \ldots \}$

$y(x) = \{ R_1, R_2, R_3, \ldots, R_m \}^T$
What’s it all about, part quatre

\[ K(x)^T = \begin{bmatrix}
\frac{\partial R_1}{\partial T_1} & \frac{\partial R_2}{\partial T_1} & \frac{\partial R_3}{\partial T_1} & \cdots & \frac{\partial R_m}{\partial T_1} \\
\frac{\partial R_1}{\partial R_1} & \frac{\partial R_2}{\partial R_1} & \frac{\partial R_3}{\partial R_1} & \cdots & \frac{\partial R_m}{\partial R_1} \\
\frac{\partial T_2}{\partial R_1} & \frac{\partial T_2}{\partial R_2} & \frac{\partial T_2}{\partial R_3} & \cdots & \frac{\partial T_2}{\partial R_m} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
\frac{\partial q_1}{\partial R_1} & \frac{\partial q_1}{\partial R_2} & \frac{\partial q_1}{\partial R_3} & \cdots & \frac{\partial q_1}{\partial R_m} \\
\frac{\partial q_2}{\partial R_1} & \frac{\partial q_2}{\partial R_2} & \frac{\partial q_2}{\partial R_3} & \cdots & \frac{\partial q_2}{\partial R_m} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
\frac{\partial q_n}{\partial R_1} & \frac{\partial q_n}{\partial R_2} & \frac{\partial q_n}{\partial R_3} & \cdots & \frac{\partial q_n}{\partial R_m}
\end{bmatrix} \]
What’s it all about, part cinq

In olden days (say 1990), computation of $K(x)^T$ required $N+1$ forward model calculations using forward (or backward) finite differencing (centered required $2N+1$). Thus these techniques were only used in limited studies.

In these modern times, using adjoint coding techniques $K(x)^T$ can be computed with the effort of about 3 forward model calculations.
What are these all the models?

• The **tangent linear** model is derived from the forward model
  - gives the derivative of the radiance with respect to the state vector (vector output, m channels)

• The **adjoint** is derived from the tangent linear model
  - gives the transpose of the derivative of the radiance with respect to the state vector (vector output, N variables)

• The **Jacobian** is derived from the adjoint model
  - gives the transpose of the derivative of the radiance with respect to the state vector by channel (matrix output, Nxm)

• At NCEP, only the forward and the Jacobian models are actually used, but all models must be developed and maintained in order to assure a testing path, and to make sure the performance is correct.
Why can’t we just use the Tangent Linear Model?

- You can.
- However, it still takes $N$ TL calculations.
- You avoid the finite differencing because the TL is the analytic derivative, but you just get a vector of radiances for each call. You still have to call it for each element of the input vector.
Testing

• Testing the code is rigorous and analytic
• Each code is tested for consistency with the model from which it was developed
• Code is tested bottom up, lowest level first.
• Full TL model is tested before moving to adjoint
• Full Adjoint is tested before moving to Jacobian
Adjoint Compiler

• Giering and others have written compilers that generate TL and adjoint code
• Some people at NCAR swear by them
• Others swear at them (just kidding)
• We feel that better optimization can be achieved by hand coding.
Summary

• Quick overview of OPTRAN

• Description of Adjoint and associated models

• Keep these brave souls who will take the coding class in your thoughts.
Class Participants Please Remain for a Few Minutes