Methods of optimal planning of remote sensing experiment in problems of satellite meteorology.

Nicolai Uvarov1, Anton Sokolov2, Anatoly Chavrov3

1G. V. Kurdjumov Institute for Metal-Physics, NASU, Ukraine, 03680, Kiev, Academician Vernadsky blvd. 36. 2Laboratoire de Physico-Chimie de l’Atmosphère (CWRIS EA 4493), Univ. du Littoral Côte d’Opale & Univ. Lille Nord de France, 1984 Av. Maurice Schumann - 59140 Dunkerque
3Institute of Numerical Mathematics RAS, Russia, 119991, Moscow, ul. Gubina. 8 (mail to: uvarovn@gmail.com)

While optimal planning of satellite experiment it is necessary to take into account the physical nature of measured values. The idea of an increase of the spectral resolution to obtain the high precision of retrieval leads to decreasing of the signal/noise ratio in such “narrow” channels. The alternative idea is an “optimal” merging of radiative energy in the various (correlated) spectral ranges in a number of “superchannels”. As it was shown, such methods can exceed a “complete” experiment of high resolution in an information content.

In this work the techniques of an optimum choice are considered of spectral channels with the fixed and variable widths. The following methods of the optimization and optimal planning were employed for a remote sensing experiments: DRM (Determination of Data Resolution Matrix), DRM(SVD), Jacobs, Iterations (selection of the sateellite channels is defined by Entropy Reductioin), superchannel technique (spectral channel with variable width - based on maximizing of Fisher’s information matrix).

The “best linear estimate” method and the “variational” technique were employed for the inversion of measurement data by the channels, obtained by various selection techniques. The atmospheric temperature and humidity profiles were retrieved. The retrieval error was calculated for the data of different spectral resolution for those channel selection techniques.

Instrument simulation – forward problem

$$y_{v,
u} = \frac{1}{v} \int d\nu \, \xi_v(\nu) \tilde{g}_v(\mu) I_{l}(\mu) d\mu + \gamma_v$$

- signal measured at frequency $\nu$,
- at the angle of where: $\mu = \cos \theta$.

$\xi_v(\nu)$ - spectral response function; $\tilde{g}_v(\mu)$ - angular function; $\gamma_v$ - instrument error.

Monochromatic radiation:

$$I_{l}(\mu,\nu>0) = I_0 + I_1 + I_2 + I_3(\mu)B(T) \exp(-\frac{1}{\mu^2}k_\nu(z_e)de) \times \exp(-\frac{1}{\mu^2}k_\nu(z_e)de) d\nu + a_\nu(\mu) \exp(-\frac{1}{\mu^2}k_\nu(z_e)de) U_r$$

$k_\nu(z_e)$ - absorption (LBL algorithm); $B(T(z))$ - Planck function; $a_\nu(\mu)$ - emissivity - reflection; $\tilde{g}_v(\mu)$ - reflection; $g_v(\mu) = 1$

Atmospheric parameters retrieval – inverse problem

- Linear: $R = x - Ry$
- Non-linear (variational). Minimization of the cost function:
- $x$ - vector to retrieve, $x_0$ - a priori estimate, $y_0$ - measurement,
- A - Jacobian
- $y_0$ - forward model; $S_0$ - weight matrices.
- $\Sigma_x$ - error covariance
- $S_0$ - predictor $x$ covariance

1. 3000 samples were taken from the ECMWF Databank for calibration and 300 for verification, the satellite measurements were simulated.
2. Linear Reduction estimate is taken as the a priori estimate for variational techniques.
3. $x$ after normalization was projected at the PC(EOF) subspace.
4. Jacobean was calculated analytically for the modified Newtonian minimization.

Modeling instrument specifications:
- Operating range: 650-950 cm$^{-1}$
- 1215-1650 cm$^{-1}$, 817-822 cm$^{-1}$
- Spectral resolution ~ 0.25 cm$^{-1}$
- Accuracy (NEDT)= 0.3 K (corresponding to IASI (8451 channels))
- The method suggests an idea of the construction of instrument adopted for the atmospheric remote sensing with spectral intervals merging.

Conclusions and perspectives:
- The numerical experiments showed the advantage of the method 5 (Channel merging), due to integration of the energy of radiation in various spectral intervals.
- The efficiency of the method increases for better spectral resolution.
- The method suggests an idea of the construction of instrument adopted for the atmospheric remote sensing with spectral intervals merging.

Temperature retrieval accuracies (23 partial channels)

Temperature and Humidity retrieval accuracies depending on number of used channels (spectral resolution 0.25cm$^{-1}$)

5. Channel merging – Superchannel technique

First step – spectral information analysis:

We resolve equlibrium values for spectral covariance matrix $Cov(y) = J \cdot J^T$ to obtain the number of available independent information components in spectra: $M = \{\lambda_1 \geq \lambda_2 \geq ... \geq \lambda_M\}$

$\lambda$ - eigenvalues of the spectral covariance matrix; $\phi_{n}$ - eigenvectors

Second step – spectral intervals merging:

We introduces new “superchannels”, which is obtained by spectral intervals merging:

$$y_i = P_{adj,y} \cdot y + w_M$$

The elements $p_{ij}$ of matrix $P_{adj,y}$ is either 0 or 1, shows, whether include interval $i$ to superchannel $j$.

Matrix $P_{adj,y}$ is defined from:

$$det(G(P_{adj,y})) = \max$$

$$G = (P_{adj,y} U_0)^T (P_{adj,y} U_0) = K^T K$$

Fischer’s information matrix.

To find the matrix $P_{adj,y}$ we are use iterative algorithm which start from some initial nondegenerate set of scales:

$$y_i^{(m)} = \begin{cases} (1-\beta_m y_i^{(m-1)}) & \text{if } f_{\text{max}}^{(m)}(y_i)<0 \\ y_i^{(m-1)} & \text{if } f_{\text{max}}^{(m)}(y_i)>0 \end{cases}$$

$K_m$ - cofactor of matrix $K$

Cramer–Rao bound

Temperature retrieval accuracies (23 partial channels)

Retrieval accuracies (23 channels)

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DRM

SVD (DRM)

Jacobs

Iterative

Variable width

Error of $T_v, K$ 0.41 0.41 0.41 0.41 0.41
Error of $T_v, K$ 1.79 1.78 1.77 1.66 1.39
Error of $Q, kg/m^2$ 0.83 0.83 0.81 0.79 0.68
Error of $Q, kg/m^2$ 0.82 0.80 0.78 0.74 0.64

Evaluation of the result at the posteriori covariance matrix is update:

$$S_{\text{new}} = S_{\text{old}} + b b^T$$

The criteria of a channel usefulness is an Entropy Reduction (ER):

$$ER = -\frac{1}{2} \log \left( \det \left( S_{\text{new}} \right) / \det \left( S_{\text{old}} \right) \right)$$

Methods of Channel selection

1. DRM

Values of the diagonal elements of a DRM matrix is a criteria of a channel usefulness.

$$\Sigma^{1/2} \cdot A^{1/2} \cdot S^{1/2} \cdot A^{1/2} \cdot \Sigma^{1/2} = U^T \Sigma^U$$

Cut noisy components:

$$A’ = \frac{\sigma^{1/2}}{\sigma^{1/2}} \leq \frac{\sigma}{\sigma} (10\%)$$

Channel selection criteria:

- line $h$ is selected that has a maximum of the ratio of the amplitude of the peak to the half width at maximum.

- At each iteration the a posteriori covariance matrix is updated:

$$S_{\text{new}} = S_{\text{old}} + b b^T$$

- The criteria of a channel usefulness is an Entropy Reduction (ER):