PHYSICAL RETRIEVAL ALGORITHM DEVELOPMENT FOR OPERATIONAL SEVIRI CLEAR SKY NOWCASTING PRODUCTS

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Abstract

The physical retrieval algorithm was recommended through the NWC SAF (Satellite Application Facility for NoWCasting) Visiting Scientist Activity (VSA). Initial evaluation with radiosondes over land and AMSR-E (Advanced Microwave Advanced Microwave Scanning Radiometer - Earth Observing System) product over ocean had shown that the recommended physical retrieval algorithm is promising for the Spinning Enhanced Visible and Infrared Imager (SEVIRI) clear sky nowcasting products. The selected algorithm has been optimized for the purpose of an operational implementation, the algorithm targets the region where atmosphere is more unstable and will potentially cause convective storm development. The physical retrieval algorithm and its improvements on the current approach are presented. As result of all activities, NWC SAF/MSG package for PGE13 **S**EVIRI **Ph**ysical **R**etrieval (SPhR) will be available in 2009 as a new product.

INTRODUCTION

The objective of this paper is to present to the users that a new product based on physical retrieval will be available from the 2009 release of SEVIRI NWC SAF software package. The new product is based on Visiting Science Activities (VSA) of Dr. Jun Li from CIMSS of University of Wisconsin-Madison.

The paper is divided in three parts. In the first part, the reason to develop now the physical retrieval product will be explained. In the second part, the algorithm proposed by Jun Li is briefly summarized. In the third part, some implementation details of the PGE13 Physical retrieval Algorithm (SPhR) and the construction of a training and validation dataset are presented.

RATIONALE OF THE NWC SAF PHYSICAL RETRIEVAL PRODUCT

In order to understand the reason to introduce now a physical retrieval product, it must be taken into account which is the main objective of NWC SAF. The main objective of NWC SAF is to produce software packages for MSG and Polar satellites. In the case of NCWSAF/MSG package, the purpose of the NWC SAF algorithms is to derive each parameter at pixel by pixel scale every 15 minutes over a region selected by the user. At the moment, 12 products are obtained in the case of NWCSAF/MSG package. These products can be classified in cloud, rain, wind and clear air products, etc. Examples and information are provided on NWC SAF web page (http://nwcsaf.inm.es). Currently NWC SAF clear air parameters, PGE06 Total Precipitable Water (TPW), PGE07 Layer Precipitable Water (LPW) and PGE08 Stability Analysis imagery (SAI), are retrieved using statistical retrievals. The core of the statistical retrieval for NWC SAF clear air products are neural networks for each parameter (Multi Layer Perceptron). This approach was selected at the beginning of the project in order to fulfil two important requirements stated in the User Requirement Document concerning the timeliness and the independence of Numerical Weather Prediction (NWP) forecasted data. The NWC SAF Steering Group (SG) has declared as operational PGE06 TPW and PGE07 LPW delivered with version 2008.

During the 11th Meeting (February 2007), the NWC SAF Steering Group (SG) proposed the AEMET Project Team to focus the work during the SAF Continuous Development and Operational Phase (CDOP) on implementing a physical retrieval approach. The physical retrieval approach was not taken into account in the previous phases of the NWC SAF due to constraints on computation time.

Following this decision, a VSA to make an assessment of this issue was approved. Jun Li from CIMSS at University of Wisconsin-Madison evaluated the advantages/disadvantages of two SEVIRI retrieval algorithms (MPEF and CM SAF approaches) and analyzed the possibility of adapting to SEVIRI the new GOES-12 Sounder physical retrieval algorithm (physical iterative approach with regression as first guess) including all the improvements. In the NWC SAF VSA report "Recommendation on Physical Retrieval Algorithm for SEVIRI Nowcasting Product", Dr. Jun Li introduces the existing physical retrieval algorithms, analyses the strength and weakness of each physical algorithm and summarizes the recommendations on the physical retrieval algorithm for SEVIRI nowcasting products. As all VSA reports, the report is available on: http://nwcsaf.inm.es/VSA.html#Visiting%20Scientist%20Reports

Other activity related with the physical retrieval was the organization of a Workshop. This workshop "Physical Retrieval of Clear Air Parameters from SEVIRI" sponsored by EUMETSAT was organized by AEMET and it took place in Madrid during 28th - 29th November 2007. All presentations are available on: http://nwcsaf.inm.es/Physical_Ret_Workshop_Open.html). The objective of this workshop was that several physical retrieval experts exchanged ideas and opinions before the implementation of a physical retrieval approach in the NWC SAF software package. As a result they made several recommendations. These are the main Algorithm Proposal Recommendations of this workshop:

- **Recommendation 1:** New Product Generator Element (PGE-13) will be added to NWCSAF/MSG Package. Dealing with Physical Retrieval based on Jun Li's recommendations, VSA Report and the work already done in the «prototype » during the VSA.
- **Recommendation 2:** Availability on 2010 as requested by CM SAF.
- **Recommendation 3:** To write the Algorithm Theoretical Base Document (ATBD) in cooperation with CM SAF and EUMETSAT.
- **Recommendation 4:** Algorithm testing and validation will be an important task in PGE13 development.

These are the recommendations for the NWC SAF physical retrieval algorithm made in Jun Li's 2007 VSA report 2007:

- Maximum likelihood approach (CM-SAF, MPEF)
- Regularization with discrepancy principal (GOES Sounder)
- SEVIRI observation error covariance matrix (CM-SAF, MPEF, GOES Sounder)
- Using RTTOV radiative transfer model and its linear tangent model for Jacobian (MPEF)
- Use forecast as background (MPEF, GOES Sounder)
- Background error covariance matrix (CM-SAF, MPEF, GOES Sounder)
- EOF representation for a profile in the physical retrieval process (GOES Sounder)
- Use regression as first guess (GOES Sounder)
- Use predetermined surface IR emissivity atlas
- Use radiance bias adjustment.

Based on the Jun Li's VSA 2007 report and the recommendations of the Workshop, the Steering Group decided to develop a Physical retrieval product on NWCSAF/MSG package. The proposed name of this new product is PGE13 **S**EVIRI **Ph**ysical **R**etrieval (SPhR).

DESCRIPTION OF THE PHYSICAL RETRIEVAL ALGORITHM

The PGE13 **S**EVIRI **Ph**ysical **R**etrieval (SPhR) algorithm is an optimal estimation algorithm with some improvements over the classical approach:

- Use of non linear regression to build the First Guess.
- Use of a regularization parameter (also called smoothing factor) introduced for convergence and solution stability
- Use of empirical orthogonal functions (EOFs) to reduce the dimension of matrixes to invert and, thus, to reduce the computation time

The algorithm will be only applied on clear pixels; PGE01 Cloud Mask (CMa) will be used to determine whether a pixel is clear or cloudy.

Use of non linear regression to built first guess

In the classical approach of optimal estimation methods, the profiles of temperature and humidity from one NWP model are used directly as first guess to the physical module. Here, a non linear regression process (see Figure 1) that uses as inputs temperature and humidity from one NWP model and the bias adjusted SEVIRI brightness temperatures (BTs) are used to obtain the profiles that will be used as first guess. This allows starting physical module with an improved first guess.

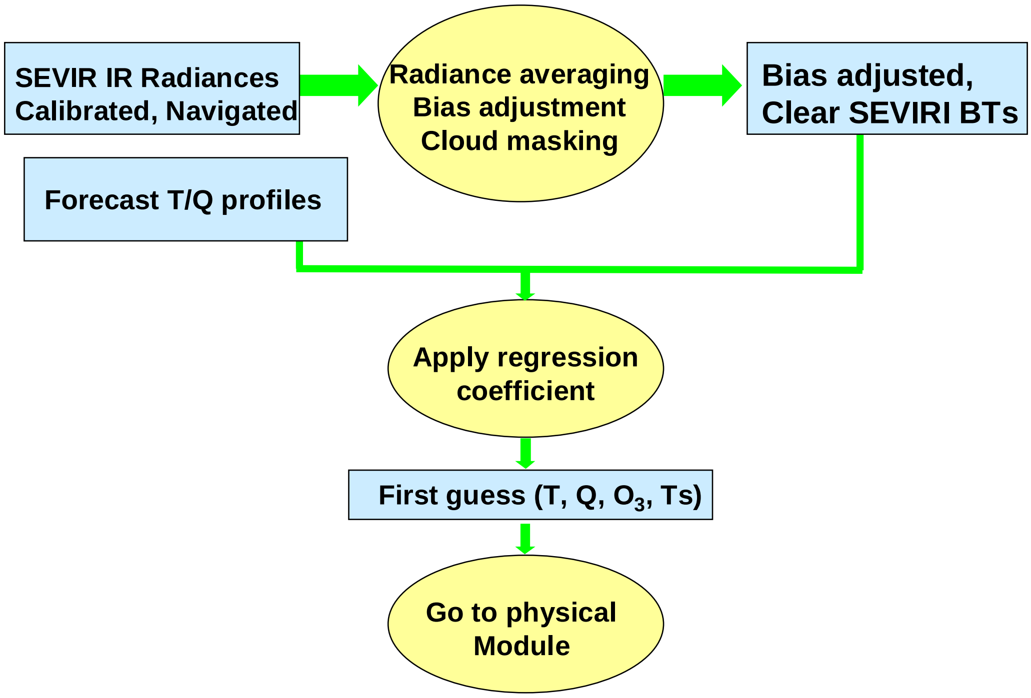

Figure 1: Flowchart with the process of non linear regression to build the first guess.

Differences in Physical module: use of regularization parameter and use of EOFs

The PGE13 SPhR approach uses an optimal method of combining observations with a background. The variational retrieval is performed by adjusting the atmospheric profile state, X, from the background, X^b, to minimize a cost function (Rodger 1976; Li and Huang 1999; Li et al. 2008). The regularization parameter (also called smoothing factor) is introduced for convergence and solution stability. The cost function is defined by

$$J(X) = [Y^m - F(X)]^T E^{-1}[Y^m - F(X)] + [X - X^b]^T \gamma B^{-1}[X - X^b], \qquad (1)$$

where γ is the regularization parameter, **B** and **E** are the error covariance matrices of background, $\mathbf{X}^b$, and the observation (radiances) vector, $\mathbf{Y}^m$, respectively, **F**(**X**) is the forward radiative transfer model operator and superscripts T and -1 are the matrix transpose and inverse, respectively.
By using the Newtonian iteration

$$X_{n+1} = X_n + J''(X_n)^{-1} \cdot J'(X_n), \qquad (2)$$

the following Quasi-Nonlinear iterative form is obtained

$$\delta X_{n+1} = (F_n'^T \cdot E^{-1} \cdot F_n' + \gamma B^{-1})^{-1} \cdot F_n'^T \cdot E^{-1} \cdot (\delta Y_n + F_n' \cdot \delta X_n), \qquad (3)$$

where **X** is the vector of temperature and humidity profile to be solved, **n** is the iteration step, **n**=0 denotes the first guess, $\delta X_n = X_n - X^b$, $\delta Y_n = Y^m - F(X_n)$, F' is the tangent linear operative (Jacobian) of forward model **F**. The RTTOV-9.2 is used for forward model (F) and Jacobian calculations (F'). The regularization parameter is adjusted in each iteration, according to the discrepancy principal (Li and Huang 1999; Li et al. 2000). The reason to introduce the regularization parameter is to balance the contributions from background and satellite observations in solution.

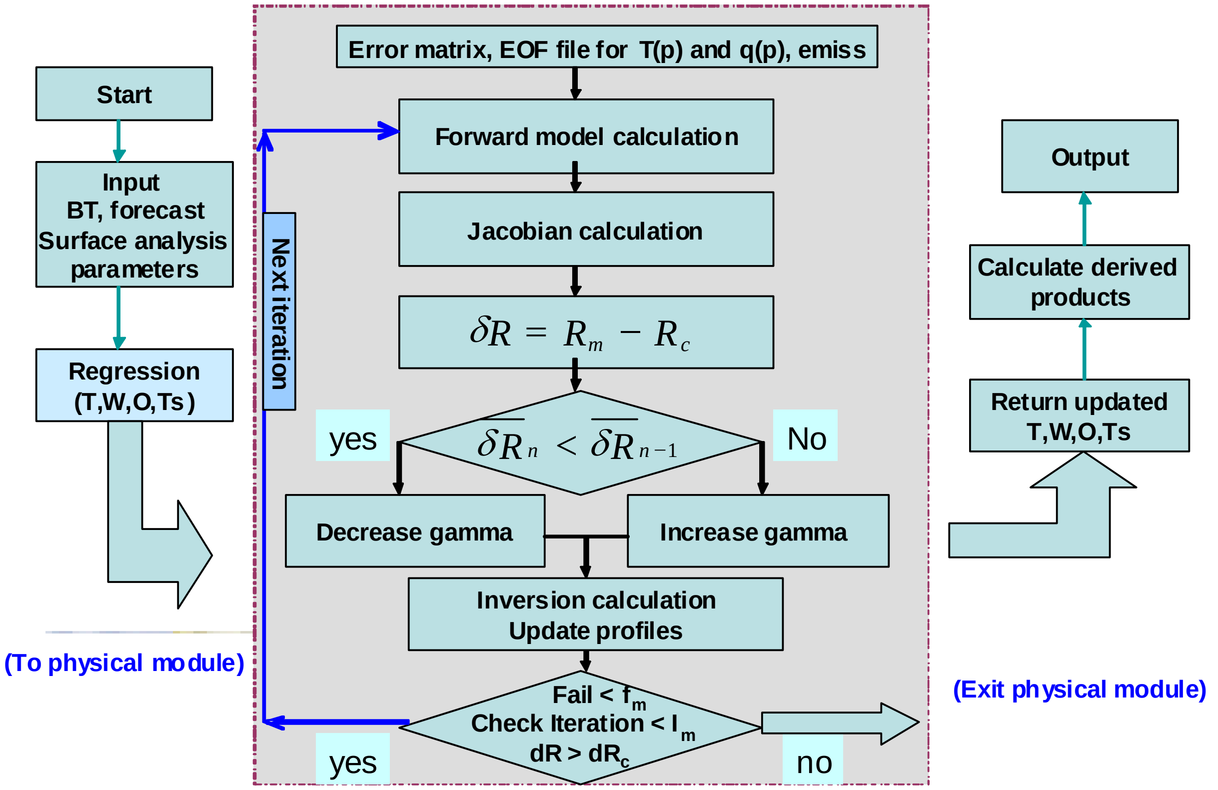

Figure 2: Flowchart with the physical module.

Since there are correlations among atmospheric variables, only a limited number of variables are needed to explain the vertical structure variation of an atmospheric profile (Smith, 1976). The number of independent structure functions can be obtained from a set of global atmospheric profile samples. Assume

$$X - X^b = \Phi A, \qquad (4)$$

Where $A = (\alpha_1, \alpha_2, ..., \alpha_M)$, and $\Phi = \begin{bmatrix} \Phi_T & 0 & 0 \\ 0 & \Phi_q & 0 \\ 0 & 0 & \Phi_{T_s} \end{bmatrix}$, Φ_T is the matrix of the first $\tilde{N}_T$ empirical orthogonal functions (EOFs) of the temperature profile, Φ_q is the matrix of the first $\tilde{N}_q$ EOFs of the water vapor mixing ratio profiles, $\Phi_{T_S} = 1$, and $M = \tilde{N}_T + \tilde{N}_q + 1$. In PGE13 SPhR processing, 2 temperatures EOFs and 3 water vapor mixing ratio EOFs are used. It is obvious that $\Phi^T \Phi = I$. Defining $\tilde{F}' = F' \cdot \Phi$, Eq. (3) becomes

$$A_{n+1} = (\tilde{F}_n^{'T} \cdot E^{-1} \cdot \tilde{F}_n^{'} + \gamma B^{-1})^{-1} \cdot \tilde{F}_n^{'T} \cdot E^{-1} \cdot (\delta Y_n + \tilde{F}_n^{'} \cdot A_n), \quad (5)$$

Where $A_o = 0$, and

$$\left\| F(A(\gamma) - Y^m \right\|^2 = \sigma^2, \quad (6)$$

Where σ is the observation error of SEVIRI, define $\left\| X \right\|^2 = \frac{1}{N} \sum_{i=1}^{N} x_i^2$, $X = (x_1, x_2, ..., x_N)$. Eq. (4) and Eq. (5) are applied to derive the solution from SEVIRI radiances.

In the SPhR retrieval process, the water vapor is expressed as the logarithm of mixing ratio due to the fact that logarithm of mixing ratio is more linear to the infrared radiances than the mixing ratio. The matrix dimensions in Eq. (3) are 87x87; but matrix dimensions in Eq. (5) are 6x6. This allows speeding up the process and reduction of the CPU time.

PGE13 SPhR IMPLEMENTATION DETAILS

Several details related to the final implementation are presented in this part.

Use of Field of Regards (FOR)

The PGE13 execution on FOR has been evaluated, instead of pixel by pixel basis, in Jun Li's 2008 VSA. This has been done in order to speed up the processing and because the processing in FOR could reduce noise. A window of 3x3 fields-of-view (FOVs) has been considered as adequate (see Figure 3) for one FOR. The width of the FOR (MxM pixels) will be an adjustable parameter in the configuration file. This will allow adjusting M depending on the size of the region to process and the machine characteristics of the user.

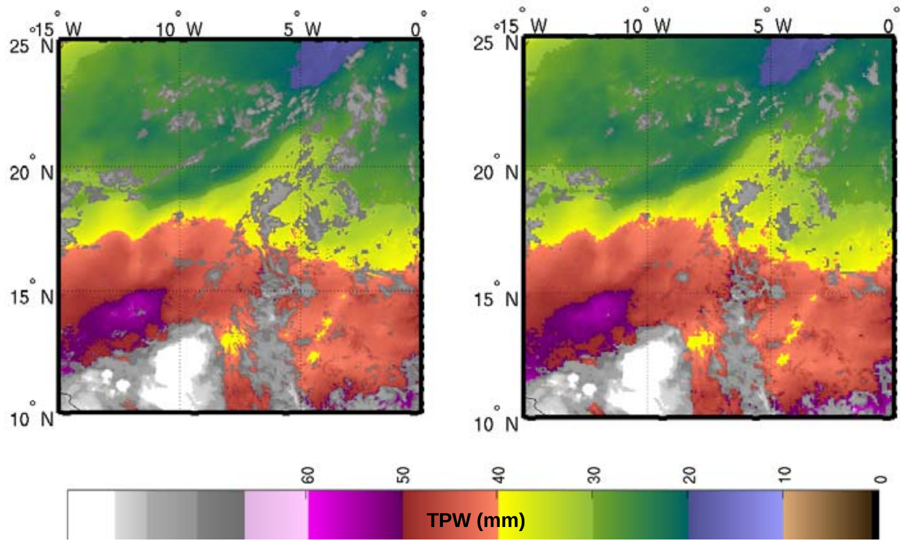

Figure 3: Example: FOR - 1x1 FOV versus FOR 3x3 FOVs SEVIRI TPW at 00UTC on 18 August 2006

Figure 4 shows the differences on the spread between RTTOV-9.2 simulated BT versus SEVIRI brightness temperature (BT) obtained with the mean of clear pixels and with the IR10.8 warmest clear pixel SEVIRI BT for grid boxes of 0.5ºx0.5º. ECMWF analysis 00 and 12 UTC has been used as input to RTTOV-9.2 radiative transfer model (RTM). Due to the differences, two methods for calculating the FOR BTs will be implemented and checked in PGE13 SPhR:

(1) Mean BT of all clear pixels within the FOR
(2) The BT at the IR10.8 warmest clear pixel within the FOR

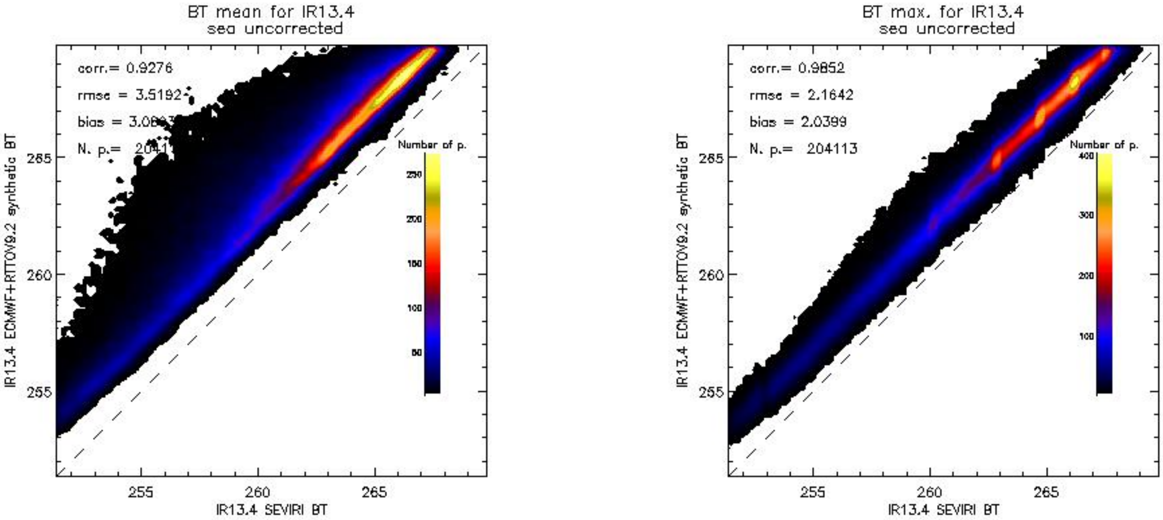

Figure 4: Scatter plots of IR13.4 SEVIRI BT vs ECMWF+RTTOV-9.2 synthetic BT. On the left, mean of SEVIRI BT clear pixel in 0.5ºx0.5º box. On the right, IR10.8 warmest clear pixel SEVIRI BT in 0.5ºx0.5º box.

Interpolation to 43 RTTOV levels of NWP profiles.

The NWC SAF provides software which should be able to work with any NWP model and it should accept the set of levels available on the NWP files provided by the users to the NWC SAF. Because it is not adequate to provide error matrices, EOFs, regression coefficient, etc for any number of pressure levels, it is necessary as first step to perform the interpolation of different NWP model to 43 RTTOV pressure levels. The solution adopted has been to develop a function that interpolates the temperature and humidity profiles from any set of pressure levels to 43 RTTOV pressure levels using the RTTOV function "rttov_intavg_prof".

This pre-processing will allow any NWCSAF/MSG package user to be able to run PGE13 SPhR without modifying the NWP model supply. To test the NWP forecast supply to PGE13 is one of the objectives of 2009 version for PGE13 release.

PGE13 SPhR training and validation dataset

It has been considered an important task to build a training and validation dataset (Recommendation 4 of the Madrid Workshop). During 2008 Jun Li VSA, the design was made to create a training and validation dataset using SEVIRI data, ECMWF model and radiosounding profiles.

This task was started on July 2008 based on the software developed during the last years for the validation of the neural networks NWC SAF clear air products (Martinez, 2007); in the past years the SEVIRI simulated radiances, necessary to implement the current NWC SAF clear air parameters, have been generated using ECMWF GRIB files as inputs to RTTOV-7. The software that calculates the SEVIRI simulated BT from ECMWF GRIB files has been updated to RTTOV-9.2. This software also allows getting interpolated profiles of T, q, O_3 at 43 RTTOV pressure levels, surface parameters, etc. One of the first results of this training and validation dataset has been a first estimation of SEVIRI BT bias correction. The improvement of the error background covariance matrices for sea and land is another task that is in progress with this PGE13 dataset. The ECMWF GRIB files (12 hours forecast and analysis) are being used. The interpolation function included in the RTTOV-9.2 code is used to make the interpolation from the 91 hybrid levels to 43 RTTOV pressure levels

BT bias correction

The dataset has been built with simulated BT (0,5º x 0,5 º ECMWF analysis GRIB files and RTTOV-9.2) and with SEVIRI BT (NWCSAF software package has been used to get effective radiances) for a period of more than one year. In this first bias correction dataset, only pixels over ocean in the MSG N region have been considered. The SEVIRI BT mean of clear pixels and the SEVIRI BT at the IR10.8 warmest clear pixel have been obtained in boxes of 0.5º x 0.5º. After outliers filtering, a robust regression using LADFIT IDL function is applied to the dataset. In Figure 5, the scatter plots of SEVIRI BT at the IR10.8 warmest clear pixel versus synthetic BT, before and after BT bias correction, are shown for several channels. Note the strong bias reduction on MSG-2 IR13.4 channel from 1.9498 to 0.0509.

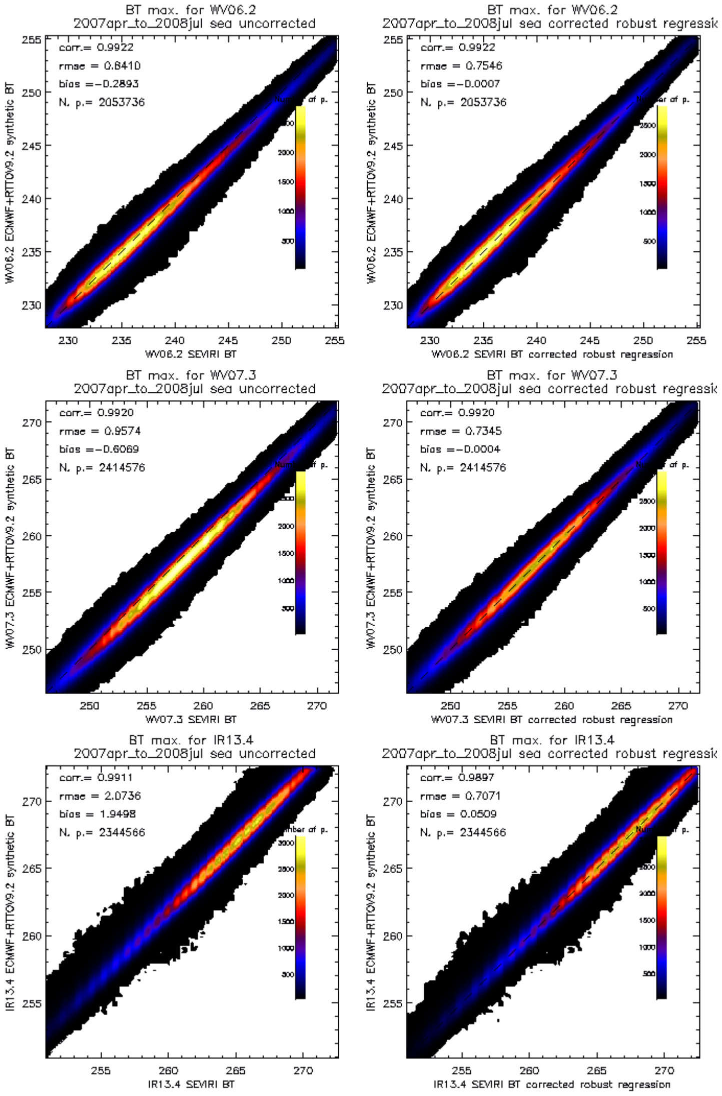

Figure 5: Scatter plots for WV6.2 (top), WV7.3 (middle) and IR13.4 (bottom) SEVIRI BT at IR10.8 warmest clear pixel in 0.5ºx0.5º box SEVIRI BT versus ECMWF+RTTOV-9.2 synthetic BT of MSGN region. On the left before BT bias correction, on the right after robust BT bias correction.

PGE13 SPhR OUTPUTS

Together with the parameters calculated directly from the retrieved profile, it was considered as adequate at Madrid Workshop to provide as other outputs the difference between the retrieved profiles and NWP model. Following this idea, the differences between the parameters obtained with the retrieved profile and the same parameters obtained with the NWP model profile will be included as additional outputs.

Then, in the first version, the following fields will be included:

1. Total precipitable water (TPW) from the retrieved profiles of temperature and humidity.
2. Precipitable water in three layers LPW (Surface - 850 hPa, 850 - 500, 500 - TOP) from the retrieved profiles of temperature and humidity
3. Lifted Index (LI) from the retrieved profiles of temperature and humidity
4. Difference between TPW from retrieved profile and TPW from NWP profiles
5. Difference between LPW from retrieved profile and LPW from NWP profiles
6. Difference between LI from retrieved profile and LI from NWP profiles
7. Quality flags

The format of the file will be HDF-5. CM SAF recommended establishing 850 and 500 hPa as limit pressure levels for LPW instead of RTTOV level used in PGE07 LPW (840 and 437).

OPTIONAL PGE13 SPhR OUTPUT

As an optional and configurable output, the retrieved profiles of temperature and humidity result of physical module and the profiles from the NWP model interpolated at 43 RTTOV levels may be obtained. The users can activate in the configuration file one option so that a binary file will be written in the $SAFNWC/tmp directory. This will allow users to debug their local implementation, to get access to the retrieved temperature and humidity profiles and to compare with the NWP profiles.

OUTLOOKS

A new NWC SAF PGE, PGE13 SPhR, is being developed. The ATBD will be finished in October 2008. A prototype code update to RTTOV-9.2 is available. This prototype together with the NWCSAF library will be the base of the PGE13 code. The objective is that the PGE13 will be available in the NWC SAF delivery 2009 or as a patch to this delivery. The feedback of the users to this 2009 version will allow getting a full operational and validated version available on 2010.

ACKNOWLEDGEMENTS

This study was carried out in the NWC SAF activities framework.

REFERENCES

Li, J., and H.-L. Huang, 1999: Retrieval of atmospheric profiles from satellite sounder measurements by use of the discrepancy principle*, Appl. Optics, Vol. 38, No. 6, 916-923.*

Li, J., W. Wolf, W. P. Menzel, W. Zhang, H.-L. Huang, and T. H. Achtor, 2000: Global soundings of the atmosphere from ATOVS measurements: The algorithm and validation, *J. Appl. Meteorol., 39:1248 – 1268.*

Li, Zhenglong, Jun Li, W. Paul Menzel, T. J. Schmit, J. P. Nelson, and S. A. Ackerman, 2008: GOES sounding improvement and application to severe storm nowcasting, *Geophysical Research Letters (submitted). 35, L03806, doi:10.1029/2007GL032797.*

Martínez M.A., et al. (2007). Improvements to the neural network retrieval of layer precipitable water including an IR SEVIRI local radiance-bias correction. *Proc. The 2007 EUMETSAT Meteorological Satellite Data User's Conference, Amsterdam, Holland*

Rodgers, C.D., 1976: Retrieval of atmospheric temperature and composition from remote measurements of thermal radiation. *Rev. Geophys. Spac. Phys., 14, 609-624.*

Smith, W. L., and H. M. Woolf, 1976: The use of eigenvectors of statistical covariance matrices for interpreting satellite sounding radiometer observations, *J. Atmos. Sci., 33, 1127-1140.*