Kalman Filter Retrieval of Surface Temperature from SEVIRI: Improved Forward Modeling, Validation and Inter-Comparison Case Studies

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1. Background
2. Aim and scope
3. Description of the Methodology
   - Physical Retrieval
   - Forward Model
4. Results
   - Surface Temperature (ST) and Emissivity ($\varepsilon$)
   - Comparison
     - With ECMWF analysis
     - With Ground Based Measurements
     - With MODIS Products
5. Conclusions
The work originated within EUMETSAT (P. Watts)

Objective: To study and formulate a general strategy to apply **spatial and temporal constraints** to the estimation of geophysical **parameters** from radiance measurements made **from geostationary platforms**, to apply the strategy to a particular example problem and to recommend a way forward to more general application to MTG FCI imager and IRS sounder data.

The study was also motivated by the quest of methodologies capable to perform a **dimensionality reduction of the data space**

In NWP the numbers of observations varies considerably, but global models perhaps assimilate of order $10^6$ observations per 12 hour window. With SEVIRI the number of observations is of order $10^8$ per 15 minutes.
Continuity is felt important in order to dynamically separate emissivity from temperature. In order words, try to exploit the different variability time scale of the two: minutes for temperature, days for emissivity.

Dimensionality reduction is felt important also in view of MTG: FCI and IRS mission.
KF is an assimilation system (may incorporate the basic physics involved in the problem: radiative transfer and dynamics).

Acting on the dynamics, we can put appropriate constraint in order to take advantage of the different time scale of emissivity and temperature.

Exploiting the time sequential architecture of KF, the dimensionality of the data space is kept scalar in time, i.e., observations are processed as they come and are not accumulated as it would be in an ordinary static Optimal Estimation method.
Since 2011, the analysis has been performed under the projects:

- EUMETSAT
  - EUM/CO/14/4600001329/PDW
  - EUM/CO/11/4600000996/PDW
- CNR/MIUR,
  - RITMARE (CNR/MIUR) Ricerca ITaliana per il MARE
- Regione Basilicata,
  - PO FSE Basilicata 2007-2013
- LSA SAF
  - IPMA, Instituto Portugues do Mar e da Atmosfera
    LSASAF_VS2016-02
Inverse Model: Kalman filter + persistence

1. Introduction

\[ R_t = F(v_t) + \varepsilon_t \]  
observation equation

\[ v_{t+1} = Hv_t + \eta_t \]  
state/evolution equation

update or analysis

\[ \hat{v}_t = \hat{v}_a + \left( K_t^T S_\varepsilon^{-1} K_t + S_a^{-1} \right)^{-1} K_t^T S_\varepsilon^{-1} (y_t - K_t (\hat{v}_a - v_o)) \]

\[ S_t = \left( K_t^T S_\varepsilon^{-1} K_t + S_a^{-1} \right)^{-1} \]

forecast

\[ \hat{v}^f_{t+1} = H\hat{v}_t \]

\[ \hat{S}^f_{t+1} = HS_t H^T + S_n \]

\[ \{ v_a = \hat{v}^f_{t+1} \]  
forecast at time t

\[ S_a = \hat{S}^f_{t+1} \]  
analysis at time t

\[ \{ \]  
covariance of \( \eta_t \)

2. Methodology

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Forward Model: \(\sigma\)-SEVIRI

- \(\sigma\)-IASI (\(\sigma\)-SEVIRI) is a general purpose pseudo-monochromatic radiative transfer model:
  - It computes Spectral High-resolution quantities for RTE

\[
R(\theta_r, \varphi_r, \sigma) = \varepsilon(\theta_r, \varphi_r, \sigma)\tau_0(\theta_r, \varphi_r, \sigma)B(T_s) + R_u(\theta_r, \varphi_r, \sigma) + R_r(\theta_r, \varphi_r, \sigma)
\]

\[
R_u(\theta_r, \varphi_r, \sigma) = \int_0^{+\infty} B(T) \frac{\partial \tau}{\partial h} dh
\]

\[
R_r(\theta_r, \varphi_r, \sigma) = \tau_0(\theta_r, \varphi_r, \sigma)\int_0^{2\pi} d\varphi_i \int_0^{\pi} f(\theta_r, \varphi_r, \theta_i, \varphi_i, \sigma)R_i(\theta_i, \varphi_i, \sigma)\cos\theta_i \sin\theta_i d\theta_i
\]

*It takes into account both Specular and Lambertian reflection*

\[
\chi_{i,N,\sigma} = \rho_{i,N} \left( C_{i,N0,\sigma} + C_{i,N1,\sigma} \Delta T_i + C_{i,N2,\sigma} \Delta T_i^2 \right)
\]

- It is based on look-up table of optical depth + interpolation procedure
- Simple dependence of the Optical Depth with respect to the Temperature and the gas concentration

*Analytical derivative, Fast and Accurate*
1. Introduction

2. Methodology

3. Results

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**Speed up the Forward Model: σ-SEVIRI**

- PCA (Principal Component Analysis) based approach to Radiative Transfer Model for SEVIRI

- Spectral High-res quantities are computed for a selected number of predictors \( (n_p) \)

- That, with a PCA based approach, are represented with a limited number of Principal Components \( (n_c) \)

- It convolves at SEVIRI ISRF with linear regression

- **Very Fast and Accurate**

\[
R_{\text{high}} = u \cdot s \cdot v^t
\]

\[
c = u^t \cdot R_{\text{high}}
\]

\[
[n_c \times 1] [n_p \times n_c] [n_p \times 1]
\]

\[
R_{\text{low}} = W \cdot c
\]

\[
[n_l \times 1] [n_l \times n_p] [n_c \times 1]
\]
Kalman filter physical retrieval of surface emissivity and temperature from geostationary infrared radiances


Application to SEVIRI window channels, for the retrieval of $T_s$ and $\varepsilon$

To retrieve Surface Temperature and emissivity we used IR SEVIRI window Channels ($n_l = 4$)

- 4 @ 8.7 μm, ($n_p = 30, n_c = 9$)
- 5 @ 9.7 μm, ($n_p = 40, n_c = 14$)
- 6 @ 10.8 μm, ($n_p = 20, n_c = 5$)
- 7 @ 12 μm, ($n_p = 30, n_c = 6$)
Background Information, Atmospheric State

ECMWF Operation Analysis from MARS platform.

High spatial Resolution (0.125x0.125)

- 60/91/137 Pressure levels
- ST, Surface Temperature
- SP, Surface Pressure
- TCC, Total Cloud Cover
- T, Temperature
- Q, Specific Humidity
- O3, Specific Ozone
Background Information, Emissivity

UW/BFEMIS, database, Monthly mean and covariance computed for the 14 years period 2003-2016.
Validation Stations: Acknowledgements

- Isabel Trigo, Instituto Portugues do Mar e da Atmosfera IP, Land SAF, Lisbon, Portugal
- Frank M. Göttscbe, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany

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Comparison with in situ measurements

Summary of the Results from the three LSA SAF validation stations

<table>
<thead>
<tr>
<th>Location</th>
<th>Mean difference with in situ data (°C)</th>
<th>Standard deviation of the difference (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dahra, Jan.-to Oct. 2011</td>
<td>-0.70</td>
<td>0.96</td>
</tr>
<tr>
<td>Evora, Jan. to Dec. 2010</td>
<td>+0.91</td>
<td>1.62</td>
</tr>
<tr>
<td>Gobabeb, Jan. to Dec. 2010</td>
<td>+0.86</td>
<td>1.18</td>
</tr>
</tbody>
</table>

Comparison with in situ Surface Temperature
Comparison with in situ measurements: Dahra

An example from Dahra station (Time series of 4 days – step 15 min)
Evora station. 1 year Scatter plot (Left). 17 days long time serie with 15 min step (Right)
Gobabeb station. 1 year Scatter plot (Left). 11 days long time serie with 15 min step (Right)
Comparison with in situ measurements: Gobabeb

- Gobabeb station. $\varepsilon@10.8$ - 1 year long time series with 15 min step
Land cover change detection with IR SEVIRI channels

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Land cover change detection, an example: Dahra

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The scheme works for the SEVIRI full disk

The case study shown here is an area surrounding Basilicata Region, including Mediterranean Sea (Tyrrenian, Ionian and Adriatic Seas)
Comparison with ECMWF data show excellent agreement (statistics based on 2,754,238 data points, 1 year)
Comparison with MODIS

- **Bias 0.07 °C**
- **Std 1.05 °C**

- **Comparison with MODIS (statistics based on 3,230,710 data points 1 year)**
The animation shows Evolution of Sea Skin Temperature in the period 2013-2016.

Each Frame represents monthly mean.

http://www2.unibas.it/gmasiello/assite/rep/Med_2013-2016_T.gif
The animation shows Evolution of Surface Temperature for the 2 of August 2013 at the temporal resolution of SEVIRI (15’).
The Monthly mean data are freely available at web site http://www2.unibas.it/gmasiello/assite/as/products.html

- At the moment they are organized in compressed ASCII files (1 per month)
- We are processing SEVIRI data for 2017 (Results will be available online as soon as possible)
- We plan to process SEVIRI data back to 2003
- We are implementing a new web portal that simplify data request enabling download of the full time resolution results. (Master Thesis of A. Coviello)
Applications to Full Disk

- The scheme works for the SEVIRI full disk

- **Full Disk (VZA<=70°):**
  - Total 3,545,871 pixels
  - 3,488,328 Land pixels
  - 57,543 In Land Water pixels
Monthly mean surface temperature
Monthly mean surface emissivity
Computational Performances

The code can run from the level of the single pixel up to the SEVIRI full disk scale

- **Full Disk (VZA<=70°):**
  - Total 3,545,871 pixels
  - 3,488,328 Land pixels
  - 57,543 In Land Water pixels
  - A single SEVIRI FD run will take about 30 min exploiting 8 threads and considering all pixels as clear sky (Ifort Compiler)
  - *Integrated and tested on IPMA LSA-SAF virtual machine for full disk retrieval of surface temperature and emissivity.*

- **Mediterranean Sea:**
  - Total 225962 pixels
  - A single SEVIRI Mediterranean Sea run will take about 8 min exploiting 1 thread and considering all pixels as clear sky (Ifort Compiler)
Conclusions

- The Kalman filter (KF) retrieval system is one of the first physically based schemes for the simultaneous retrieval of surface emissivity and temperature.
- The KF retrieval is unique in its capability to exploit the time continuity of geostationary infrared observations.
- The SEVIRI KF retrieval is fully characterized in terms of its variance-covariance structure. The theoretical precision is better than 0.2 K for sea and land surface.
- Potentially, the scheme can accommodate time-spatial constraints in case they are available. For now we use a simple persistence model for the state equation.
- Comparison with in situ, ECMWF, polar satellite observations shows a very good agreement for temperature.
- The KF methodology developed for SEVIRI is robust even at the full time resolution of 15 minutes.
- The algorithm can be specialized for land or sea or both and a land-based version has been integrated and tested on IPMA LSA-SAF virtual machine for full disk retrieval of surface temperature and emissivity.