KALMAN FILTER RETRIEVAL OF SURFACE TEMPERATURE AND EMISSIVITY FROM SEVIRI OBSERVATIONS AND COMPARISION WITH IASI AND MODIS PRODUCTS

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Abstract

In this paper, a suitable form of the Kalman filter is applied for the simultaneous retrieval of emissivity and surface temperature from SEVIRI observations. Exploiting the Kalman filter dynamical properties, this novel retrieval approach is capable of specifically taking into account for the time continuity of SEVIRI observations. SEVIRI results are compared to surface emissivity-temperature products obtained using IASI observations. The comparison has been performed considering a Sahara Desert target area, which is located within the Ourgla province (Algeria). Satellite observations for this area have been analysed for the month of July 2010. Surface temperature and emissivity retrieved from SEVIRI show a good agreement with IASI products. Comparison with space-time collocated ECMWF surface temperature shows that the ECMWF model has a negative bias during daytime. The bias can reach values as large as 10 K. A better agreement is found at night-time. For daytime observations, a negative bias is also found when we compare SEVIRI retrievals with MODIS surface temperature products.

1 INTRODUCTION

Infrared instrumentation on geostationary satellites is now rapidly approaching the spectral quality and accuracy of modern sensors flying on polar platforms. Currently at the core of EUMETSAT geostationary meteorological programme is the Meteosat Second Generation (MSG). However EUMETSAT is preparing for Meteosat Third Generation (MTG). The capability of geostationary satellites to resolve the diurnal cycle and hence to provide time-resolved sequences or time series of observations is a source of information which could suitably constrain the derivation of geophysical parameters. Nowadays, also because of lack of time-continuity, when dealing with observations from polar platforms, the problem of deriving geophysical parameters is normally solved by considering each single observation as independent from past and future events. For historical reason, the same approach is currently pursued with geostationary observations, which are still now dealt with as they were polar observations.

To fill this gap, a surface temperature (T_s) and emissivity (ε) retrieval methodology for the atmospheric window infrared channels of the Meteosat Second Generation (MSG) SEVIRI (Spinning Enhanced Visible and Infrared Imager) has been recently developed in the framework of the project EUM/CO/114600000996/PDW (Serio et al. 2012). The methodology exploits the Kalman filter (Kalman and Bucy, 1961, see also Rodgers 2000 for a discussion of the Kalman filter in the context of retrieval applications from satellite observations) to convey temporal constraints in the retrieval of surface parameters though time series of geostationary satellite data. To this end, it is worth mentioning that SEVIRI provides data every 15 minutes.

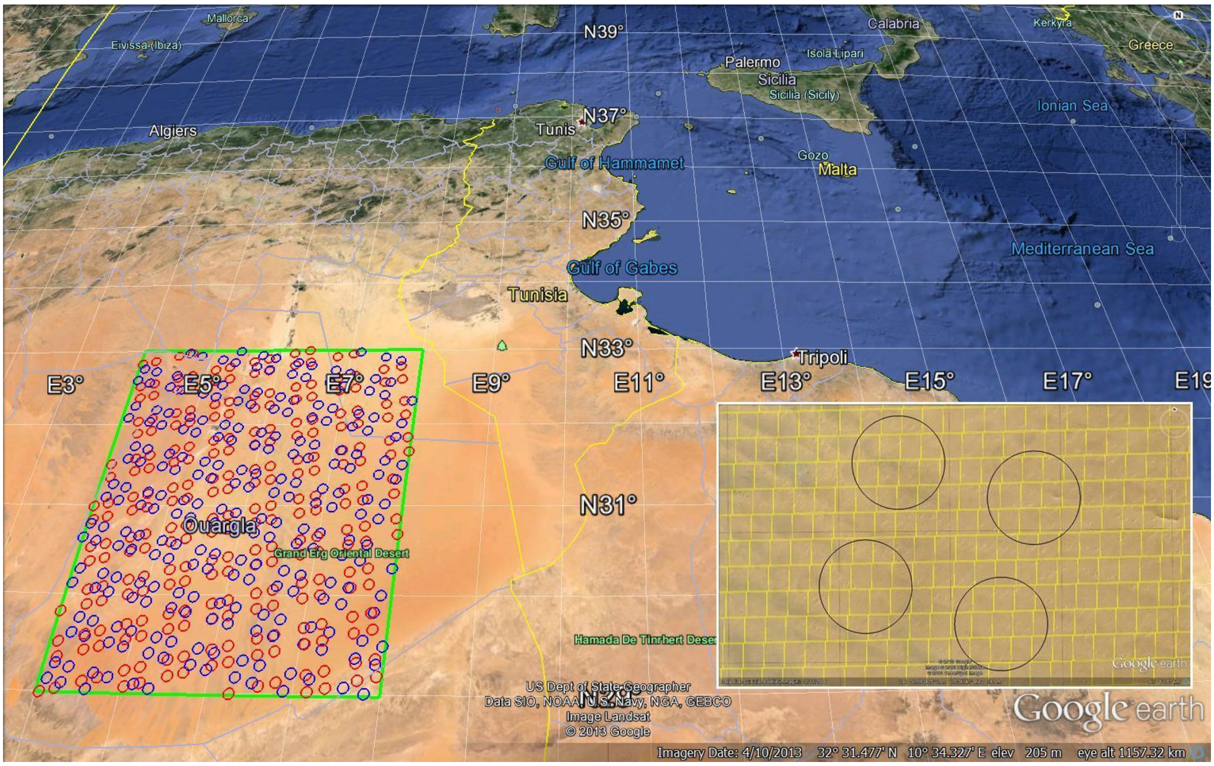

Figure 1: **The target area from Google earth. The green box indicates the region investigated for the comparison. A select few day (red circles)-night (blue circles) IASI footprints are shown in figure. The figure insert shows an example of SEVIRI-IASI collocation.**

In order to assess the quality of these retrievals, they have been compared to IASI (Infrared Atmospheric Sounding Interferometer, Hilton et al, 2012) T_s-ε products obtained with a retrieval methodology developed by Masiello and Serio (2013). Furthermore, for the specific case of surface temperature, a comparison is also provided with ECMWF (European Centre for Medium range Weather Forecasts) model and MODIS (Moderate Resolution Imaging Spectroradiometer) operational products for T_s.

This paper is organized as follow: section 2 describes the data and summarizes the methods used to retrieve surface emissivity and temperature. SEVIRI and IASI daily maps of emissivity and temperature are inter-compared in section 3; where we also compare SEVIRI T_s products with those derived from co-located ECMWF analyses and MODIS observations. Conclusions are outlined in section 4.

2 DATA AND METHODOLOGY

SEVIRI and IASI observations have been acquired for the month of July 2010 over the target area shown in Fig. 1, which extends from 4° to 8° degrees East longitude and 29° to 33° North latitude, at an average altitude of about 200 m. Sand dunes prevail with a low vegetative cover. The target area, which includes the Ourgla province (Algeria) in the Sahara Desert, contains 14266 SEVIRI pixels. The area is covered by two Metop-A Orbits per day, one during daytime, approximately at 9 a.m., and one during night-time, around 8 p.m., for a total of about 10 IASI scan lines, which correspond to more than 400 (200 during the day, 200 during the night) IASI footprints, hence spectra, per day.

For the whole target area shown in Fig. 1, we have also acquired ancillary information for the characterization of the thermodynamical atmospheric state. This information is provided by ECMWF analysis products for the surface temperature, T_s and the atmospheric profiles of temperature, water vapour and ozone $[T,Q,O]$ at the canonical hours 0:00, 6:00, 12:00 and 18:00. ECMWF model data are provided on 0.5×0.5 degrees (lat,lon) grid. In each ECMWF grid box there are on average $\approx$200

SEVIRI pixels, for which we assume that the atmospheric state vector is the time co-located ECMWF analysis.
In addition MODIS (Land Surface Temperature 5-Minute L2 Swath 1 km, MYD11_L2 and MOD11_L2 version 041[1]) data for T_s were acquired for 7 July 2010, for the purpose of comparison with SEVIRI products.

The T_s-ε retrieval methodology we have used for SEVIRI observations has been developed by Amoroso et al 2013, Masiello et al 2013a. The technique exploits the unique high temporal resolution of data acquisition by geostationary satellites and their capability to resolve the diurnal cycle. A Kalman filter approach was implemented for applying temporal constraints on the retrieval of surface emissivity and temperature. A persistence state model was used for the state vector. By properly tuning the parameters of the state equation, the different time scales of emissivity and temperature could be modelled and hence a method which allows one to separate the radiative effects of the two parameters could be developed.

For IASI we use a retrieval methodology which has been developed by Masiello and Serio (2013), Masiello et al (2013b). According to this methodology, the problem of simultaneous physical retrieval of surface emissivity and temperature, atmospheric temperature, water vapor and ozone profiles is formulated according to an inverse problem with multiple regularization parameters. A novel approach has been set up, which seeks an effective solution to the inverse problem in a generalized *L*-curve framework (Hansen, 1992). The a-priori information for the surface emissivity is obtained on the basis of laboratory data and satellite-based climatology, whereas that for the atmospheric parameters by climatology and/or weather forecasts. To ensure we deal with a problem of fewer unknowns than observations, the dimensionality of the emissivity has been reduced through its expansion in Fourier series. The overall methodology combines Optimal Estimation (e.g. Rodgers, 2000) with a 2-D *L*-curve criterion (e.g. Belge, 2002).

For both SEVIRI and IASI the inverse approaches rely on suitable a-priori information for emissivity. To this end we have used the University of Wisconsin (UW) Baseline Fit (BF) Emissivity database (UW/BFEMIS database, e.g. http://cimss.ssec.wisc.edu/iremis/ Seemann et al., 2008). The UW/BFEMIS database is derived from the monthly mean operational Aqua/MODIS (Moderate Resolution Imaging Spectroradiometer) products (called MYD11C3) using a conceptual model called the Baseline Fit method developed from laboratory measurements of surface emissivity.

The available band emissivities cannot be straigh interpolated to the SEVIRI channels and the IASI spectral bands, because this would be a too crude approximation. This problem has been addressed in Borbas and Ruston (2010) where an Empirical Orthogonal Function (EOF) regression was applied between the UW/BFEMIS database and the first five eigenvectors at high spectral resolution of a representative set of laboratory measurements of surface emissivity. A similar algorithm, which is used in this study, has been developed by Masiello et al (2013b). As in Borbas and Ruston (2010), the interpolation algorithm is based on the Empirical Orthogonal Function (EOF) decomposition of a suitable training data set of high spectral resolution emissivity spectra from laboratory measurements (see Masiello et al (2013b) for further details). The interpolation algorithm is used to transform the low spectral resolution emissivity as available from the UW/BFEMIS data base to the IASI spectral resolution. In case of IASI the interpolation algorithm yields the emissivity spectrum which is then used as the background information to constrain the IASI retrieval. In case of SEVIRI, the interpolation algorithm is first used to yield the IASI spectrum and second to convolve the IASI emissivity spectrum with the SEVIRI spectral response function to finally get the SEVIRI channels emissivity.

Further details about the retrieval procedure for IASI and SEVIRI can be found in Grieco et al. (2007), Masiello et al. (2009), Amoroso et al (2013), Masiello and Serio (2013), Masiello et al (2013a,b).

3 RESULTS

To have a proper comparison with IASI emissivity retrieval, this has been transformed to SEVIRI-like channel emissivity through convolution of the IASI retrieved emissivity spectrum with the SEVIRI channel spectral response. Figure 2 exemplifies the comparison for 4 July 2010.

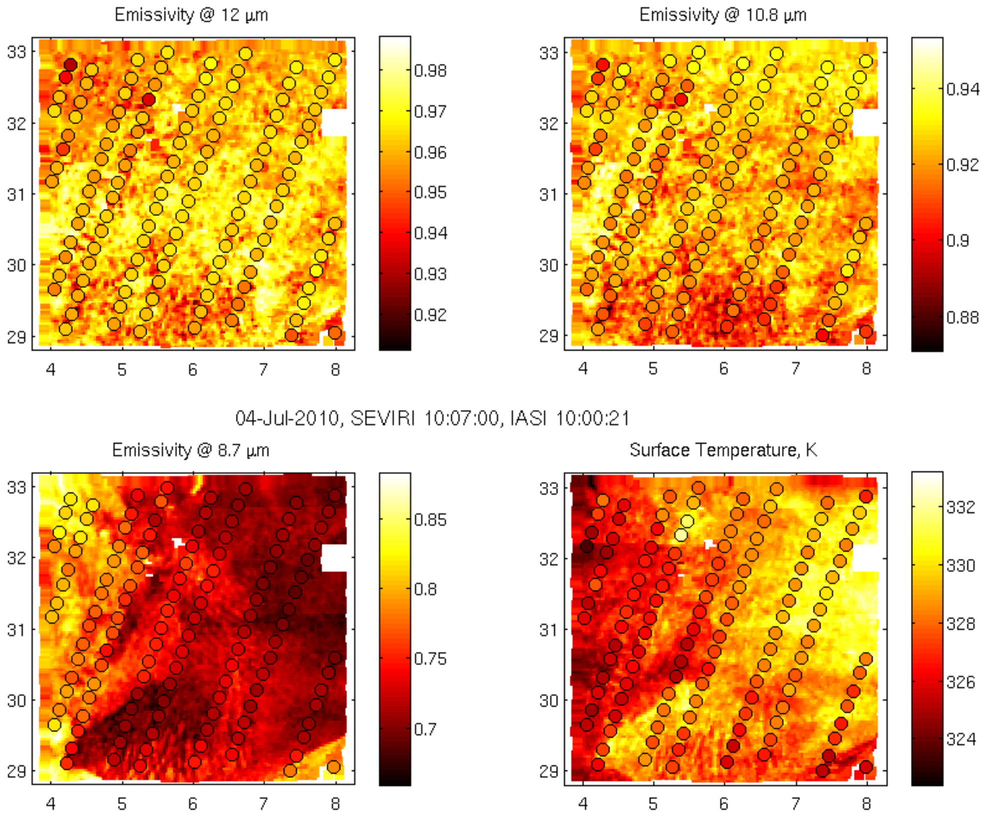

Figure 2: **Comparison for surface emissivity and temperature for 4 July 2010 in the afternoon. The first three panels show the comparison for the emissivity at the SEVIRI window channels (12 µm, 10.8 µm and 8.7 µm) while the last panel compares the surface temperature for the same day. The maps refer to the SEVIRI retrieved products. IASI products are shown with circles.**

This figure compares SEVIRI to IASI for the channels at 12 µm (top left panel a) and 10.8 µm (top right panel). At these channels, desert sand emissivity has a poor variability, which is nicely reflected from the emissivity retrieval. The average difference of emissivity between SEVIRI and IASI (using only the SEVIRI pixels co-located with IASI) is 0.000 at 12 µm and 0.001 at 10.8 µm.

Much more interesting is the comparison at 8.7 µm (shown in the bottom left-hand-side panel of Fig. 2), because this channel is located just in the middle of the quartz reststrahlen band. Now the emissivity map shows much more variability and the structures captured by SEVIRI are also nicely seen (although at a coarser spatial resolution) within the IASI map. The average emissivity difference between SEVIRI and IASI is, for this case, -0.004. On overall we have that IASI compares very nicely to SEVIRI and the average values of SEVIRI and IASI emissivity, over the spatial field at hand, differ on the third decimal digit alone. A good comparison is also seen for skin temperature (see Fig. 2). Structures seen in the SEVIRI map are also shown in that of IASI and the difference (over the co-located pixels) is of 0.9 K

The time series for surface temperature from one single SEVIRI pixel, shown in Figure 3a, allows us to appreciate the high consistency between SEVIRI and IASI. Furthermore, the scatter plot shown in Fig. 3b exemplifies that the consistency is quite good both for daytime and for night-time observations. Figure 3a also provides a comparison with the time-space collocated ECMWF analysis for T_s It is seen that there is a very nice comparison at night-time hours, however at midday, ECMWF has a cold bias which can reach 10 K and more.

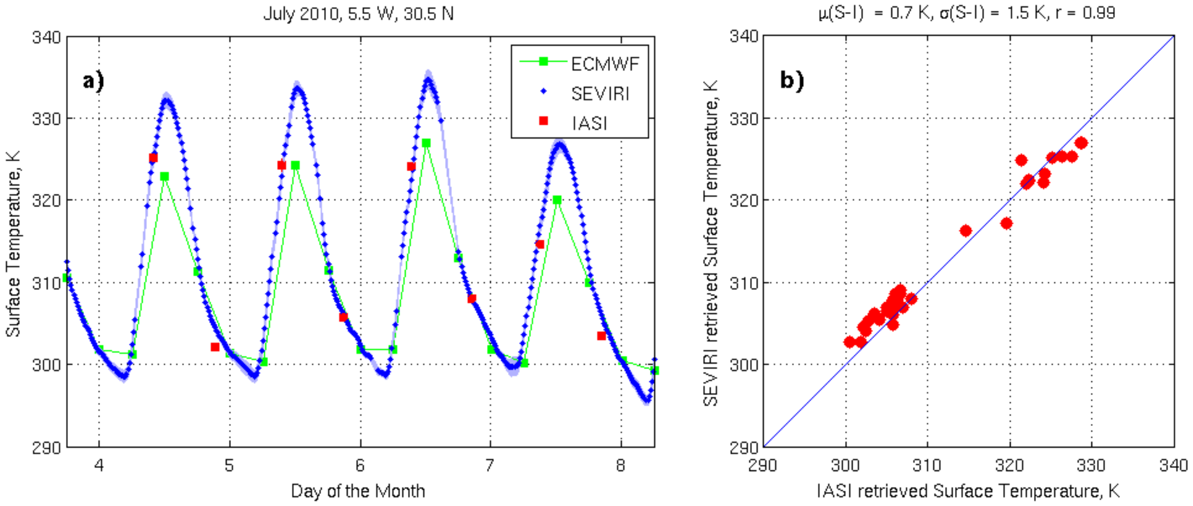

Figure 3: **Comparison between SEVIRI and IASI retrieved Skin Temperature. The panel a) shows the retrieved surface temperature (SEVIRI, blue line and IASI, red dot). In the same panel the ECMWF analysis is shown in green. Panel b) shows the scatter plot of retrieved surface temperature for the whole month of July 2010, the mean difference (SEVIRI-IASI) is 0.7 K, with a standard deviation of 1.5 K and a correlation index higher than 0.99.**

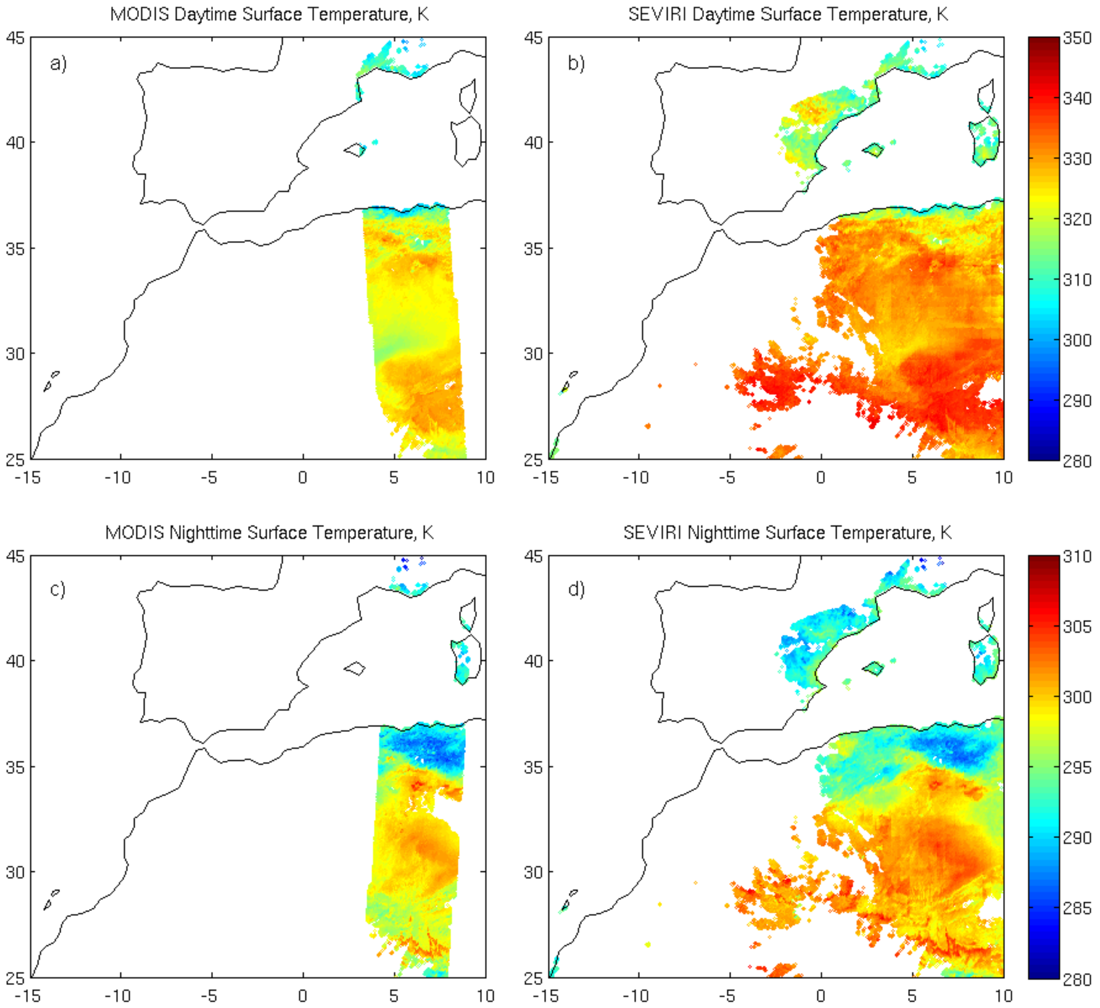

Figure 4: **Comparison between SEVIRI retrieved skin temperature (a and c) and MODIS L2 products, v 041 (b and d) for 7 July 2010. Results shown in panels a) and b) correspond to hours around midday, panel c) and d) around midnight.**

Finally, Fig. 4 shows a comparison of the surface temperature derived from MODIS and SEVIRI, respectively. The comparison is exemplified for 7 July 2010, which is mostly characterized by clear sky during MODIS overpasses. An important aspect of this comparison is that SEVIRI and MODIS show the same spatial pattern and gradients for the T_s field. However, MODIS seems to have a cold bias with respect to SEVIRI. The cold bias is less than 2 K at night-time, however it is of the order of 10 K at midday and attains its larger value over the Sahara Desert, where we know that there could be a diurnal emissivity variation (Li et al 2012).

In this respect, it should be stressed that the physical retrieval scheme we use for SEVIRI can take into account emissivity variations during the day, conversely the split-window type algorithm used with MODIS cannot. In fact, it assumes a constant emissivity during the day.

4 CONCLUSIONS

The Kalman filter methodology for the simultaneous retrieval of surface emissivity and temperature from SEVIRI observations has been applied to a target area over the Sahara Desert. The results have been intercompared with IASI and MODIS equivalent products. The retrieval exercise shows that the Kalman filter methodology developed for SEVIRI is robust even at the full time resolution of 15 minutes.

The comparison between IASI and SEVIRI shows a very good agreement. It should be stressed that the methods developed for IASI and SEVIRI are both physical schemes which can take into account, e.g., emissivity diurnal variations.

A comparison with surface temperature from the ECMWF analysis shows that the ECMWF model is characterized by a cold bias during daytime.

A similar finding has been also evidenced in the case of the MODIS surface temperature. The cold bias can reach 10 K and more for daytime measurements over the desert. This is likely the result of the split-window type algorithm used with MODIS, which does not take diurnal emissivity variations into account and assumes a constant emissivity during the day. In this respect, our findings specifically point out the importance of applying simultaneous physically-based algorithms to retrieve surface temperature and emissivity.

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REFERENCES

Amoroso, M., De Feis, I., Masiello, G., Serio, C., Venafra, S. and Watts, P. (2013) Spatio-temporal constraints for emissivity and surface temperature retrieval: Preliminary results and comparisons for SEVIRI and IASI observation. EARSeL eProceedings, **12**(2): pp 136-148. Available on line at website http://www.eproceedings.org/static/vol12_2/12_2_venafra1.html.

Belge, M., Kilmer, M.E. and Miller, E.L. (2002). Efficient determination of multiple regularization parameters in a generalized L-curve framerwork. Inverse Problems **18**, pp. 1161-1183. doi:10.1088/0266-5611/18/4/314.

Borbas, E.E. and Ruston, B.C. (2010) The RTTOV UWiremis IR land surface emissivity module. NWP SAF, EUMETSAT.

Grieco, G., Masiello, G., Matricardi, M., Serio, C., Summa, D., and Cuomo, V., (2007) Demonstration and validation of the ϕ-IASI inversion scheme with NAST-I data, Q. J. R. Meteorol. Soc., **133**(S3), pp 217–232. doi: 10.1002/qj.162.

Hansen, P.C. (1992) Analysis of Discrete Ill-Posed Problems by Means of the L-Curve, SIAM Review, **34**, pp 561-580, doi:10.1137/1034115.

Hilton, F., Armante, R., August, T., Barnet, C., Bouchard, A., Camy-Peyret, C., Capelle, V., Clarisse, L.,Clerbaux, C., Coheur, P.F., Collard, A., Crevoisier, C., Dufour, G., Edwards, D., Faijan, F., Fourri´e, N., Gambacorta, A., Goldberg, M., Guidard, V., Hurtmans, D., Illingworth, S., Jacquinet-Husson, N., Kerzenmacher, T., Klaes, G., Lavanant, L., Masiello, G., Matricardi, M., Mc- Nally, A., Newman, S., Pavelin, E., Payan, S., P´equignot, E., Peyridieu, S., Phulpin, T., Remedios, J., Schl¨ussel, P., Serio, C., Strow, L., Stubenrauch, C., Taylor, J., Tobin, D.,Wolf,W. and Zhou, D. (2012) Hyperspectral Earth Observation from IASI: four years of accomplishments. B. Am. Meteorol. Soc., **93**, pp 347-370. doi:10.1175/BAMS-D-11-00027.1.

Kalman, R. E., and Bucy R.S. (1961) New Results in Linear Filtering and Prediction Theory. Transactions of the ASME - Journal of Basic Engineering **83**, pp 95-107. doi:10.1115/1.3658902.

Li, Z., Li, J., Li, Y., Zhang, Y., Schmit, T.J., Zhou, L., Goldberg, M.D., and Menzel, W.P. (2012) Determining diurnal variations of land surface emissivity from geostationary satellites, J. Geophys. Res., **117**, D23302. doi:10.1029/2012JD018279.

Masiello, G., Serio, C., Carissimo, A., Grieco, G., and Matricardi, M. (2009) Application of φ-IASI to IASI: retrieval products evaluation and radiative transfer consistency, Atmospheric Chemistry and Physics, **9**, pp 8771-8783. doi:10.5194/acp-9-8771-2009.

Masiello G., and Serio C., (2013) Simultaneous physical retrieval of surface emissivity spectrum and atmospheric parameters from Infrared Atmospheric Sounder Interferometer spectral radiances. Appl. Opt. **52**, pp 2428-2446. doi: 10.1364/AO.52.002428

Masiello, G., Serio, C., De Feis, I., Amoroso, M., Venafra, S., Trigo, I.F., Watts P. (2013a), Kalman filter physical retrieval of geophysical parameters from high temporal resolution geostationary infrared radiances: the case of surface emissivity and temperature, Atmos. Meas. Tech. Discuss. **6,** pp 6873-6933, doi:10.5194/amtd-6-6873-2013

Masiello, G., Serio, C., Venafra, S., De Feis, I., and Borbas, E.E. (2013b). Diurnal variation in Sahara desert sand emissivity during the dry season from IASI observations. J. Geophys. Res. doi:10.1002/jgrd.50863.

Rodgers C. D. (2000) Inverse methods for atmospheric sounding, Theory and Practice World Scientific, Singapore.

Seemann, S.W., Borbas, E.E., Knuteson, R.O., Stephenson, G.R., and Huang, H.L. (2008), Development of a Global Infrared Land Surface Emissivity Database for Application to Clear Sky Sounding Retrievals from Multispectral Satellite Radiance Measurements, J. Appl. Meteorol. Clim., **47**, pp 108-123. doi:10.1175/2007JAMC1590.1.

Serio C., Masiello G., Amoroso M., Venafra S., Amato U. and De Feis, I., (2012) Study on space-time constrained Parameter Estimation from Geostationary data, Final Report EUMETSAT (Contract EUM/CO/11/4600000996/PDW), EUMETSAT, Darmstadt, Germany. Revised by P. Watts.

1. More details on MODIS products are at web sites https://lpdaac.usgs.gov/products/modis_products_table/mod11_l2 (Terra Platform) and https://lpdaac.usgs.gov/products/modis_products_table/myd11_l2 (Aqua Platform).