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MUTLICLIM – From CHAMP towards Multi-Satellite Climate Monitoring based on the MetOp and COSMIC Missions

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FINAL REPORT - Executive Summary

# MULTICLIM

## From CHAMP towards Multi-Satellite Climate Monitoring based on the MetOp and COSMIC Missions

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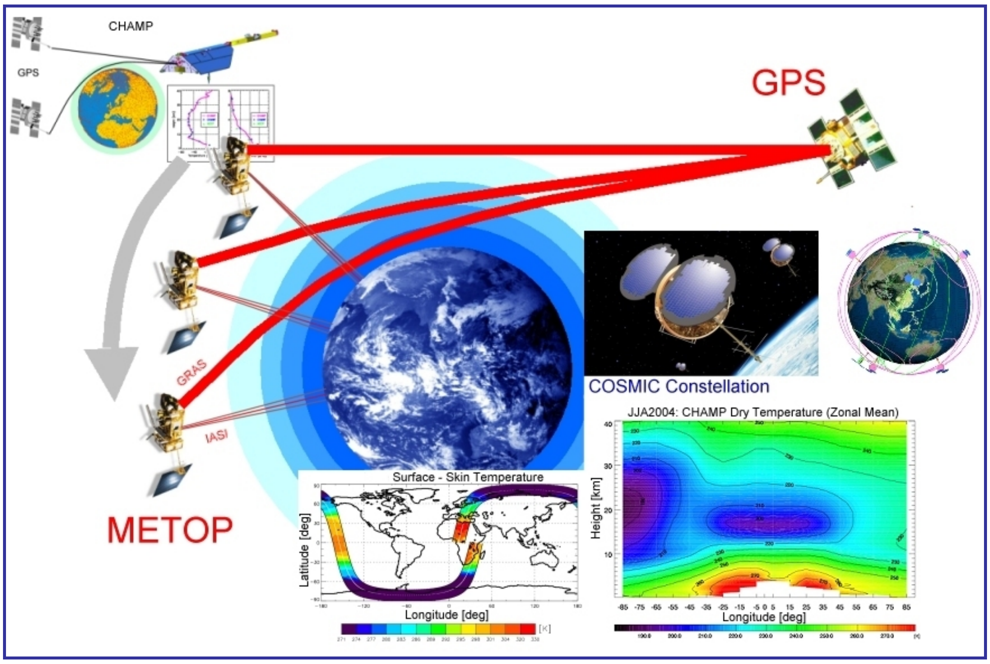


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# Executive Summary

## Deutschsprachige Kurzzusammenfassung

Das übergeordnete Ziel des MULTICLIM Projektes war zur Vorbereitung eines globalen Klima-Monitorings der oberen Troposphäre und unteren Stratosphäre der Erde mit hoher Genauigkeit und Konsistenz beizutragen und damit zu einer verbesserten Detektion und Vorhersage von Klimavariabilität und Klimawandel. Schlüssel-Datensätze für diesen Zweck sind jene von Radiookkultation und des Infrarot-Atmosphären-Sondierungs-Interferometers (IASI), wobei letzteres im Fokus des MULTICLIM Projektes stand.

Ein primäres Ziel des neuen IASI Instruments an Bord der Europäischen operationellen Wettersatelliten MetOp (der erste Satellit MetOp-A ist seit Oktober 2006 im Orbit) ist die Verbesserung der vertikalen Auflösung von Temperatur- und Wasserdampfprofilmessungen auf ca. 1–2 km in der Troposphäre sowie der Genauigkeit auf mind. 1 K in der Temperatur und ca. 10% in der Feuchte. Eine wissenschaftliche Hauptmotivation für dieses Ziel ist die Schlüsselrolle des Wasserdampfs in der oberen Troposphäre wegen seiner Auswirkungen auf das globale Klima: nur kleine Feuchteänderungen und -trends bewirken schon deutliche Änderungen in der Wärmestrahlung der Erde und damit bei der Stärke des Treibhauseffekts. IASI sollte eine genauere Berechnung der Klimaänderungen ermöglichen und insbesondere der klimatischen Relevanz der oberen Troposphäre dabei. Zusätzlich verspricht IASI signifikante Beiträge zur Numerischen Wettervorhersage durch seine genauen und räumlich dicht gewonnenen Temperatur- und Wasserdampfprofile für den Bedarf der operationellen Meteorologie und der Wetterforschung.

Als Beitrag im Rahmen des gemeinsam von ESA und EUMETSAT getragenen “MetOp Research Announcement of Opportunity” wurde im MULTICLIM Projekt ein IASI Datenprozessierungssystem zur Atmosphärenprofilberechnung weiter entwickelt sowie die Erstellung von globalen Klimatologien mit hoher räumlicher Auflösung aus IASI Profilen vorbereitet und demonstriert. Weiters wurden Temperatur-, Feuchte- und Ozonprofile sowie Meeresoberflächentemperaturen, welche aus einem „Test-Orbit“ echter MetOp IASI Daten berechnet wurden, mit Hilfe von örtlich-zeitlich passenden Daten von Wetteranalyse-Feldern des Europäischen Zentrums für Mittelfrist-Wettervorhersage validiert.

Das Projekt lieferte damit einerseits wertvolle Beiträge zur Validierung von IASI-Daten während der Kommissionierungsphase des MetOp-A Satelliten und bereitete andererseits den Weg zur weiteren Verbesserung und breiteren Anwendung des IASI Prozessierungssystems für Klimastudien.

## English Summary (with short summaries of project reports enclosed)

The overarching goal of the MULTICLIM project was to prepare for global monitoring of the climate evolution of the Earth’s upper troposphere/lower stratosphere region with high accuracy and consistency and thereby help to improve the ability to detect, attribute, and predict climate variability and change. The key datasets for this purpose are radio occultation (RO) data and Infrared Atmospheric Sounder Interferometer (IASI) data, of which the latter were in the focus of the MULTICLIM project.

One of the primary objectives of the IASI sensor on board the European MetOp satellites (the first satellite MetOp-A being in orbit since October 2006) is the improvement of the vertical resolution of temperature and water vapor profiles to about 1–2 km in the troposphere as well as to improve the retrieval accuracy to within 1 K in temperature and about 10% in humidity. A main scientific motivation for this is the key role played by water vapor in the upper troposphere and its effects on the global climate, since only small changes in humidity and its trends have serious implications on the amount of thermal energy escaping to space and thus on the strength of the Earth's greenhouse effect. IASI is expected to supply more accurate quantification of climate variability and change, particularly contributing to our knowledge of the climate relevance of the upper troposphere. Additionally, the IASI data promise to greatly assist numerical weather prediction (NWP) in delivering accurate and frequent temperature and humidity profiles for operational and meteorological research needs.

Contributing in the framework of the joint ESA and EUMETSAT MetOp Research Announcement of Opportunity, the MULTICLIM project undertook to advance IASI retrieval algorithms and to prepare IASI climatology processing for climatologies at high horizontal resolution, but also with horizontal grids matching RO climatologies prepared in a separate project. Furthermore, retrieved temperature, humidity, and ozone profiles as well as sea surface temperature (SST) data from a "test orbit" of real MetOp IASI data were validated against co-located data from analysis fields of the European Centre for Medium-Range Weather Forecasts (ECMWF).

The project valuably contributed to the validation of IASI data during the MetOp-A satellite commissioning phase as well as paved the way to further advancement and broader application of the IASI retrieval system for climate studies.

Attached to the Executive Summary, this "Final Report" comprises two reports, describing the results of the MULTICLIM work in detail. Below the main results of these two reports are briefly summarized, first for the ENHANCEMENT REPORT then for the VALIDATION REPORT.

**ENHANCEMENT REPORT — Advanced retrieval of atmospheric profiles and SST from IASI data**

In this report an advanced temperature, humidity, ozone, and SST (sea surface temperature, more precisely, surface skin temperature of the ocean) retrieval system, integrating an efficient channel selection method, is introduced and demonstrated. Additionally, a careful error analysis and characterization of the retrieved profiles is given.

The retrieval system is based, in terms of forward modeling, on the usage of the fast radiative transfer model RTIASI (a science community model distributed by EUMETSAT). RTIASI was found to be suitable for the calculation of radiances and Jacobians for temperature, humidity, ozone, and SST for our purpose of a combined temperature, humidity, ozone profile and SST retrieval from IASI spectra and it provided satisfactory forward model error characteristics.

Since the IASI instrument has more than 8000 channels we implemented channel reduction algorithms as the otherwise large computational burden is neither necessary nor practical in the climatological application we target. A two-step procedure for down-selecting the channels was introduced. The first step includes the removal of channels containing significant contributions from parts of the spectrum not relevant for the retrieval of the atmospheric parameters dealt with here. The second step is the selection of the most informative channels out of the remaining sample.

From two approaches tested, the "information content" (IC) approach and "maximum sensitivity" (MS) approach, we found both computationally efficient and robust and leading to similarly good retrieval performance. As still the IC approach performs slightly better, we adapted this as future baseline. Investigating by how much the total number of 8461 IASI channels can be reduced without appreciable decrease in retrieval performance we found that ~300 channels (~3.5% of total) is sufficient, enabling a computationally very fast processing.

The solution of the inverse problem was implemented via a joint optimal estimation scheme for temperature, humidity, ozone, and SST. The moderate non-linearity of the radiative transfer problem was taken into account by using an iterative Gauss-Newton type inversion algorithm based on a Taylor series expansion about a first guess (a priori) state.

We investigated the retrieval performance of the joint optimal estimation system based on a complete MetOp orbit of simulated IASI data (~23,000 spectra) with main results as follows.

In general we found that the system provides profiles of temperature and humidity, which improve significantly over the a priori profiles from an ECMWF 24h forecast throughout the retrieval domains of interest in the atmosphere. In the case of ozone, improvements were found especially in those stratospheric regions which exhibit high concentrations of this gas, i.e., around the peak of the atmospheric ozone layer, where rms errors were reduced to near 10% over a priori errors of 20%. The SST retrieval was found very robust and accurate with rms errors at the 0.1 K level, essentially independent of a priori information.

Weaknesses in retrieving atmospheric parameters occur at levels where the sensitivity of the relevant weighting functions in the Jacobian matrix is limited, such as in the case of temperature in the upper stratosphere, in the case of humidity in the lower troposphere (e.g., top of boundary layer gradients) and in the stratosphere (no reasonable sensitivity), and in the case of ozone in regions of not sufficiently high concentrations of ozone. The sensitivity to SST is overall very good, thanks to the "atmospheric window" channels.

Quantifying more closely temperature and humidity accuracy and vertical resolution, we found that the processing system robustly retrieves tropospheric and lower stratospheric temperature to 0.5–1 K accuracy, at ~2–10 km vertical resolution. Tropospheric specific humidity is retrieved to 15–20% accuracy (< 15% below 850 hPa) with ~1.5–3 km vertical resolution. The coarse temperature resolution from formal estimates (Averaging Kernel full-widths at half maximum and Backus-Gilbert measures) is due to relaxed humidity a priori error specifications for strengthening a priori independence of the retrieved data. Overall the performance is similar to the one reported by other authors based on independent algorithms.

Detailed insight into retrieval system performance properties was obtained from formal error analysis and characterization where we discussed in this report retrieval error correlation, retrieval-to-apriori error ratio, as well as weighting, gain, and signal to noise functions.

In comparing the joint multi-parameter retrieval to simplified single-parameter retrievals it was clearly found that the joint processing significantly improves over the single-parameter retrieval. While this provided no surprise in itself, these evaluations represented a strong further test and verification of the new retrieval system and provided us with solid confidence in its robustness and utility for future large-scale application.

The system is scheduled to process MetOp IASI data into profiles which form the basis of generating climatological fields. Particular interest lies in climate monitoring of middle and upper troposphere moisture changes along with changes in SST and the thermal structure of the troposphere. As this report indicated, the IASI data hold high potential to significantly improve upon current operational meteorological satellite data for these purposes. The processing system was employed and further evaluated in the subsequent initial validation of a “test orbit” of real IASI data described in the VALIDATION REPORT.

**VALIDATION REPORT — Initial validation of atmospheric profiles and SST retrieved from MetOp IASI data and preparation of climatology processing**

This report describes the validation of atmospheric profiles (temperature, humidity, ozone) and SST, retrieved with the processing system from real IASI data, against ECMWF analysis fields. Additionally it describes the preparation of a climatology processing system, which uses the heritage of radio occultation projects but is extended regarding the higher data density of the IASI instrument compared to radio occultation measurements.

The first part of the report presents results of the initial validation based on a test orbit data set provided by EUMETSAT, ranging from April 2 to April 3, 2007. In terms of the retrieval algorithm and processing system we used our processing system described in the ENHANCEMENT REPORT summarized above. We investigated the retrieval performance of this joint optimal estimation system based on a complete MetOp orbit of real IASI data, starting on April 2, 2007, at 23:20 UTC, and ending on April 3, 2007, at 0:23 UTC. We validated the IASI-derived dataset (clear-air profiles, i.e., those which passed cloudy profiles elimination) against co-located profiles from a high-resolution ECMWF atmospheric analysis of April 3, 2007, 0:00 UTC.

In general we found, consistent with the simulation study of the ENHANCEMENT REPORT, that the system provides profiles of temperature and humidity, which improve over the a priori profiles from an ECMWF 24h forecast throughout the retrieval domains of interest in the atmosphere. In the case of ozone, improvements were found especially in those stratospheric regions with high concentrations, i.e., around the peak of the ozone layer, in line with the simulation study. The SST retrieval was not found as robust as in the simulation study but was still very accurate with rms errors at the sub-Kelvin level. Reasons for degraded performance to this end originate from limitations in realistic surface (emissivity) modeling and weaknesses in detection of clouds, i.e., an inclusion of partly cloudy pixels in the retrieval process and the non-detectability of low clouds by current cloud detection algorithms.

Weaknesses in retrieving atmospheric parameters occur specifically at levels where the sensitivity of the relevant weighting functions in the Jacobian matrix is limited, such as found in the simulation study. The sensitivity to SST is overall very good, thanks to the “atmospheric window” channels.

In comparing the joint multi-parameter retrieval to simplified single-parameter retrievals it was found that the joint processing significantly improves over the single-parameter retrieval, consistent with the results of the simulation study. This provided us with further confidence in the robustness and utility of the joint retrieval for future climate monitoring application, after the next steps of advancement such as in cloud detection and cloud clearing.

The results obtained from this initial validation also provided clear guidance for next and meanwhile on-going advancements, including a further improvement of the statistical model of the a priori uncertainties for temperature and humidity as well as the usage of the newest version of the forward model RTIASI, which contains a new scheme for prediction of the water vapor continuum, a refinement of the vertical pressure grid, an inclusion of some more trace gases as profile variables, an introduction of a solar term to evaluate the solar radiance reflected by a land or water surface, and an inclusion of clouds and aerosols. The updated processing system will also include a cloudy profiles elimination step in the system.

Overall the initial validation indicates that the IASI data hold — while still further processing improvements are needed for this very “young” dataset — high potential to significantly improve upon current operational satellite data for weather and climate applications.

On the prepared climatology processing of IASI-retrieved profiles, presented in the second part of the report, the developed Wegener Center climatology processing system (CLIPS) was tested with different representative datasets, including “IASI proxy” atmospheric profiles densely sampled from ECMWF analysis fields and real radio occultation data.

It was confirmed that the possible horizontal resolution of climatologies from IASI is higher than from radio occultation (e.g., MetOp GRAS), the latter being superior in the vertical resolution. Furthermore, the information gain on horizontal-geographical climate variability due to higher resolution of IASI has been well illustrated.

In summary, regarding the future promise of the European MetOp operational mission in this field, the combination of IASI and GRAS information is truely the method of choice. It is highly promising, as it allows, based on the complementary strengths of IASI and GRAS, for excellent climate monitoring at both high horizontal and vertical resolution scales.

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