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D11 Executive Summary

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"Scientific Concept Study for Wide-Swath High-Resolution
Cloud Profiling"

Background

This study focuses on the synergistic retrieval of cloud information from active and passive observations. While this synergistic approach is well established for precipitation [Skofronick-Jackson et al., 2017, Hou et al., 2013], it is used less so for clouds.

Passive submillimeter and microwave sensors like the Ice Cloud Imager (ICI) and the Microwave Imager (MWI) on the upcoming MetOp-SG-B satellite have a great potential for estimating the bulk mass of clouds. Being the first operational down looking passive submillimeter sensor ICI has an even higher potential for estimating the bulk mass of ice clouds. Passive submillimeter and microwave sensors also have to some extent the potential to provide information about the vertical structure of clouds, but compared to a nadir looking cloud radar their vertical resolution is coarse. Nadir looking cloud radar satellites like CloudSat [Stephens et al., 2002] with its 94 GHz radar provide high resolution vertical profiles of water content (WC) but are limited to along track measurements, whereas ICI and MWI have a wide swath of about 1700 km but provide only limited information about the vertical structure.

The upcoming EarthCARE [Illingworth et al., 2014] mission with its synergistic lidar and radar observations will deliver valuable information on clouds as already similar observations by CloudSat and CALIPSO [Deng et al., 2010, 2015] show. With view of clouds the main advantage of a synergistic lidar and radar retrieval is that it is much more sensitive to thin ice clouds than radar only.

ICI with its high submillimeter channels will be more sensitive to ice clouds than all previous passive microwave sensors. The combination of EarthCARE and ICI complement each other ideally. Unfortunately, MetOp-SG-B and EarthCARE will have only limited number of collocations due to their different orbits. Furthermore, EarthCARE is a science mission, which means that is lifetime is much shorter than operational satellite missions like Metop-SG. Given the robustness of CloudSat [Stephens et al., 2018] and the high sensitvity of ICI the idea arises to combine a CloudSat-type radar satellite and ICI with view of ice clouds and with MWI for further possible synergies.

Study Goal

The main goal of the study is to investigate the synergies of combining ICI and Microwave Imager MWI on board of the upcoming Metop-SG-B with a CloudSat type cloud radar for cloud retrieval. There are two main synergies:

1. the direct synergy in view of a combined active and passive cloud retrieval and
2. the indirect synergy in view of using the information retrieved from the synergistic retrieval for passive cloud retrievals.

Concept

The basic concept, which is depicted in Fig. 1 and Fig. 2, is a radar satellite flying ahead of Metop-SG-B on the same orbit. The altitude of Metop-SG-B will be 830 km. The radar satellite is called from here on LIRAS (Liquid and Ice Particles Detection and Ranging Satellite). LIRAS will have a nadir looking cloud radar, which will from here on be called LCPR (LIRAS Cloud Profiling Radar). The on-going operation of CloudSat [Stephens et al., 2002, 2018] after more than 10 years in space shows the robustness of its design. This makes the CloudSat design well suited for a radar satellite flying together with Metop-SG-B with its nominal lifetime of 8.5 years[1]. Due to the higher altitude LCPR will have a slightly reduced sensitivity, -29 dBZ instead of -30 dBZ as for CloudSat. ICI and MWI on-board of Metop-SG-B are conical scanning radiometers with a looking angle of 45°. A looking angle of 45° results in a local incidence angle of 53° at Earth's surface. The swath width of ICI and MWI is 1700 km. By LIRAS flying ≈ 135 s ahead of Metop-SG-B, LCPR will look coincidentally at the same part of the atmosphere as ICI and MWI at their swath center.

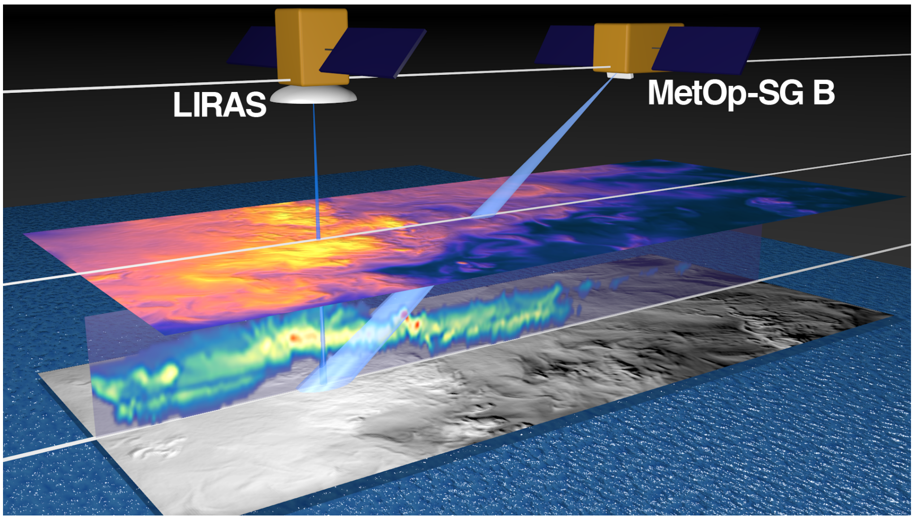

Figure 1: Artist's rendition of the mission concept. LIRAS flying ahead of MetOp-SG-B. (top layer) brightness temperature at 325.15 ± 9.5, (bottom layer) ice water path and (vertical slice) radar cross section.

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[1] Applicable document 1: `https://directory.eoportal.org/web/eoportal/satellite-missions/m/metop-sg`

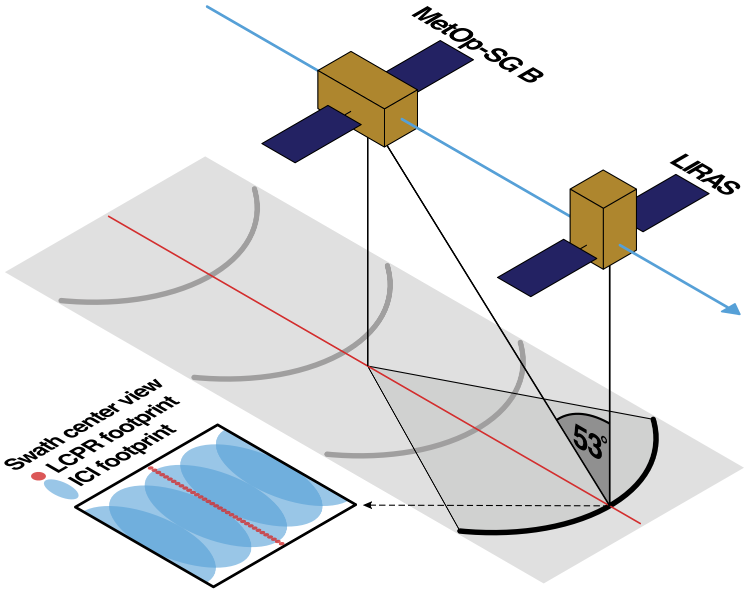

Figure 2: Schematic of the proposed satellite constellation

Methodology

- The analysis of the synergies relies on simulated observations of LCPR, ICI and MWI. Scenes from runs of Environment Canada's high-resolution numerical weather prediction model known as the Global Environmental Multiscale Model (GEM, Côté et al. [1998]) and from runs of the ICOsahedral Non-hydrostatic (ICON, Zängl et al., 2015) model were utilized as input for the simulations. The ICON model is a joint project of the German Weather Service (DWD) and the Max Planck Institute for Meteorology (MPI-M). LCPR, ICI and MWI were simulated using the Atmospheric Radiative Transfer Simulator (ARTS, Buehler et al. [2018], Eriksson et al. [2011]).

- To investigate the direct synergy, a synergistic 1d-var (OEM) active passive retrieval was developed and implemented into ARTS. For the synergistic retrieval the channels of MWI with frequencies below 89 GHz were excluded, because of too different footprint sizes. The retrieval targets are the mass density and the normalized number density of ice, the mass density and the normalized number density of rain, the mass density of cloud liquid, and relative humidity.

- To investigate the indirect synergy, the 3D construction algorithm of Barker et al. [2011] and two additional algorithms based on an ensemble filter were applied on ICI observations. The algorithms use locally the results from the synergistic swath center retrieval to retrieve off-center cloud properties by setting up a local ad-hoc database for the retrieval. Furthermore, a retrieval database for a Bayesian Monte Carlo Integration (BMCI) retrieval was constructed from results of the synergistic swath center retrieval. The BMCI retrieval was applied separately ICI and MWI observations. The retrieval targets are profiles of the mass densities of ice, of rain, of cloud liquid water and profiles of water vapor volume mixing ratio.

Results

1. Direct synergy

   Fig. 3 shows exemplary the mass density of ice (ice water content, IWC) retrieved with the synergistic retrieval for the edge of the ITCZ over the tropical pacific, which is dominated by ice clouds. Additionally, the true IWC is shown. For this retrieval the effects of the different footprints were neglected and ICI and MWI are assumed to have the same footprint as LCPR. The visual agreement between the retrieved IWC and the true IWC is good. All basic features are well resolved. At the cloud base some even large IWCs are not estimated. This is due to the retrieval assumptions that ice can exist only for temperature $< 273\,\mathrm{K}$. The radar only retrieval in Fig. 3 underestimates the IWC. This indicates the benefit of the used passive channels. Further analysis indicate that the strongest impact from the passive channels is due to the 664 GHz channel.

   Additionally, Fig. 3 shows also the median fractional error (MFE[2]) for IWC. It summarizes the performance of the synergistic retrieval for this example scene. The synergistic retrieval and the radar only retrieval have a similar MFE for IWC $< 10^{-5}\,\mathrm{kg\,m^{-3}}$. The MFE decreases from $\approx 150\%$ at an IWC of $10^{-6}\,\mathrm{kg\,m^{-3}}$ to $\approx 50\%$ an IWC of $10^{-5}\,\mathrm{kg\,m^{-3}}$. Whereas the MFE of the synergistic is in the order of for IWC $> 10^{-5}\,\mathrm{kg\,m^{-3}}$, the MFE of the radar only retrieval increases with increasing IWC. For IWC $> 4 \cdot 10^{-5}\,\mathrm{kg\,m^{-3}}$ it is $> 100\%$. For mixed phase clouds or when precipitating snow is dominating (not shown) the performance of the synergistic retrieval is similar to the radar only retrieval.

   For the other proposed retrieval targets, which are relative humidity, mass den-

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[2]

$$MFE\,(x) = \text{median}\left(\exp_{10}\left(\left|\log_{10}\frac{x_{retrieved}}{x_{truth}}\right|\right) - 1\right) \tag{1}$$

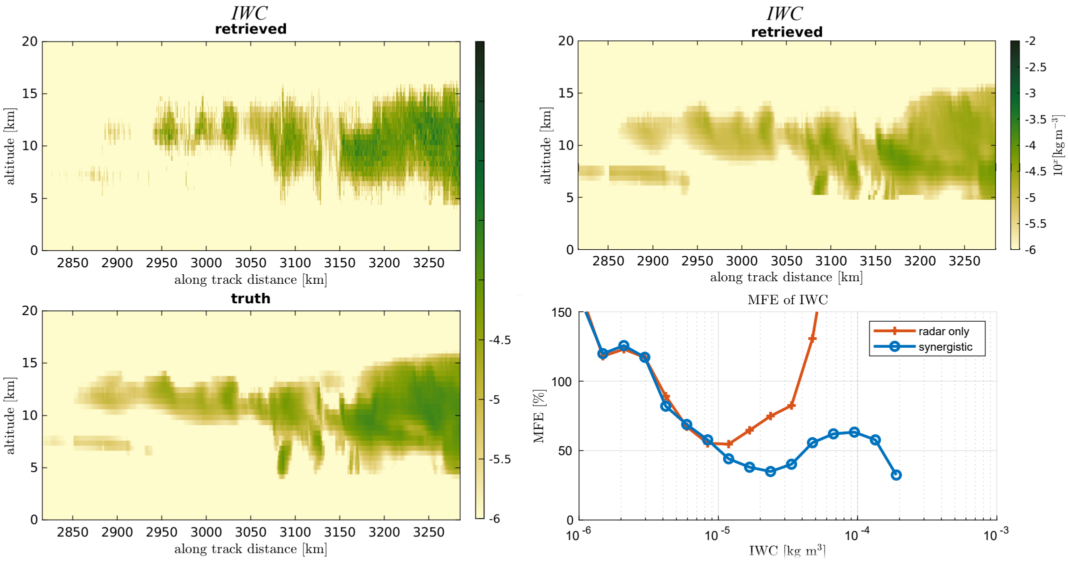

Figure 3: Example result of the synergistic swath center retrieval for the edge of the ITCZ over the tropical pacific. (top left) Ice water content (IWC) retrieved with the synergistic swath center retrieval. (top right) IWC retrieved with radar only retrieval. (bottom left) True IWC. (bottom right) Median fractional error (MFE) of IWC.

sity of cloud liquid, mass density of rain, normalized number density of rain and normalized number density of snow, the results are not as good as for IWC. There are some indications that for scenes dominated by ice clouds and for high IWC a second moment of the particle size distribution of ice can be retrieved to some extent. Furthermore, the synergistic retrieval is able to estimate the basic vertical structure of relative humidity. The synergistic retrieval does not show much skill in retrieving rain or liquid water. This is expected considering the relatively high frequency of the LCPR and the omission of the low-frequency MWI channels from the retrieval.

2. Indirect synergy:

   The 3D construction algorithm of Barker et al. [2011] and two additional algorithms, which are based on an ensemble filter, were tested by applying them on simulated ICI observations. For the test, we assumed that we have a perfect knowledge of the atmospheric states at the swath center and beamfilling effects were neglected. Furthermore the background database and the simulated measurements of the test scene are based on the same microphysical assumptions and have a similar distribution of the atmospheric states. Under these assumptions, except near the swath center and for small amounts of hydrometeors, the algorithms have a worse performance in view of the MFE of the desired retrieval quantities than the BMCI single instrument retrieval or at least a similar performance.

Fig. 4 shows exemplary for three different retrieval setups applied on $\approx 250,000$ simulated observations over the tropical pacific the median fractional error (MFE) of ice water path (IWP) using ICI. The IWP is the vertically integrated IWC. The blue and red lines denote the reference and the synergistic database retrieval, respectively. The reference retrieval is the BMCI single instrument retrieval using the reference database. The reference database consist of simulated brightness temperatures and states from atmospheric model runs over tropical ocean. The setup of the reference retrieval is idealized as the simulated observations and the used database are based on the same assumptions. The measurement noise is the only considered error source for the reference retrieval. The synergistic retrieval database was simulated by stochastically adding Gaussian distributed errors to the reference databases. The synergistic database has three major error sources: noise of the observed measurement vectors, errors due to the different footprints of radar and radiometer, and errors of the retrieved states. Noise is simply given by the sensor specifications, the footprint error was estimated from simulations and the error of the state vector is based on the performance of the synergistic swath center retrieval. The grey shade areas in Fig. 4 denote the range between the maximum and minimum MFE for retrievals where a set of different fully simulated database were used for the retrieval. These fully simulated database are different mixtures of the reference databases, which were additionally modified by adding a Gaussian distributed modeling error.

For IWP the MFE of the the synergistic database retrievals for ICI and MWI are in general 10 to 30 percentage points higher than the reference result. Compared to the fully simulated database retrievals, the MFE is mostly at the lower edge of the MFE range of the fully simulated database retrievals. The lower edge of the MFE of the fully simulated database retrievals are only slightly higher than the reference results indicating that the modeling error has only limited influence on the performance. The upper edge of the MFE range is mostly higher than the lower edge by more than 40 percentage points, which indicate the influence of the a priori statistics. For the retrieval of rain, cloud liquid and water vapor, the results are not as good as for ice. For water vapor, the performance of

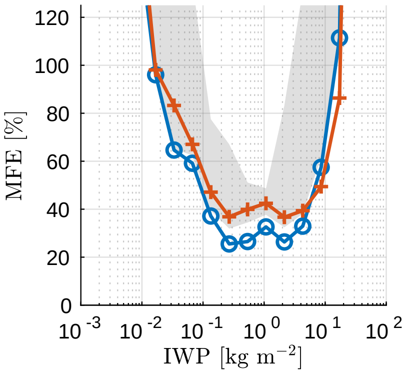

Figure 4: Median fractional error (MFE) of the passive retrieval for ice water path (IWP) using ICI over tropical ocean. The blue and red lines denote the reference and the synergistic database retrieval, respectively. The grey shade denote the range between the maximum and minimum MFE for retrievals where a set of different fully simulated database were used for the retrieval.

the synergistic database retrieval is bad for ICI as for MWI. The performance for MWI is better than ICI, because most of the liquid clouds, rain and, water vapor are confined to the lower troposphere, which is opaque in the tropics at ICI frequencies, whereas it is not for some of the MWI channels. This due to the high errors of the synergistic swath center retrieval for water vapor, which could be the results that the synergistic swath center retrieval exclude the channels below 89 GHz. Similar findings hold for liquid cloud and rain. Though MWI can sense the lower troposphere the retrieval setup is not optimal for the retrieval of liquid hydrometeors, because tests with different scenes and independent of the used database show strong variations in the performance. For the MWI channels that can sense the lower troposphere water vapor and liquid hydrometeors signals are similar, which makes it difficult to distinguish between them.

Conclusions

1. Direct synergy:
    - The results clearly show the existence of synergies between the LCPR RADAR and the passive microwave and sub-mm observations, in which the main synergies are found for frozen hydrometeor retrieval.
    - The synergistic retrieval of frozen hydrometeors works well for ice clouds and has a better performance than the radar only retrieval indicating the

  benefit of the passive channels for the retrieval. To some extent, even a second moment of the particle size distribution can be retrieved for frozen hydrometeors. For mixed phase clouds and for precipitating ice the benefit of the passive observations is limited.

  - In contrast to the retrieval of frozen hydrometeors, the synergistic retrieval does not work well for rain and liquid clouds. This is expected considering the relatively high frequency of the LCPR and the omission of the low-frequency MWI channels from the retrieval. The synergistic retrieval is able to estimate the basic vertical structure of relative humidity.
  - It is likely that better performance can be achieved, if the retrieval is refined further than the conceptual character within this study.

2. Indirect synergy:
   - The 3D construction algorithm of Barker et al. [2011] and the two additional algorithms that are based on an ensemble filter have, except close to the swath center and for small amounts of hydrometeors, a worse or at best similar performance in view of the desired retrieval quantities than a BMCI retrieval, which uses a global database. An additional problem with these methods is that it can happen that the local database is insufficient. For example, if the swath center is clear sky within the given search area but there are clouds some kilometers away from the swath center.
   - The passive retrieval of frozen hydrometeors significantly benefits from retrieval databases based on the synergistic retrieval, whereas the retrieval of water vapor does not. So, it would make sense to combine especially ICI with a CloudSat type cloud radar. The frozen hydrometeor retrieval benefits, because the errors of the frozen hydrometeor states within the synergistic retrieval database are small enough so that the statistics of the synergistic retrieval database results in a good approximation of the real a priori statistics. For water vapor the errors of the water vapor states within the synergistic retrieval database are so big that the statistics of the synergistic retrieval database does not result in a good approximation of the real a priori statistics, which results in the bad performance of the synergistic retrieval database for water vapor. For the retrieval of liquid hydrometeors, we cannot make any conclusion on the benefit of the synergistic retrieval, because our retrieval setup is not optimal for the retrieval of liquid hydrometeors. However, the success of the GPM mission [Skofronick-Jackson et al., 2017] indicates, that if a more optimal retrieval is used, the

liquid hydrometoer retrieval is likely to benefit from a synergistic retrieval, too.

Recommendations

It is recommended to explore the active/passive synergy further with real observations. For this purpose combined measurements e. g. of the International Submillimetre Airborne Radiometer (ISMAR, Fox et al., 2017) together with the HALO Microwave Package (HAMP, Mech et al., 2014) would be particularly useful. Additionally, it is recommended to explore the possibility of using groundbased cloud radar in combination with ISMAR to explore the active/passive synergy further. Furthermore, it requires resources to further develop and test robust and fast synergistic retrievals.

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