Capabilities of the HAMP HALO microwave package and first results of the NARVAL campaign

Emiliano Orlandi\textsuperscript{1}, Mario Mech\textsuperscript{1}, Felix Ament\textsuperscript{2}, Maria Barrera Verdejo\textsuperscript{1}, Susanne Crewell\textsuperscript{1}, Andreas Fix\textsuperscript{4}, Martin Hagen\textsuperscript{4}, Lutz Hirsch\textsuperscript{3}, Christian Klepp\textsuperscript{2}, Bjorn Stevens\textsuperscript{3}

\textsuperscript{1}Institute for Geophysics and Meteorology, University of Cologne
\textsuperscript{2}Meteorological Institute, University of Hamburg
\textsuperscript{3}Max-Planck Institute for Meteorology
\textsuperscript{4}DLR Oberpfaffenhofen
Outline

• The HALO research aircraft
  – Remote sensing payload
  – Focus on the HAMP radiometer

• The NARVAL campaign
  – First results

• Outlook
  – T,q, and rain-rate retrievals
HALO aircraft for geo- and atmospheric sciences

Gulfstream G550

Distance: max. 9000 km
Flight altitude: max. 15.5 km
Duration: max. 11 Std.
Payload: max. 3 t
Bellypod instrumentation

NARVAL core

Microwave radiometers  DIAL  Cloud radar
MIRA-36 cloud radar

<table>
<thead>
<tr>
<th>Parameter</th>
<th>MIRA-36</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>35.563 GHz</td>
</tr>
<tr>
<td>Peak power</td>
<td>30 kW</td>
</tr>
<tr>
<td>Pulse length&lt;sup&gt;a&lt;/sup&gt;</td>
<td>200 ns</td>
</tr>
<tr>
<td>Pulse repetition&lt;sup&gt;a&lt;/sup&gt;</td>
<td>5 kHz</td>
</tr>
<tr>
<td>Integration time, coherent&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.05 s</td>
</tr>
<tr>
<td>Integration time, incoherent&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1 s</td>
</tr>
<tr>
<td>Range resolution&lt;sup&gt;1&lt;/sup&gt;</td>
<td>30 m</td>
</tr>
<tr>
<td>Beam width</td>
<td>0.6°</td>
</tr>
<tr>
<td>Footprint</td>
<td>130 m&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Sensitivity ground based operation</td>
<td>-48 dBZ&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>Expected sensitivity airborne operation</td>
<td>-38 dBZ&lt;sup&gt;c&lt;/sup&gt; -30 dBZ&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td>Minimum detectable LDR Parameters</td>
<td>-40 dB</td>
</tr>
</tbody>
</table>

<sup>a</sup> adjustable  
<sup>b</sup> at 13 km range  
<sup>c</sup> at 5 km with 1 s avg.  
<sup>d</sup> at 13 km with 1 s avg.  

(Mech et al., 2014)
Microwave radiometers

Table 2. HAMP passive bands with their noise equivalent delta temperature (NeDT), absolute accuracy (Acc.), beam width (Full Width at Half Maximum, FWHM), their main use in retrieving atmospheric variables, and corresponding satellite instruments. Upcoming missions (instruments) are given in italic letters.

<table>
<thead>
<tr>
<th>Band</th>
<th>Frequencies [GHz]</th>
<th>NeDT [K]/Acc. [K]</th>
<th>FWHM</th>
<th>Application</th>
<th>Satellite</th>
</tr>
</thead>
<tbody>
<tr>
<td>K H₂O</td>
<td>22.24,23.04, 23.84,25.44, 26.24,27.84, 31.40</td>
<td>0.1/0.5</td>
<td>5.0°</td>
<td>humidity profile, integrated water vapor,</td>
<td>AMSU-A, SSM/I, AMSR-E, GPM(GMI)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>liquid water path,</td>
<td>MetOp-SG (MWS,MWI)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>rain</td>
<td></td>
</tr>
<tr>
<td>V O₂</td>
<td>50.3,51.76, 52.8,53.75, 54.94,56.66, 58.00</td>
<td>0.2/0.5</td>
<td>3.5°</td>
<td>temperature profile, liquid water path,</td>
<td>AMSU-A, SSM/I(S)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>precipitating hydrometeors</td>
<td>MetOp-SG (MWS,MWI)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W window</td>
<td>90.0</td>
<td>0.25/1.5</td>
<td>3.3°</td>
<td>liquid water path, snow water path</td>
<td>AMSU-B, SSM/I(S), AMSR-E, GPM(GMI)</td>
</tr>
<tr>
<td>channel</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F O₂</td>
<td>118.75±8.5,118.75±4.2, 118.75±2.3,118.75±1.4</td>
<td>0.6/1.5</td>
<td>3.3°</td>
<td>temperature profile precipitating hydrometeors</td>
<td>MetOp-SG (MWS,MWI)</td>
</tr>
<tr>
<td></td>
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<tr>
<td>G H₂O</td>
<td>183.31±12.5,183.31±7.5, 183.31±5.0,183.31±3.5,183.31±2.5,183.31±1.5, 183.31±0.6</td>
<td>0.6/1.5</td>
<td>2.7°</td>
<td>humidity profile (upper troposphere), ice water</td>
<td>AMSU-B, SSM/I(S), GPM(GMI)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>path</td>
<td></td>
</tr>
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(Mech et al., 2014)
# Microwave radiometers

<table>
<thead>
<tr>
<th></th>
<th>22 GHz</th>
<th>50 GHz</th>
<th>118 + 90 GHz</th>
<th>183 GHz</th>
<th>RADAR</th>
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<tbody>
<tr>
<td>Cross-track</td>
<td>450 m</td>
<td>310 m</td>
<td>290 m</td>
<td>235 m</td>
<td>55 m</td>
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<tr>
<td>Footprint 5 km</td>
<td></td>
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<tr>
<td>10 km</td>
<td>900 m</td>
<td>610 m</td>
<td>575 m</td>
<td>475 m</td>
<td>105 m</td>
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<tr>
<td>14 km</td>
<td>1.2 km</td>
<td>850 m</td>
<td>800 m</td>
<td>650 m</td>
<td>150 m</td>
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<tr>
<td>Along-track</td>
<td></td>
<td></td>
<td></td>
<td>+220 m</td>
<td></td>
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<tr>
<td>@ 800 km/h</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Power consumption</td>
<td>180 W</td>
<td>150 W</td>
<td>140 W</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calibration</td>
<td></td>
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<tr>
<td>Absolute</td>
<td></td>
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</tr>
<tr>
<td>External ambient</td>
<td></td>
<td></td>
<td></td>
<td>Component</td>
<td></td>
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<tr>
<td>and cold (liq N$_2$) targets</td>
<td></td>
<td></td>
<td></td>
<td>based</td>
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<tr>
<td>Internal</td>
<td></td>
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<td></td>
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<tr>
<td>Gain: noise diode</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>System noise:</td>
<td></td>
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<tr>
<td>Dicke switch</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Internal load</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Weight</td>
<td>60 kg</td>
<td>60 kg</td>
<td>60 kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dimensions</td>
<td>46 x 56 x 54 cm$^3$</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
Fig. 3. HAMP clear air weighting functions (nadir downward-looking). Shown are the water vapor (two left most) and the temperature (two right most) weighting functions for a HALO ceiling height of about 13 km. The U.S. 1976 Standard Atmosphere over a black surface was assumed for the calculations. (Mech et al., 2014)
Simulated radiometer measurements

Radiative transfer modelling

Fig. 4. Simulated rain rates in mm h\(^{-1}\) for the Hoek van Holland case on 19 September 2001 at 18 UTC. The red line and blue arrow indicate the artificial flight path shown in Figs. 5 and 6.

(Mech et al., 2014)
DIAL – Wales I

DLR Oberpfaffenhofen: water vapor lidar on board of HALO

(seed laser system, pump laser, OPOs, 48 cm telescope, data acquisition (obscured), detect box)
Mini-DOAS

University of Heidelberg

- Limb and nadir viewing geometry
- Limb scanning capability for vertical profiling
- 3 wavelength regions:

<table>
<thead>
<tr>
<th></th>
<th>Wavelength region [nm]</th>
<th>Resolution FWHM [nm]</th>
<th>Targeted trace gases</th>
</tr>
</thead>
<tbody>
<tr>
<td>UV</td>
<td>310 – 440</td>
<td>0.7</td>
<td>$O_3$, HONO, $SO_2$, $CH_2O$, $BrO$, ClO, ClO$_2$</td>
</tr>
<tr>
<td>VIS</td>
<td>420 – 650</td>
<td>1.2</td>
<td>$O_3$, $O_4$, $NO_2$, $C_2H_2O_2$, $BrO_2$, IO, IO$_2$, I$_2$</td>
</tr>
<tr>
<td>NIR</td>
<td>1100 - 1680</td>
<td>6.8</td>
<td>$H_2O$: vapour, liquid, ice, CO$_2$, CH$_4$</td>
</tr>
</tbody>
</table>
University of Leipzig + Research Center Jülich

Radiance
- viewing angle = 2°
- VIS: 350-1000 nm, NIR: 1000-2000 nm
- FWHM: 1.5 nm (VIS), 8-9 nm (NIR)

Actinic flux density
Dropsondes

DLR Oberpfafenhofen

*During its missions, Canberra aircraft releases Vaisala's RD93 GPS dropsonde used in hurricane and weather research.*
NARVAL flights

NARVAL-South
Trade winds
10 – 21 December 2013
• 8 flights over tropical and subtropical Atlantic
• 75 dropsondes released

NARVAL-North
Post frontal
7 – 21 January 2014
• 5 flights over North Atlantic
• 2 transfer flights with several ground-based super-site overpasses
• 42 dropsondes released

Precipitation in shallow maritime convection

September 23 2014
IWV, LWP retrieval

NARVAL-South
10 – 21 December 2013
• 8 flights over tropical and subtropical Atlantic
• 75 dropsondes released

• HAMP (K band + window channels) used to retrieve integrated water vapor (IWV) and liquid water path (LWP)
• K-band allows retrievals for the whole atmospheric column also in the presence of thick clouds
IWV, LWP retrieval

IWV

Retrieved integrated water vapor against measured by dropsondes during NARVAL South

LWP

Sensitivity of 31, 50 and 90 GHz Tb to liquid hydrometeors

BIAS = 0.25 kg/m²
RMSE = 1.8 kg/m²
Theoretical RMSE = 0.6 kg/m²
IWV, LWP retrieval

**IWV**

- BIAS = 0.25 kg/m$^2$
- RMSE = 1.8 kg/m$^2$
- Theoretical RMSE = 0.6 kg/m$^2$

Retrieved integrated water vapor against measured by dropsondes during NARVAL South

**LWP**

- Sensitivity = 10 g/m$^2$
- Theoretical RMSE = 15 g/m$^2$

LWP retrieval using 31, 50 and 90 GHz windows + K band channels
OUTLOOK-1: T and Q retrieval

Influence of ECMWF background error covariances on the retrieval of temperature and humidity using the HAMP radiometer

Variational retrieval:

\[ J(x) = \frac{1}{2} (x - x_b)^T B^{-1} (x - x_b) \]
\[ + \frac{1}{2} [y - H(x)]^T R^{-1} [y - H(x)]. \]

\( x \) = retrieved profile
\( y \) = measurements
\( x_b \) = background/a-priori state
\( B \) = background error covariance
\( R \) = measurement error covariances
\( H \) = Jacobian dy/dx
OUTLOOK-1: T and Q retrieval

Influence of ECMWF background error covariances on the retrieval of temperature and humidity using the HAMP radiometer

• Many retrievals of T and Q from ground- and satellite-based instruments are based on variational schemes.
• NWP models are often used as a-priori (Cimini 2006, Hewison 2007, ...)
• Knowledge of a-priori information and uncertainties is crucial for these methods.
• How to evaluate a-priori error?
  ▪ Use different methods and assess their influence on retrieved T and Q.
OUTLOOK-2: combined Q retrieval

- Q retrieval: **LIDAR and radiometer combination**
  Maria Barrera Verdejo – PhD student at Koeln

**RADIOMETER**: lower vertical resolution
  BUT sensitive to whole column

**LIDAR**: high vertical resolution
  BUT cannot penetrate clouds
  limited vertical extent daytime
OUTLOOK-3: Rain-rate retrieval

- **Validation** of HOAPS RR retrieval (SSMI)
  - Impact on the water cycle

- **Missed precipitation** by TRMM/TMI, AMSU-B, MODIS
  - Because of foot-print 25km 16km 1km
  - Because of sensitivity – TRMM/PR lowest rain rate .5 mm/h (17dBz)

- **Upscale** ratio observed/unobserved precipitation to a global scale for water budget studies

**Develop rain-rate retrievals** for HAMP:

1. Narval-N – radiometer: use high frequency channels, sensitive to snow scattering. Derive rain-rate from correlation with snow column.
2. Narval N and S – radar:
   - Z-RR relations → RADAR Ze need to be well calibrated!!
   - Attenuation-RR → independent from radar calibration
Summary

• **HALO remote sensing suite:** radiometer, cloud radar, DIAL lidar, mini-doas, IR-VIS spectrometer, dropsondes

• **HAMP radiometer:** 26 channels 60, 118 GHz O\(_2\) lines
  22, 183 GHz H\(_2\)O lines

• **NARVAL**
  South: 7 flights over tropical Atlantic – shallow convection
  North: 5 flights over North Atlantic – Post-frontal precipitation

• **LWP, IWV retrieval:** K + window channels – sensitive to low LWP

• **OUTLOOK:**
  • **T, Q retrievals** combining model and radiometer Tb
  • **Q retrieval** combining LIDAR and radiometer
  • **Rain-rate retrieval** radar, radiometer and combination of them

Thanks for your attention!
• Retrieval strategy:
Use the 75 dropsondes launched during NARVAL South
Include idealized clouds:
1. from surface up to 3km
2. LWP from 0 to 2 kg/m²

Simulate $T_b$ for 8000 resulting profiles
Develop regression coefficients for the HAMP radiometer

Apply regression coefficients to bias-corrected HAMP $T_b$.

Bias correction remove the flight-mean difference between simulated $T_b$ from dropsonde and measured $T_b$.
It should remove bias due to calibration and errors in the radiative transfer model.
OUTLOOK-1: T and Q retrieval

Influence of ECMWF background error covariances on the retrieval of temperature and humidity using the HAMP radiometer

- Variational retrieval:

\[ J(x) = \frac{1}{2} (x - x_b)^T B^{-1} (x - x_b) \]

\[ + \frac{1}{2} [y - H(x)]^T R^{-1} [y - H(x)] \]

\( Y = \) measurements

\( X_b = \) background/a-priori state

\( B = \) background error covariance

\( R = \) measurement error covariances