Workshop on Airborne Radiometry for Water Vapor and Liquid Water Retrievals: Summary and Recommendations

March 26, 2015

Writing Committee:
Paquita Zuidema and Julie Haggerty
with contributions from Maria Cadeddu, Jorgen Jensen, Emiliano Orlandi, J. Vivekanandan, and Zhien Wang

Workshop Organizing Committee:

Paquita Zuidema
Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, FL

Julie Haggerty and Jorgen Jensen
NCAR Earth Observing Lab, Boulder, CO

Summary

Airborne remote sensing has improved significantly over the last two decades, with NSF investing in new radars and lidars for its aircraft fleet. A workshop held on 23-24 September, 2014, in Boulder, CO, reviewed scientific requirements for and instrument improvements in airborne microwave radiometry in this context. The surveyed microwave radiometers provide two important new sources of information: 1) the geophysical constraints on new vertically-resolved radar and lidar retrievals of aerosol, water vapor, and cloud liquid water; 2) a potentially three-dimensional thermodynamic mapping capable of providing new insights into long-standing mesoscale problems. Simultaneously, miniaturization is creating smaller radiometers with lower power needs, higher frequencies, improved stabilities, and more modular designs. This technological breakthrough allows micro- and millimeter-wave radiometers to become more integrated into a synergistic suite of active and passive remote sensors. Ideal radiometer characteristics were identified, and institutional processes recommended by which NSF might promote the development and/or acquisition of a new sensor.

Introduction

Airborne remote-sensing capabilities have improved significantly within the past two decades, evolving from basic broadband radiation measurements to active radar and lidar systems providing observations of unprecedented vertical resolution of the Earth's atmosphere. To a large degree, the progress reflects a combination of commercial technical innovations that support miniaturization, decrease power consumption, improve instrument stabilities, and allow for more modular designs. In keeping with these developments, NSF has expanded its aircraft deployment pool to include active remote sensors for its three aircraft facilities. These include the 355-nm wavelength Wyoming Cloud Lidar (WCL; Wang et al., 2009), a 94 GHz (3.2 mm wavelength) Wyoming Cloud Radar (WCR), and the newly-developed downward-looking Multi-function Airborne Raman Lidar (MARLi) for its King Air and C-130 planes. For its newer high-altitude Gulfstream-V (G-V) plane, NSF has supported the development of the passive Microwave Temperature Profiler (MTP, Haggerty et al., 2014), the 94-GHz HIAPER Cloud Radar (HCR), and the airborne and ground-based High Spectral Resolution Lidar (HSRL). The lidars provide information on the aerosol vertical structure and cloud boundaries, with the MARLi also sensing the water vapor and temperature vertical profiles. The WCR provides measurements on cloud and precipitation microphysical structure that have already led to new insights on low cloud behavior (e.g., Stevens et al., (2005) and Wood et al., (2011), based on the NSF DYCOM-II[1] and VOCALS[2] campaigns). The HCR will see its first deployment in the summer of 2015. The active radiation sensors can be complemented by the passive HIAPER Airborne Radiation Package (HARP) on the G-V plane, which includes updated broadband visible and infrared sensors and the Solar Spectral Flux Radiometer (SSFR), with future plans to incorporate the HARP into the C-130.

These developments come in the wake of the retirement of NSF's Multi-Channel Radiometer (MCR; NCAR (2007)) and the Airborne Imaging Microwave Radiometer (AIMR; Haggerty et al. (2002)). Their retirement in effect deprioritizes instrumentation that appear to fall more clearly within NASA's goals for supporting its satellite remote sensing retrieval development. The advent of the newer active sensors within the NSF deployment pool, together with a previously-identified lack of humidity path-integrated and profiling capabilities within the NSF deployment pool (Smith et al., 2013) and a similar lack of compact passive microwave radiometers within the NASA and DOE instrument pools, encourage a revisitation of NSF deployment pool priorities. These factors motivated the workshop on airborne radiometry for water vapor and liquid water retrievals held at NCAR on September 23-24, 2014.

Workshop Format

The workshop reviewed the scientific requirements that could be addressed by radiometers capable of retrieving atmospheric water vapor and liquid water. The sensors considered were primarily, but not exclusively, microwave and millimeter wavelength range radiometers. The workshop also included an instrumentation survey to more fully understand current and near-term development of hardware and software systems employing microwave and millimeter radiometric technology. The first day of the workshop was composed of invited presentations and discussion on the scientific requirements, followed by presentations on airborne remote sensing. The list of participants and the agenda are included in Appendix A.

---

[1] Dynamics and Chemistry of Marine Stratocumulus-II
[2] VAMOS Ocean-Cloud-Atmosphere-Land Study

A subset of the invited participants that excluded private sector instrument builders convened on the second morning of the workshop. Their mandate was to synthesize the discussion on scientific requirements, available technology, and infrastructure and institutional resources towards developing a set of technical and institutional process recommendations for the NSF Lower Atmospheric Observing Facilities program.

Emergent Science Measurement Goals

A consensus view emerged that:

- Microwave radiometry for water vapor and liquid water retrievals most usefully serves science goals for the lower and free troposphere. Current microwave radiometric technology cannot meet the requirements for retrieval accuracy well in the extremely dry conditions of the upper troposphere/lower stratosphere and this regime was not considered with much detail.
- For the cloudy boundary layer and mixed-phase clouds, *path-integrated liquid water and water vapor measurements* are critical for cloud and environment characterization and for more comprehensive cloud property retrievals. Multi-frequency measurements are necessary for robust retrievals within a range of humidity environments, from the low-latitudes to the Arctic.
- Free-tropospheric needs, driven by mesoscale research (e.g., hurricanes), center on *humidity profiling* in both tropical and mid-latitude environments. This serves to understand the earth's water cycle, with specific science goals including the impact of mid-tropospheric humidity upon the development of convection; understanding atmospheric rivers; quantifying orographic effects; improving cloud forecast prediction; and quantifying the maritime boundary layer.

Instrument Specifications to Address Science Goals

The sensors surveyed span the range of readiness from operational to conceptual, and a listing of the individual instruments that summarizes their technical specifications, documented applications, and maturity level is provided in Appendix B. The salient points we wish to emphasize are listed below. Fig. 1 illustrates the atmospheric opacity as a function of frequency to illustrate the dominant application of specified frequencies.

- The airborne radiometric *profiling of water vapor* requires:
    - At least one and up to four key direct-sensing H_2O_v bands (e.g., 183 GHz absorption and wing lines)
    - At least one and up to three key O_2 bands spanning multiple channels for temperature profiling (e.g., 50-57 and 118 GHz)
    - At least one and up to five window bands for cloud/precipitation sensing and correction (e.g., 37 and 90 GHz)
    - Scanning capability allowing the sensor to sample either three-dimensionally or above and below the aircraft
- The airborne *path-integrated sensing of liquid water* requires:
    - At least one and ideally two water vapor absorption bands (19 or 22 GHz, or 183 GHz absorption line)
    - Information on cloud temperature
    - At least one and up to four window bands for cloud/precipitation sensing (e.g., 37 GHz, 90 GHz and 183 GHz wing lines)
    - If downward-pointing, measurements at low frequencies for surface characterization (e.g. 10 GHz)

- Tradeoffs exist between achievable horizontal resolution and physical space requirements: Smaller footprints are achieved using larger antennas, which require moderately large apertures and correspondingly large aircraft bays. The trade-off in particular affects the lower frequencies (19-25 GHz), as the antenna sizes needed to match a particular footprint size also increase with wavelength.

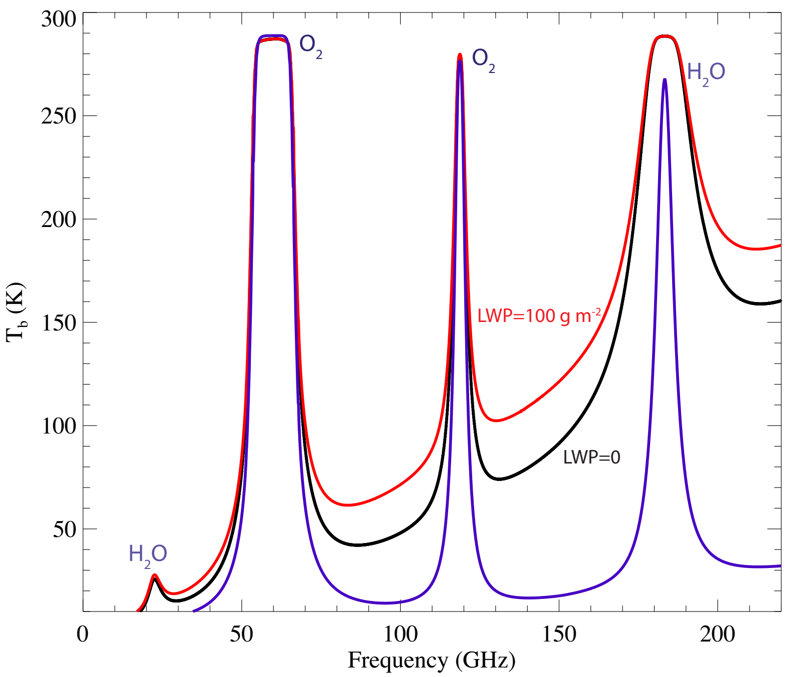

Fig 1: Surface downwelling brightness temperatures as a function of frequency, for a water vapor path of 11 mm with liquid water path (LWP) of 0 and 100 g m-2 (black and red lines, respectively), and a water vapor path of 2 mm (purple line). The gases responsible for the absorption lines are indicated.

The surveyed radiometers provide brightness temperature measurements at frequencies applicable to both boundary layer and free-troposphere science. Both science applications benefit from multi-frequency measurements. The radiance measurements critical for liquid and mixed-phase cloud characterization, particularly in more humid environments, must span a large range of frequencies that permit separate characterization of water vapor and liquid water. This range ideally encompasses 22 GHz (for water vapor path characterization) in combination with all of the 37, 90, or 183 GHz frequencies (for liquid water path characterization). Humidity profiling requires multi-frequency measurements to produce the necessary range of vertical weighting functions: 20-30, 90 and 183 GHz for water vapor, and 50-60 GHz and 118 GHz for the coincident temperature profiles. The NSF deployment pool already includes a temperature profiling capability, though a new sensor could in theory profile both temperature and humidity simultaneously.

Nevertheless the radiometer sizes and antenna fields of view naturally distinguish their scientific application. Newer, more compact integrated systems can fit into a standard wing-mounted canister, but then their smaller antennas produce larger angular fields of view. For example, the 22 GHz antenna of the Profiling Radiometer for Atmospheric and Cloud Observation (PRACO) has a 15° field of view. At a 1 km vertical distance, such as may typify an aircraft mission that includes in-situ cloud sampling, the spatial resolution of 250 m is reasonable, with the compact radiometer size allowing for easier integration with other sensors (e.g., Wang et al., 2012). For an upper-altitude mission dedicated to mesoscale characterization (e.g., hurricane research), however, a 10 km altitude corresponds to a surface spatial resolution of 2.5 km, and a larger antenna is desired. This consideration selects for bulkier instruments such as the PSR and HAMSR.

The radiometer size can also be indicative of its technical readiness level. The larger instruments tend to be more mature and to have experienced significant field testing (e.g., PSR, HAMSR, FAAM instruments). The newer, more compact designs, have generally experienced less vendor-independent calibration and retrieval development (e.g., the ProSensing G-band Vapor Radiometer and the PRACO). The newer designs may have also had less opportunity for testing out in the field. A counter-example is the NSF MTP, which is both compact and mature, thanks in part to NSF-supported deployments. The potential to scale down larger instruments with modern electronics and other components holds promise, with the challenge then being to ensure the requisite readiness level for a confident deployment.

"Best practices" Instrument and Retrieval Mentorship

'Best-practices' hold that scientists develop their own retrievals, perhaps in collaboration with a vendor/developer, rather than relying on vendor-supplied retrievals. This recommendation has different implications for the appropriate mentorship model, again depending on scientific application. For cloudy boundary layer applications, for which path-integrated measurements are sufficient, responsibility for an NSF instrument and its retrievals can reside with a university scientist as well as within NCAR. The challenge, instead, is to determine the means for including the best-performing radiometer into the deployment pool. PI-driven leases of a private sector radiometer have satisfied short-term campaign requirements, but the instrument used relies on a limited frequency range, requiring ancillary moisture measurements that introduce the greatest uncertainty within the retrieval (Zuidema et al., 2012). Multi-frequency measurements can more optimally estimate both water vapor and liquid water paths. The optimal instrument is not yet available for warm clouds, and campaign-driven leases of an instrument intended for mixed-phase stratiform characterization have served as a stopgap to fill a short-term need. In the long-run this does not serve the research community well, ultimately providing less value to NSF than commitment to a more capable radiometer.

Humidity profiling requires more sophisticated retrieval development than does the development of path-integrated retrievals. Retrieval methods can in theory be developed from early, dedicated test flight datasets and provided as part of a subsequent campaign instrument request to the PI. The initial retrieval development, not linked to any particular campaign, would most likely require collaboration between university scientists, instrument developers, and NCAR scientists (or else need to motivate a new hire within NCAR). More accurate retrievals specific to each campaign can be achieved with further investment.

'Best practices' also hold that the radiometers are regularly calibrated. Different manufacturers use different approaches, with consensus on the best approach lacking, and in some cases information sharing is limited by patent rights. 'Best practices' also holds that retrieval method development be complemented by incorporation of the latest gaseous absorption coefficients, which are still not fully known at the higher frequencies. Calibration and model evaluation can be best achieved by comparison to the many DOE radiometers at the Southern Great Plains site because DOE's long history of evaluation of multiple-vendor instruments promises a uniform, unbiased approach. Mentorship should include these activities, through either a University or at NCAR.

Summary and Recommendations

Technical

Water vapor path, cloud liquid water path, and free-tropospheric humidity profiling constitute scientifically-significant measurements that are not provided by current instruments within NSF's deployment pool. The microwave radiometers surveyed here can provide two important new sources of information: 1) the geophysical constraints on new vertically-resolved radar and lidar retrievals of aerosol, water vapor, and cloud liquid water; 2) a potentially three-dimensional thermodynamic mapping capable of providing new insights into long-standing mesoscale problems. Simultaneously, miniaturization is creating smaller radiometers with lower power needs, higher frequencies, improved stabilities, and more modular designs. This technological breakthrough allows micro- and millimeter-wave radiometers to become more integrated into a synergistic suite of active and passive remote sensors. The ability to resolve spatial atmospheric inhomogeneities, especially in boundary-layer cloud fields, nevertheless remains a function of the radiometer antenna size. The trade-offs imply that two radiometers possessing different antenna sizes are ideally available within the NSF deployment pool to satisfy requirements for spatial resolution within a wide range of environmental conditions.

The radiometers, irrespective of size, should possess:

1. multi-frequency humidity and liquid water sensing (20-30, 90, 183 GHz) capability
2. modularity of frequency components
3. ability to be deployed upon multiple aircraft
4. views above and below aircraft
5. complete documentation of internal measurements and calibration procedures
6. vendor-independent calibration and retrieval development plan
7. ground-based deployability to aid radiometer assessment at the Southern Great Plains ARM site.

Radiometers emphasizing a compact design should fit into a standard cloud probe canister.

Institutional

Possible processes by which NSF might promote the development and/or acquisition of a new sensor include:

1. A joint development effort between NCAR and a university laboratory, other government laboratory, or private sector company that already possesses a development capability. In some cases, a prototype sensor of interest may already exist.
2. An expansion of the new ARISTO (Airborne Research Instrumentation Testing Opportunity) program to include vendor-independent calibration and retrieval development for existing, possibly vendor-owned, instruments of potential interest for purchase by NSF, but lacking a high technical readiness.

We recommend against a leasing arrangement as it does not encourage the development of an optimal radiometer, and does not encourage a strong instrument mentorship.

Sensor maintenance, calibration, operation and retrieval development can occur at either NCAR or at a university. A radiometer providing path-integrated values requires less investment and can be easily mentored through a university, whereas the retrieval development for a radiometer capable of free-tropospheric humidity profiling likely requires collaboration between university scientists, instrument developers, and NCAR scientists (or else need to motivate a new hire within NCAR).

References

Haggerty, J., K. Schick, M.J. Mahoney, and B.H. Lim, 2014: The NCAR Microwave Temperature Profiler: Data applications from recent deployments. Proc. 13th Specialist Meeting on Microwave Radiometry and Remote Sensing of the Environment, 24-27 March, Pasadena, CA.

Haggerty, J., J. Curry, and G. Liu, 2002: Potential for estimating cloud liquid water path over sea ice from airborne passive microwave measurements. *J. Geophys. Res.*, DOI: 10.1029/2001JD000585

Mech, M., E. Orlandi, S. Crewell, F. Ament, L. Hirsch, M. Hagen, G. Peters, and B. Stevens, 2014: HAMP – the microwave package on the High Altitude and Long range research aircraft HALO. *Atmos. Meas. Tech. Discuss***., 7**, 4623-4657. doi:10.5194/amtd-7-4623-2014.

Pazmany, A., 2007: A compact 183 GHz radiometer for airborne and ground-based vapor and liquid water sensing. IEEE Trans. *Geosci. Rem. Sens.*, **45**, 2202–2206

NCAR (2007): NCAR's Multi-channel Cloud Radiometer. http://www.eol.ucar.edu/raf/MCR/MCRpage.html

Smith, R., et al., 2013: The Lower Atmospheric Observing Facilities Workshop: Meeting the Challenges of Climate System Science. 18-19 June, 2012. Available through https://www.eol.ucar.edu/system/files/LAOF_Workshop_Report_FINAL_06112013.pdf

Stevens B., and 7 co-authors, 2005: Pockets of open cells and drizzle in marine stratocumulus. *Bull. Am. Meteor. Soc.*, doi: 10.1175/BAMS-86-1-51.

Wang, Z., Wechsler, P., Kuestner, W., French, J., Rodi, A., Glover, B., Burkhart, M., and Lukens, D., 2009: Wyoming Cloud Lidar: instrument description and applications, *Opt. Ex.*, **17**, 13576–13587.

Wang, Z., French, J., Vali, G., Wechsler, P., Haimov, S., Rodi, A., Deng, M., Leon, D., Snider, J., and Peng, L., 2012: Single aircraft integration of remote sensing and in situ sampling for the study of cloud microphysics and dynamics, *B. Am. Meteorol. Soc.*, **93**, 653-766. doi:10.1175/BAMS-D-11-00044.1

Wood, R., C. S. Bretherton, D. Leon, A. D. Clarke, P. Zuidema, G. Allen and H. Coe, 2011: An aircraft case study of the spatial transition from closed to open mesoscale cellular convection over the Southeast Pacific. *Atmos. Chem. Phys.*, **11**, pp. 2341-2370, doi:10.5194/acp-11/2341-2011

Zuidema, P., D. Leon, A. Pazmany and M. Cadeddu, 2012: Aircraft millimeter-wave passive sensing of cloud liquid water and water vapor during VOCALS-REx. *Atmos. Chem. Phys.*, **12**, pp. 355-369, doi:10.5194/acp-12-355-2012

Appendix A

List of Workshop Participants

Name	Affiliation	Email Address
A.J. Gasiewski	University of Colorado	Al.Gasiewski@colorado.edu
Aaron L Swanson	Northrup Grumman	aaron.swanson@ngc.com
Tanner, Alan B	JPL	alan.b.tanner@jpl.nasa.gov
Boon H Lim	JPL	Boon.H.Lim@jpl.nasa.gov
Bruce Kindel	University of Colorado	Bruce.Kindel@lasp.colorado.edu
Calvin Liang	Northrup Grumman	calvin.liang@ngc.com
Chris Davis	NCAR	cdavis@ucar.edu
Emiliano Orlandi	University of Cologne	eorlandi@meteo.uni-koeln.de
James B. Mead	ProSensing	mead@prosensing.com
Jorgen Jensen	NCAR	jbj@ucar.edu
Jothiram Vivekanandan	NCAR	vivek@ucar.edu
Julie Haggerty	NCAR	haggerty@ucar.edu
Linnea Avallone	NSF	lavallon@nsf.gov
Marta Nelson	Radiometrics	m.nelson@radiometrics.com
Marian Klein	BEST	marian.klein@boulderest.com
Matthew Hayman	NCAR	mhayman@ucar.edu
Maria Cadeddu	Argonne National Labs	mcadeddu@anl.gov
Paquita Zuidema	University of Miami	pzuidema@rsmas.miami.edu
Rob Kursinski	MOOG	rkursinski@moog.com
Sebastian Schmidt	University of Colorado	sebastian.schmidt@lasp.colorado.edu
Shannon T Brown (382G)	JPL	Shannon.T.Brown@jpl.nasa.gov
Stuart Beaton	NCAR	beaton@ucar.edu
Stuart Fox	UK Met Office	stuart.fox@metoffice.gov.uk
Wen-chau Lee	NCAR	wenchau@ucar.edu
William G. Read	JPL	William.G.Read@jpl.nasa.gov
Zhien Wang	University of Wyoming	ZWang@uwyo.edu

Workshop on Airborne Radiometry for Water Vapor and Liquid Water Retrievals
September 23-24, 2014
NCAR Foothills Laboratory

Tuesday, September 23, FL1-2198 (EOL Atrium)

9-9:15 Opening Remarks

Welcome and logistics: Julie Haggerty, Vanda Grubišić

Workshop objectives: Paquita Zuidema

National Science Foundation perspectives and interests: Linnea Avallone

Session 1: Requirements for Airborne Water Vapor and Liquid Measurements in Select Research Areas

9:15-9:35 Boundary Layer Research: Paquita Zuidema, U of Miami

9:35-9:55 Free-Tropospheric and Hurricane Research: Chris Davis, NCAR

9:55-10:15 Gravity Wave Research : Dave Fritts, CORA

Session 2: Existing Airborne Radiometry Capabilities

10:15-10:30 Existing Radiometer Capabilities on the FAAM aircraft: Stuart Fox, UK Met Office

10:30-10:45 Break

10:45-11:05 The Wyoming King Air and Mixed-Phase Clouds: Zhien Wang, U of Wyoming

11:05-11:25 Capabilities of the HAMP HALO microwave package and first results of the NARVAL campaign: Emiliano Orlandi, U of Cologne

11:25-11:40 Current and Historical Airborne Radiometer Measurements from NCAR aircraft: Julie Haggerty, NCAR

11:40-12:00 Discussion

12:00-1:00 Lunch (provided)

Session 3: Instrumentation

1:00-1:15 Overview of NSF-NCAR Airborne Platforms: Jorgen Jensen

1:15-1:35 Benefits and Drawbacks of Thermodynamics Phase and Liquid Water Path Retrievals from Passive Shortwave Spectrometry: Sebastian Schmidt, U of Colorado

1:35-1:55 Airborne G-Band Water Vapor Radiometer: James Mead, ProSensing

1:55-2:15 Profiling Radiometer for Atmospheric and Cloud Observations (PRACO): Marian Klein, BEST

2:15-2:35 Simulated Water Vapor Profile Retrievals from High-Altitude Aircraft using a 183-GHz Radiometer: William Read, Boon Lim, and Alan Tanner, JPL

2:35-2:55 Upper-troposphere and lower-stratosphere water vapor retrievals from the 1400 and 1900 nm water vapor bands: Bruce Kindel (U of Colorado), Peter Pilewskie, Sebastian Schmidt, T. Thornberry, A. Rollins, and T. Bui

2:55-3:15 High Altitude Monolithic Microwave Integrated Circuit (MMIC) Sounding Radiometer *(HAMSR):* Shannon Brown, JPL

3:15-3:35 break

3:35-3:55 Airborne Water Vapor Science, Radiometer Requirements and Capabilities: Al Gasiewski, U of Colorado

3:55-4:15 How the DOE ARM experience can help airborne water vapor and liquid water radiometry: Maria Cadeddu, Argonne National Lab

4:15-4:35 Ground-based microwave radiometer development: Marta Nelson, Radiometrics

4:35-5:15 Discussions

6:30 Optional group dinner (location tbd)

Wednesday, September 24, Research Aviation Facility (10802 Airport Ct., Broomfield)

8:00-8:30 Breakfast (provided)

8:30-9:30 Aircraft tour at the Research Aviation Facility (all)

9:30-12:30 Executive Committee session (invited participants only)

12:30 Adjourn

Appendix B: Instrument Listing

UK Facility for Airborne Atmospheric Measurements (FAAM) radiometers:
1) Dual-frequency Extension to In-flight Observing System (DEIMOS): 23.8, 50.3 GHZ, dual pol, along track, up or down view
2) Microwave Airborne Radiometer Scanning System (MARSS): an AMSU-B replicator with channels at 89, 157, 183 ±1,3,7 GHz. along track, up and down views
3) International Sub-Millimeter Airborne Radiometer (ISMAR): 118-664 GHZ including oxygen line, water vapor lines, windows (dual pol), developing 874 GHz channel. Developed for ice clouds
4) Airborne Research Interferometer Evaluation System (ARIES): IR channels, cross track scan
SWS/SHIMS: hemispheric irradiance, shortwave.
All retrievals developed in-house within the UK Met Office.
workshop representative: Stuart Fox

German High Altitude and Long Range Research Aircraft (HALO)
HALO Microwave Package (HAMP): Three instruments, which combined measure in the water vapor (22.24, 23.04, 23.84.25.44,26.24,27.84,32.4, 183±), Oxygen (50-60 GHz, 118 GHz), and window (90 GHz) channels. Retrievals developed by U of Cologne-based science team.
Workshop representative: Emiliano Orlandi. See Mech et al., 2014 for more detail.

ProSensing, Inc. Airborne G-Band Water Vapor Radiometer
GVR: G-band (183 +- 1, 3, 7, and 14 GHz), upward looking only, precipitable water and liquid waterpath retrievals in cold, arid environments. Available through lease. Prototype currently owned by Northrop-Grumman Aerospace Systems, with discussions underway to donate to the U. of Miami. Neural-net vendor-provided retrieval, physically-based retrieval responsibility of PI-leasee.
Workshop representative: James Mead

Boulder Environmental Sciences and Technology (BEST)
Profiling Radiometer for Atmospheric and Cloud Observations (PRACO): channels at 22-30 GHz, 51-59, 118, and 183. Pod compatible, GPS antenna integrated, no field testing yet.
Workshop representative: Marian Klein

NASA JPL High Altitude Monolithic Microwave integrated Circuit (MMic) Sounding Radiometer
HAMSR: atmospheric temperature and humidity sounder, with 25 channels encompassing 50-60 GHz, 118, 183. Cross track scanning, has experienced significant NASA field campaign use. NASA-developed retrievals. Workshop representative: Boon Lim

University of Colorado Polarimetric Scanning Radiometer (PSR)
Developed for assessment of NASA satellite microwave sensors, measurements at 6.7, 10.7 GHz, 18.7, 21.5 37,55, 89, and the 183 GHz channels, some of which are polarimetric. Cross-track scanning, significant field use, large antenna. Retrievals developed in-house.
Workshop representative: Al Gasiewski

Radiometrics
temperature/humidity surface-based microwave profilers (MP-series). Channels between 22-30 GHz and 51-59 GHz. Physically-based retrieval development left to user. Workshop representative: Stick Ware

NSF deployment pool Passive Shortwave Spectrometry:
Solar Spectral Flux Radiometer (SSFR) and the HIAPER Airborne Radiation Package (HARP)
Workshop representative: Sebastian Schmidt