

# Accurate Low Cost Thermodynamic Observing System

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# 1. Identification and Significance of the Innovation

NOAA has fielded valuable but expensive weather observing systems (e.g. Nexrad, satellites, rawinsondes, automated weather systems) for use in initializing numerical weather prediction models. However, complementary observing systems are needed that are lower in cost, providing plentiful, regular observations of data sparse regions.

High impact weather is closely linked to the temperature and humidity (thermodynamic) structure of the planetary boundary layer. The boundary layer is the region where severe convective weather originates and exacts its human and economic tolls. The need for plentiful, regular thermodynamic soundings in this region is widely recognized. Properly calibrated microwave profiling radiometers can provide these soundings.



Figure 1. Microwave profiler and rawinsonde thermodynamic sounding comparison<sup>1</sup>.

Example 5-min radiometer and 6-hr rawinsonde soundings are compared in Figure 1 during the 2010 Winter Olympics at Whistler, B.C. Good agreement is seen in spite of the fact that the radiometer was located at the base of the ski gondola 100 m higher than the rawinsonde launch

<sup>&</sup>lt;sup>1</sup> Ware et al, 2013.



site located 2-km away on the floor of the Whistler Valley. Figure 2 shows example microwave profiler observations from a Boundary Layer Network<sup>2</sup> site in the Dallas-Ft. Worth region.

NWS meteorologists have already proven the value of microwave radiometer thermodynamic observations to improve aviation weather advisories<sup>3</sup>. However, cryogenic (liquid nitrogen) calibration at six month intervals is required to ensure radiometer observation accuracy<sup>4</sup>. In addition, cryogenic calibration is subject to degradation by liquid water condensation, standing waves<sup>5</sup>, and oxygen dissolution in liquid nitrogen on exposure to air<sup>6</sup>. Short term calibration changes are also inherent in microwave radiometry that result in accuracy degradation during intervals between cryogenic calibrations<sup>7</sup>.



Figure 2. Microwave profiler observation of a frontal passage at Flower Mound, TX.

We propose to develop and demonstrate an innovative automatic microwave radiometer

<sup>&</sup>lt;sup>2</sup> <u>http://radiometrics.com/products-services/boundary-layer-network</u>

<sup>&</sup>lt;sup>3</sup> See Potential NOAA Applications (Section 10.1) and Appendix B.

<sup>&</sup>lt;sup>4</sup> Maschwitz et al, 2013.

<sup>&</sup>lt;sup>5</sup> Pospichal et al, 2012.

<sup>&</sup>lt;sup>6</sup> Paine et al, 2014.

<sup>&</sup>lt;sup>7</sup> Brown et al, 2007.



calibration (ACal) system. The ACal system will optimize radiometer observation accuracy, reduce operational costs, and provide output files optimized for assimilation in numerical weather models. Additional cost savings can be realized by operating ACal radiometers at existing NWS facilities (Appendix A). The commercial market for this technology includes hundreds of domestic and international thermodynamic observation networks and sites.

# 2. Technical Objectives

Our primary technical objective is to build and demonstrate an inexpensive new observing system that will complement the existing observing system at data sparse times and locations. The proposed system will augment NOAA's data assimilation capability and improve forecast quality. Current microwave radiometer technology is subject to calibration error and uncertainty that limits widespread operational assimilation of its thermodynamic observations<sup>8</sup>. We propose to surpass this limitation with an innovative low cost automated calibration and accuracy verification (ACal) system.

ACal will generate brightness temperatures by forward-modelling<sup>9</sup> existing online NOAA radiosonde and model gridded analysis<sup>10</sup> data. It will automatically adjust radiometer calibration parameters to bring observed and forward-modeled brightness temperatures into agreement. Thermodynamic observations from an ACal radiometer will be provided in netcdf<sup>11</sup> format along with accuracy information required for routine operational assimilation. Widespread availability of accurate, low cost thermodynamic observations will lead to improved aviation weather advisories and weather forecasts. An observation network using this technology can be installed and operated at existing NWS facilities at low incremental cost.

# 3. Work Plan

# 3.1 Technical Approach

The accuracy of thermodynamic retrievals from microwave profiler brightness temperature (Tb) observations depends on calibration accuracy and frequency. Calibration is typically performed every six months using a cryogenic (liquid nitrogen) target. Our proposed ACal method makes use of model gridded analysis<sup>12</sup>, or collocated rawinsonde soundings<sup>13</sup> (when available), during

<sup>&</sup>lt;sup>8</sup> Caumont et al, 2016.

<sup>&</sup>lt;sup>9</sup> Westwater et al, 2005; Rambabu et al, 2014.

<sup>&</sup>lt;sup>10</sup><u>https://www.ready.noaa.gov/READYmetdata.php</u>

<sup>&</sup>lt;sup>11</sup> <u>https://www.unidata.ucar.edu/software/netcdf</u>

<sup>&</sup>lt;sup>12</sup> Güldner et al, 2013.

<sup>&</sup>lt;sup>13</sup> Martinet et al, 2017.



clear weather conditions.

Microwave radiometer calibration based on collocated rawinsonde soundings is well established <sup>14</sup>. We plan statistical comparison of thermodynamic observation accuracy for radiometer calibration based on gridded analysis vs. rawinsondes. This comparison will be based on collocated radiometer and rawinsonde observations, in cooperation with the NWS Denver-Boulder Weather Forecast Office (WFO), and potentially with other NWS WFOs.

# 3.2 Task Descriptions

Updated thermodynamic profiles from 12-hr rawinsondes and 1-hr NOAA High Resolution Rapid Refresh (HRRR) gridded forecast and analysis are available online. We will obtain rawinsonde soundings at Denver (CO) and Ft. Worth (TX) and HRRR gridded data at the corresponding rawinsonde launch site locations. We will then compare rawinsonde and gridded data to estimate gridded forecast and analysis accuracy at these two locations. We will continue with forward-modeling to convert rawinsonde and gridded data into brightness temperatures for use in radiometer calibration.

	Months after Receipt of Contract						
		1	2	3	4	5	6
	Tasks						
1	Gain access to HRRR gridded analysis						
2	Compute radiosonde (RS) vs. HRRR profile statistics						
3	Compute forward-modeled (FM) RS vs. HRRR Tb statistics						
4	Calibrate radiometer with RS Tb						
5	Compute RS vs RS-calibrated radiometer profile statistics						
6	Calibrate radiometer with HRRR Tb						
7	Compute RS vs HRRR-calibrated radiometer profile statistics						
8	Compare RS and HRRR-calibrated Tb and profile accuracies						
9	Develop Automatic Calibration (ACal) code						
10	Provide radiometer profiles in netcdf format						
11	Develop profile accuracy verification						
12	Demonstrate radiometer netcdf data assimilation						
	Deliverables						
1	Kickoff Meeting						
2	Bi-Monthly Status Reports						
4	Final Report						

The accuracy of soundings retrieved from gridded data radiometer calibration will be estimated by comparison with rawinsondes. Next we will commence ACal code development and testing

<sup>&</sup>lt;sup>14</sup> Löhnert et al, 2012.



based on forward-modeled rawinsonde and gridded data. Radiometer output files will be provided in netcdf format including profile accuracy information. Finally, we will subcontract a modeling group<sup>15</sup> to demonstrate assimilation of the netcdf files into numerical weather models. Additional tasks include a kickoff meeting, bi-monthly status reports, and a final report. Task and deliverable timelines are summarized in Table 1.

# **3.3** Meeting the Technical Objectives

NOAA technology and SBIR contracts supported development of commercial microwave radiometry by Radiometrics (RDX) more than 30 years ago, resulting in a global installed base of more than 300 units. RDX continues today as the world leading manufacturer of ground-based microwave radiometer profilers. RDX is highly motivated and well qualified to further refine this technology by ACal development to improve profile accuracy, reduce operational costs, and optimize data output for model assimilation.

# **3.4** Task Labor Categories and Schedules

The proposed research and development will be initiated during Phase I by RDX Principal and Co-Investigators following the timelines summarized in Table 1. Further refinement of the automated calibration, accuracy verification and assimilation optimization development will be proposed in detail for Phase II. Modeling experts at OU CAPS or STAR LLC may be subcontracted to assist with Phase I and II tasks.

# 4. Related Research and Development

A Launch Weather Decision Support System (LWDSS) is currently in development by Radiometrics and OU CAPS under NASA STTR contract. The LWDSS exploits thermodynamic and liquid water observations by microwave profilers to improve launch operation efficiency and safety, and will also assimilate Radar Wind Profiler data.

# 5. References

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- Caumont, O., D. Cimini, U. Löhnert, L. Alados-Arboledas, R. Bleisch, F. Buffa, M. Ferrario, A. Haefele, F. Madonna and G. Pacek, <u>Assimilation of humidity and temperature observations retrieved from</u> <u>ground-based microwave radiometers into a convective-scale NWP model</u>, QJRMS, 2016.
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- Löhnert, U., and O. Maier, <u>Operational profiling of temperature using ground-based microwave</u> radiometry at Payerne: prospects and challenges, AMT, 2012.

<sup>&</sup>lt;sup>15</sup> For example, expert modelers at OU CAPS and STAR LLC.

- Martinet, P., D. Cimini, F. De Angelis, G. Canut, V. Unger, R. Guillot, D. Tzanos and A. Paci, <u>Combining</u> <u>ground-based microwave radiometer and the AROME convective scale model through 1DVAR</u> <u>retrievals in complex terrain: an Alpine valley case study</u>, AMT, 2017.
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- Pospichal, B., G. Maschwitz, N. Küchler and T. Rose, <u>Standing Wave Patterns at Liquid Nitrogen Calibration</u> of <u>Microwave Radiometers</u>, ISTP, 2012.
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- Shimizu, S., R. Kato, Y. Uji, K. Simose, K. Iwanami, T. Maesaka and S. Suzuki, <u>Real-time data assimilation of</u> ground-based microwave radiometer network for short-range rainfall forecast in Tokyo, EMS, 2017.
- Westwater, E., D. Cimini, M. Klein, V. Leuski, V. Mattioli, A. Gasiewski, S. Dowlatshahi, J. Liljegren, B. Lesht and J. Shaw, <u>Microwave and Millimeter Wave Forward Modeling Results from the 2004 North Slope</u> of Alaska Arctic Winter Radiometric Experiment, ARM-STM, 2005.
- Ware, R., D. Cimini, E. Campos, G. Giuliani, S. Albers, M. Nelson, S. Koch, P. Joe and S. Cober, <u>Thermodynamic and liquid profiling during the 2010 Winter Olympics</u>, Atmos. Res., 2013.

# 6. Key Personnel and Bibliography of Directly Related Work

# 6.1 Randolph Ware (Principal Investigator)

Founder and Chief Scientist, Radiometrics Corporation

# Degrees

B.S., math, chemistry and physics, B.S., University of Colorado, 1966.

M.S., physics, M.S., University of Colorado, 1969.

Ph.D., experimental nuclear physics, University of Colorado, 1974.

# Work Experience

Founder, Chief Scientist – Radiometrics Corporation, 1988 - present.

Visiting Scientist – NCAR, Mesoscale and Microscale Meteorology Division, 2007-2011; Earth Observing Laboratory, 2011- 2015; Research Applications Laboratory, 2015 - present.

Founder, Director – University NAVSTAR Consortium (UNAVCO), 1984-1998.

Principal Investigator – SuomiNet Program, UCAR, 1999-2004.

Principal Investigator – GPS/MET (now COSMIC) Satellite Radio Occultation Program, UCAR, 1991-95.

Science Fellow – CIRES, 1985-91.

US Congress – Science Fellow, Office of Technology Assessment, 1983-84.

Founder, Boulder Brewing Company, 1980.

Research Associate – CIRES, 1979-1984.

Research Associate – Joint Institute for Laboratory Astrophysics, 1974-1978.

Research Assistant – University of Colorado Nuclear Physics Laboratory Cyclotron, 1968-1974.

U.S. Marine Corps, 1962-64.



#### **Publications and Patents**

Dr. Ware has published 87 peer-reviewed articles principally focused on microwave remote sensing of the atmosphere. He holds 9 patents.

### 6.2 Kimberly Reed (Investigator)

Atmospheric Scientist, Radiometrics; Visiting Scientist, NCAR Research Applications Laboratory.

#### Degrees

B.S., Meteorology & Climatology, University of Illinois at Urbana – Champaign, 2008
M.S., Atmospheric Science, University of Illinois at Urbana – Champaign, 2011
Ph.D., Atmospheric Science, University of Illinois at Urbana – Champaign, 2017

#### Work Experience

Visiting Scientist, NCAR Research Applications Laboratory, 2016 – present Atmospheric Scientist and Systems Engineer, Radiometrics, 2015 – present Meteorologist and Mission Scientist, MetAtmos LTD, 2015 Graduate Research Assistant, NASA Earth and Space Science Fellow, 2009 – present

#### Publications

- Reed, K. A., and S. W. Nesbitt, An Evaluation of Cold-Season Precipitation Microphysical Properties from a Radar Perspective, In Progress, 2017.
- Reed, K. A., and S. W. Nesbitt, Environmental Controls on Tropical Orographic Precipitation According to the Tropical Rainfall Measuring Mission, In Progress, 2017.
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- Serke, D. J., K. A. Reed, J. Negus, L. Blanchette, R. Ware, and P. Kennedy, A Narrow-Beam, Multi-Frequency, Scanning Radiometer and Its Application to In-Flight Icing Detection. Journal of Atmospheric Research. 2017.

#### 6.3 Tim Wilfong (Investigator)

Atmospheric Scientist and Launch Range Specialist, Radiometrics Corporation

#### Degrees

Master of Science in Meteorology – Pennsylvania State University, 1976. Bachelor of Science in Meteorology -- Pennsylvania State University, 1970.



# Work Experience

- Staff Meteorologist, Detect Inc., 2013-2016; Radiometrics, 2016 present: Provide technical oversight to the installations and performance evaluations of Raptor Wind Profiler line. Develop and test new signal processing techniques.
- Chief Scientist, Next Generation National Profiler Network, Honeywell Technical Services Inc., 2007 2013: Provided oversight to the development, installation, and testing of the NGNPN which was planned to be up to 53 autonomous wind profiler radar sites.
- RSA Weather Product Manager, Lockheed Martin, 2000 2003: Managed and provided technical direction for the \$40M weather subsystem that was part of Range Standardization and Automation (RSA).
- Senior Scientist, Science and Technology Corporation, NOAA Environmental Technologies Lab, 1996 2000: Provided program oversight for NOAA program to improve wind profiler signal processing technology.

# **Recent Publications**

- Wilfong, T., D. Berchoff, K. Brewster, F. Carr, N. Gasperoni, E. Lau, S. McLaughlin, R. Ware and M. Xue, <u>Ground-Based Remote Sensing Techniques for Space Launch Decision Support</u>, AMS, 2018.
- Wilfong, T., R. Ware, D. Berchoff, M. Beauharnois, L. Blanchette, K. Brewster, J. Brotzge, F. Carr, W. Conway, B. Demoz, J. Freedman, N. Gasperoni, I. Gultepe, K. Knupp, E. Lau, D. Holland, E. Joseph, C. MacDonald, M. Mahaffey, S. McLaughlin, R. Parmentier, K. Reed, P. Roller, N. Sette, C. Thorncroft, S. Vanderburg, D. Voytenko and P. Wiker, <u>Continuous Thermodynamic and Wind Profiling for High-Impact Weather Forecasting</u>, AMS, 2018.

# 7. Relationship with Phase II or other Future R/R&D

Further refinement of the proposed automated calibration, accuracy verification and assimilation development is planned for Phase II by RDX investigators with assistance from OU CAPS under subcontract. Synergy is expected with NASA supported RDX and CAPS work using microwave profiler thermodynamic and liquid water observations to improve launch operations efficiency and safety. The team is committed to developing the complementary ACal and LWDSS systems, and is looking forward to coordinating the proposed efforts through Phase II into Phase III commercialization.

# 8. Company Information and Facilities

Radiometrics Corporation (RDX) developed its first microwave radiometer product under NOAA SBIR contract in 1986. RDX then pioneered commercial microwave radiometer manufacturing and sales. Since that time RDX has sold more than 300 microwave radiometer products worldwide, most of which continue in operation today. RDX operates 15,000, and 5,000 square foot facilities in Boulder and Longmont, Colorado, including office, laboratory, machine shop, production, and test facilities, and an office in Norman, Oklahoma.

# 9. Subcontracts and Consultants

We are considering subcontracts to the University of Oklahoma (OU) Center for the Analysis and



Prediction of Storms (CAPS) and STAR LLC. These subcontractors would provide assistance with development and testing of forward-modeling, sounding accuracy statistics and verification, and model assimilation.

# **10.** Potential Applications

### **10.1** Potential NOAA Applications

National Weather Service (NWS) meteorologists provide aviation weather advisories to U.S. Center Weather Service Units (CWSU) supporting the U.S. Air Route Traffic Control Centers (ARTCC). The CWSU were formed in response to thunderstorm-related commercial passenger aircraft fatalities. National Weather Service meteorologists directly support air traffic control by providing detailed information including the following aviation weather advisories:

- Center Weather Advisories (CWA), up to 2 hours
- Meteorological Impact Statements (MIS), 2-12 hours.

NWS meteorologists at the Denver CWSU have been using microwave profiler data for the past several years, taking advantage of the continuous radiometric thermodynamic soundings and stability index time series to improve CWA and MIS advisories. In particular, convection, icing and freezing level advisories are typically improved when radiometric soundings are available. Details are provided by the Meteorologist in Charge at the Boulder, Colorado, National Weather Service Forecast Office in Appendix B.



*Figure 3. RDX microwave profilers at the NWS rawinsonde station in Denver.* 



Radiometer operation costs can be minimized if space, security, power and internet are already available at a site location. For example, RDX operated microwave profilers at the Denver rawinsonde station in cooperation with the Denver-Boulder NWS Weather Forecast Office during 2011-2012 (*Figure 3*). During this time period, the Denver CWSU discovered the value of continuous thermodynamic soundings for CWA and MIS advisory improvements. The CWSU has used the soundings to improve advisories since then, contingent on data availability.

During Phase II and III we plan to demonstrate automated radiometer calibration and operations in cooperation with the Denver-Boulder WFO and CWSU. Resulting advisory and model forecast improvements could potentially be expanded to include more than 200 NWS WFO, CWSU and rawinsonde launch locations (Appendix A). Such expansion would greatly increase thermodynamic observations of the data sparse boundary layer, at low cost.

# **10.2** Potential Non-NOAA Commercial Applications

The proposed automatically calibrated low-cost thermodynamic observing system has potential applications at U.S. and international airports and space launch ranges. Applications also include the following domestic and international thermodynamic observation networks and sites: New York State Mesonet (17 sites)<sup>16</sup>, MWRnet (70 sites)<sup>17</sup>, India Air Force network (20 sites)<sup>18</sup>, Tokyo network (10 sites)<sup>19</sup>, Korean Air Force network (8 sites), Boundary Layer Network (16 sites)<sup>20</sup>, and more than 100 individual site locations in China, India and elsewhere.

The potential non-NOAA commercial market for this technology includes hundreds of domestic and international thermodynamic observation networks and individual stations.

# **11.** Similar Proposals and Awards

There are no similar proposals or awards for the proposed work.

# **12.** Budget – included in submission package

# 13. Appendix A: CWSU, WFO and Rawindsonde Sites

Existing NWS CWSU, WFO and rawindsonde facility sites are shown in Figures 4-6 that could potentially host ACal radiometer operations, providing security, power and internet support at low incremental cost. Radiometer operations at these sites would contribute to an emerging national thermodynamic observation system.

<sup>&</sup>lt;sup>16</sup> <u>http://www.nysmesonet.org</u>

<sup>&</sup>lt;sup>17</sup> <u>http://cetemps.aquila.infn.it/mwrnet</u>

<sup>&</sup>lt;sup>18</sup> <u>https://www.info-electronics.co.in/projects.html</u>

<sup>&</sup>lt;sup>19</sup> Shimizu et al, 2017.

<sup>&</sup>lt;sup>20</sup> <u>http://radiometrics.com/data/uploads/2012/12/EN-RDX\_BLN.pdf</u>





Figure 4. The 21 CWSU located at U.S. Air Traffic Control Centers<sup>21</sup>.



Figure 5. The 122 U.S. Weather Forecast Offices<sup>22</sup>.

<sup>&</sup>lt;sup>21</sup> <u>http://www.nws.noaa.gov/aviation/pages/CWSU/CWSU.php</u>

<sup>&</sup>lt;sup>22</sup> <u>https://en.wikipedia.org/wiki/List\_of\_National\_Weather\_Service\_Weather\_Forecast\_Offices</u>





Figure 6. The 102 NWS rawindsonde launch sites (there are 23 additional sites in Alaska, the Pacific and Caribbean)<sup>23</sup>.

<sup>&</sup>lt;sup>23</sup> <u>https://www.weather.gov/upperair/nws\_upper</u>



# 14. Appendix B: WFO-CWSU Support Letter



UNITED STATES DEPARTMENT OF COMMERCE National Oceanic and Atmospheric Administration National Weather Service Forecast Office, WS1 Boulder, Colorado 80305 Tuesday, January 23, 2018

Memorandum For:

NOAA Grant Evaluation Committee

From:

Nezette Rydell, Meteorologist in Charge Att Full National Weather Service Forecast Office, Boulder, Co

National Weather Service Denver Center Weather Service Unit (CWSU) and Weather Forecast Office Boulder, CO (WFO) meteorologists have used continuous thermodynamic sounding information when it has been available via http://weatherview.radiometrics.com to improve aviation forecasts and weather advisories to the FAA over the last several years. This information has been helpful in forecasting near-term weather for Denver International Airport (DIA) and surrounding areas, particularly in regard to convection, inversions, and with freezing drizzle, snow, and icing.

During convective season, real-time soundings provided by RDX have been instrumental in diagnosing the actual presence or absence of mid- and upper-level instability as compared to model forecasts, directly aiding the forecasting and evolution of showers or thenderstorms at/near DIA and arrival and departure gates.

These soundings were also used in winter seasons; aiding in near real-time to monitor phenomena such as surface inversion strength (to forecast wind speed and direction and low stratus), and for monitoring of depth of low-level moisture and temperature profiles for forecast adjustments with regard to the onset timing of freezing drizzle, rain, and changeover to snow.

We estimate our forecasters used this data, when available, several times a week, and in rapidly evolving weather events, multiple times per day. The temporal resolution for these observations, roughly every 30-40 minutes, provided significant confidence to our staff in updated forecasts and warning operations.

