Thermodynamic Profiling for Weather Modification Operations and High Impact Weather Alerting Services

1. Introduction

Continuous boundary layer thermodynamic and wind soundings are widely recognized as essential for accurate high-impact local weather forecasting[1] and the support of operational weather modification activities. A radiometer Mesonet will generate a unique dataset for supporting and improving the effectiveness of weather modification efforts, and not incidentally, can also provide critical early warnings of High Impact weather events impacting agriculture, industry, transportation and public safety.

The implementation of such a Mesonet in Greece could therefore have benefits far beyond those envisioned for ELGA's hail suppression activities. Radiometrics is a key player in a private US radiometer network which provides continuous thermodynamic soundings and derived data services to public and private clients[2]. We suggest that ELGA consider the present hail suppression project as an opportunity for common development and demonstration by ELGA and Radiometrics of commercially viable radiometer-derived data services by our organizations. We will be happy to work with ELGA to develop a concept for establishment of Mesonet-generated value added early warning services in Greece.

2. Radiometer Accuracy

Radiometer brightness temperature accuracy can be determined by observation of cryogenic blackbody targets, by atmospheric tipping, and by comparison with forward modeled clear-air radiosonde soundings. Radiometer temperature and humidity retrieval accuracy can be determined by comparison with radiosonde and tower observations.

2.1 Cryogenic Targets

Cryogenic blackbody target observations are commonly used for microwave radiometer calibration and accuracy validation[3]. Actual cryogenic blackbody targets

[1] NRC, 2009; Bodeker et al, 2015; Illingworth et al, 2015; Appendix A; Appendix B.
[2] Boundary Layer Network; Sigma Soundings.
[3] Westwater et al, 2005.

are imperfect, with inherent uncertainties from absorption loss, reflection, standing waves, ambient oxygen and humidity condensation, and calibration path contaminants[4]. Cryogenic calibration accuracy can be determined by comparison with tipping calibration and forward modeled radiosondes.

Cryogenic calibration accuracy is target design dependent. A closed target prevents oxygen condensation that occurs when liquid nitrogen contacts ambient air -- an inherent source of uncertainty in open cryogenic target temperature. As a result, there are significant differences between closed (top-mount) and open (side-mount) cryogenic target calibration accuracies. For example, reported accuracy for closed targets is 0.5 K[5] and for open targets is greater than 5 K[6].

2.2 Atmospheric Tipping

Atmospheric observations at different elevation angles can be used to calibrate (and validate) radiometer accuracy during stable clear-air atmospheric conditions. This method uses the relationship between atmospheric opacity and elevation angle for calibration. Tipping can be used to calibrate radiometer channels that observe low optical depths (e.g. K-band, 20-30 GHz, ~1 cm wavelength) with 0.5 K accuracy[7].

2.3 Radiosonde Comparison

Radiosonde temperature and humidity profiles can be converted via forward modeling into brightness temperatures for direct comparison with radiometer brightness temperature observations (during clear conditions). Radiometer calibration history and uncertainty, radiosonde observation error, weather conditions and climatology contribute to comparison statistics. Example worst case single lower V-band error statistics are 2 K bias and 0.5 K std for 68 all-weather radiosonde comparisons[8] and 4 K bias and 2 K std for 268 clear sky comparisons[9].

Radiosonde and radiometer temperature and humidity profiles can be compared in all weather conditions. For such comparisons, it is important to understand the

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[4] Pospichal et al, 2012; Paine et al, 2014; Pospichal, 2014.
[5] Miacci et al, 2014.
[6] Löhnert et al, 2012; Pospichal, 2014; Ware and Nelson, 2014.
[7] Han and Westwater, 2000.
[8] Ware et al, 2013.
[9] Löhnert et al, 2013.

difference between radiometer volumetric observations at a fixed location and radiosonde point measurements along uncontrolled flight paths. Perspective on this difference is provided by considering observation error assigned to radiosonde soundings when they are assimilated in numerical weather models[10]. Taking these differences into account, radiosonde and radiometer thermodynamic sounding accuracies are roughly equivalent[11].

2.4 Tower Comparison

Tower, radiometer and wind lidar observation comparison "reveals that a lidar and radiometer measure wind and temperature with the same accuracy as tower instruments, while also providing advantages for monitoring stability and turbulence."[12] Another tower, radiometer and radiosonde observation comparison showed radiosonde-equivalent observation error up to 2-km height[13].

3. Infrared Thermometer Accuracy

The inherent accuracy of the zenith infrared sensor is an important specification. However, sensor mounting and beam steering choices dominate operational accuracy and reliability. We found that external-mount infrared sensors using front surface gold mirrors are subject to water intrusion and corrosion with associated accuracy degradation and sensor failure[14]. As a result we mounted our infrared sensor inside the radiometer cabinet where it is protected from harsh environmental conditions, ensuring optimum accuracy and long term reliability.

4. Variational Analysis

Radiometer and numerical weather model gridded analysis are combined in Sigma Soundings using one-dimensional variational (1DVAR) methods[15]. This approach provides continuous high accuracy thermodynamic and wind soundings of the troposphere and lower stratosphere by combining radiometer observations with model ingested radiosonde, satellite, aircraft and other measurements. Continuous

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[10] Appendix C.
[11] Güldner and Spänkuch, 2001; Cimini et al, 2011; Güldner, 2013.
[12] Friedrich et al, 2013.
[13] Ware et al, 2010.
[14] Plomondon and Sharp, 2013.
[15] Hewison et al, 2006; Cimini et al, 2011, 2015; Appendix A; Sigma Sounding Index.

forecast index time series generated from Sigma Soundings are powerful new tools for high-impact local weather forecasting[16]. Wind radar and lidar profiles can be merged with radiometer soundings[17]. Variational methods can also be used to assimilate radiometer brightness temperature observations into numerical weather models[18].

5. References

Baxter, R., R. Ware, F. Solheim, D. Patton, J. Oreamuno, G. Frederick and P. Wiker, Continuous Thermodynamic Profiling for Air Quality Applications, National Air Quality Conference, 2010.

Bodeker, G., S. Bojinski, D. Cimini, R. Dirksen, M. Haeffelin, J. Hannigan, D. Hurst, T. Leblanc, F. Madonna, M. Maturilli, A. Mikalsen, R. Philipona, T. Reale, D. Seidel, D. Tan, P. Thorne, H. Vömel and J. Wang, Reference upper air observations for climate: From concept to reality, BAMS, 2015.

Cimini, D., E. Westwater and A. Gasiewski, Temperature and humidity profiling in the Arctic using ground-based millimeter-wave radiometry and 1DVAR, TGRS, 2010.

Cimini, D., E. Campos, R. Ware, S. Albers, G. Giuliani, J. Oreamuno, P. Joe, S. Koch, S. Cober and E. Westwater, Thermodynamic atmospheric profiling during the 2010 winter Olympics Using ground-based microwave radiometry, TGRS, 2011.

Friedrich, K., J. Lundquist, M. Aitken, E. Kalina and R. Marshall, Stability and turbulence in the atmospheric boundary layer: An intercomparison of remote sensing and tower observations, GRL, 2012.

Güldner J., and D. Spänkuch, Remote Sensing of the Thermodynamic State of the Atmospheric Boundary Layer by Ground-Based Microwave Radiometry, JAOT, 2001.

Güldner, J., A model-based approach to adjust microwave observations for operational applications: results of a campaign at Munich airport in winter, AMT, 2013.

Han, Y., and E. Westwater, Analysis and Improvement of Tipping Calibration for Ground-Based Microwave Radiometers, TGRS, 2000.

Hewison, T., 1D-VAR Retrieval of Temperature and Humidity Profiles from Ground-based Microwave Radiometers, TGRS, 2006.

Illingworth, A., D. Cimini, C. Gaffard, M. Haeffelin, V. Lehmann, U. Löhnert, E. O'Connor and D. Ruffieux, Exploiting existing ground-based remote sensing networks to improve high resolution weather forecasts, BAMS, 2015.

[16] Novakovskaia et al, 2012; Nelson et al, 2013; Madhulatha et al, 2013, Cimini et al, 2015.
[17] Nelson et al, 2013; Appendix B; ABC News: High Wind Warning System, 2015.
[18] Illingworth et al, 2015.

Löhnert, U., and O. Maier, Operational profiling of temperature using ground-based microwave radiometry at Payerne: prospects and challenges, AMT, 2012.
Miacci, M., C. Angelis, A. Calheiros and L. Machado, Some considerations of the cryogenic calibration technique for microwave and millimeter wave ground-based radiometry, JMOEA, 2014.
Mattioli, V., E. Westwater, D. Cimini, J. Liljegren, B. Lesht, S. Gutman and F. Schmidlin, Analysis of Radiosonde and Ground-Based Remotely Sensed PWV Data from the 2004 North Slope of Alaska Arctic Winter Radiometric Experiment, JAOT, 2007.
U.S. National Research Council, Observing Weather and Climate from the Ground Up, A Nationwide Network of Networks, 2009.
Paine, S., D. Turner and N. Küchler, Understanding thermal drift in liquid nitrogen loads used for radiometric calibration in the field, JAOT, 2014.
Plomondon, E., and M. Sharp, Service Bulletin: Calibration Target maintenance, 2013.
Pospichal, B., G. Maschwitz, N. Küchler and T. Rose, Standing Wave Patterns at Liquid Nitrogen Calibration of Microwave Radiometers, 9th International Symposium on Tropospheric Profiling, 2012.
Pospichal, B., COST-TOPROF Joint Calibration Experiment, Lindenberg, Germany, 2014.
Ware, R., F. Solheim, G. Frederick, Thermodynamic Profiler Temperature Sounding Accuracy, National Air Quality Conference, 2010.
Ware, R., D. Cimini, E. Campos, G. Giuliani, S. Albers, M. Nelson, S. Koch, P. Joe and S. Cober, Thermodynamic and liquid profiling during the 2010 Winter Olympics, Atmospheric Research, 2013.
Ware, R., M. Nelson, MP-3000A and HATPRO Calibration Comparison, 2014.
Westwater, E., S. Crewell, C. Mätzler and D. Cimini, Principles of Surface-based Microwave and Millimeter wave Radiometric Remote Sensing of the Troposphere, Quaderni Soc. Ital. Elettromag, 2005.

6. Appendices

A. Sigma Soundings Flyer
B. AppNote – Continuous Thermodynamic and Wind Soundings
C. TechNote – Radiosonde Observation Accuracy
D. AppNote – Thermodynamics and Nowcasting
E. TechNote – MP-3000 Features
F. MP-3000 and HATPRO Comparison