Proposal:	**1DVAR Retrievals from Ground-Based Microwave Radiometer Observations**
To:	Meteorological Service of Canada
From:	Radiometrics Corporation
Contract No:	KE175-09-1364 0

Report:	**Work Item 1**
By:	Domenico Cimini, CETEMPS, University of L'Aquila
Issue:	1
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Date:	5 Mar 2010
Approval:	Randolph Ware, Ed R. Westwater
Date:	9 Mar 2010

List of Acronyms

1DVAR	One-Dimensional Variational
ASL	Above Sea Level
$\mathbf{B_T}$	Temperature profile covariance error matrix
$\mathbf{B_Q}$	Humidity profile covariance error matrix
EC	Environmental Canada
LAPS	Local Analysis and Prediction System
MSC	Meteorological Service of Canada
MWRP	Microwave Radiometer Profiler
NOAA	U.S. National Oceanic and Atmospheric Administration
NWP	Numerical Weather Prediction
Q	Atmospheric specific humidity
RAOB	Radiosonde Observation
T	Atmospheric temperature
Tb	Brightness temperature
Tir	Infrared temperature
Tsrf	Surface air temperature

Introduction

The Meteorological Service of Canada (MSC) obtains continuous thermodynamic (temperature, humidity and liquid) soundings at Whistler, B.C., from a ground-based Radiometrics MP-3000A microwave radiometer using neural network methods. Neural network or regression methods are traditionally used to retrieve thermodynamic profiles from radiometer observations (Solheim et al., 1998; Knupp et al., 2009). However, retrieval accuracy can be improved using One-Dimensional Variational (1DVAR) methods that use a forward-modeled local numerical weather forecast as a first guess (Deblonde and English, 2003; Hewison, 2006; Cimini et al., 2009). This approach avoids error inherent in neural network or regression retrieval methods and benefits from current surface, radiosonde, satellite, radar and other data residing in the local forecast. The Principal Investigators proposed to develop 1DVAR thermodynamic profile retrievals.

Work Statement and Timeline

Principal Investigator Randolph Ware (Chief Scientist, Radiometrics) is responsible for overall contract management. Co-Investigator Domenico Cimini (U. L'Aquila, Italy) is responsible for comparing thermodynamic profile observations and simulations from forward model profiles, and compute 1DVAR retrievals, with guidance from Ed Westwater (CIRES, U. Colorado, US).

Timeline: 14 weeks after award of contract, with time required for each work statement item specified in the budget section.

Work Statement: D. Cimini's specific responsibilities are listed in below.

Work Item	Task	Timeline (weeks)	Workload (hours)
1	Provide statistical comparisons of observed (radiometer) and forward-modeled brightness temperatures (Tb) from high resolution GEM (provided by EC), RUC (from NOAA) or WRF (from NCAR)	1	40
2	Deliver 1DVAR temperature, humidity and liquid profile retrievals from numerical weather model profile forecasts and radiometer Tb observations at the Whistler radiometer site	5	200
3	Generate 1DVAR retrievals in standard MP-3000A level2 format	1	40

Work Item 1 Report

The proposed Work Item 1 activities are: *Provide statistical comparisons of observed (radiometer) and forward-modeled brightness temperatures (Tb's) from high resolution GEM (provided by EC), RUC (from NOAA) or WRF (from NCAR)*.

Rationale: Statistical comparison of observed and simulated data is required for 1DVAR development, in order to determine instrument bias and Numerical Weather Model (NWM) background error covariance (B).

Data: The following datasets were obtained and used in the analysis:

- Tb's observed by MP-3031A at Whistler were provided by EC/MSC through ftp connection with the radiometer computer.

- Atmospheric pressure, temperature, and humidity soundings measured by radiosondes launched from Nesters were provided by EC/MSC through ftp connection with the MP-3031A acquisition computer.
- Atmospheric pressure, temperature, humidity, and cloud liquid and ice water profiles produced by the Local Analysis and Prediction System (LAPS) at grid points surrounding the Whistler radiometer site were retrieved by Graziano Giuliani (CETEMPS, U. L'Aquila) from the LAPS output available through NOAA at http://laps.noaa.gov/domains/psd/data/lapsprd/.

Method: Radiometer Tb observations at an elevation angle lower than zenith were used to avoid signal contamination from liquid water, ice, and/or snow accumulated on the radiometer radome and from signal saturation from vertical observation of a near-vertical column of strong precipitation. The Whistler radiometer observed at zenith and at 15 degrees elevation in the down valley direction. Tb simulations were obtained by processing RAOB and LAPS soundings with radiative transfer equations (Schroeder and Westwater, 1991) including the absorption model described in Liljegren et al. (2005). The first level of both RAOB and LAPS sounding had to be adjusted to match the altitude of the MP-3031A site (776 m ASL). This was obtained by:

- Discarding the RAOB levels from the launch site (Nesters, 659 m ASL) to the radiometer site.
- Interpolating LAPS sounding values at pressures higher than the surface pressure to the radiometer site altitude.

RAOB Tb's were forward modeled twice: once assuming clear sky (no hydrometeor) and once assuming the Decker model (Decker et al., 1978; Mattioli et al., 2009). LAPS Tb's were forward modeled from temperature, water vapor, liquid and ice water profile analyses at 30 min intervals.

Results: Tb time series and scatter plot comparisons, and surface air temperature (Tsrf) and sky infrared temperature (Tir) time series from 2010 day 42 (11 Feb) to 57 (26 Feb) are shown in Figures 2-23. Observed and simulated Tb's and Tsrf and Tir show similar trends. Clear (Tir =< 223.2 K) and cloudy (Tir > 223.2 K) thresholds were applied (this threshold may not detect high cirrus clouds, but their microwave emission is assumed to be negligible for this study). Naturally, the agreement between measured and simulated Tb is much better during clear sky periods, due to LAPS analysis and Decker model errors, and the intrinsic variability of clouds. RAOB and LAPS Tb simulations show reasonable agreement with MP-3031A observations. Observation minus simulation (Obs-Sim) residuals scatter plots for all conditions and for clear-sky only are provided in Figures 24-46. Clear sky Obs-Sim statistics in Table 1 show the following:

1) RAOB K-band (water vapor and liquid) channels show 1.5 to 3.0 K bias. This may be caused by one or more of the following: (a) radiosonde dry-bias, (b) water vapor absorption model uncertainty, and (c) MP-3031A calibration bias.
2) RAOB V-band (temperature and liquid water) channels agree very well (within the expected accuracy) except for 1-2 K bias in the 51.1-52.8 GHz channels.

3) LAPS lower K-band channels show 3 to 4 K average bias and upper channels show bias similar to RAOB. This is consistent with LAPS moisture overestimation in the upper troposphere-lower stratosphere for the lower channels and by (1a-c) above for the upper channels.

4) LAPS V-band channels show significantly different slope for most channels. This is consistent with a ~5 K overestimation of the thermal diurnal cycle by LAPS.

LAPS moisture and thermal cycle overestimations vs. RAOB are also seen in temperature and humidity profile comparisons (Figure 47).

Temperature and specific humidity profile background error covariance matrices ($\mathbf{B_T}$, $\mathbf{B_Q}$) were computed from simultaneous LAPS, RAOB and radiometer profiles during the Vancouver Winter Olympics (12-28 Feb 2010). $\mathbf{B_T}$ and $\mathbf{B_Q}$ were computed both at LAPS and standard MP-3031A profile retrieval height levels. $\mathbf{B_T}$ and $\mathbf{B_Q}$ are shown in Figure 48, and the square-root of $\mathbf{B_T}$ and $\mathbf{B_Q}$ diagonal terms are shown in Figure 49.

Summary: MP-3031A observations, radiosonde and LAPS model analysis profiles collected nearby Whistler, BC (Canada) during the 2010 Vancouver Winter Olympics were processed and analyzed. Statistical information obtained (Tb bias, $\mathbf{B_T}$, $\mathbf{B_Q}$) is essential for 1DVAR retrieval development. Furthermore, features were found that shall be kept in mind for 1DVAR development and evaluation.

References

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Schroeder, J., and E. Westwater, Guide to Microwave Weighting Function Calculations, **NOAA Tech. Memo. ERL WPL-225**, 1992.

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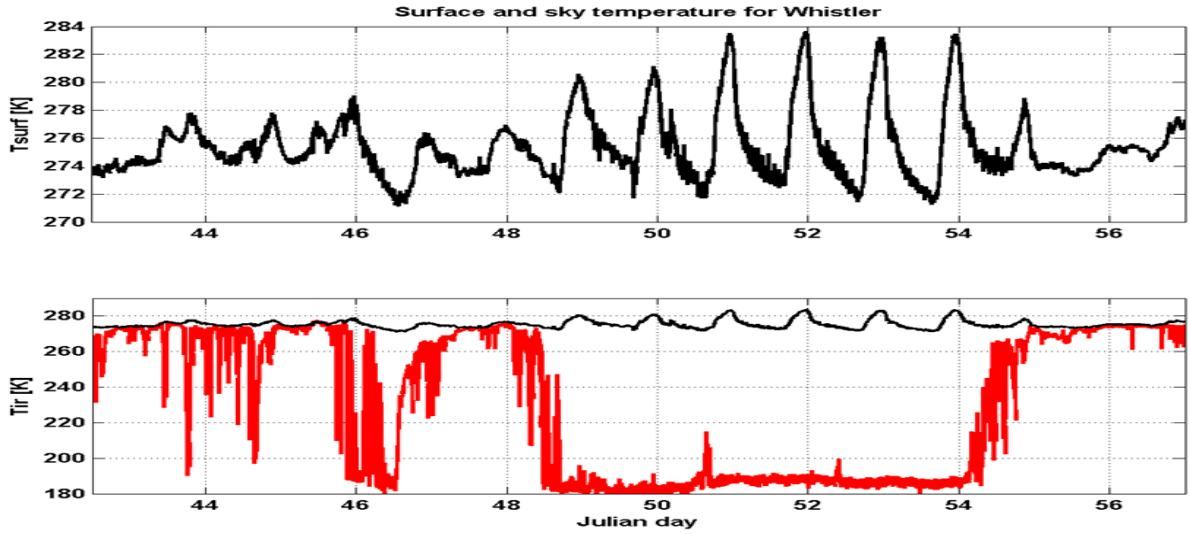
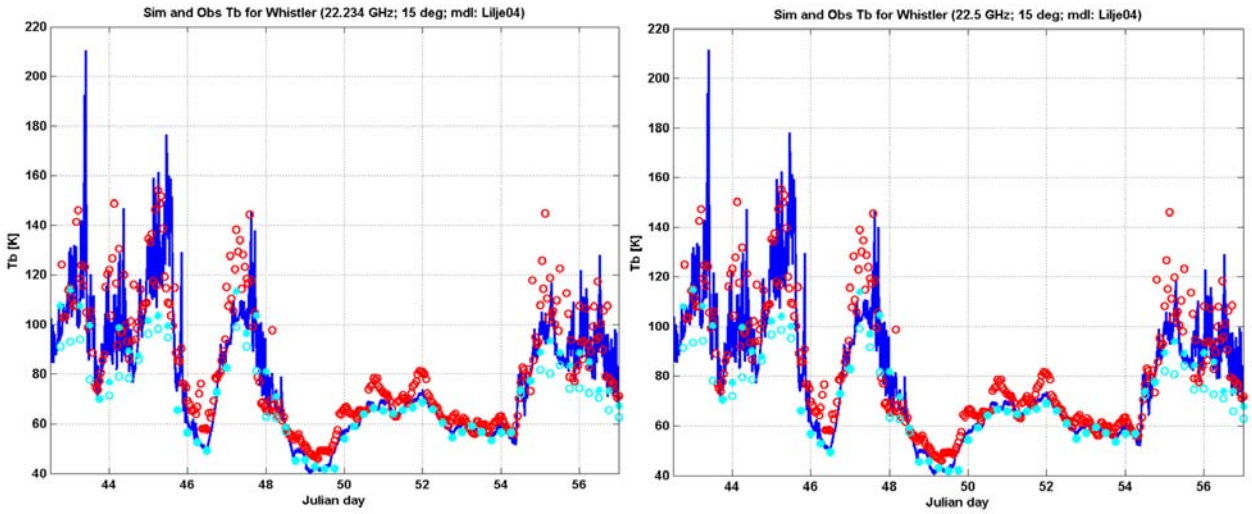
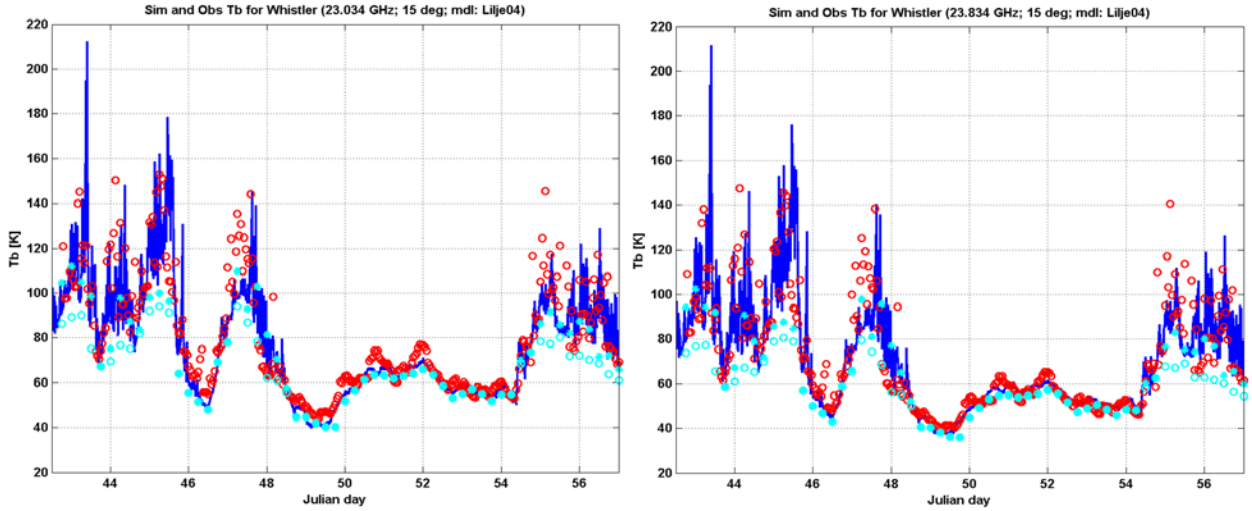
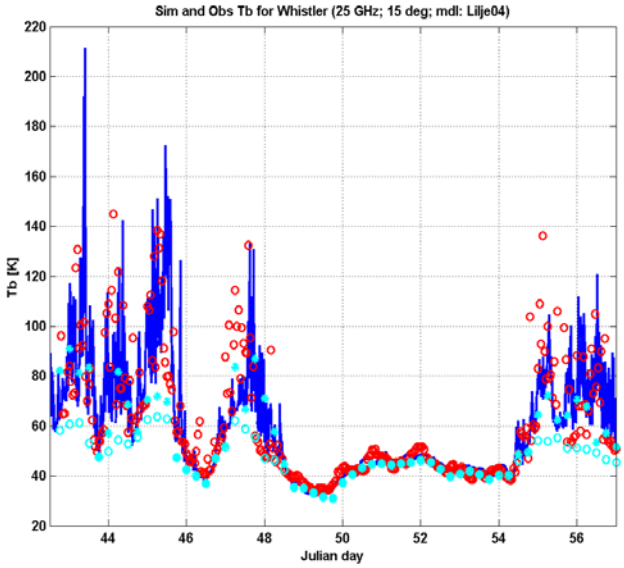


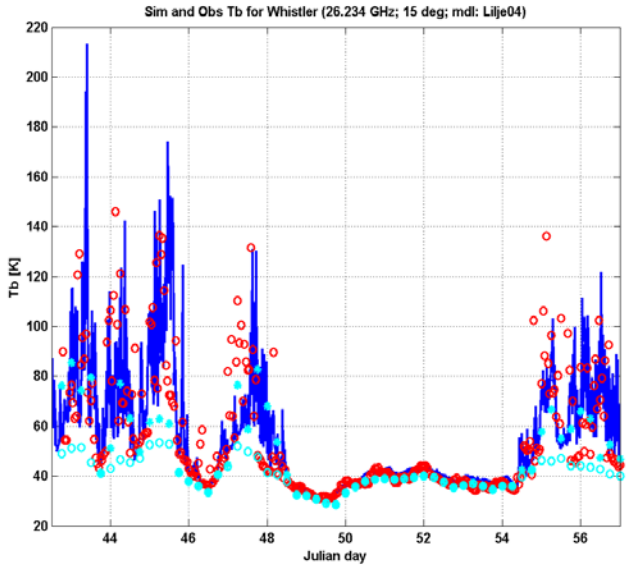
Figure 1. Surface air temperature (Tsrf, black) and sky infrared temperature (Tir, red) time series.

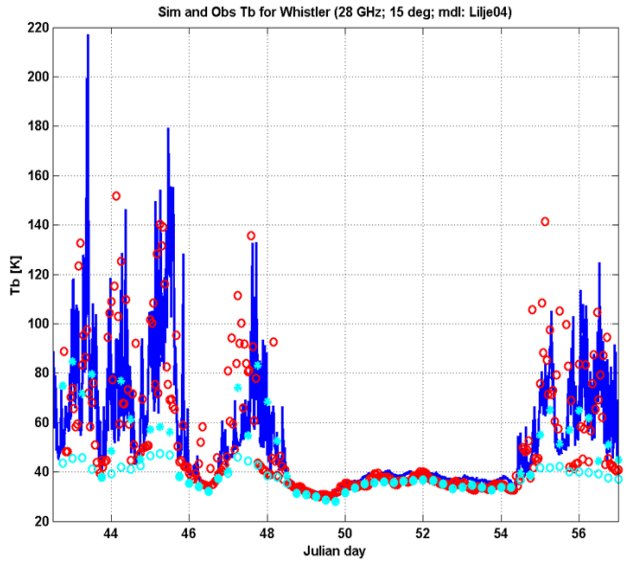


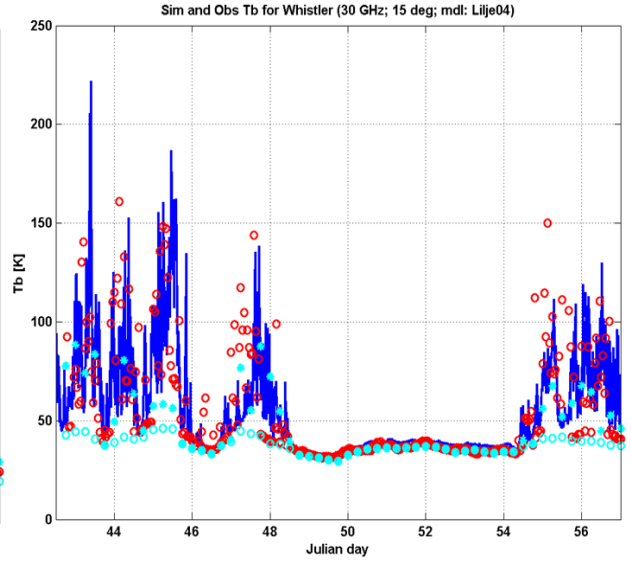
Figures 2 - 23. Brightness temperature (Tb) observations (blue) and LAPS simulations (red) and radiosondes (clear: cyan circles; cloudy: cyan stars) soundings for the MP-3031A frequency channels.

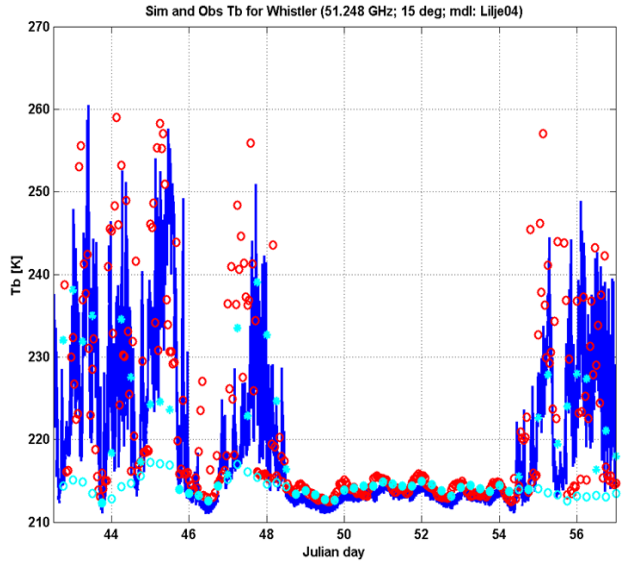


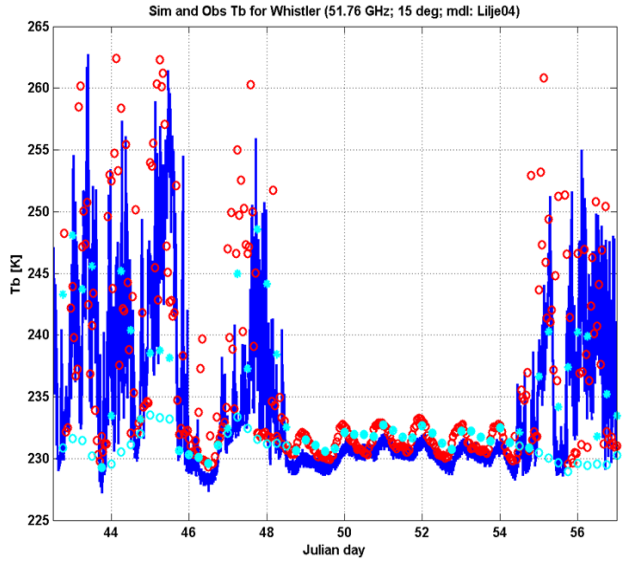

Sim and Obs Tb for Whistler (25 GHz; 15 deg; mdl: Lilje04)
Tb [K]
Julian day

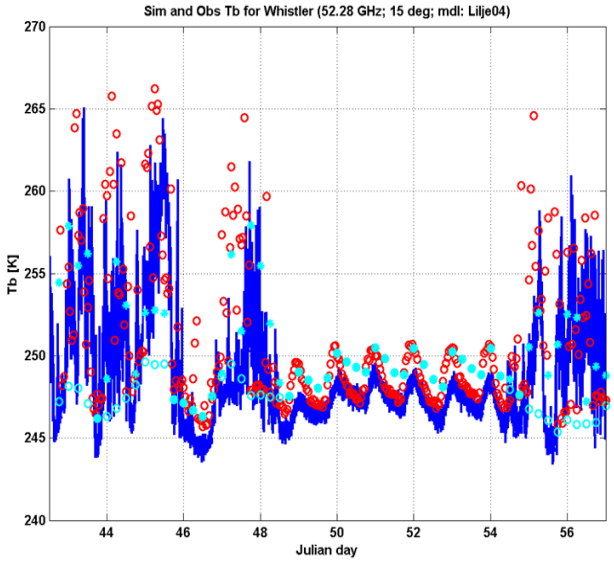

Sim and Obs Tb for Whistler (26.234 GHz; 15 deg; mdl: Lilje04)
Tb [K]
Julian day

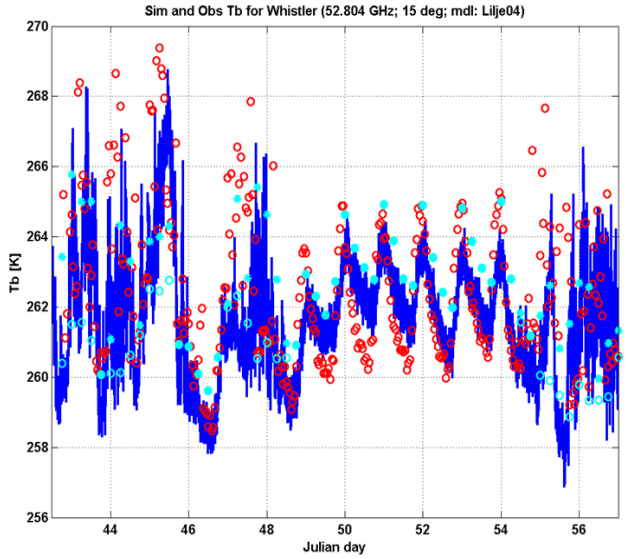

Sim and Obs Tb for Whistler (28 GHz; 15 deg; mdl: Lilje04)
Tb [K]
Julian day

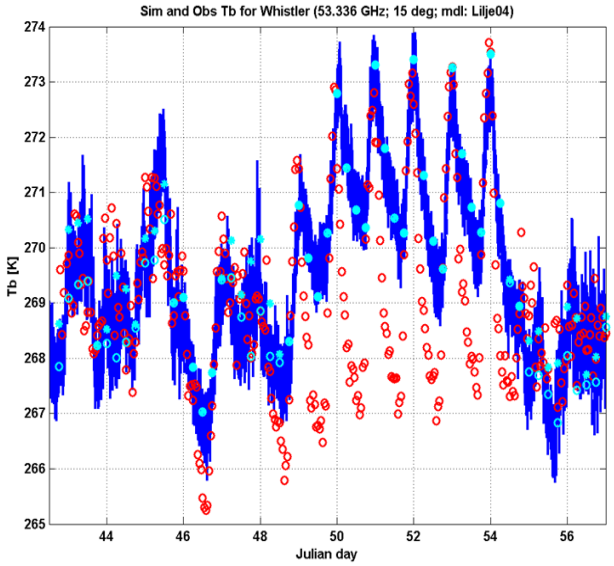

Sim and Obs Tb for Whistler (30 GHz; 15 deg; mdl: Lilje04)
Tb [K]
Julian day

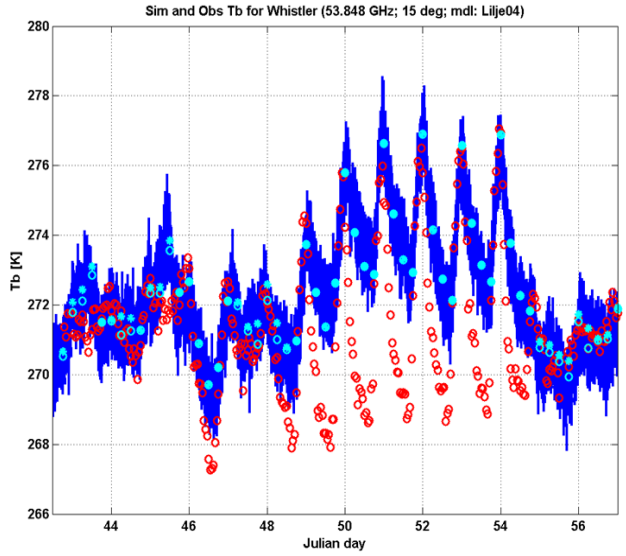

Sim and Obs Tb for Whistler (51.248 GHz; 15 deg; mdl: Lilje04)
Tb [K]
Julian day

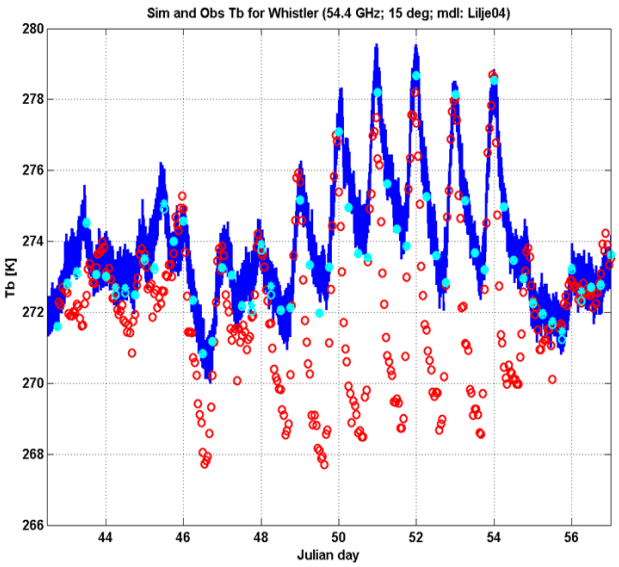

Sim and Obs Tb for Whistler (51.76 GHz; 15 deg; mdl: Lilje04)
Tb [K]
Julian day

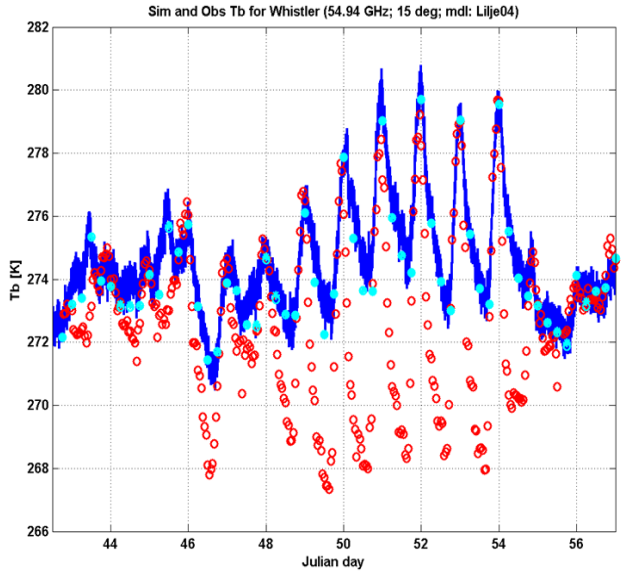

Sim and Obs Tb for Whistler (52.28 GHz; 15 deg; mdl: Lilje04)
Tb [K]
Julian day

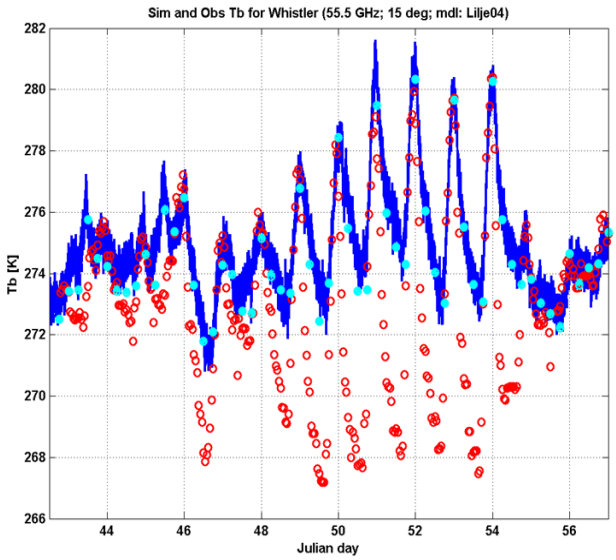

Sim and Obs Tb for Whistler (52.804 GHz; 15 deg; mdl: Lilje04)
Tb [K]
Julian day

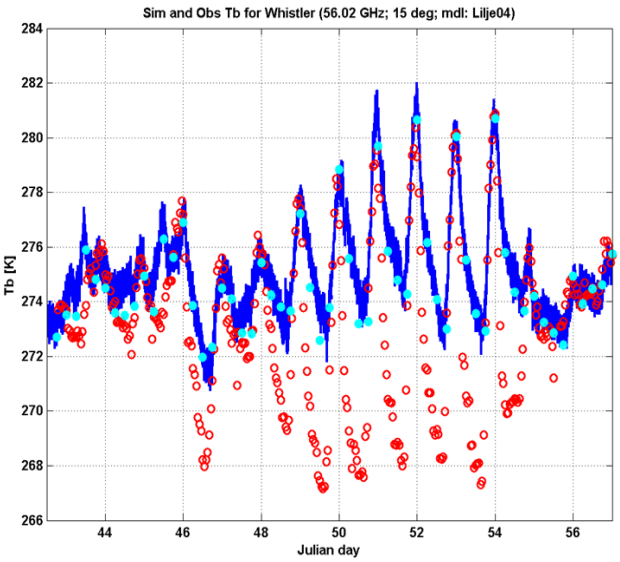

Sim and Obs Tb for Whistler (53.336 GHz; 15 deg; mdl: Lilje04)
Tb [K]
Julian day

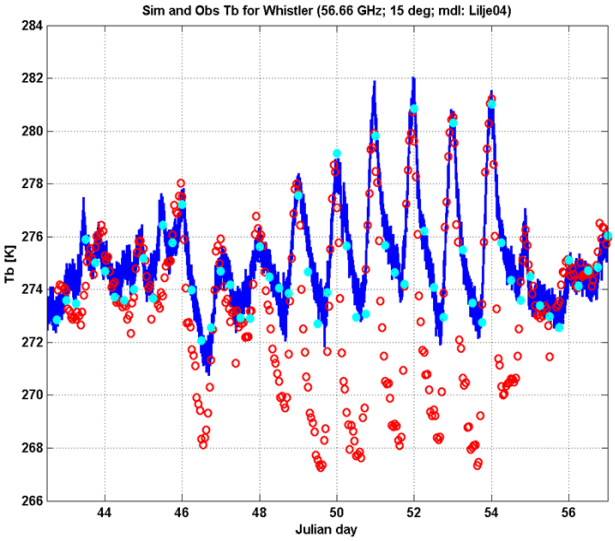

Sim and Obs Tb for Whistler (53.848 GHz; 15 deg; mdl: Lilje04)
Tb [K]
Julian day

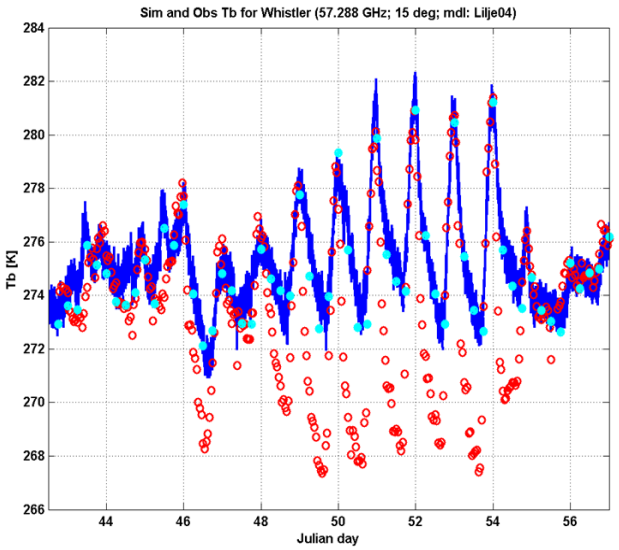

Sim and Obs Tb for Whistler (54.4 GHz; 15 deg; mdl: Lilje04)
Tb [K]
Julian day

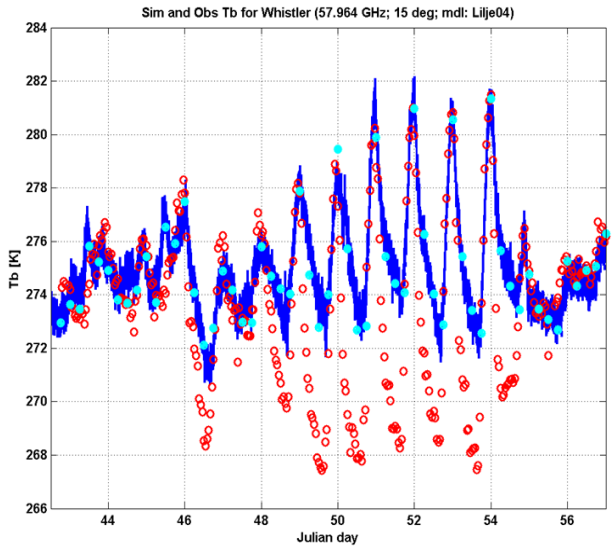

Sim and Obs Tb for Whistler (54.94 GHz; 15 deg; mdl: Lilje04)
Tb [K]
Julian day

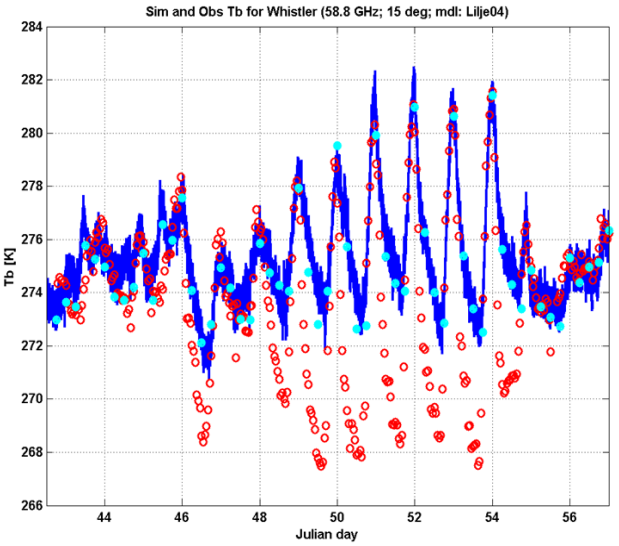

Sim and Obs Tb for Whistler (55.5 GHz; 15 deg; mdl: Lilje04)
Tb [K]
Julian day

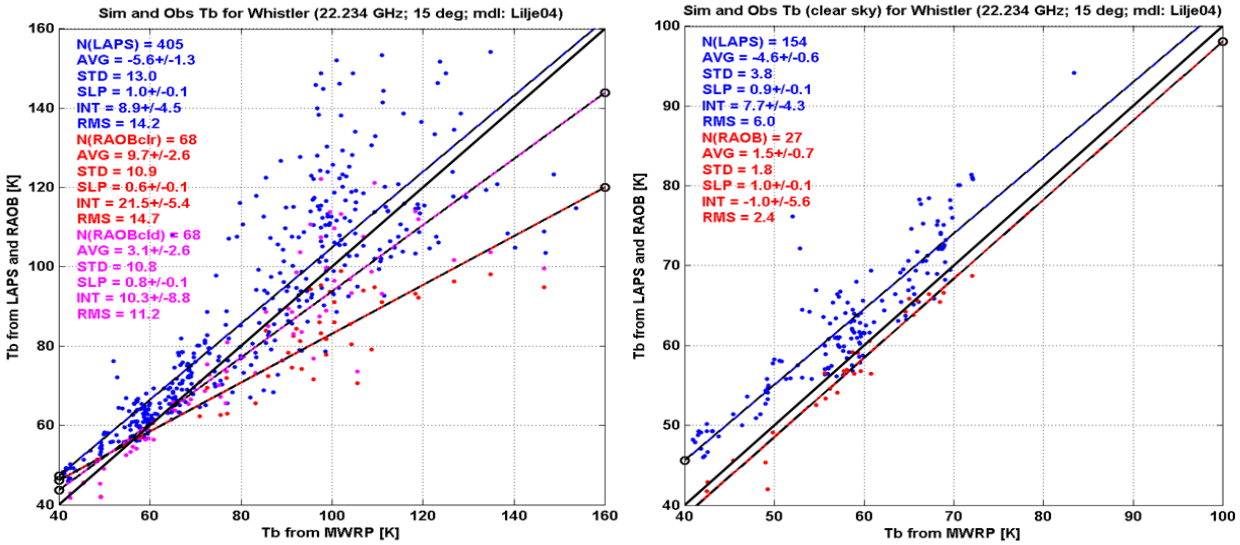

Sim and Obs Tb for Whistler (56.02 GHz; 15 deg; mdl: Lilje04)
Tb [K]
Julian day


Sim and Obs Tb for Whistler (56.66 GHz; 15 deg; mdl: Lilje04)
Tb [K]
Julian day

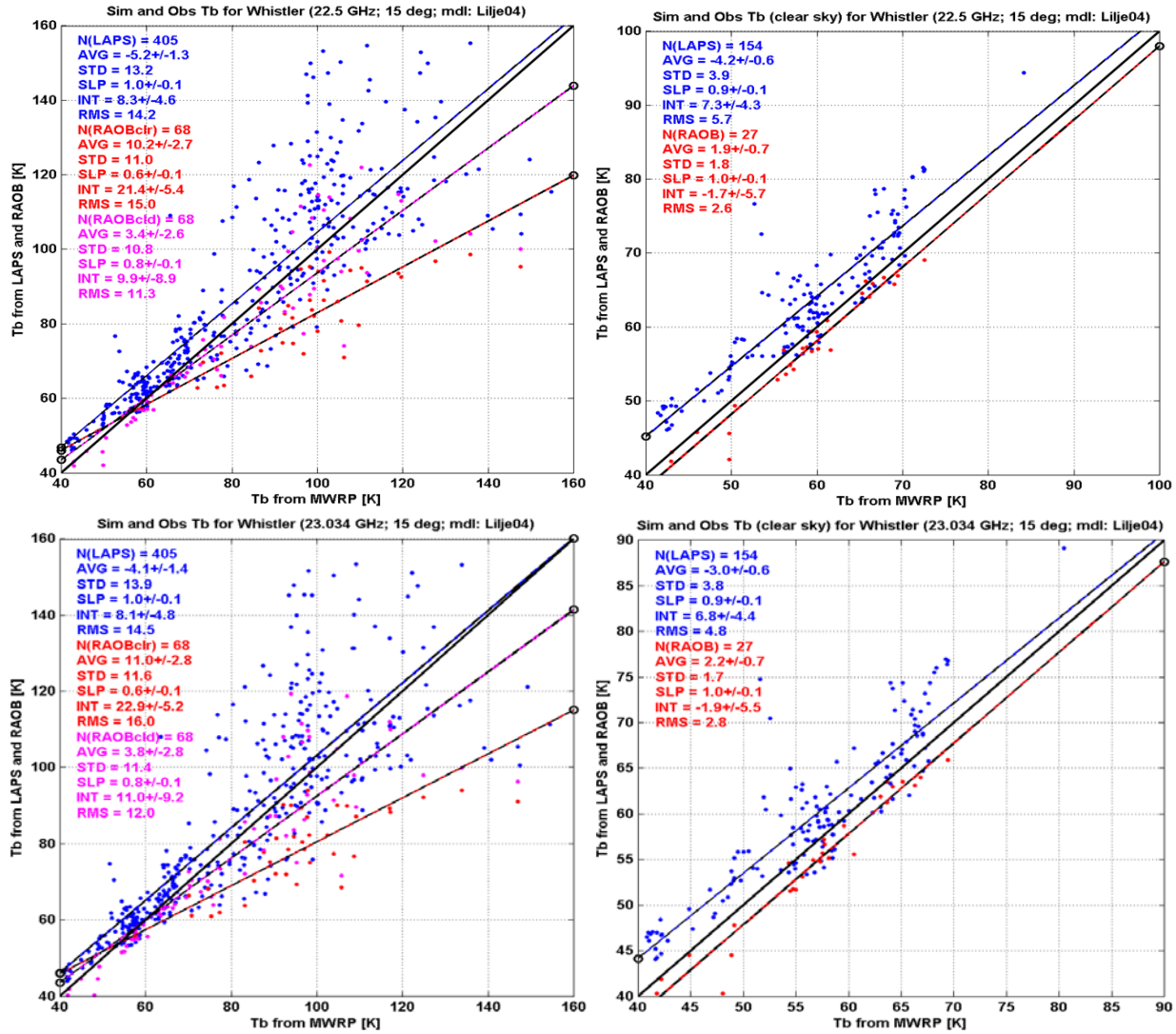

Sim and Obs Tb for Whistler (57.288 GHz; 15 deg; mdl: Lilje04)
Tb [K]
Julian day

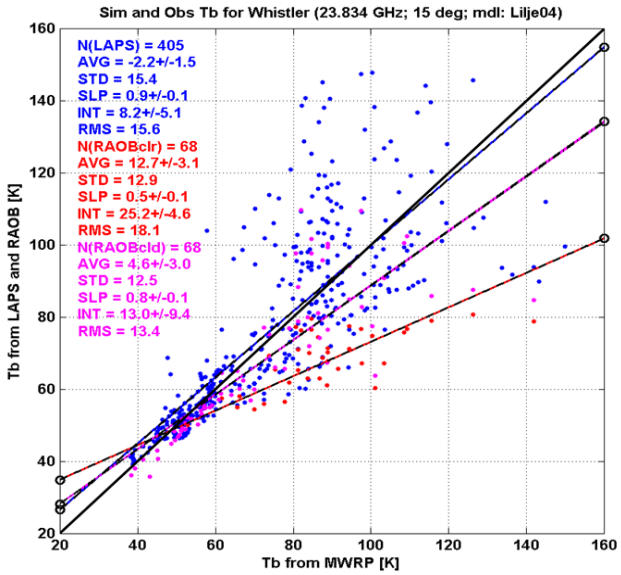

Sim and Obs Tb for Whistler (57.964 GHz; 15 deg; mdl: Lilje04)
Tb [K]
Julian day

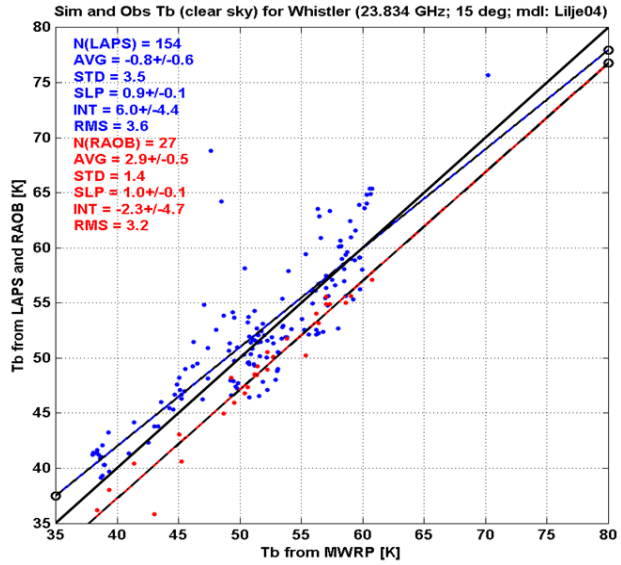

Sim and Obs Tb for Whistler (58.8 GHz; 15 deg; mdl: Lilje04)
Tb [K]
Julian day

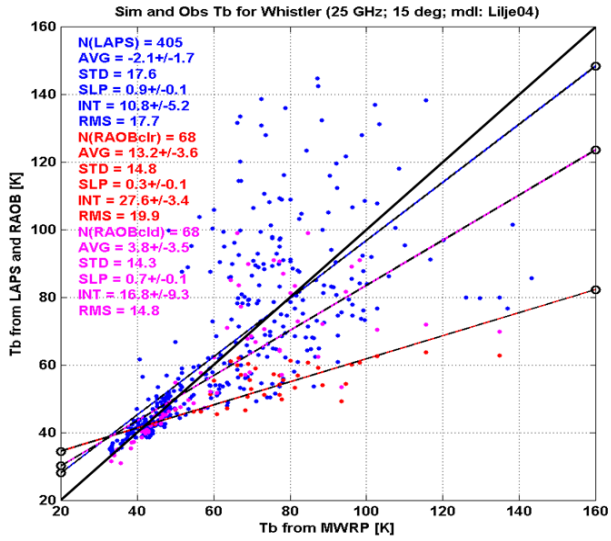


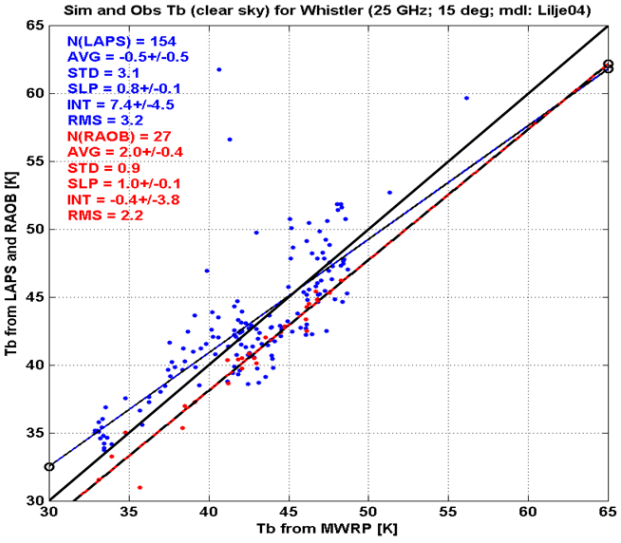
Figures 24 - 46. LAPS (blue) and radiosonde (cloudy: red; clear: magenta) simulated Tb scatter plots for the MP-3013A frequency channels. Left: all data; right: clear-sky only.

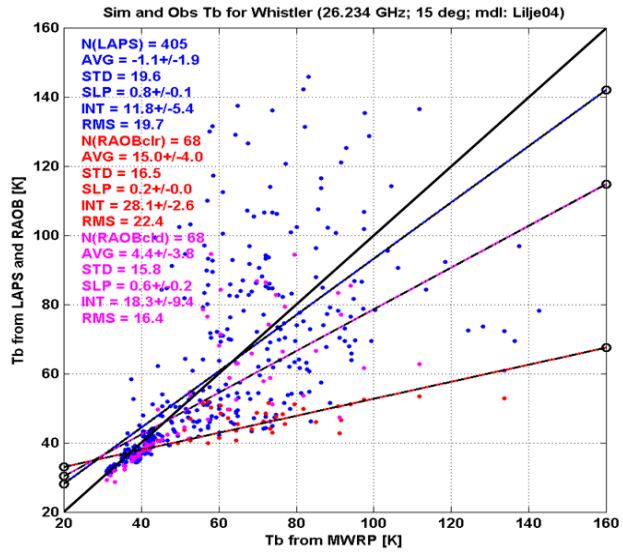


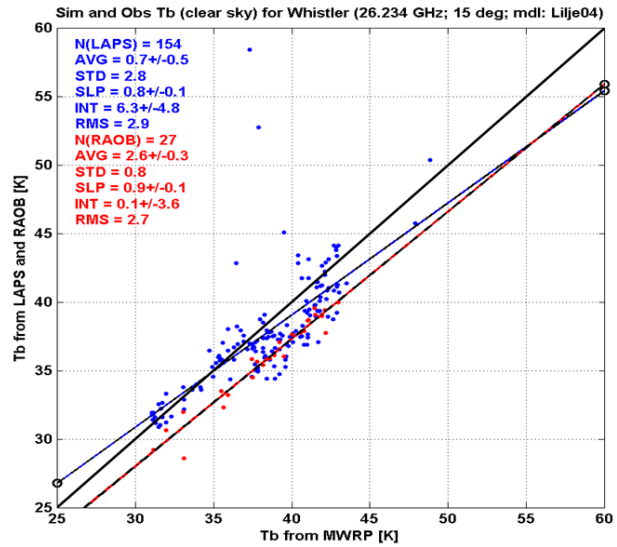

Sim and Obs Tb for Whistler (23.834 GHz; 15 deg; mdl: Lilje04)
N(LAPS) = 405
AVG = -2.2+/-1.5
STD = 15.4
SLP = 0.9+/-0.1
INT = 8.2+/-5.1
RMS = 15.6
N(RAOBclr) = 68
AVG = 12.7+/-3.1
STD = 12.9
SLP = 0.5+/-0.1
INT = 25.2+/-4.6
RMS = 18.1
N(RAOBcld) = 68
AVG = 4.6+/-3.0
STD = 12.5
SLP = 0.8+/-0.1
INT = 13.0+/-9.4
RMS = 13.4
Tb from LAPS and RAOB [K]
Tb from MWRP [K]

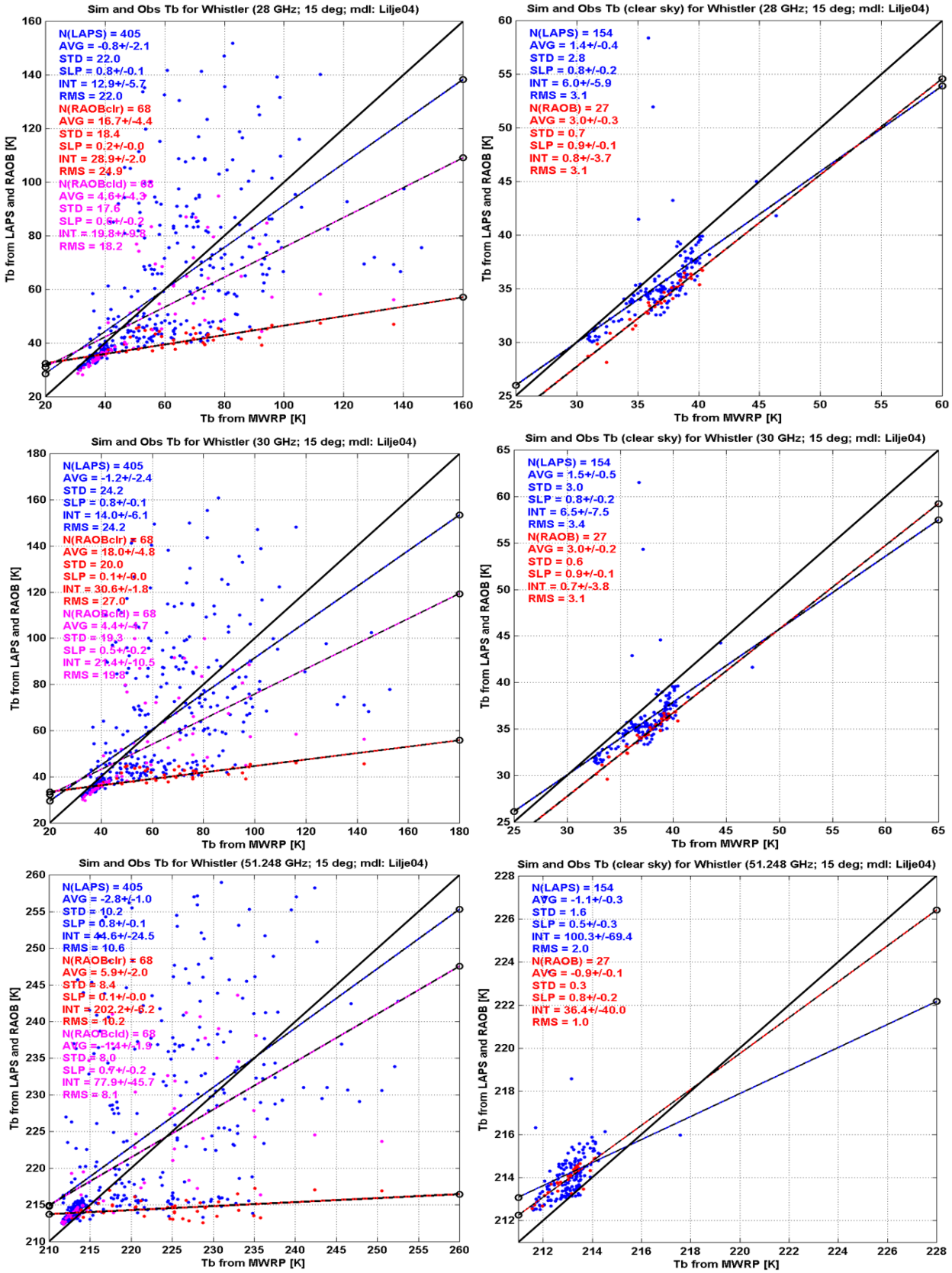

Sim and Obs Tb (clear sky) for Whistler (23.834 GHz; 15 deg; mdl: Lilje04)
N(LAPS) = 154
AVG = -0.8+/-0.6
STD = 3.5
SLP = 0.9+/-0.1
INT = 6.0+/-4.4
RMS = 3.6
N(RAOB) = 27
AVG = 2.9+/-0.5
STD = 1.4
SLP = 1.0+/-0.1
INT = -2.3+/-4.7
RMS = 3.2
Tb from LAPS and RAOB [K]
Tb from MWRP [K]

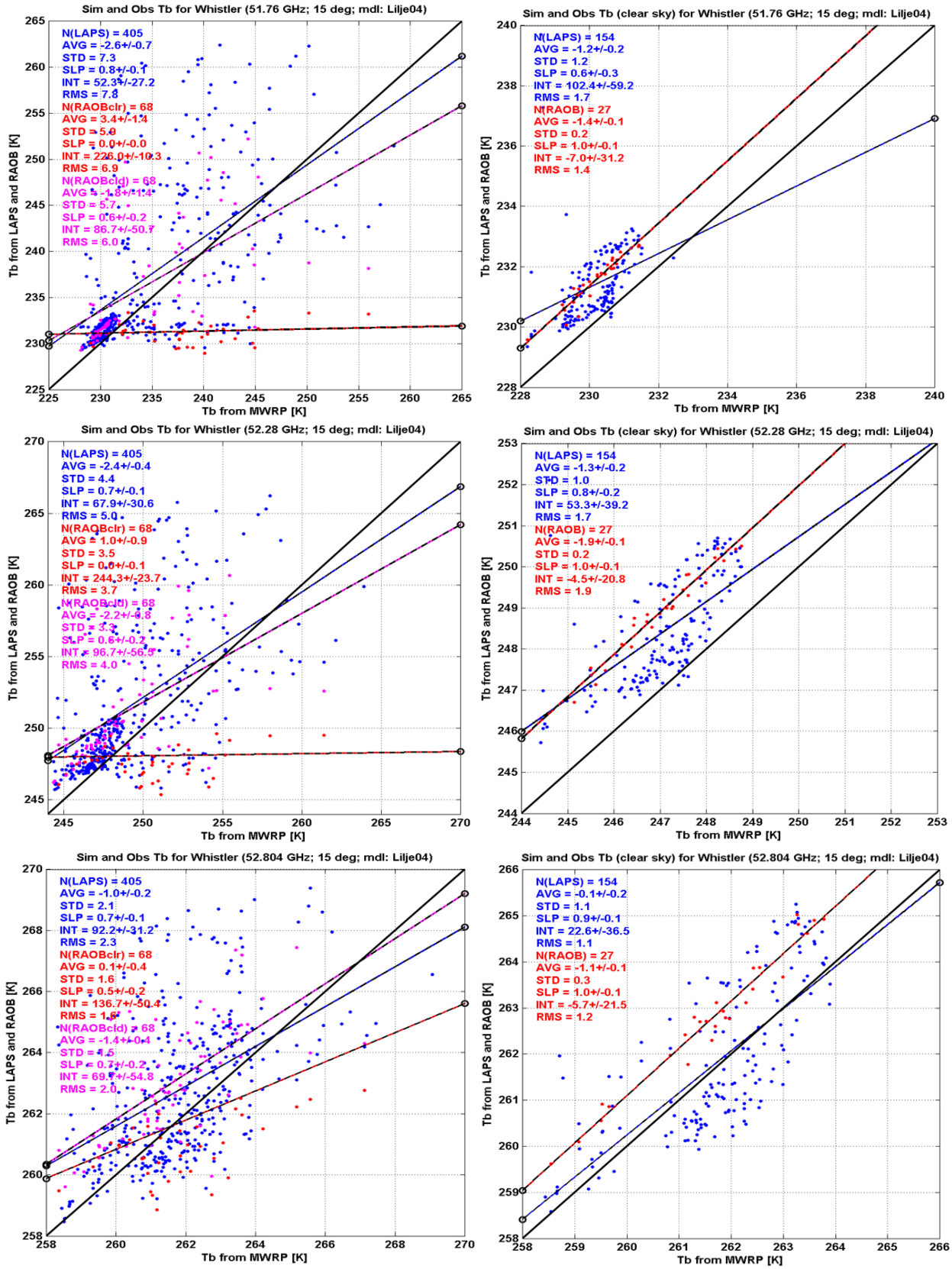

Sim and Obs Tb for Whistler (25 GHz; 15 deg; mdl: Lilje04)
N(LAPS) = 405
AVG = -2.1+/-1.7
STD = 17.6
SLP = 0.9+/-0.1
INT = 10.8+/-5.2
RMS = 17.7
N(RAOBclr) = 68
AVG = 13.2+/-3.6
STD = 14.8
SLP = 0.3+/-0.1
INT = 27.6+/-3.4
RMS = 19.9
N(RAOBcld) = 68
AVG = 3.8+/-3.5
STD = 14.3
SLP = 0.7+/-0.1
INT = 16.8+/-9.3
RMS = 14.8
Tb from LAPS and RAOB [K]
Tb from MWRP [K]

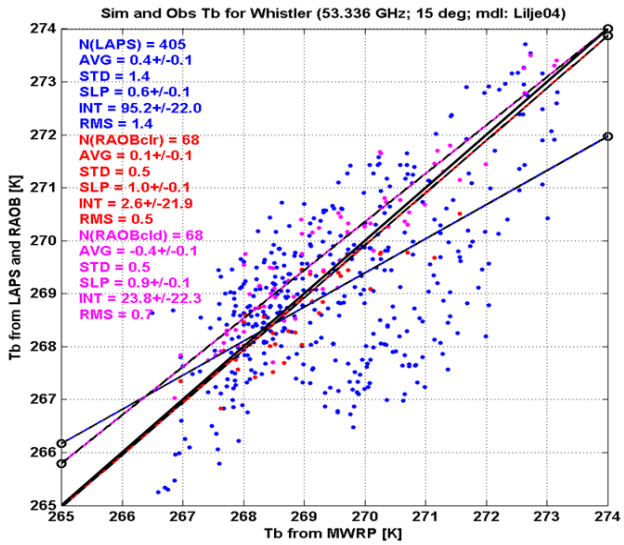

Sim and Obs Tb (clear sky) for Whistler (25 GHz; 15 deg; mdl: Lilje04)
N(LAPS) = 154
AVG = -0.5+/-0.5
STD = 3.1
SLP = 0.8+/-0.1
INT = 7.4+/-4.5
RMS = 3.2
N(RAOB) = 27
AVG = 2.0+/-0.4
STD = 0.9
SLP = 1.0+/-0.1
INT = -0.4+/-3.8
RMS = 2.2
Tb from LAPS and RAOB [K]
Tb from MWRP [K]

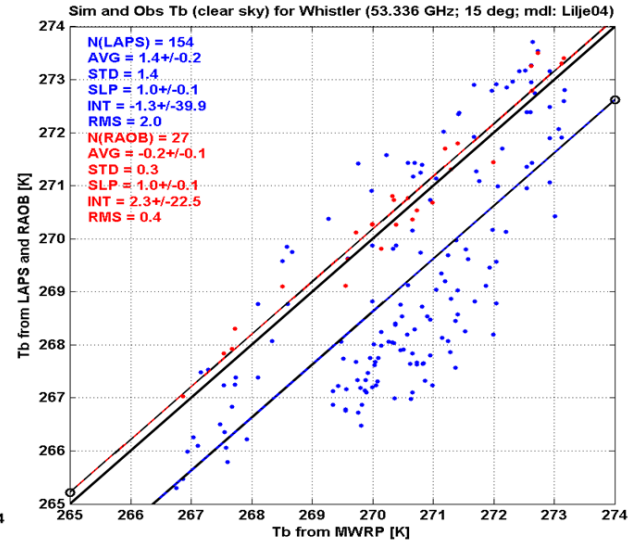

Sim and Obs Tb for Whistler (26.234 GHz; 15 deg; mdl: Lilje04)
N(LAPS) = 405
AVG = -1.1+/-1.9
STD = 19.6
SLP = 0.8+/-0.1
INT = 11.8+/-5.4
RMS = 19.7
N(RAOBclr) = 68
AVG = 15.0+/-4.0
STD = 16.5
SLP = 0.2+/-0.0
INT = 28.1+/-2.6
RMS = 22.4
N(RAOBcld) = 68
AVG = 4.4+/-3.8
STD = 15.8
SLP = 0.6+/-0.2
INT = 18.3+/-9.4
RMS = 16.4
Tb from LAPS and RAOB [K]
Tb from MWRP [K]

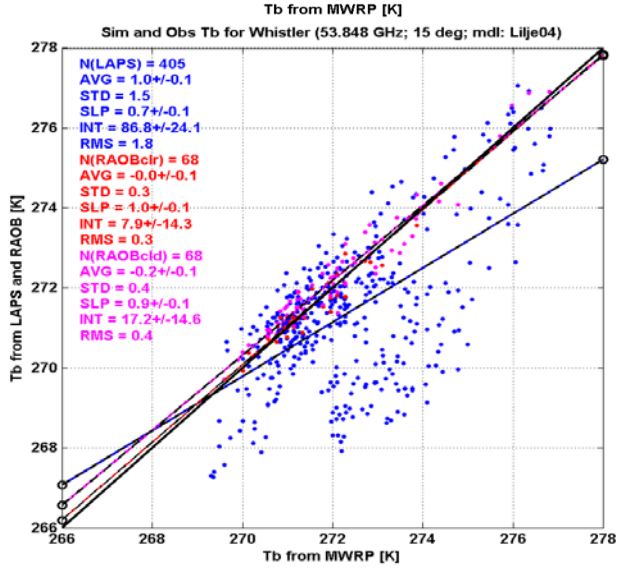

Sim and Obs Tb (clear sky) for Whistler (26.234 GHz; 15 deg; mdl: Lilje04)
N(LAPS) = 154
AVG = 0.7+/-0.5
STD = 2.8
SLP = 0.8+/-0.1
INT = 6.3+/-4.8
RMS = 2.9
N(RAOB) = 27
AVG = 2.6+/-0.3
STD = 0.8
SLP = 0.9+/-0.1
INT = 0.1+/-3.6
RMS = 2.7
Tb from LAPS and RAOB [K]
Tb from MWRP [K]

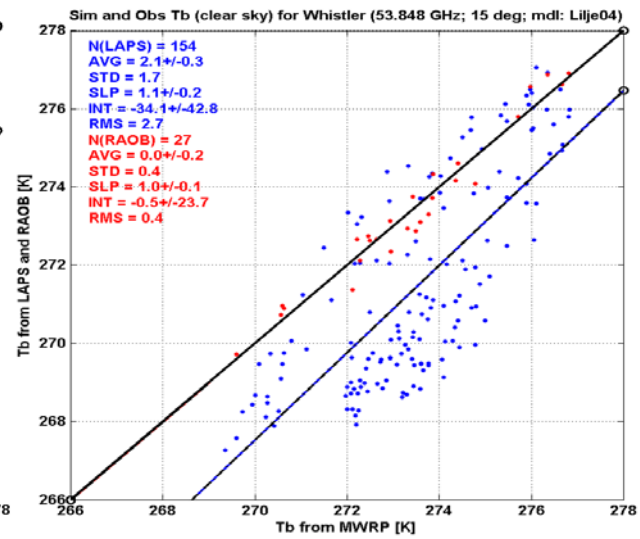

Sim and Obs Tb for Whistler (28 GHz; 15 deg; mdl: Lilje04)
N(LAPS) = 405
AVG = -0.8+/-2.1
STD = 22.0
SLP = 0.8+/-0.1
INT = 12.9+/-5.7
RMS = 22.0
N(RAOBclr) = 68
AVG = 16.7+/-4.4
STD = 18.4
SLP = 0.2+/-0.0
INT = 28.9+/-2.0
RMS = 24.9
N(RAOBcld) = 68
AVG = 4.6+/-4.3
STD = 17.6
SLP = 0.6+/-0.2
INT = 19.8+/-9.8
RMS = 18.2
Tb from LAPS and RAOB [K]
Tb from MWRP [K]
Sim and Obs Tb (clear sky) for Whistler (28 GHz; 15 deg; mdl: Lilje04)
N(LAPS) = 154
AVG = 1.4+/-0.4
STD = 2.8
SLP = 0.8+/-0.2
INT = 6.0+/-5.9
RMS = 3.1
N(RAOB) = 27
AVG = 3.0+/-0.3
STD = 0.7
SLP = 0.9+/-0.1
INT = 0.8+/-3.7
RMS = 3.1
Tb from LAPS and RAOB [K]
Tb from MWRP [K]
Sim and Obs Tb for Whistler (30 GHz; 15 deg; mdl: Lilje04)
N(LAPS) = 405
AVG = -1.2+/-2.4
STD = 24.2
SLP = 0.8+/-0.1
INT = 14.0+/-6.1
RMS = 24.2
N(RAOBclr) = 68
AVG = 18.0+/-4.8
STD = 20.0
SLP = 0.1+/-0.0
INT = 30.6+/-1.8
RMS = 27.0
N(RAOBcld) = 68
AVG = 4.4+/-4.7
STD = 19.3
SLP = 0.5+/-0.2
INT = 21.4+/-10.5
RMS = 19.8
Tb from LAPS and RAOB [K]
Tb from MWRP [K]
Sim and Obs Tb (clear sky) for Whistler (30 GHz; 15 deg; mdl: Lilje04)
N(LAPS) = 154
AVG = 1.5+/-0.5
STD = 3.0
SLP = 0.8+/-0.2
INT = 6.5+/-7.5
RMS = 3.4
N(RAOB) = 27
AVG = 3.0+/-0.2
STD = 0.6
SLP = 0.9+/-0.1
INT = 0.7+/-3.8
RMS = 3.1
Tb from LAPS and RAOB [K]
Tb from MWRP [K]
Sim and Obs Tb for Whistler (51.248 GHz; 15 deg; mdl: Lilje04)
N(LAPS) = 405
AVG = -2.8+/-1.0
STD = 10.2
SLP = 0.8+/-0.1
INT = 44.6+/-24.5
RMS = 10.6
N(RAOBclr) = 68
AVG = 5.9+/-2.0
STD = 8.4
SLP = 0.1+/-0.0
INT = 202.2+/-6.2
RMS = 10.2
N(RAOBcld) = 68
AVG = -1.4+/-1.9
STD = 8.0
SLP = 0.7+/-0.2
INT = 77.9+/-45.7
RMS = 8.1
Tb from LAPS and RAOB [K]
Tb from MWRP [K]
Sim and Obs Tb (clear sky) for Whistler (51.248 GHz; 15 deg; mdl: Lilje04)
N(LAPS) = 154
AVG = -1.1+/-0.3
STD = 1.6
SLP = 0.5+/-0.3
INT = 100.3+/-69.4
RMS = 2.0
N(RAOB) = 27
AVG = -0.9+/-0.1
STD = 0.3
SLP = 0.8+/-0.2
INT = 36.4+/-40.0
RMS = 1.0
Tb from LAPS and RAOB [K]
Tb from MWRP [K]

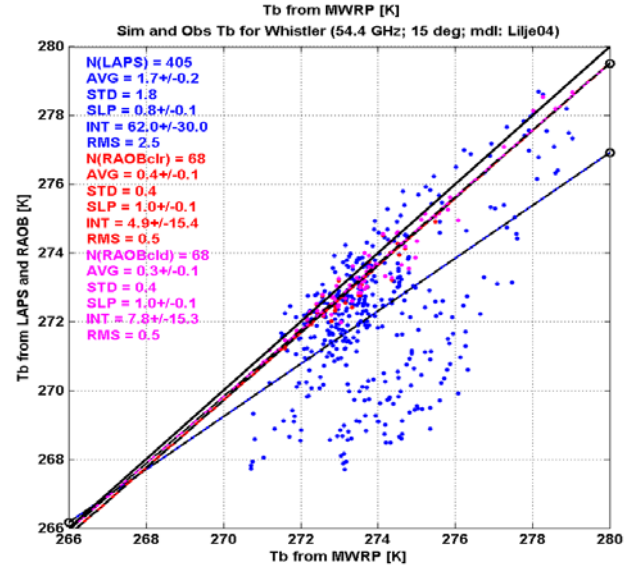

Sim and Obs Tb for Whistler (51.76 GHz; 15 deg; mdl: Lilje04)
N(LAPS) = 405
AVG = -2.6+/-0.7
STD = 7.3
SLP = 0.8+/-0.1
INT = 52.3+/-27.2
RMS = 7.8
N(RAOBclr) = 68
AVG = 3.4+/-1.4
STD = 5.9
SLP = 0.0+/-0.0
INT = 226.0+/-10.3
RMS = 6.9
N(RAOBcld) = 68
AVG = -1.8+/-1.4
STD = 5.7
SLP = 0.6+/-0.2
INT = 86.7+/-50.7
RMS = 6.0
Tb from LAPS and RAOB [K]
Tb from MWRP [K]
Sim and Obs Tb (clear sky) for Whistler (51.76 GHz; 15 deg; mdl: Lilje04)
N(LAPS) = 154
AVG = -1.2+/-0.2
STD = 1.2
SLP = 0.6+/-0.3
INT = 102.4+/-59.2
RMS = 1.7
N(RAOB) = 27
AVG = -1.4+/-0.1
STD = 0.2
SLP = 1.0+/-0.1
INT = -7.0+/-31.2
RMS = 1.4
Tb from LAPS and RAOB [K]
Tb from MWRP [K]
Sim and Obs Tb for Whistler (52.28 GHz; 15 deg; mdl: Lilje04)
N(LAPS) = 405
AVG = -2.4+/-0.4
STD = 4.4
SLP = 0.7+/-0.1
INT = 67.9+/-30.6
RMS = 5.0
N(RAOBclr) = 68
AVG = 1.0+/-0.9
STD = 3.5
SLP = 0.0+/-0.1
INT = 244.3+/-23.7
RMS = 3.7
N(RAOBcld) = 68
AVG = -2.2+/-0.8
STD = 3.3
SLP = 0.6+/-0.2
INT = 96.7+/-56.5
RMS = 4.0
Tb from LAPS and RAOB [K]
Tb from MWRP [K]
Sim and Obs Tb (clear sky) for Whistler (52.28 GHz; 15 deg; mdl: Lilje04)
N(LAPS) = 154
AVG = -1.3+/-0.2
STD = 1.0
SLP = 0.8+/-0.2
INT = 53.3+/-39.2
RMS = 1.7
N(RAOB) = 27
AVG = -1.9+/-0.1
STD = 0.2
SLP = 1.0+/-0.1
INT = -4.5+/-20.8
RMS = 1.9
Tb from LAPS and RAOB [K]
Tb from MWRP [K]
Sim and Obs Tb for Whistler (52.804 GHz; 15 deg; mdl: Lilje04)
N(LAPS) = 405
AVG = -1.0+/-0.2
STD = 2.1
SLP = 0.7+/-0.1
INT = 92.2+/-31.2
RMS = 2.3
N(RAOBclr) = 68
AVG = 0.1+/-0.4
STD = 1.6
SLP = 0.5+/-0.2
INT = 136.7+/-50.4
RMS = 1.8
N(RAOBcld) = 68
AVG = -1.4+/-0.4
STD = 1.5
SLP = 0.7+/-0.2
INT = 69.7+/-54.8
RMS = 2.0
Tb from LAPS and RAOB [K]
Tb from MWRP [K]
Sim and Obs Tb (clear sky) for Whistler (52.804 GHz; 15 deg; mdl: Lilje04)
N(LAPS) = 154
AVG = -0.1+/-0.2
STD = 1.1
SLP = 0.9+/-0.1
INT = 22.6+/-36.5
RMS = 1.1
N(RAOB) = 27
AVG = -1.1+/-0.1
STD = 0.3
SLP = 1.0+/-0.1
INT = -5.7+/-21.5
RMS = 1.2
Tb from LAPS and RAOB [K]
Tb from MWRP [K]

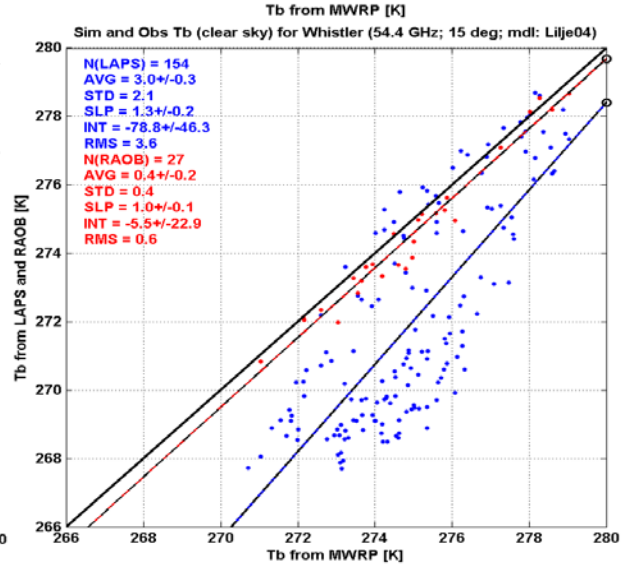

Sim and Obs Tb for Whistler (53.336 GHz; 15 deg; mdl: Lilje04)
N(LAPS) = 405
AVG = 0.4+/-0.1
STD = 1.4
SLP = 0.6+/-0.1
INT = 95.2+/-22.0
RMS = 1.4
N(RAOBclr) = 68
AVG = 0.1+/-0.1
STD = 0.5
SLP = 1.0+/-0.1
INT = 2.6+/-21.9
RMS = 0.5
N(RAOBcld) = 68
AVG = -0.4+/-0.1
STD = 0.5
SLP = 0.9+/-0.1
INT = 23.8+/-22.3
RMS = 0.7
Tb from LAPS and RAOB [K]
Tb from MWRP [K]

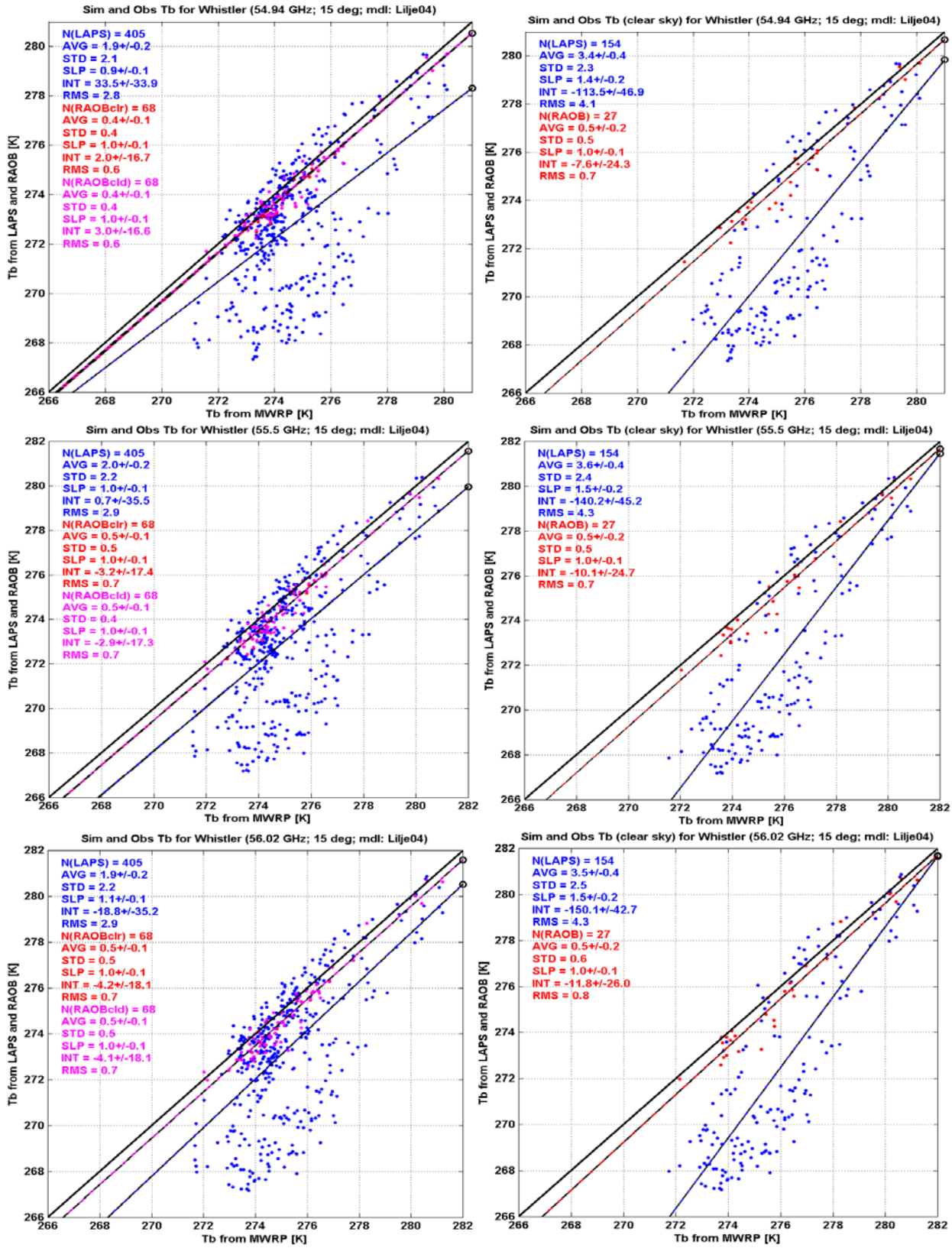

Sim and Obs Tb (clear sky) for Whistler (53.336 GHz; 15 deg; mdl: Lilje04)
N(LAPS) = 154
AVG = 1.4+/-0.2
STD = 1.4
SLP = 1.0+/-0.1
INT = -1.3+/-39.9
RMS = 2.0
N(RAOB) = 27
AVG = -0.2+/-0.1
STD = 0.3
SLP = 1.0+/-0.1
INT = 2.3+/-22.5
RMS = 0.4
Tb from LAPS and RAOB [K]
Tb from MWRP [K]


Sim and Obs Tb for Whistler (53.848 GHz; 15 deg; mdl: Lilje04)
N(LAPS) = 405
AVG = 1.0+/-0.1
STD = 1.5
SLP = 0.7+/-0.1
INT = 86.8+/-24.1
RMS = 1.8
N(RAOBclr) = 68
AVG = -0.0+/-0.1
STD = 0.3
SLP = 1.0+/-0.1
INT = 7.9+/-14.3
RMS = 0.3
N(RAOBcld) = 68
AVG = -0.2+/-0.1
STD = 0.4
SLP = 0.9+/-0.1
INT = 17.2+/-14.6
RMS = 0.4
Tb from LAPS and RAOB [K]
Tb from MWRP [K]


Sim and Obs Tb (clear sky) for Whistler (53.848 GHz; 15 deg; mdl: Lilje04)
N(LAPS) = 154
AVG = 2.1+/-0.3
STD = 1.7
SLP = 1.1+/-0.2
INT = -34.1+/-42.8
RMS = 2.7
N(RAOB) = 27
AVG = 0.0+/-0.2
STD = 0.4
SLP = 1.0+/-0.1
INT = -0.5+/-23.7
RMS = 0.4
Tb from LAPS and RAOB [K]
Tb from MWRP [K]


Sim and Obs Tb for Whistler (54.4 GHz; 15 deg; mdl: Lilje04)
N(LAPS) = 405
AVG = 1.7+/-0.2
STD = 1.8
SLP = 0.8+/-0.1
INT = 62.0+/-30.0
RMS = 2.5
N(RAOBclr) = 68
AVG = 0.4+/-0.1
STD = 0.4
SLP = 1.0+/-0.1
INT = 4.9+/-15.4
RMS = 0.5
N(RAOBcld) = 68
AVG = 0.3+/-0.1
STD = 0.4
SLP = 1.0+/-0.1
INT = 7.8+/-15.3
RMS = 0.5
Tb from LAPS and RAOB [K]
Tb from MWRP [K]


Sim and Obs Tb (clear sky) for Whistler (54.4 GHz; 15 deg; mdl: Lilje04)
N(LAPS) = 154
AVG = 3.0+/-0.3
STD = 2.1
SLP = 1.3+/-0.2
INT = -78.8+/-46.3
RMS = 3.6
N(RAOB) = 27
AVG = 0.4+/-0.2
STD = 0.4
SLP = 1.0+/-0.1
INT = -5.5+/-22.9
RMS = 0.6
Tb from LAPS and RAOB [K]
Tb from MWRP [K]


Sim and Obs Tb for Whistler (54.94 GHz; 15 deg; mdl: Lilje04)
N(LAPS) = 405
AVG = 1.9+/-0.2
STD = 2.1
SLP = 0.9+/-0.1
INT = 33.5+/-33.9
RMS = 2.8
N(RAOBclr) = 68
AVG = 0.4+/-0.1
STD = 0.4
SLP = 1.0+/-0.1
INT = 2.0+/-16.7
RMS = 0.6
N(RAOBcld) = 68
AVG = 0.4+/-0.1
STD = 0.4
SLP = 1.0+/-0.1
INT = 3.0+/-16.6
RMS = 0.6
Sim and Obs Tb (clear sky) for Whistler (54.94 GHz; 15 deg; mdl: Lilje04)
N(LAPS) = 154
AVG = 3.4+/-0.4
STD = 2.3
SLP = 1.4+/-0.2
INT = -113.5+/-46.9
RMS = 4.1
N(RAOB) = 27
AVG = 0.5+/-0.2
STD = 0.5
SLP = 1.0+/-0.1
INT = -7.6+/-24.3
RMS = 0.7
Sim and Obs Tb for Whistler (55.5 GHz; 15 deg; mdl: Lilje04)
N(LAPS) = 405
AVG = 2.0+/-0.2
STD = 2.2
SLP = 1.0+/-0.1
INT = 0.7+/-35.5
RMS = 2.9
N(RAOBclr) = 68
AVG = 0.5+/-0.1
STD = 0.5
SLP = 1.0+/-0.1
INT = -3.2+/-17.4
RMS = 0.7
N(RAOBcld) = 68
AVG = 0.5+/-0.1
STD = 0.4
SLP = 1.0+/-0.1
INT = -2.9+/-17.3
RMS = 0.7
Sim and Obs Tb (clear sky) for Whistler (55.5 GHz; 15 deg; mdl: Lilje04)
N(LAPS) = 154
AVG = 3.6+/-0.4
STD = 2.4
SLP = 1.5+/-0.2
INT = -140.2+/-45.2
RMS = 4.3
N(RAOB) = 27
AVG = 0.5+/-0.2
STD = 0.5
SLP = 1.0+/-0.1
INT = -10.1+/-24.7
RMS = 0.7
Sim and Obs Tb for Whistler (56.02 GHz; 15 deg; mdl: Lilje04)
N(LAPS) = 405
AVG = 1.9+/-0.2
STD = 2.2
SLP = 1.1+/-0.1
INT = -18.8+/-35.2
RMS = 2.9
N(RAOBclr) = 68
AVG = 0.5+/-0.1
STD = 0.5
SLP = 1.0+/-0.1
INT = -4.2+/-18.1
RMS = 0.7
N(RAOBcld) = 68
AVG = 0.5+/-0.1
STD = 0.5
SLP = 1.0+/-0.1
INT = -4.1+/-18.1
RMS = 0.7
Sim and Obs Tb (clear sky) for Whistler (56.02 GHz; 15 deg; mdl: Lilje04)
N(LAPS) = 154
AVG = 3.5+/-0.4
STD = 2.5
SLP = 1.5+/-0.2
INT = -150.1+/-42.7
RMS = 4.3
N(RAOB) = 27
AVG = 0.5+/-0.2
STD = 0.6
SLP = 1.0+/-0.1
INT = -11.8+/-26.0
RMS = 0.8
Tb from LAPS and RAOB [K]
Tb from MWRP [K]

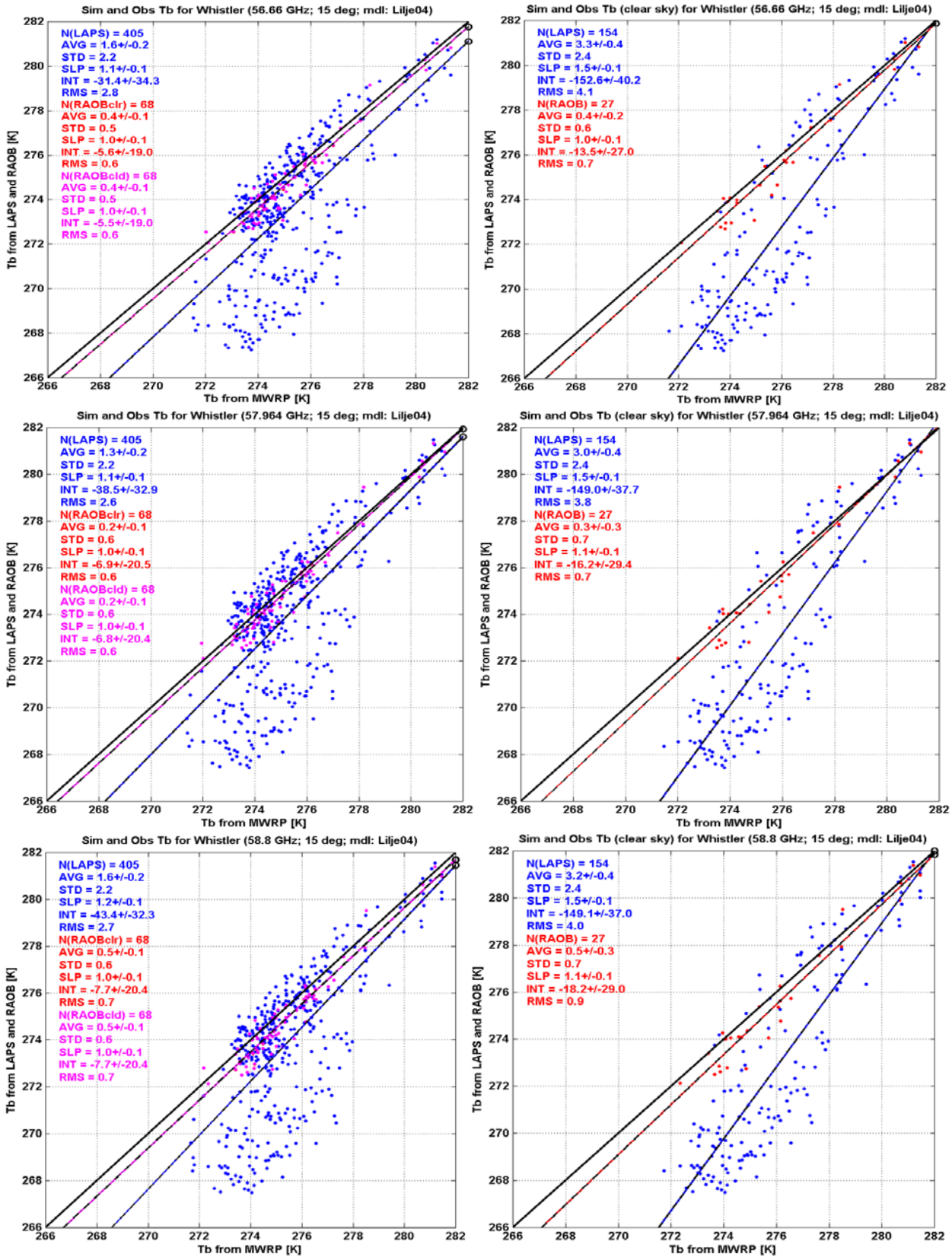

Sim and Obs Tb for Whistler (56.66 GHz; 15 deg; mdl: Lilje04)
N(LAPS) = 405
AVG = 1.6+/-0.2
STD = 2.2
SLP = 1.1+/-0.1
INT = -31.4+/-34.3
RMS = 2.8
N(RAOBclr) = 68
AVG = 0.4+/-0.1
STD = 0.5
SLP = 1.0+/-0.1
INT = -5.6+/-19.0
RMS = 0.6
N(RAOBcld) = 68
AVG = 0.4+/-0.1
STD = 0.5
SLP = 1.0+/-0.1
INT = -5.5+/-19.0
RMS = 0.6
Sim and Obs Tb (clear sky) for Whistler (56.66 GHz; 15 deg; mdl: Lilje04)
N(LAPS) = 154
AVG = 3.3+/-0.4
STD = 2.4
SLP = 1.5+/-0.1
INT = -152.6+/-40.2
RMS = 4.1
N(RAOB) = 27
AVG = 0.4+/-0.2
STD = 0.6
SLP = 1.0+/-0.1
INT = -13.5+/-27.0
RMS = 0.7
Sim and Obs Tb for Whistler (57.964 GHz; 15 deg; mdl: Lilje04)
N(LAPS) = 405
AVG = 1.3+/-0.2
STD = 2.2
SLP = 1.1+/-0.1
INT = -38.5+/-32.9
RMS = 2.6
N(RAOBclr) = 68
AVG = 0.2+/-0.1
STD = 0.6
SLP = 1.0+/-0.1
INT = -6.9+/-20.5
RMS = 0.6
N(RAOBcld) = 68
AVG = 0.2+/-0.1
STD = 0.6
SLP = 1.0+/-0.1
INT = -6.8+/-20.4
RMS = 0.6
Sim and Obs Tb (clear sky) for Whistler (57.964 GHz; 15 deg; mdl: Lilje04)
N(LAPS) = 154
AVG = 3.0+/-0.4
STD = 2.4
SLP = 1.5+/-0.1
INT = -149.0+/-37.7
RMS = 3.8
N(RAOB) = 27
AVG = 0.3+/-0.3
STD = 0.7
SLP = 1.1+/-0.1
INT = -16.2+/-29.4
RMS = 0.7
Sim and Obs Tb for Whistler (58.8 GHz; 15 deg; mdl: Lilje04)
N(LAPS) = 405
AVG = 1.6+/-0.2
STD = 2.2
SLP = 1.2+/-0.1
INT = -43.4+/-32.3
RMS = 2.7
N(RAOBclr) = 68
AVG = 0.5+/-0.1
STD = 0.6
SLP = 1.0+/-0.1
INT = -7.7+/-20.4
RMS = 0.7
N(RAOBcld) = 68
AVG = 0.5+/-0.1
STD = 0.6
SLP = 1.0+/-0.1
INT = -7.7+/-20.4
RMS = 0.7
Sim and Obs Tb (clear sky) for Whistler (58.8 GHz; 15 deg; mdl: Lilje04)
N(LAPS) = 154
AVG = 3.2+/-0.4
STD = 2.4
SLP = 1.5+/-0.1
INT = -149.1+/-37.0
RMS = 4.0
N(RAOB) = 27
AVG = 0.5+/-0.3
STD = 0.7
SLP = 1.1+/-0.1
INT = -18.2+/-29.0
RMS = 0.9
Tb from LAPS and RAOB [K]
Tb from MWRP [K]

Table 1. Clear-sky Tb radiometer observation minus radiosonde simulation (Obs-Sim) statistics. From left to right: channel number, frequency (GHz), number of elements (SMPL), mean Obs-Sim difference (BIAS), standard deviation (STD), root-mean-square (RMS), correlation coefficient (COR), slope (SLP) and intercept (INT) of linear fit, and standard error (SDE).

chan#	freq	SMPL	BIAS	STD	RMS	COR	SLP	INT	SDE
2	22.234	27	1.55	1.83	2.42	0.97	0.99	-1.04	1.87
3	22.500	27	1.86	1.84	2.65	0.97	1.00	-1.65	1.88
5	23.034	27	2.18	1.71	2.81	0.97	1.00	-1.94	1.75
7	23.834	27	2.90	1.35	3.25	0.98	0.99	-2.29	1.38
10	25.000	27	1.97	0.95	2.22	0.98	0.96	-0.40	0.95
13	26.234	27	2.59	0.78	2.75	0.97	0.93	0.06	0.76
17	28.000	27	2.97	0.68	3.10	0.97	0.90	0.85	0.63
21	30.000	27	3.00	0.58	3.11	0.96	0.90	0.72	0.55
22	51.248	27	0.93	0.34	1.00	0.88	0.83	36.41	0.32
23	51.760	27	1.37	0.25	1.42	0.95	1.04	-6.98	0.25
24	52.280	27	1.90	0.22	1.94	0.98	1.03	-4.54	0.23
25	52.804	27	1.14	0.28	1.20	0.98	1.03	-5.74	0.29
26	53.336	27	0.17	0.35	0.39	0.98	0.99	2.35	0.35
27	53.848	27	0.00	0.40	0.40	0.98	1.00	-0.48	0.40
28	54.400	27	0.41	0.42	0.59	0.98	1.02	-5.54	0.42
29	54.940	27	0.46	0.47	0.67	0.98	1.03	-7.57	0.48
30	55.500	27	0.53	0.51	0.74	0.98	1.03	-10.15	0.52
31	56.020	27	0.53	0.56	0.78	0.98	1.04	-11.81	0.56
32	56.660	27	0.40	0.61	0.73	0.98	1.05	-13.49	0.61
33	57.288	27	0.50	0.64	0.82	0.97	1.06	-16.44	0.63
34	57.964	27	0.28	0.68	0.74	0.97	1.06	-16.22	0.68
35	58.800	27	0.52	0.68	0.86	0.97	1.06	-18.22	0.67

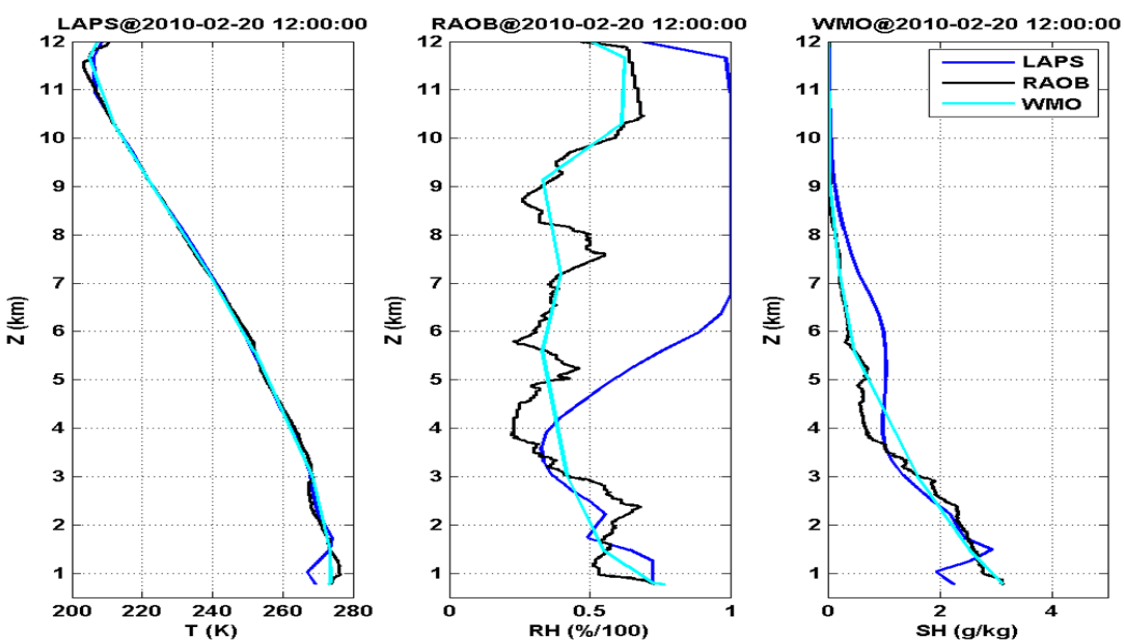


Figure 47. Clear sky temperature (T), relative humidity (RH) and specific humidity (Q) profiles from LAPS (blue) and high (black) and low (cyan) resolution radiosondes.

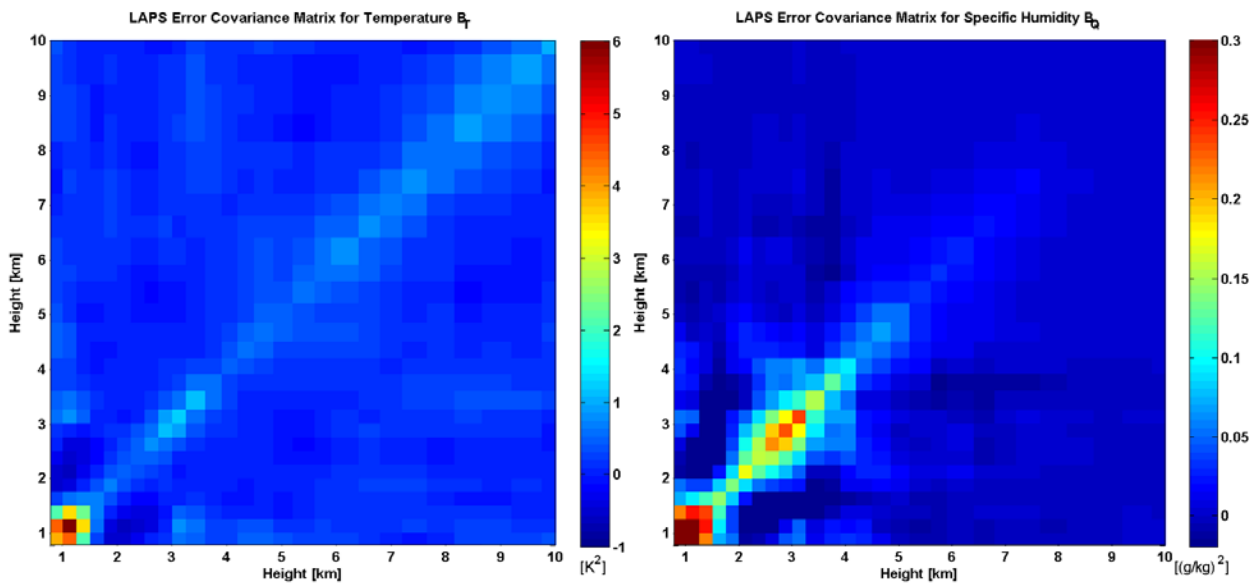


Figure 48. Temperature B_T and specific humidity B_Q background error covariance matrices computed from 68 LAPS-RAOB comparisons near the MP-3031A site at Whistler.

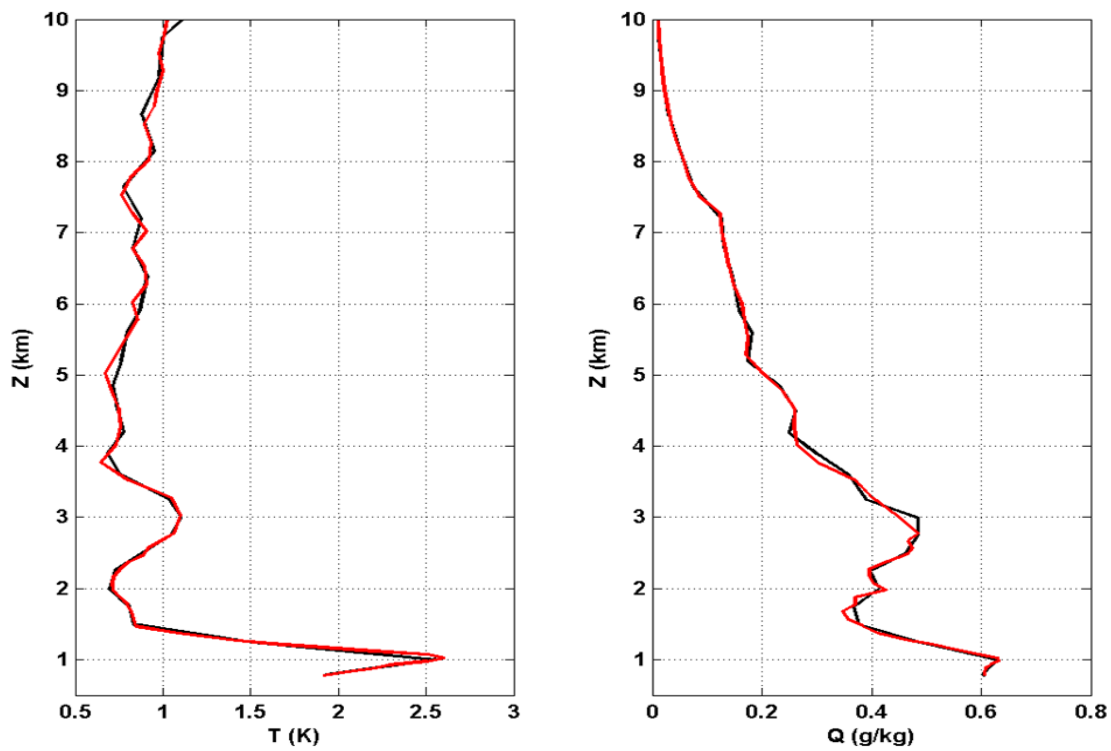


Figure 49. Diagonal terms (square root) of B_T (left) and B_Q (right) at LAPS analysis (black) and radiometer (level 2) retrieval (red) height levels.