

Mehrkanal-Mikrowellenradiometer für die Meteorologische Fernerkundung



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Gliederung

1. Diese Einleitung
2. Mikrowellenfernerkundung in der Meteorologie:
Wie und warum?
3. Entwurf und Konstruktion des Radiometers
4. Technische Details
5. Retrieval Techniken
6. Erprobung
7. Diskussion

Mikrowellenfernerkundung in der Meteorologie (I)

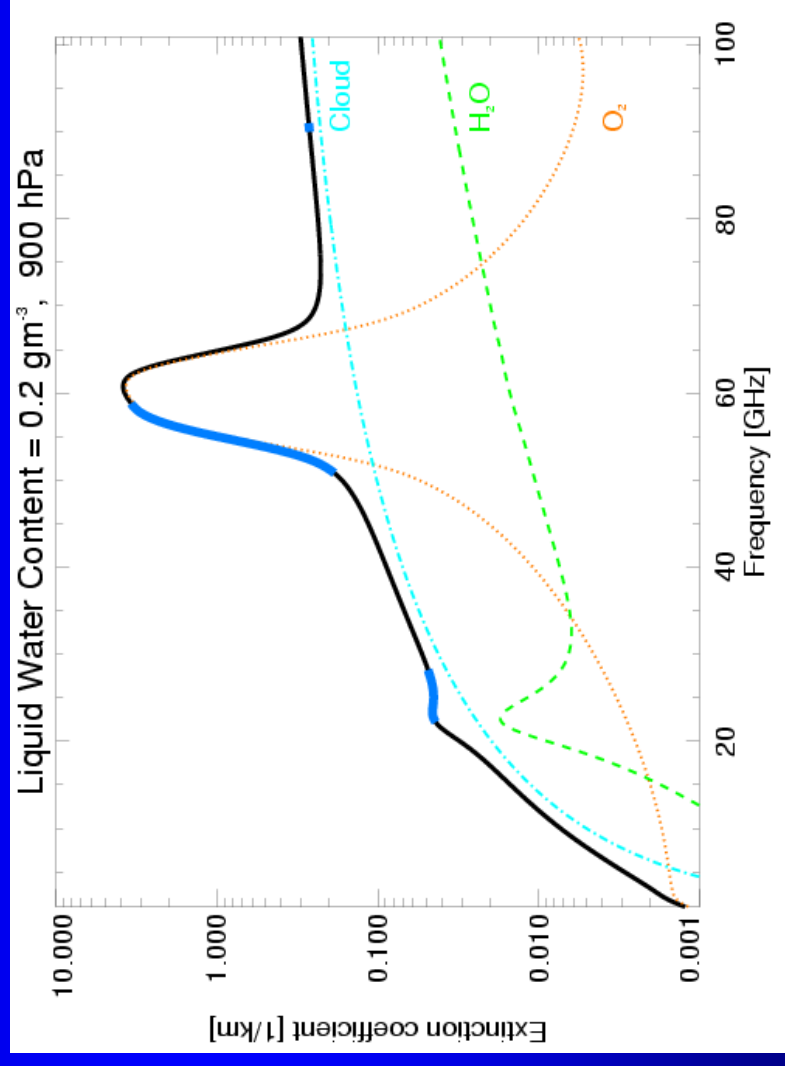
- **Passive** Mikrowellenmessungen (hier: bodengebunden) (thermische Strahlung, keine aktiven Systeme wie Radar...)
- Emission, Absorption, Streuung durch die Atmosphäre: **Gase** (H₂O, O₂, N₂) und **Hydrometeore** (Wolken, Niederschlag)

- **Radiometrische Messung:**

Strahlungstemperaturen bei mehreren Frequenzen (Boundary-Layer: auch mehrere Elevationswinkel)

- **Meteorologische Variablen:**

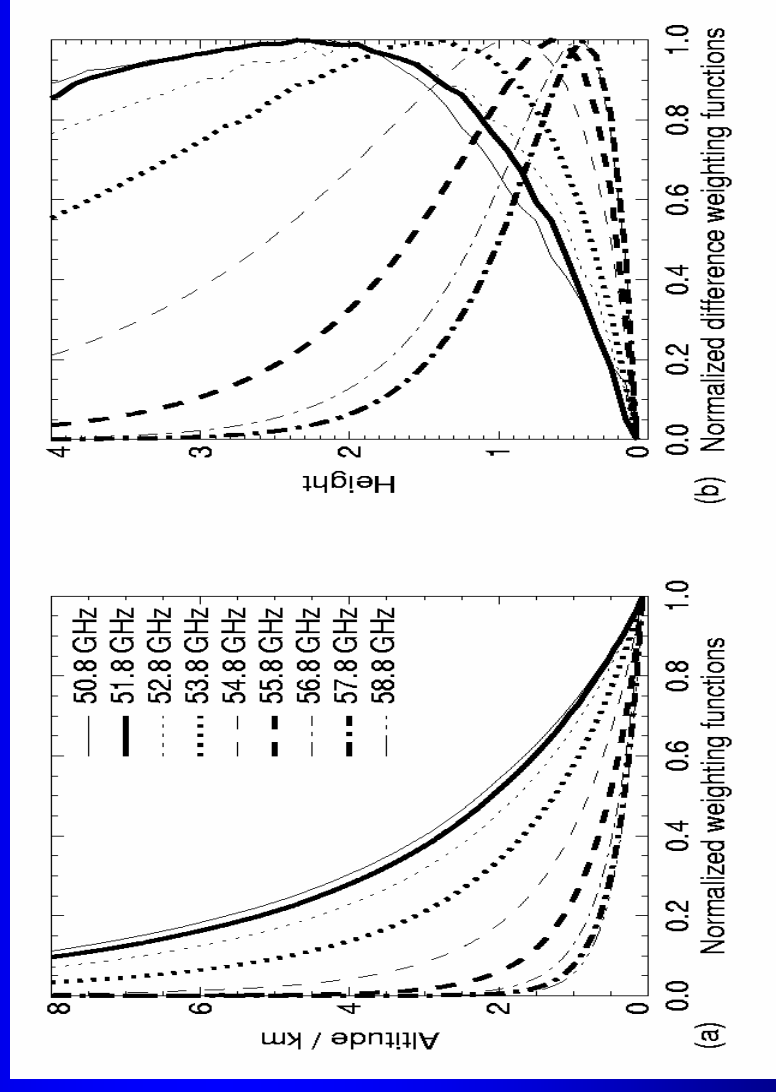
IWV, LWP, Vertikalprofile von Temperatur und Feuchte, Stabilitätsindices (LI, KI, KO, TT)



Mikrowellenfernerkundung in der Meteorologie (II)

- **Vorwärtsmodell:** Berechnung von Strahlungstemperaturen aus einer vorgegebenen Atmosphäre
- **Retrieval:** Invertierung der Vorwärtsrechnung, Berechnung Atmosphärischer Größen aus Strahlungstemperaturen

- **Vertikale Information:** verschiedene Höhen durch variable Frequenzen oder variable Elevation
- **Probleme:**
 - Invertierung mehrdeutig
 - Begrenzter Informationsgehalt (14 Kanäle)



Radiometer Konzept für Meßnetze

- Wartungsarm (**Low Maintenance**)
- Geringer Preis (**Low Cost**)
- Gleichzeitige Messung aller Kanäle (Konsistenz!)
-> **Schnell** (1s) , 100% duty cycle, **variable Bandbreite**
- Vermeidung von Störsignalen („**direct detection**“, **kein LO!**)
- Automatisierte **Steuerungssoftware** und Datenerfassung
- **Online-Retrieval** und direkte Auswertung
- Gute Möglichkeiten zur Einbindung in Datennetze
- Zugriff auf Rohdaten und Level-2 Daten
- Kombination von Geräten möglich: Tandem-Konfiguration, Ansteuerung von IR-Radiometer schon vorgesehen
- Lieferung von optimierten Algorithmen
(sofern der Kunde passende Radiosonden-Archive liefert)

Radiometer-Typen bei RPG

Frequencies:

Humidity Profiling (Trop):
22-31.4 GHz Band (7 chan.)

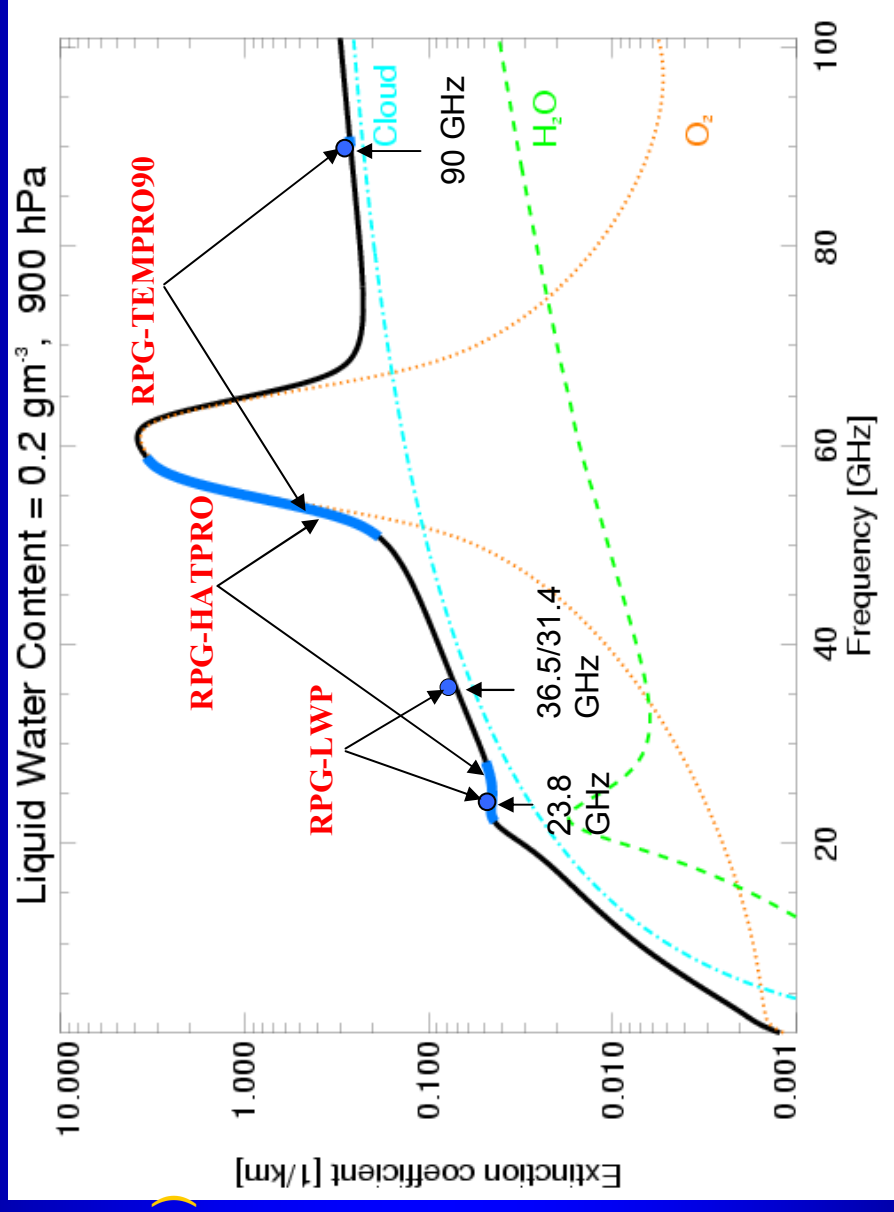
LWP/IWV, Wet/Dry Del.:
23.8/36.5 (31.4) GHz

**Temp. Profiling
(Trop&BL):**

50-59 GHz Band (7 chan.)

LWP-Improvement:
90 GHz Channel

Humidity Profiling (BL):
183 GHz Channel



Oft verwendete Radiometer Frequenzen

Radiometer Konfigurationen / Frequenzbereiche

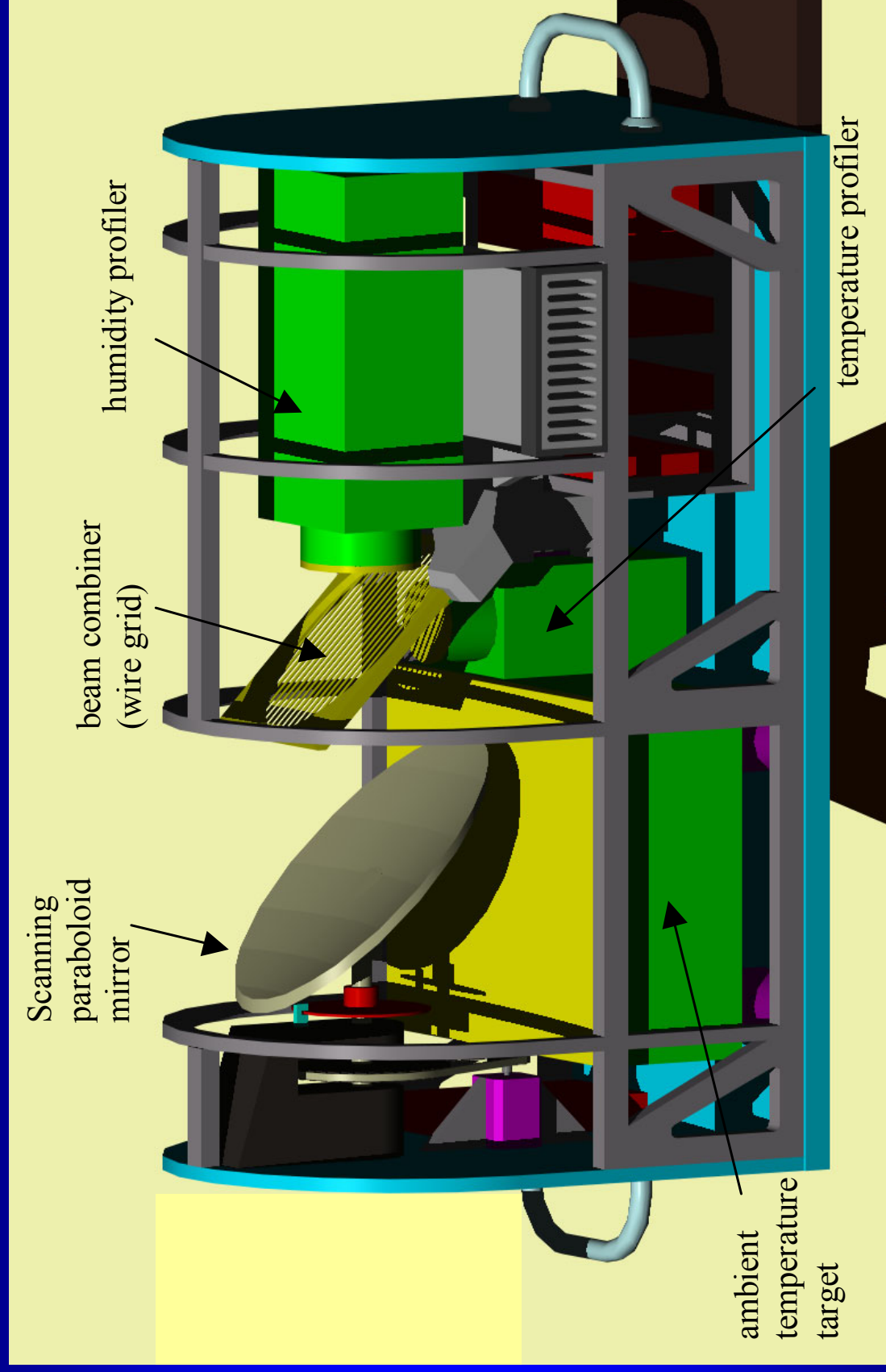
- 22.4 - 31.4 GHz
- 50.0 - 58.0 GHz
- 90.0 GHz
- 150 GHz
- 183.3 GHz
(3 bis 6 Kanäle)



Technische Details

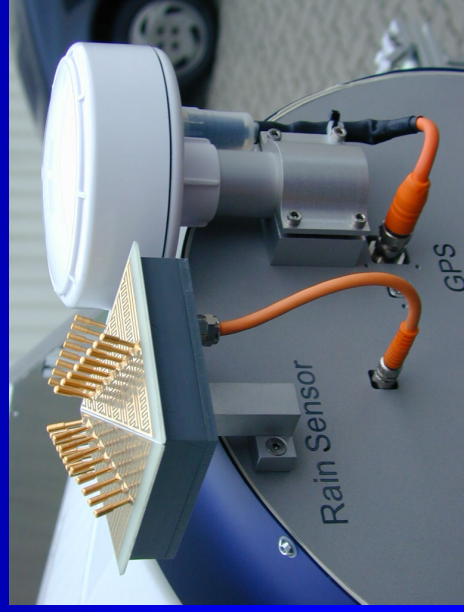


System Layout



General Instrument Concept

Weather Station and Time Reference:



Rain Sensor: Provides rain flag for measurement documentation, control of shutter system

GPS-Clock: Provides time reference standard for synchronization to satellite data

Humidity Sensor: Provides input data for retrievals, Dew Blower heating



Temperature Sensor: Provides input data for retrievals

Pressure Sensor: Provides input data for retrievals, LN-target calibration

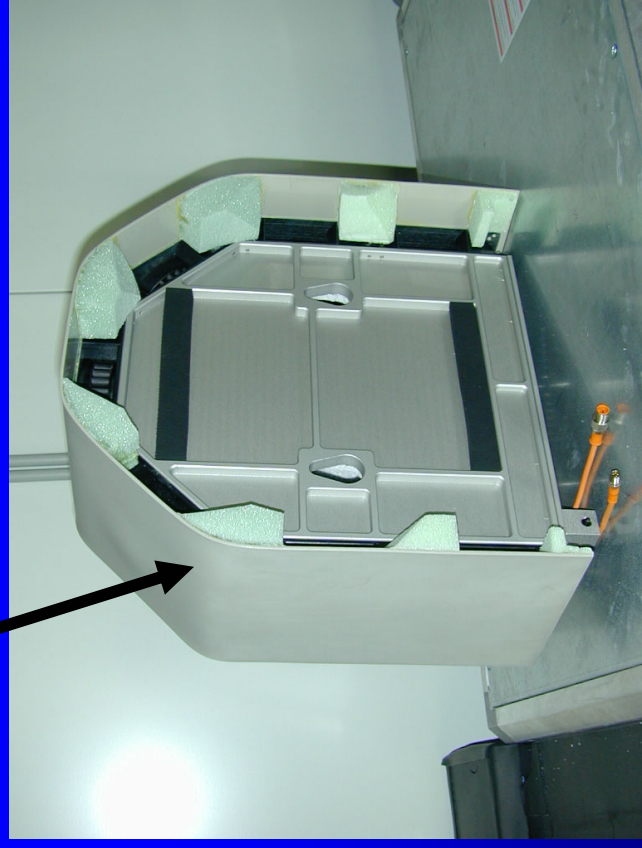
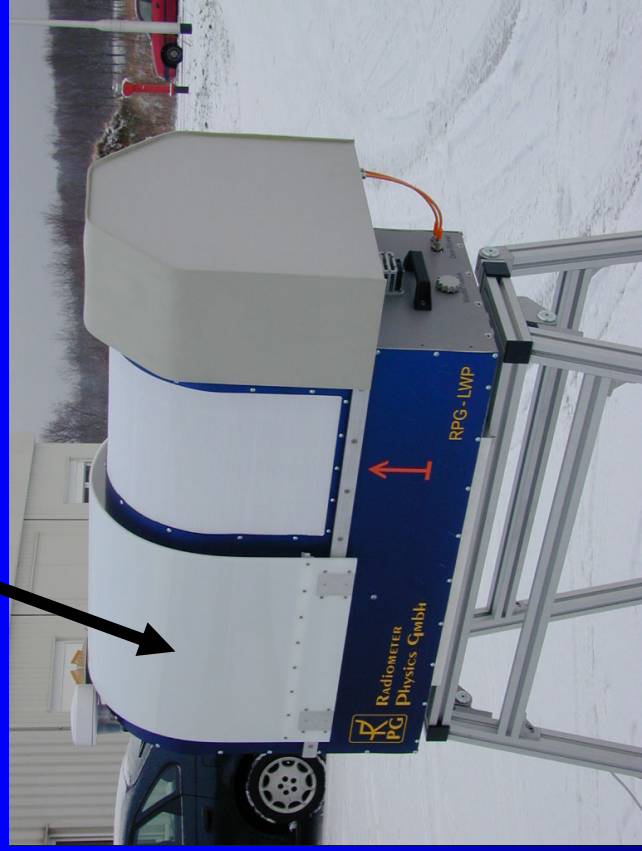
Optional IR-Radiometer: Cloud base height detection

General Instrument Concept

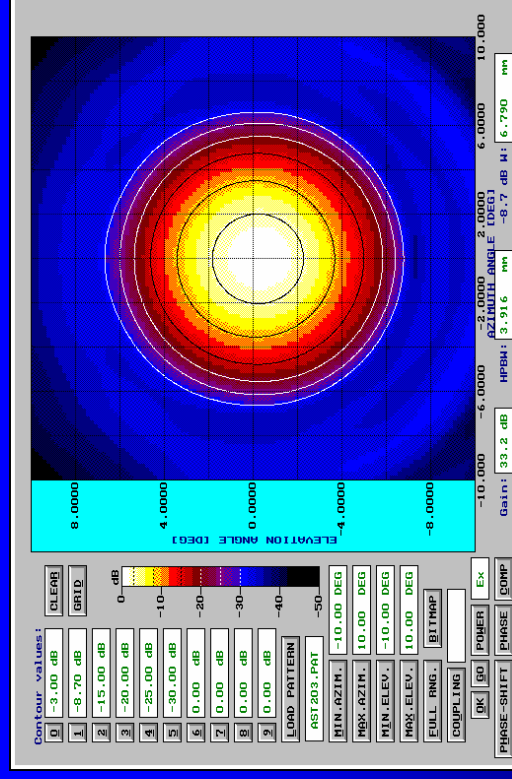
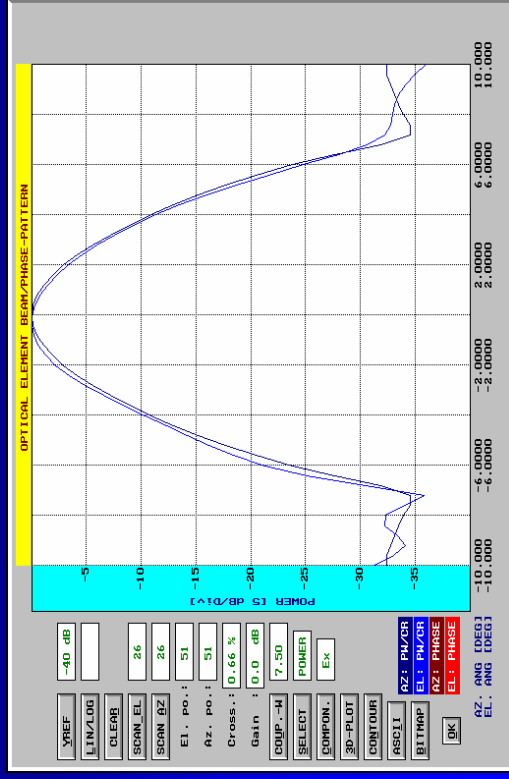
Rain, Hail, Snow and Dew Protection System:

Optional Automatic Shutter System: Dew Blower:

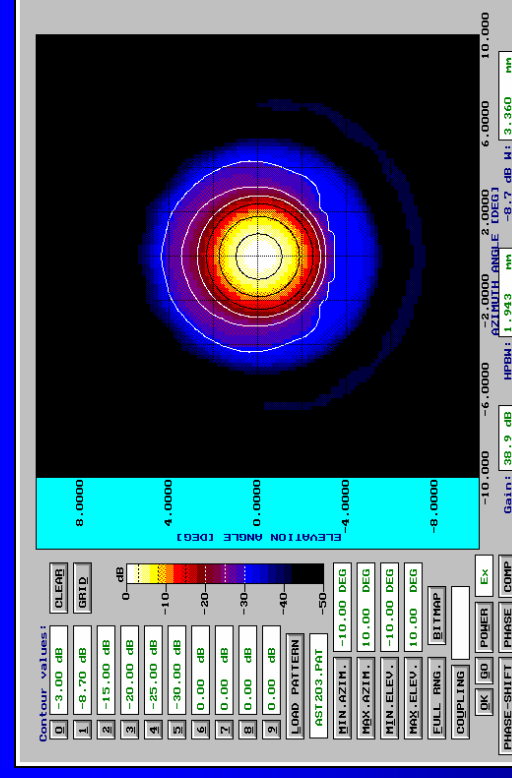
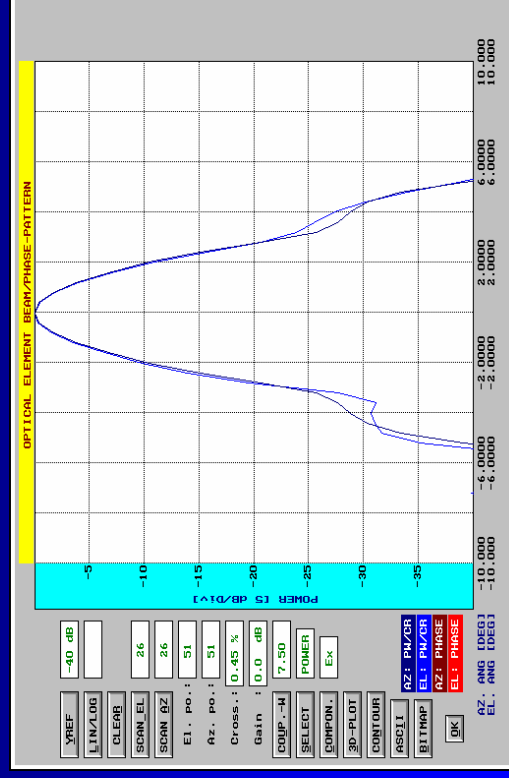
- Controlled by Rain Sensor
- Removable
- Heater controlled by H.-Sensor



Optical Performance



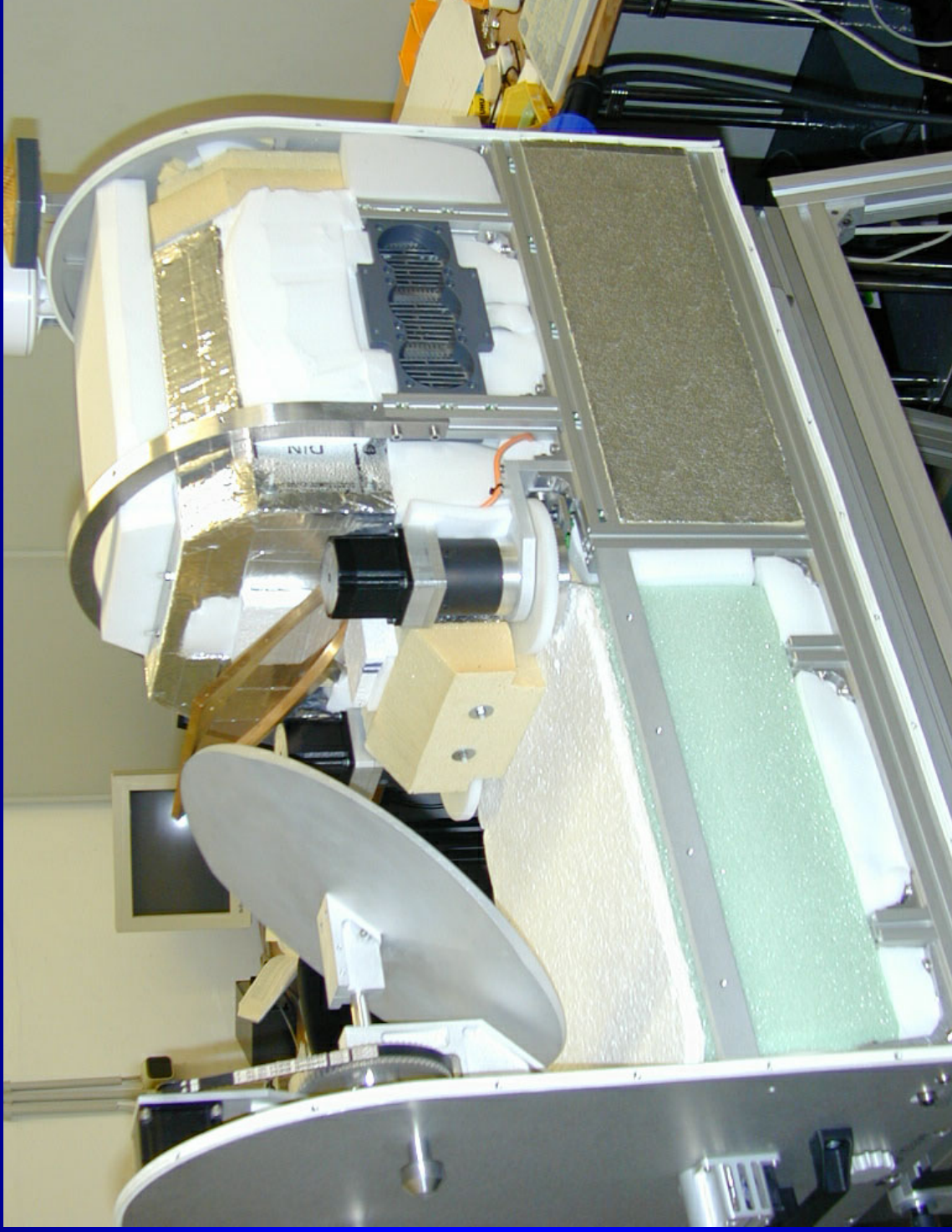
23.8 GHz, HPBW = 3.9°, Sidelobes: <-30 dB



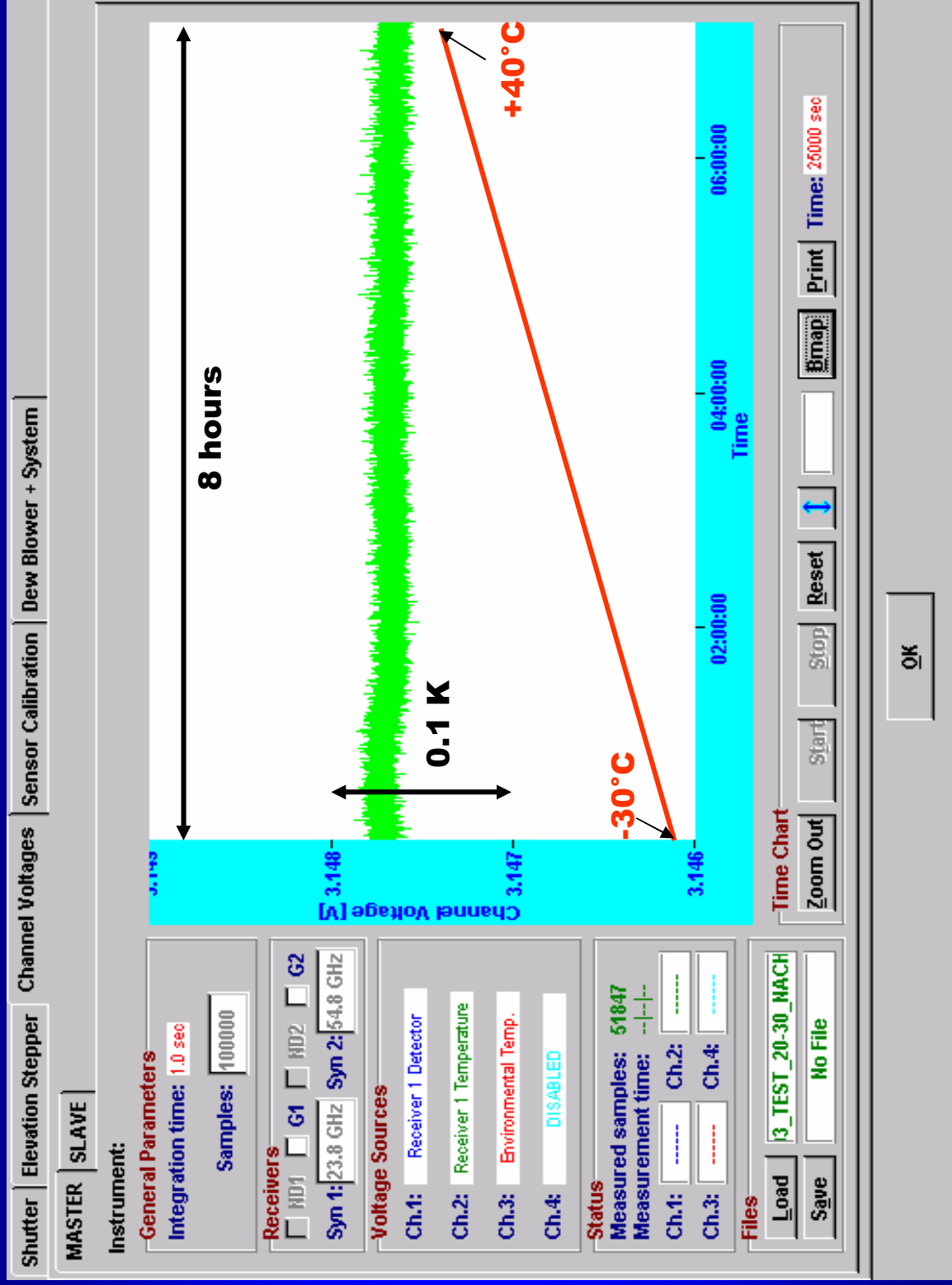
55.0 GHz, HPBW = 1.9°, Sidelobes: <-30 dB



Receiver Thermal Stabilization



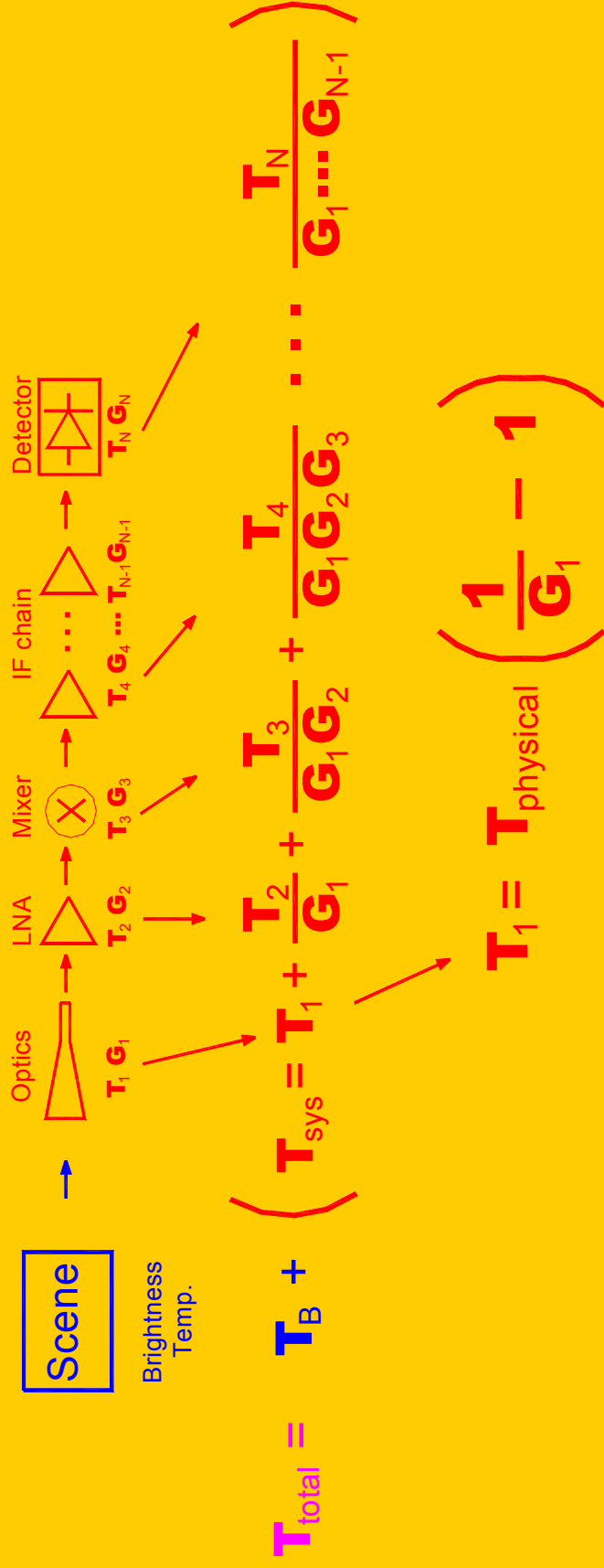
Receiver Thermal Stabilization



Calibration and Error Sources

ALL lossy receiver components should be thermally stabilized!

Receiver Noise Errors

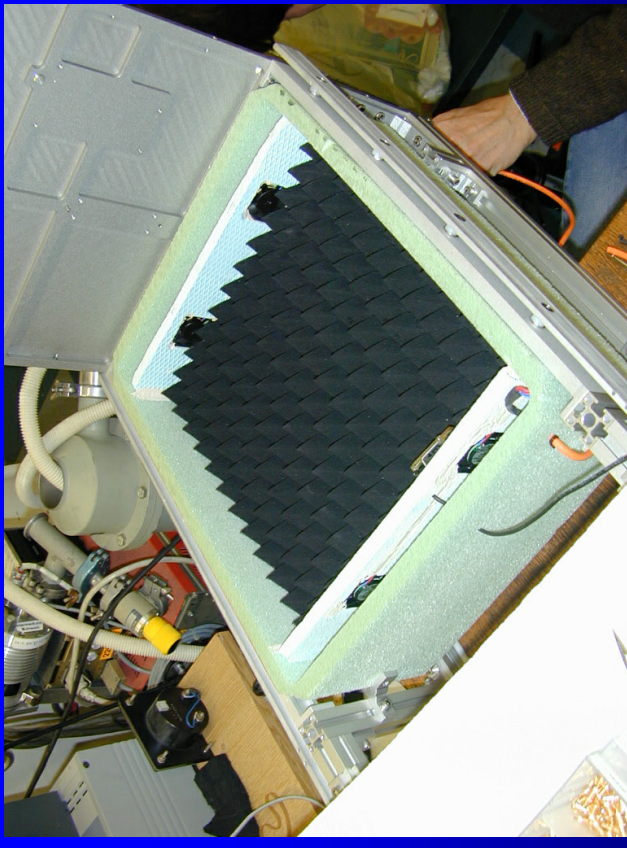
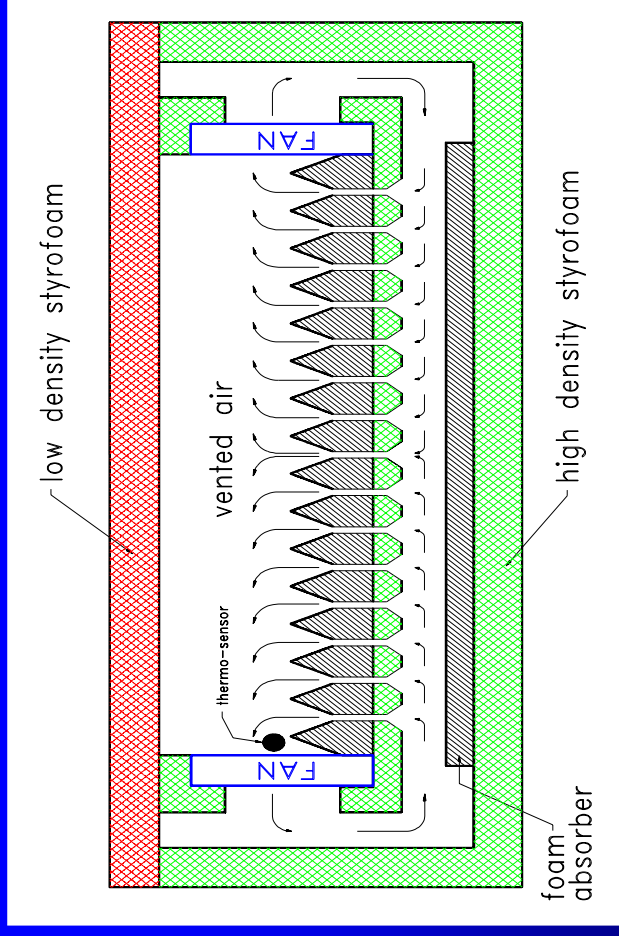


typical optical Losses:
 $G_1 = -1.0 \text{ dB} = 0.8 \text{ (20\%)}$ $\rightarrow \Delta T_{\text{physical}} = 10 \text{ }^\circ\text{C} \Rightarrow \Delta T_1 = 2.5 \text{ }^\circ\text{C} !!$

Calibration and Error Sources

Ambient Temperature Calibration Target

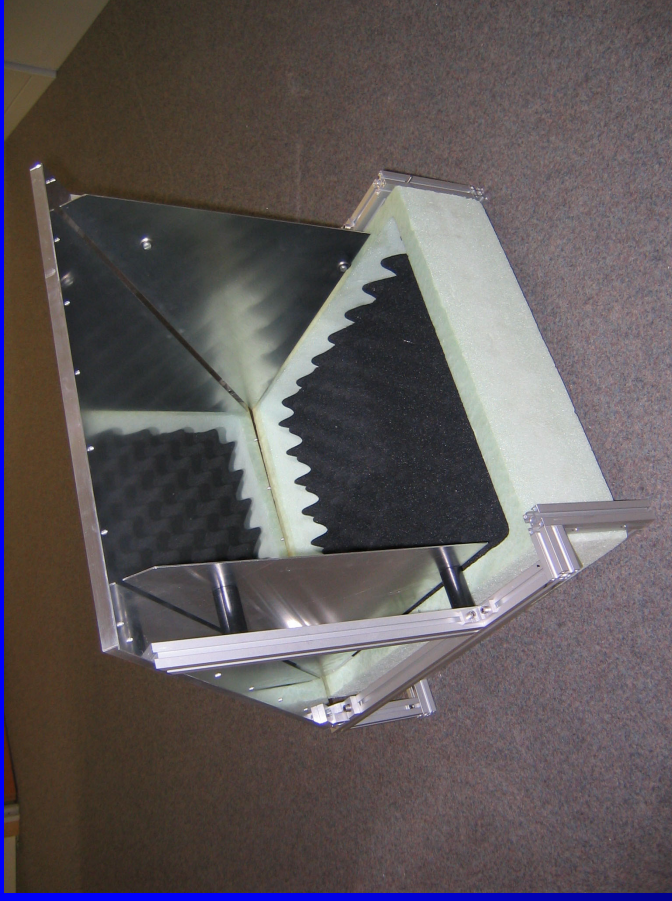
- Cancellation of thermal gradients across the target in vertical and horizontal directions by venting
- Self-heating of temperature sensor avoided by airflow
- Precision calibrated temperature sensor



Calibration and Error Sources

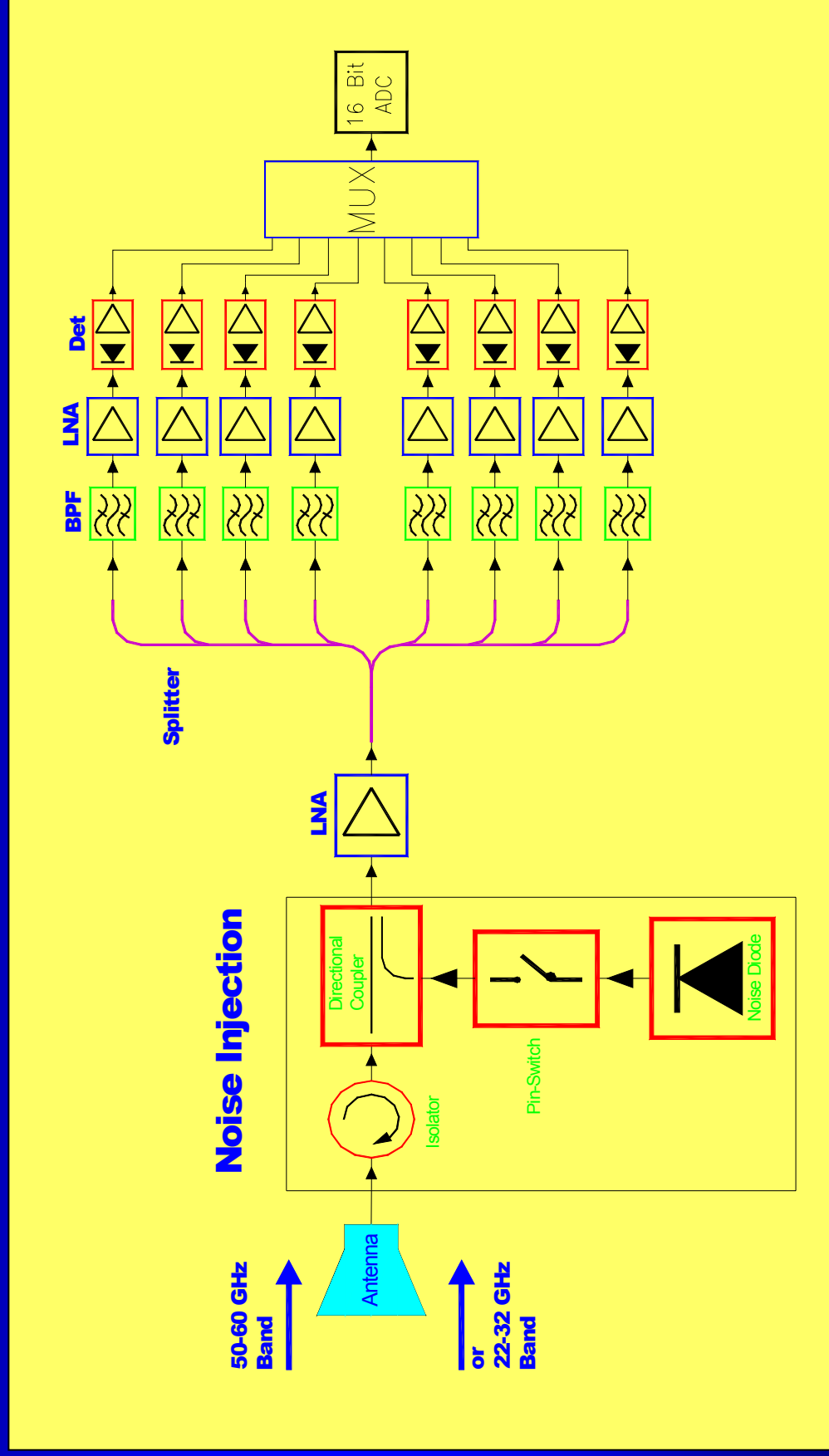
Liquid Nitrogen Cooled Calibration Target

- no humidity formation on styrofoam surfaces
- Calibration of reflector losses and reflection from liquid surface
- Barometric Pressure correction of boiling temperature



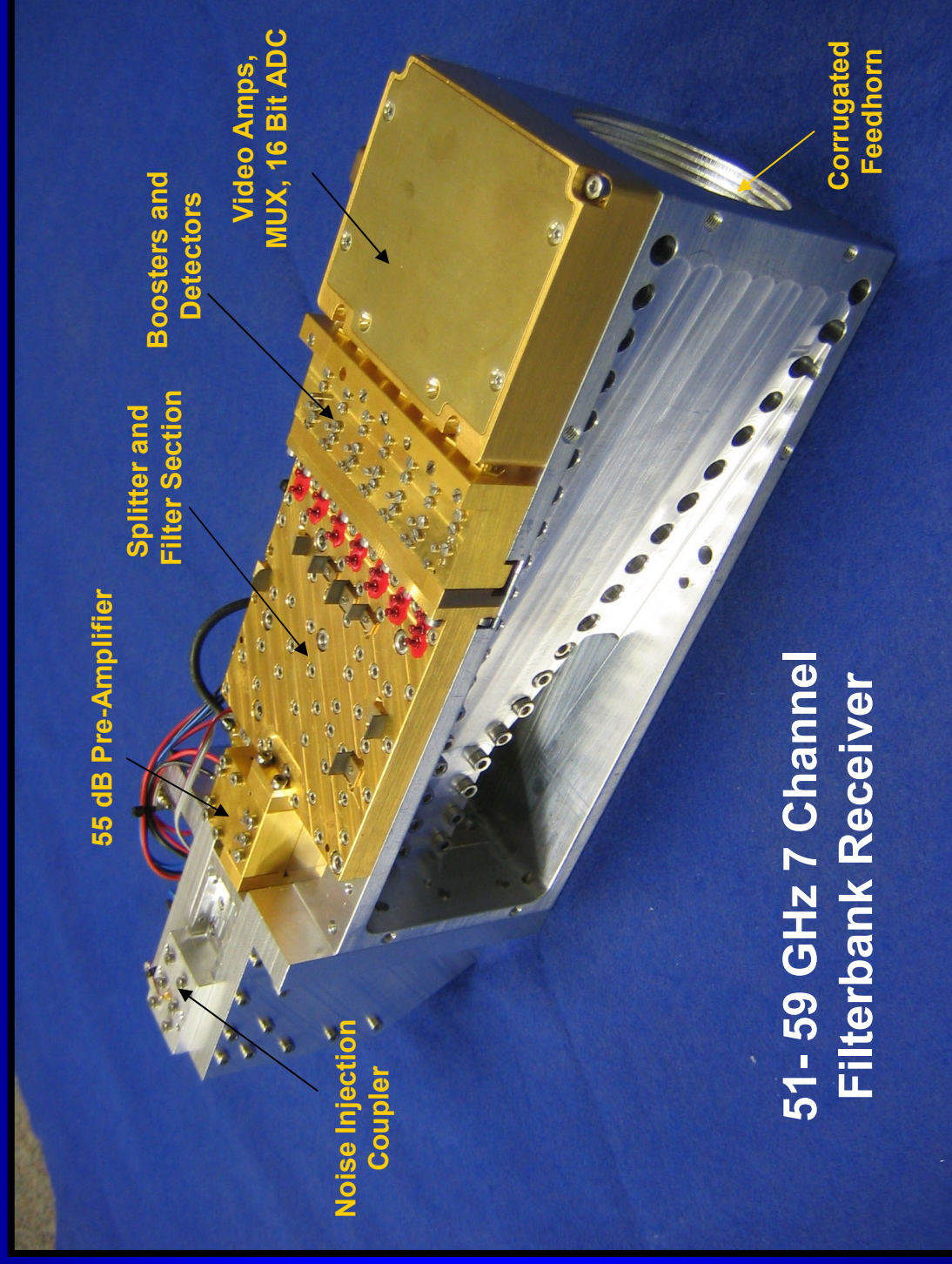
New HATPRO Receiver Design

Dual Profiler Direct Detection Filterbank Receivers based on
MMIC Technology.



New HATPRO Receiver Design

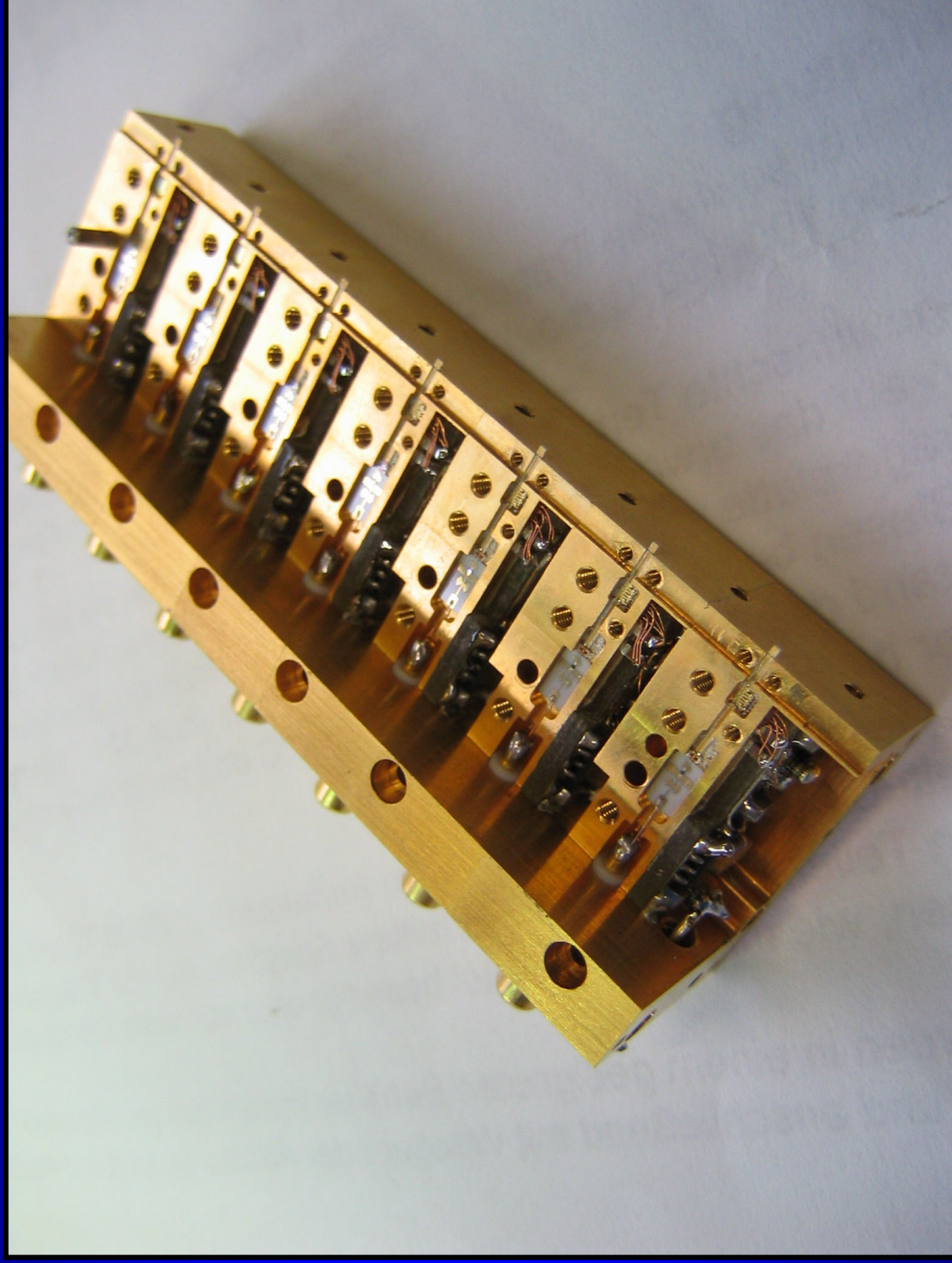
Compact Layout



51- 59 GHz 7 Channel Filterbank Receiver

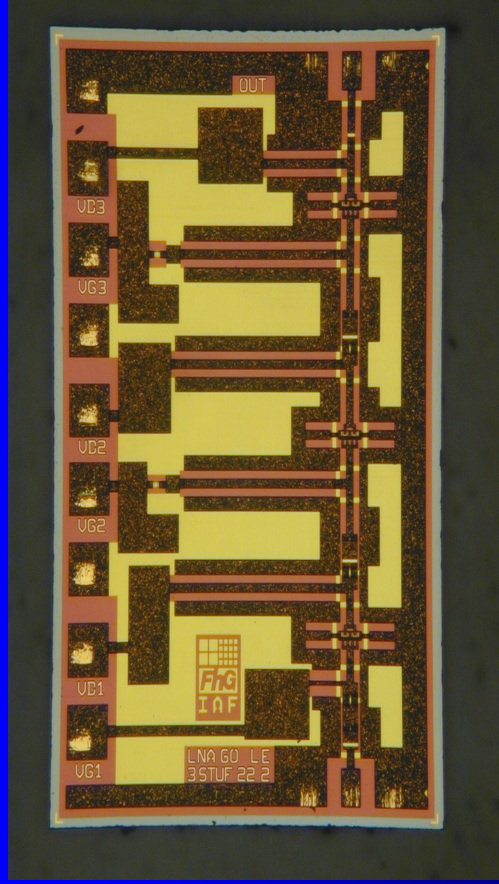
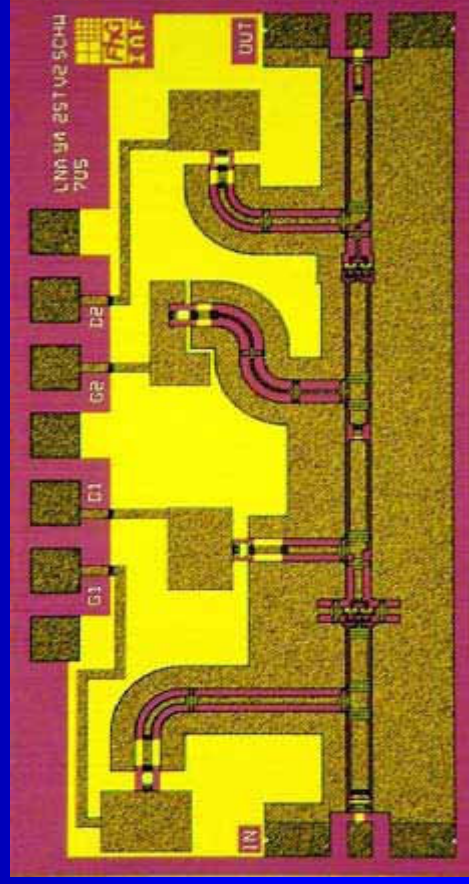
New HATPRO Receiver Design

Compact Layout

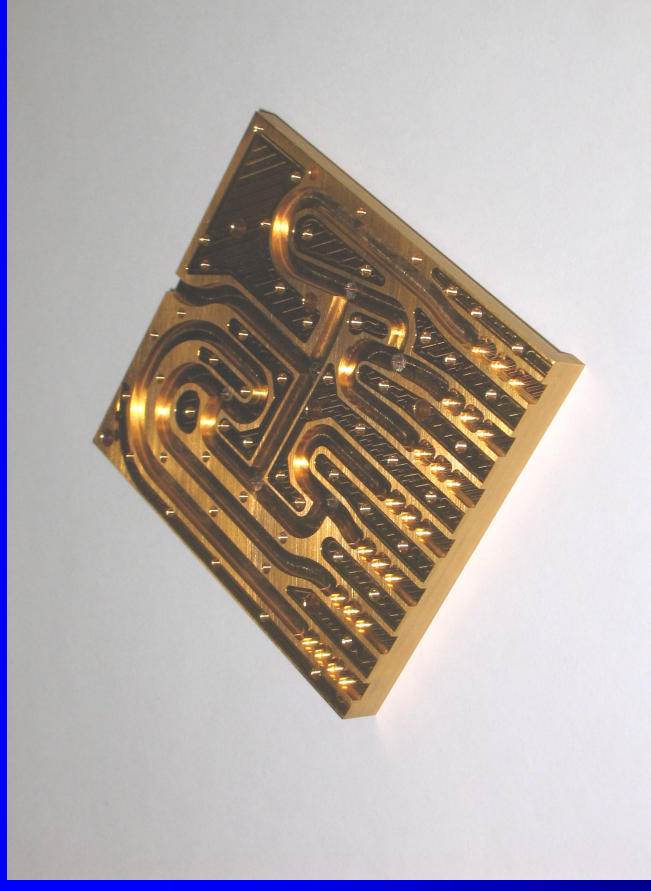


Direct Detection Receiver Components

45-65 GHz LNAs, 2.5 dB NF



Power Splitter + Bandpass-
Filters



HATPRO Receiver Design

Summary of Benefits of Direct Detection Filterbank Design:

- Simultaneous measurements of all frequency channels
- Much higher temporal resolution for all products (LWP/IWV: 1sec, profiles: 20 sec) compared to single detection receivers
- 5 times faster calibration procedures than with sequentially scanning receivers
- Feasibility of individual channel bandwidth selection (important for boundary layer profiling). One broad band 58 GHz channel to give high radiometric accuracy for boundary layer profiling
- No mixer sideband filtering required, no LO drifts
- Reduced sensitivity to interfering external signals (mobile phones etc.) due to avoidance of frequency down conversion

Retrieval Algorithms



Retrieval Algorithmen

- **Rein Statistische** Algorithmen (im Gegensatz zu physikalisch-iterativen, Look-Up Tables oder der Optimal Estimation)
- Strahlungstransportsimulation basierend auf Radiosonden
- **Quadratische Regressionen**
- Nur Zenith Beobachtungen für volle Troposphäre (bis 10km)
- Boundary Layer: 6 Elevationswinkel (bis 5 Grad) für detailliertes Temperaturprofil in den unteren 1000 m
- Mögliche Erweiterungen:
 - EOF Analyse anstelle unabhängiger Schichttemperaturen auf festem Vertikalgitter
 - Physikalische Retrieval
- Probleme: Mehrdeutigkeit der Strahlungsdaten, Inversionen

Simulation

- Qualitätskontrolle der Radiosondendaten
- Wolkenanalyse: Schwellwörterkennung, modifizierter adiabatischer LWC
- Berechnung des IWW, LWP, Stabilitätsindices
- Vereinfachter Strahlungstransport (unpolarisiert, keine Streuung)
- Interpolation auf regelmässiges Vertikalgitter
- Zusatz von Rauschen (je nach Radiometer)
- Test der Algorithmen an unbenutzten Daten

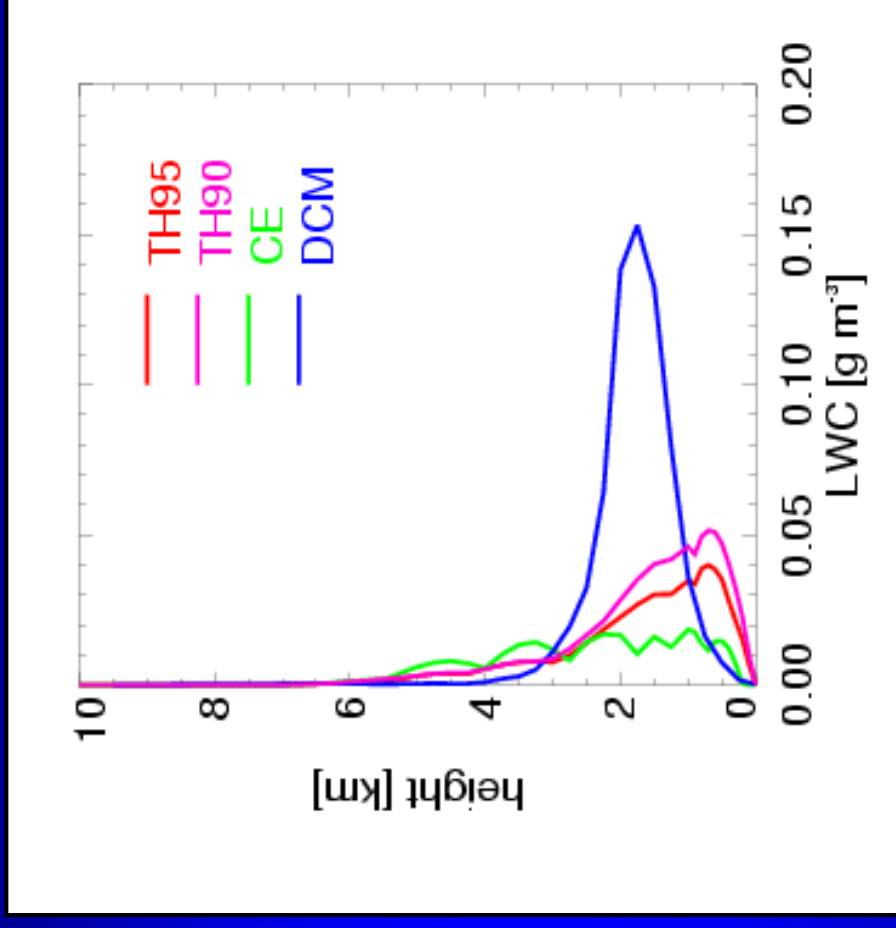
$$\frac{d\bar{\mathbf{I}}(z, \theta)}{\frac{1}{\mu} dz} = -\bar{\sigma}_e(z, \theta) \bar{\mathbf{I}}(z, \theta) + \bar{\sigma}_a(z, \theta) B(T(z))$$

- Alternative Erweiterung für regnende Atmosphären
- Polarisierter Strahlungstransport mit Mehrfachstreuung
 - Asphärische Hydrometeore

Wolkenanalyse

- Verschiedene Verfahren möglich
- Einfluss auf die Retrieval vorhanden
- Beurteilung und Überprüfung der verschiedenen Verfahren schwierig

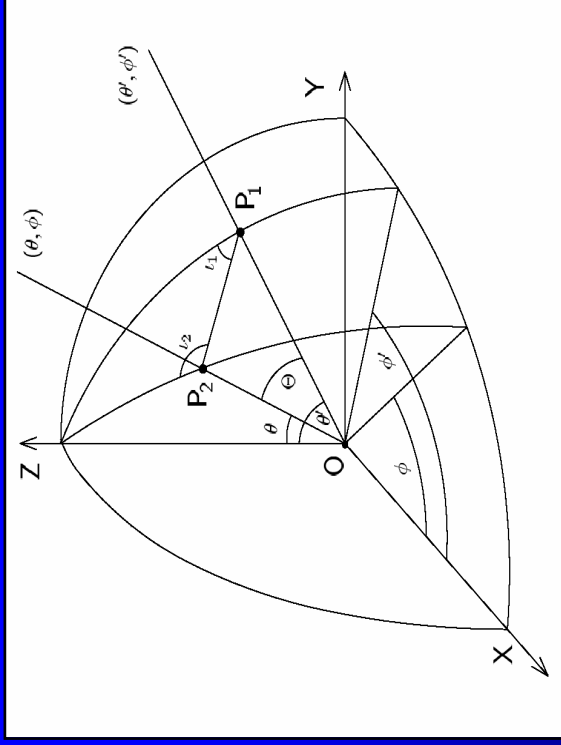
TH95, **TH90** – threshold RH
CE – Gradients in T and RH
DCM – convective cloud model



Mean diagnosed LWC
(liquid water content)

Vector radiative transfer equation VRTE

$$\begin{aligned} \frac{d^3 \bar{\mathbf{I}}(x, y, z, \theta, \phi)}{\frac{1}{\gamma} dx \frac{1}{\delta} dy \frac{1}{\mu} dz} &= - \bar{\sigma}_e(x, y, z, \theta, \phi) \bar{\mathbf{I}}(x, y, z, \theta, \phi) \\ &+ \bar{\sigma}_a(x, y, z, \theta, \phi) B(T(x, y, z)) \\ &+ \int_0^{2\pi} \int_0^{\pi} \bar{\bar{\mathbf{P}}}(x, y, z, \theta, \phi, \theta', \phi') \bar{\mathbf{I}}(x, y, z, \theta', \phi') \sin \theta' d\theta' d\phi' \end{aligned}$$

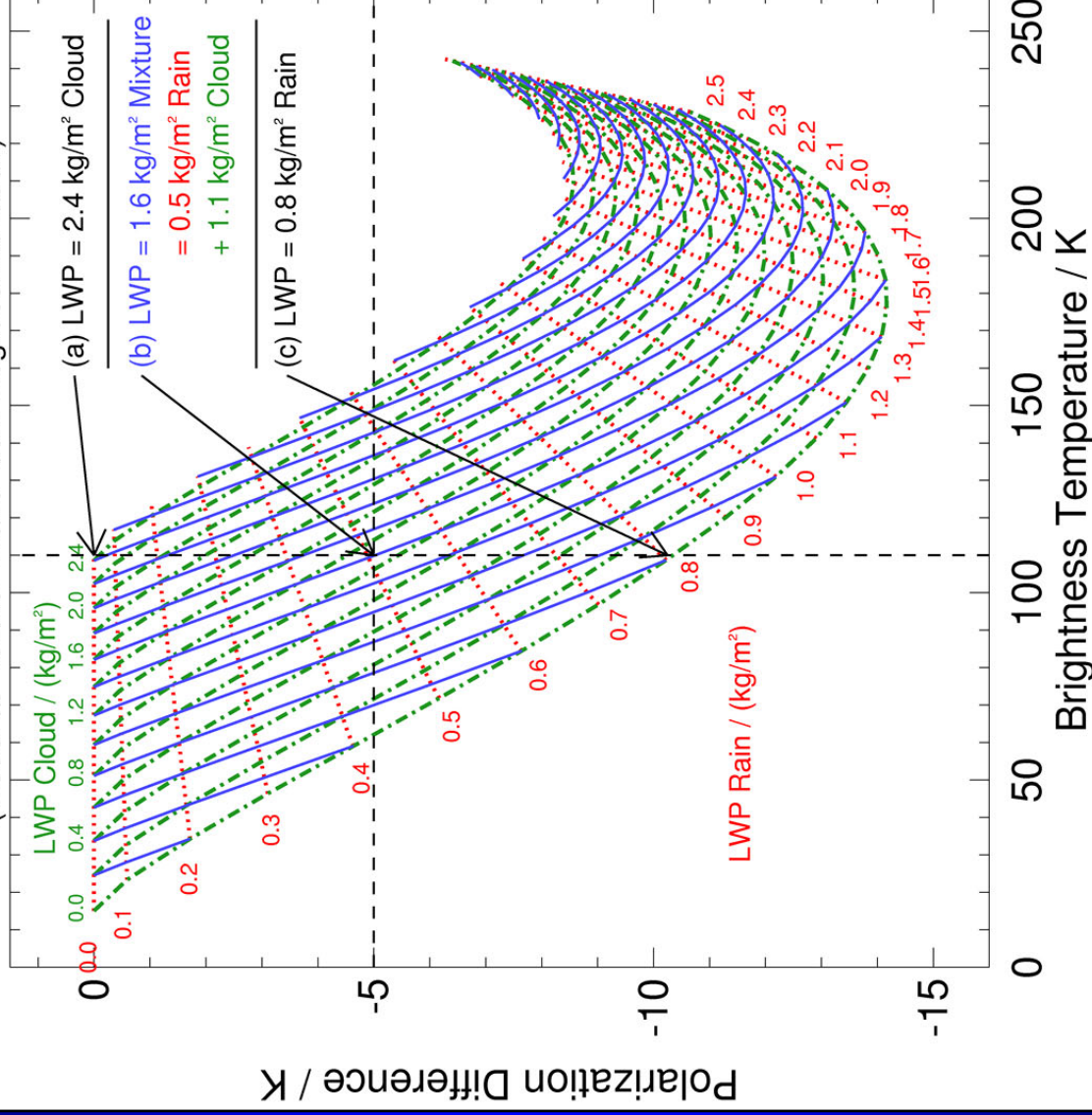


Angles and planes of polarization

Proposed Retrieval Method

Czekala et al, Geophys. Res. Lett. 28 (2), 267–270, 2001.

Combined TB/PD Response of Different LWP Compositions
(Model at 19.0 GHz and 30.7 Degrees Elevation)

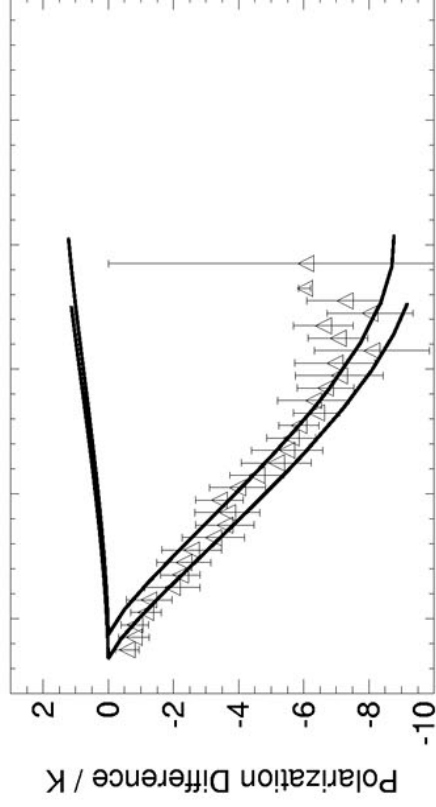


- Along **red** lines: **rain LWP constant**, increasing cloud LWP (left to right)
- Along **green** lines: **cloud LWP constant**, increasing rain LWP (top to bottom)
- Along **blue** lines: **total LWP constant**
- Simultaneous measurement of brightness temperature and polarization difference
- Independent retrieval of cloud and rain fractions possible
- Accuracy of polarization measurement crucial
- Re-calibration with clear sky conditions

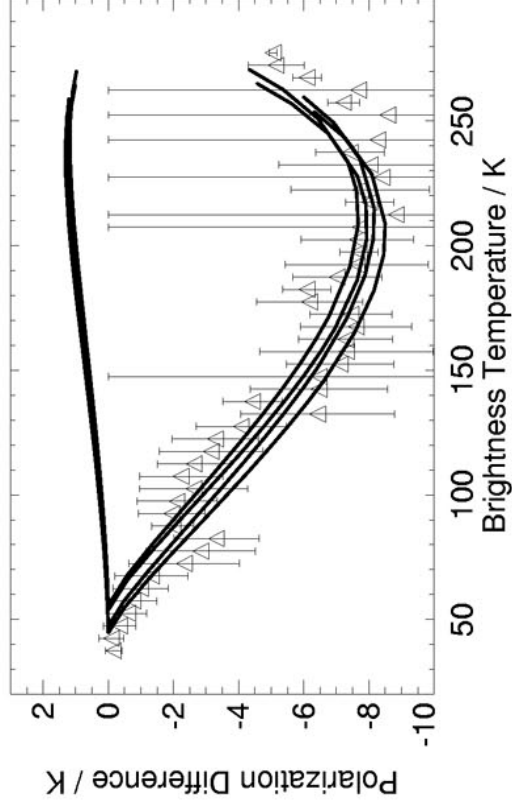
More Measurements

Czekala et al, J. Appl. Meteorology 40 (11), 1918–1932, 2001.

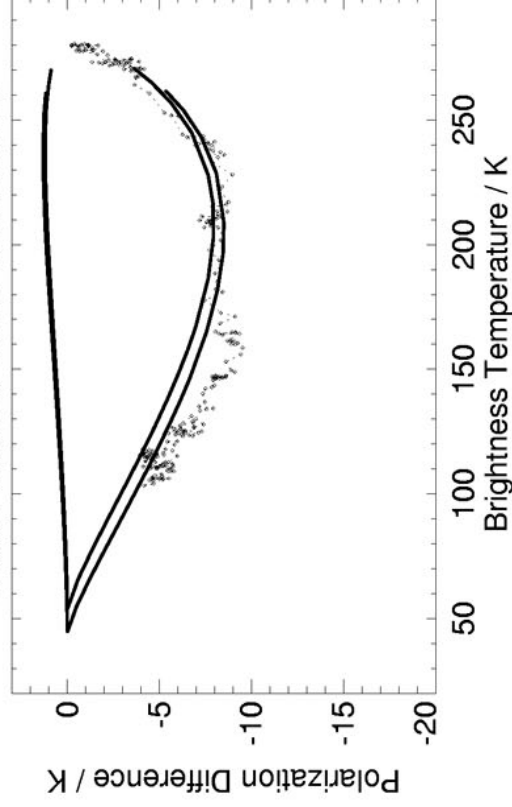
Observations from 08.06.1999



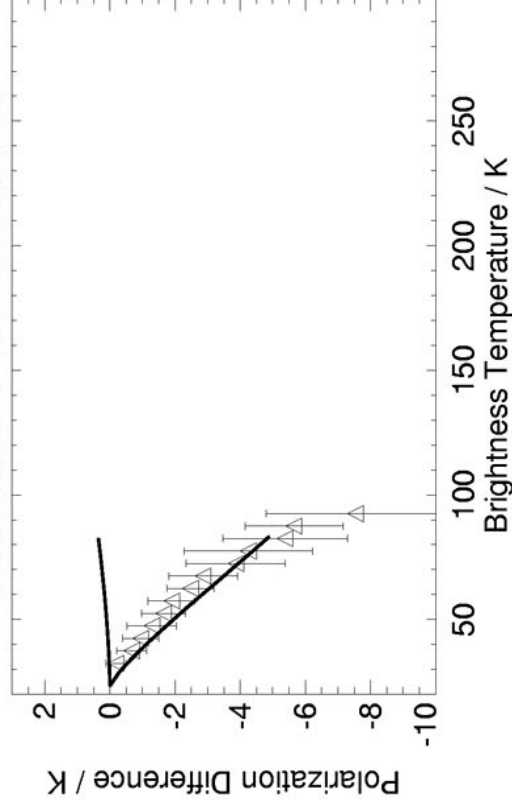
Observations from 24.07.1996



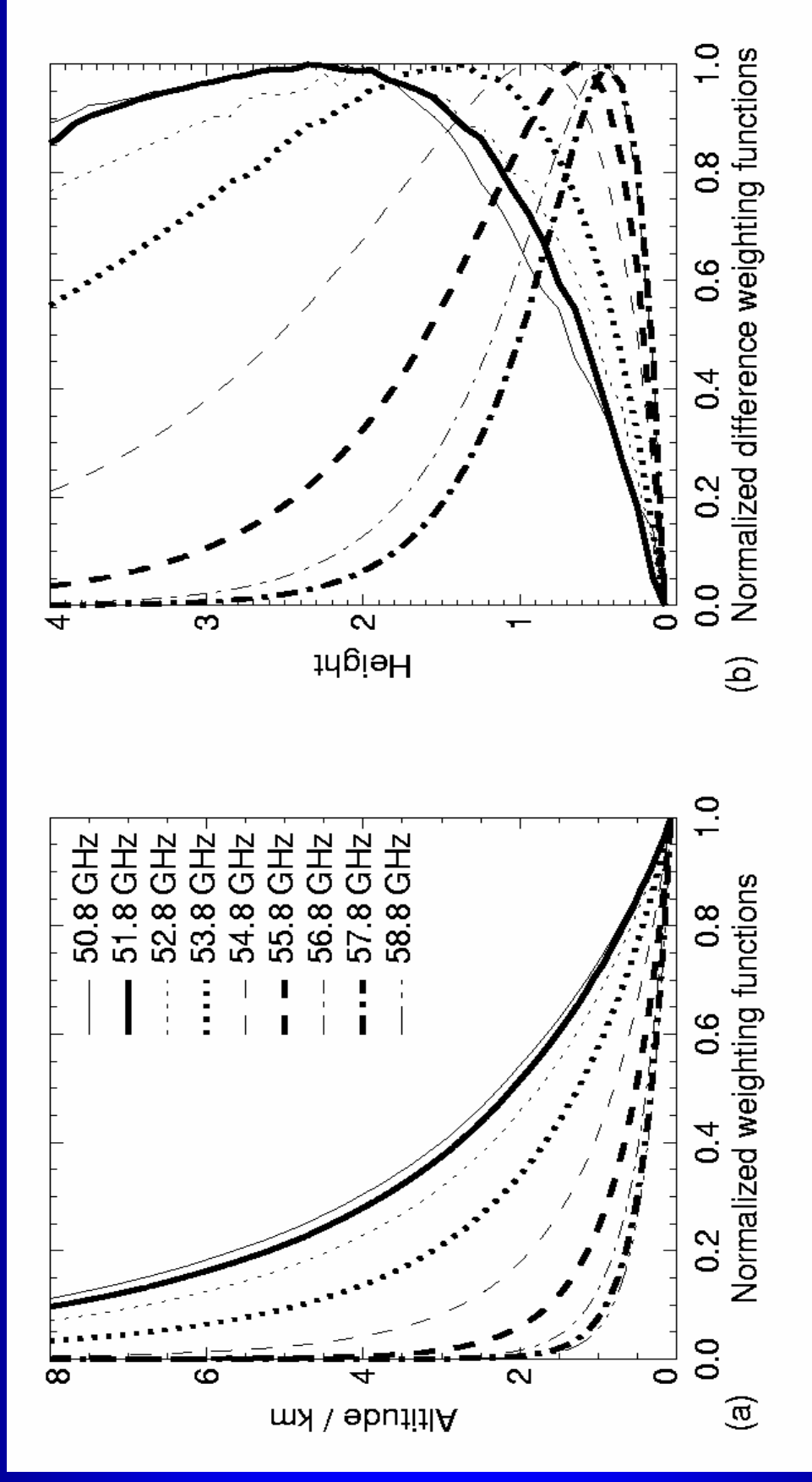
Observations from 19.07.1999



Observations from 02.03.1999



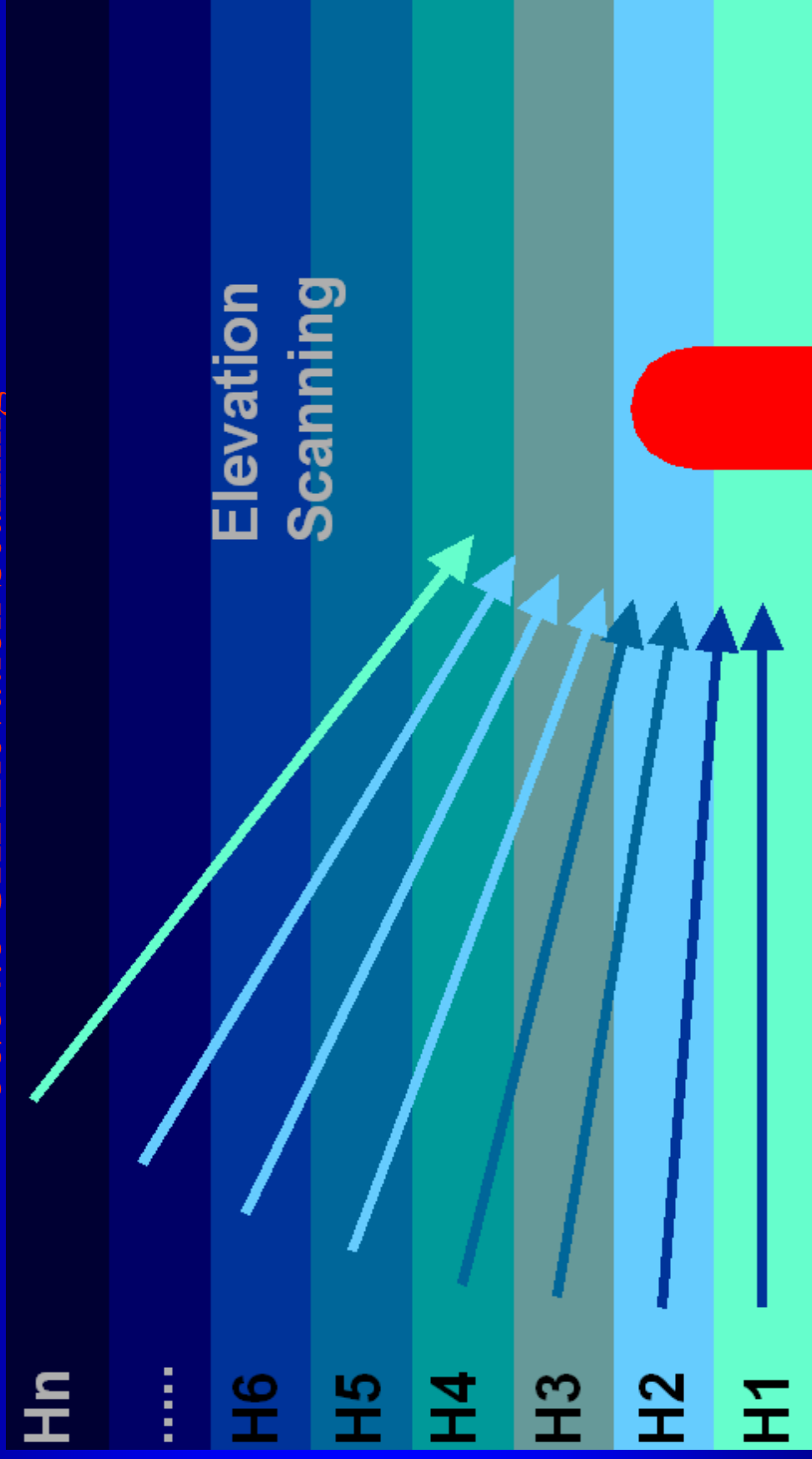
Messprinzip I: Frequenzabhängige Emissionshöhe



54 und 58 GHz sehr gut geeignet für Boundary layer scanning

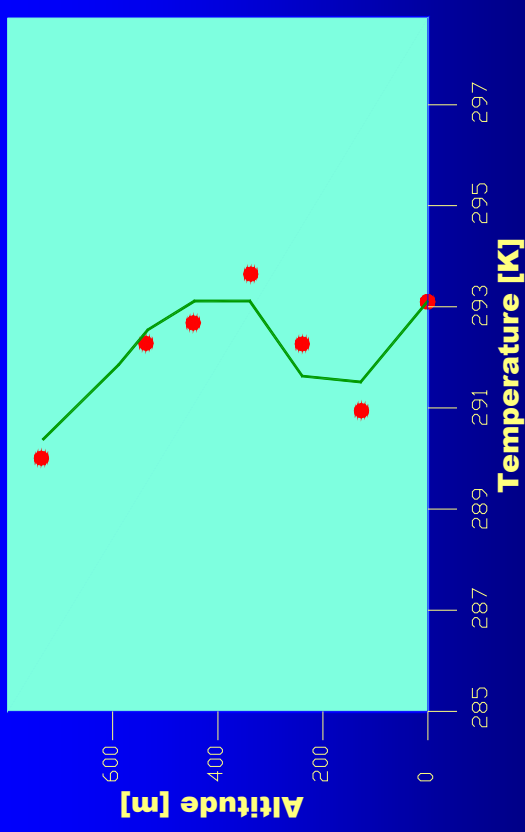
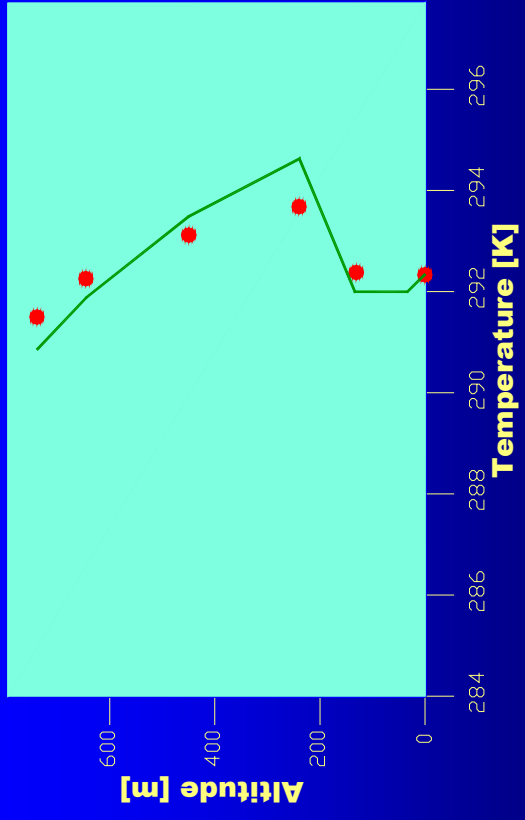
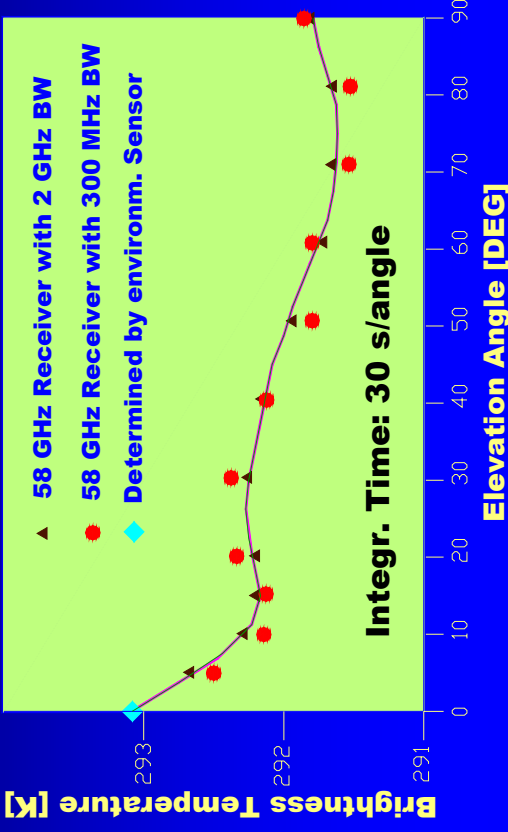
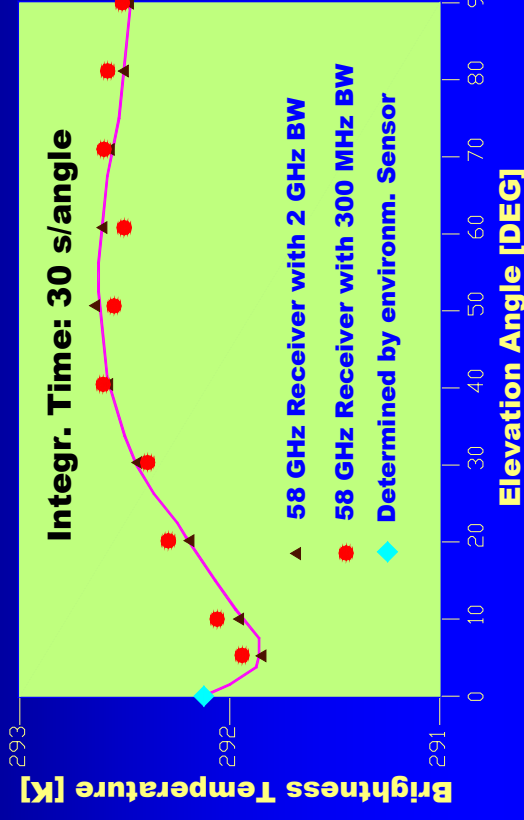
Messprinzip II: Winkelabhängige Emissionhöhe

58/54.8 GHz Elevation Scanning

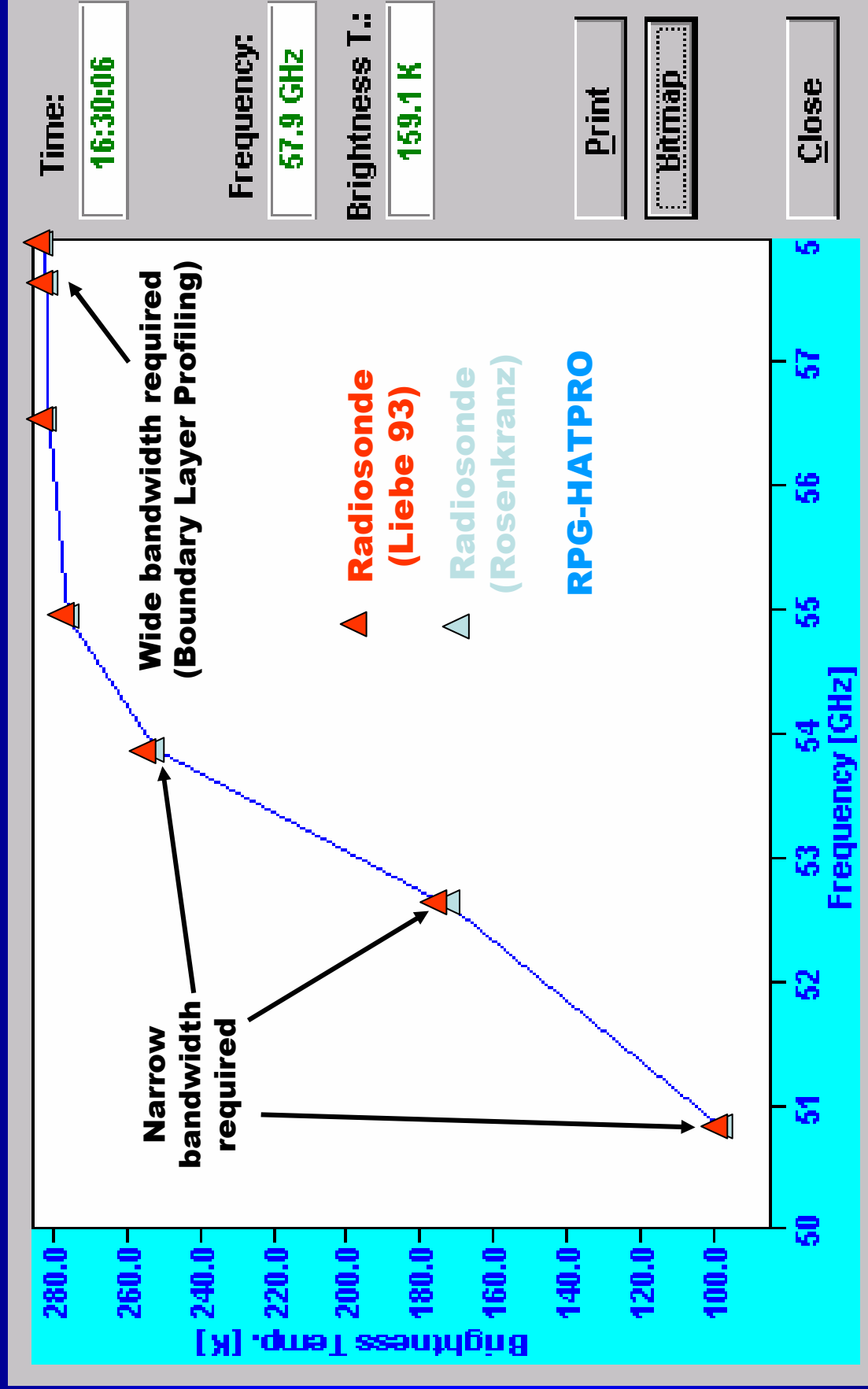


Boundary Layer Temperature Profiling

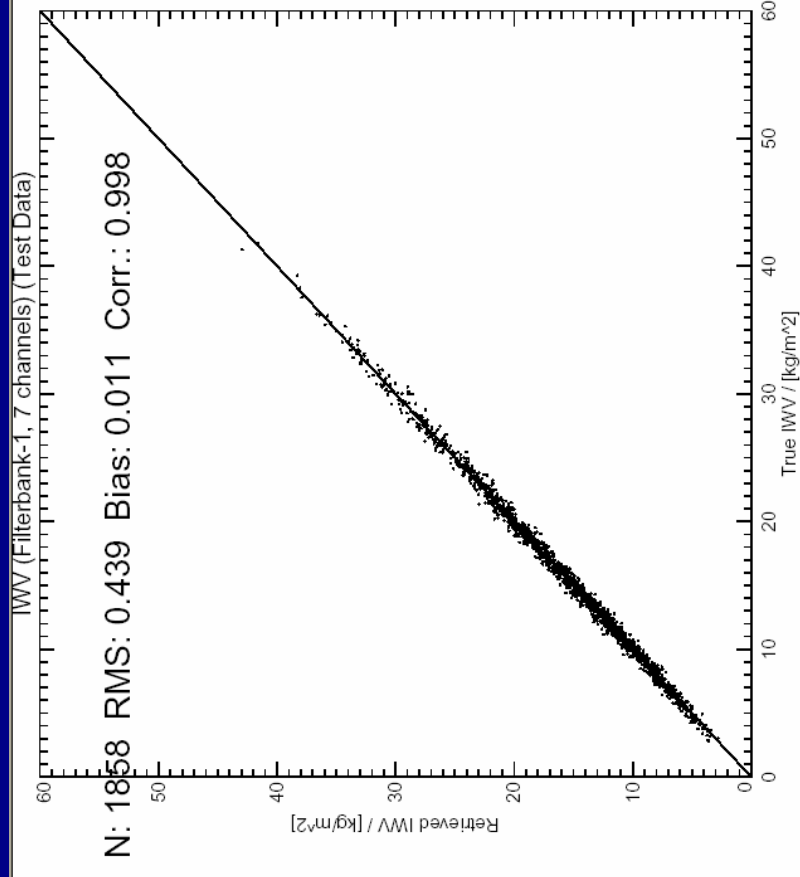
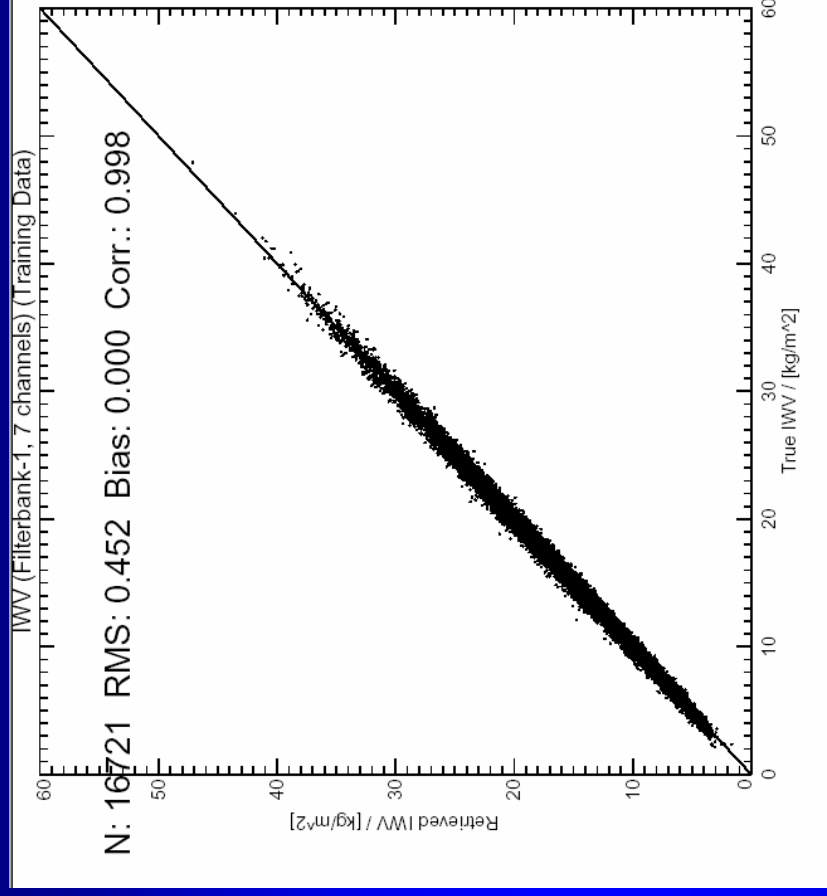
Influence of 58 GHz channel sensitivity



50-60 GHz Channel Bandwidth



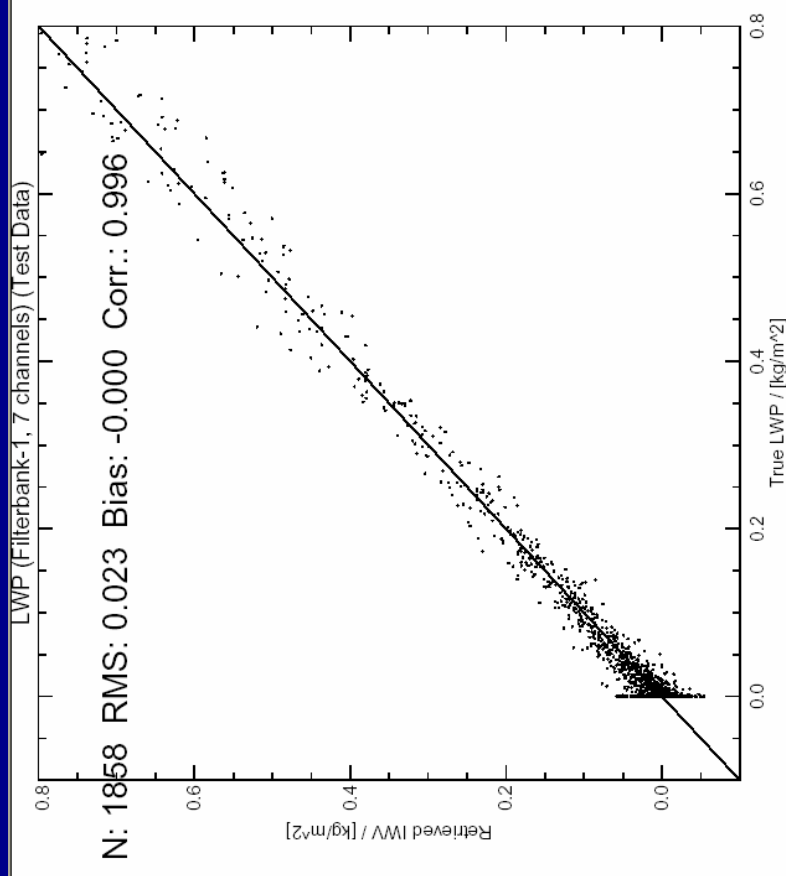
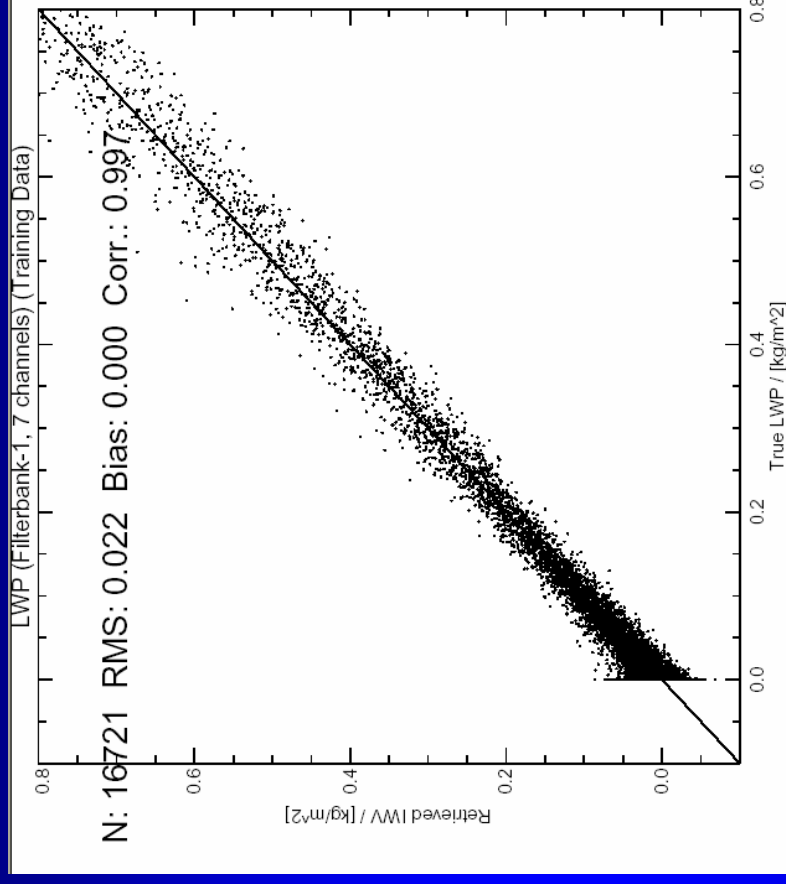
IWV Retrieval



- Customer: University Salford, UK
- 18580 hochaufgelöste Radiosonden
- Regenfälle sind enthalten
- Clear-sky RMS ca. 0.2 kg/m²

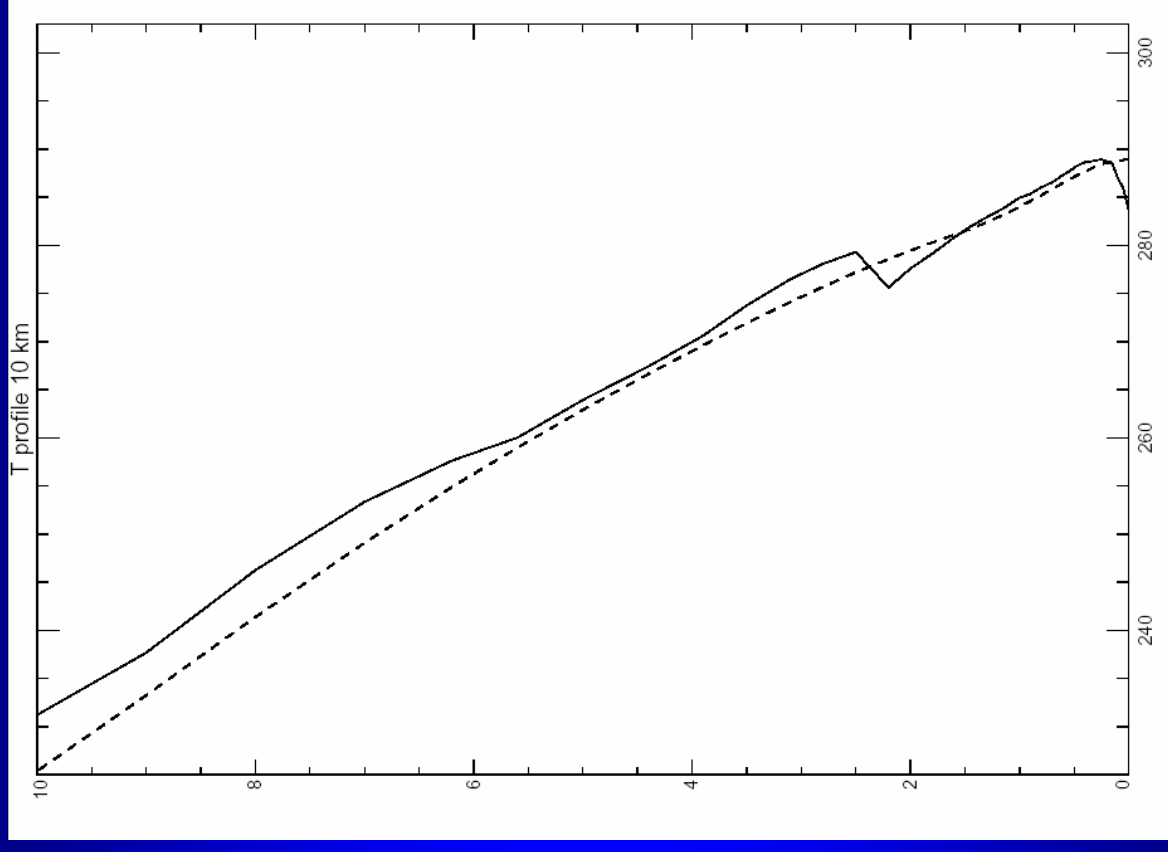
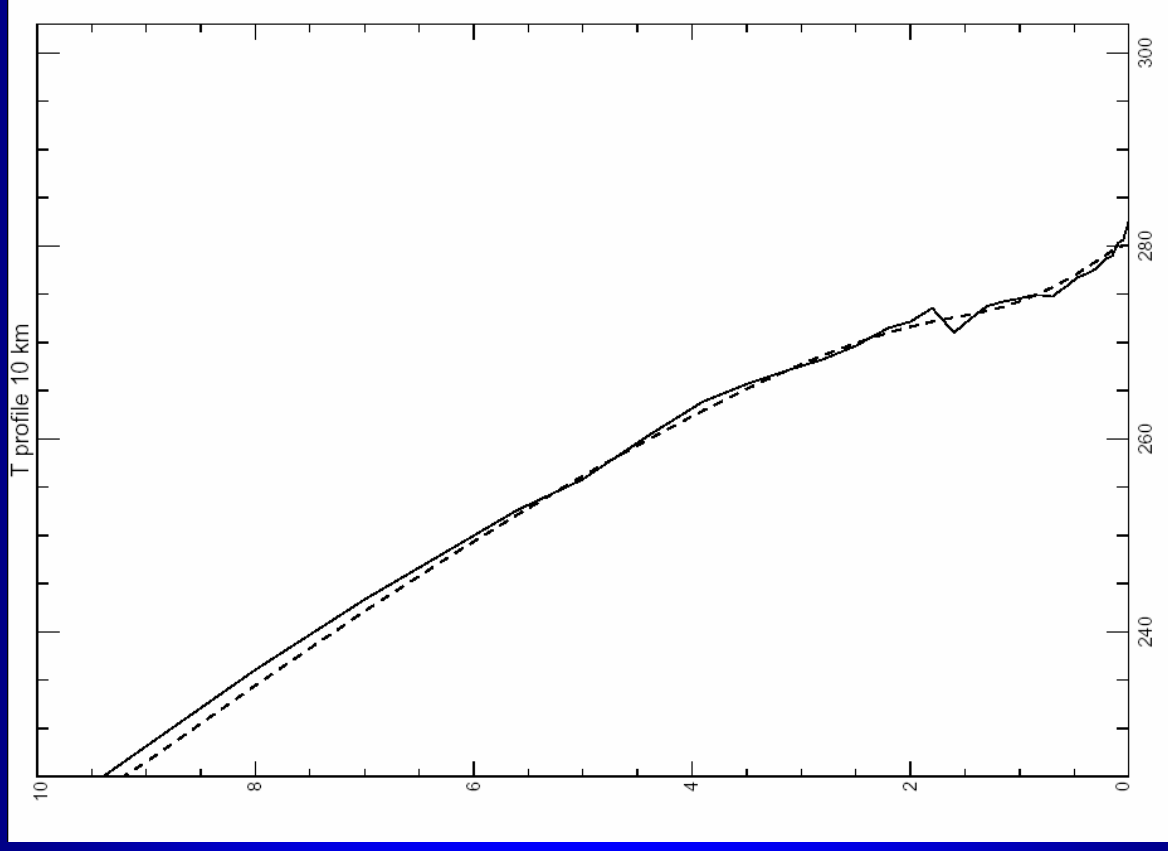


LWP Retrieval

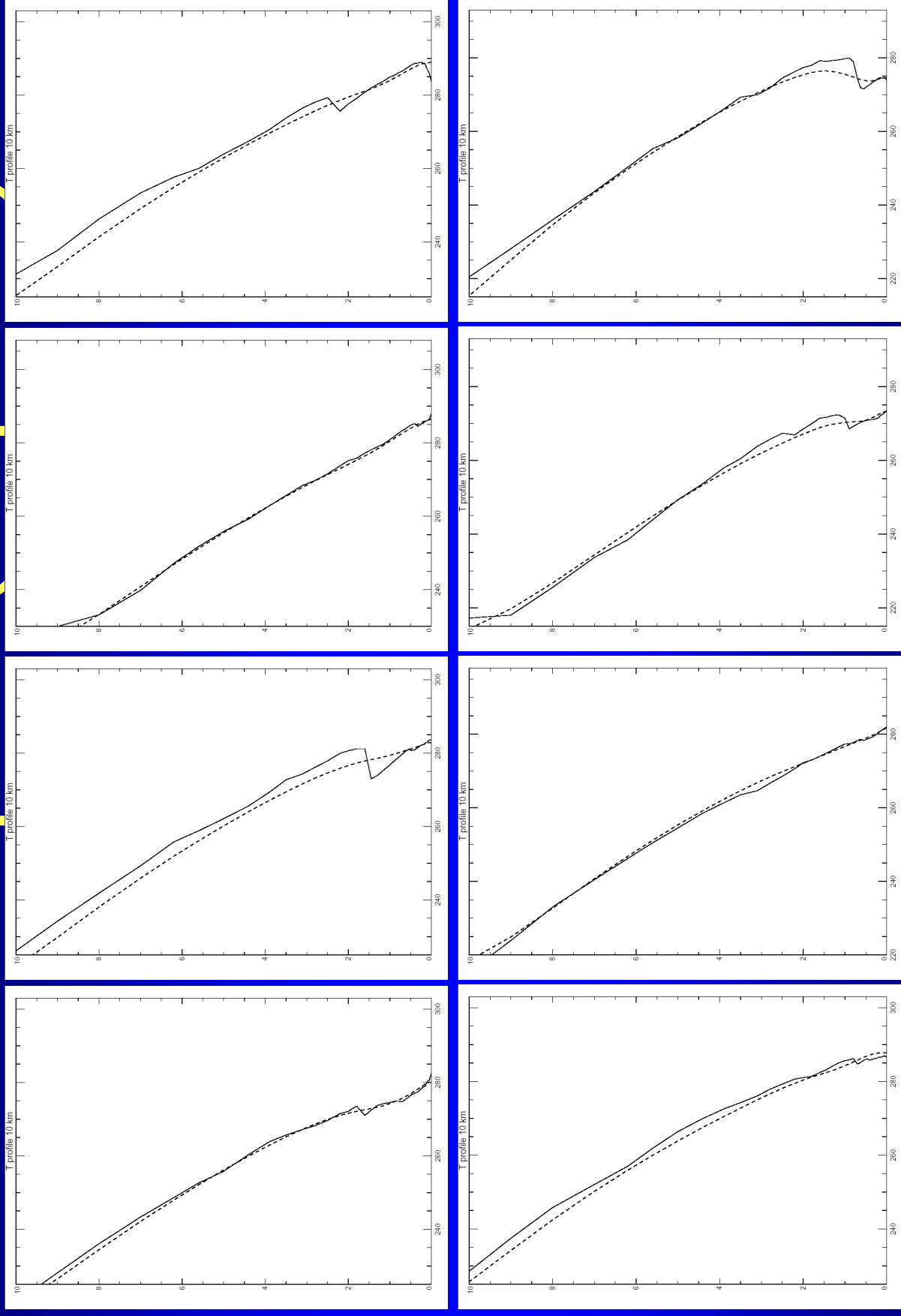


- Universität Salford, UK
- 18580 hochaufgelöste Radiosonden
- RMS für Wolken-LWP kleiner als bei Berücksichtigung der regnenden Fälle

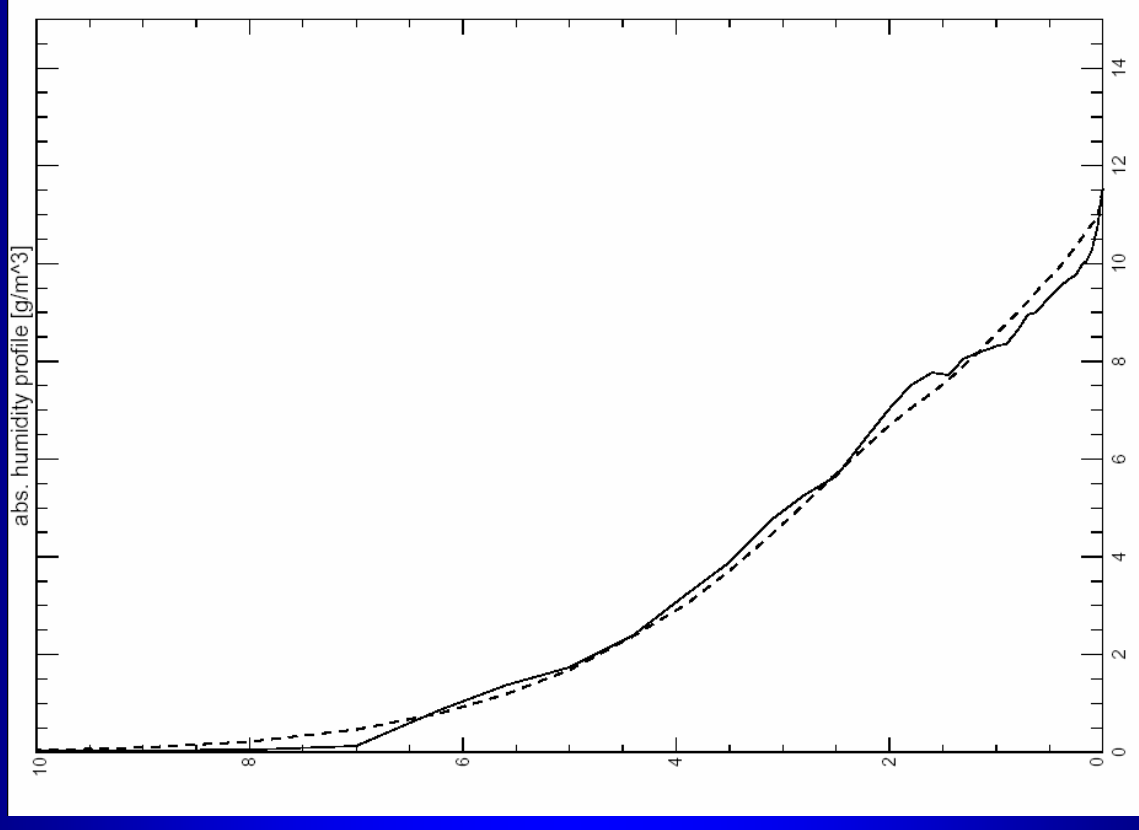
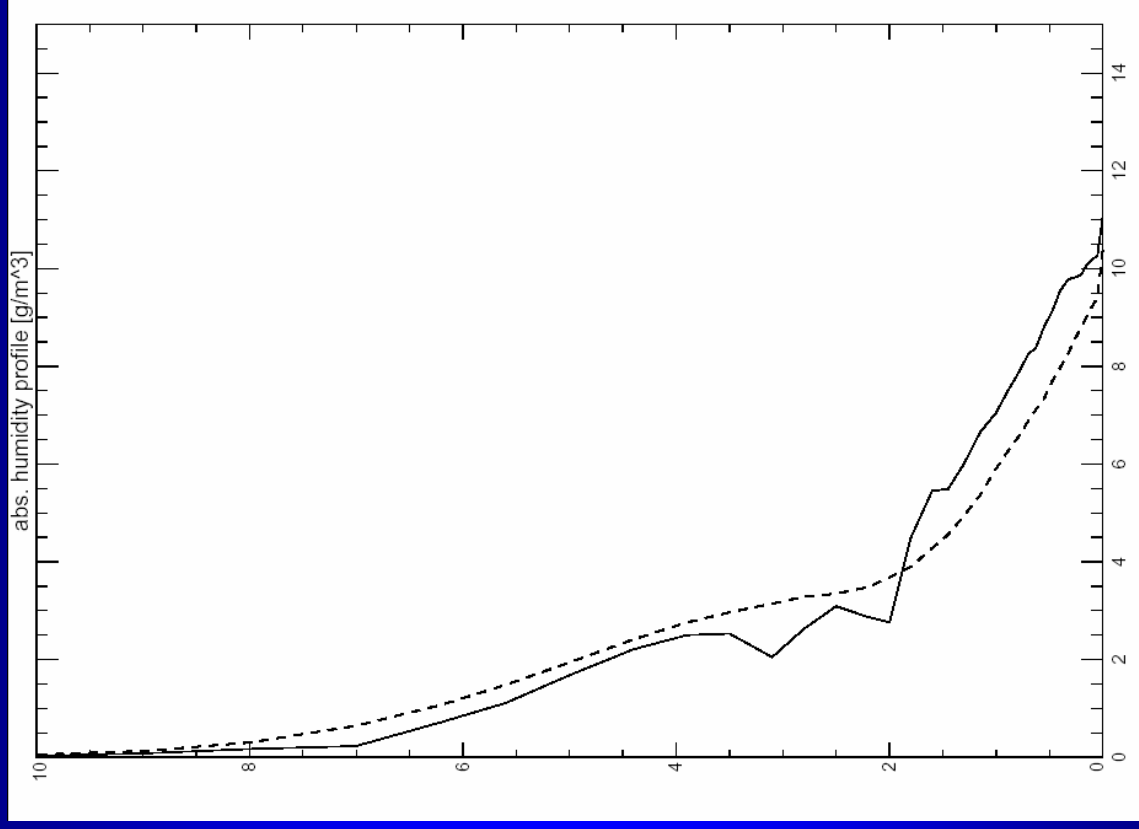
Vertikalprofile (Temperatur)



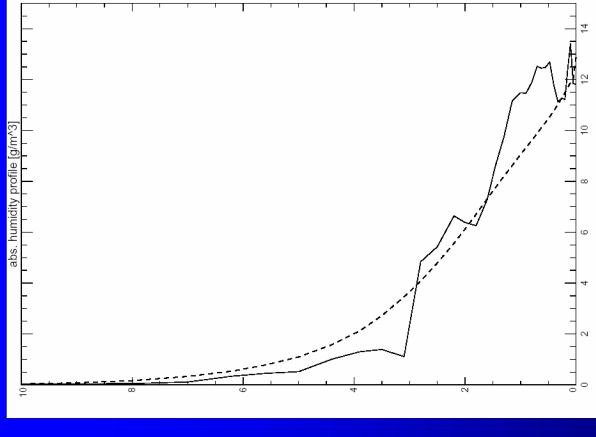
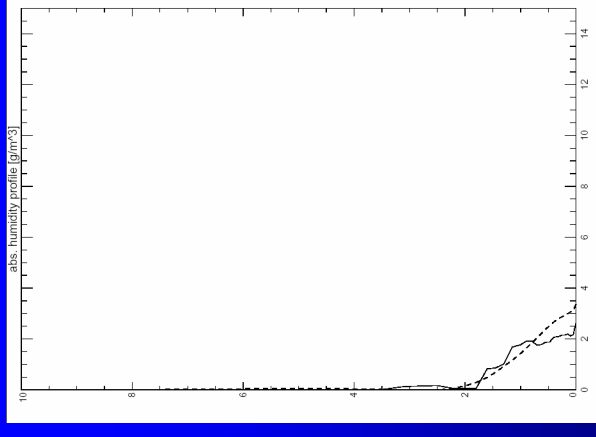
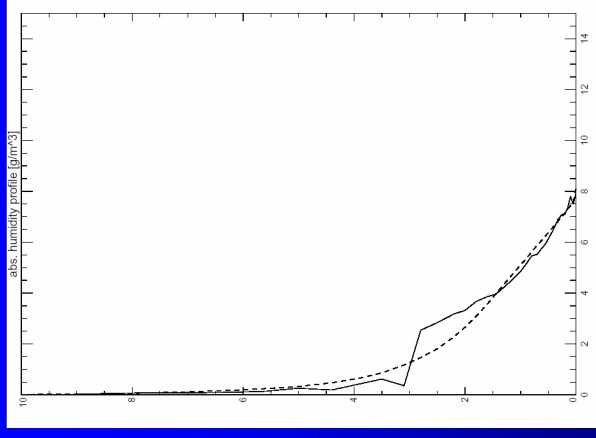
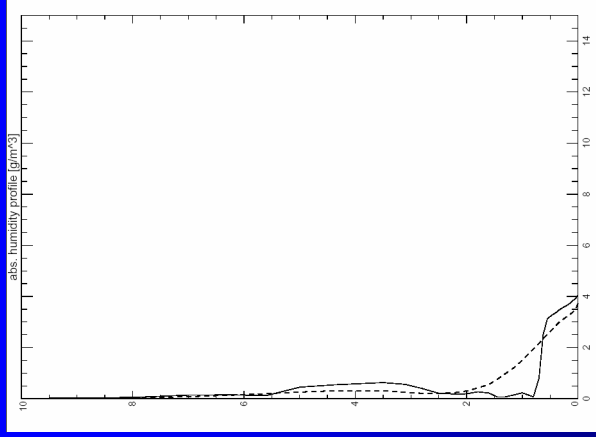
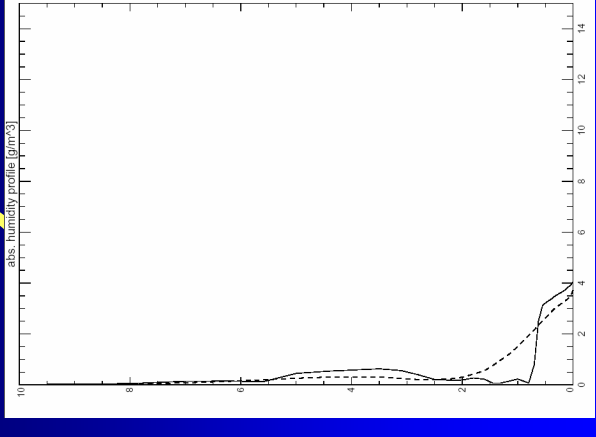
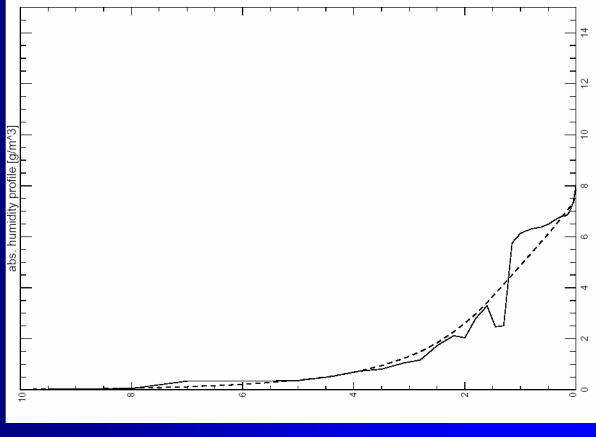
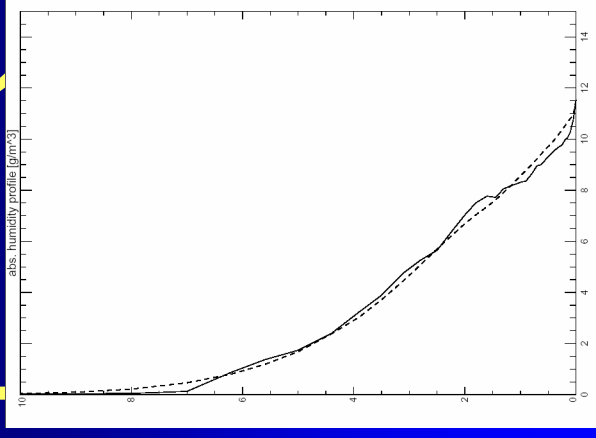
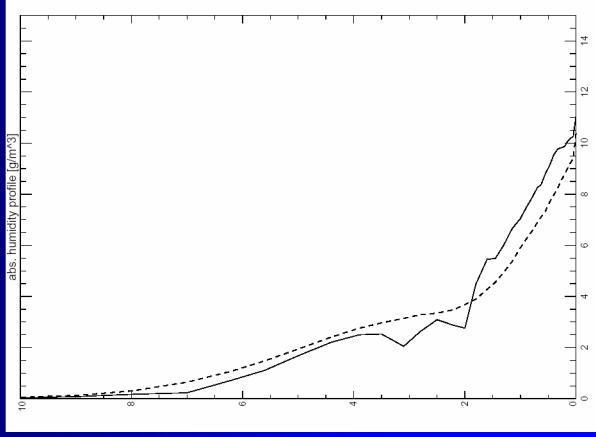
Vertikalprofile (Temperatur)



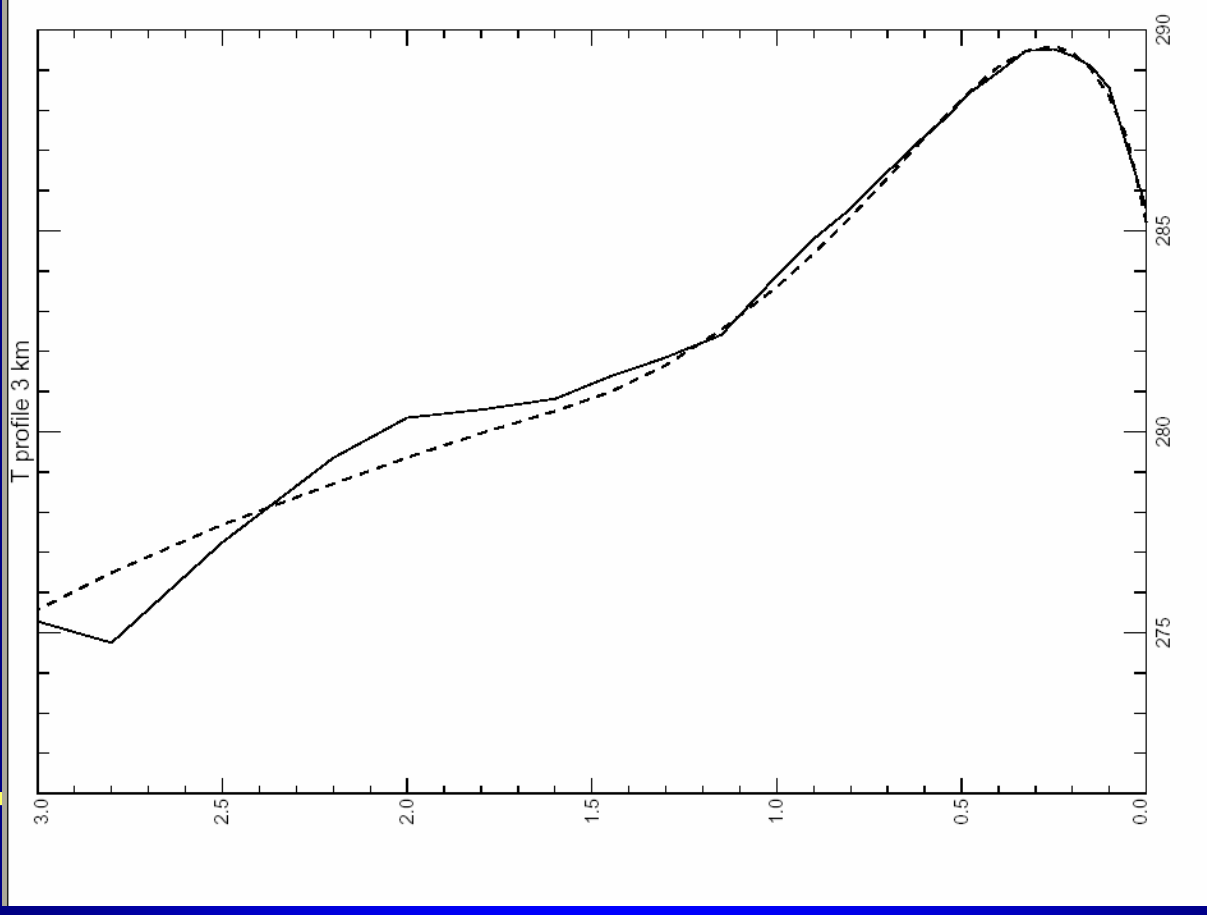
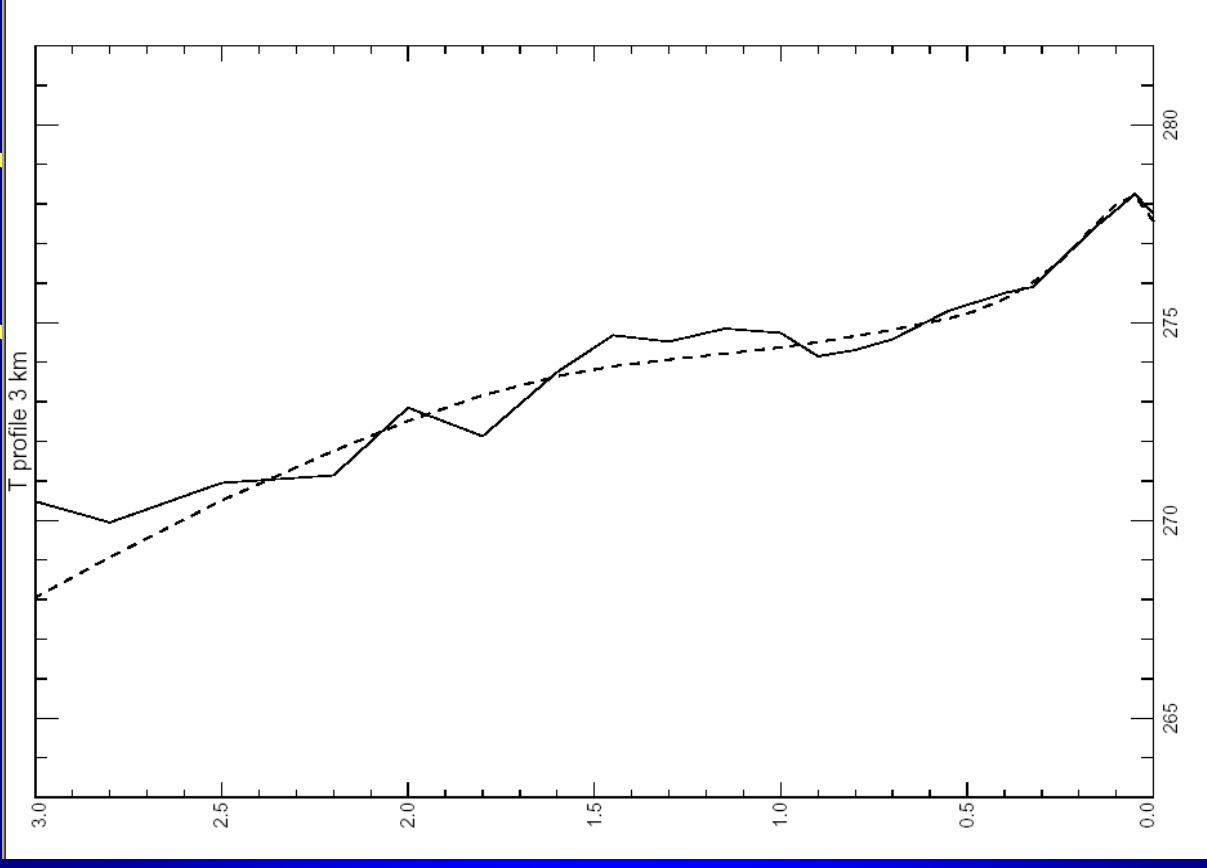
Vertikalprofile (Absolute Feuchte)



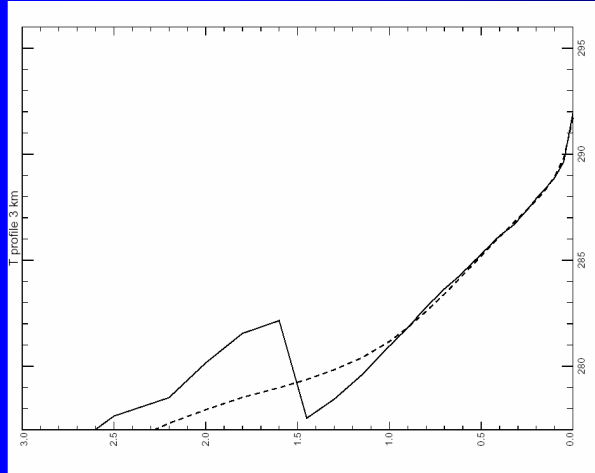
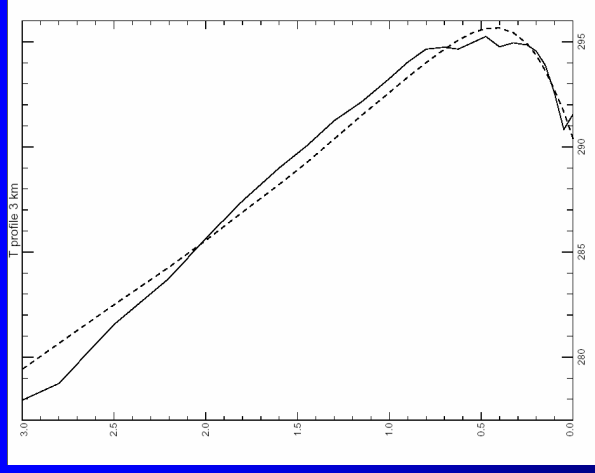
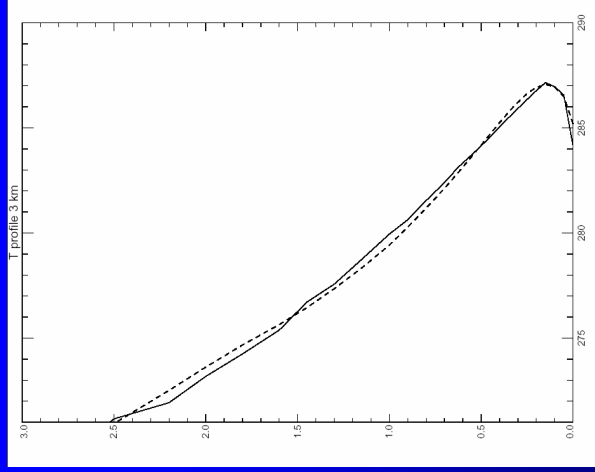
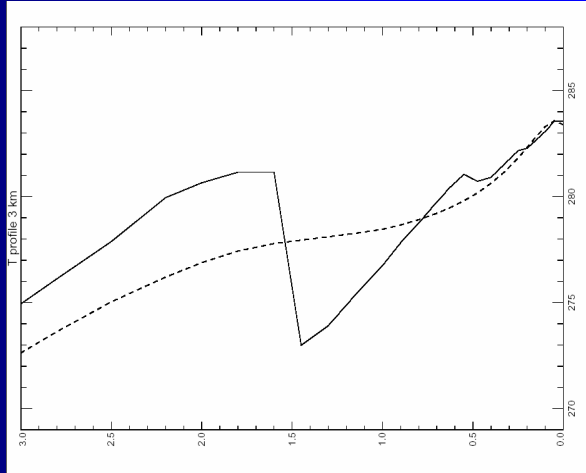
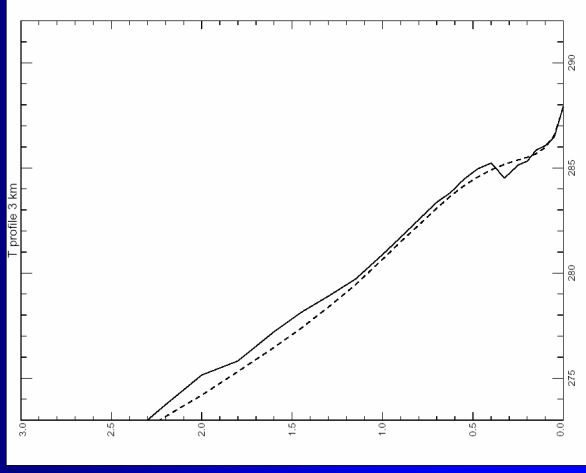
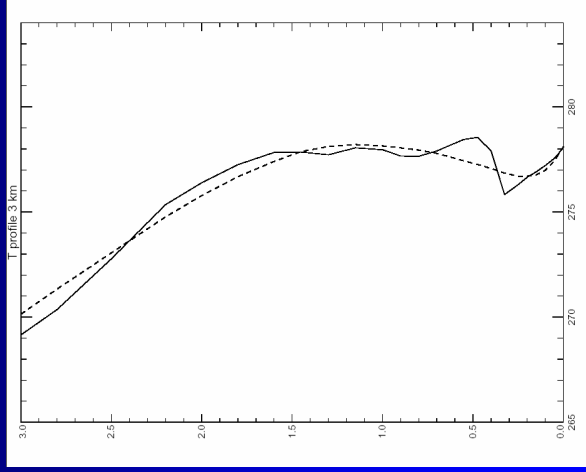
Vertikalprofile (Absolute Feuchte)



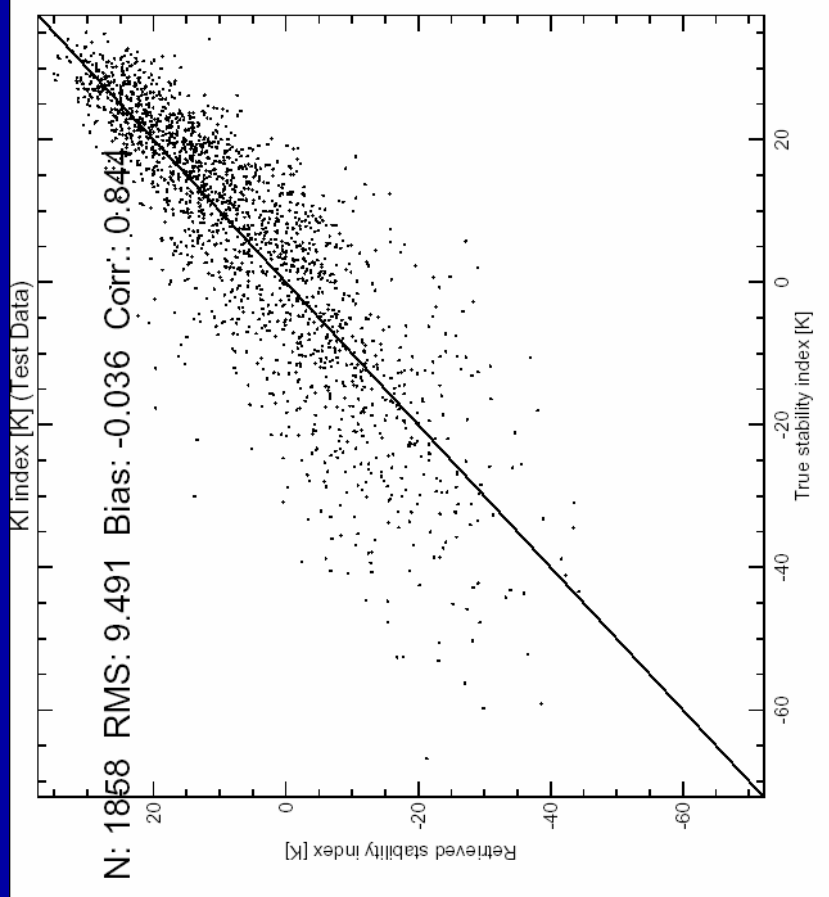
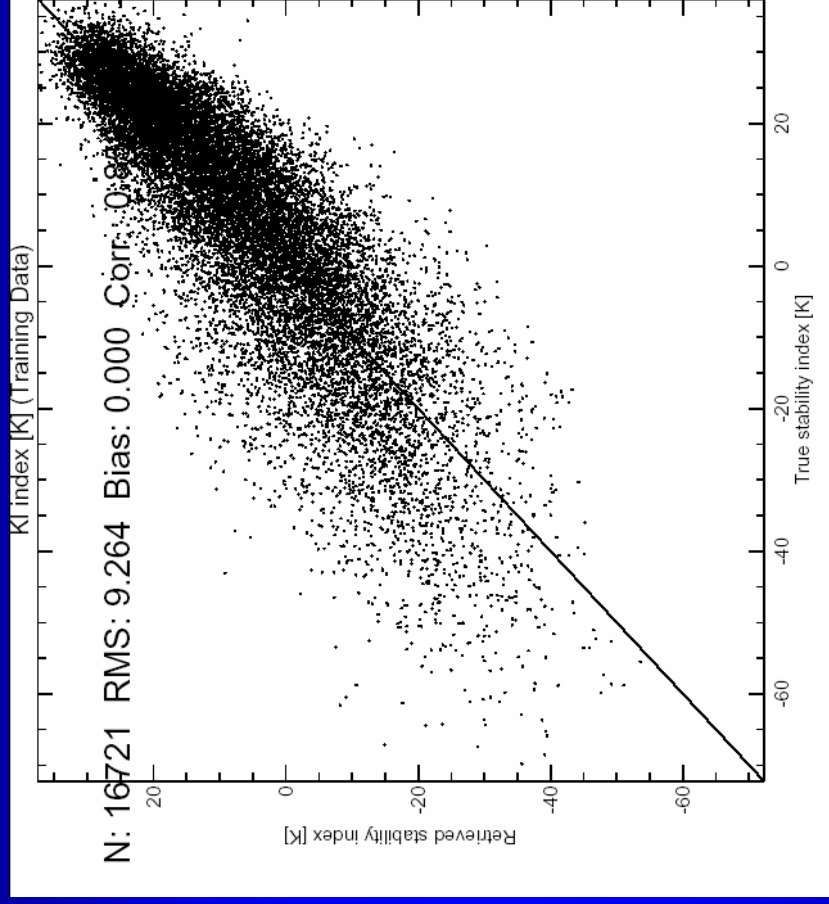
Boundary Layer Temperatur Profile



Boundary Layer Temperature Profile



Atmosphärische Stabilität: K-Index



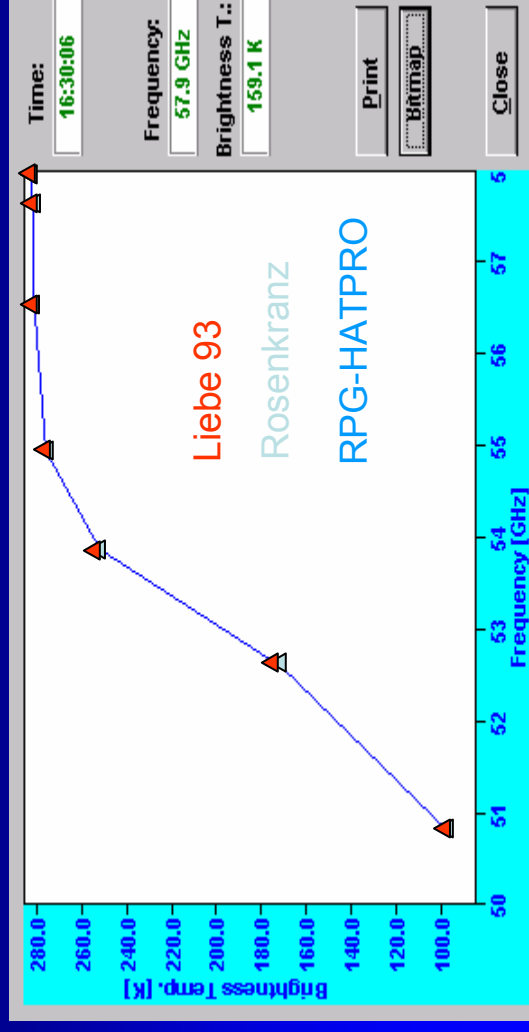
Messergebnisse und Vergleiche



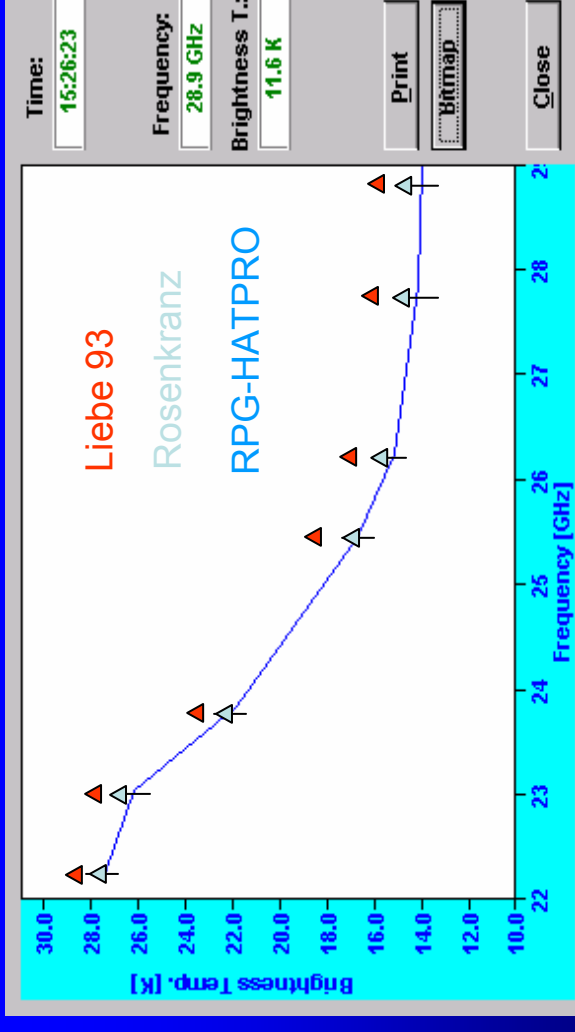
Verification with Radiosonde Data

BBC2 Measurement Campaign in
Cabauw/NL (2.5.2003 – 23.5.2003)

Oxygen Line
(Clear Sky)



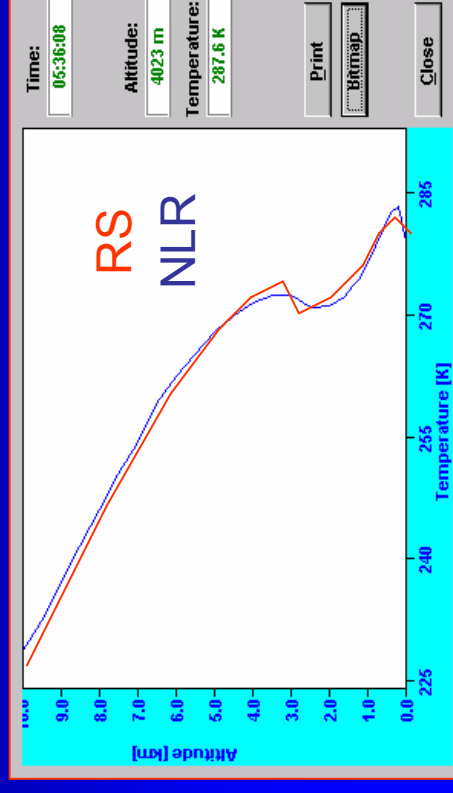
Water Vapour Line
(Clear Sky)



Verification with Radiosonde Data

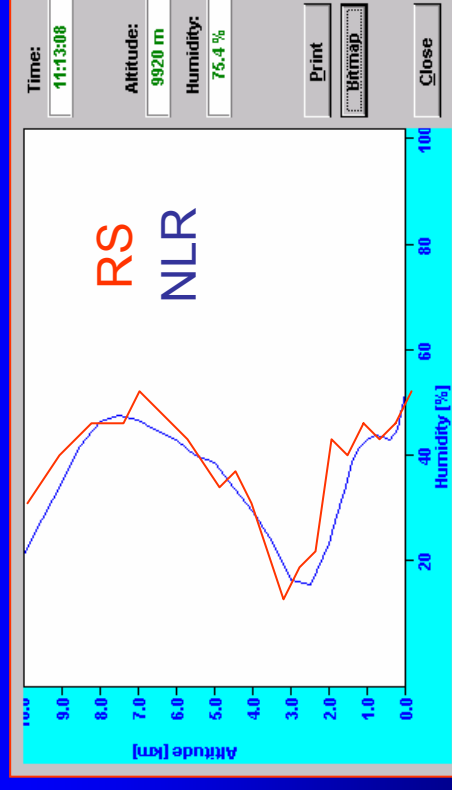
BBC2 Measurement Campaign in Cabauw/NL

Temperature Profiles



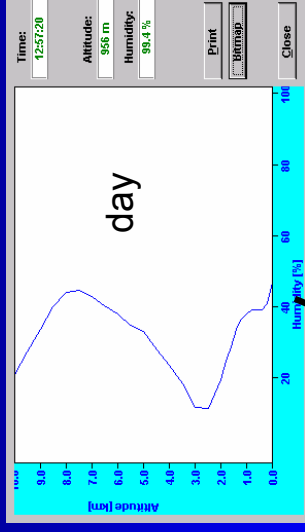
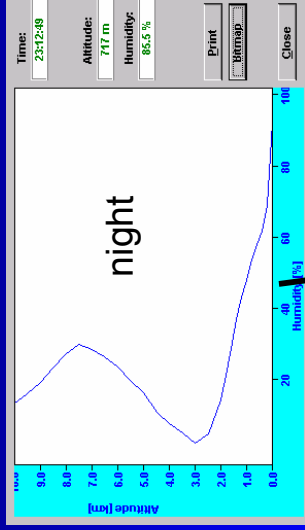
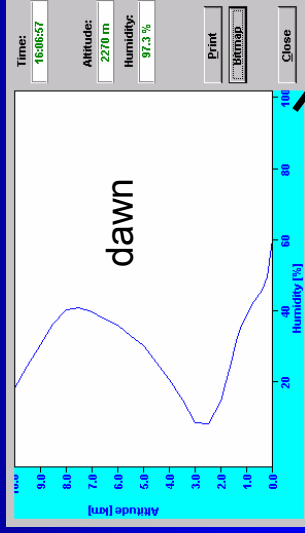
Clear Sky Conditions

Humidity Profiles

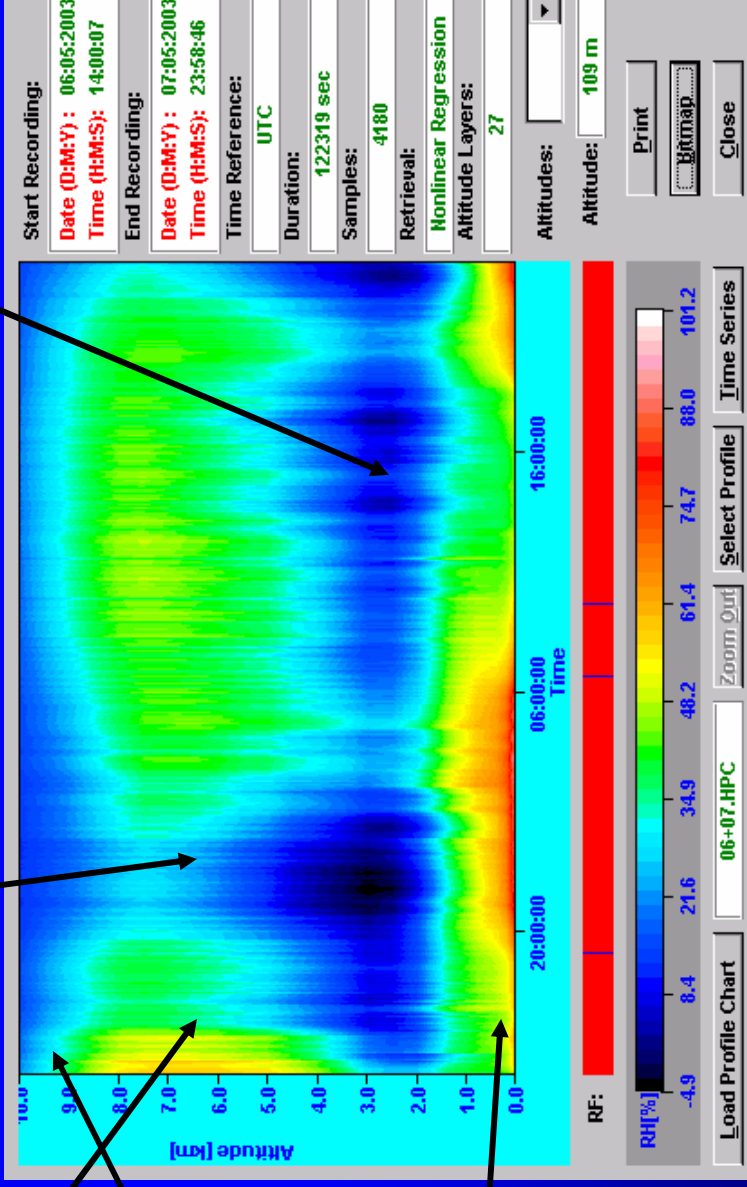
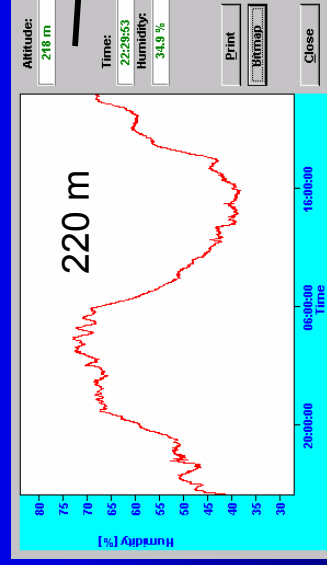
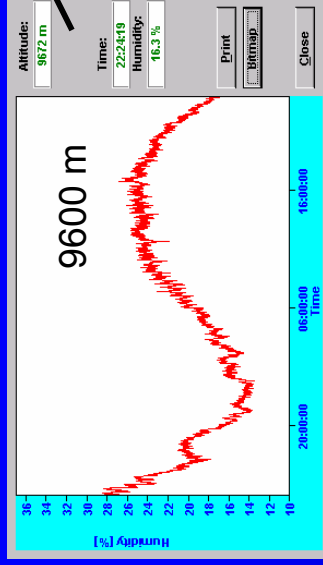


HATPRO Humidity Profile Charts

Humidity Profiles

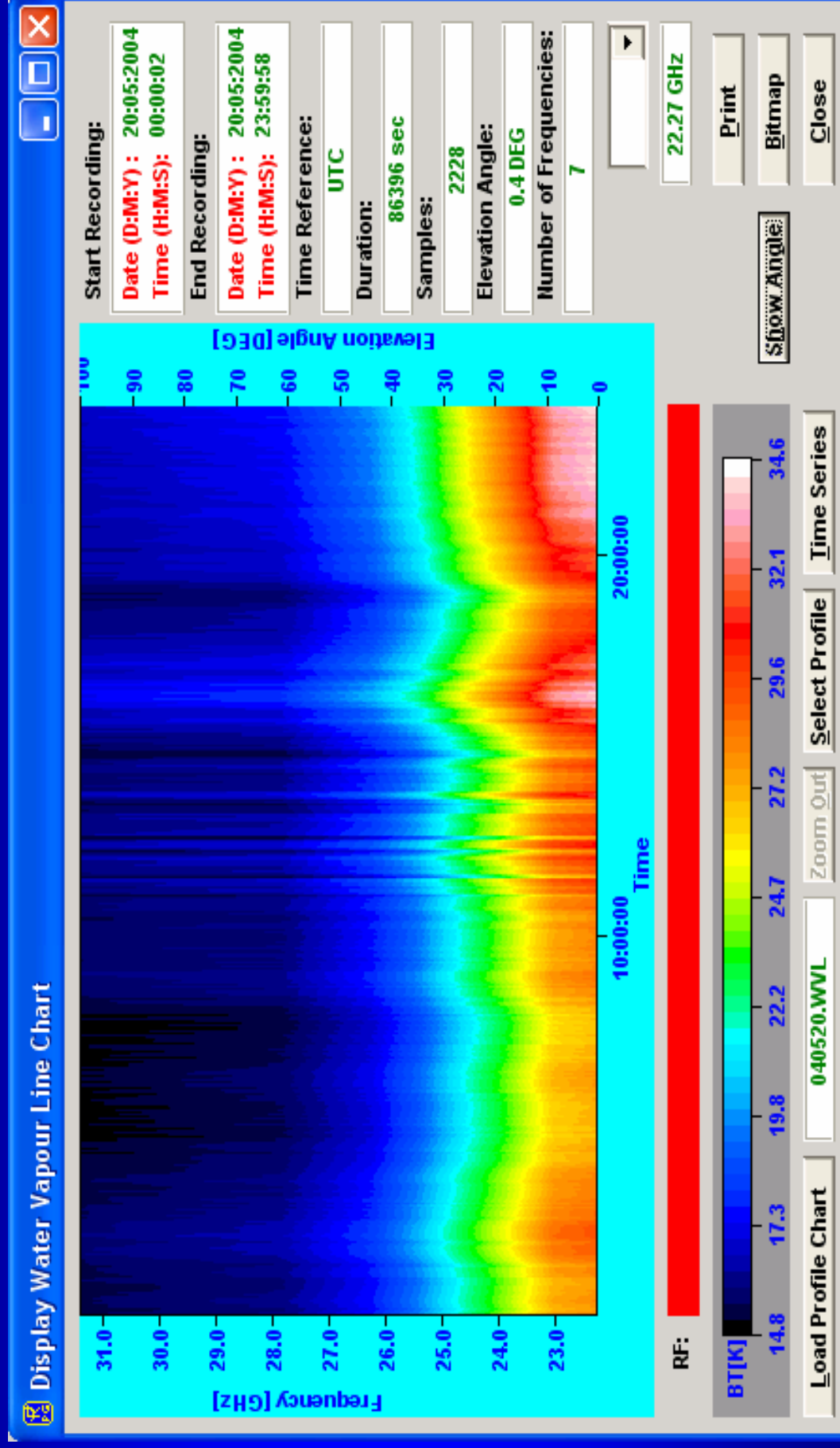


Time Series



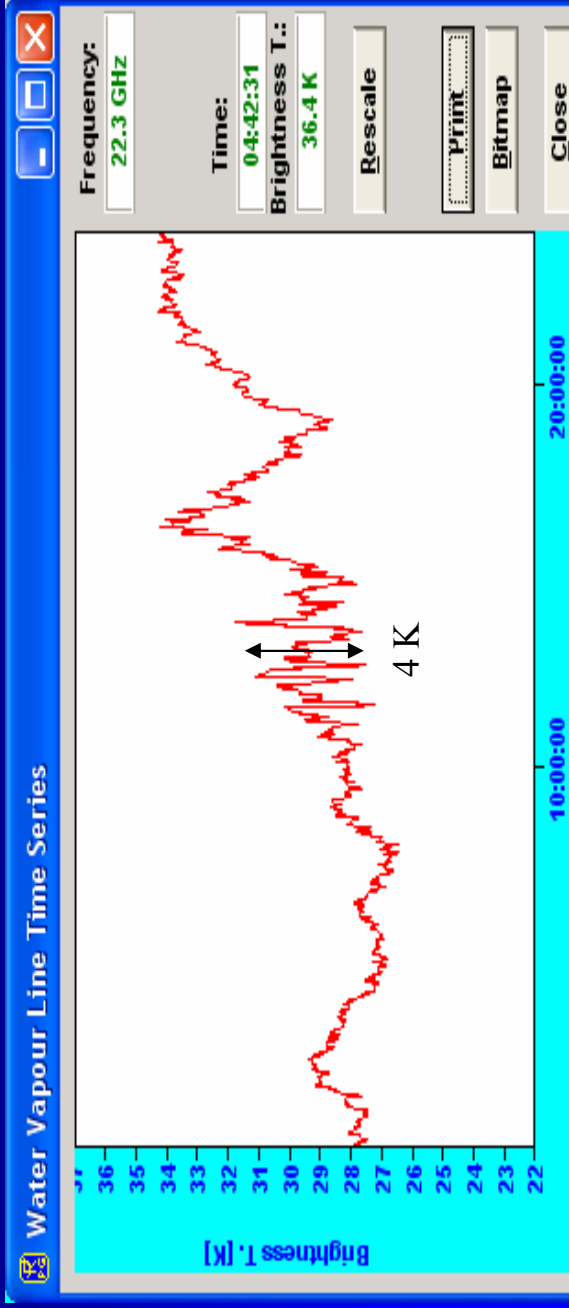
Humidity Fluctuations

VAPIC Campaign in Pallaiseau/France, May 2004

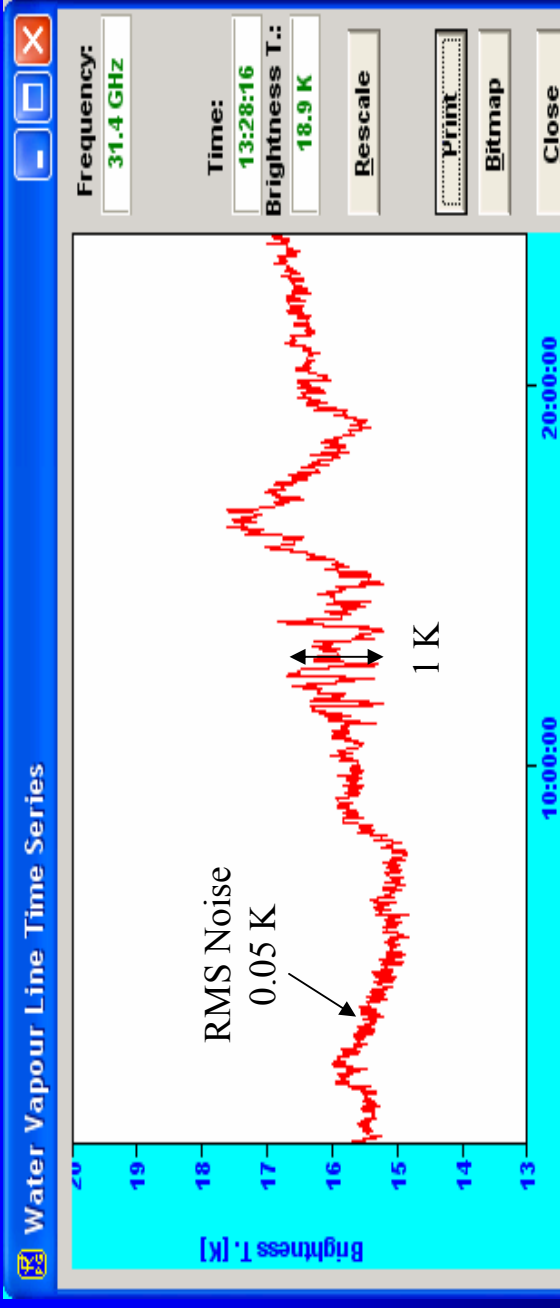


Humidity Fluctuations

22.35 GHz



31.4 GHz

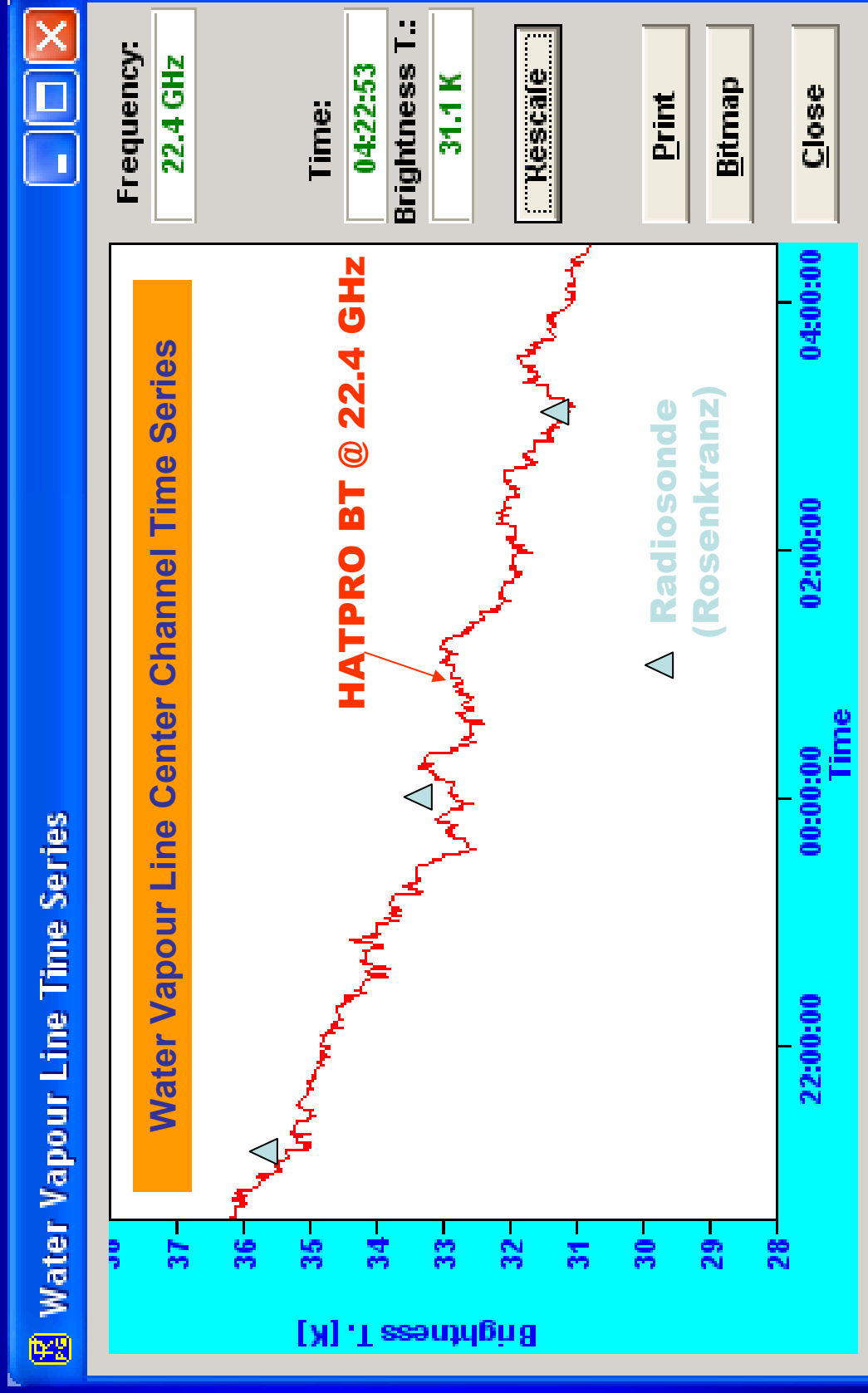


Humidity Fluctuations



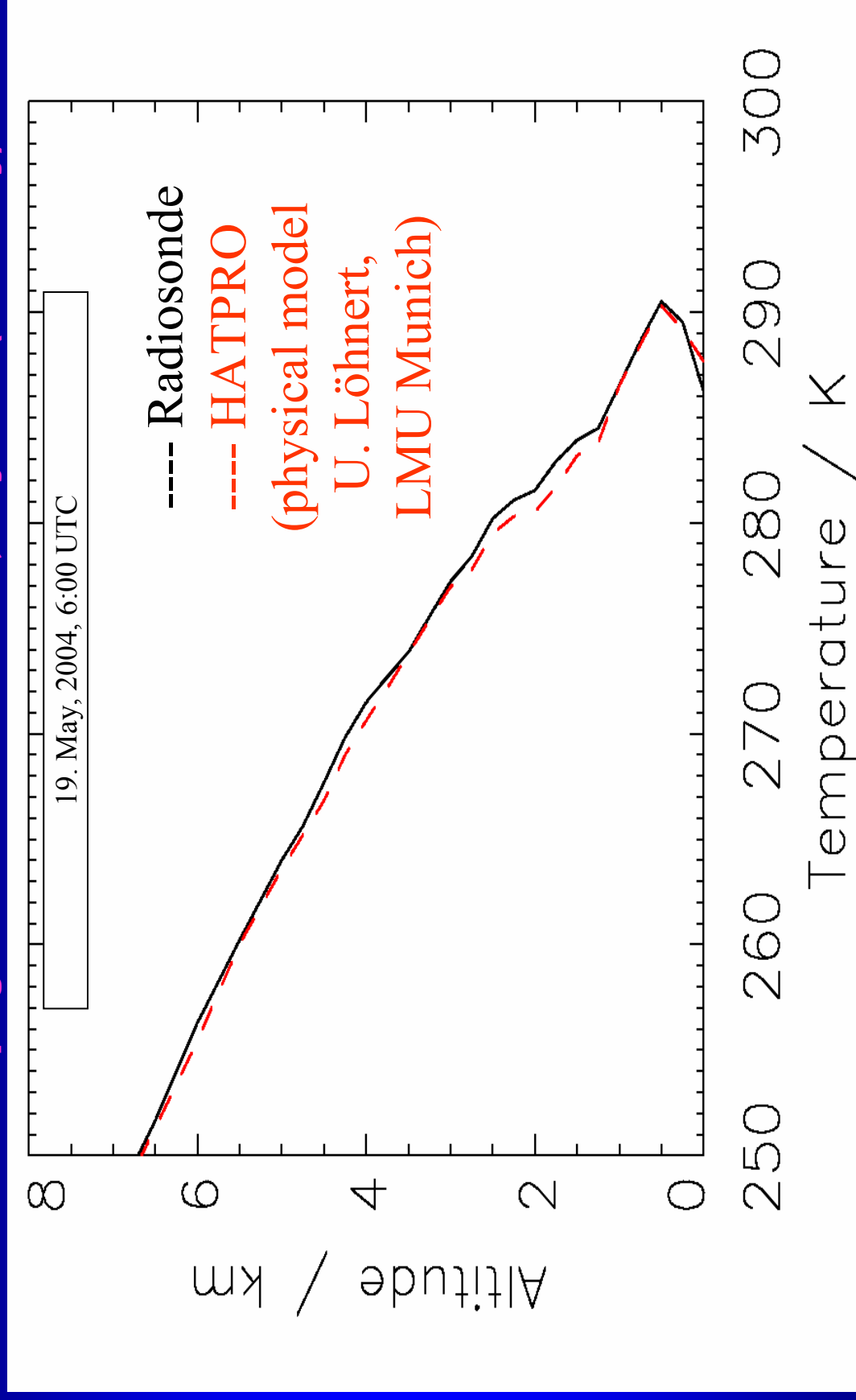
HATPRO Brightness Temp. Time Series

VAPIC Campaign in Pallaiseau/France, May 2004

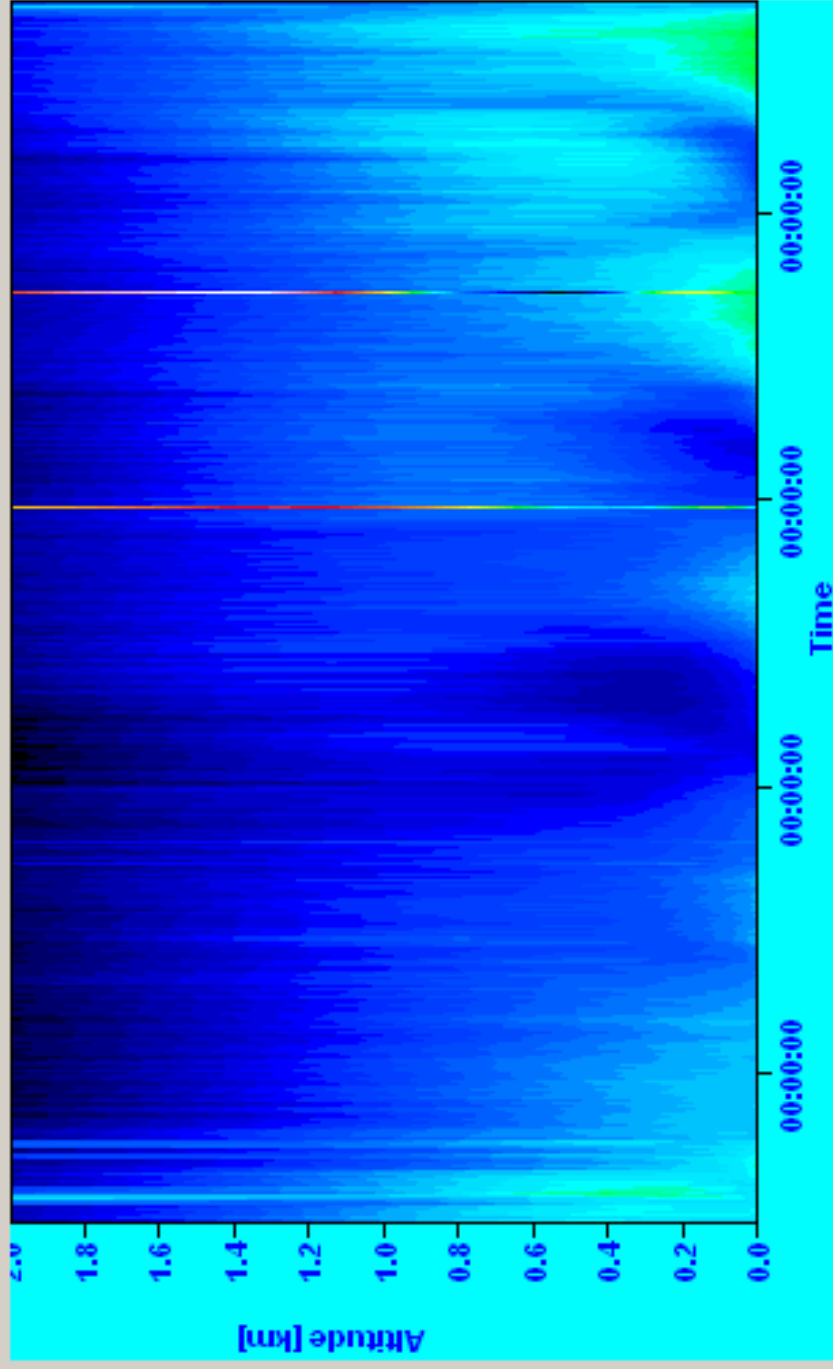


Verification with Radiosonde Data

VAPIC Campaign in Pallaiseau/France, May 2004 (Clear Sky)



Display Temperature Profiles (Boundary Layer)



Start Recording:

Date (D:M:Y): 24:06:2005

Time (H:M:S): 11:16:38

End Recording:

Date (D:M:Y): 28:06:2005

Time (H:M:S): 17:59:02

Time Reference:

Local Time

Duration:

369744 sec

Samples:

484

Retrieval:

Linear Regression

Altitude Layers:

21

Altitudes:

Altitude: 21 m

Temperature Contours

Add

Del

Redr.

On

Close

Load Profile Chart

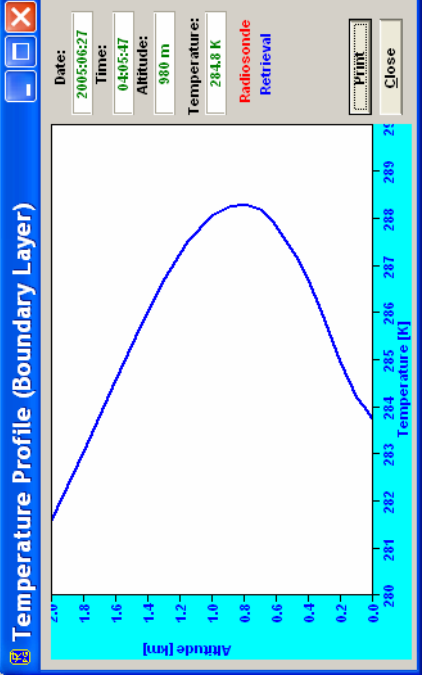
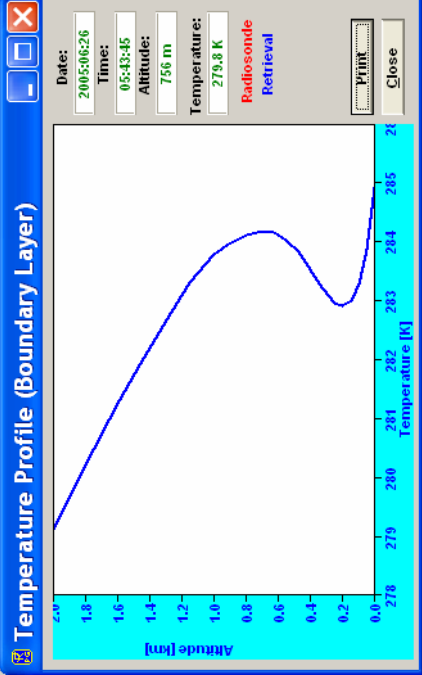
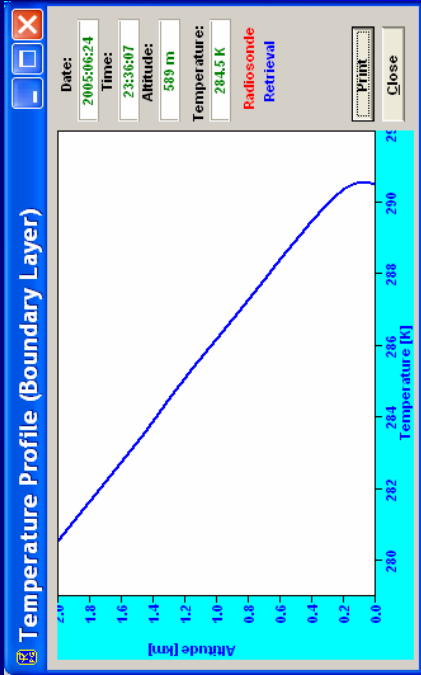
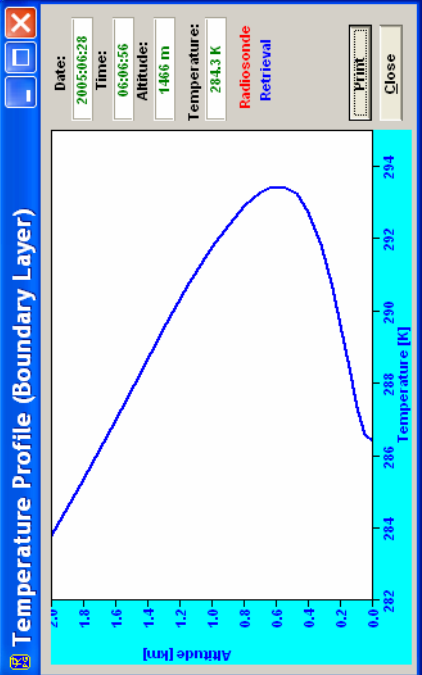
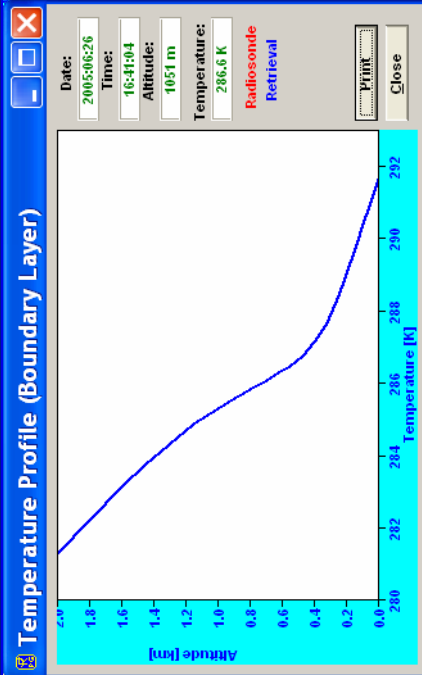
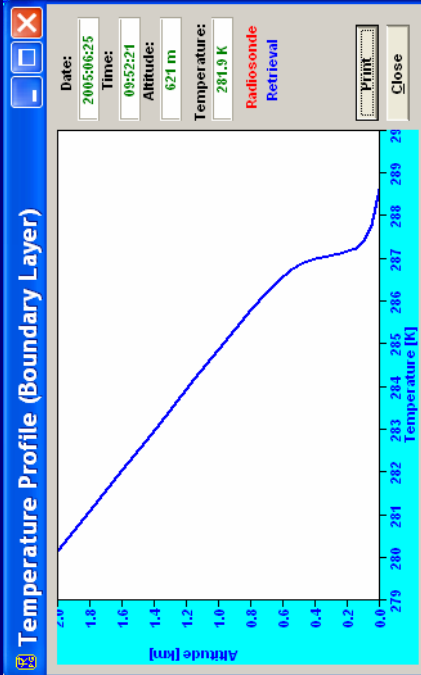
050624_28.TPB

Time Series

Import RS Data

Display RS Data

Select Profile



Zusammenfassung

1. *Filterbank* Radiometer mit *direct-detection* sind notwendig für die konsistente Messung meteorologischer Parameter
2. Kompaktes hoch-integriertes Design ermöglicht wartungsarmen Langzeitbetrieb
3. Gut vernetzbare Steuerungssoftware ermöglicht einfache Integration in Messnetze und Datennetzwerke
4. Diese Radiometer sind derzeit ohne Konkurrenz (ähnliche Systeme bieten für einen deutlich höheren Preis schlechtere Leistungen, sind teilweise prinzipiell nicht einsetzbar)

Weiter Informationen: www.radiometer-physics.de
czekala@radiometer-physics.de