Water Vapor Mm-wave Spectrometer

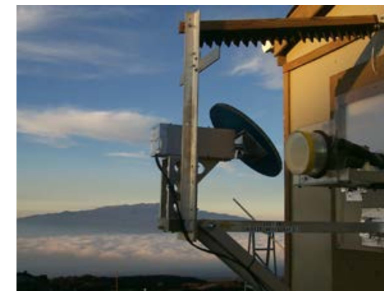
Gerald E. Nedoluha, R. Michael Gomez,
Brian C. Hicks, Richard M. Bevilacqua
Naval Research Laboratory

Water Vapor Mm-wave Spectrometer (WVMS)

22 GHz radiometers
Water vapor profile measurements from 40-80 km
Measurements from 3 NDSC sites:
Lauder, New Zealand (45^{o}S, 169.7^{o}E):
Nov. 1992-Apr. 1993, Jan. 1994-present

Table Mountain, CA (34.4^{o}N, 242.3^{o}E): May 1993-Nov. 1997

Mauna Loa, HA (19.5^{o}N, 204.4^{o}E): Mar. 1996-present

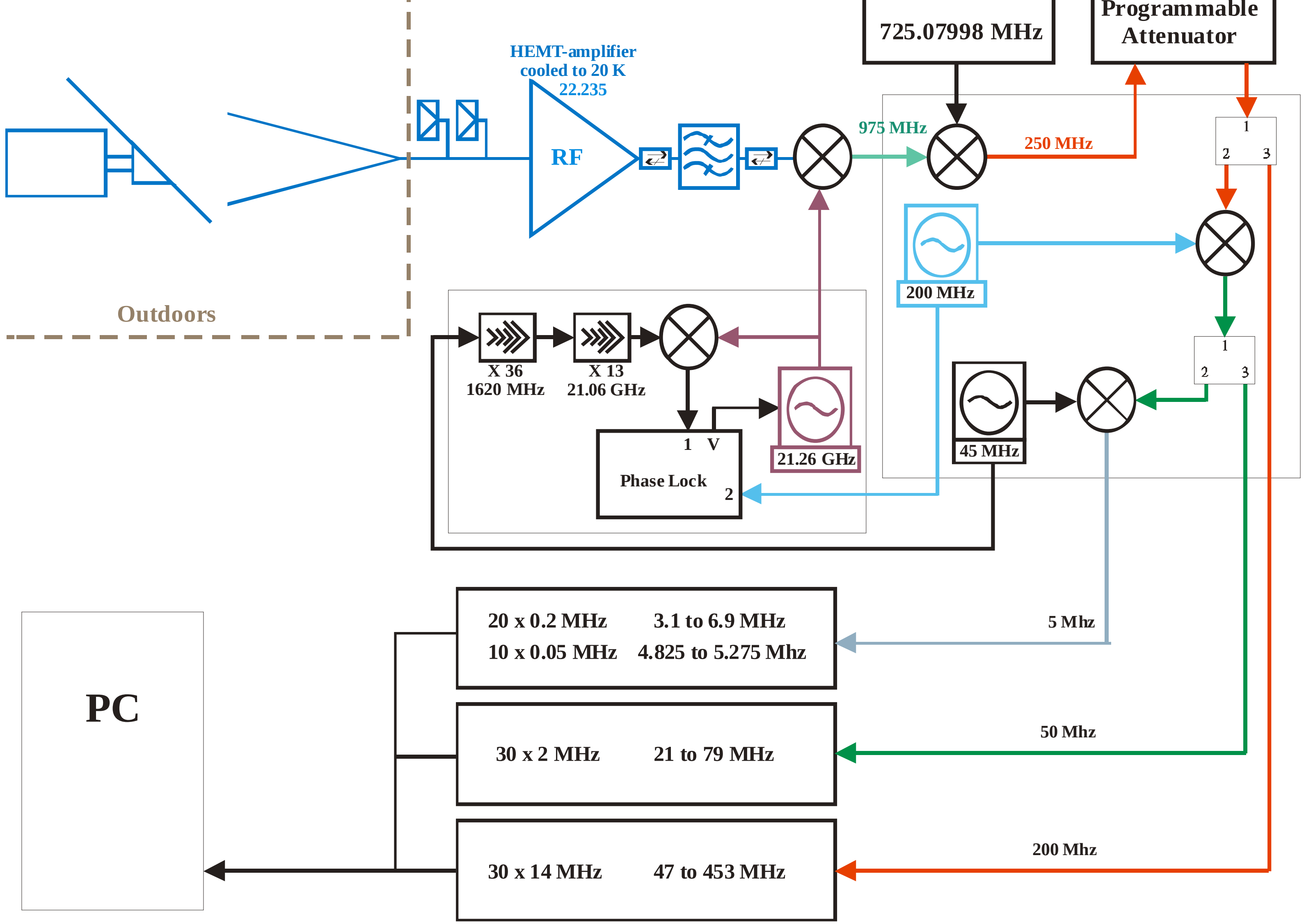


Instrument description

- Front end
  - Corrugated feed horn with beam size ~8^o FWHM
  - Rotating aluminum plate mirror at 45^o to feedhorn
  - Fixed absorber bar used for noise balance

- Back end
  - HEMT amplifier (20K)
  - Noise diode calibration source
  - Spectrometer centered at 22.235 GHz
  - Single side-band
  - New spectrometers (WVMS3 Mauna Loa, WVMS2 Table Mountain)
    - 10x50kHz, 20x200kHz, 30x1MHz, 30x14MHz
  - Old spectrometer (WVMS1 Lauder)
    - 20x200KHz, 20x2MHz, 10x40MHz

[redacted]



HEMT-amplifier
cooled to 20 K
22.235
RF
Outdoors
725.07998 MHz
Programmable
Attenuator
975 MHz
250 MHz
1
2
3
200 MHz
1
2
3
45 MHz
X 36
1620 MHz
X 13
21.06 GHz
1
V
Phase Lock
2
21.26 GHz
20 x 0.2 MHz
3.1 to 6.9 MHz
10 x 0.05 MHz
4.825 to 5.275 Mhz
5 Mhz
30 x 2 MHz
21 to 79 MHz
50 Mhz
30 x 14 MHz
47 to 453 MHz
200 Mhz
PC

Calibrating the noise diode

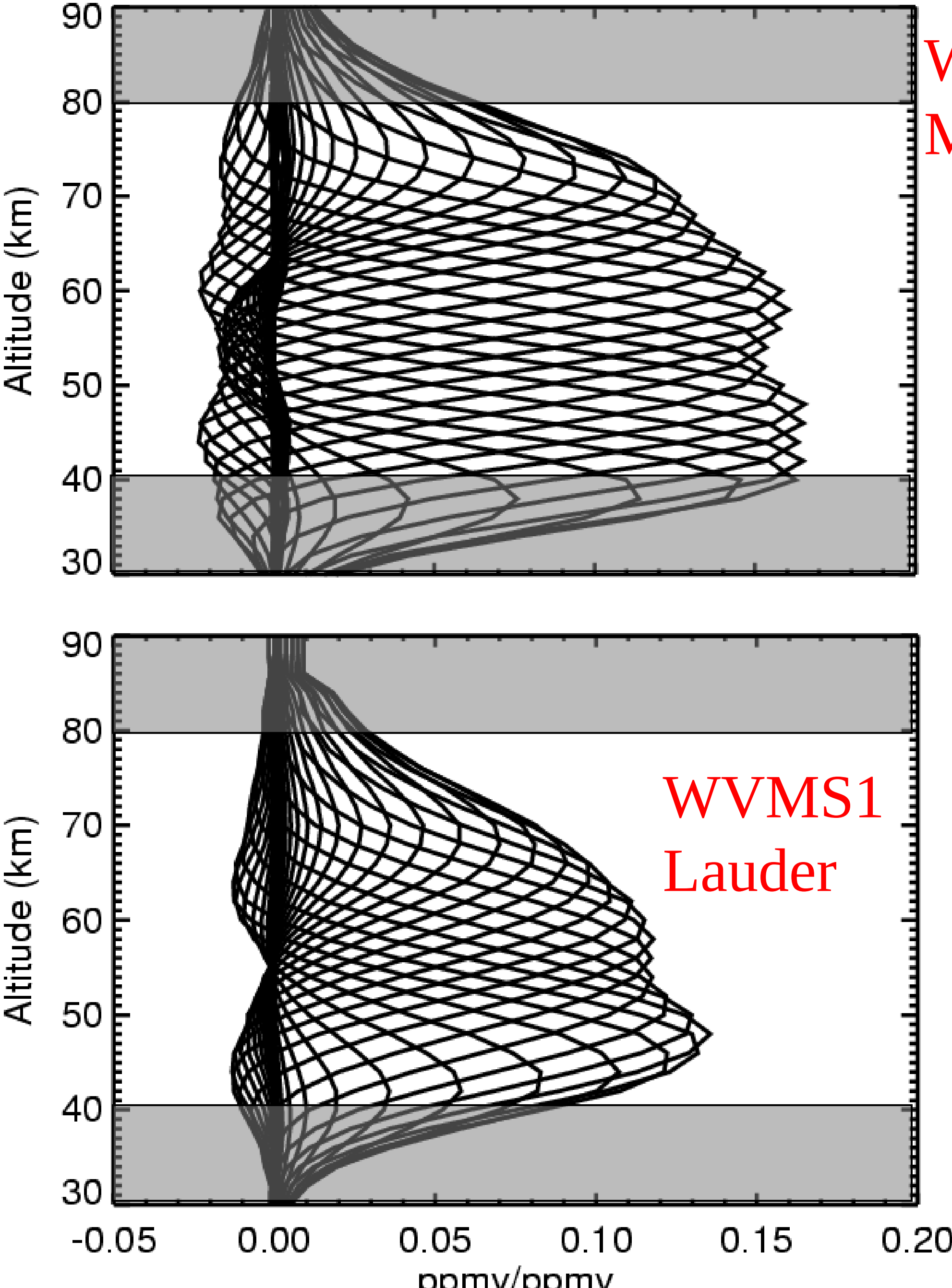
Bar for noise balancing

Data taking procedure

- Tipping measurement
  - Using angles from 45^o (limited by absorber bar) to 75^o (limited by horizon)
  - Find least-squares fit to

    $T_{sys}=T_{rx}+T_{atm}[1-\exp(-\mu\tau_{trop})]$

    solving for T_{sys}, T_{rx}, and τ_{trop}
- Find a signal angle such that T_{sig}~T_{ref}, where T_{ref} is measured near zenith and includes a contribution from the absorber bar
- Make 5 sets of 3 measurements and average together
  - T_{sig} with noise diode off
  - T_{ref} with noise diode off
  - T_{ref} with noise diode on



Averaging kernels for 500 scan integrations from WVMS3 at Mauna Loa, and WVMS1 at Lauder.

Note the difference in the sensitivity of the 2 instruments

All HALOE data compared with WVMS is convolved with these averaging kernels

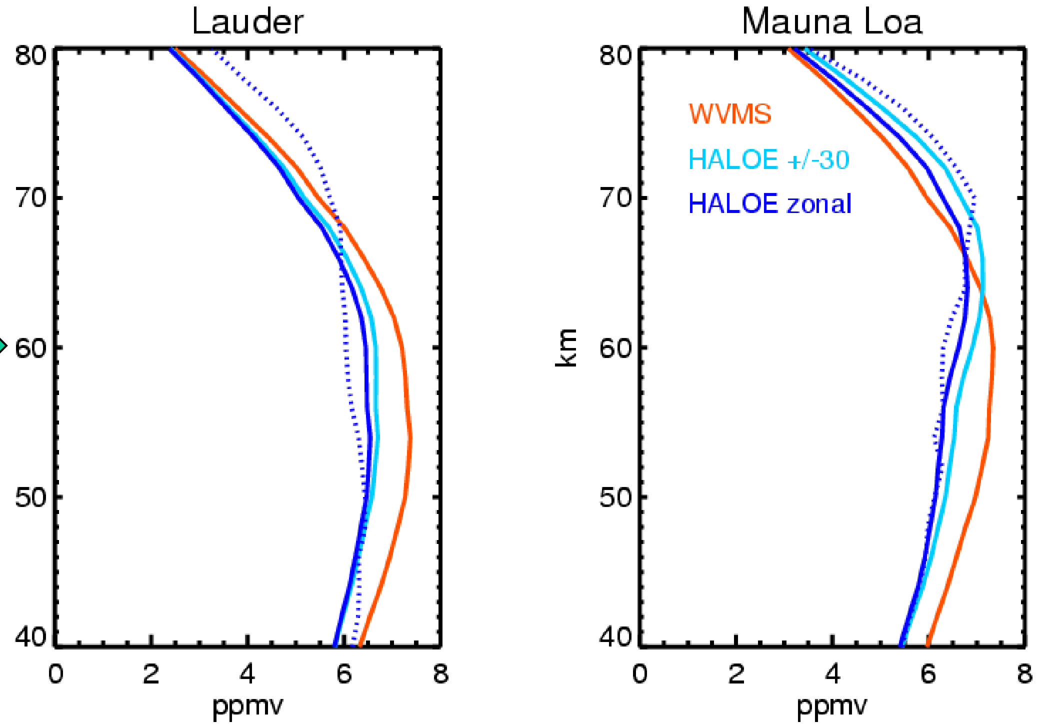
Average of coincident measurements:

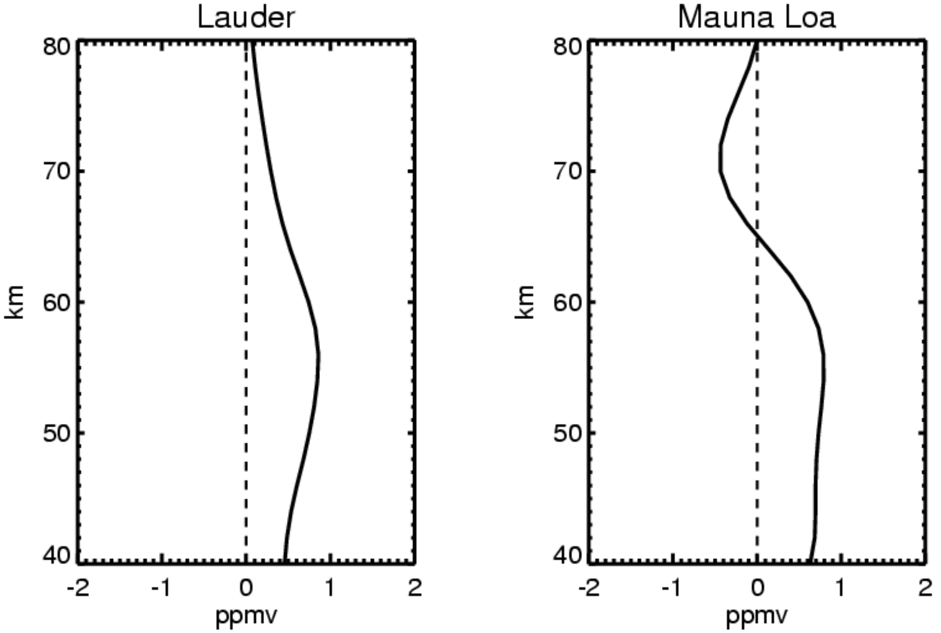
-WVMS

-HALOE (+/- 5º latitude
+/-30º longitude)

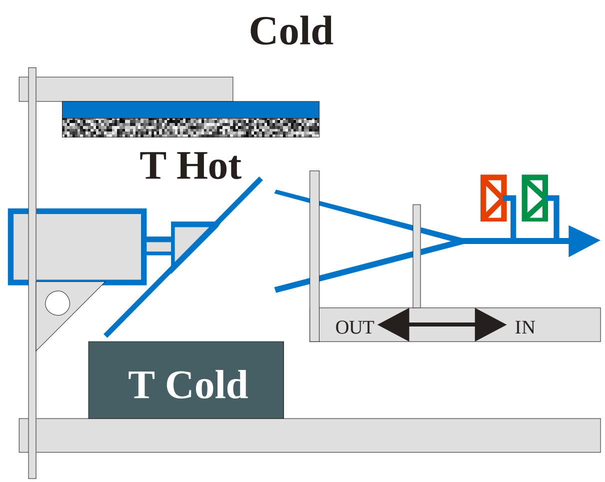
-HALOE zonal (+/- 5º latitude)

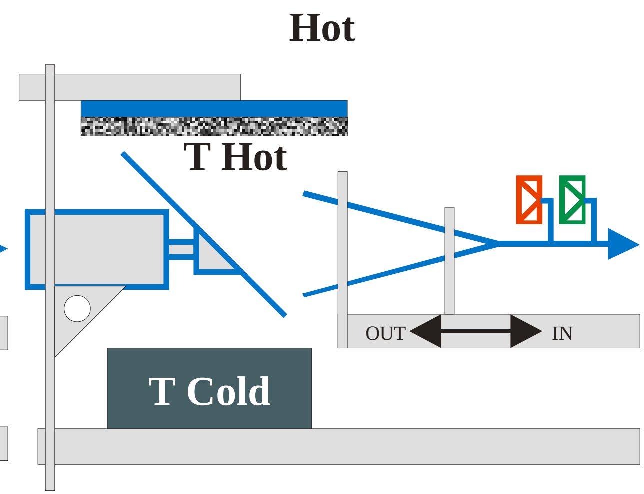
-unconvolved HALOE zonal (dots)





WVMS-HALOE





Cold 1 = (out+in)/2

Cold ND1 = (out+in)/2

Cold ND2 = (out+in)/2

Cold 2 = (out+in)/2

Hot = (out+in)/2

$$\text{Noise Diode 1 Temperature} = \frac{(\text{Cold ND1} - \text{Cold1}) * (\text{T Hot} - \text{T Cold})}{(\text{Hot} - \text{Cold 2})}$$

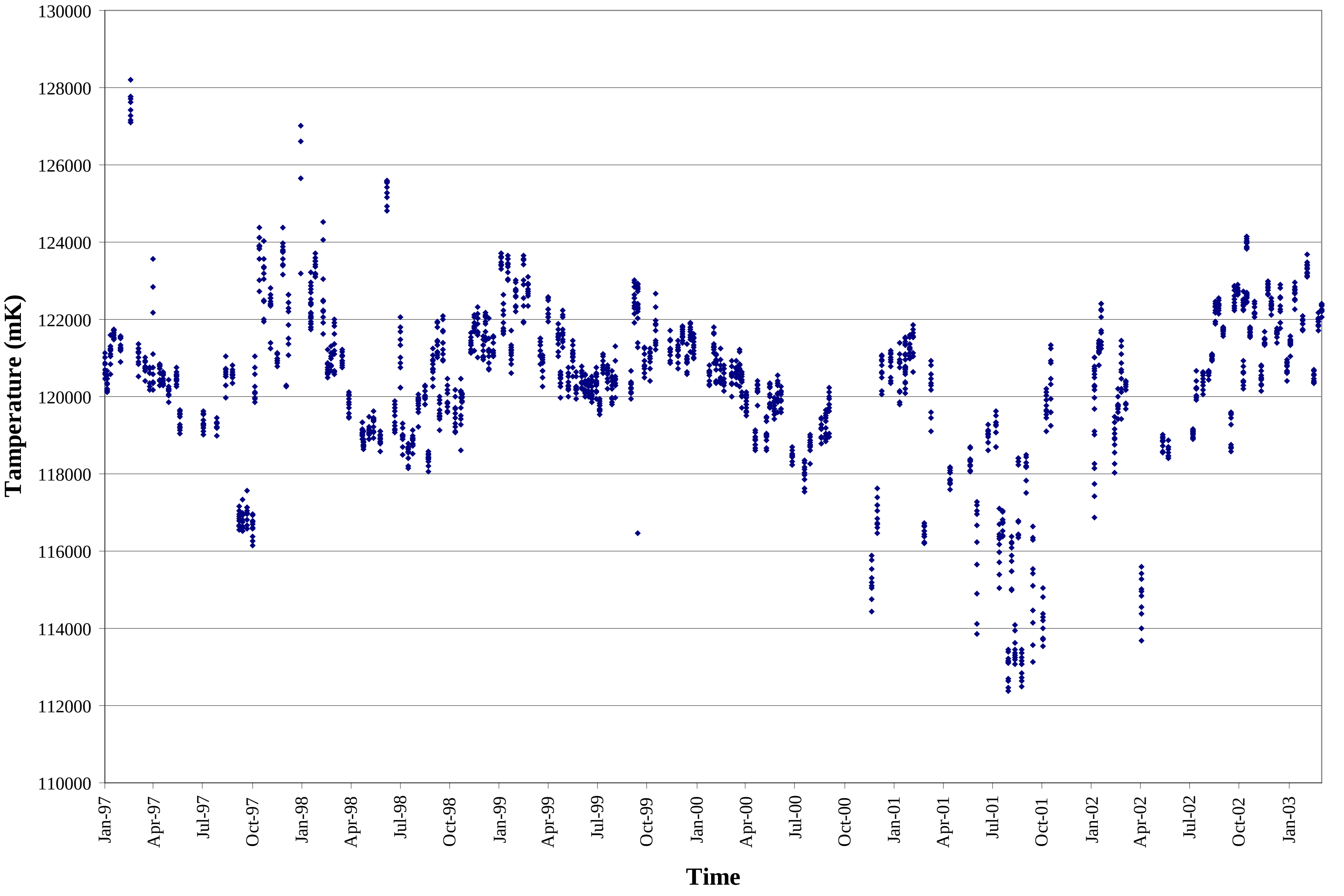
$$\text{Noise Diode 2 Temperature} = \frac{(\text{Cold ND2} - \text{Cold1}) * (\text{T Hot} - \text{T Cold})}{(\text{Hot} - \text{Cold 2})}$$

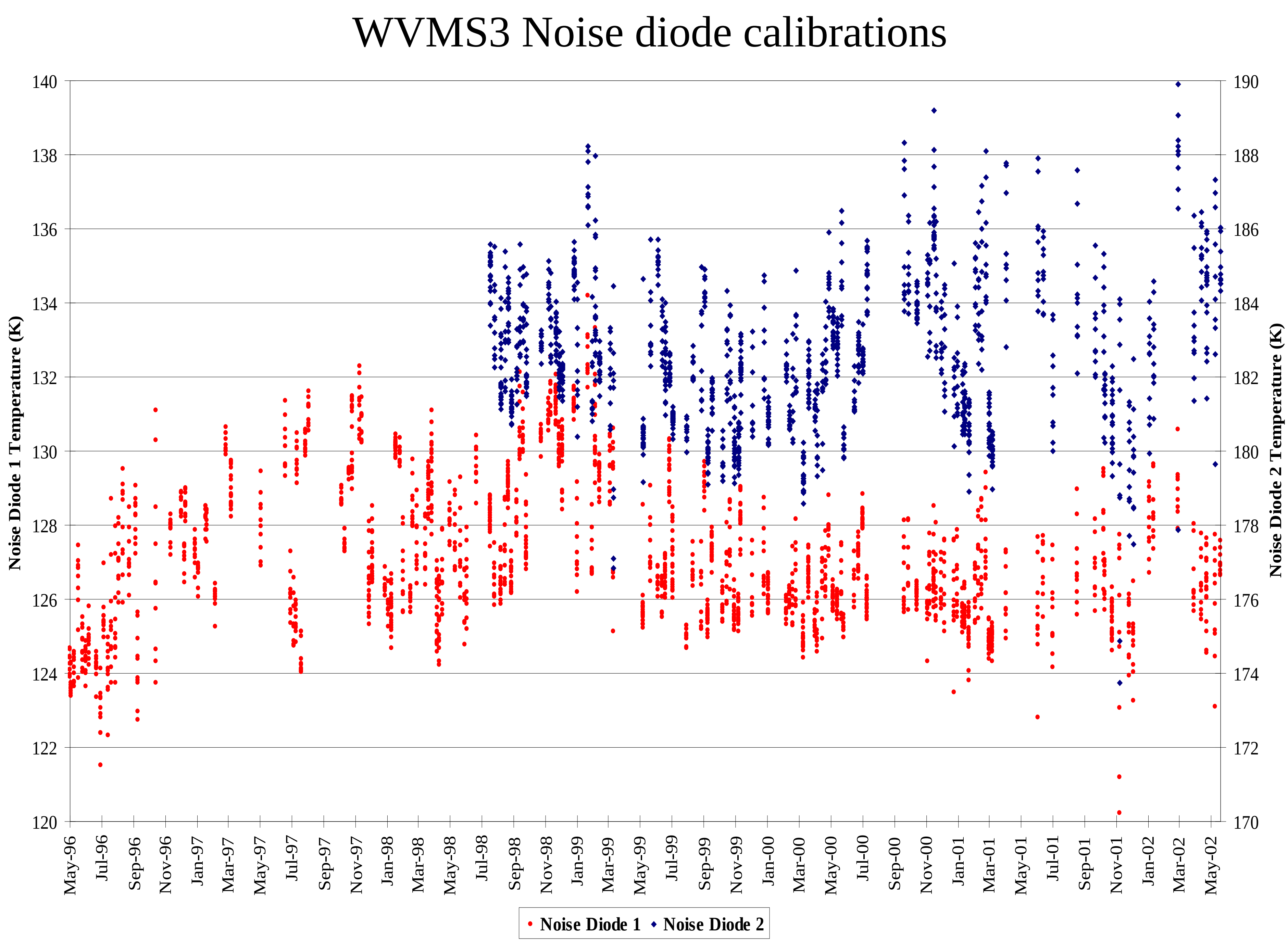
$$\text{Receiver Temperature} = \frac{(\text{Cold1}) * (\text{T Hot} - \text{T Cold})}{(\text{Hot} - \text{Cold 2})} - \text{TCold}$$

Calibration

- Calibrate the noise diode ~weekly using a liquid nitrogen load
  - Assume that variations between weekly calibration are mainly NOT caused by real variations in the noise diode signal, but watch for change over prolonged periods
- All measurements rely on the stability of the noise diode

WVMS1 Noise diode calibration




WVMS3 Noise diode calibrations
Noise Diode 1 Temperature (K)
Noise Diode 2 Temperature (K)
140
138
136
134
132
130
128
126
124
122
120
190
188
186
184
182
180
178
176
174
172
170
May-96
Jul-96
Sep-96
Nov-96
Jan-97
Mar-97
May-97
Jul-97
Sep-97
Nov-97
Jan-98
Mar-98
May-98
Jul-98
Sep-98
Nov-98
Jan-99
Mar-99
May-99
Jul-99
Sep-99
Nov-99
Jan-00
Mar-00
May-00
Jul-00
Sep-00
Nov-00
Jan-01
Mar-01
May-01
Jul-01
Sep-01
Nov-01
Jan-02
Mar-02
May-02
Noise Diode 1
Noise Diode 2

What can cause a bad calibration?

- Peaks of cold load above liquid nitrogen (windy)
- Hot load temperature not correctly measured (non-uniform temperature)
  - Brought outside from hot container and not allowed to equilibrate
  - Direct sun

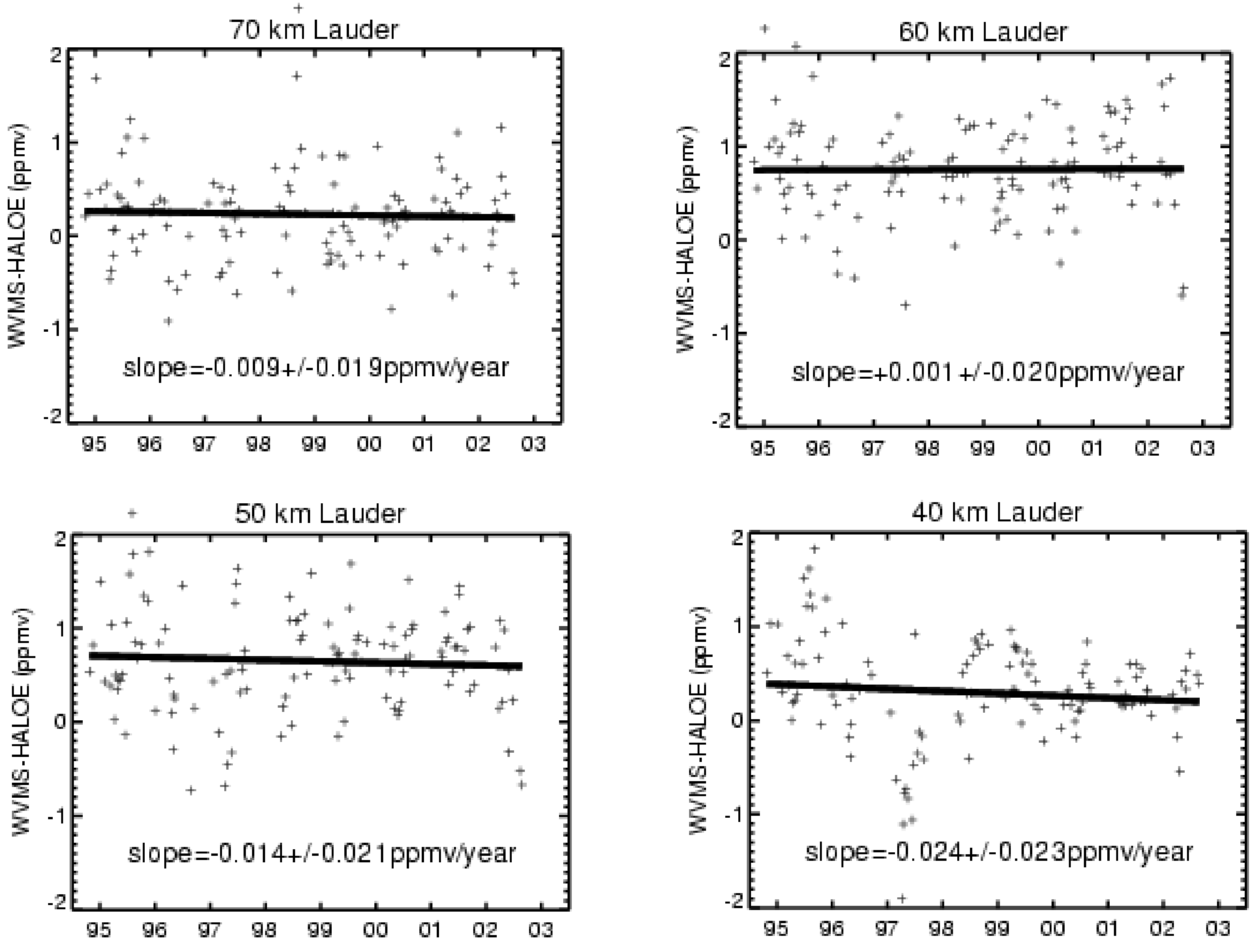
Trend detection with the WVMS instruments

- Calibration
  - Individual measurements are calibrated against a noise diode
  - Noise diode is calibrated weekly using liquid nitrogen
- Pointing
  - 1^{o} error in pointing causes an error ~5% in retrieved water vapor
  - Laser alignment technique used to ensure accurate pointing
- Consistency
  - Improvements to stability are always good
  - Minimal changes made to sensitivity

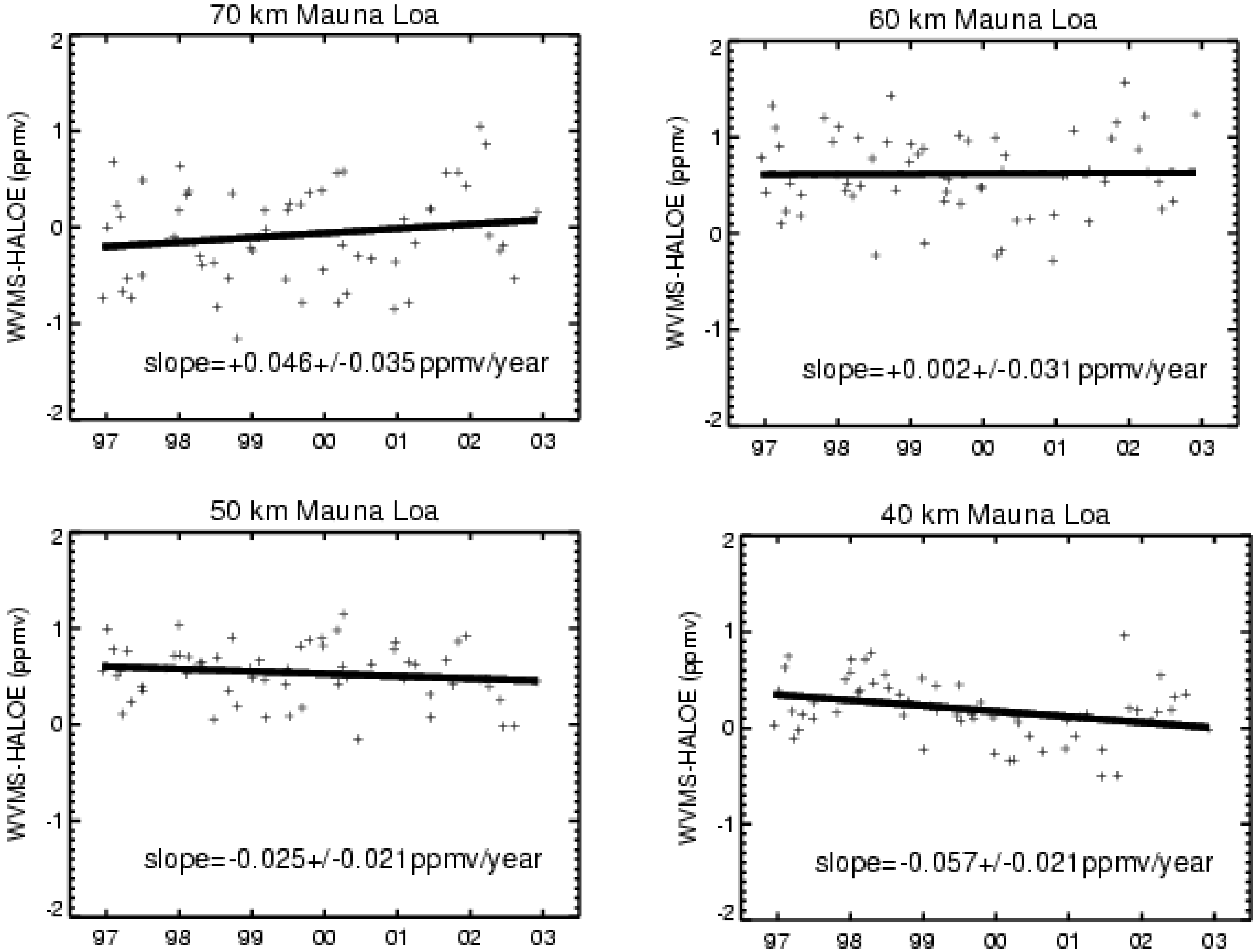
Hard choices

- Vary signal angle or reference angle?
  - Varying the reference angle is intuitively better because this allows one to optimize the signal angle and hence maximize T_{sig}, but baselines tend to be reference angle dependent.
- How close to the horizon should we look?
  - Lower angles generally give more signal, but measurement becomes more sensitive to errors in pointing and to uncertainty in τ_{trop}

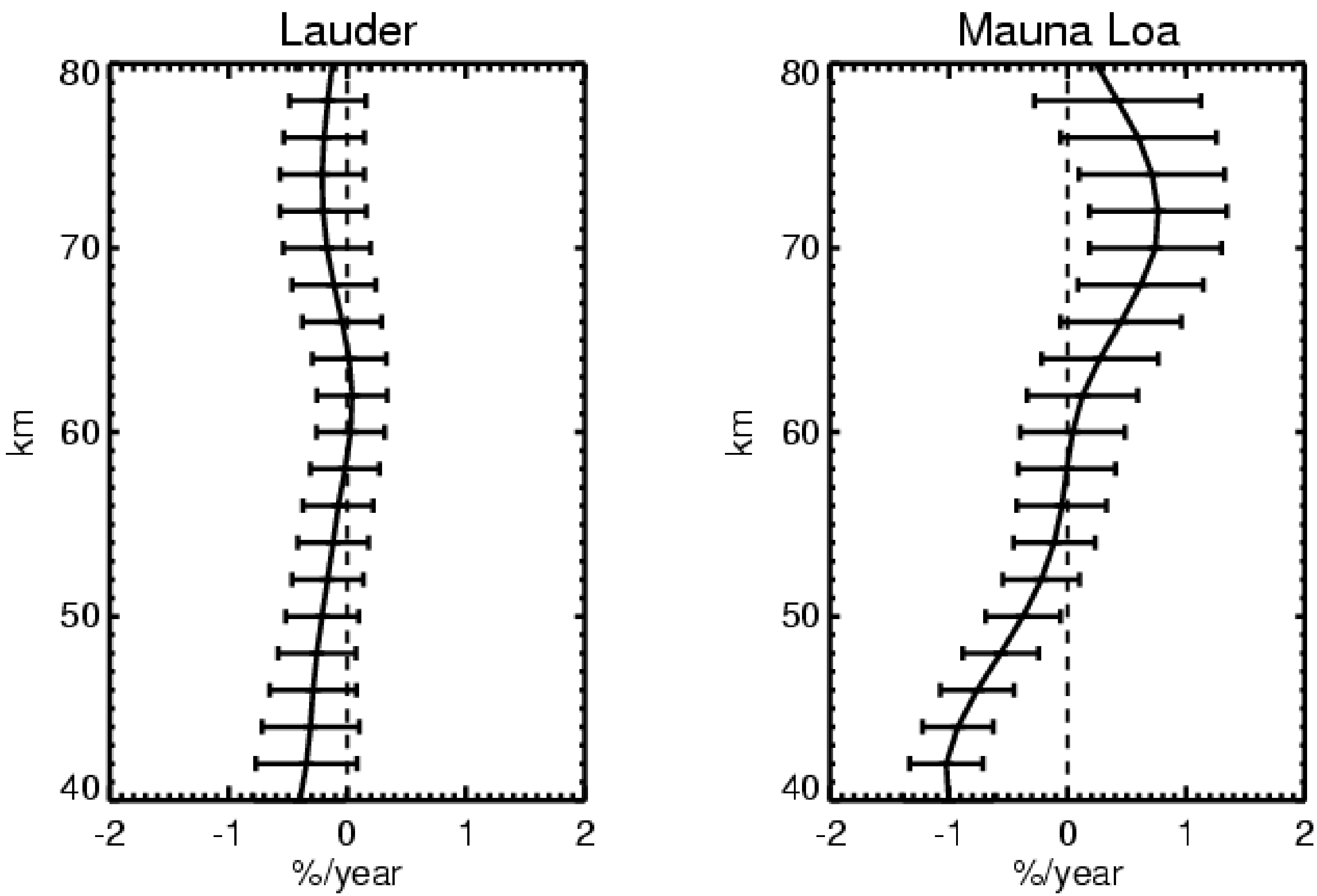
Coincident WVMS-HALOE comparisons at Lauder, and best-fit slopes

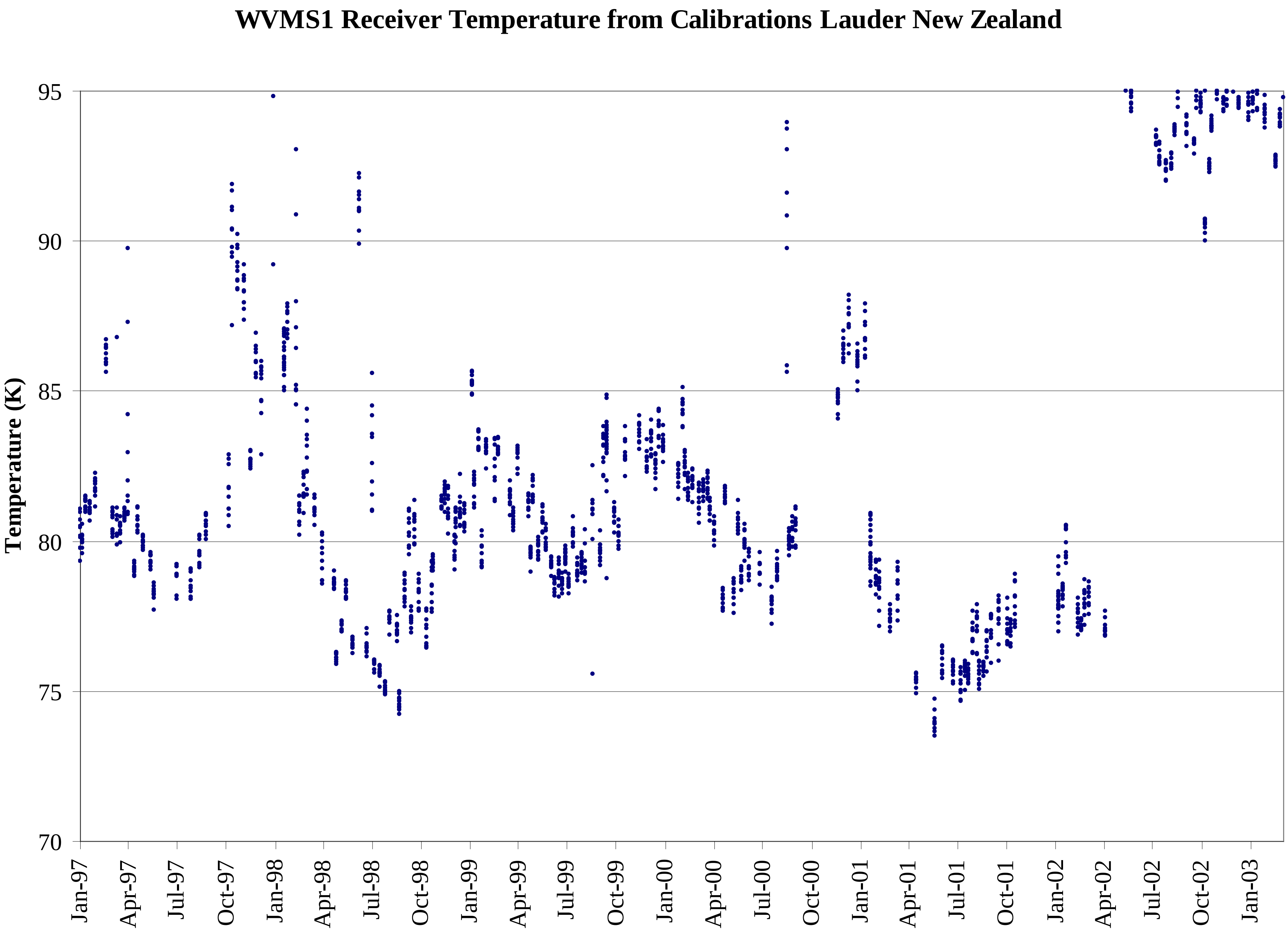


Coincident WVMS-HALOE comparisons at Mauna Loa

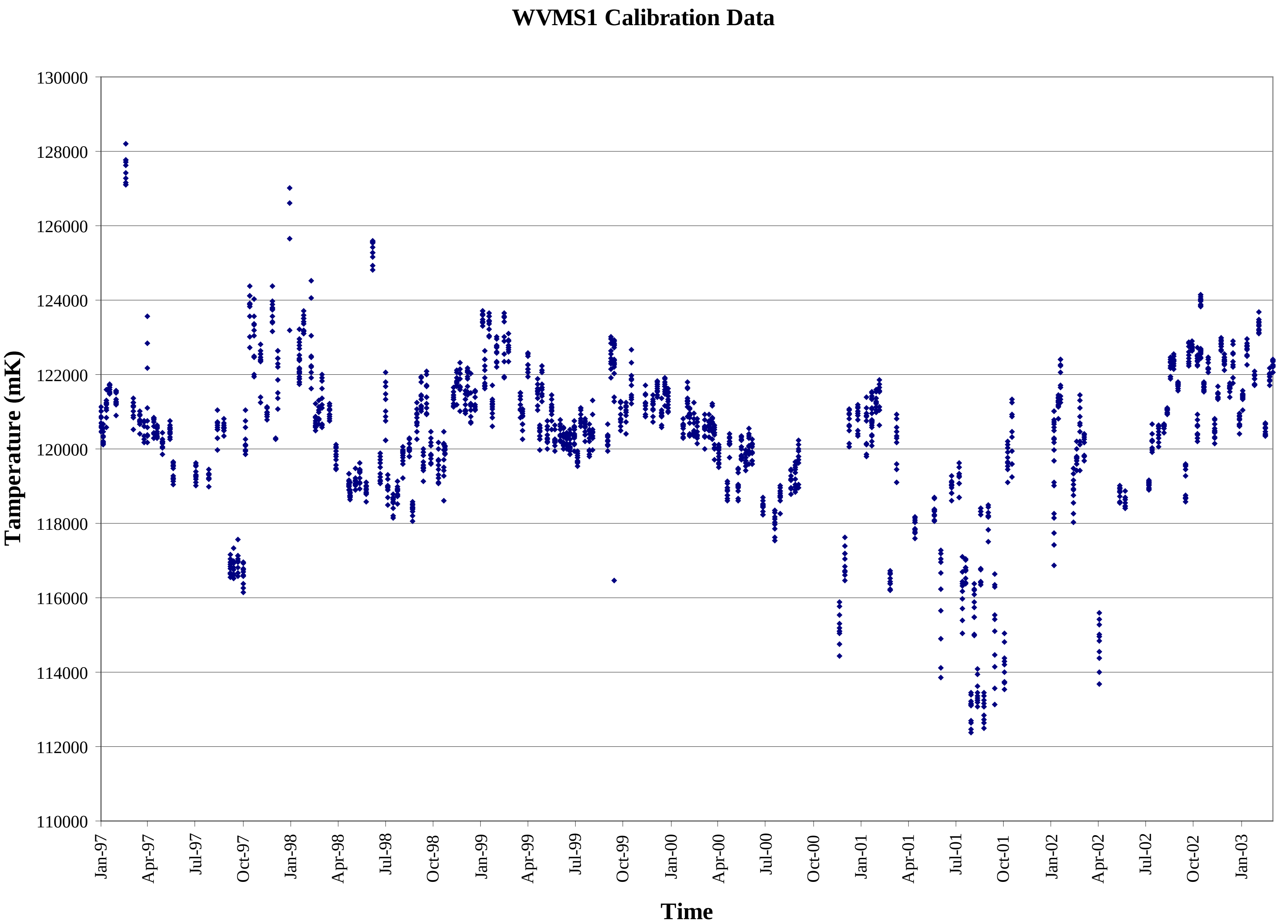


WVMS-HALOE trends from coincident measurements

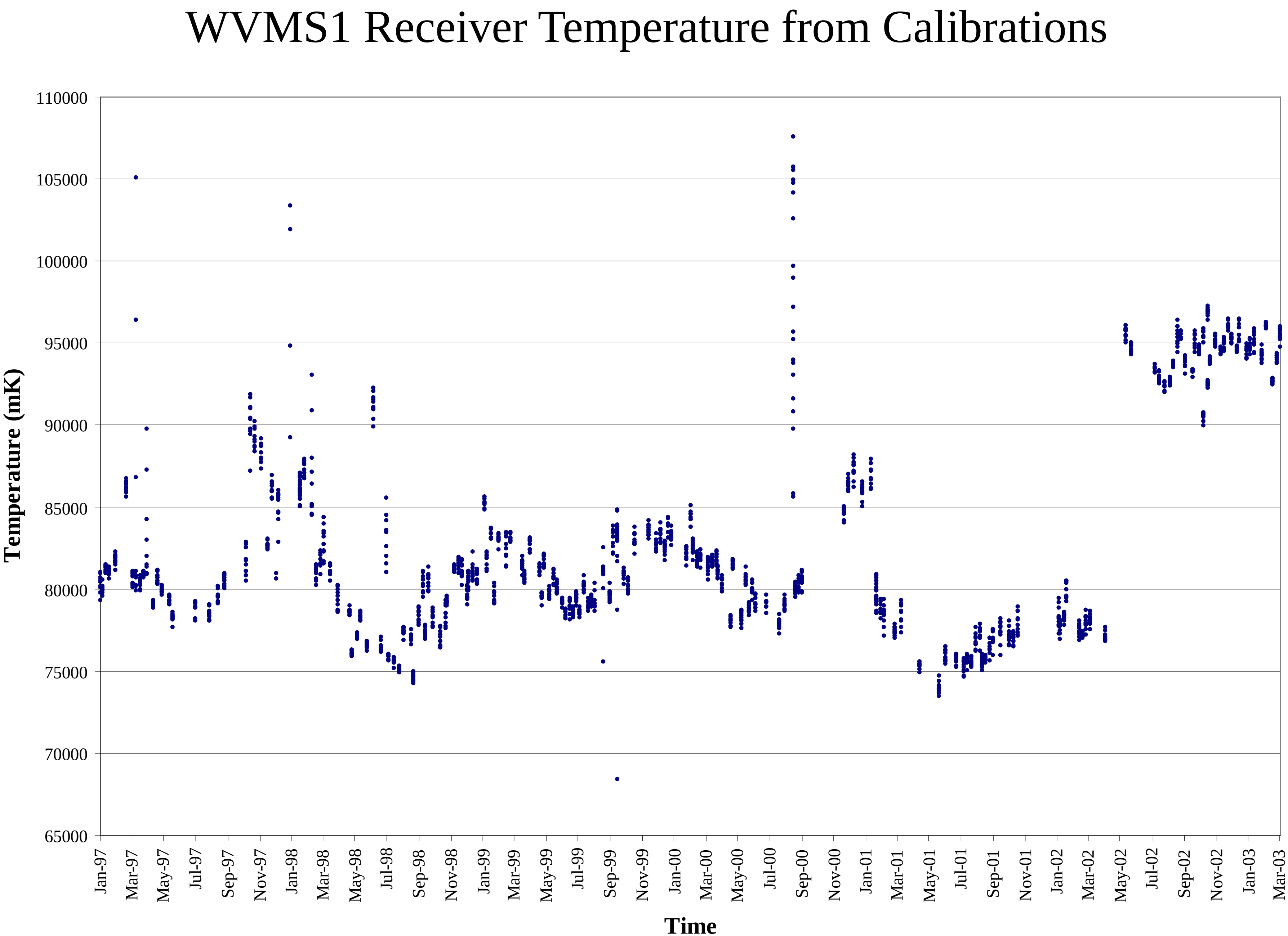




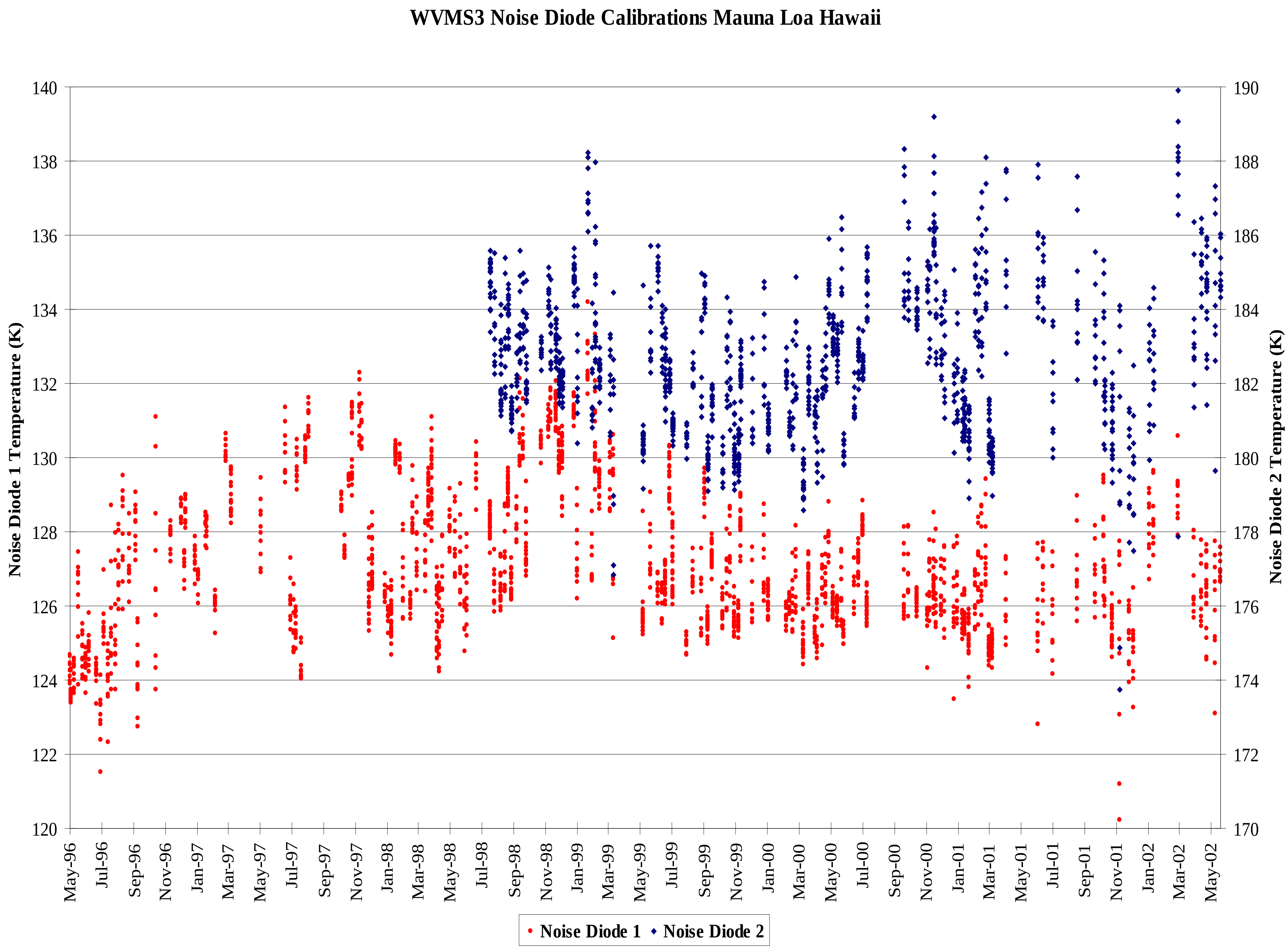
WVMS1 Receiver Temperature from Calibrations Lauder New Zealand
Temperature (K)
95
90
85
80
75
70
Jan-97
Apr-97
Jul-97
Oct-97
Jan-98
Apr-98
Jul-98
Oct-98
Jan-99
Apr-99
Jul-99
Oct-99
Jan-00
Apr-00
Jul-00
Oct-00
Jan-01
Apr-01
Jul-01
Oct-01
Jan-02
Apr-02
Jul-02
Oct-02
Jan-03

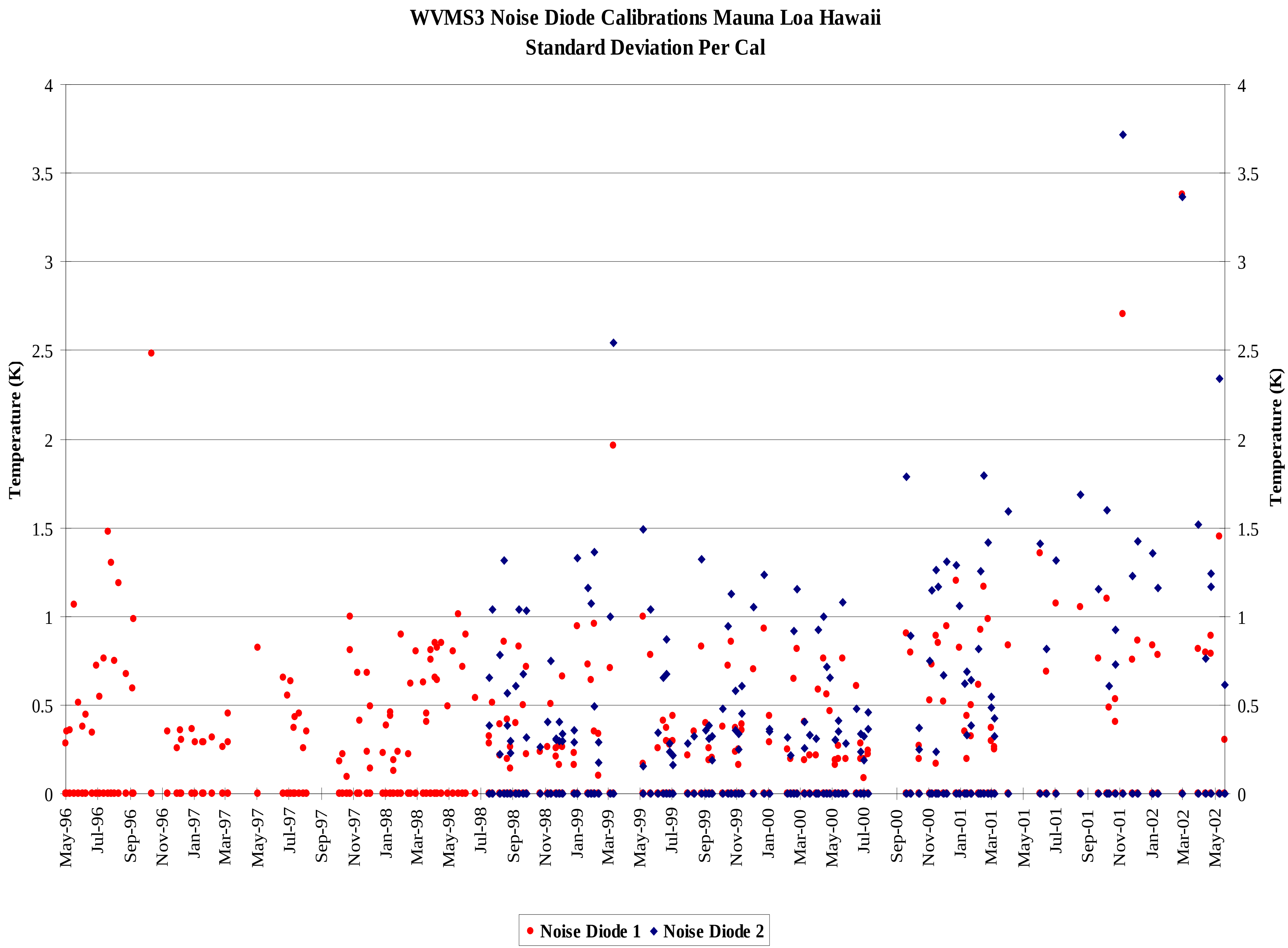


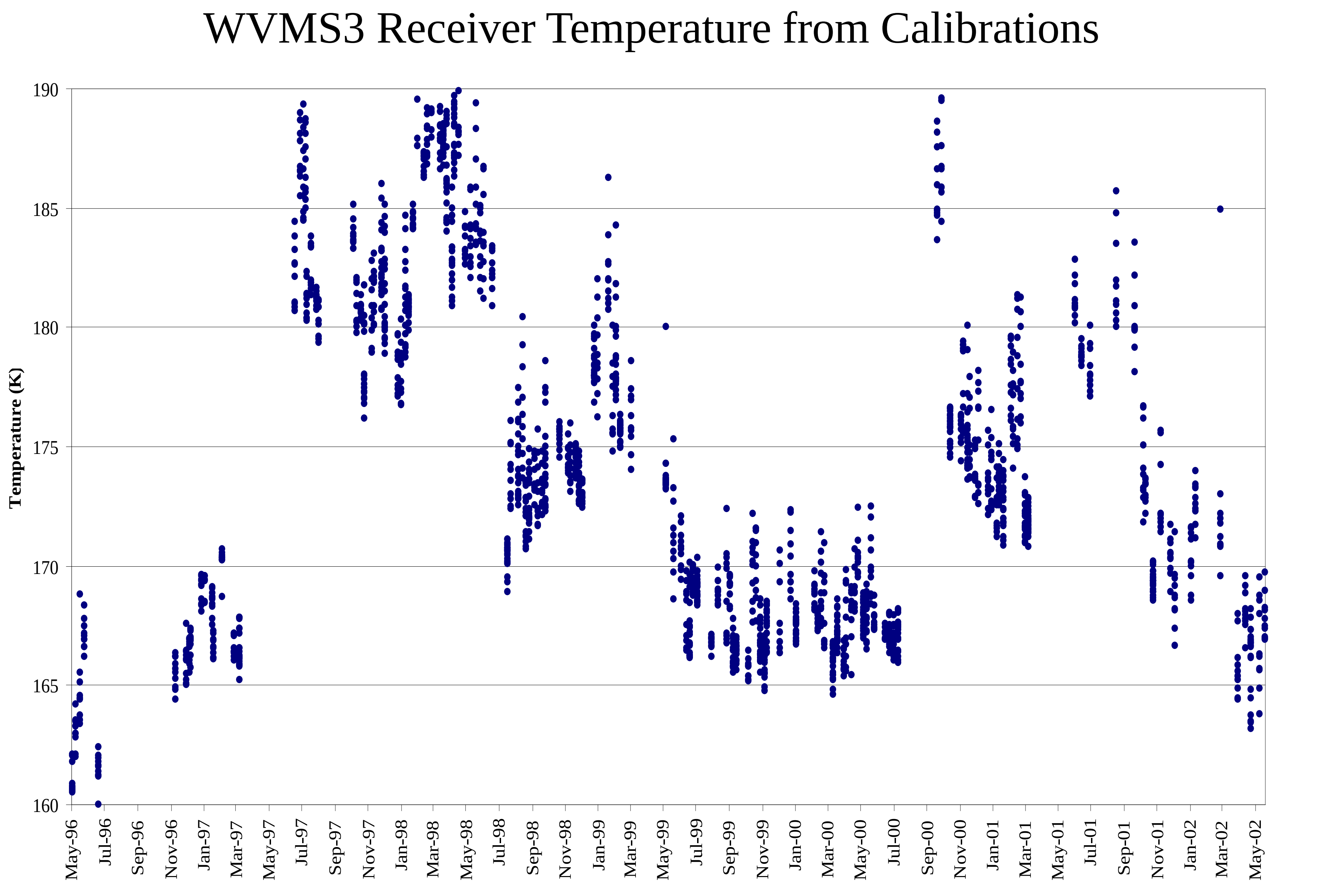
WVMS1 Calibration Data
Tamperature (mK)
130000
128000
126000
124000
122000
120000
118000
116000
114000
112000
110000
Jan-97
Apr-97
Jul-97
Oct-97
Jan-98
Apr-98
Jul-98
Oct-98
Jan-99
Apr-99
Jul-99
Oct-99
Jan-00
Apr-00
Jul-00
Oct-00
Jan-01
Apr-01
Jul-01
Oct-01
Jan-02
Apr-02
Jul-02
Oct-02
Jan-03
Time



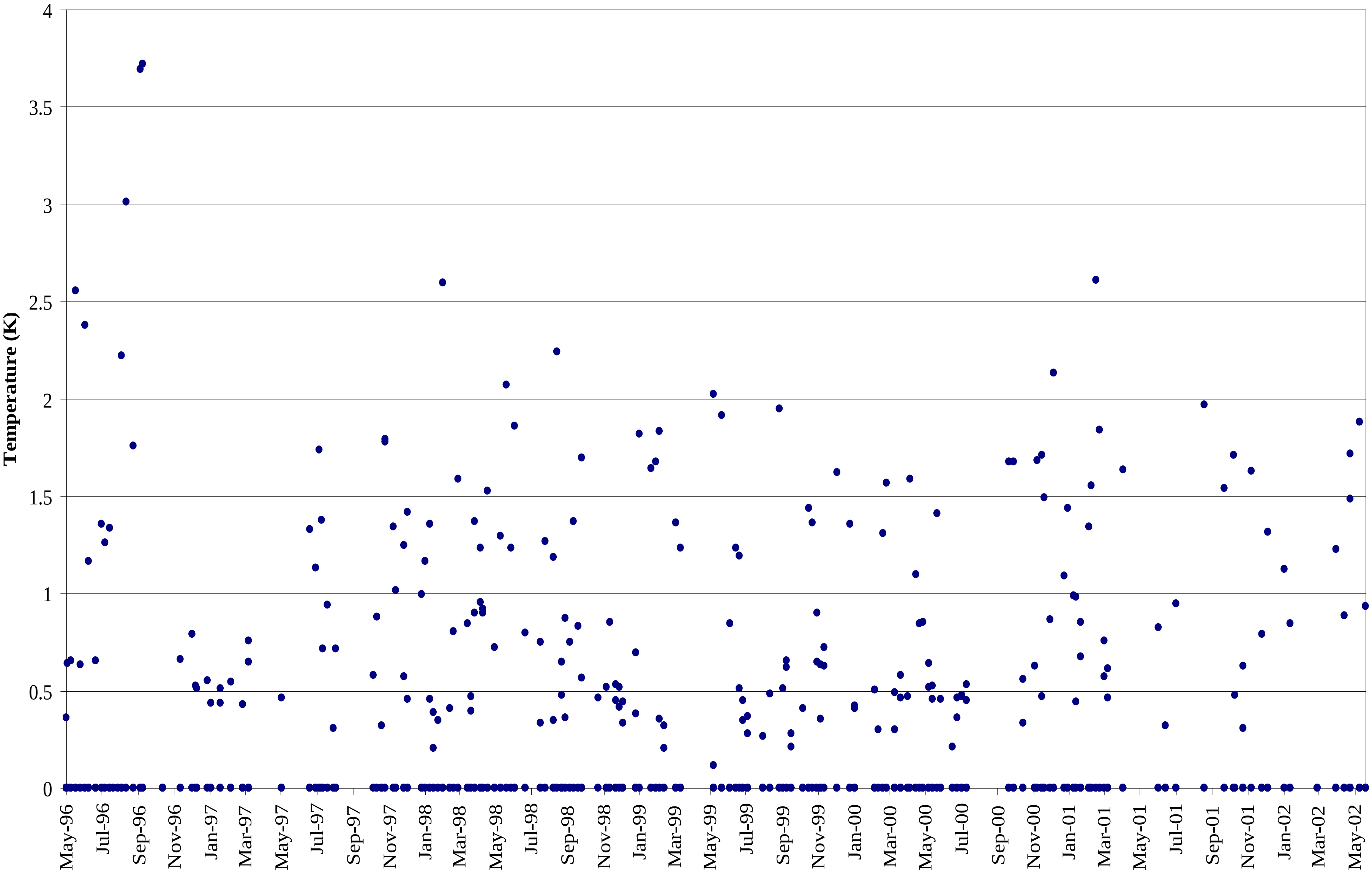
WVMS1 Receiver Temperature from Calibrations
Temperature (mK)
110000
105000
100000
95000
90000
85000
80000
75000
70000
65000
Jan-97
Mar-97
May-97
Jul-97
Sep-97
Nov-97
Jan-98
Mar-98
May-98
Jul-98
Sep-98
Nov-98
Jan-99
Mar-99
May-99
Jul-99
Sep-99
Nov-99
Jan-00
Mar-00
May-00
Jul-00
Sep-00
Nov-00
Jan-01
Mar-01
May-01
Jul-01
Sep-01
Nov-01
Jan-02
Mar-02
May-02
Jul-02
Sep-02
Nov-02
Jan-03
Mar-03
Time

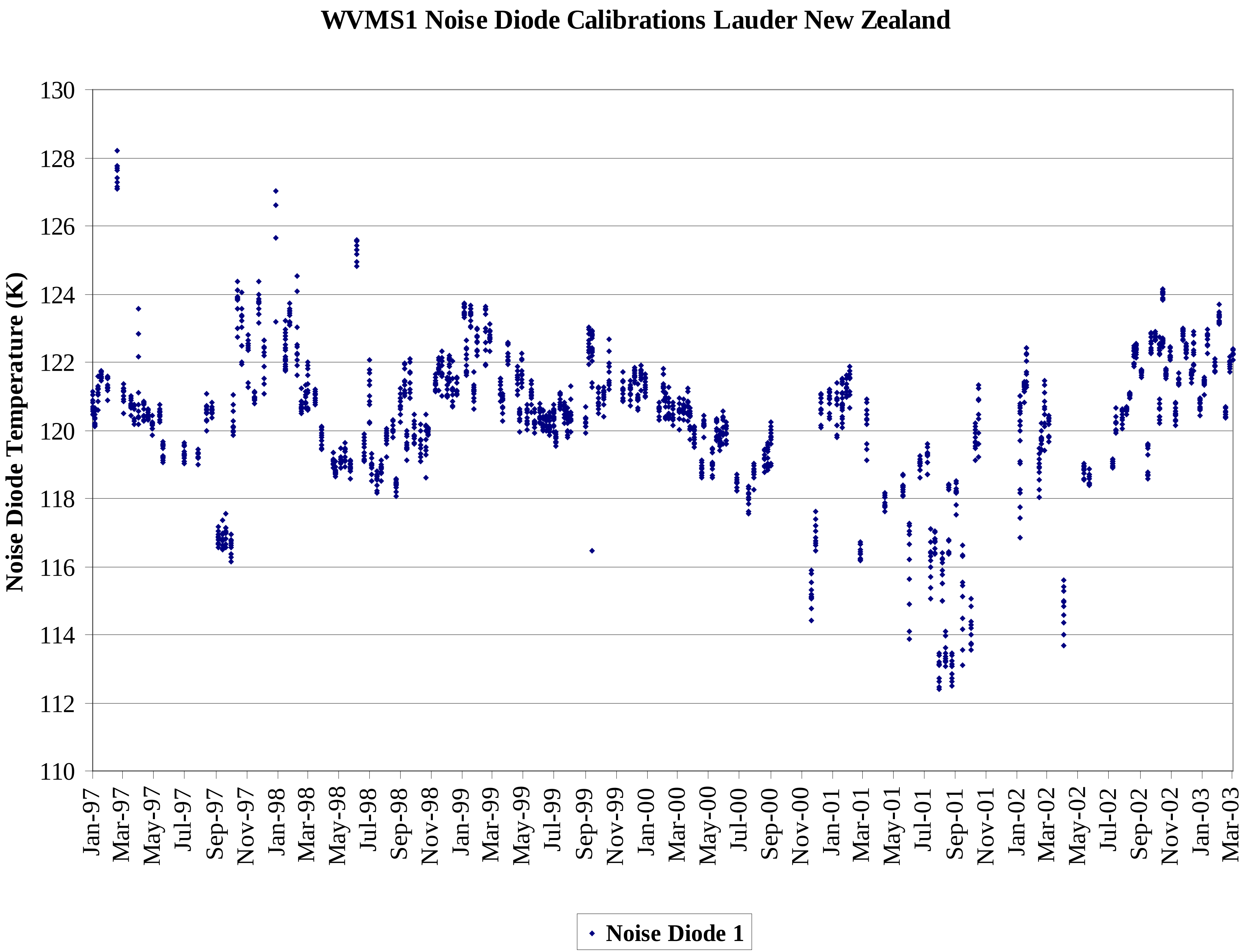

WVMS3 Noise Diode Calibrations Mauna Loa Hawaii
Noise Diode 1 Temperature (K)
Noise Diode 2 Temperature (K)
140
138
136
134
132
130
128
126
124
122
120
190
188
186
184
182
180
178
176
174
172
170
May-96
Jul-96
Sep-96
Nov-96
Jan-97
Mar-97
May-97
Jul-97
Sep-97
Nov-97
Jan-98
Mar-98
May-98
Jul-98
Sep-98
Nov-98
Jan-99
Mar-99
May-99
Jul-99
Sep-99
Nov-99
Jan-00
Mar-00
May-00
Jul-00
Sep-00
Nov-00
Jan-01
Mar-01
May-01
Jul-01
Sep-01
Nov-01
Jan-02
Mar-02
May-02
Noise Diode 1
Noise Diode 2


WVMS3 Noise Diode Calibrations Mauna Loa Hawaii
Standard Deviation Per Cal
Temperature (K)
0
0.5
1
1.5
2
2.5
3
3.5
4
May-96
Jul-96
Sep-96
Nov-96
Jan-97
Mar-97
May-97
Jul-97
Sep-97
Nov-97
Jan-98
Mar-98
May-98
Jul-98
Sep-98
Nov-98
Jan-99
Mar-99
May-99
Jul-99
Sep-99
Nov-99
Jan-00
Mar-00
May-00
Jul-00
Sep-00
Nov-00
Jan-01
Mar-01
May-01
Jul-01
Sep-01
Nov-01
Jan-02
Mar-02
May-02
Noise Diode 1
Noise Diode 2

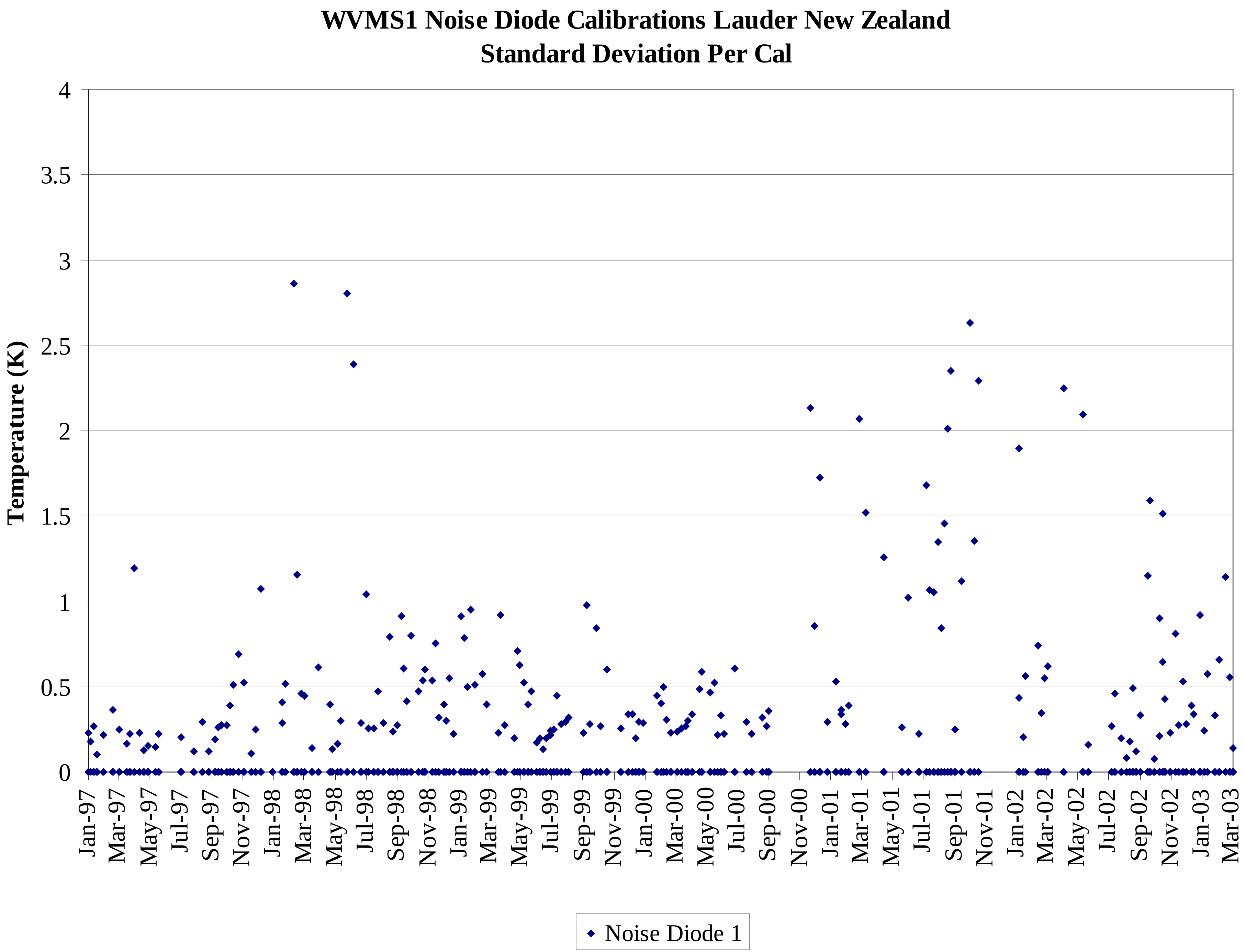

WVMS3 Receiver Temperature from Calibrations
Temperature (K)
190
185
180
175
170
165
160
May-96
Jul-96
Sep-96
Nov-96
Jan-97
Mar-97
May-97
Jul-97
Sep-97
Nov-97
Jan-98
Mar-98
May-98
Jul-98
Sep-98
Nov-98
Jan-99
Mar-99
May-99
Jul-99
Sep-99
Nov-99
Jan-00
Mar-00
May-00
Jul-00
Sep-00
Nov-00
Jan-01
Mar-01
May-01
Jul-01
Sep-01
Nov-01
Jan-02
Mar-02
May-02

WVMS3 Receiver Temperature from Calibrations, σ per calibration

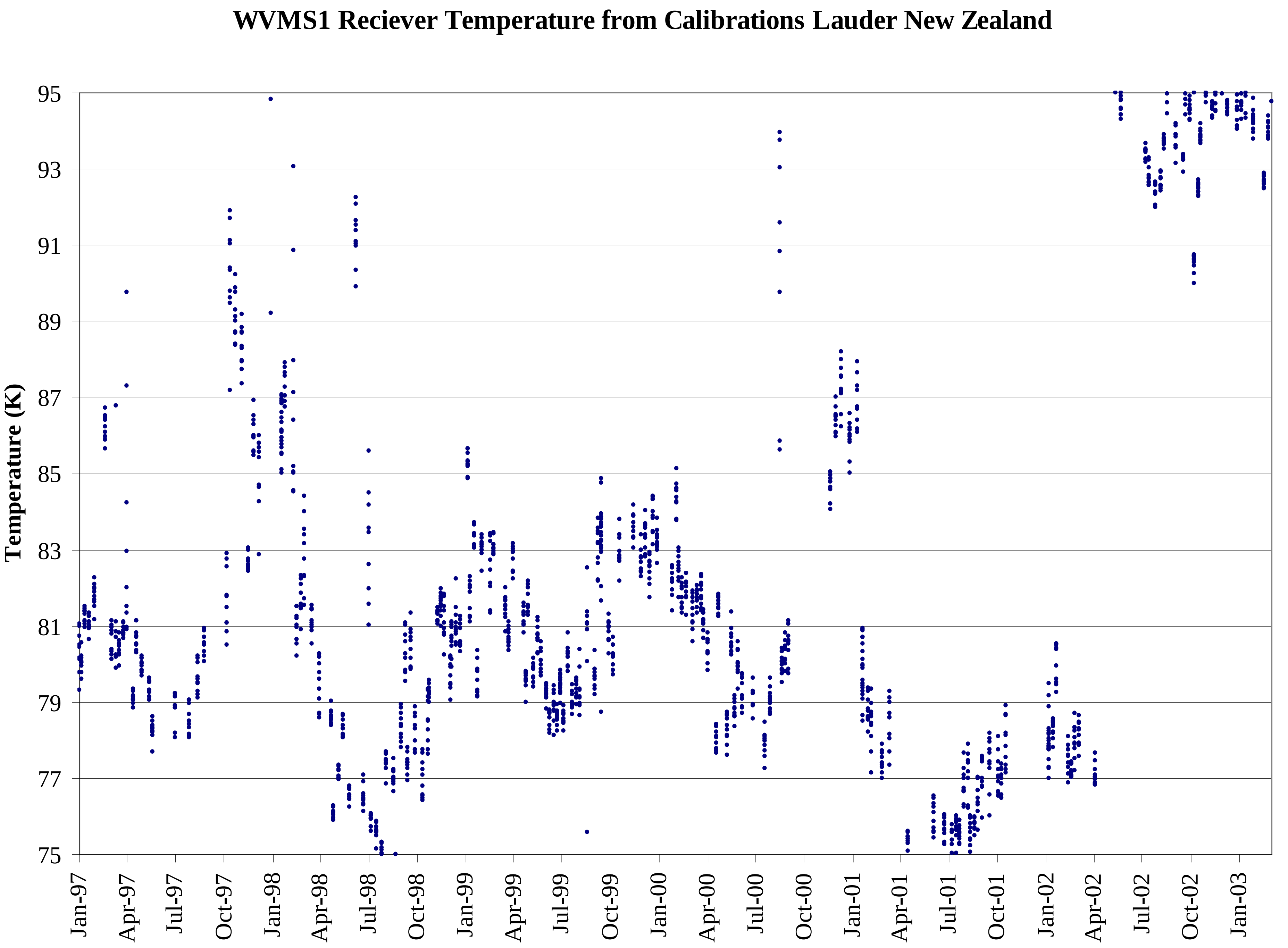




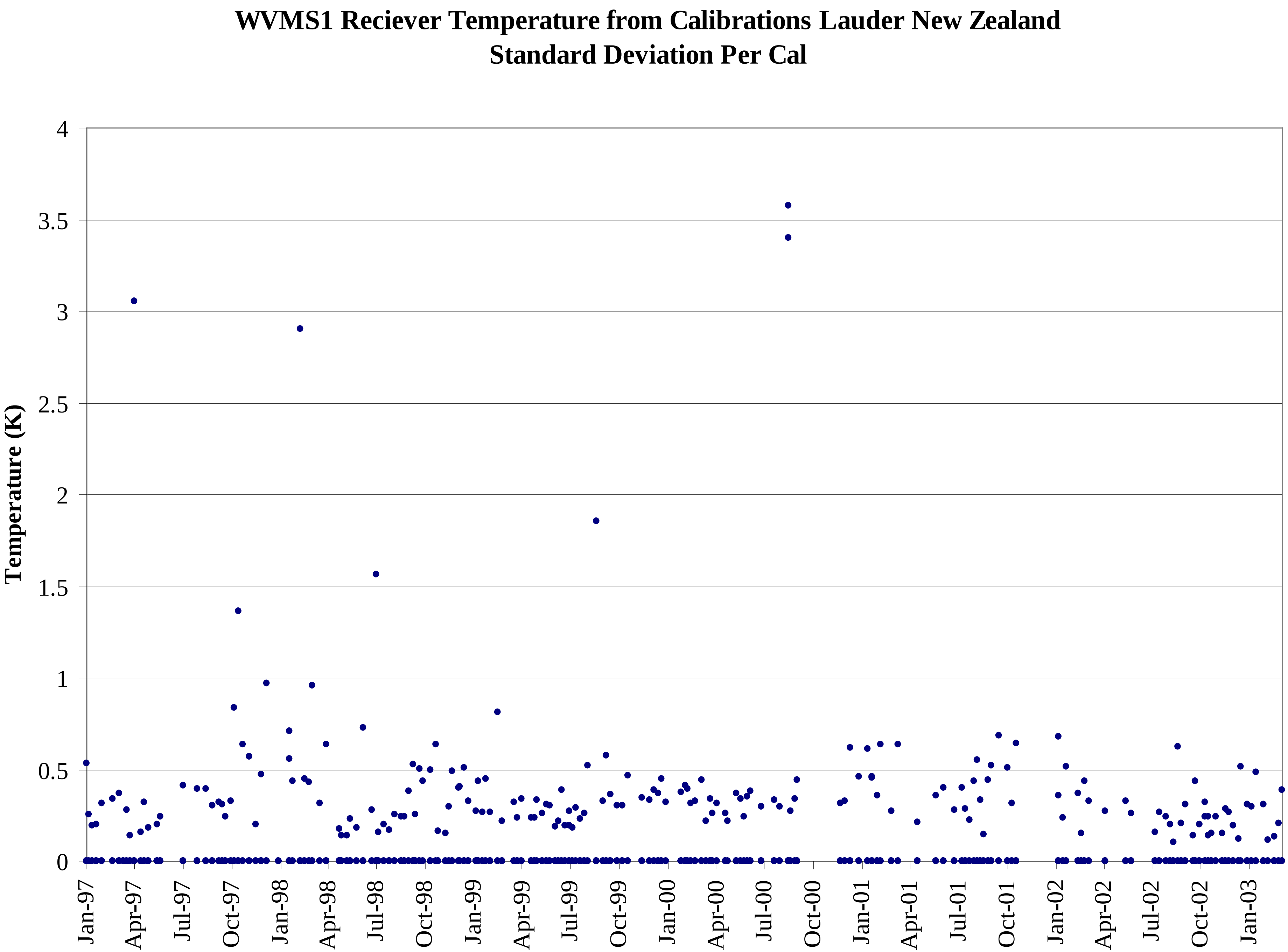
WVMS1 Noise Diode Calibrations Lauder New Zealand
Noise Diode Temperature (K)
130
128
126
124
122
120
118
116
114
112
110
Jan-97
Mar-97
May-97
Jul-97
Sep-97
Nov-97
Jan-98
Mar-98
May-98
Jul-98
Sep-98
Nov-98
Jan-99
Mar-99
May-99
Jul-99
Sep-99
Nov-99
Jan-00
Mar-00
May-00
Jul-00
Sep-00
Nov-00
Jan-01
Mar-01
May-01
Jul-01
Sep-01
Nov-01
Jan-02
Mar-02
May-02
Jul-02
Sep-02
Nov-02
Jan-03
Mar-03
Noise Diode 1



WVMS1 Noise Diode Calibrations Lauder New Zealand
Standard Deviation Per Cal
Temperature (K)
4
3.5
3
2.5
2
1.5
1
0.5
0
Jan-97
Mar-97
May-97
Jul-97
Sep-97
Nov-97
Jan-98
Mar-98
May-98
Jul-98
Sep-98
Nov-98
Jan-99
Mar-99
May-99
Jul-99
Sep-99
Nov-99
Jan-00
Mar-00
May-00
Jul-00
Sep-00
Nov-00
Jan-01
Mar-01
May-01
Jul-01
Sep-01
Nov-01
Jan-02
Mar-02
May-02
Jul-02
Sep-02
Nov-02
Jan-03
Mar-03
Noise Diode 1



WVMS1 Reciever Temperature from Calibrations Lauder New Zealand
Temperature (K)
95
93
91
89
87
85
83
81
79
77
75
Jan-97
Apr-97
Jul-97
Oct-97
Jan-98
Apr-98
Jul-98
Oct-98
Jan-99
Apr-99
Jul-99
Oct-99
Jan-00
Apr-00
Jul-00
Oct-00
Jan-01
Apr-01
Jul-01
Oct-01
Jan-02
Apr-02
Jul-02
Oct-02
Jan-03



WVMS1 Reciever Temperature from Calibrations Lauder New Zealand
Standard Deviation Per Cal
Temperature (K)
4
3.5
3
2.5
2
1.5
1
0.5
0
Jan-97
Apr-97
Jul-97
Oct-97
Jan-98
Apr-98
Jul-98
Oct-98
Jan-99
Apr-99
Jul-99
Oct-99
Jan-00
Apr-00
Jul-00
Oct-00
Jan-01
Apr-01
Jul-01
Oct-01
Jan-02
Apr-02
Jul-02
Oct-02
Jan-03

Remote Data Access

- Data is brought back ~weekly from field sites over phone lines using PCAnywhere software
  - No firewall problems
  - Don’t have a choice – we’re still running DOS programs
- We keep only the tips, the 20 minute averages of the calibrated T_{sig}-T_{ref}, and a few system parameters

Retrievals

- Optimal estimation based scheme
- 14 MHz channels used only for tips
- Assumed baseline error – Degrades lower altitude retrieval sensitivity
  - Baseline fits were used during a brief period in 1996 at Mauna Loa, when the baselines were unusually bad
  - Spectral resolution is reduced far away from line center, making baseline fits more difficult

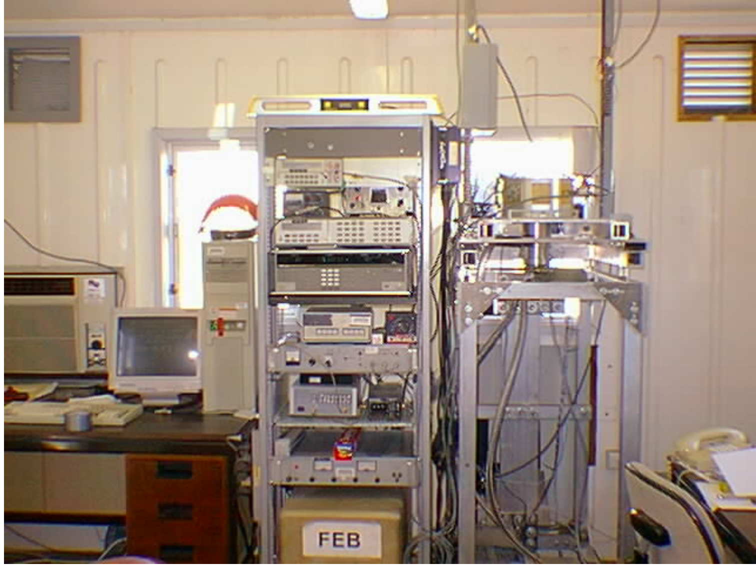
Retrievals

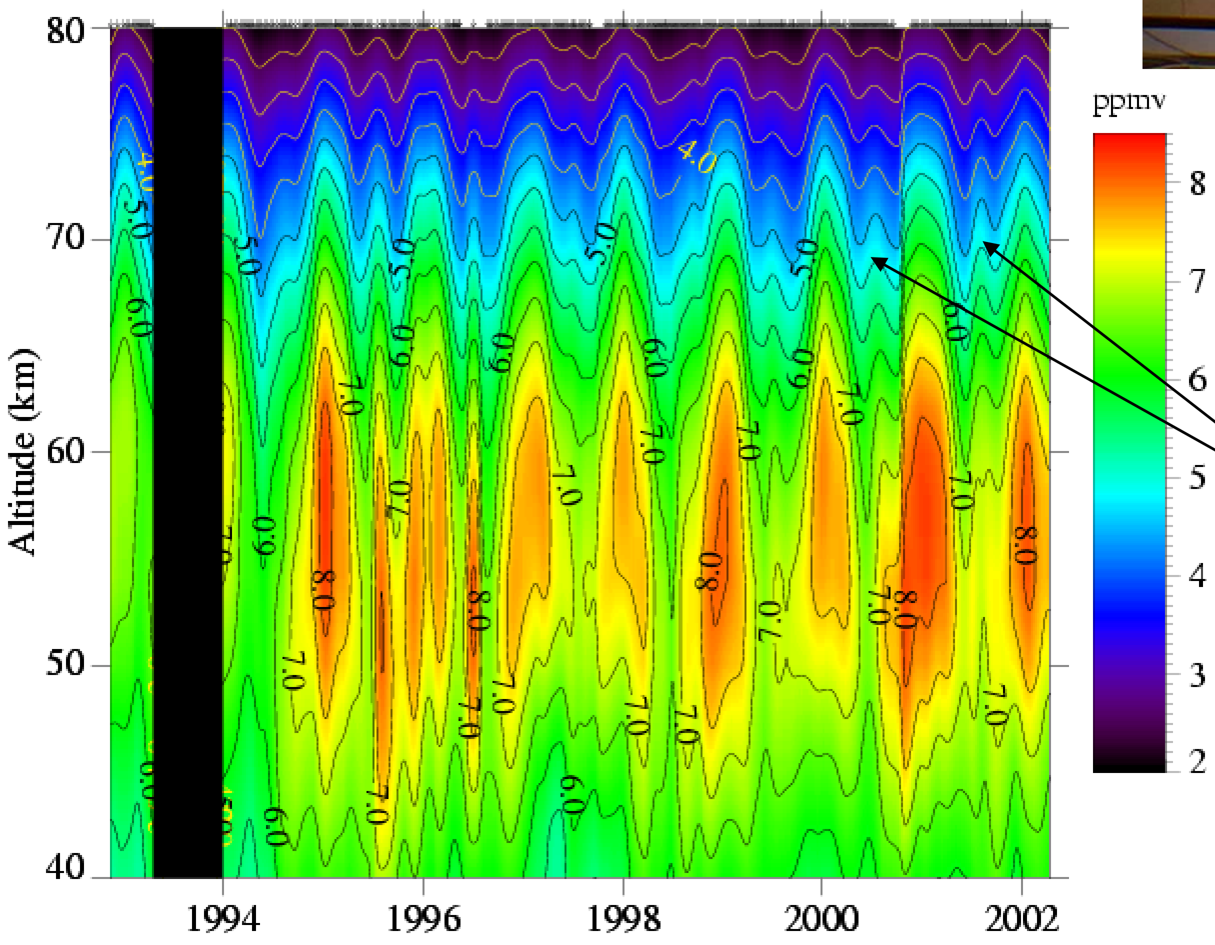
- Forward model is run all the way to the ground, using tips to provide the tropospheric optical depth (assuming a 2 km scale height for H_2O)
- Retrievals are generally performed over 500 averaged scans (~1 week)
  - Important to obtain best sensitivity in the mesosphere
  - Reduces a priori influence everywhere – important for trend studies

Philosophy

- What can a ground-based microwave instrument offer in a world of satellite data?
  - Validation
  - We can fix our instruments!
    - Measurements can be made for as long as spare parts and funding are available –trend studies
  - Continuous observations from one spot
    - Diurnal variations – photochemistry, tides

Data since 1993 from Lauder, New Zealand (45.0S, 169.7E)

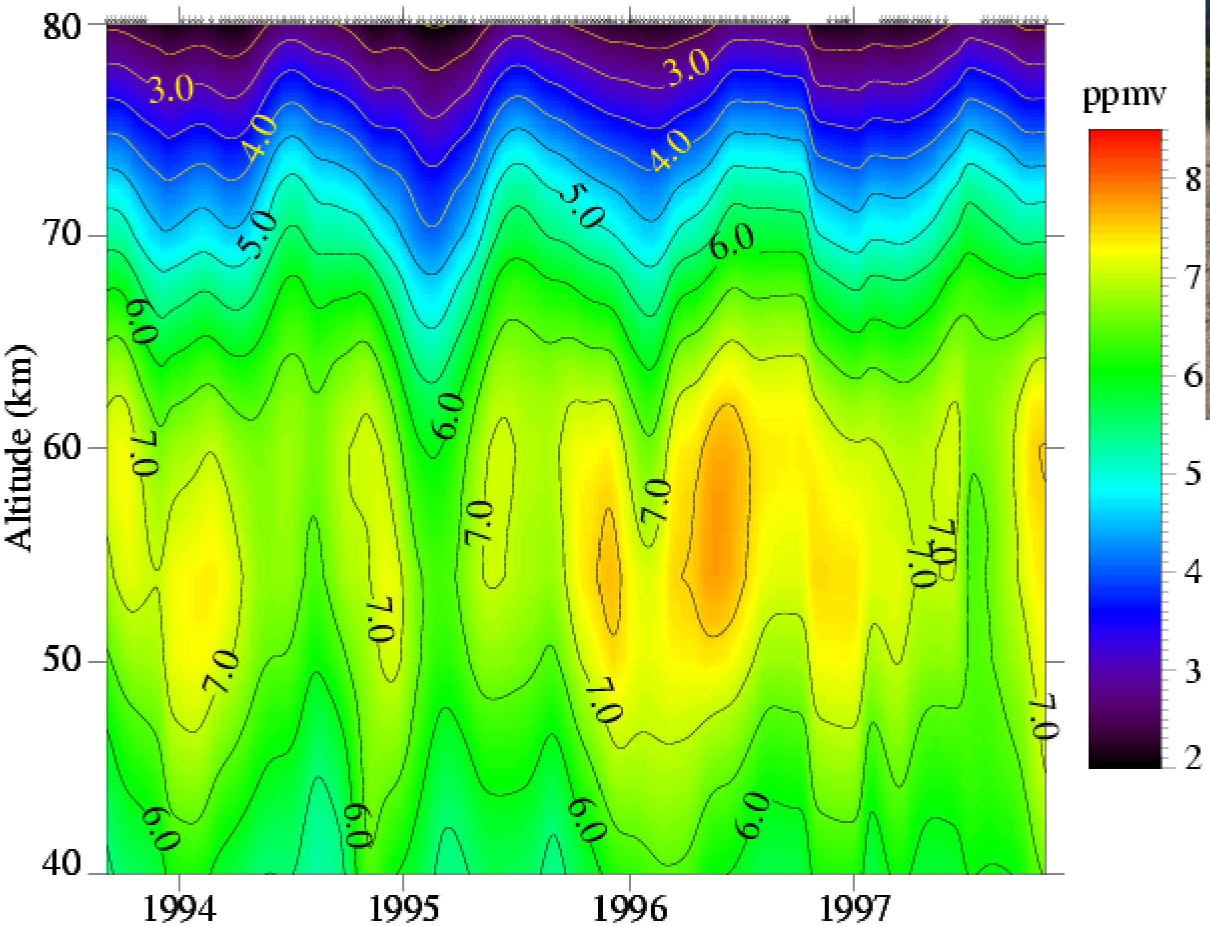




In addition to a large annual cycle, these measurements show a large semi-annual cycle in the upper mesosphere.

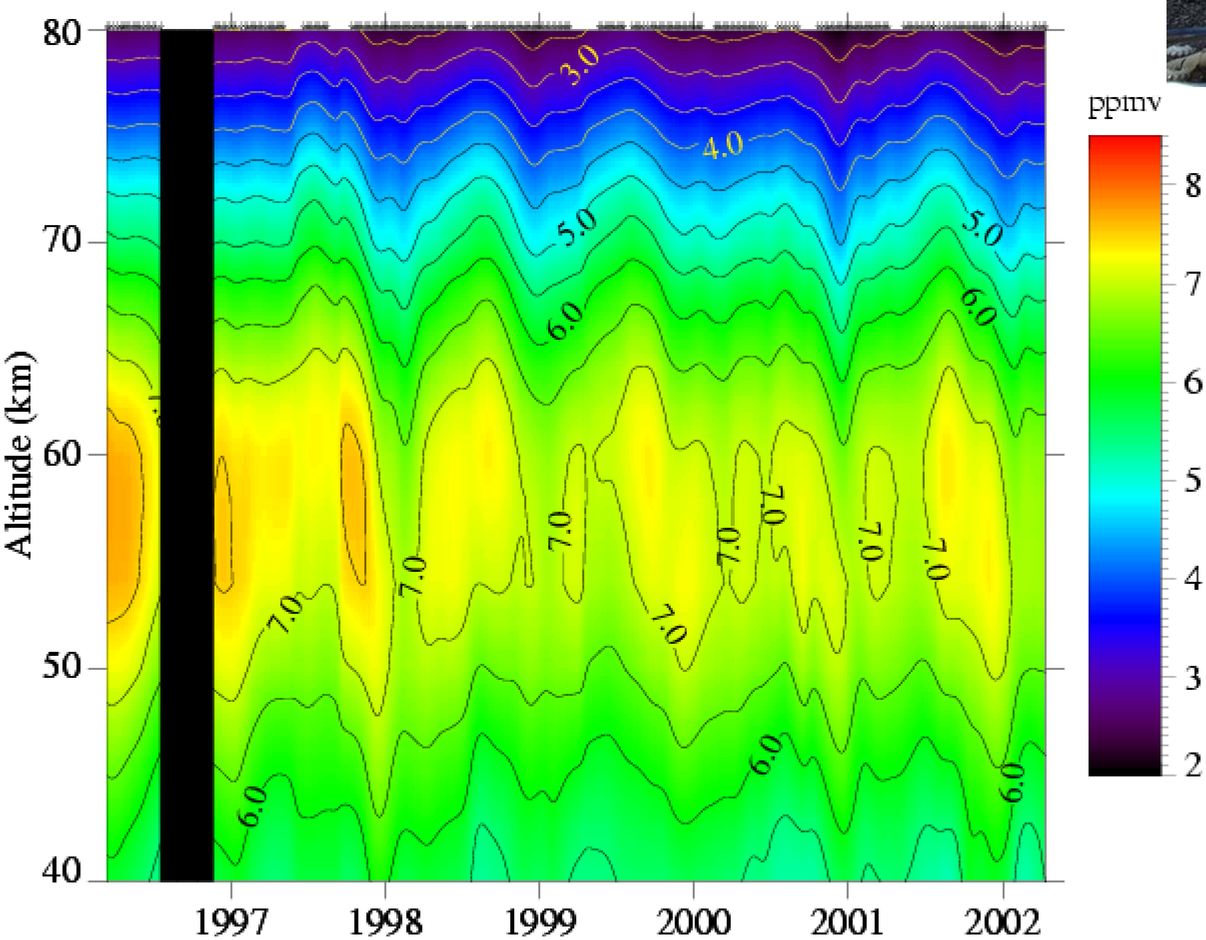
Data from Table Mountain, California (34.4N, 242.3E) from 1993-1997

Used to corroborate H_2O increase observed in early 1990s by HALOE



Water Vapor Millimeter-wave Spectrometer
WVMS
U. S. Naval Research Laboratory
10th Anniversary
1992-2002

Data since March 1996 from Mauna Loa, Hawaii (19.5N, 204.4E)



Our best dataset for future trend calculations

Water Vapor Millimeter-wave Spectrometer

WVMS

U. S. Naval Research Laboratory

10th Anniversary

1992-2002

Mechanisms that affect water vapor trends from ~20-60 km

- Tropical tropopause temperature (+0.1 K => ~ +1% water vapor)
- Details of transport from troposphere to stratosphere - Rosenlof
  - Widening of tropical upwelling
  - Changes in ratio of summer/winter net upwelling
- Methane entering the stratosphere
- Middle atmospheric circulation (changes in H_2O due to changes in CH_4 oxidation – mainly a problem around 40 km)

Water vapor trend fits

Fit using (t in years):

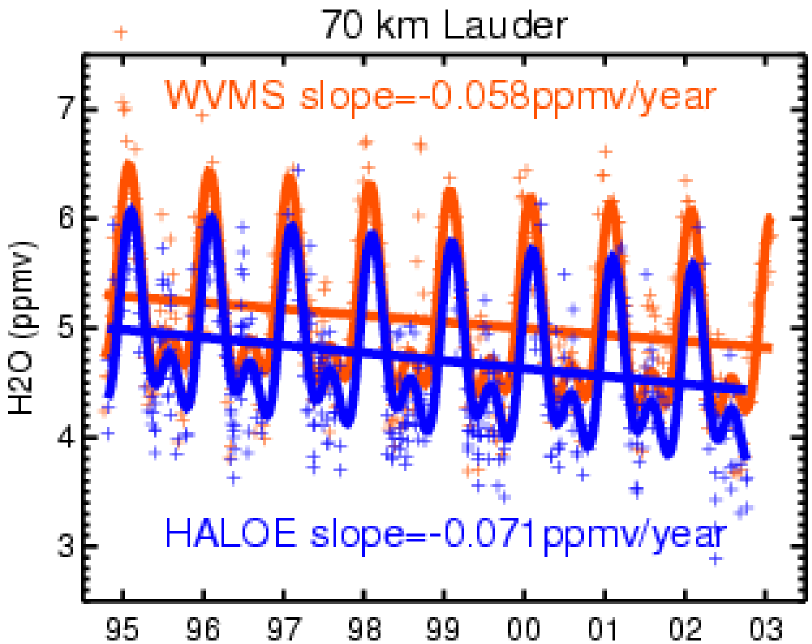
$$f = a_0 +$$

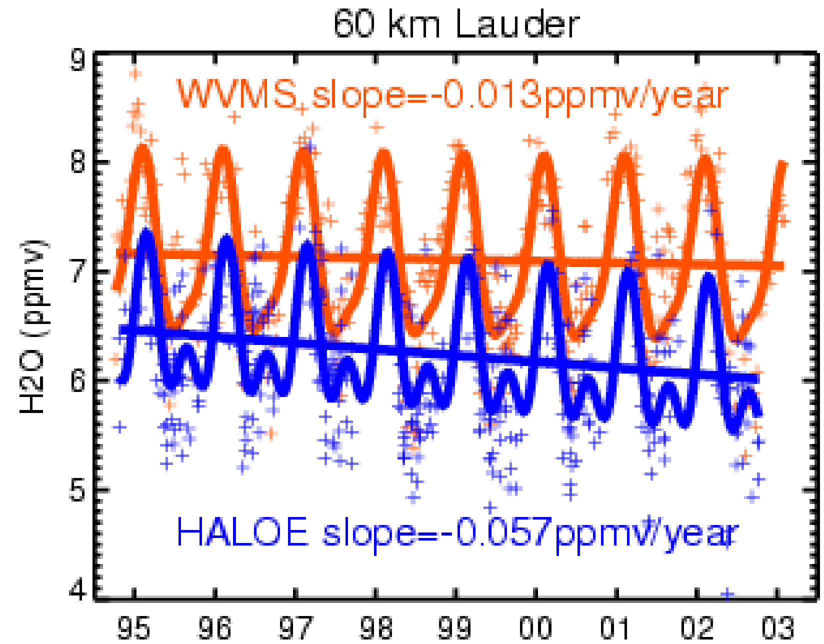
(annual) $a_1\sin(2\pi t) + a_2\cos(2\pi t) +$

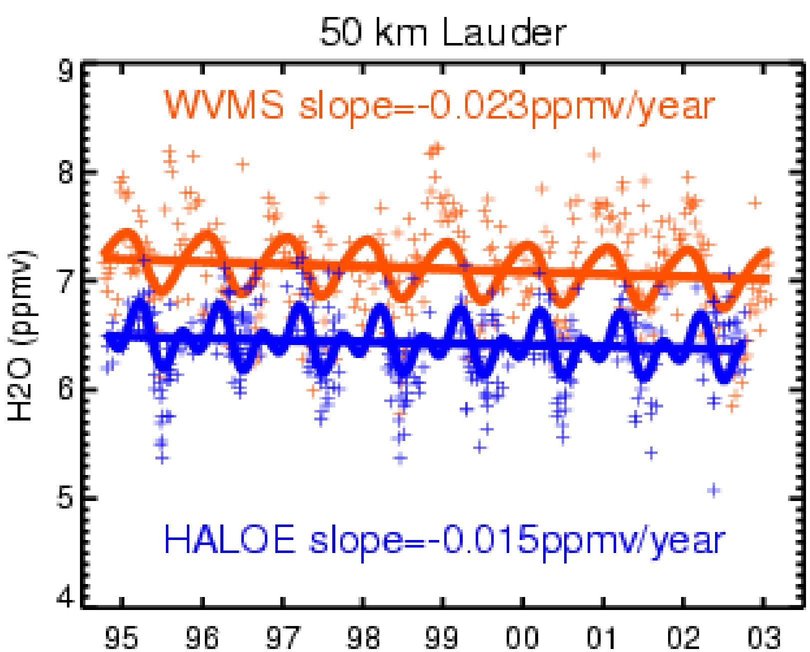
(semi-annual) $a_3\sin(4\pi t) + a_4\cos(4\pi t) +$

(QBO) $a_5\sin((12/27)2\pi t)+a_6\sin((12/27)2\pi t$

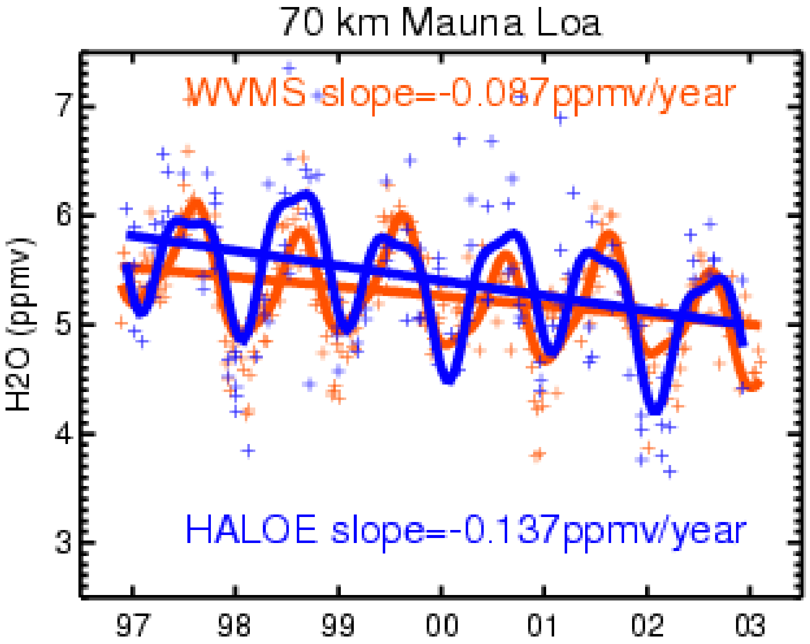
(linear trend) $+ a_7 t$

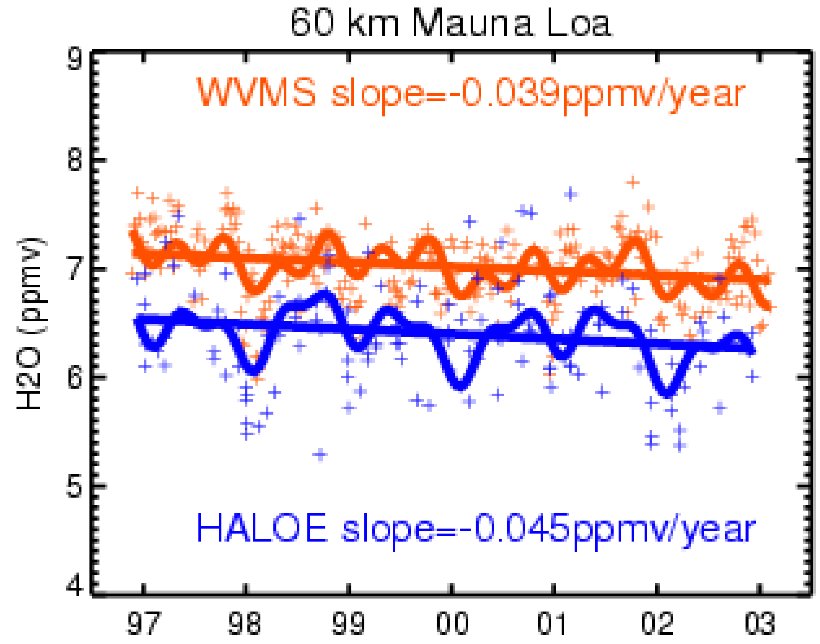


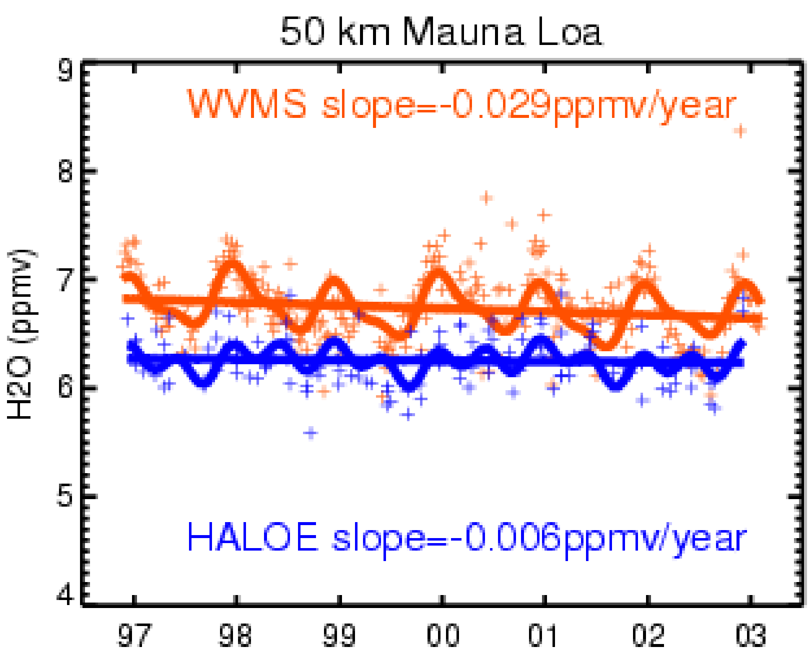




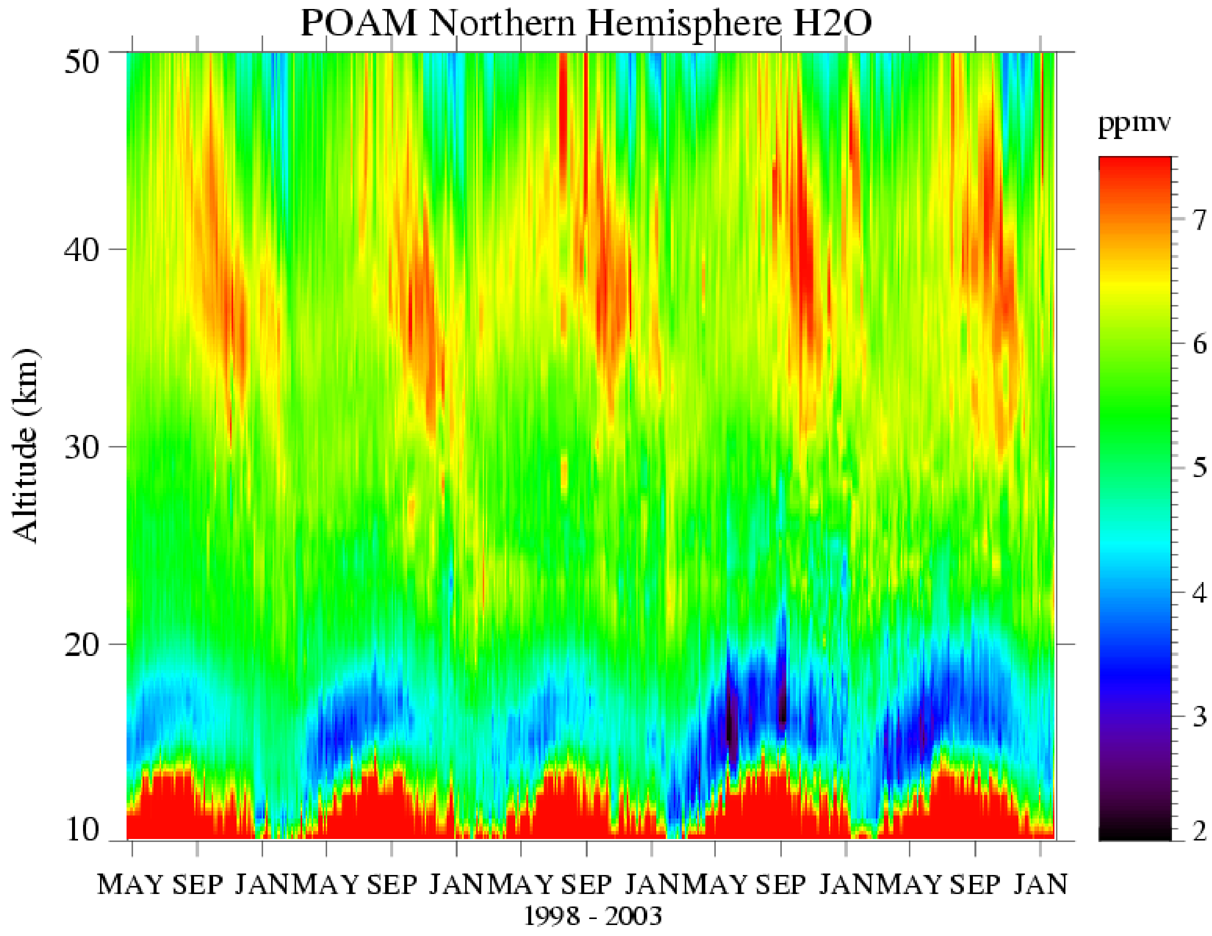
HALOE and WVMS data and best-fits for Lauder







HALOE and WVMS data and best-fits for Mauna Loa



POAM III Northern Hemisphere H2O measurements since April 1998, covering latitudes from 55N-71N

Summary of linear trend analysis

- WVMS and HALOE both showed a large increase in water vapor in the first half of the 1990s (almost 10%)

- WVMS and coincident HALOE measurements since 1996, and POAM and coincident HALOE measurements since 1998 show smaller linear trends, with roughly an equal number being positive as negative.

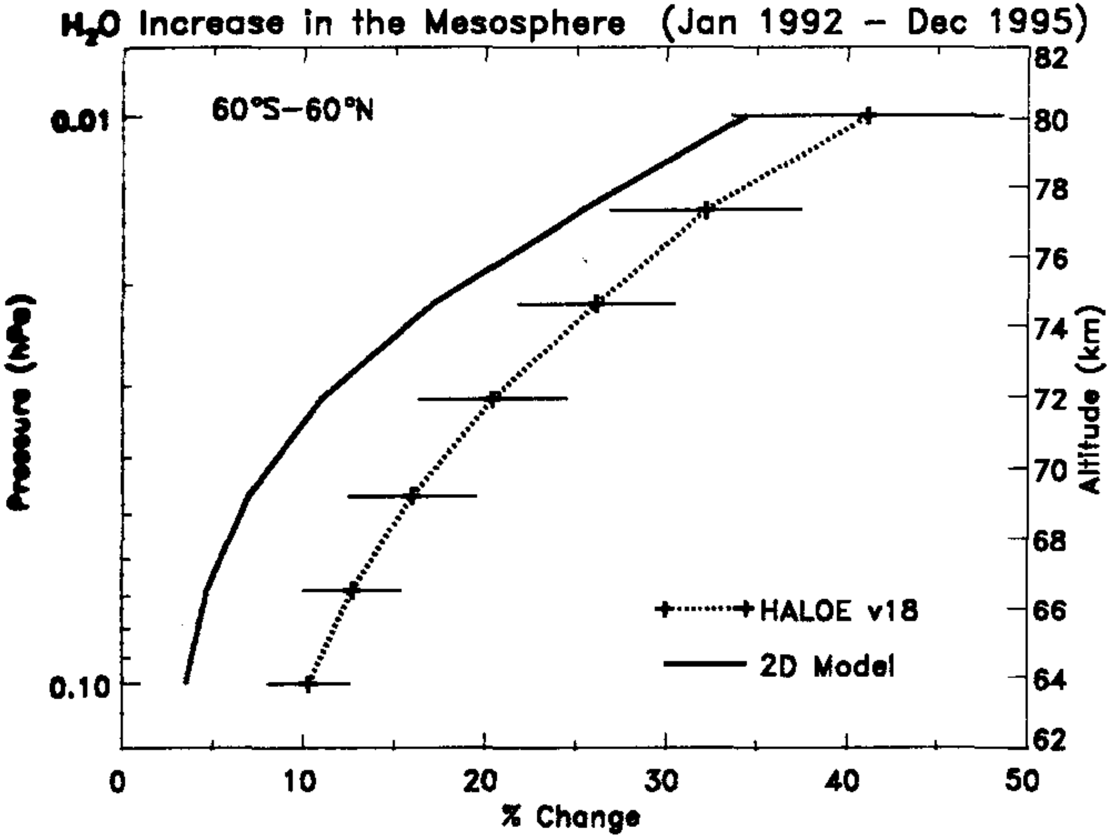


Figure 4. Height profiles of the 4 year trend estimated from both the model and the HALOE data averaged over 60°S to 60°N.

From Chandra et al., GRL, 1997

Conclusions

- Large increase in water vapor in the middle atmosphere from 1991-1996 (~10%).
- No clear trend from 1996-present.
- Some indication of an increase over last 2-3 years.
- Complicated pattern of water vapor variations gives an increase of ~0.5 ppmv (~1%/year) for the HALOE mission (1992-present).
- A 1%/year increase is very similar to the annual increase quoted by Rosenlof et al. [2001] for the years 1954-2001, and by Oltmans et al. [2000] for the years 1964-2000.

WVMS

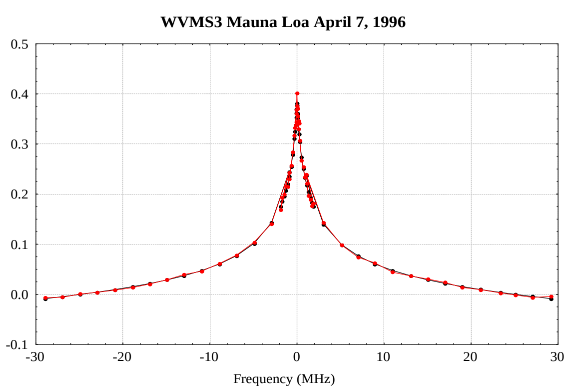
Vapor Millimeter-wave

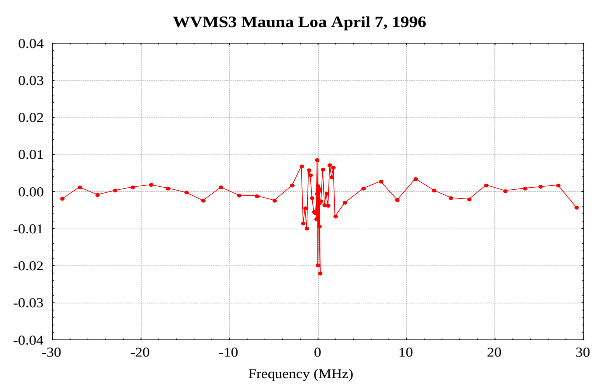
• Part of the international Network for the Detection of Stratospheric Change (NDSC)

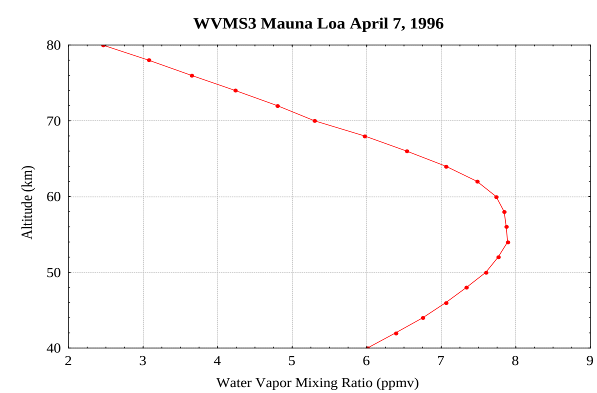
• Continuous measurements of water vapor in the stratosphere and mesosphere to determine seasonal variability and interannual changes

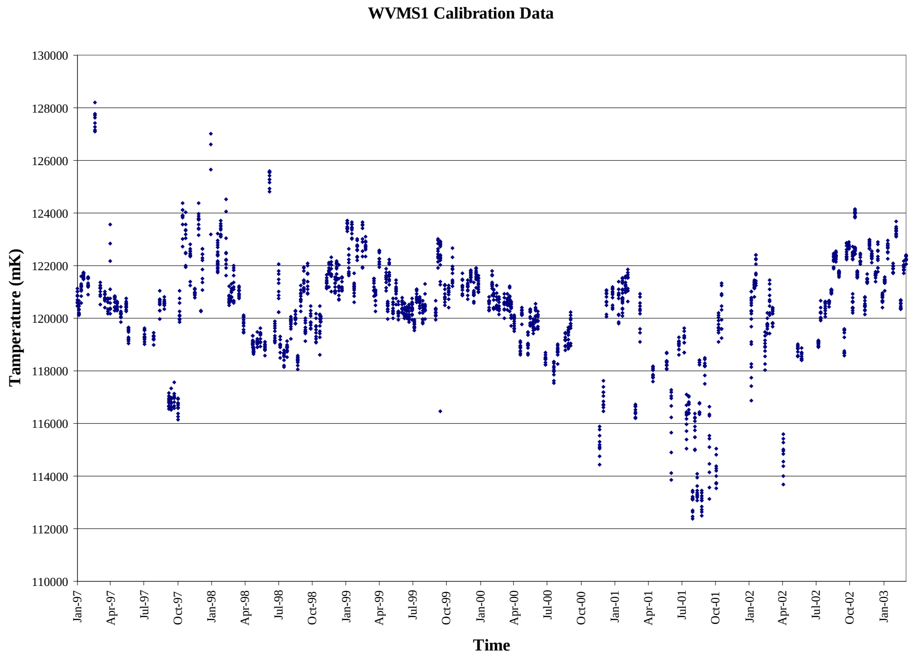
• Ground based microwave spectroscopy to measure the pressure broadened 22.2 GHz water vapor line

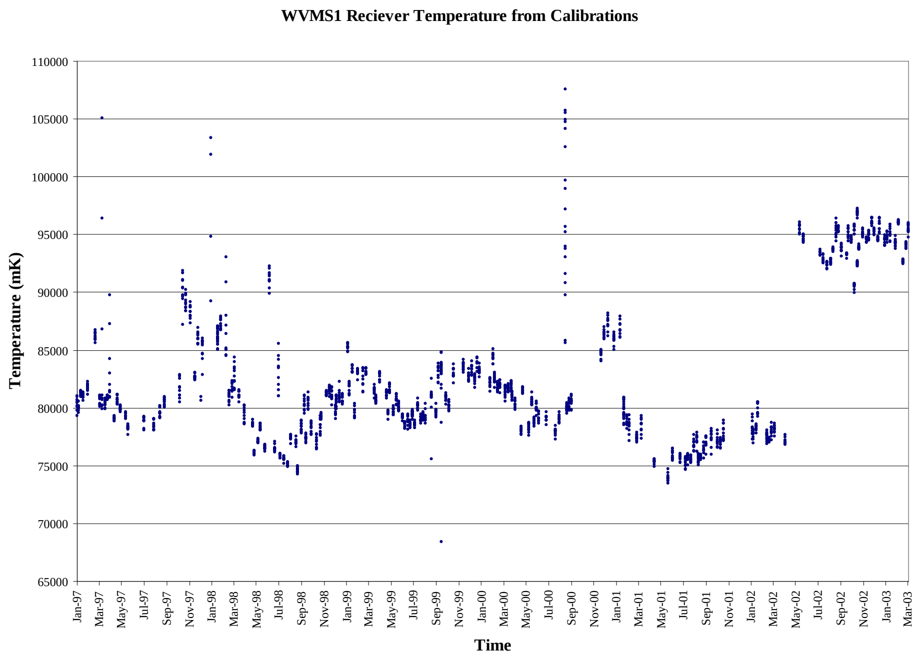
• Retrieve mixing ratios using optimal estimation








WVMS1 Calibration Data
Tamperature (mK)
130000
128000
126000
124000
122000
120000
118000
116000
114000
112000
110000
Jan-97
Apr-97
Jul-97
Oct-97
Jan-98
Apr-98
Jul-98
Oct-98
Jan-99
Apr-99
Jul-99
Oct-99
Jan-00
Apr-00
Jul-00
Oct-00
Jan-01
Apr-01
Jul-01
Oct-01
Jan-02
Apr-02
Jul-02
Oct-02
Jan-03
Time


WVMS1 Reciever Temperature from Calibrations
Temperature (mK)
110000
105000
100000
95000
90000
85000
80000
75000
70000
65000
Jan-97
Mar-97
May-97
Jul-97
Sep-97
Nov-97
Jan-98
Mar-98
May-98
Jul-98
Sep-98
Nov-98
Jan-99
Mar-99
May-99
Jul-99
Sep-99
Nov-99
Jan-00
Mar-00
May-00
Jul-00
Sep-00
Nov-00
Jan-01
Mar-01
May-01
Jul-01
Sep-01
Nov-01
Jan-02
Mar-02
May-02
Jul-02
Sep-02
Nov-02
Jan-03
Mar-03
Time