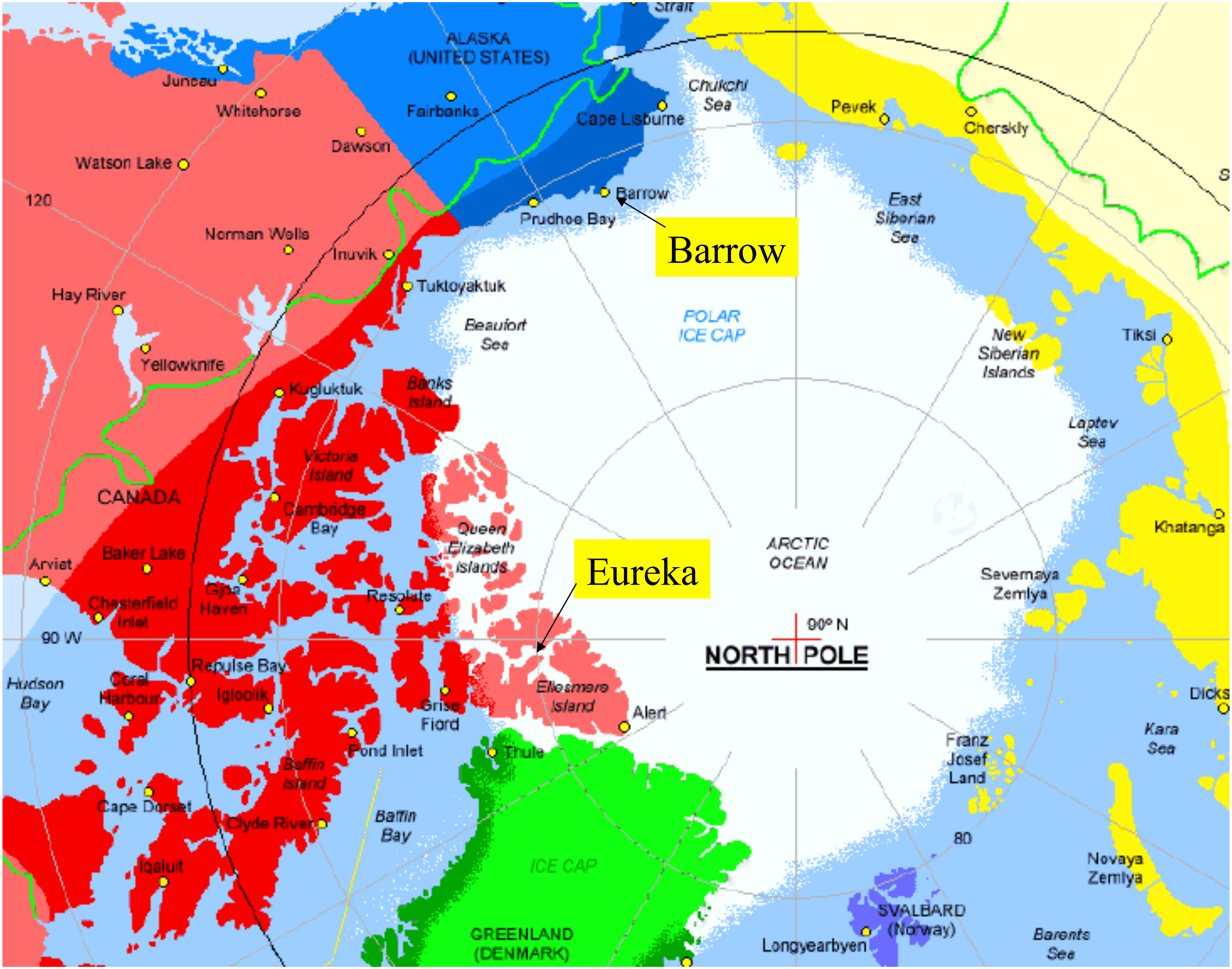
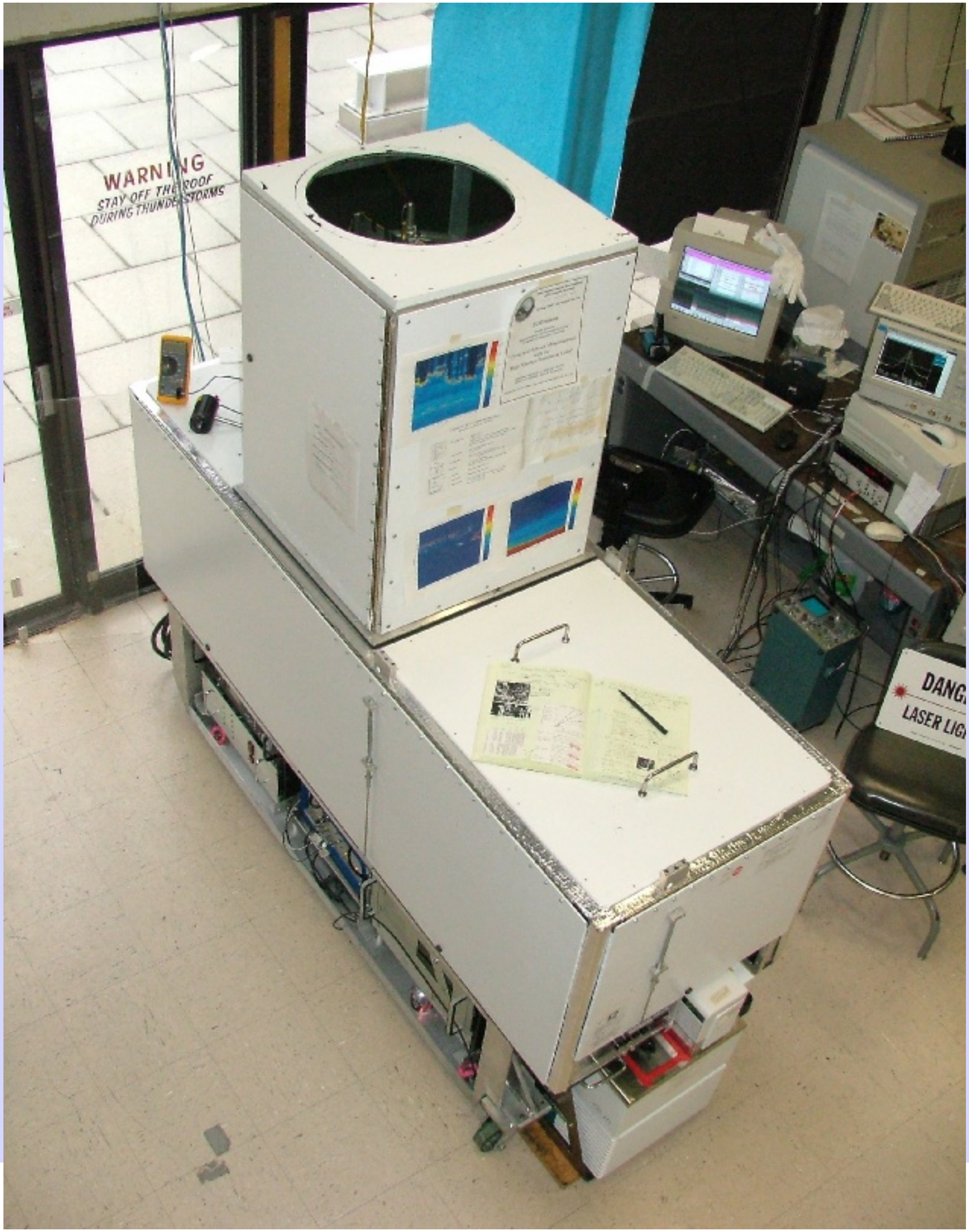
High Spectral Resolution Lidar

Ed Eloranta

http://lidar.ssec.wisc.edu

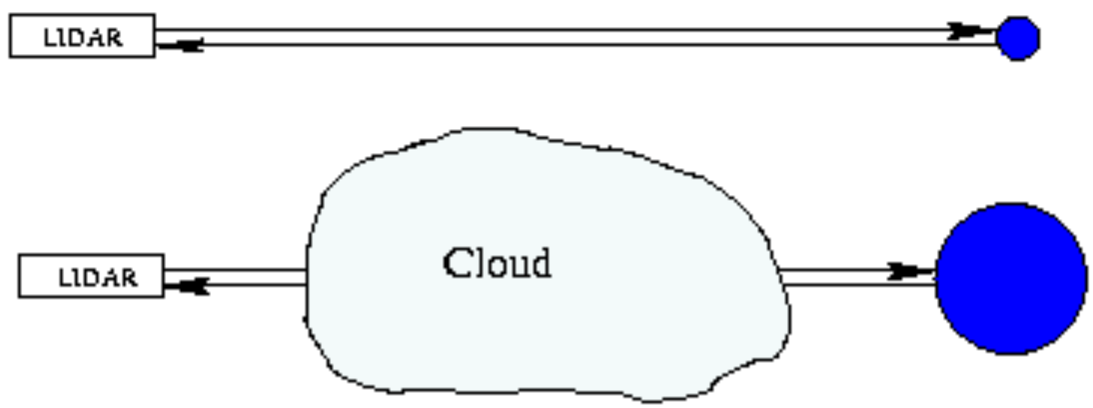


Strait
ALASKA
(UNITED STATES)
Juneau
Whitehorse
Fairbanks
Cape Lisburne
Chukchi
Sea
Pevek
Cherskly
Dawson
Watson Lake
120
Barrow
Prudhoe Bay
Barrow
East
Siberian
Sea
Norman Wells
Inuvik
Tuktoyaktuk
Hay River
Beaufort
Sea
POLAR
ICE CAP
New
Siberian
Islands
Tiksi
Yellowknife
Kugluktuk
Banks
Island
Laptev
Sea
Victoria
Island
CANADA
Cambridge
Bay
Queen
Elizabeth
Islands
ARCTIC
OCEAN
Khatanga
Eureka
Baker Lake
Arviat
Gjoa
Haven
Resolute
Severnaya
Zemlya
Chesterfield
Inlet
90° N
NORTH POLE
90 W
Repulse Bay
Hudson
Bay
Coral
Harbour
Igloolik
Ellesmere
Island
Alert
Grise
Fiord
Dicks
Kara
Sea
Pond Inlet
Thule
Franz
Josef
Land
Baffin
Island
Cape Dorset
Clyde River
Baffin
Bay
80
ICE CAP
Novaya
Zemlya
Iqaluit
SVALBARD
(Norway)
GREENLAND
(DENMARK)
Longyearbyen
Barents
Sea


WARNING
STAY OFF THE ROOF
DURING THUNDERSTORMS


NSF
National
Science
Foundation
National Center for Atmospheric Research

$$P(r) \sim \beta_s(r)\frac{\mathcal{P}(180,r)}{4\pi}exp(-2\int_0^r \beta_e(r)dr)$$



Traditional aerosol lidar can not distinguish between changes in target reflectivity and attenuation between the lidar and the target

The power, $p_c(r)$, received by a standard aerosol lidar where the scattering cross sections of aerosols, $\beta_a(r)$, and molecules, $\beta_m(r)$, both contribute:

$$p_c(r) \sim \frac{1}{r^2} \cdot (\frac{P(180,r)}{4\pi}\beta(r) + \frac{3}{8\pi}\beta_m(r)) \cdot exp(-2\int(\beta_a(r) + \beta_m(r)) \cdot dr)$$

If we can separate returns from aerosols, $p_a(r)$, and molecules, $p_m(r)$:

$p_a(r) \sim \frac{1}{r^2} \cdot \frac{P(180,r)}{4\pi}\beta_a(r) \cdot exp(-2\int(\beta_a(r) + \beta_m(r)) \cdot dr)$ – aerosol return,

$p_m(r) \sim \frac{1}{r^2} \cdot \frac{3}{8\pi}\beta_m(r) \cdot exp(-2\int(\beta_a(r) + \beta_m(r)) \cdot dr)$ – molecular return

where $\frac{P(180,r)}{4\pi}$ is the backscatter phase function.

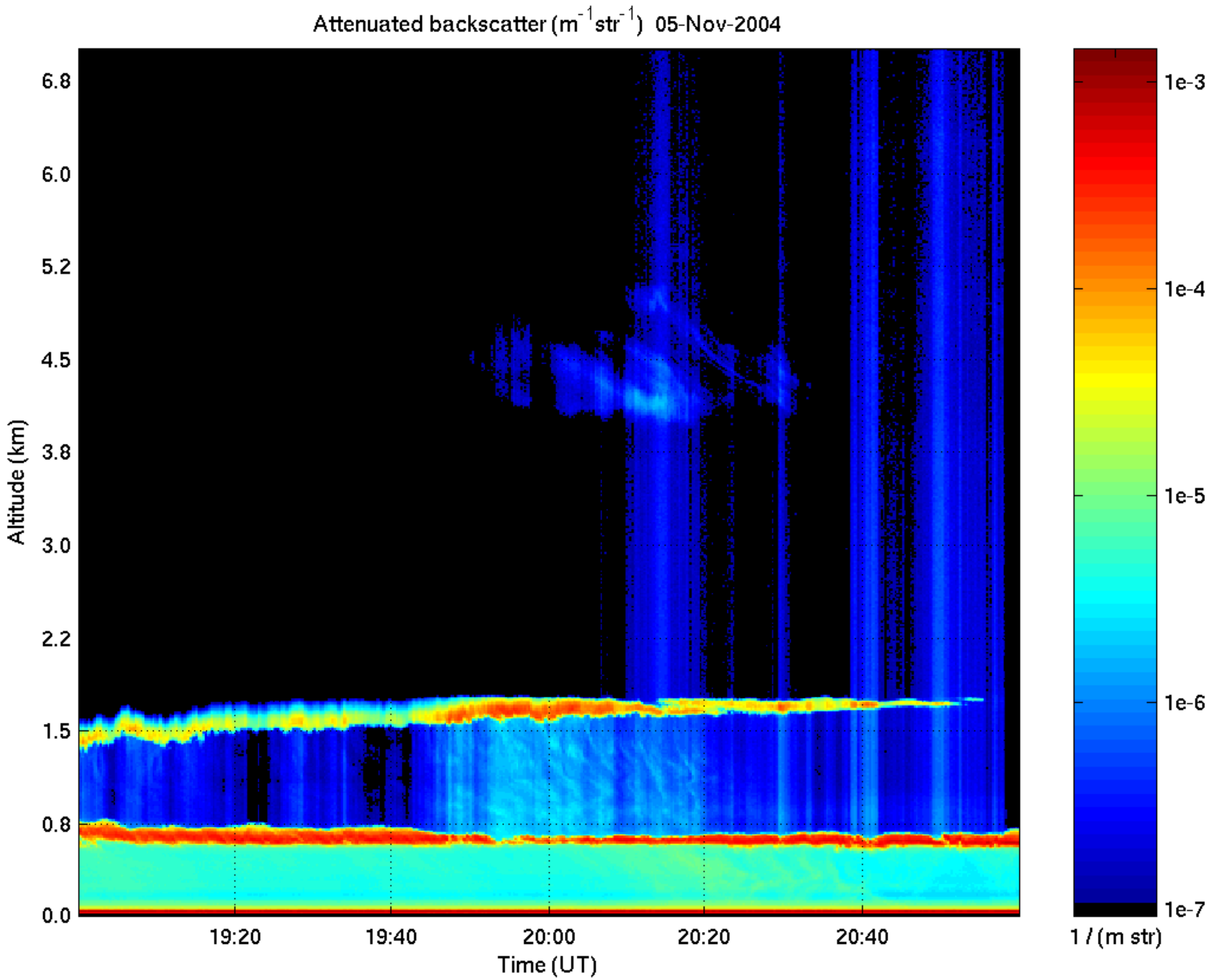
The backscatter ratio can be obtained from the ratio of these returns:

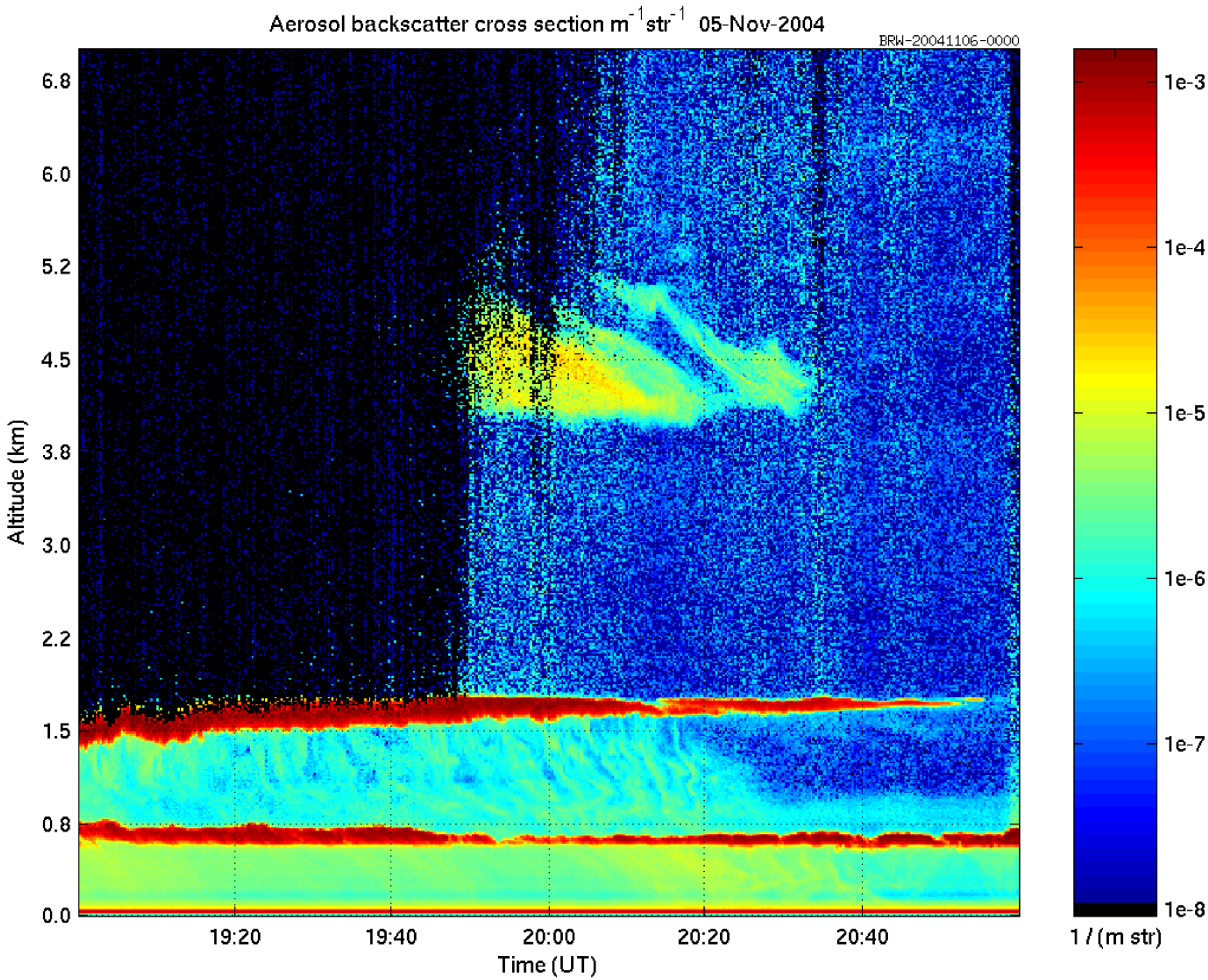
$R(r) = \frac{p_a(r)}{p_m(r)} = \frac{\frac{P(180,r)}{4\pi} \cdot \beta_a(r)}{\frac{3}{8\pi} \cdot \beta_m(r)}$ where $\beta_m(r)$ ~atmospheric density profile, $\rho(r)$.

$$\beta'_a(r) = \frac{P(180,r)}{4\pi} \cdot \beta_a(r) = \frac{3}{8\pi} \cdot \beta_m(r) \cdot \frac{p_a(r)}{p_m(r)}$$

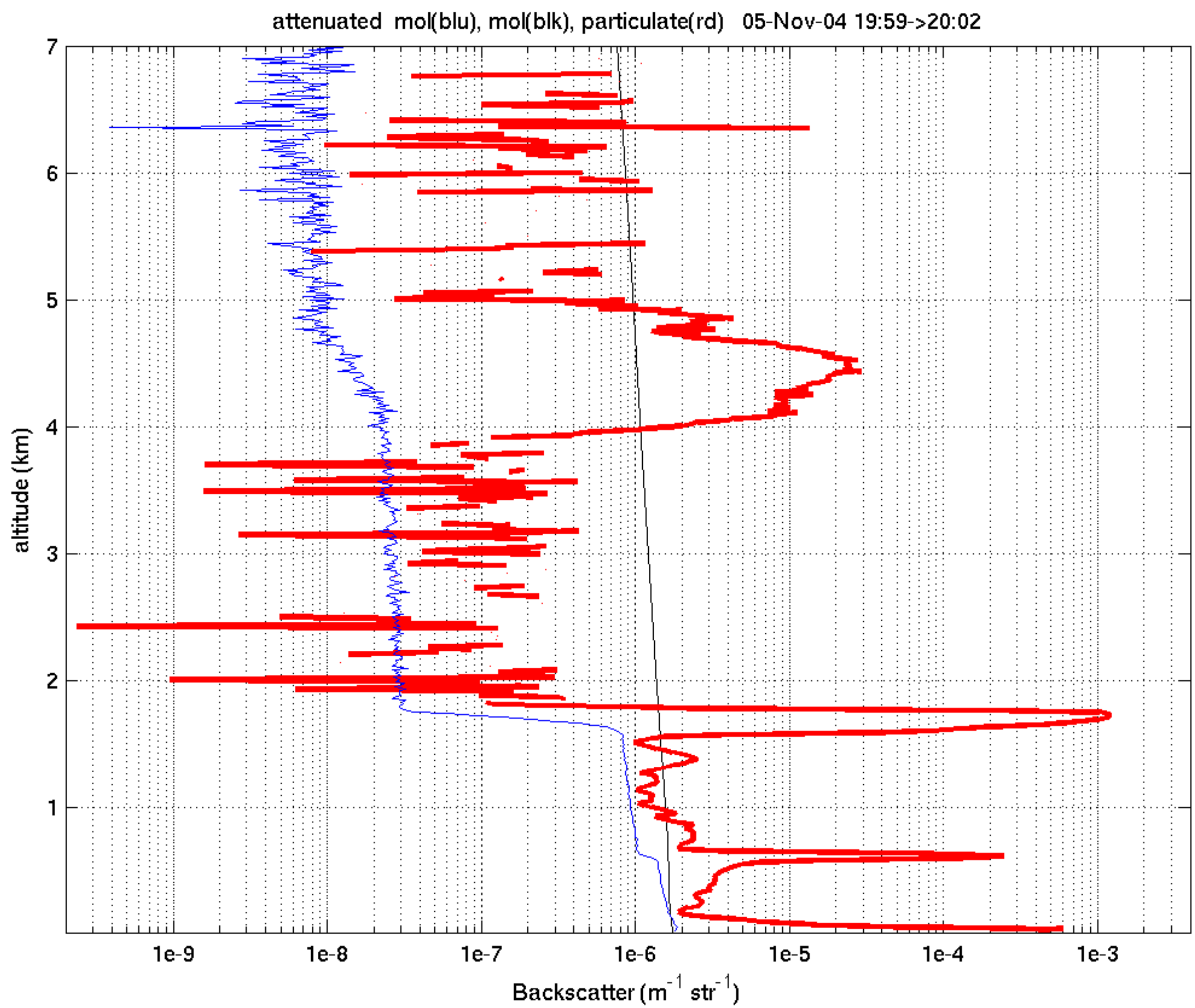
The optical depth between $r_1$and r_2 is derived by comparing the molecular return to that expected from a purely molecular atmosphere:

$$\tau(r_1, r_2) = \frac{1}{2} \cdot log(\frac{r_1^2\rho(r_2) \cdot p_m(r_1)}{r_2^2\rho(r_1) \cdot p_m(r_2)})$$


Attenuated backscatter (m^{-1}str^{-1}) 05-Nov-2004
Altitude (km)
6.8
6.0
5.2
4.5
3.8
3.0
2.2
1.5
0.8
0.0
19:20
19:40
20:00
20:20
20:40
Time (UT)
1e-3
1e-4
1e-5
1e-6
1e-7
1 / (m str)



Aerosol backscatter cross section m^{-1}str^{-1} 05-Nov-2004
BRW-20041106-0000
Altitude (km)
6.8
6.0
5.2
4.5
3.8
3.0
2.2
1.5
0.8
0.0
19:20
19:40
20:00
20:20
20:40
Time (UT)
1e-3
1e-4
1e-5
1e-6
1e-7
1e-8
1 / (m str)


attenuated mol(blu), mol(blk), particulate(rd) 05-Nov-04 19:59->20:02
altitude (km)
Backscatter (m-1 str-1)
1e-9
1e-8
1e-7
1e-6
1e-5
1e-4
1e-3
1
2
3
4
5
6
7

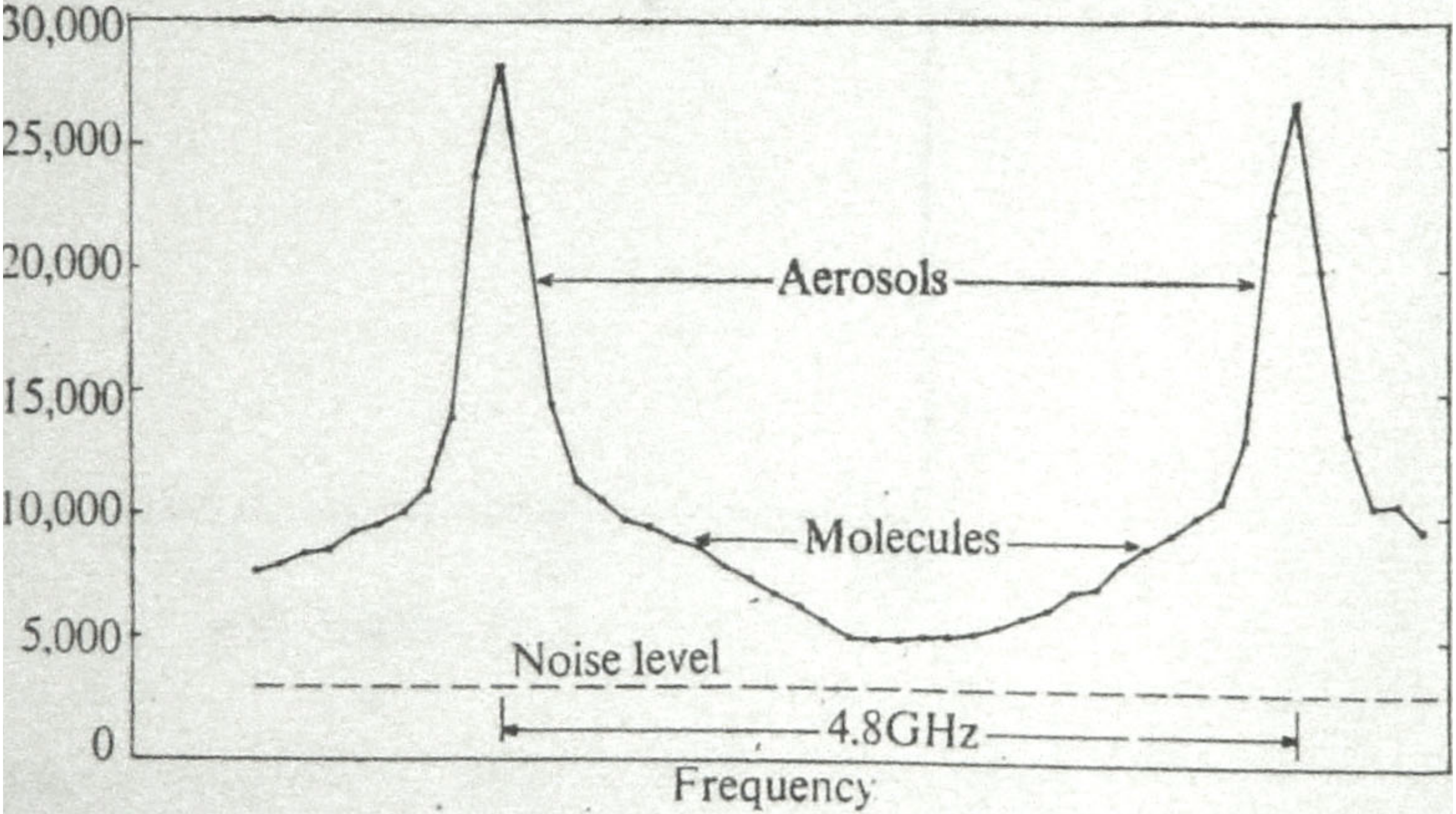
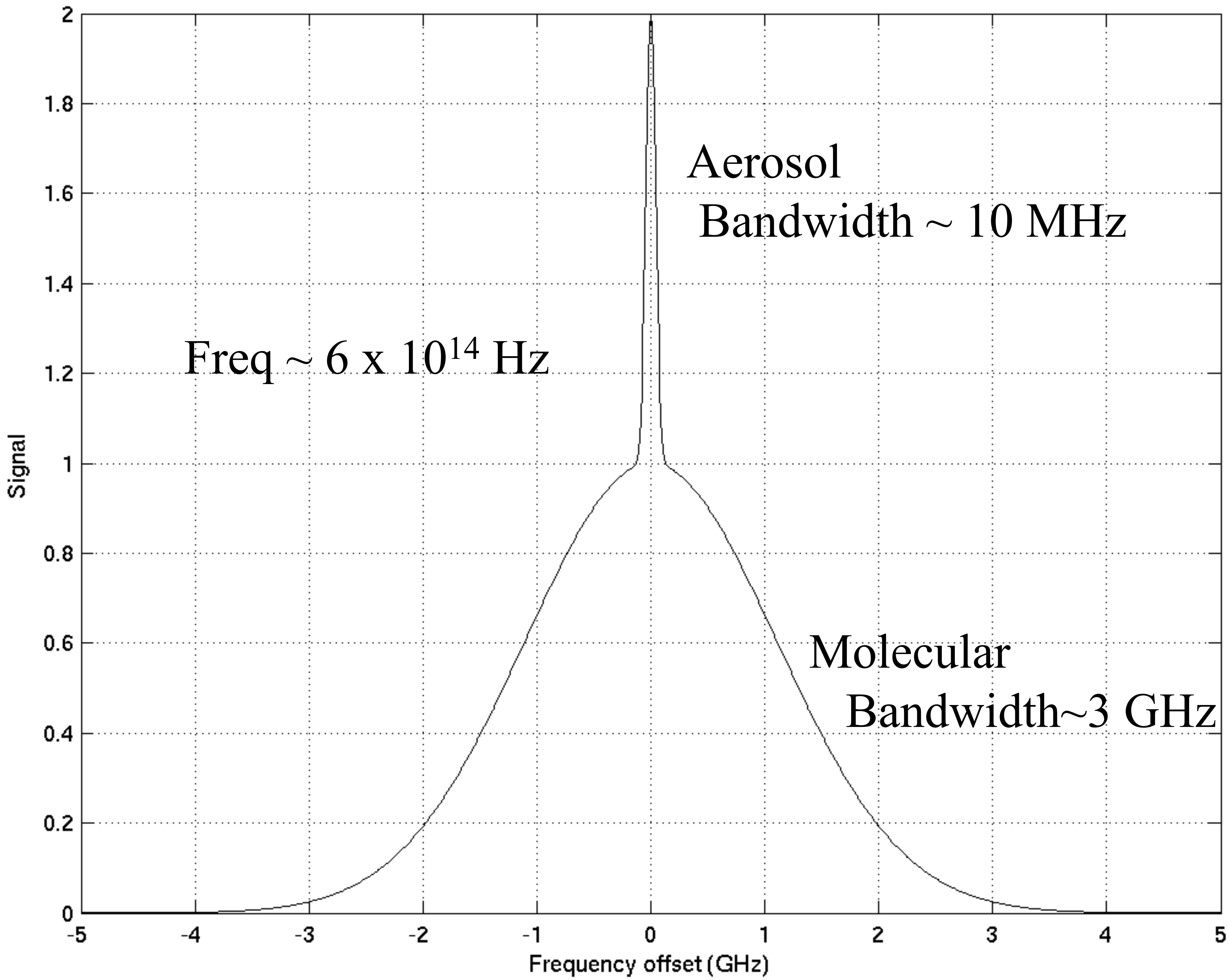
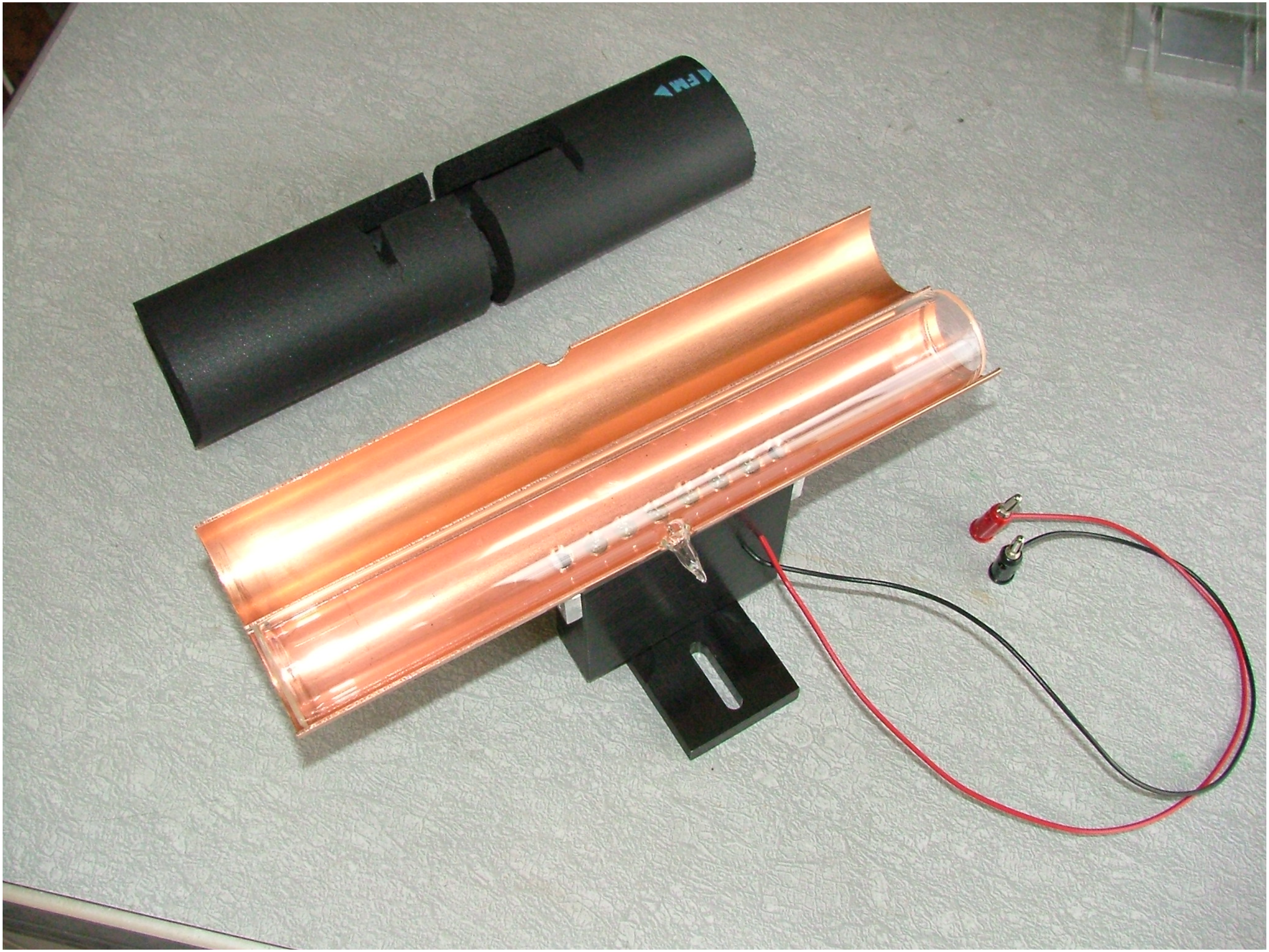


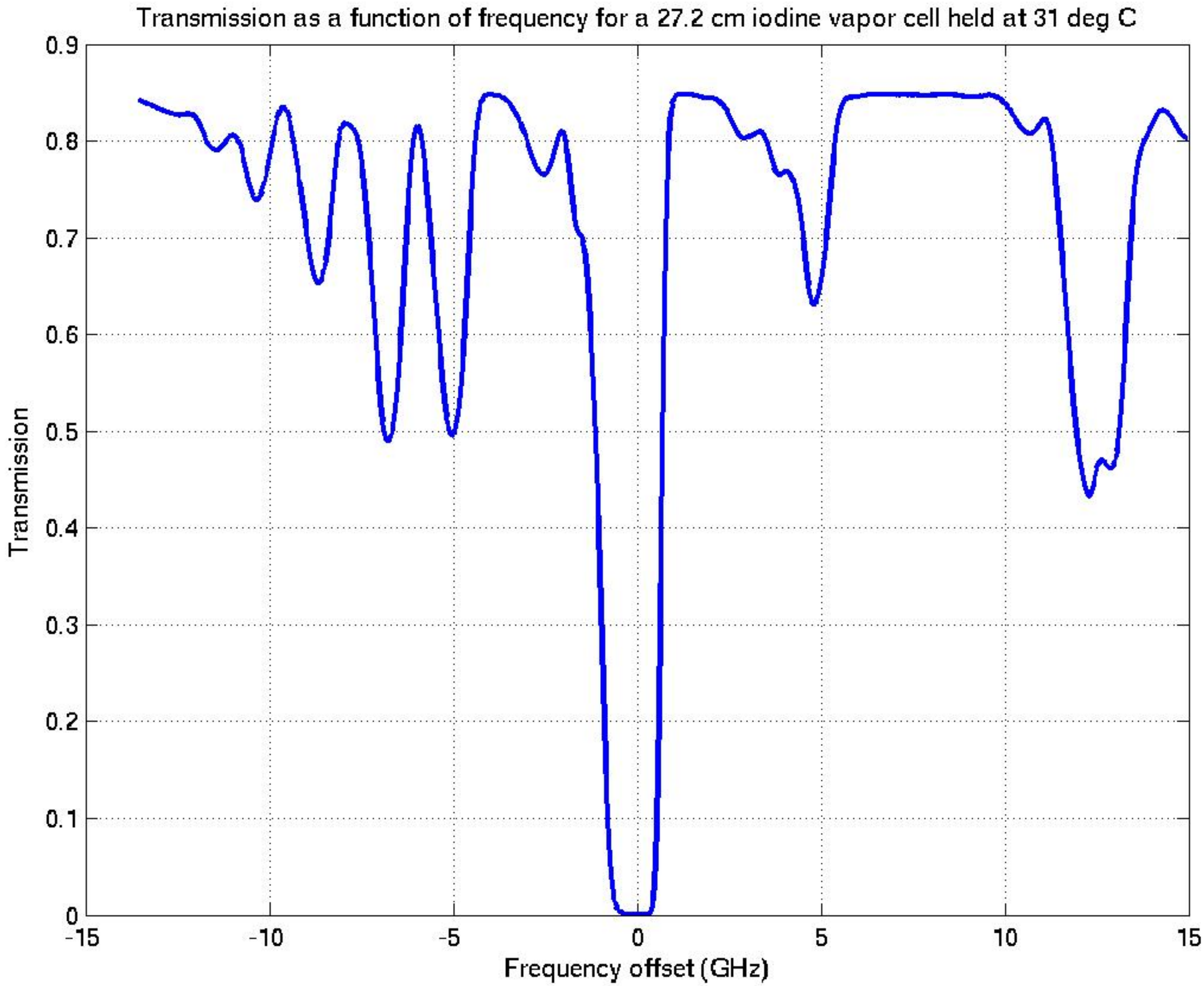
Fig. 1 Spectrum of echoes from air. Contributions of molecules from aerosols can be separated.

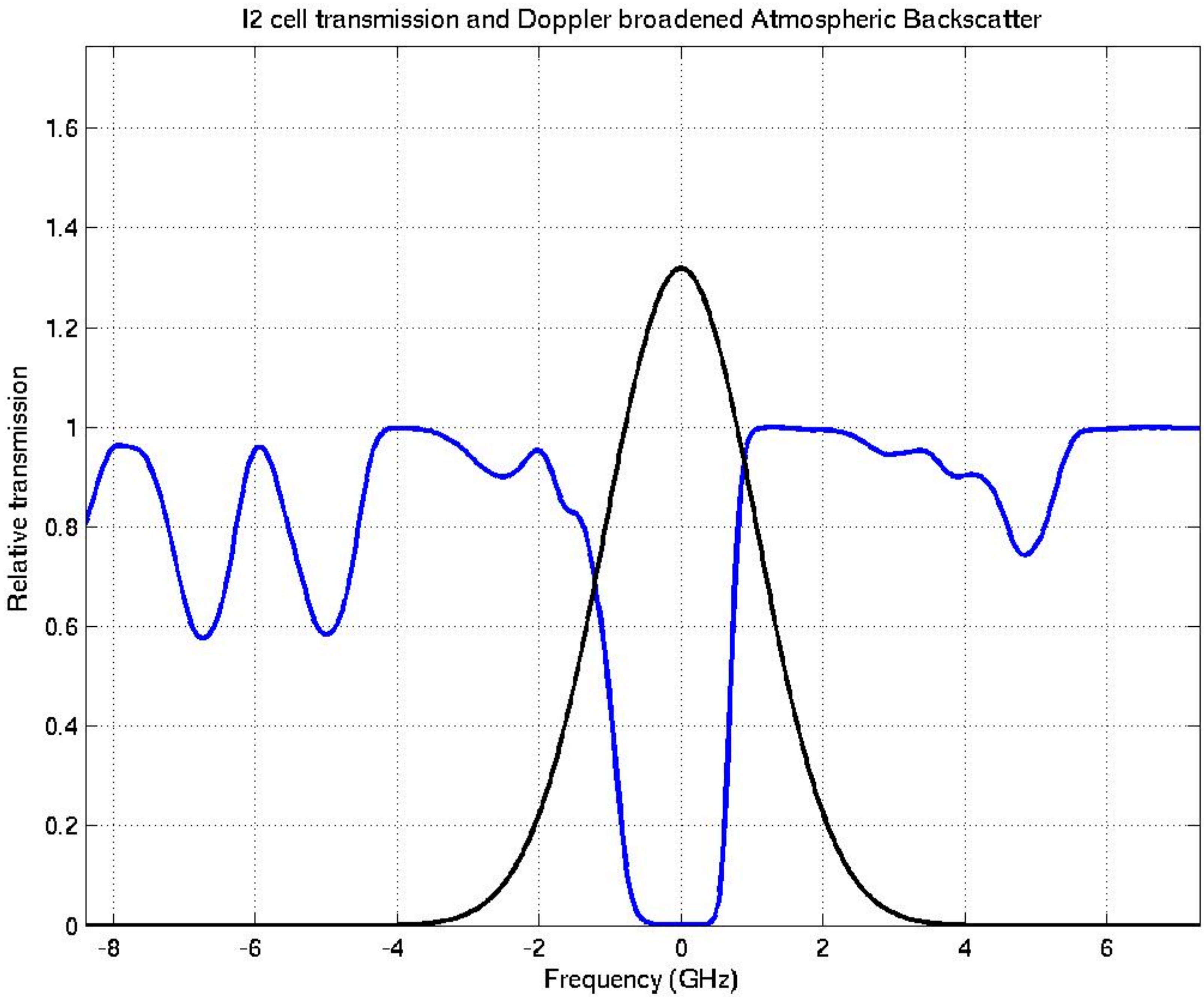
Fiocco et al., Nature Physical Science, Vol. 229, Jan 18, 1971, pp 78-79.

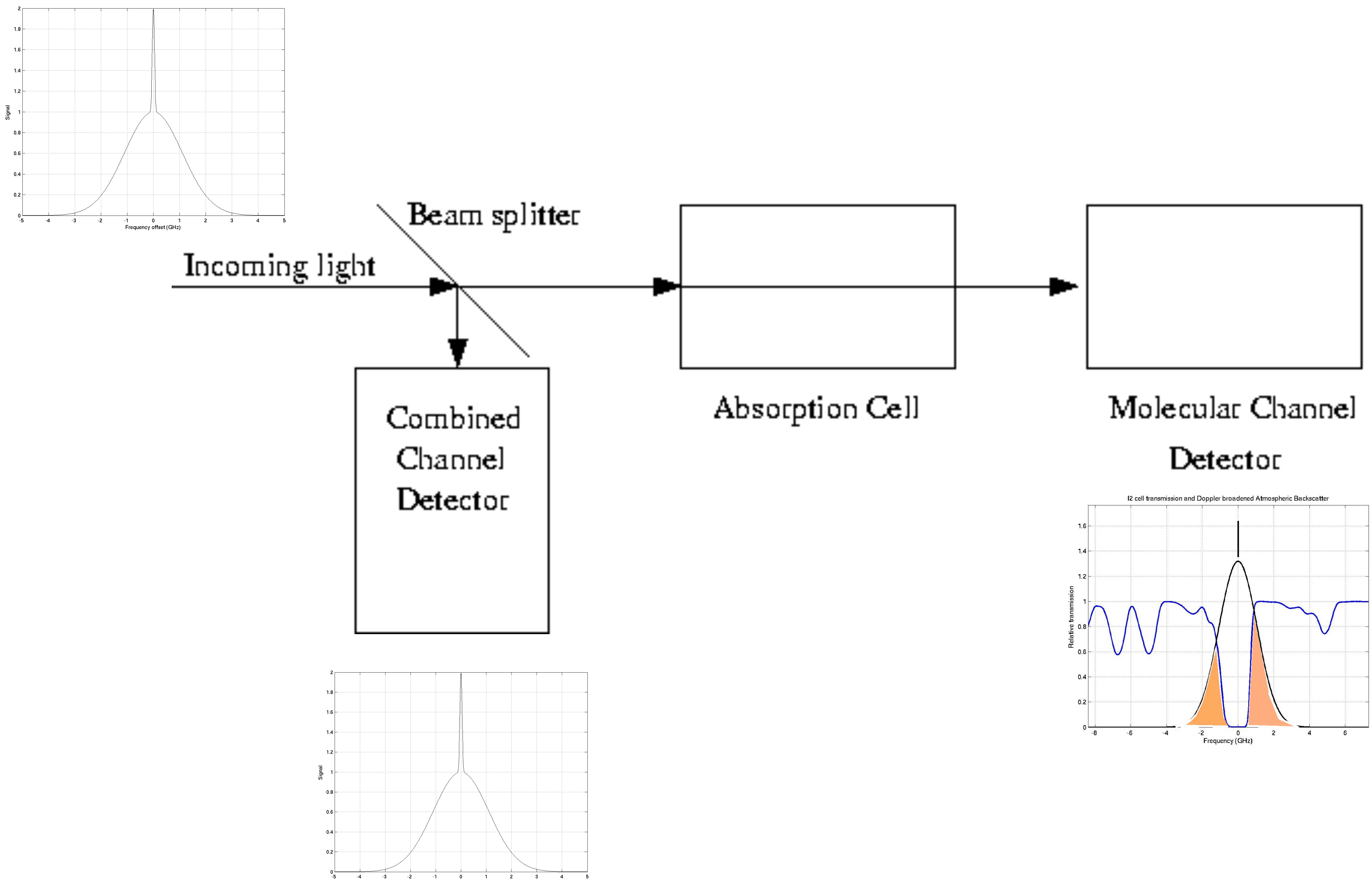


Aerosol
Bandwidth ~ 10 MHz
Freq ~ 6 x 10^14 Hz
Molecular
Bandwidth~3 GHz
Signal
Frequency offset (GHz)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-5
-4
-3
-2
-1
0
1
2
3
4
5




Transmission as a function of frequency for a 27.2 cm iodine vapor cell held at 31 deg C
Transmission
Frequency offset (GHz)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-15
-10
-5
0
5
10
15


I2 cell transmission and Doppler broadened Atmospheric Backscatter
Relative transmission
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-8
-6
-4
-2
0
2
4
6
Frequency (GHz)


Beam splitter
Incoming light
Combined
Channel
Detector
Absorption Cell
Molecular Channel
Detector
Signal
Frequency offset (GHz)
I2 cell transmission and Doppler broadened Atmospheric Backscatter
Relative transmission
Frequency (GHz)

Basic HSRL Equations

$S_c = G_{ac}N_a + G_{mc}N_m$; eq 1—Signal in the combined channel

$S_m = G_{am}N_a + G_{mm}N_m$; eq 2—Signal in the molecular channel

Where $G_{ik}$are gains of the two channels when exposed to $N_a$aerosol and $N_m$molecular photons.

Solving for N_m and $N_a$yields:

$N_m = \frac{S_m/G_{am} - S_c/G_{ac}}{(G_{mm}/G_{am}) - (G_{mc}/G_{ac})}$; eq 3—Number of molecular photons incident as function of signals

$N_a = \frac{S_c/G_{mc} - S_m/G_{mm}}{(G_{ac}/G_{mc}) - (G_{am}/G_{mm})}$; eq 4–Number of aerosol photons incident as function of signals

With G_{ac} =gain of the combined channel when exposed to aerosol photons

Define other gains relative to G_{ac}:

$G_{mc} = C_{mc} \cdot G_{ac}$, $G_{am} = C_{am} \cdot G_{ac}$, $G_{mm} = C_{mm} \cdot G_{ac}$

$N_m = (1/G_{ac}) \cdot \frac{S_m/C_{am} - S_c}{(C_{mm}/C_{am}) - C_{mc}} = (1/G_{ac}) \cdot \frac{S_m - C_{am}S_c}{C_{mm} - C_{mc}C_{am}}$

$N_a = (1/G_{ac}) \cdot \frac{S_c/C_{mc} - S_m/C_{mm}}{(1/C_{mc}) - (C_{am}/C_{mm})} = (1/G_{ac}) \cdot \frac{S_c/C_{mc} - S_m/C_{mm}}{(1/C_{mc}) - (C_{am}/C_{mm})} = (1/G_{ac}) \cdot \frac{C_{mm}S_c - C_{mc}S_m}{C_{mm} - C_{mc}C_{am}}$

The scattering ratio is then:

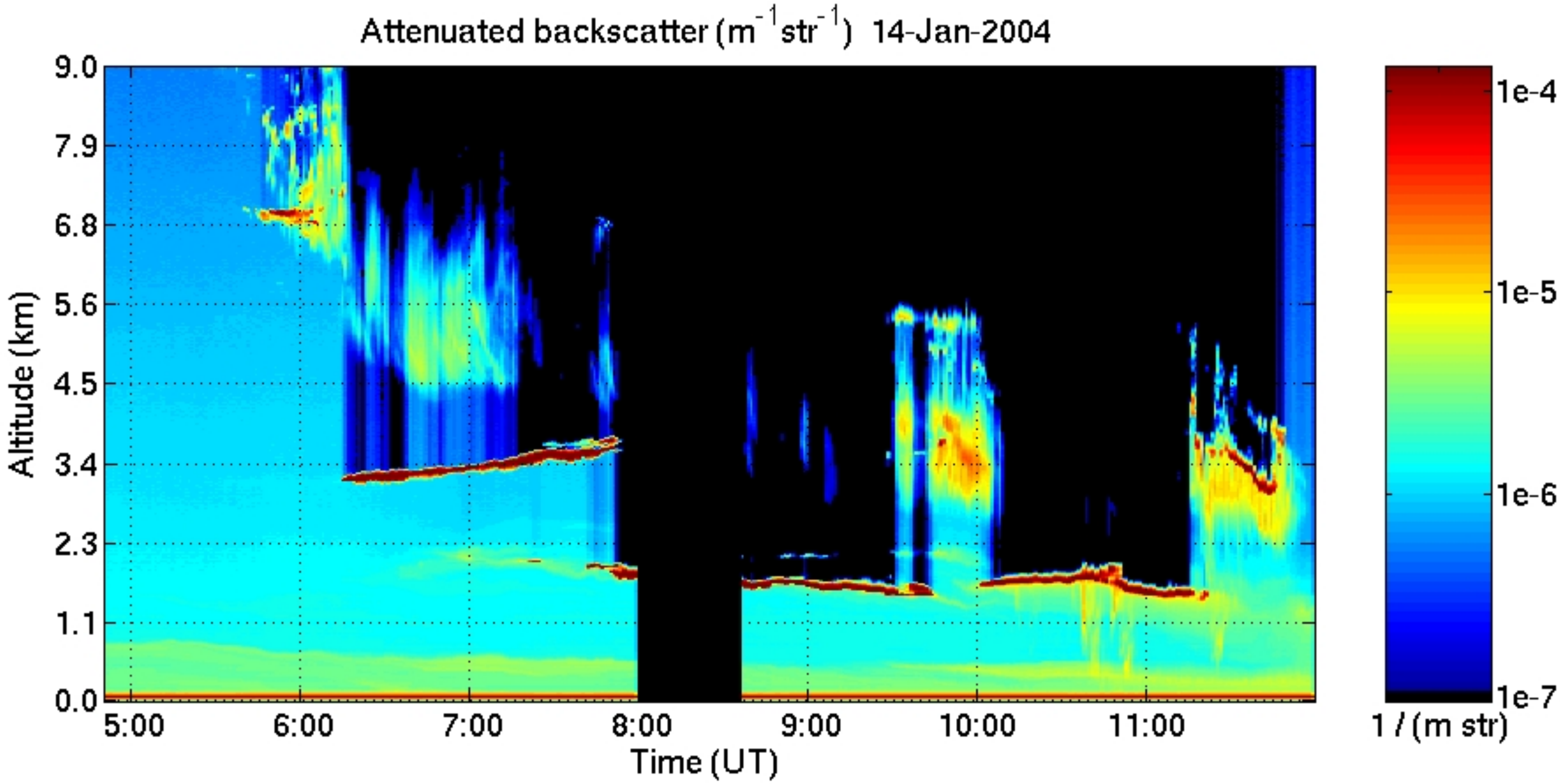
$\frac{N_a}{N_m} = \frac{C_{mm}S_c - C_{mc}S_m}{S_m - C_{am}S_c}$

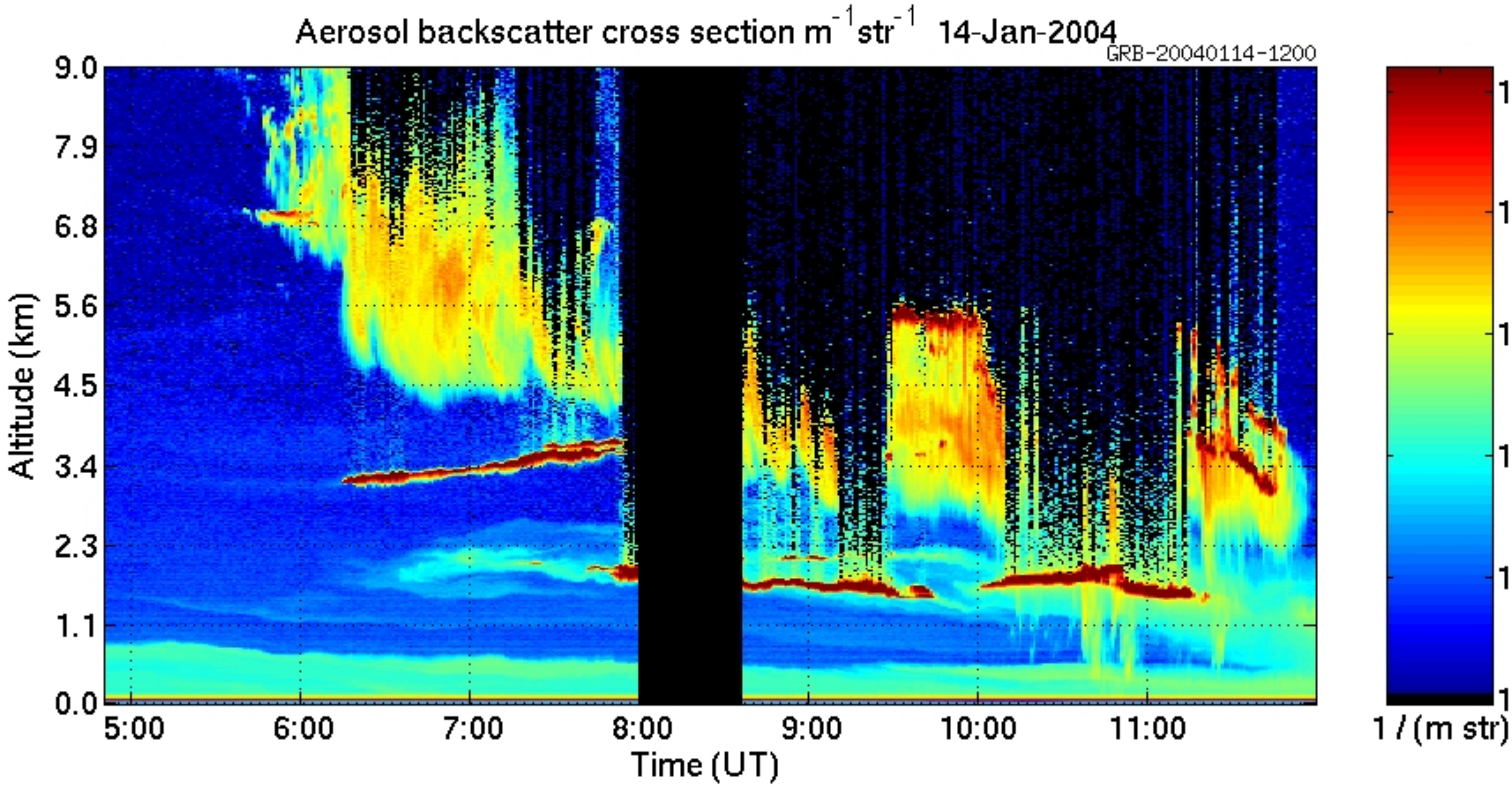
The backscatter cross section, β'_a, is:

$\beta'_a(r) = \beta_a(r) \cdot \frac{P(180,r)}{4\pi} = \frac{N_a(r)}{N_m(r)} \cdot \beta_m(r)$, where β_a =scattering cross section, $\frac{P(180,r)}{4\pi}$ =backscatter phase function.

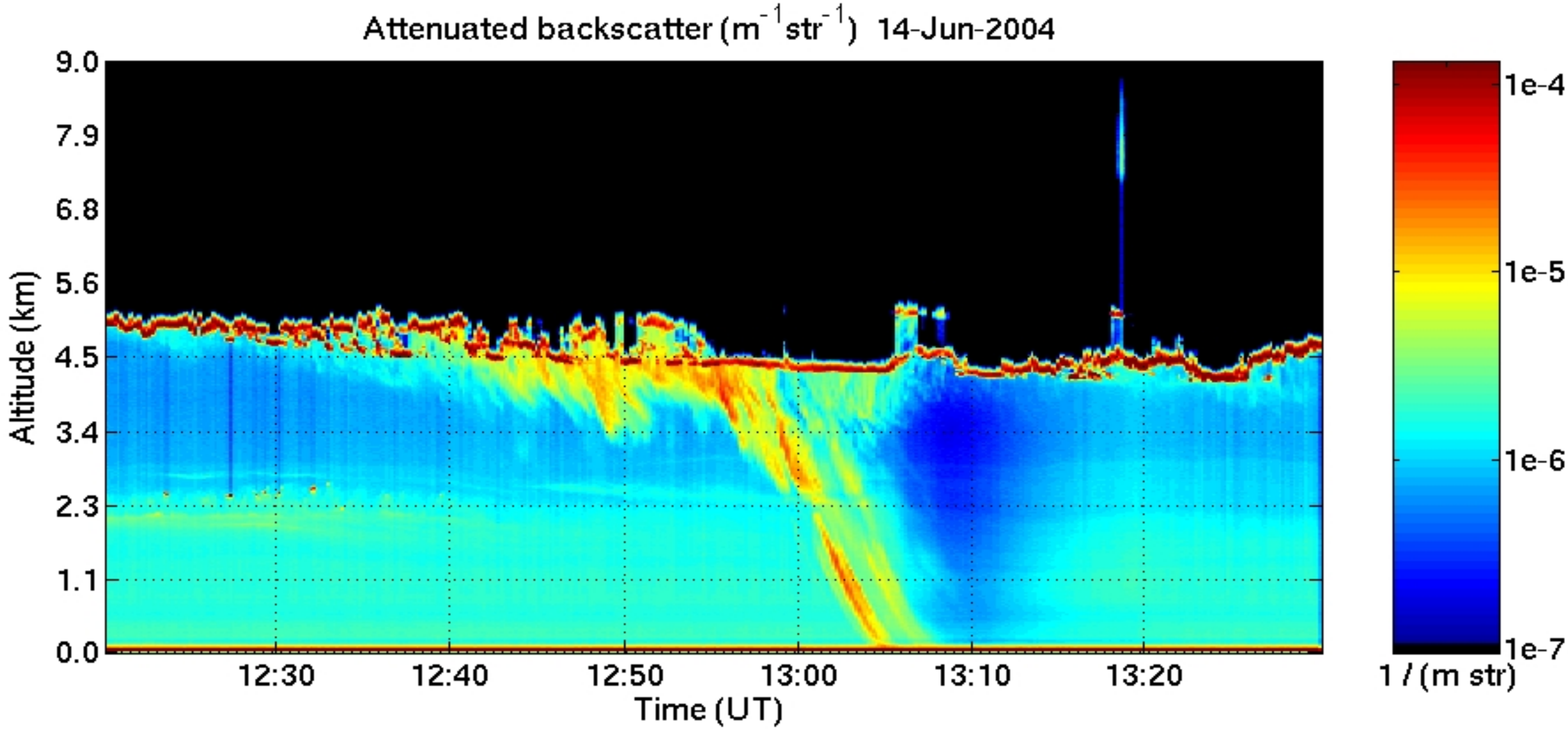
the optical depth,τ, between two points $r_1 and r_2$is:

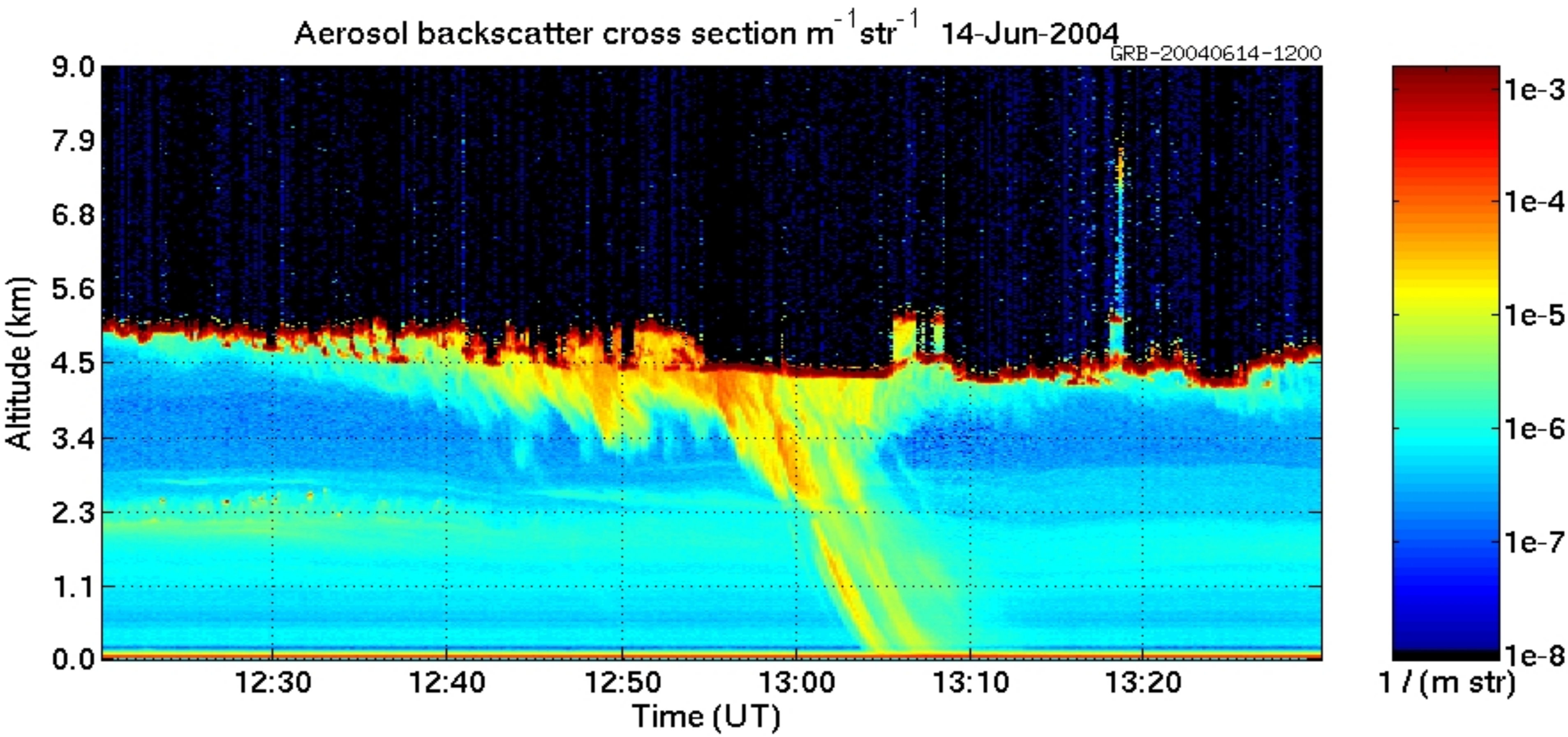
$\tau(r_2 - r_1) = \frac{1}{2} \cdot log(\frac{r_1^2\rho(r_2) \cdot N_m(r_1)}{r_2^2\rho(r_1) \cdot N_m(r_2)})$, where $\rho(r)$= the atmospheric density profile


Attenuated backscatter (m⁻¹str⁻¹) 14-Jan-2004
9.0
7.9
6.8
5.6
4.5
3.4
2.3
1.1
0.0
Altitude (km)
5:00
6:00
7:00
8:00
9:00
10:00
11:00
Time (UT)
1e-4
1e-5
1e-6
1e-7
1 / (m str)

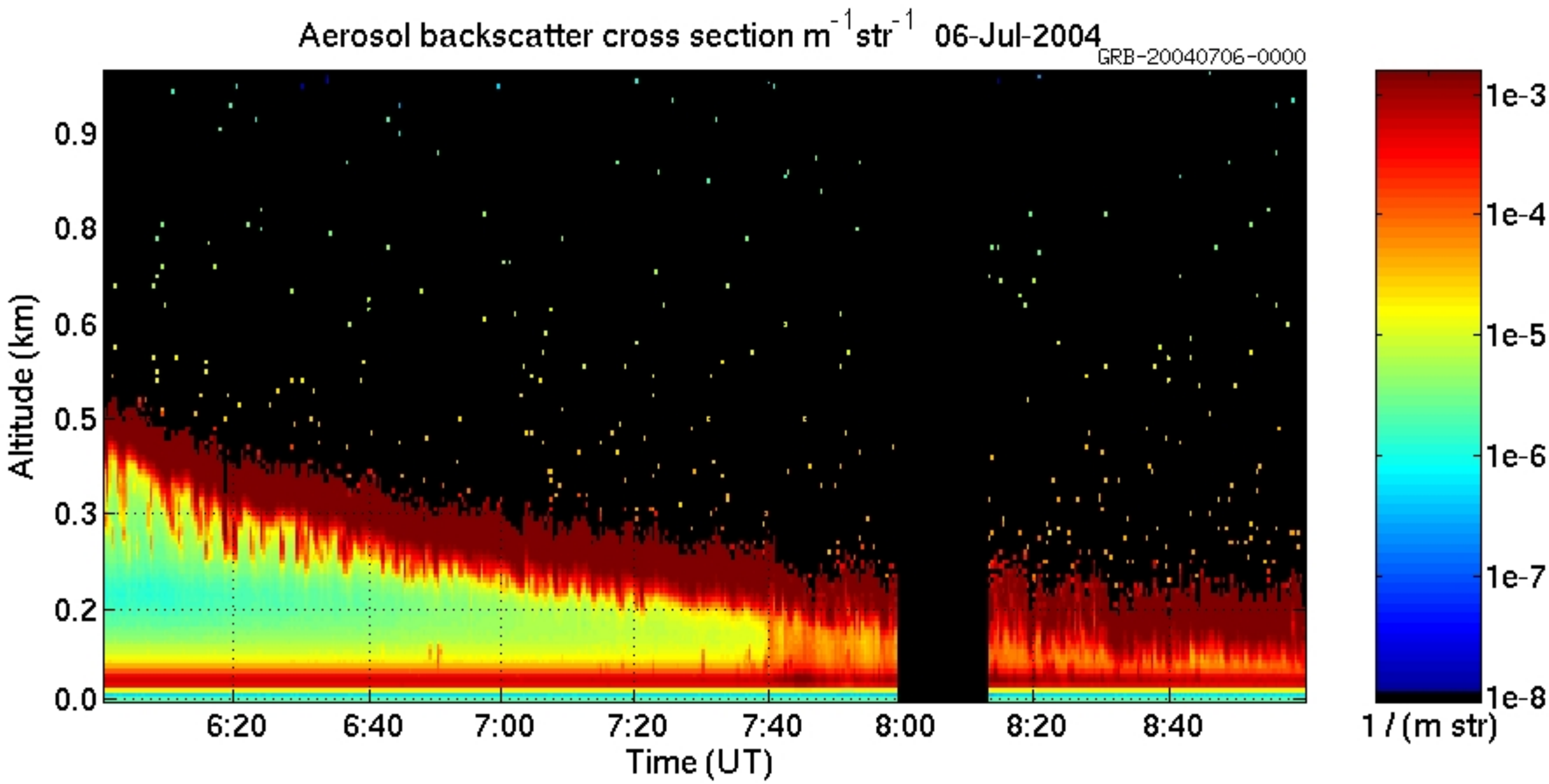


Aerosol backscatter cross section m^{-1}str^{-1} 14-Jan-2004
GRB-20040114-1200
Altitude (km)
9.0
7.9
6.8
5.6
4.5
3.4
2.3
1.1
0.0
5:00
6:00
7:00
8:00
9:00
10:00
11:00
Time (UT)
1e-3
1e-4
1e-5
1e-6
1e-7
1e-8
1 / (m str)

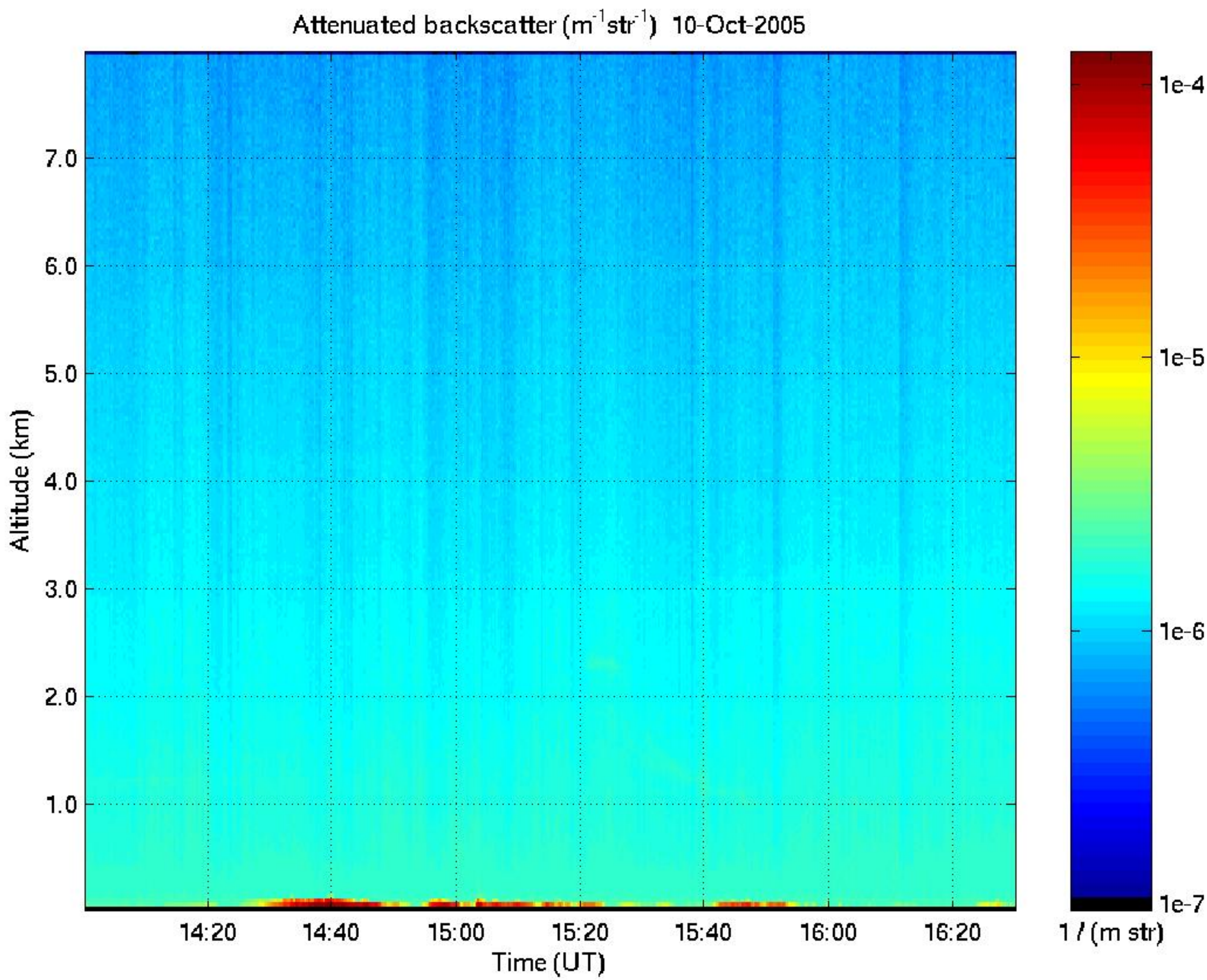

Attenuated backscatter (m^-1 str^-1) 14-Jun-2004
Altitude (km)
9.0
7.9
6.8
5.6
4.5
3.4
2.3
1.1
0.0
12:30
12:40
12:50
13:00
13:10
13:20
Time (UT)
1e-4
1e-5
1e-6
1e-7
1 / (m str)



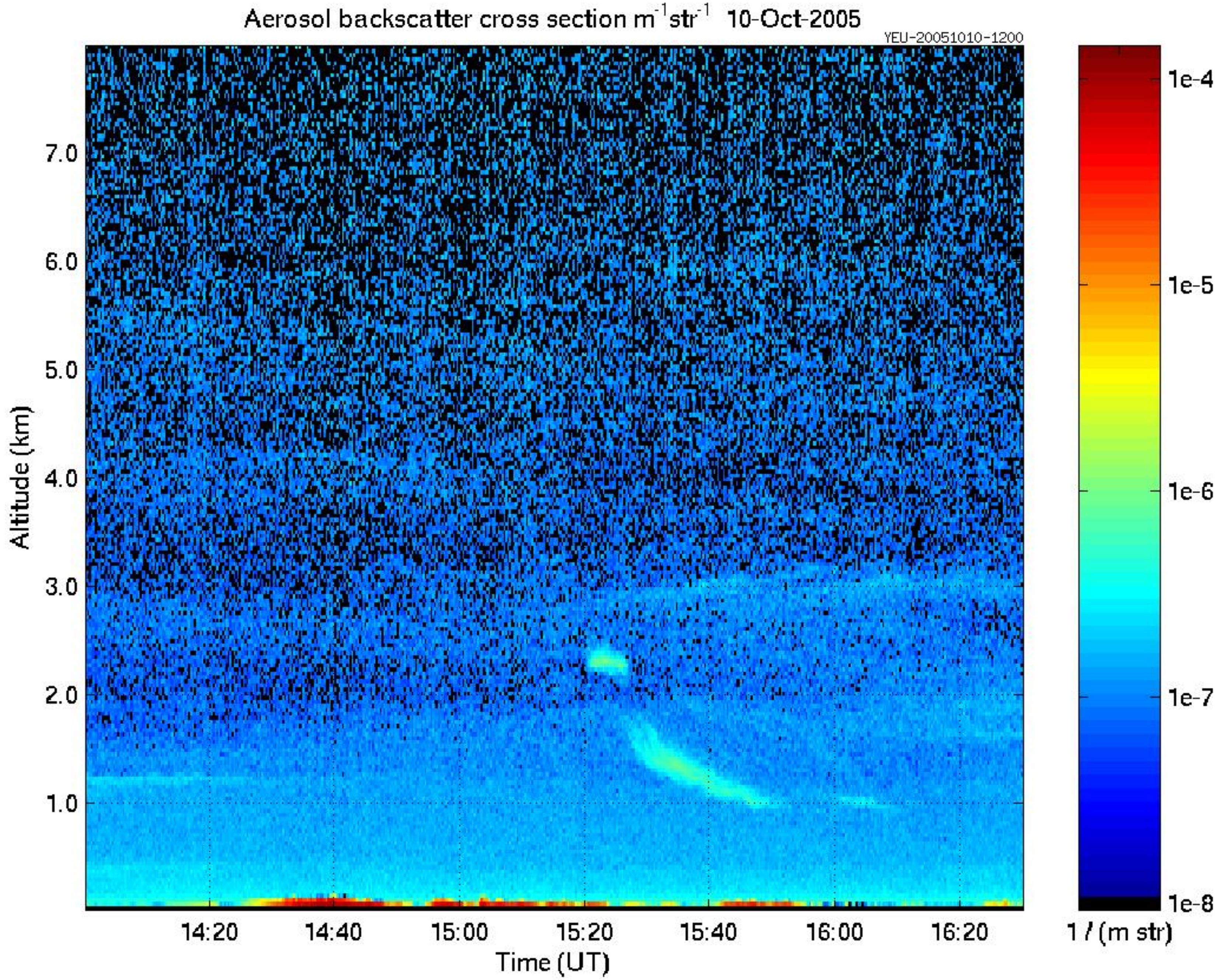
Aerosol backscatter cross section $m^{-1}str^{-1}$ 14-Jun-2004
GRB-20040614-1200
Altitude (km)
9.0
7.9
6.8
5.6
4.5
3.4
2.3
1.1
0.0
12:30
12:40
12:50
13:00
13:10
13:20
Time (UT)
1e-3
1e-4
1e-5
1e-6
1e-7
1e-8
1 / (m str)



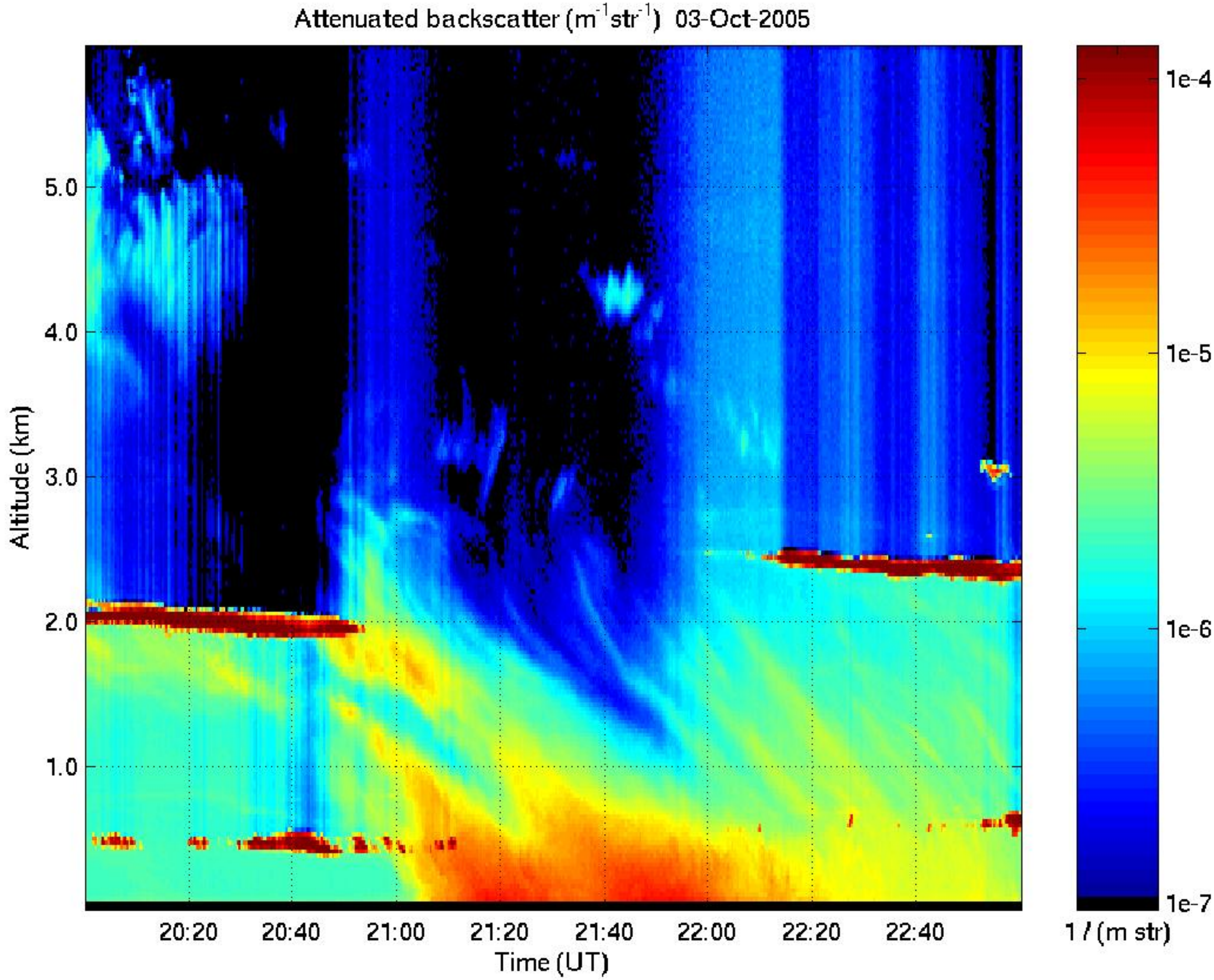
Aerosol backscatter cross section m^{-1}str^{-1} 06-Jul-2004
GRB-20040706-0000
Altitude (km)
0.0
0.2
0.3
0.5
0.6
0.8
0.9
6:20
6:40
7:00
7:20
7:40
8:00
8:20
8:40
Time (UT)
1e-3
1e-4
1e-5
1e-6
1e-7
1e-8
1 / (m str)



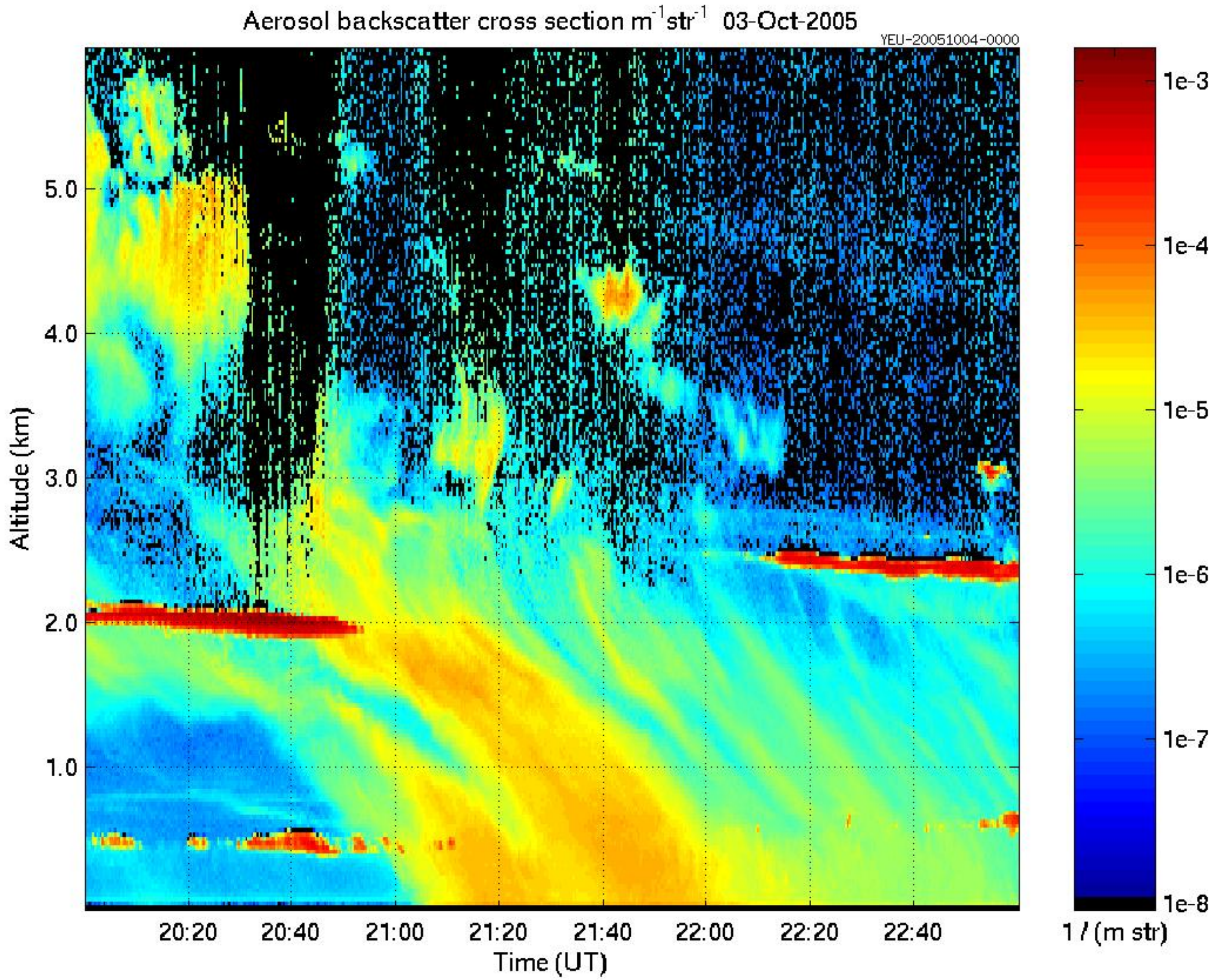
Attenuated backscatter ($m^{-1}str^{-1}$) 10-Oct-2005
7.0
6.0
5.0
4.0
3.0
2.0
1.0
Altitude (km)
14:20
14:40
15:00
15:20
15:40
16:00
16:20
Time (UT)
1e-4
1e-5
1e-6
1e-7
1 / (m str)

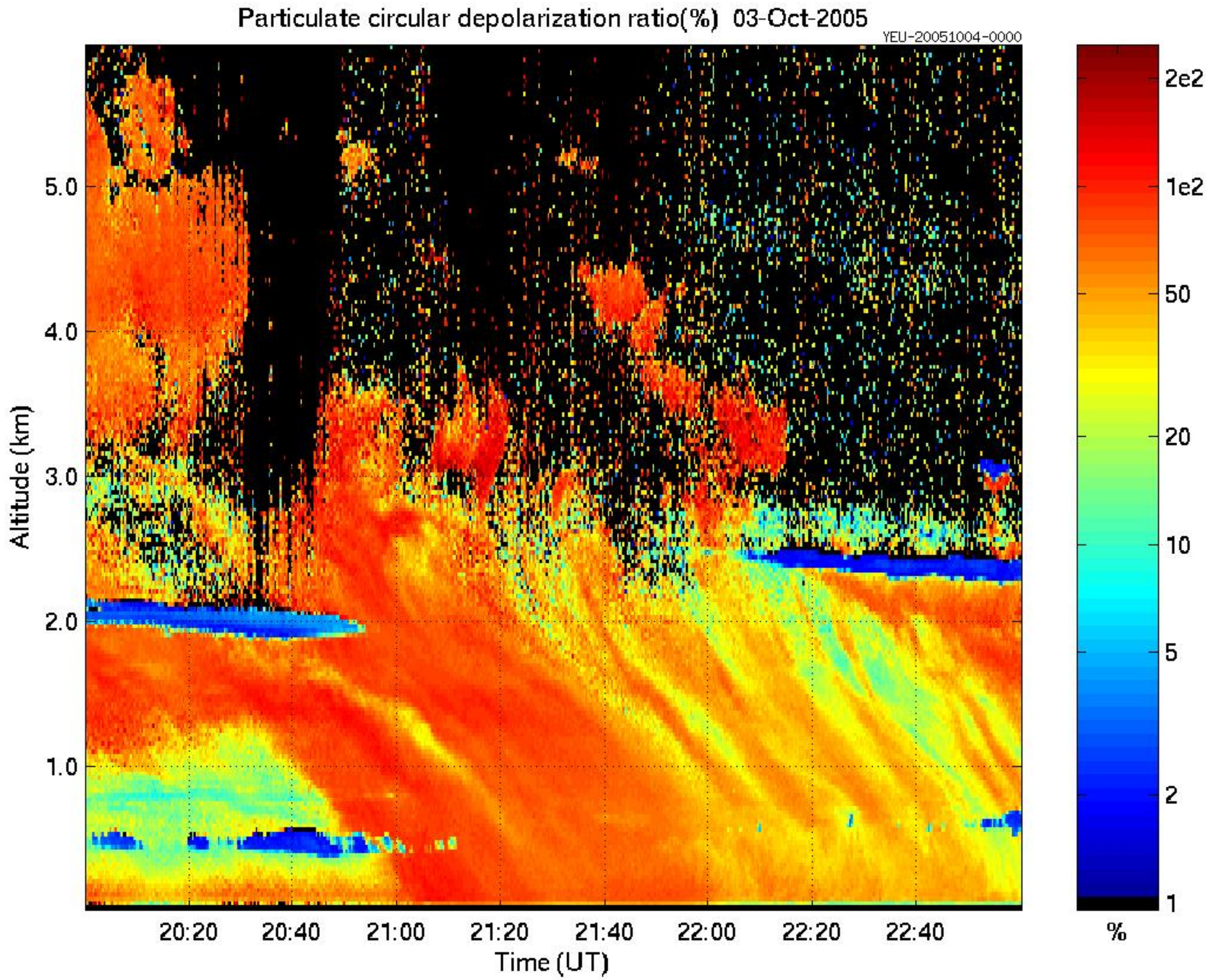


Aerosol backscatter cross section m^{-1}str^{-1} 10-Oct-2005
YEU-20051010-1200
Altitude (km)
7.0
6.0
5.0
4.0
3.0
2.0
1.0
14:20
14:40
15:00
15:20
15:40
16:00
16:20
Time (UT)
1e-4
1e-5
1e-6
1e-7
1e-8
1 / (m str)

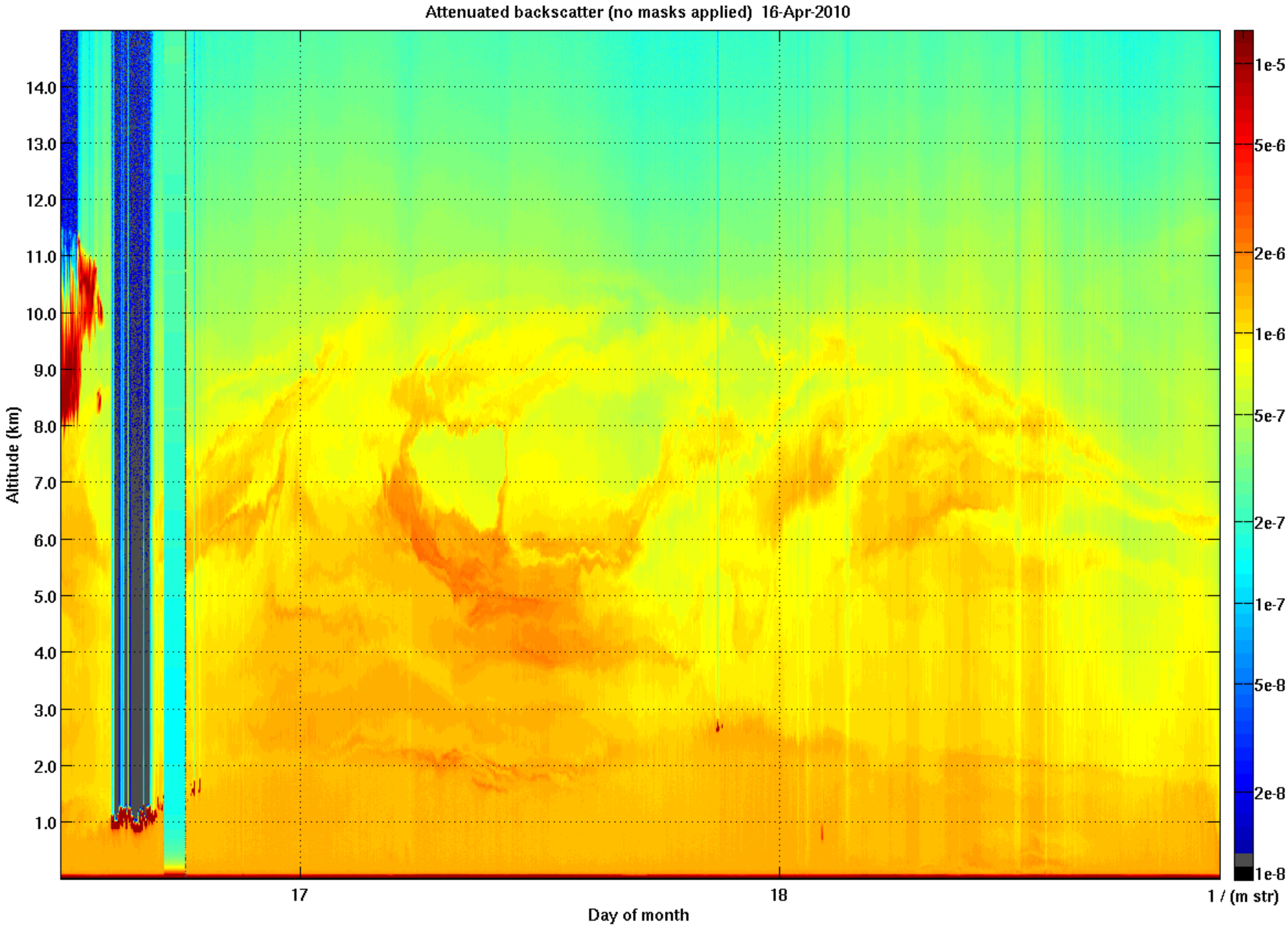


Attenuated backscatter ($m^{-1}str^{-1}$) 03-Oct-2005
Altitude (km)
5.0
4.0
3.0
2.0
1.0
20:20
20:40
21:00
21:20
21:40
22:00
22:20
22:40
Time (UT)
1e-4
1e-5
1e-6
1e-7
1 / (m str)

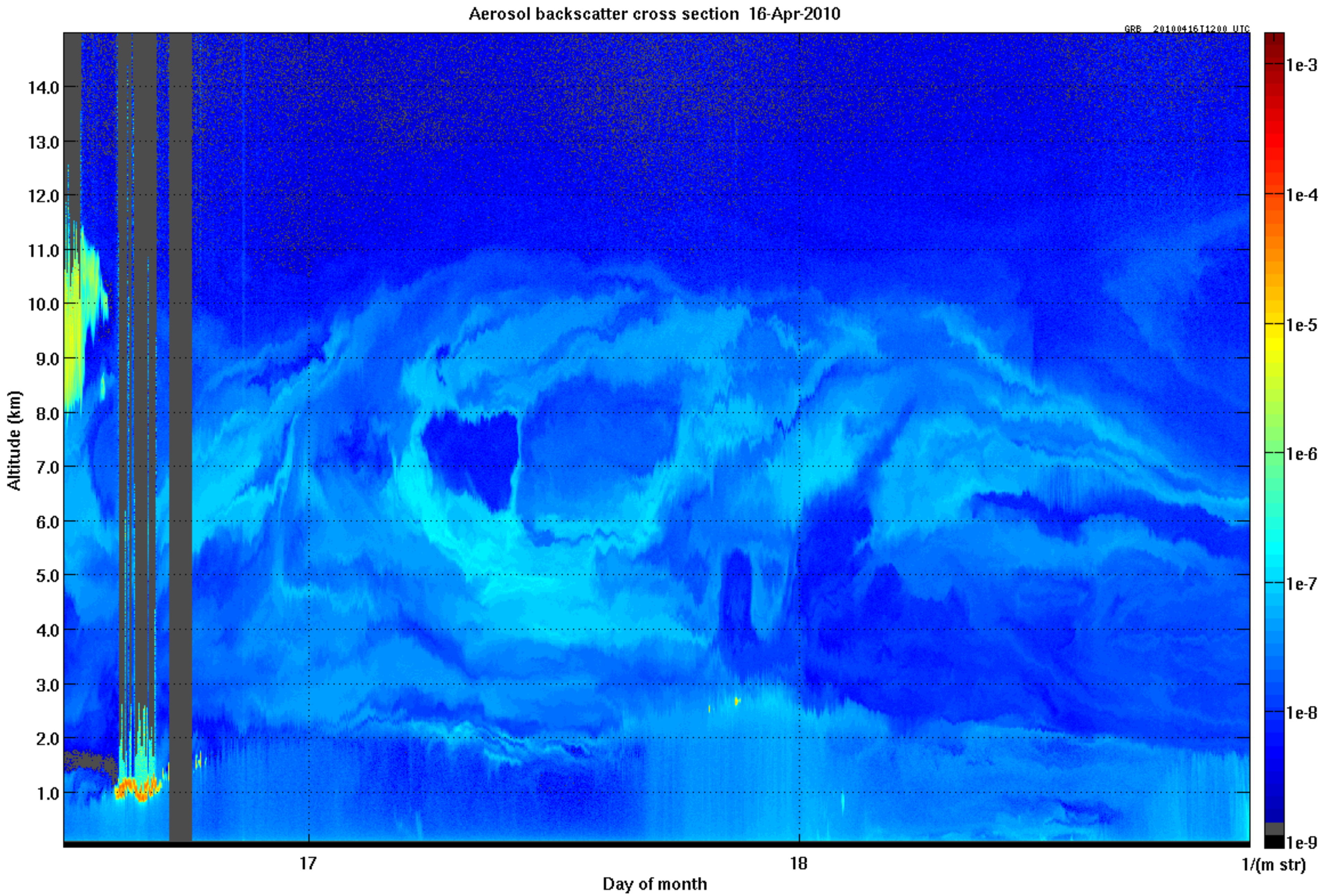

Aerosol backscatter cross section $m^{-1}str^{-1}$ 03-Oct-2005
YEU-20051004-0000
Altitude (km)
5.0
4.0
3.0
2.0
1.0
20:20
20:40
21:00
21:20
21:40
22:00
22:20
22:40
Time (UT)
1e-3
1e-4
1e-5
1e-6
1e-7
1e-8
1 / (m str)

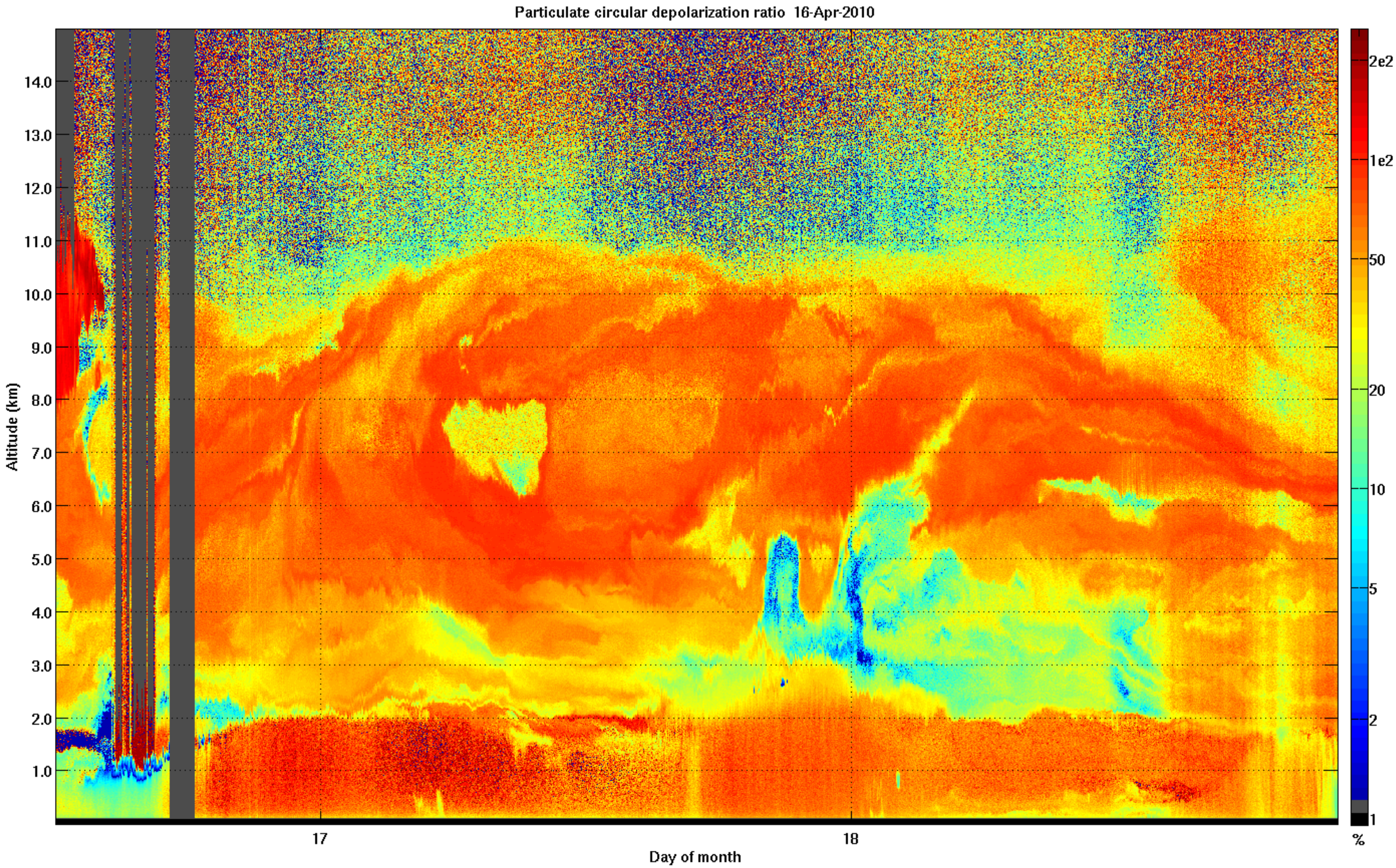


Particulate circular depolarization ratio(%) 03-Oct-2005
YEU-20051004-0000
Altitude (km)
5.0
4.0
3.0
2.0
1.0
20:20
20:40
21:00
21:20
21:40
22:00
22:20
22:40
Time (UT)
2e2
1e2
50
20
10
5
2
1
%



Attenuated backscatter (no masks applied) 16-Apr-2010
Altitude (km)
14.0
13.0
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
17
18
Day of month
1e-5
5e-6
2e-6
1e-6
5e-7
2e-7
1e-7
5e-8
2e-8
1e-8
1 / (m str)


Aerosol backscatter cross section 16-Apr-2010
GRB 20100416T1200 UTC
Altitude (km)
14.0
13.0
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
17
18
Day of month
1e-3
1e-4
1e-5
1e-6
1e-7
1e-8
1e-9
1/(m str)



Particulate circular depolarization ratio 16-Apr-2010
Altitude (km)
14.0
13.0
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
17
18
Day of month
2e2
1e2
50
20
10
5
2
1
%

Advantages of 532 nm operation

--Iodine adsorption line for filtering

--Important wavelength for radiative transfer

--Allows use of doubled Nd:YAG laser

--Strong molecular scattering

Problem with 532 nm—eye safety

--Wavelength region with smallest permitted exposure

max single pulse exposure = 5e-7 J/cm^2

Eye safety

532 nm wavelength has smallest permitted exposure

ANSI safe exposure <= 5e-7 $(PRF/4)^{-1/4}$ J/cm^2

Where PRF = the pulse repetition frequency

This forces high repetition rates and large apertures

Range ambiguity limits R < ~ 4kHz, i.e. r_{max} <~ 40 km

Cost, complexity, turbulence limit aperture to ~0.5 m.

Thus max transmitted energy laser pulse is limited to:

$p25^2*5e\text{-}7*1000^{-1/4}$ =0.174 mJ/pulse

and the maximum transmitted power is:

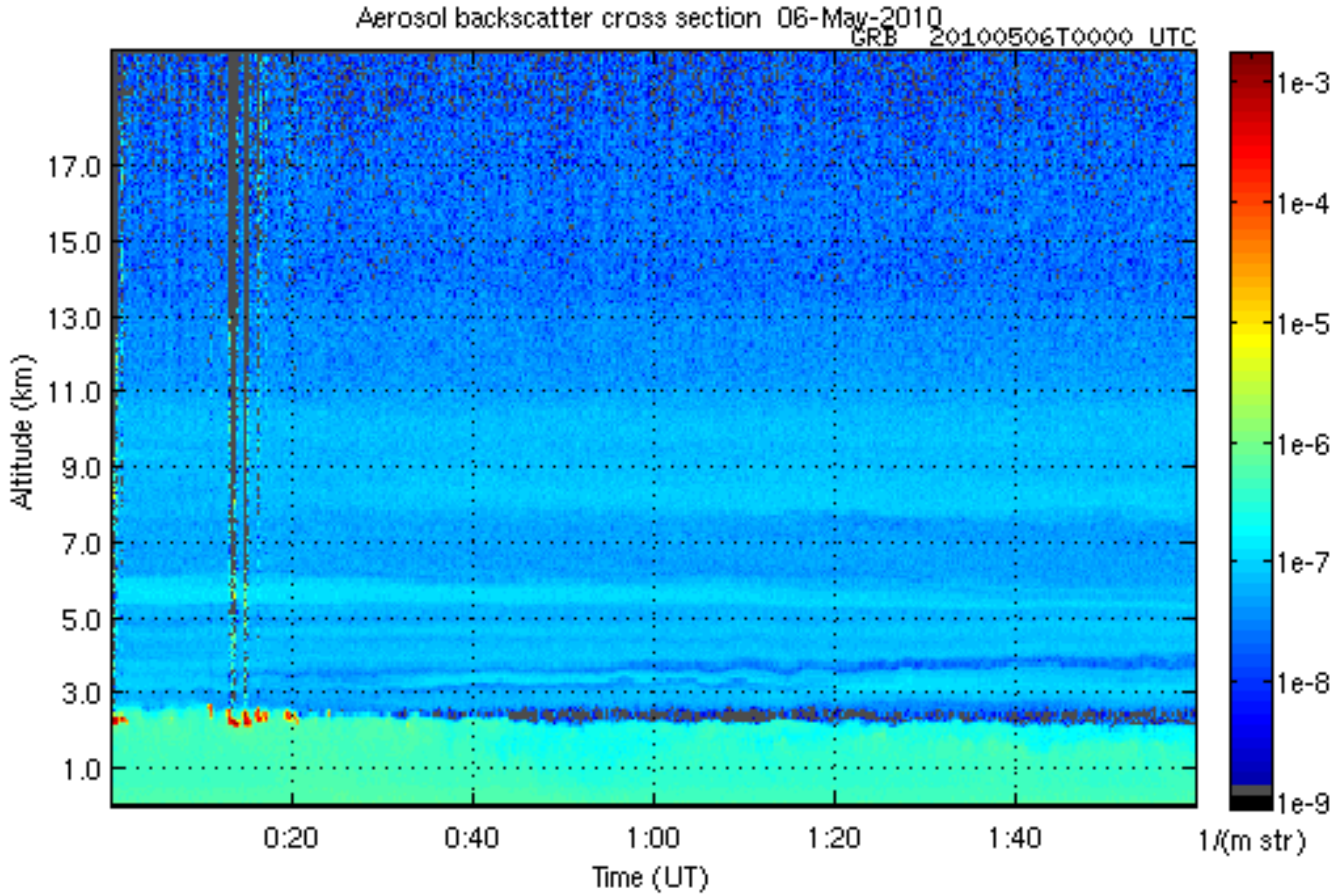
0.174e-3*4000 Hz = 0.7 Watt

-- Low energy laser pulses reduce the signal to noise ratio of the lidar
small lidar returns must compete with scattered sunlight

--this forces
a small receiver acceptance angles (40-100 microradians)
a narrow spectral bandpass ~8 GHz

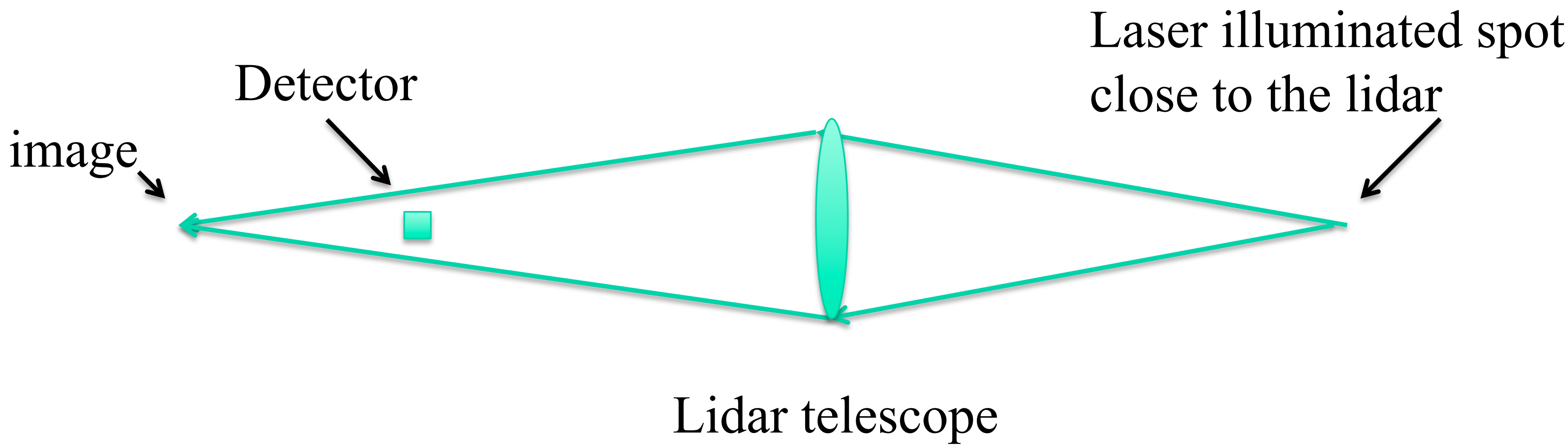
Arctic HSRL Specifications

- Altitude coverage ~75m-->30 km
- Altitude resolution 7.5 m
- Time resolution :
- -Backscatter, depolarization profiles 0.5 sec
- -Optical depth profiles >20 sec
- Eye safe at output
- Wavelength 532 nm
- Power 200 → 600 mW
- Repetition rate 4 kHz
- Field of view 45 microradians
- Sky noise filter bandwidth 8 GHz
- Typical background noise/bin >1 photon/1000 laser pulses
- Receiver diameter 0.4 m
- I2 filter bandwidth 1.8 GHz

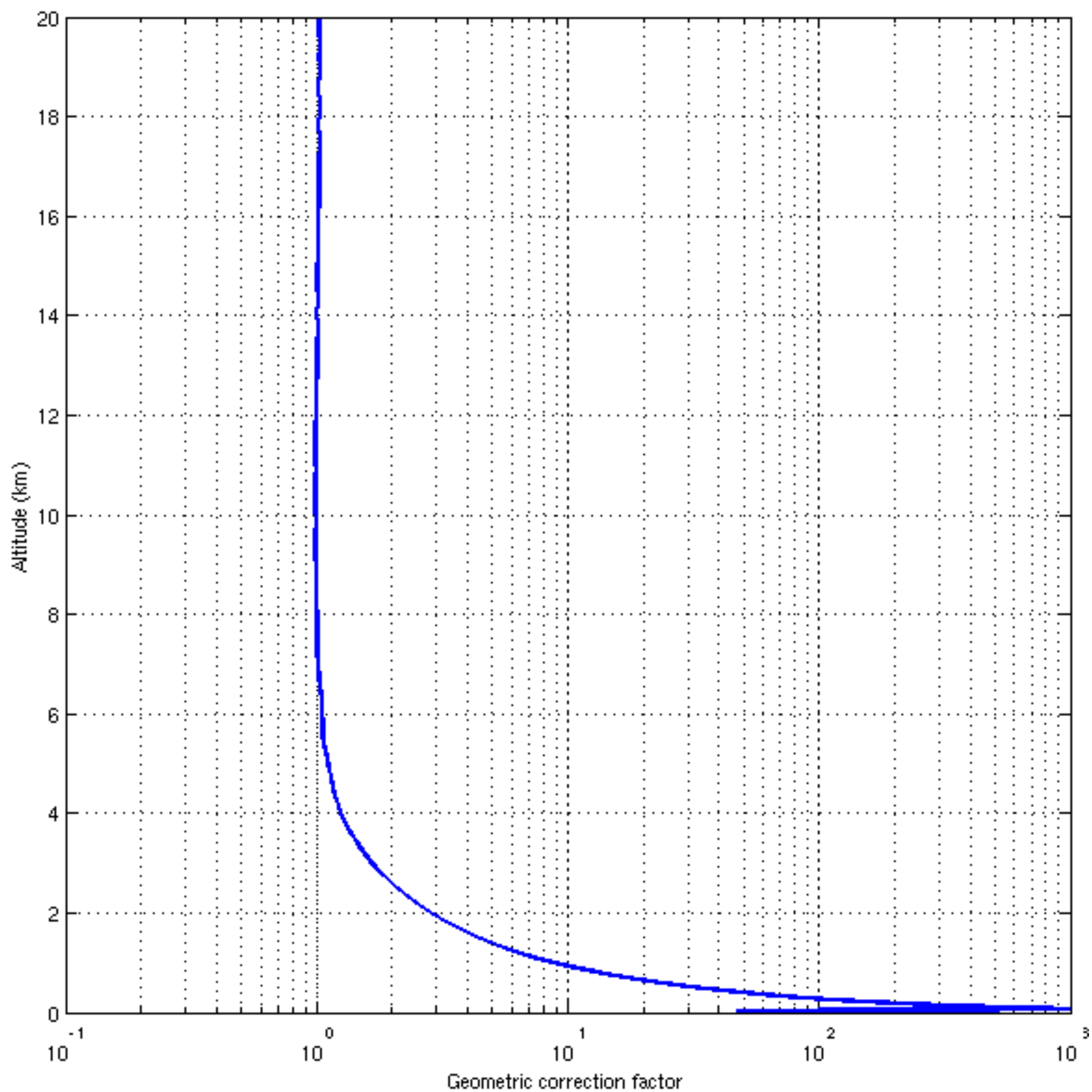


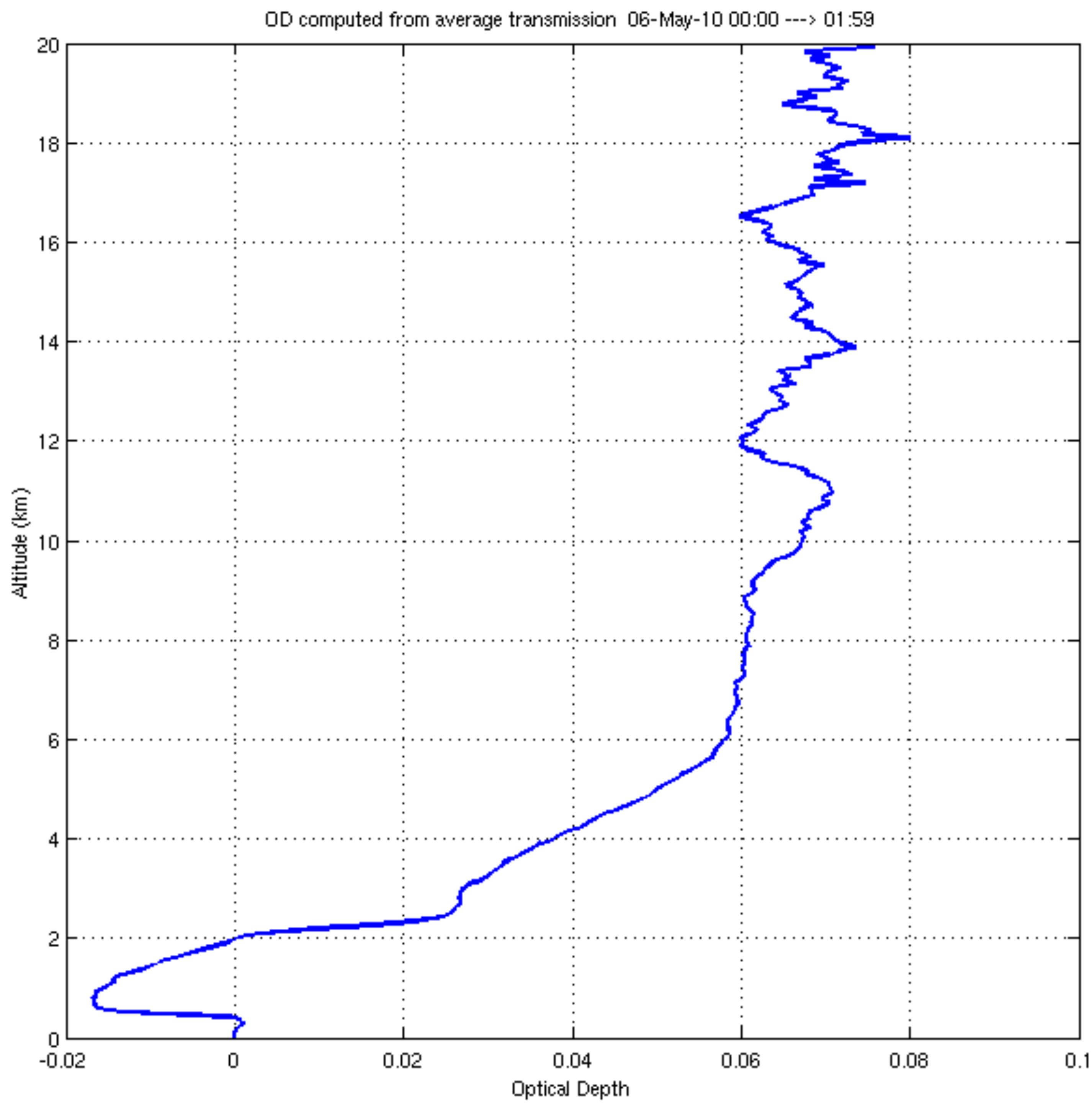
Aerosol backscatter cross section 06-May-2010
GRB 20100506T0000 UTC
Altitude (km)
17.0
15.0
13.0
11.0
9.0
7.0
5.0
3.0
1.0
0:20
0:40
1:00
1:20
1:40
Time (UT)
1e-3
1e-4
1e-5
1e-6
1e-7
1e-8
1e-9
1/(m str)

Geometric correction --- overlap correction



A lidar with a small field-of-view will require a large geometric correction at close range because the out of focus image becomes much larger than the detector.


Altitude (km)
20
18
16
14
12
10
8
6
4
2
0
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
Geometric correction factor



OD computed from average transmission 06-May-10 00:00 ---> 01:59
Altitude (km)
Optical Depth
0
2
4
6
8
10
12
14
16
18
20
-0.02
0
0.02
0.04
0.06
0.08
0.1

Comparison between potential systems

-- Raman

scattering cross section~ Rayleigh/1000
requires high average power ~10's W
large diameter receiver, typically ~0.6 m
can accommodate larger FOV's
relatively simple

--I2 HSRL 532nm

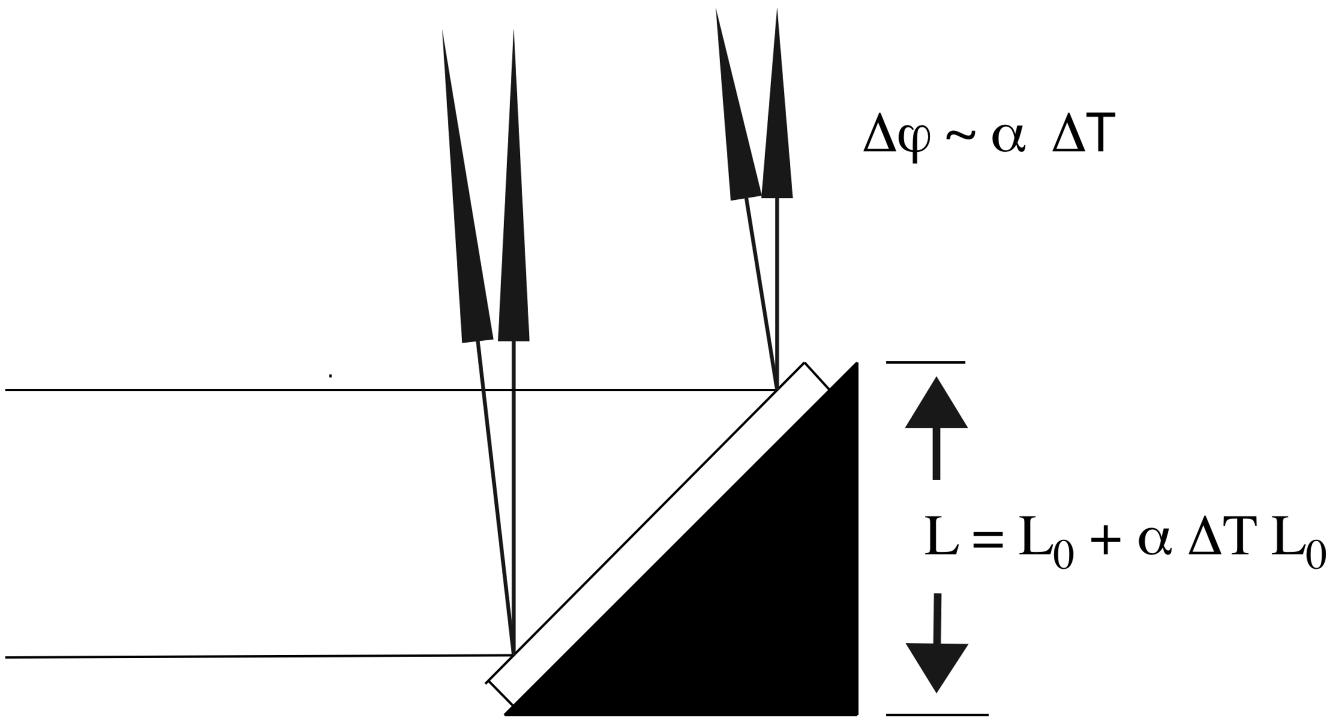
scattering cross section ~Rayleigh/4
lower average power ~0.5 W
somewhat smaller receiver ~0.4 m
can accommodate larger FOV's
relatively complex

--Fabry-Perot HSRL 355 nm

larger cross section that 532nm
more complex than I2
field-of-view due to Fabry-Perot

HSRL data can be found at:

http://lidar.ssec.wisc.edu

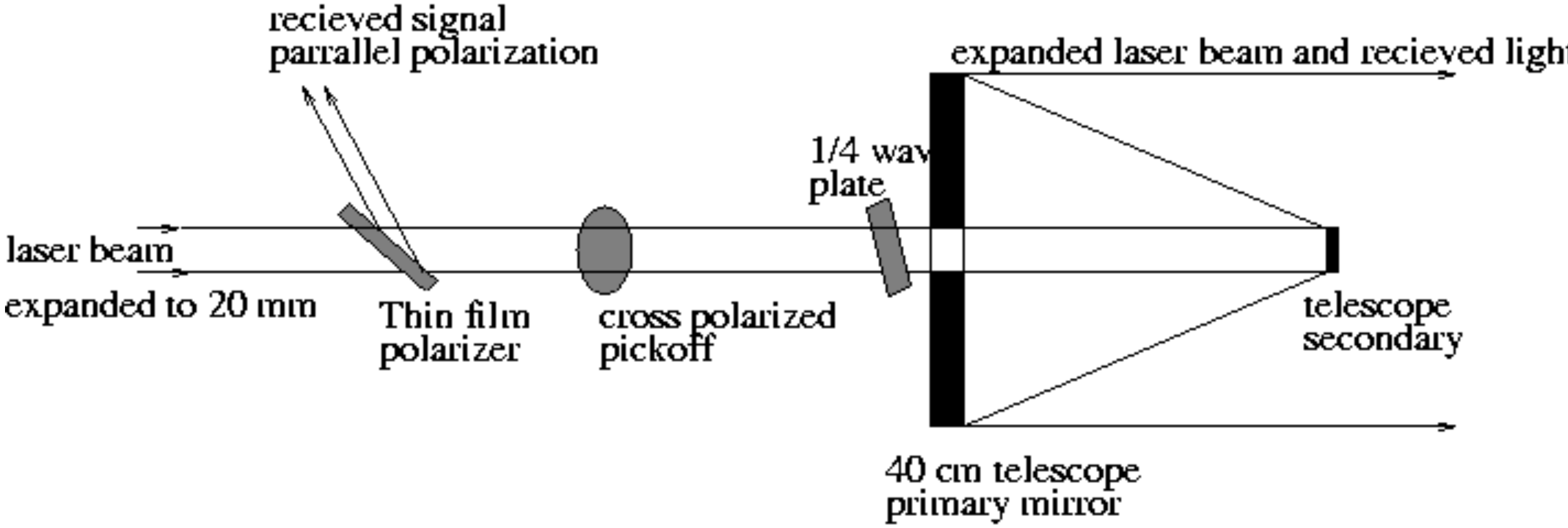


Thermal expansion of components effect the alignment of transmitter with the receiver. Here we consider the example of an 45 deg aluminum mountin block for a beam turning mirror.

Angle shift due to 10 deg C temperature change: $\Delta\varphi \sim \alpha\ \Delta T \sim 2.5 * 10^{-5} * 10$

$\Delta\varphi \sim 250$ microradian

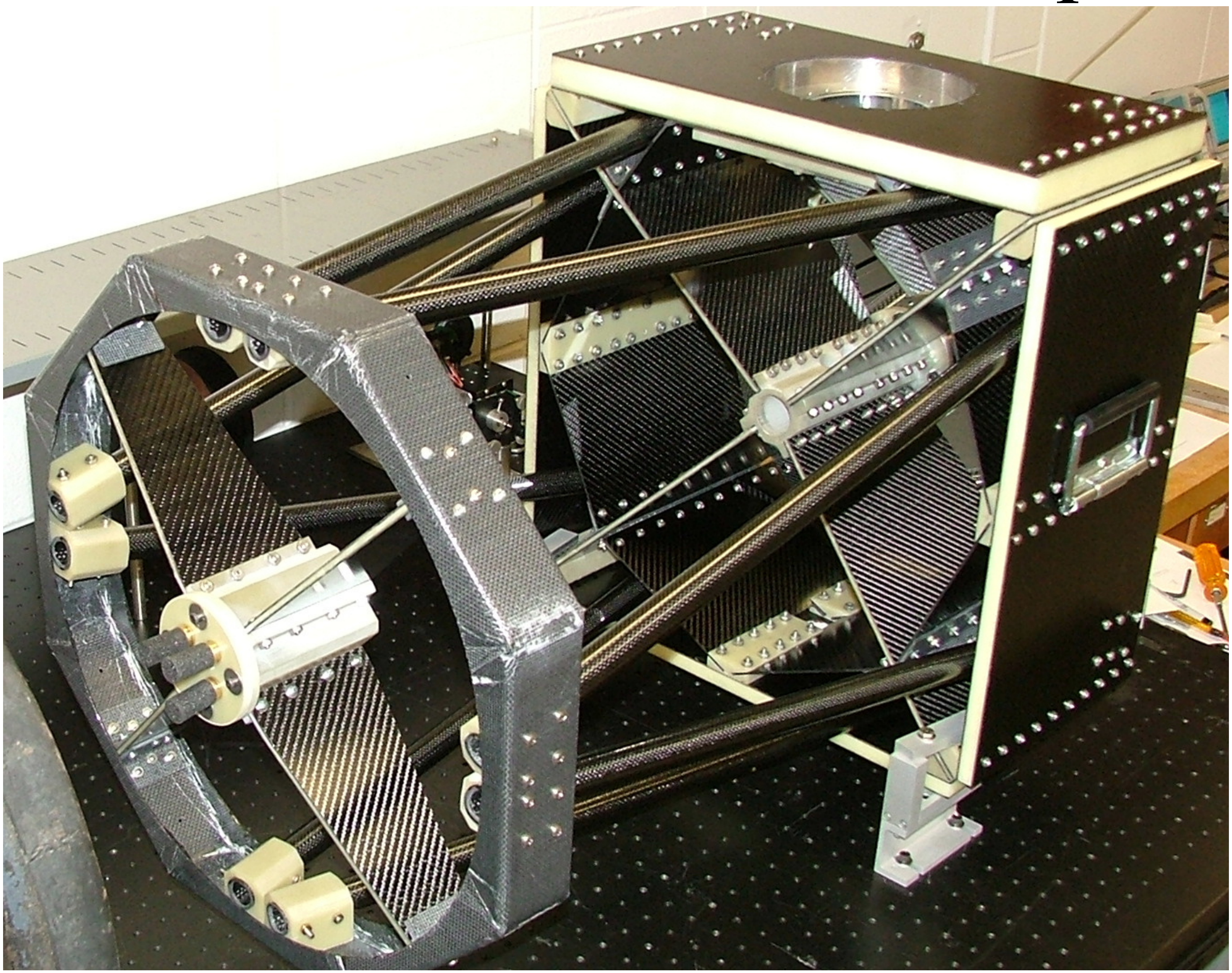
AHSRL transmit-receive telescope



--The 20 mm diameter linearly-polarized laser beam is converted to circular polarization by ¼ wave plate before expansion 40 cm.

--The received signal is converted to linear polarization on return through the ¼ wave plate. Approx. 10% of the signal is separated to measure the cross-polarized component. The parallel-polarized component is separated from the transmit beam by the thin-film polarizer.

Transmit-Receive Telescope



I was asked to comment on following:

--Cost?

~$ 1M

--Laser power, possible interference with Cerenkov measurements?

532 nm, maximum eyesafe power ~0.5 W

--Maintenance cost?

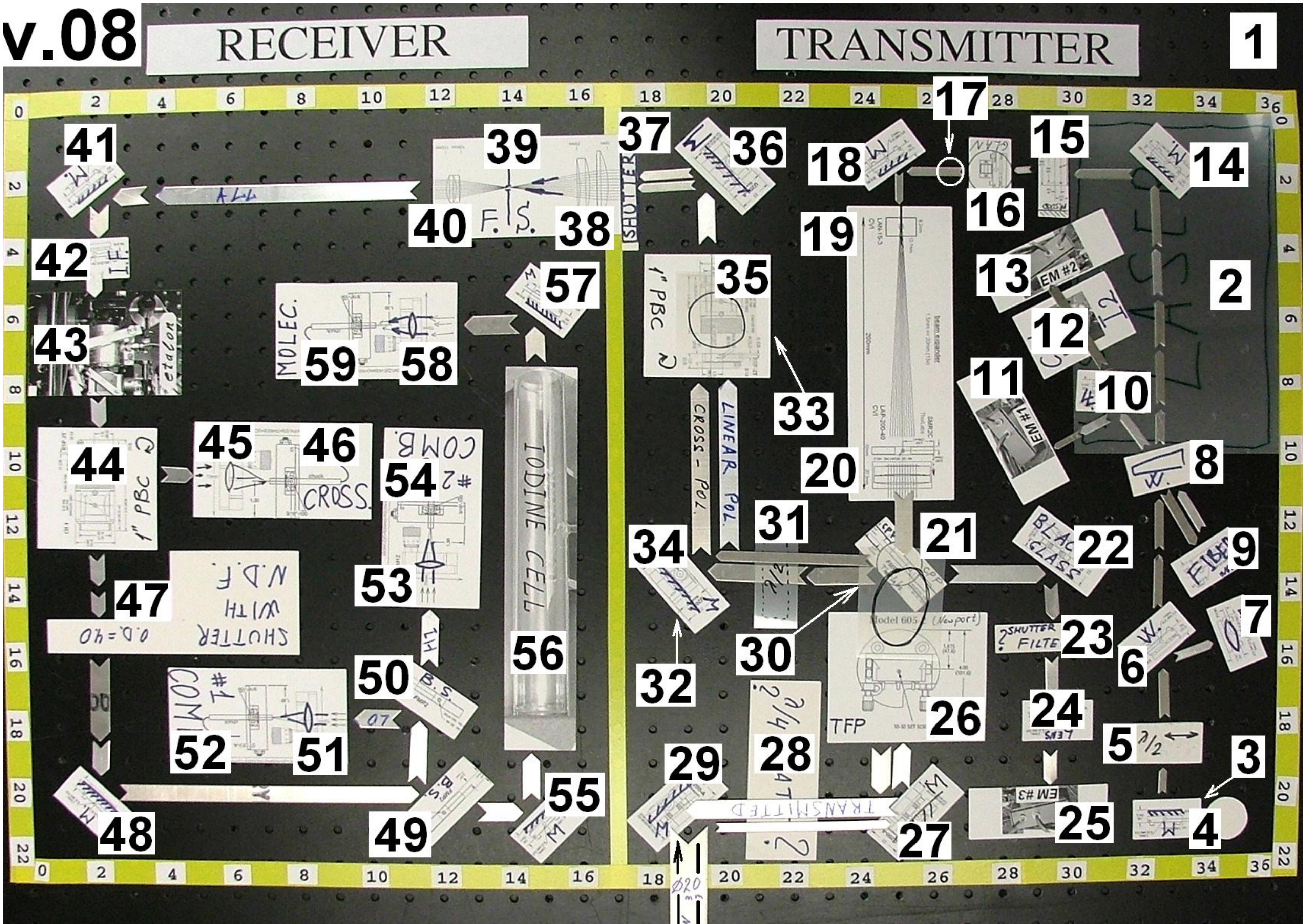
Relatively low, visit Arctic site ~ 2-3 times/year

--External data requirements?

Radiosonde profiles from national weather service.


EXIT
CAUTION

v.08


RECEIVER
TRANSMITTER
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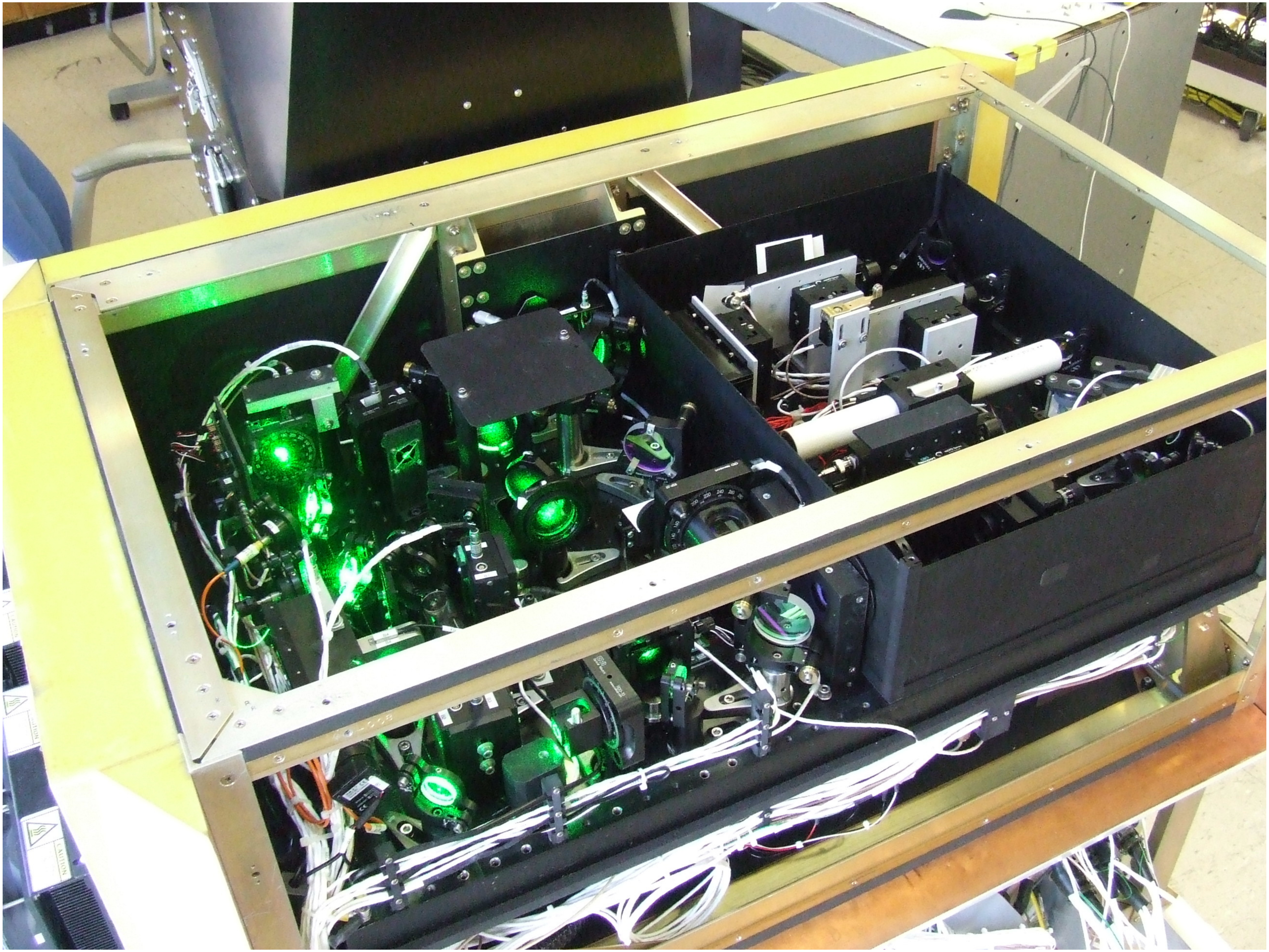
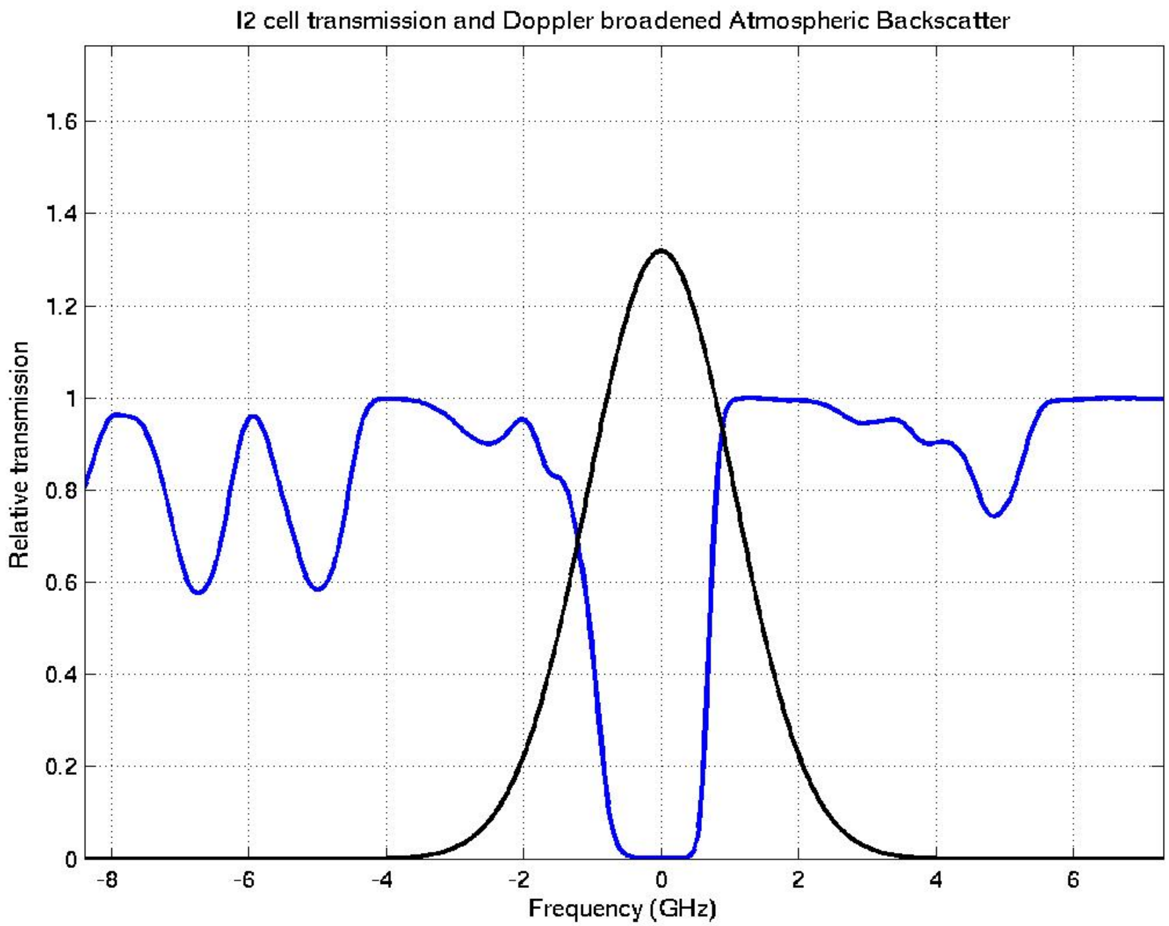
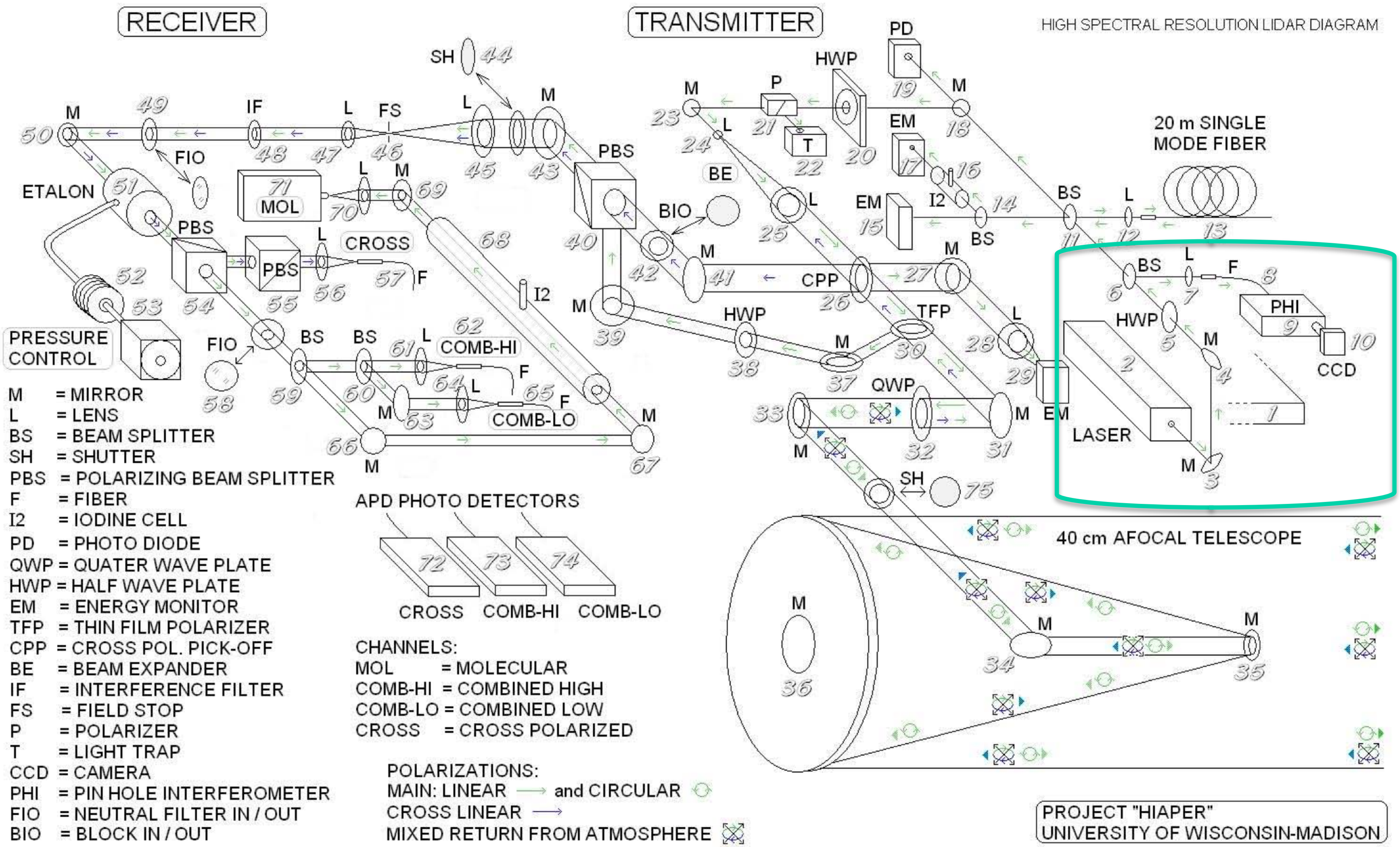
LASER
I.F.
etalon
1" PBC
CROSS
COMB. #2
N.D.F. WITH SHUTTER O.D.=4.0
COMB. #1
B.S.
IODINE CELL
MOLEC.
F.S.
SHUTTER
1" PBC
CROSS - POL.
LINEAR POL.
EM #2
EM #1
EM #3
FIBER
BLACK GLASS
SHUTTER FILTER
TFP
λ/4 ?
TRANSMITTED
Ø20 mm
GLAN
I2



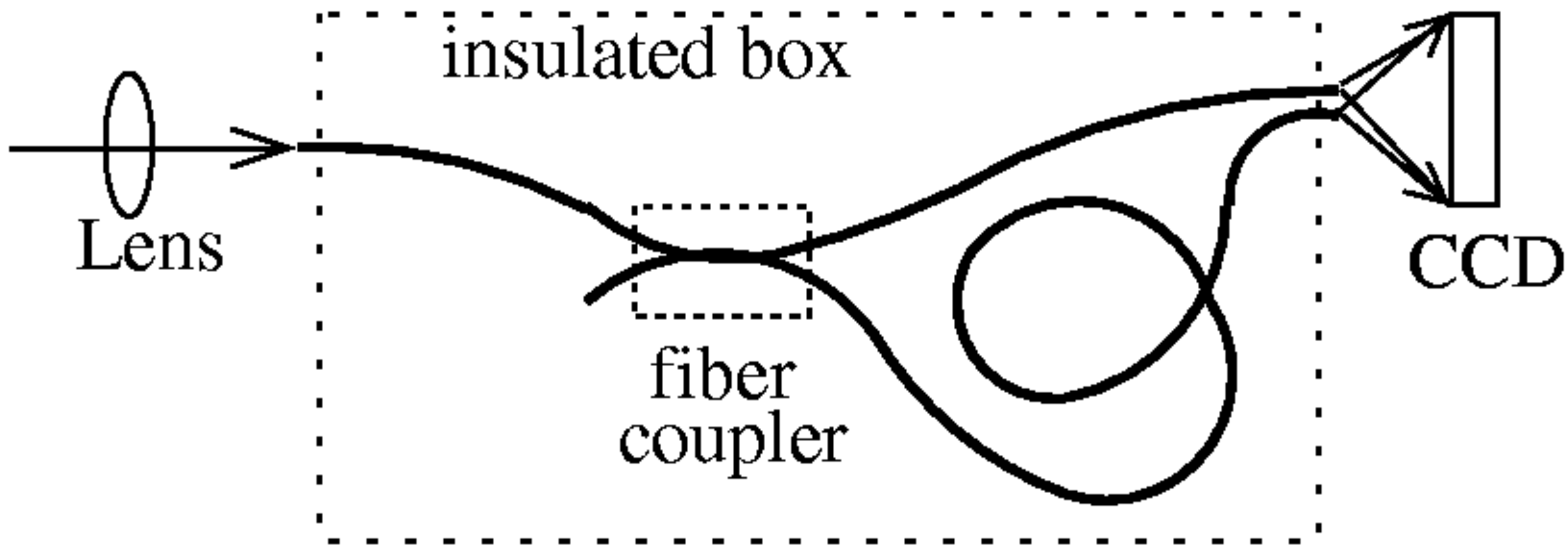
HSRL calibration requires a spectral scan to determine bandpass of filters



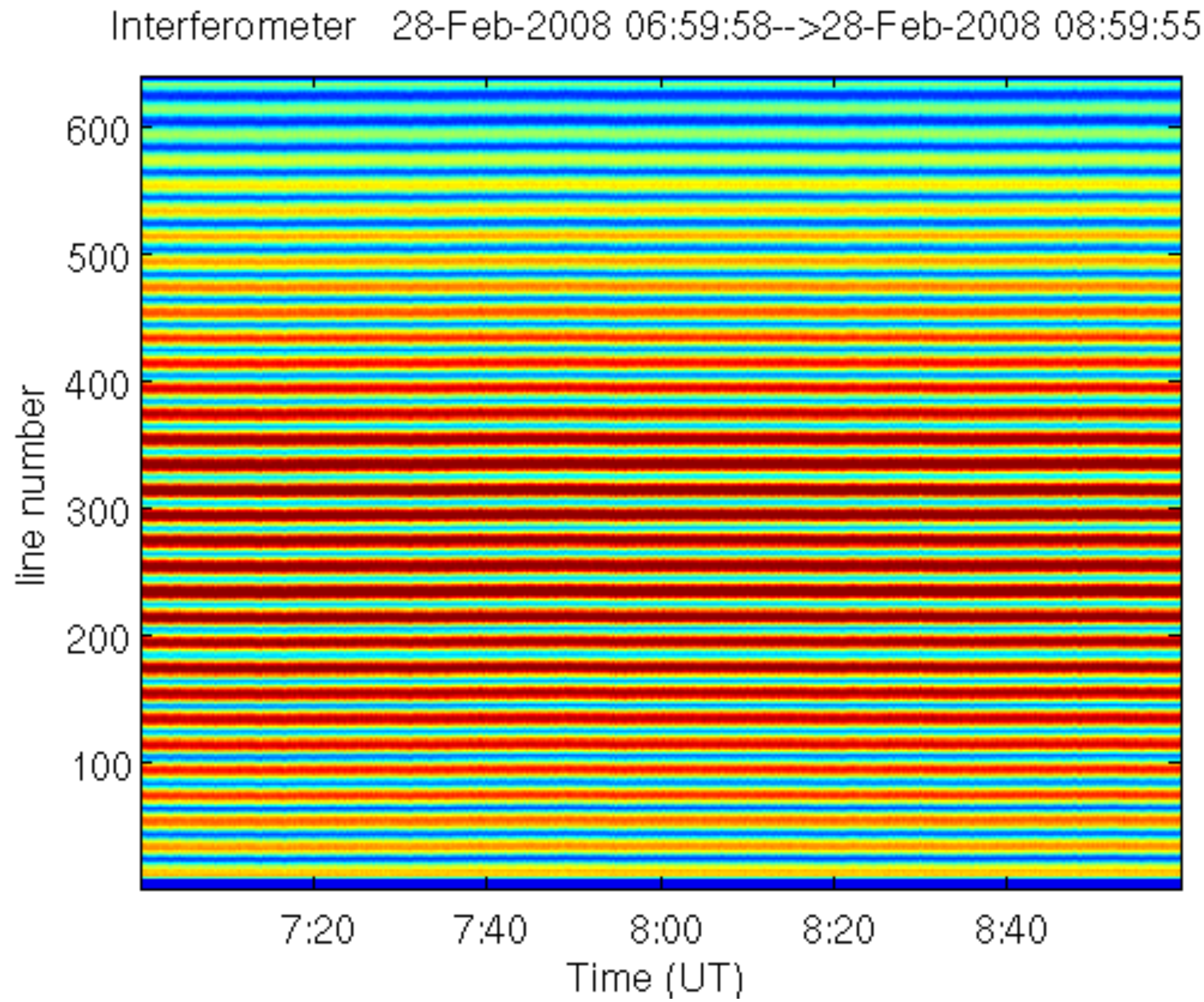
Laser and interferometer



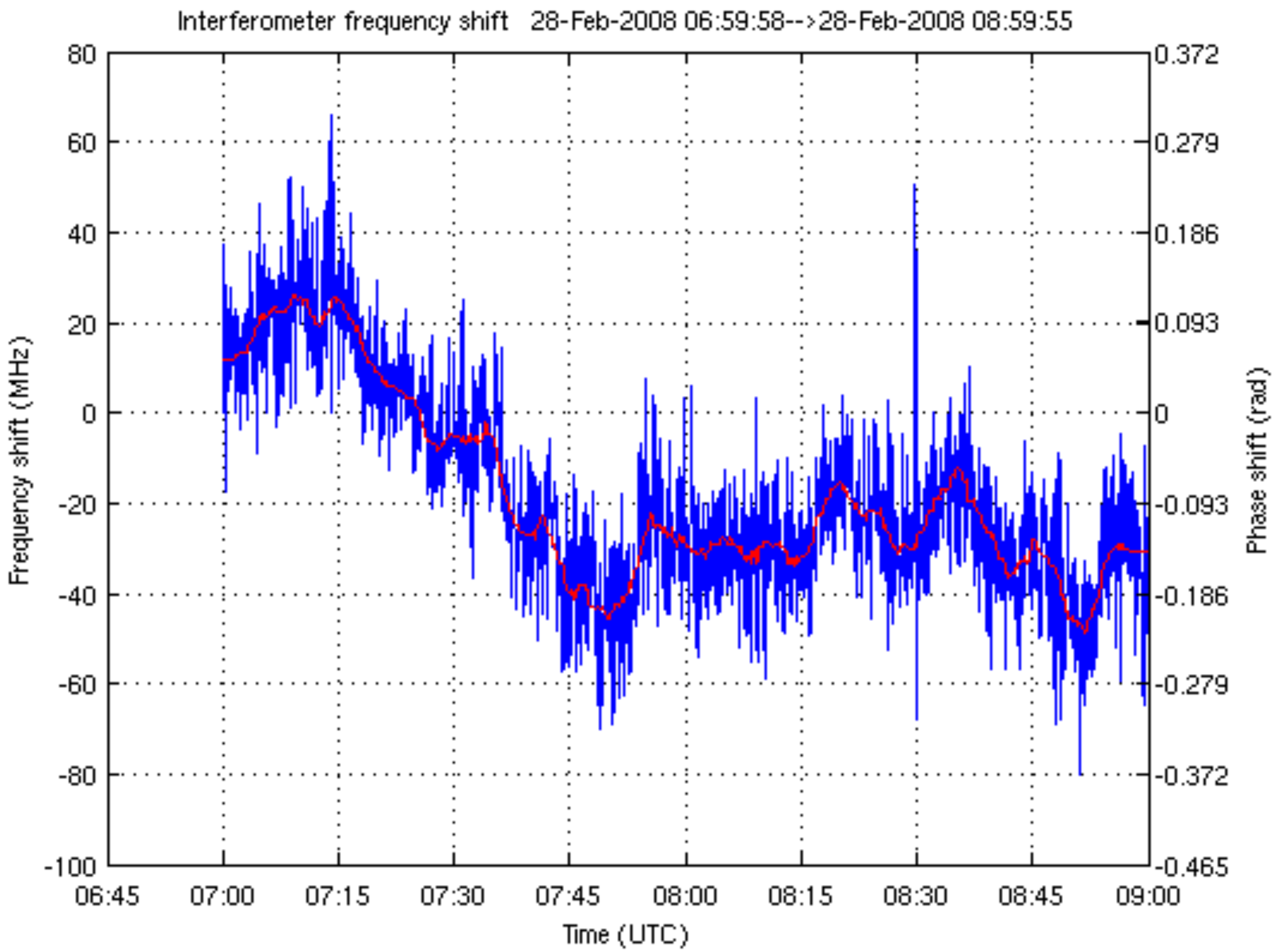
Young's pinhole interferometer



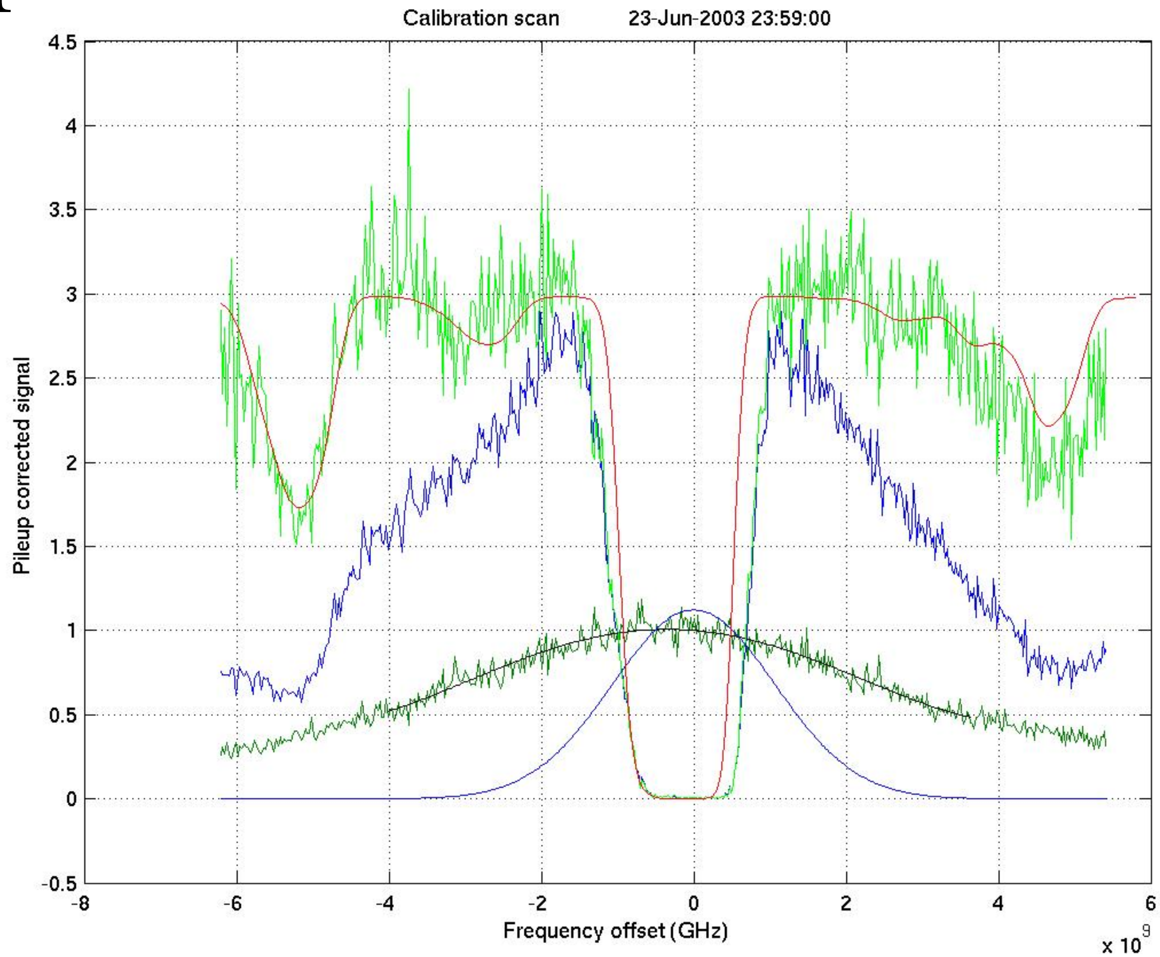
One column from interferometer



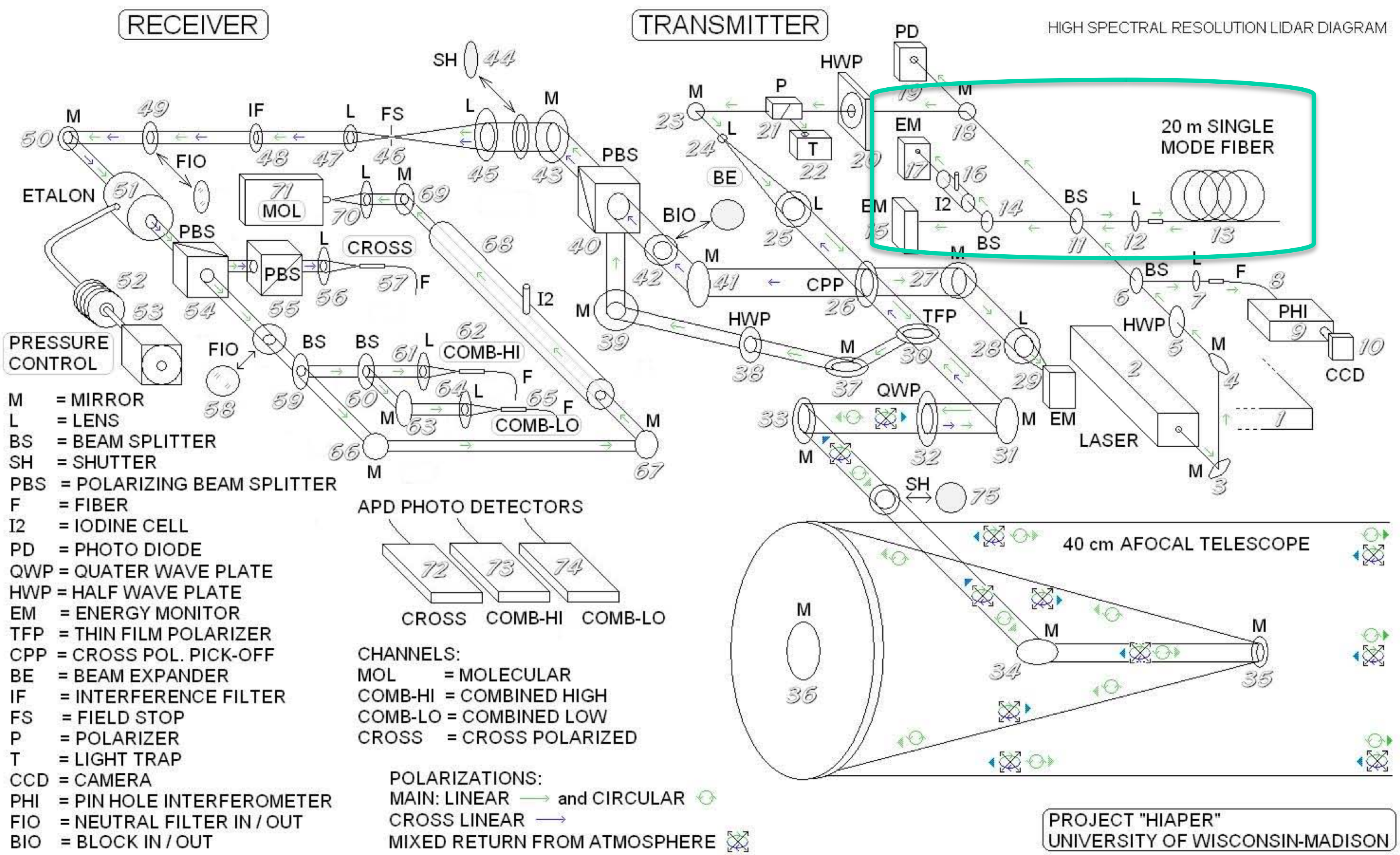
Frequency vs time from interferometer



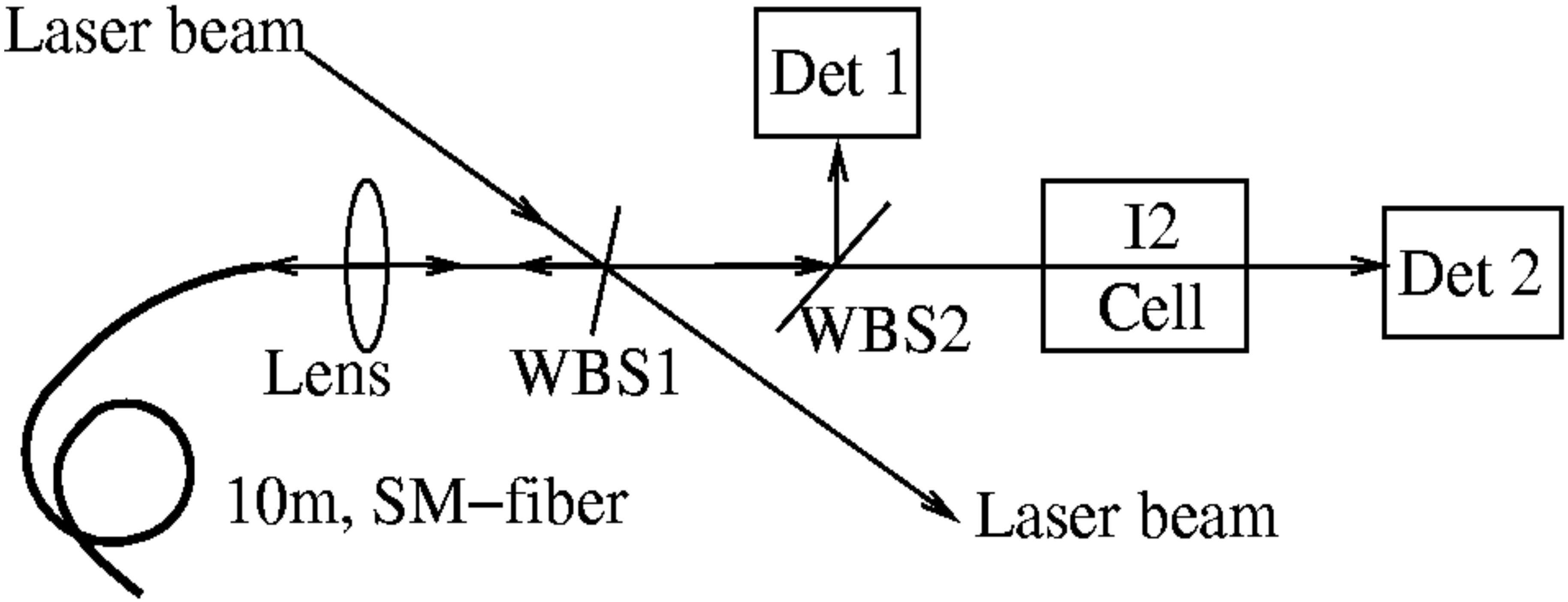
Spectral scan for calibration



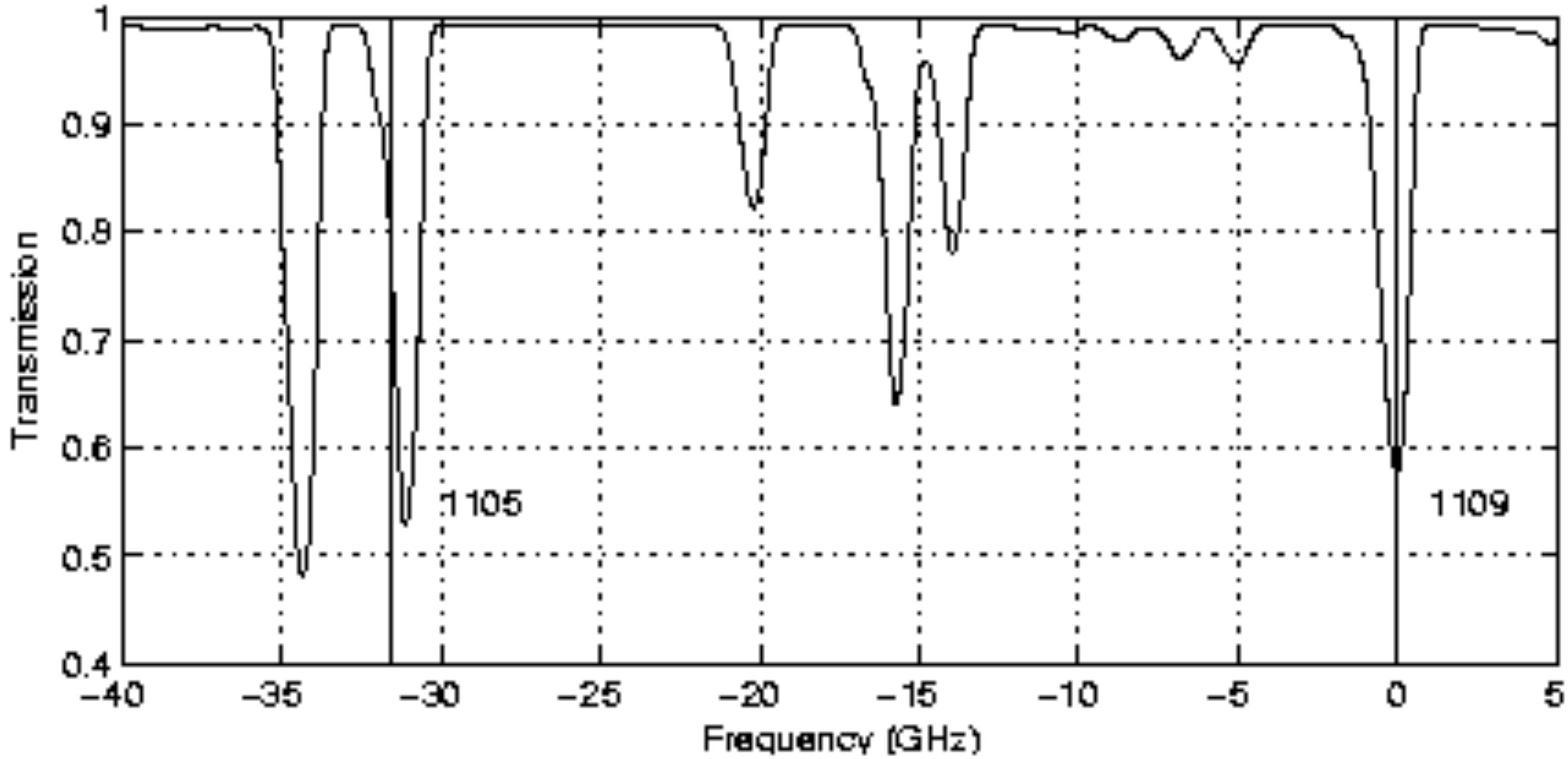
Brillouin frequency locking



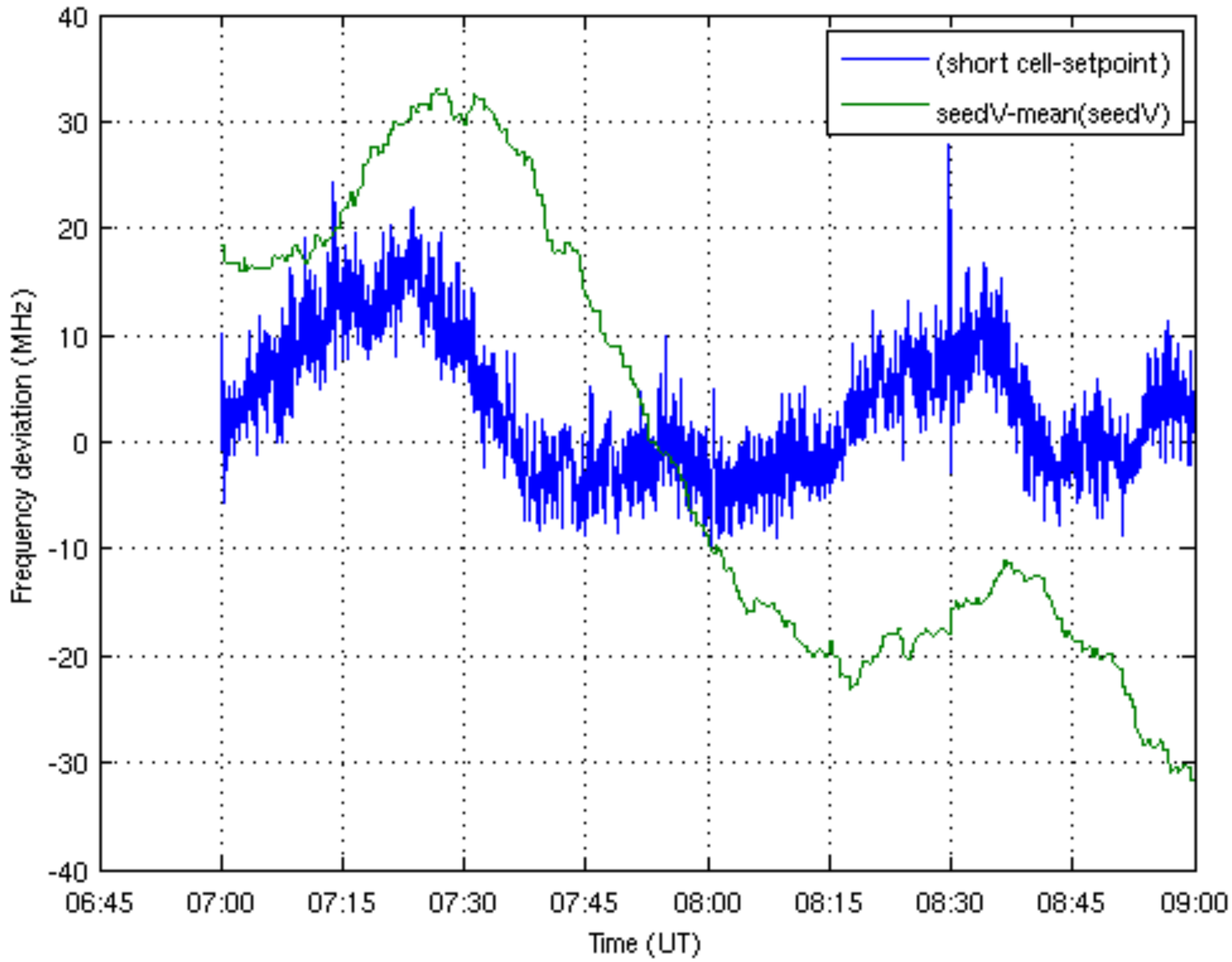
Brillouin frequency locking system

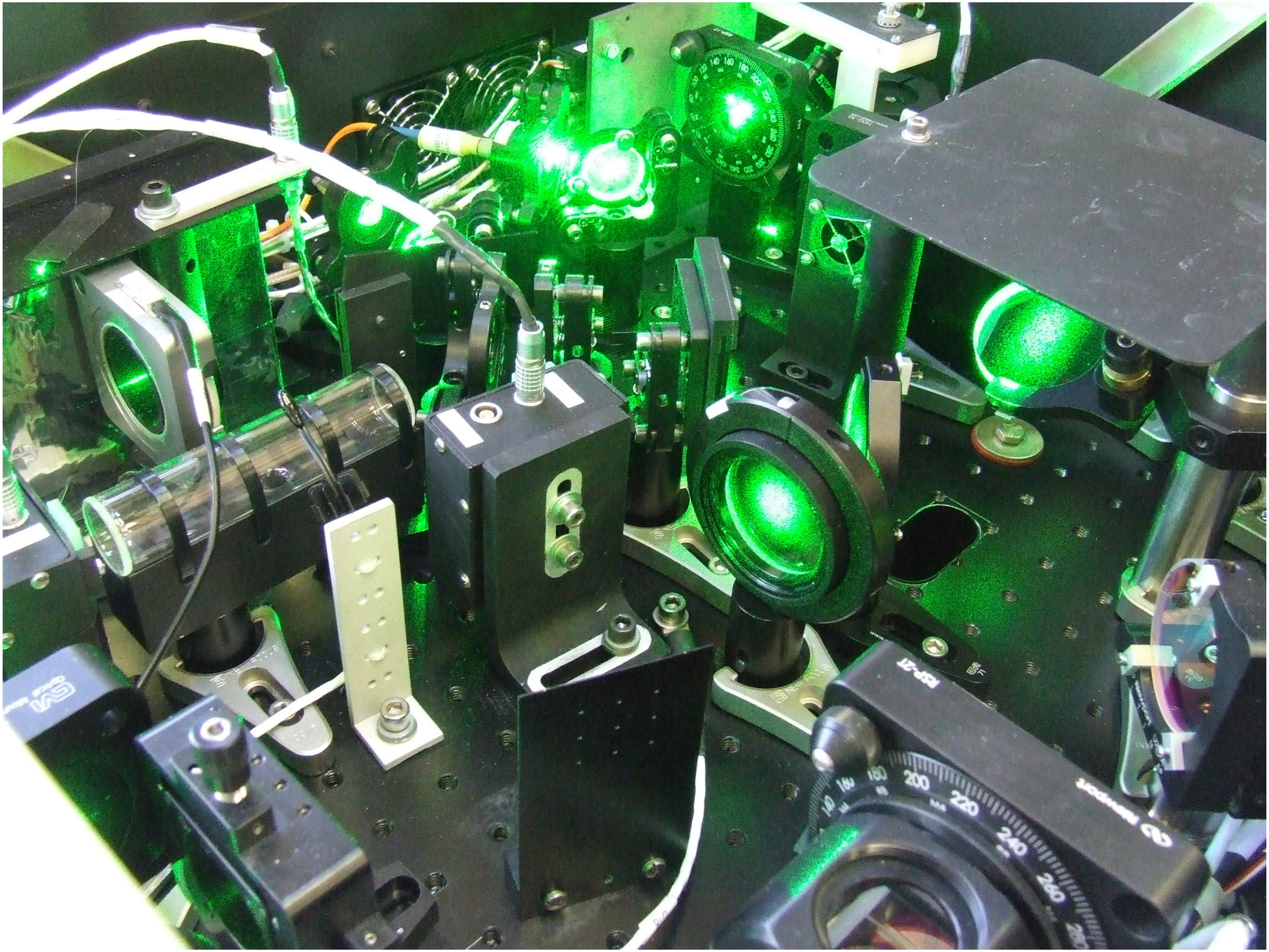


Transmission of 2-cm iodine cell

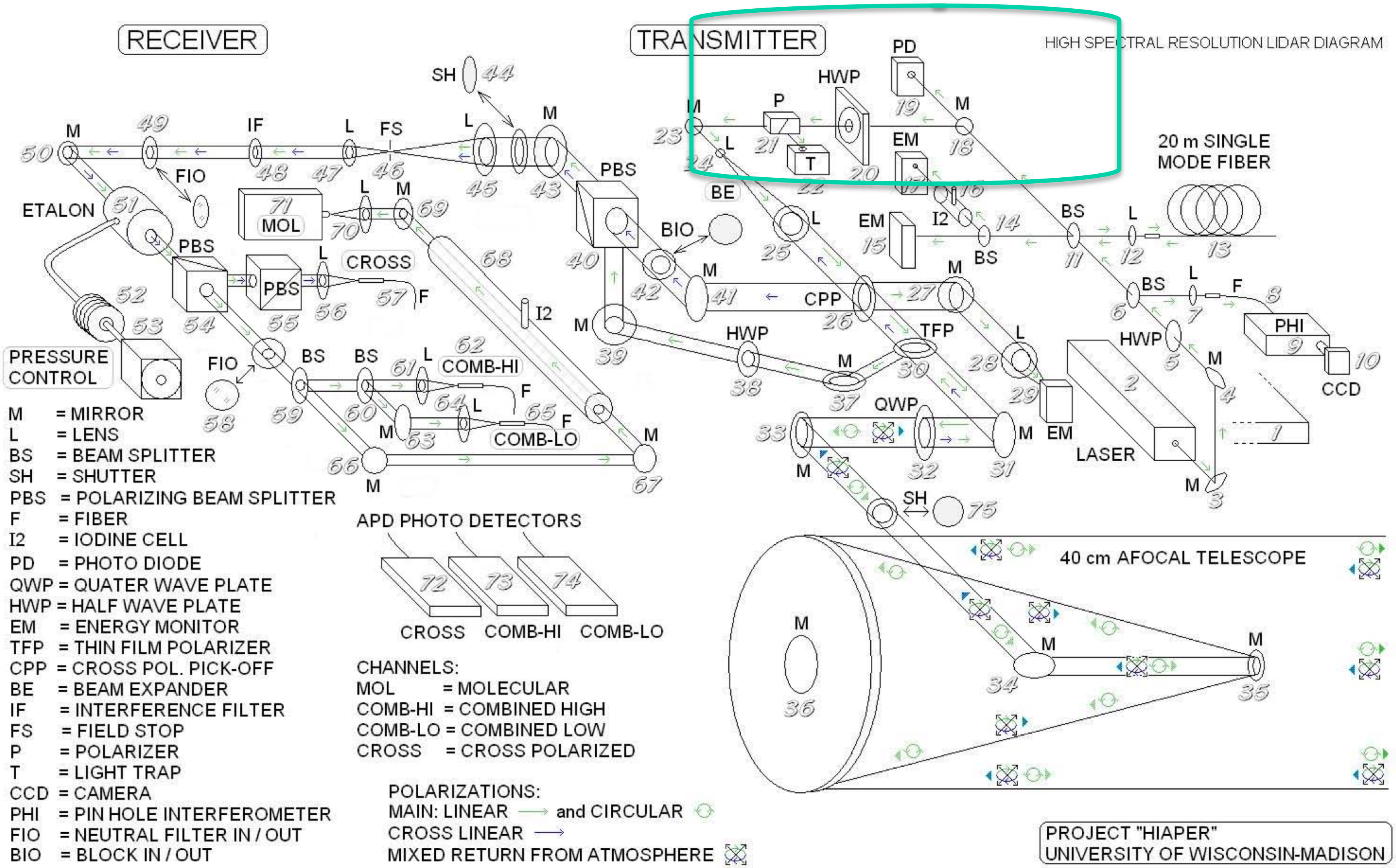


Example of frequency locking

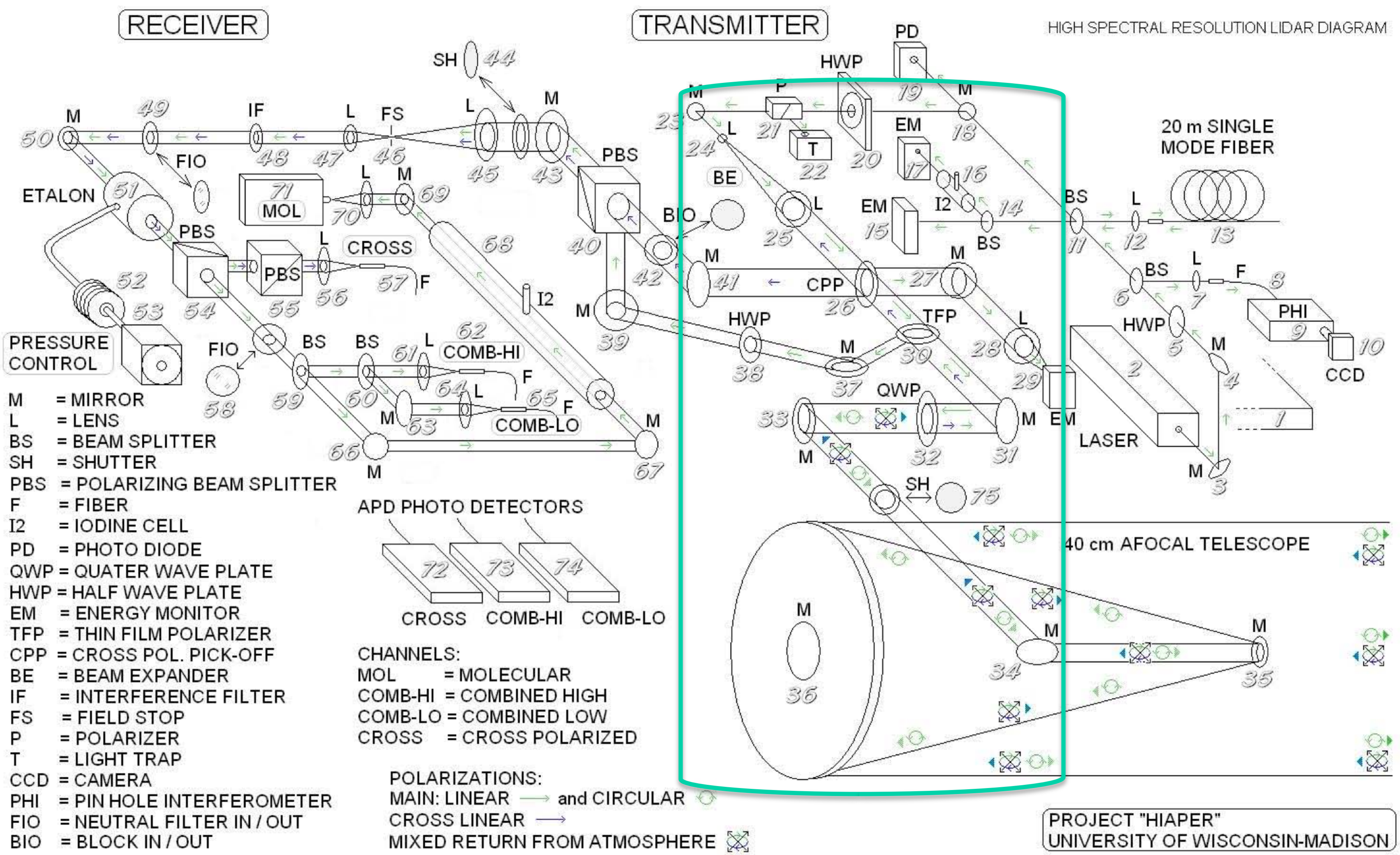



RSP-2T
Newport
NEW FOCUS

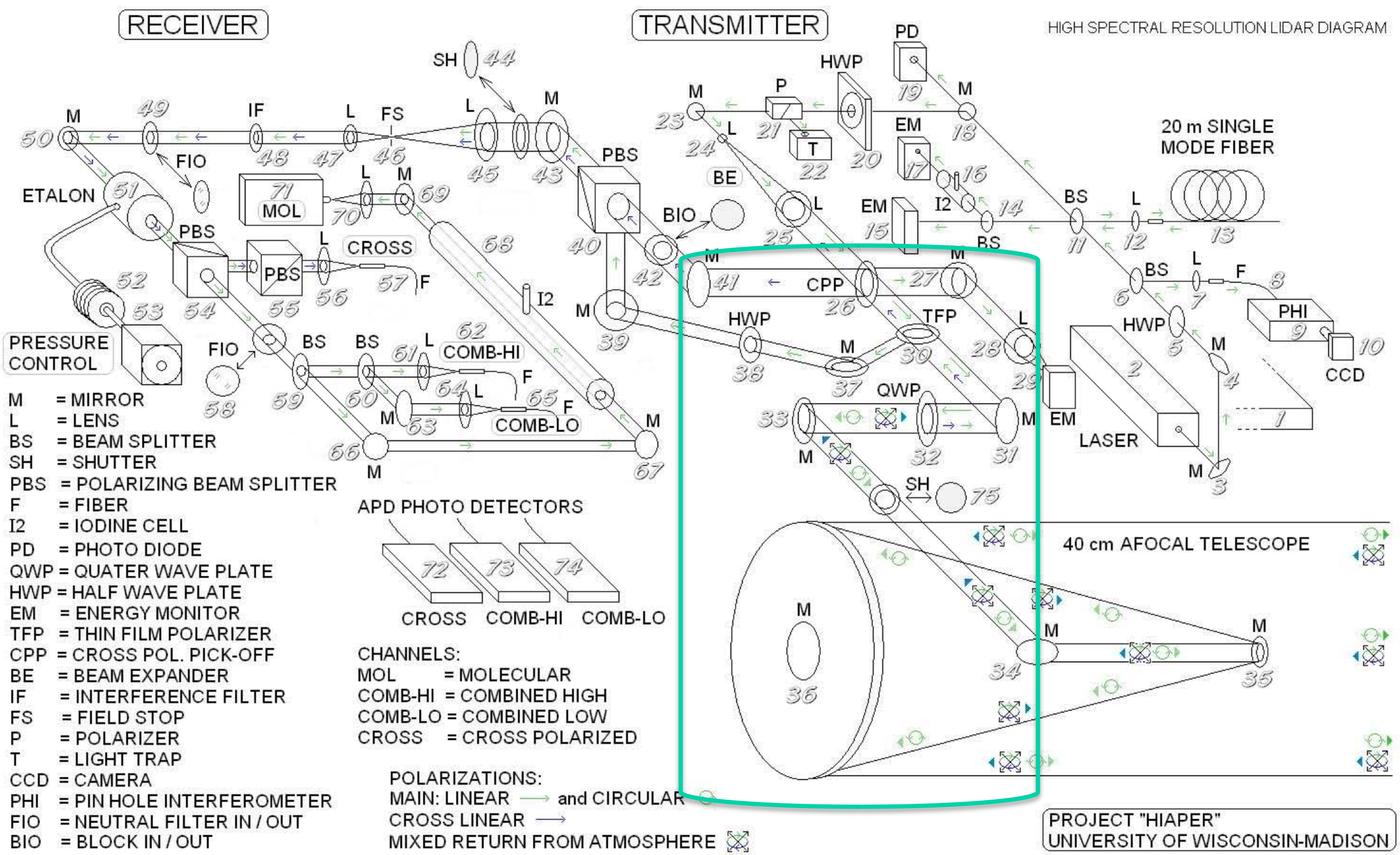
Power control and photo diode timing detector

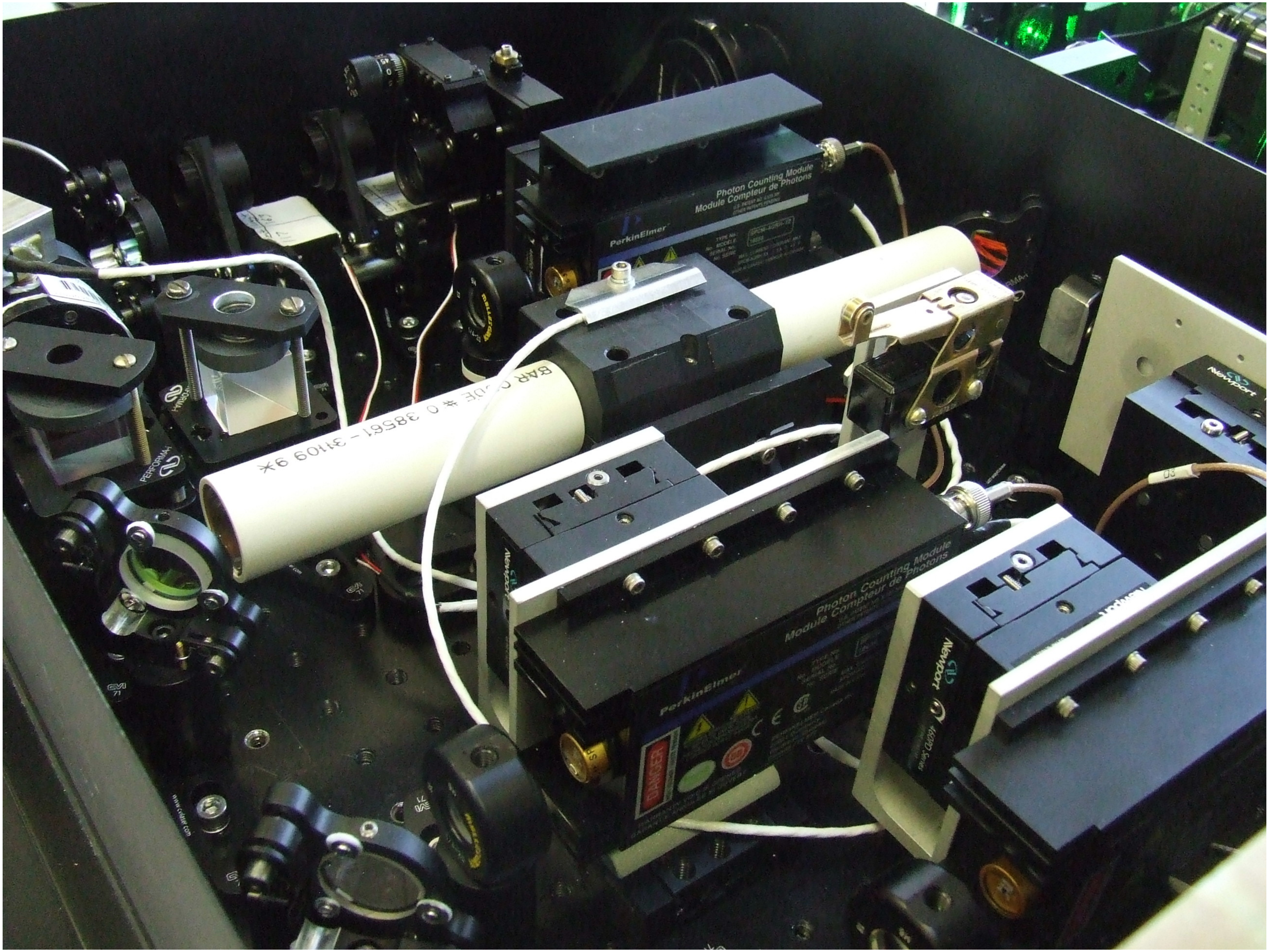


Beam expansion and e-monitor



Received light passes through ¼ plate, cross-pol and parallel pickups




Photon Counting Module
Module Compteur de Photons
PerkinElmer
BAR CODE # 0 38561-31109 9
Photon Counting Module
Module Compteur de Photons
PerkinElmer
DANGER
Newport
Newport

Specifications

Transmitter:	**GVHSRL**	**Langley HSRL**
Repetition rate	4000 Hz	200 Hz
Wavelength	532 nm	532 nm
Energy	82 uJ	2.5 mJ
Ave power	339 mW	500 mW
Receiver:		
Aperture	40 cm	40 cm
Bandwidth	8 GHz	60 GHz
Quantum Eff	55%	10% (?)
Field of View	100 mrad	250-1000 mrad
Optical trans	~34%	57%
Signal strength ~	1	0.27 (Area*Pwr*QE*h)
Sky Noise ~	0.24	3.4 (Area*BW*W*QE*h)