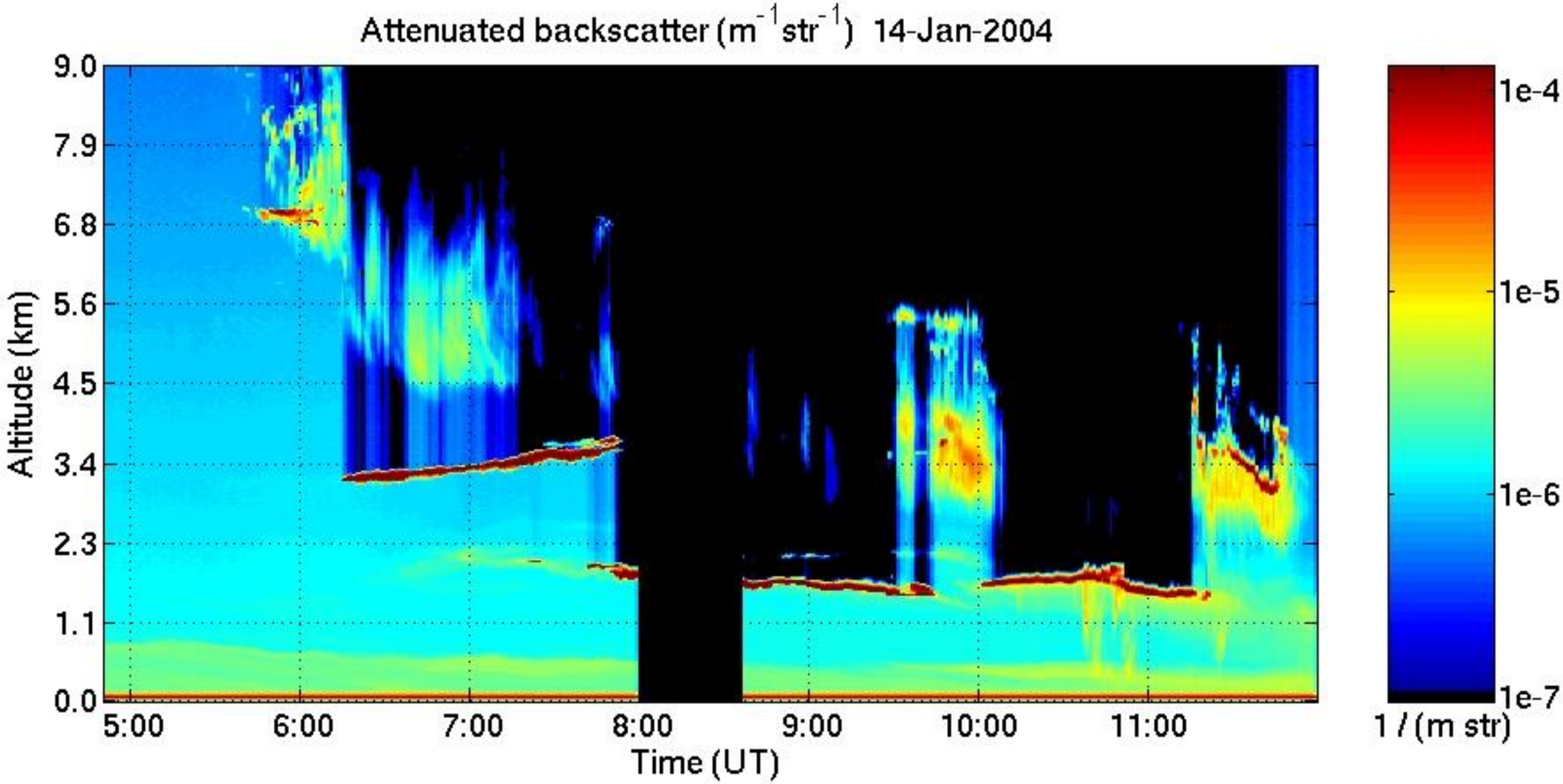
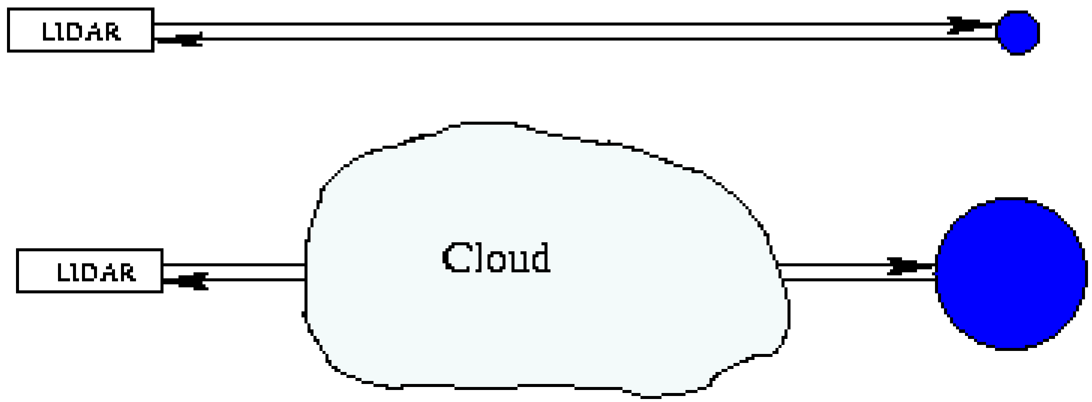
High Spectral Resolution Lidar

Ed Eloranta—Univ. of Wis.
http://lidar.ssec.wisc.edu



Attenuated backscatter (m-1 str-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)

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



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

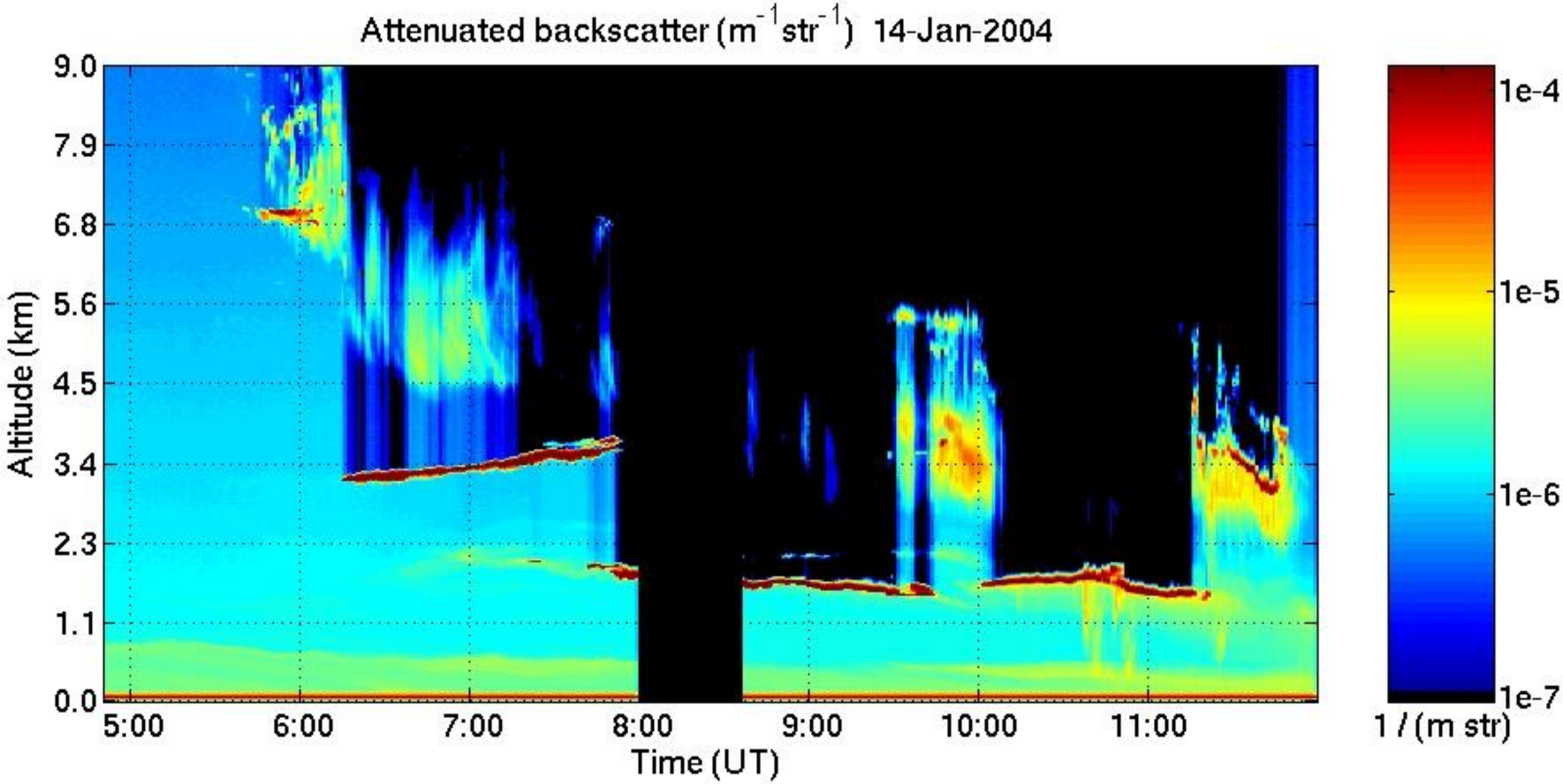
$p_a(r) \sim \frac{1}{r^2} \cdot \frac{P(180,r)}{4\pi}\beta_a(r) \cdot exp(-2\int(\beta_a(r) + \beta_m(r)) \cdot dr)$ – aerosol return,

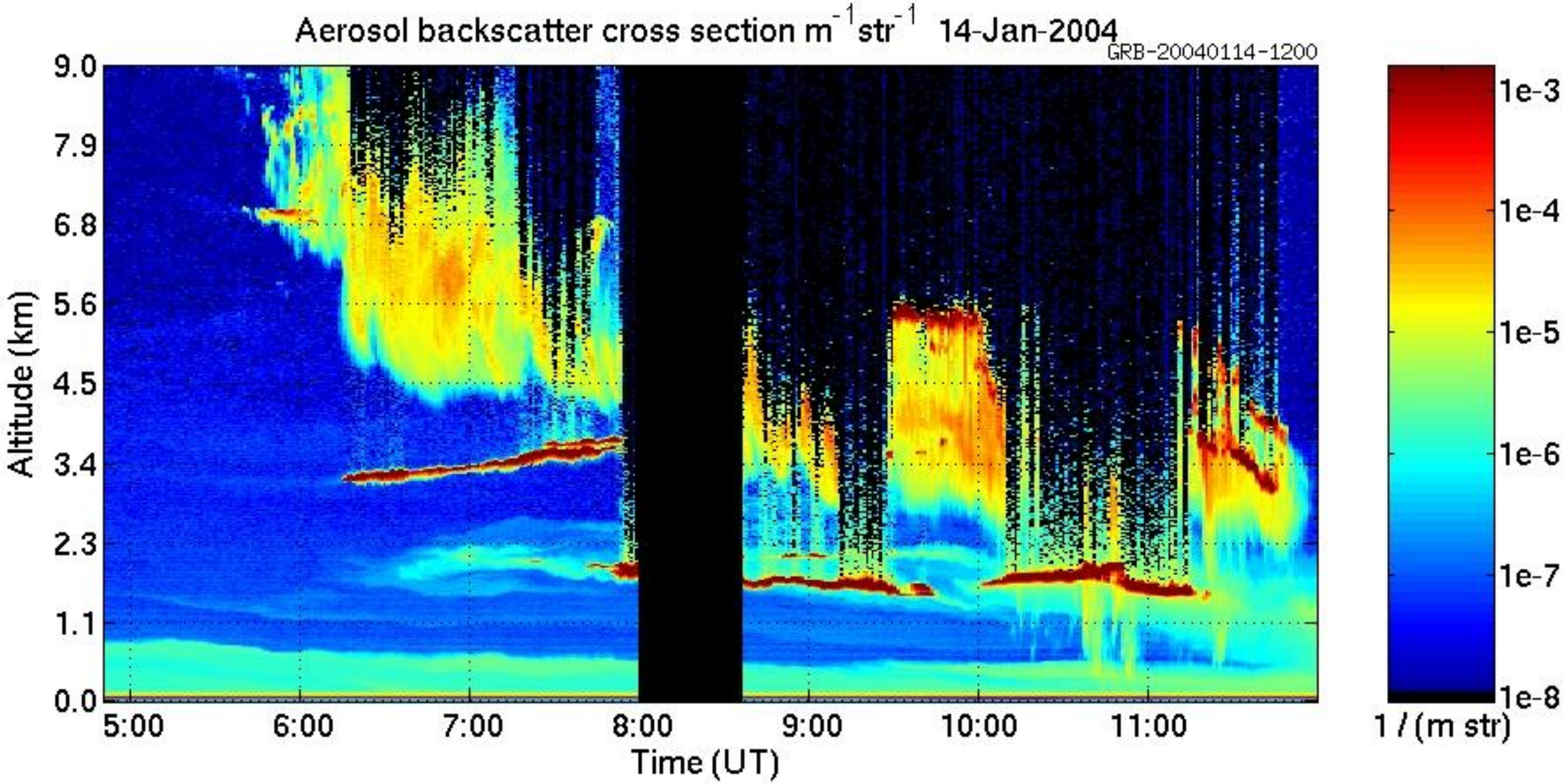
$p_m(r) \sim \frac{1}{r^2} \cdot \frac{3}{8\pi}\beta_m(r) \cdot exp(-2\int(\beta_a(r) + \beta_m(r)) \cdot dr)$ – molecular return

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

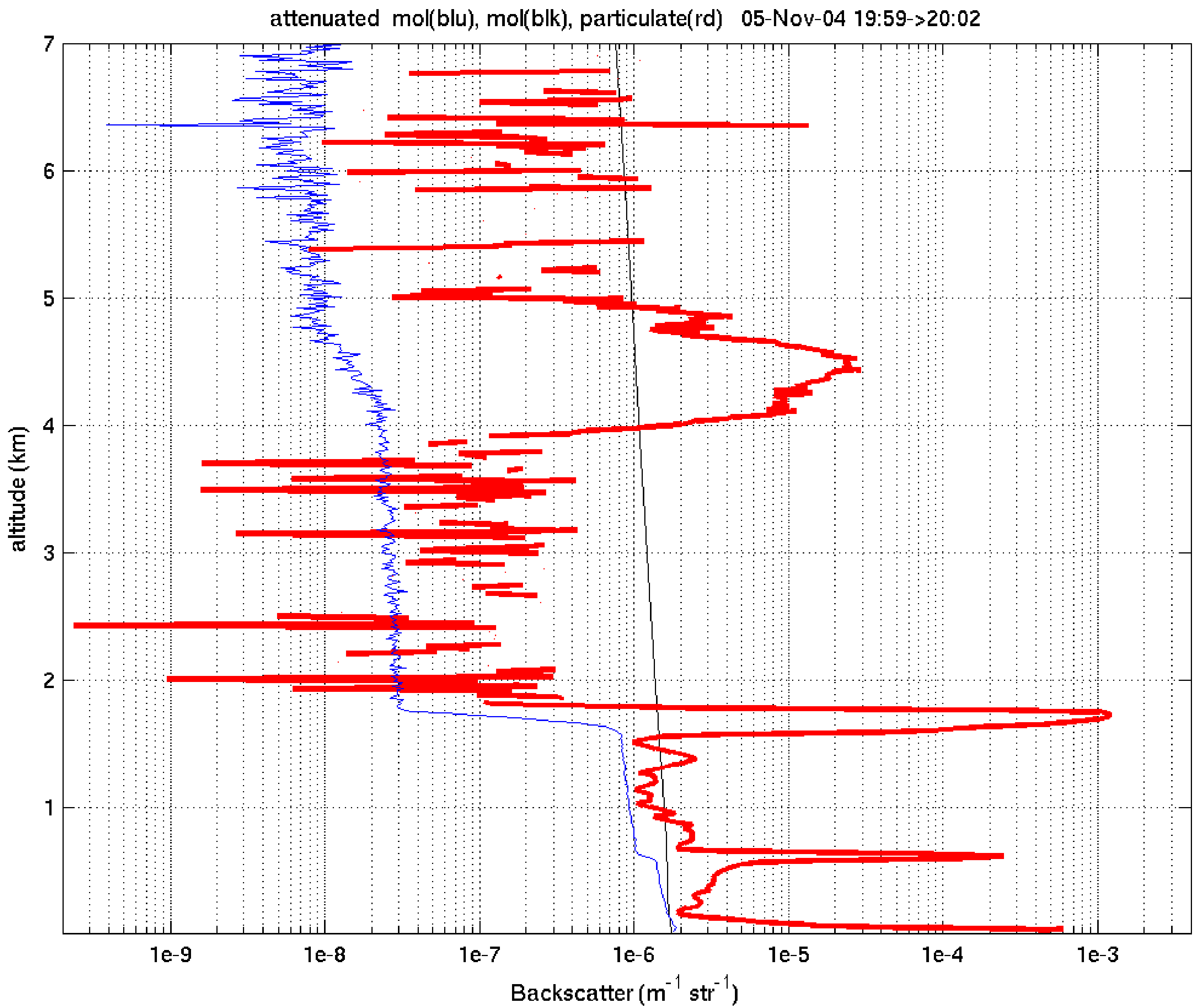
The optical depth between $r_1$and r_2 is derived by comparing the molecular return to that expected from a purely molecular atmosphere:

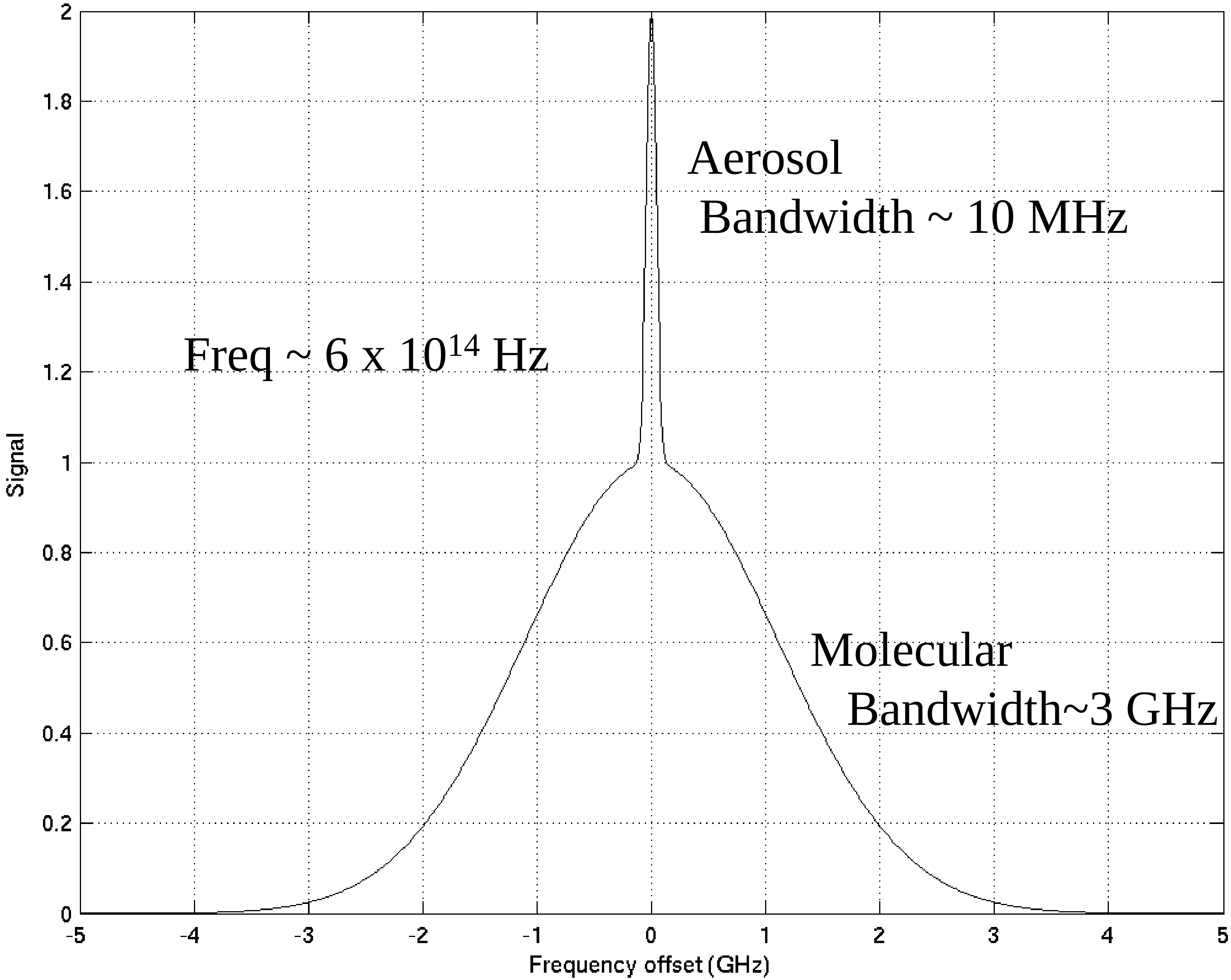
$\tau(r_1, r_2) = \frac{1}{2} \cdot log(\frac{r_1^2\rho(r_2) \cdot p_m(r_1)}{r_2^2\rho(r_1) \cdot p_m(r_2)})$

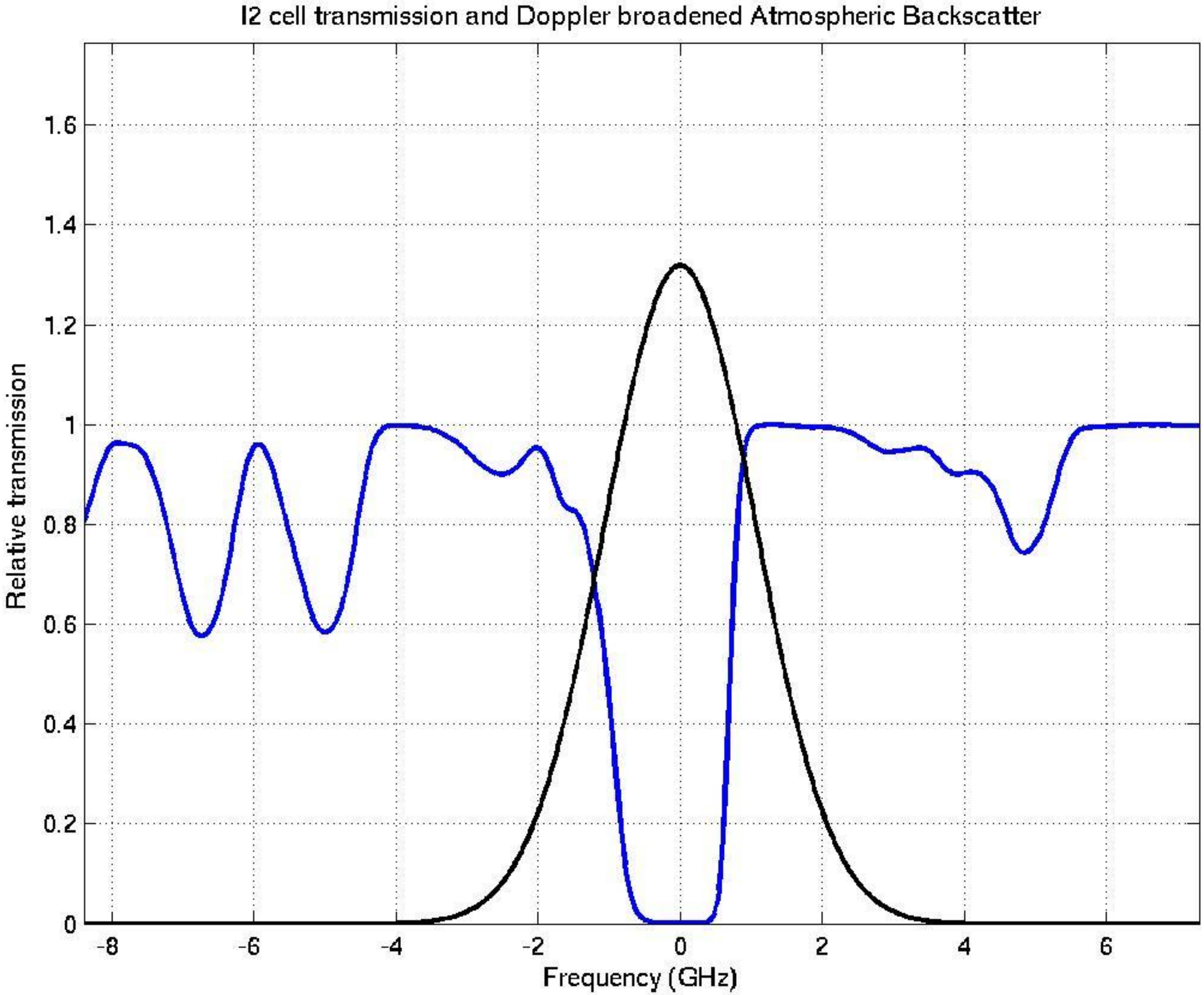

Attenuated backscatter ($m^{-1} str^{-1}$) 14-Jan-2004
Altitude (km)
9.0
7.9
6.8
5.6
4.5
3.4
2.3
1.1
0.0
5:00
6:00
7:00
8:00
9:00
10:00
11:00
Time (UT)
1e-4
1e-5
1e-6
1e-7
1 / (m str)

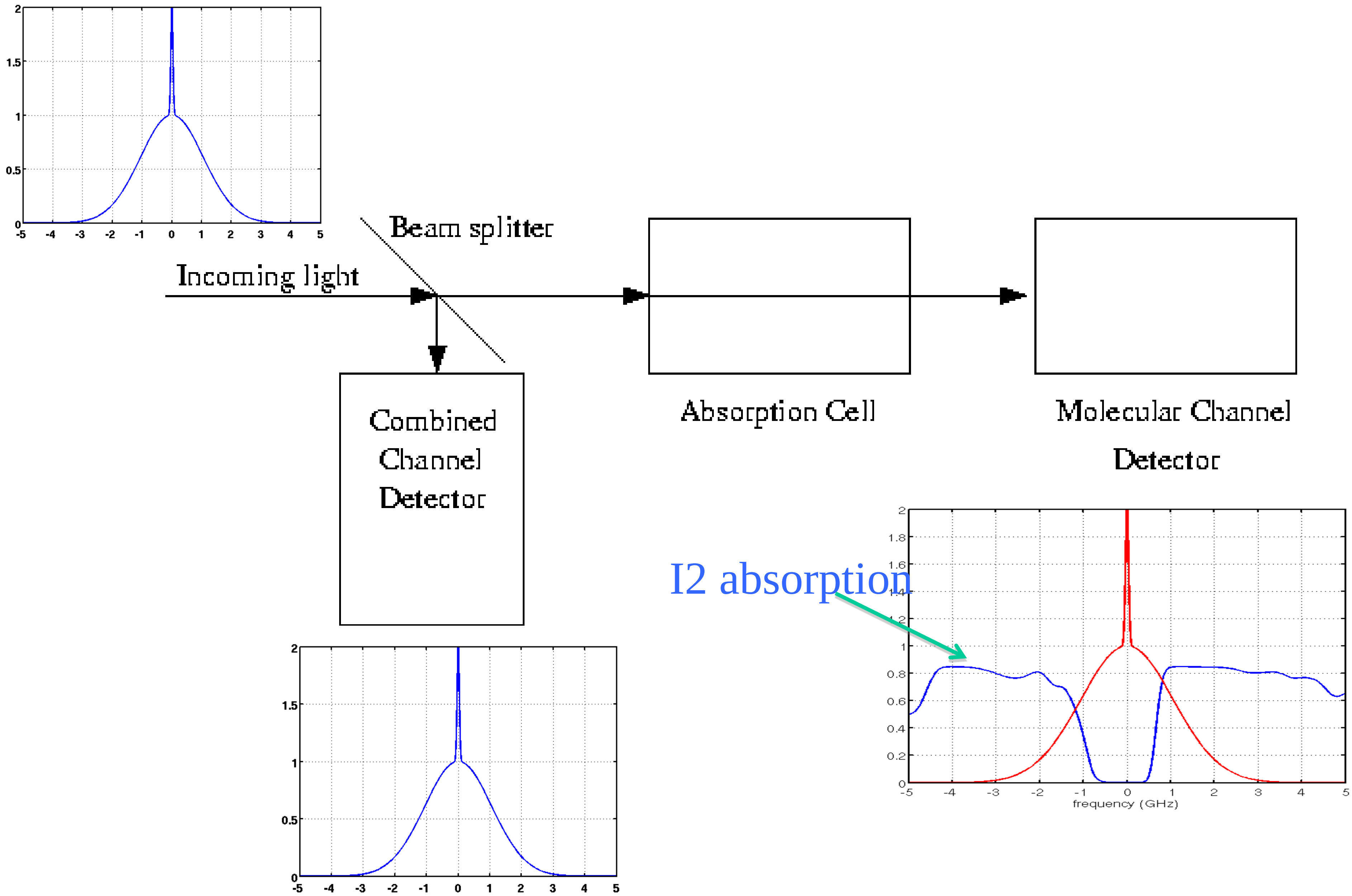


Aerosol backscatter cross section m^{-1}str^{-1} 14-Jan-2004
GRB-20040114-1200
9.0
7.9
6.8
5.6
4.5
3.4
2.3
1.1
0.0
Altitude (km)
5:00
6:00
7:00
8:00
9:00
10:00
11:00
Time (UT)
1e-3
1e-4
1e-5
1e-6
1e-7
1e-8
1 / (m str)

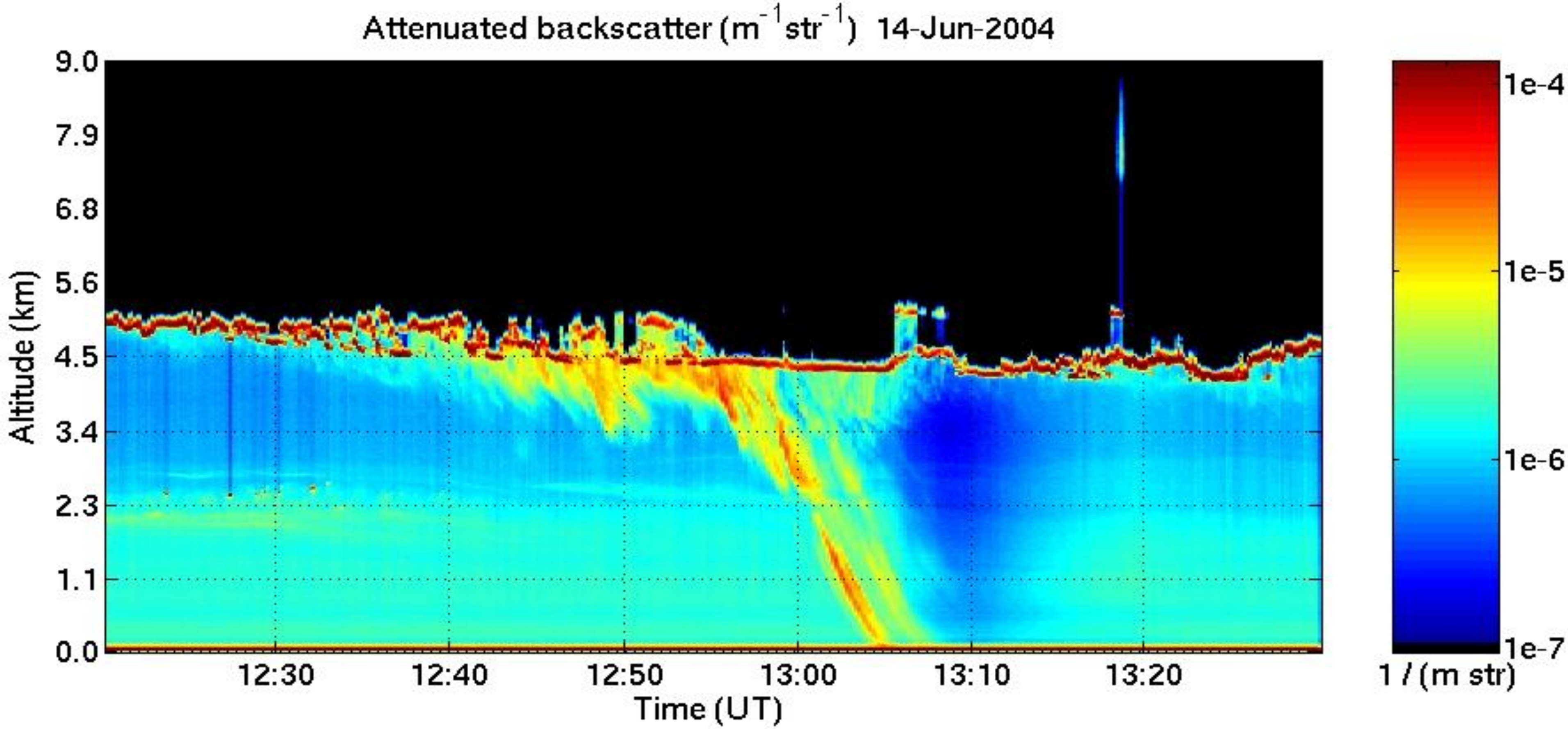

attenuated mol(blu), mol(blk), particulate(rd) 05-Nov-04 19:59->20:02
altitude (km)
Backscatter (m-1 str-1)
1e-9
1e-8
1e-7
1e-6
1e-5
1e-4
1e-3
1
2
3
4
5
6
7

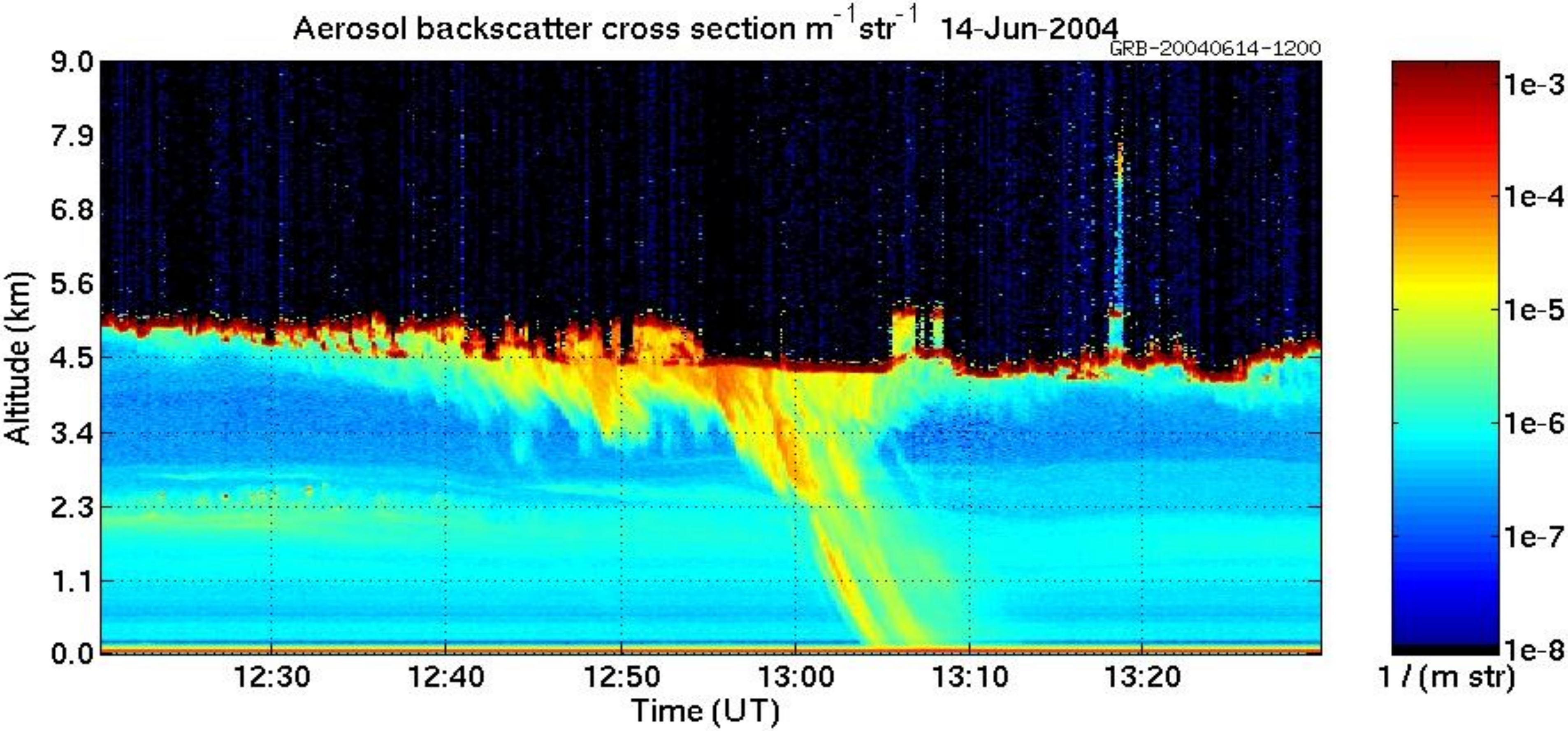

Aerosol
Bandwidth ~ 10 MHz
Freq ~ 6 x 10^14 Hz
Molecular
Bandwidth~3 GHz
Signal
Frequency offset (GHz)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
-5
-4
-3
-2
-1
0
1
2
3
4
5


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)

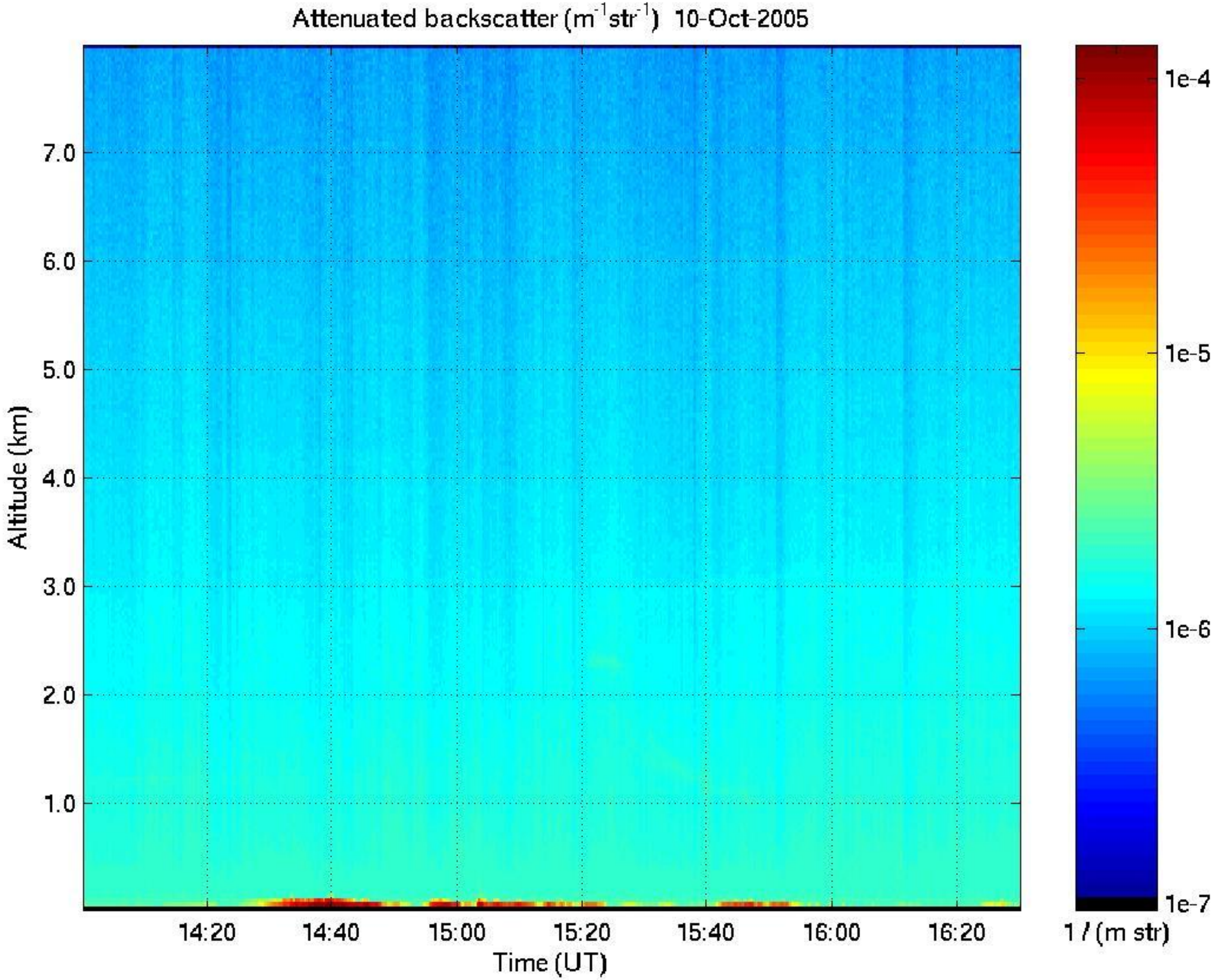


Beam splitter
Incoming light
Combined Channel Detector
Absorption Cell
Molecular Channel Detector
I2 absorption
frequency (GHz)

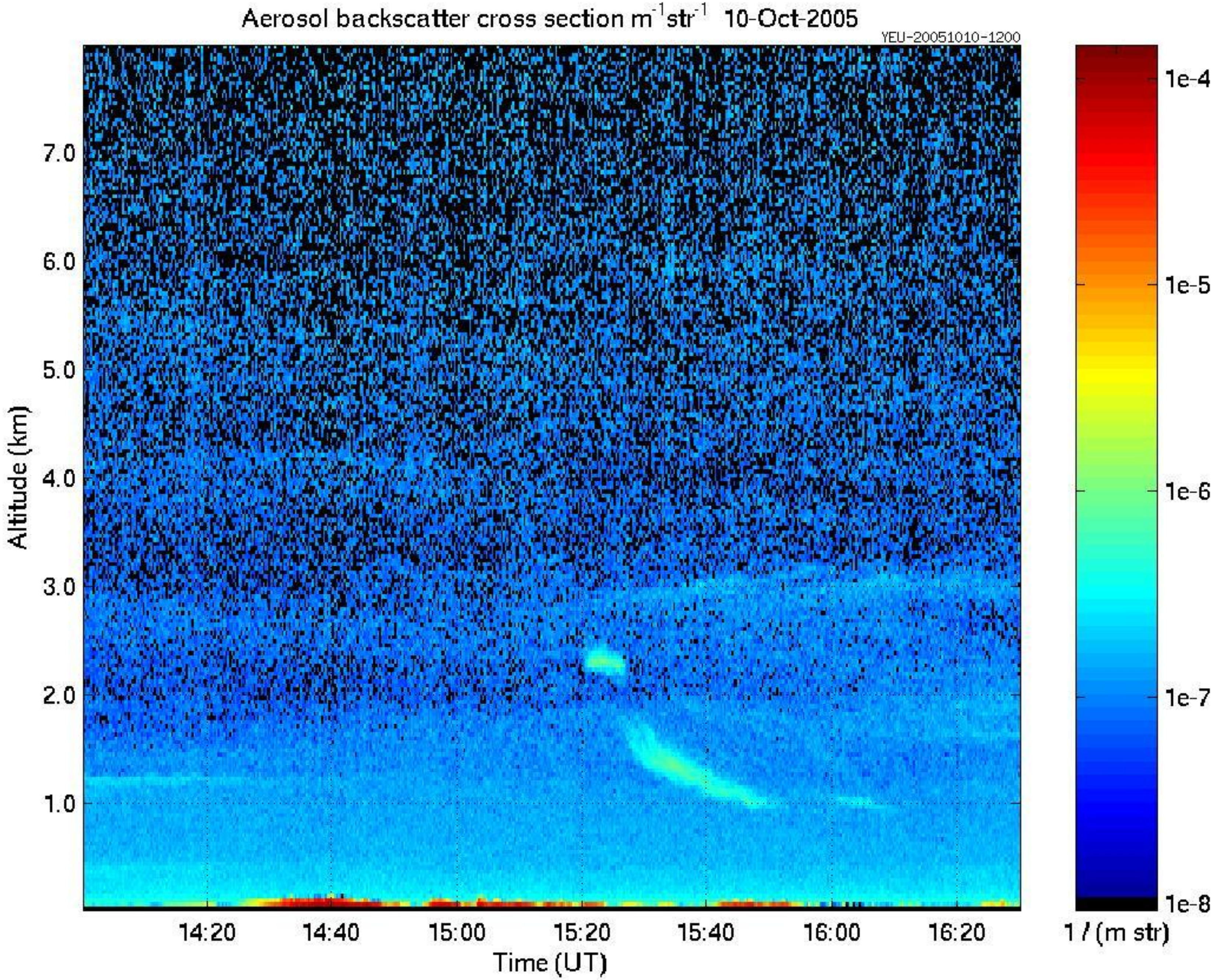

Attenuated backscatter ($m^{-1}str^{-1}$) 14-Jun-2004
9.0
7.9
6.8
5.6
4.5
3.4
2.3
1.1
0.0
Altitude (km)
12:30
12:40
12:50
13:00
13:10
13:20
Time (UT)
1e-4
1e-5
1e-6
1e-7
1 / (m str)



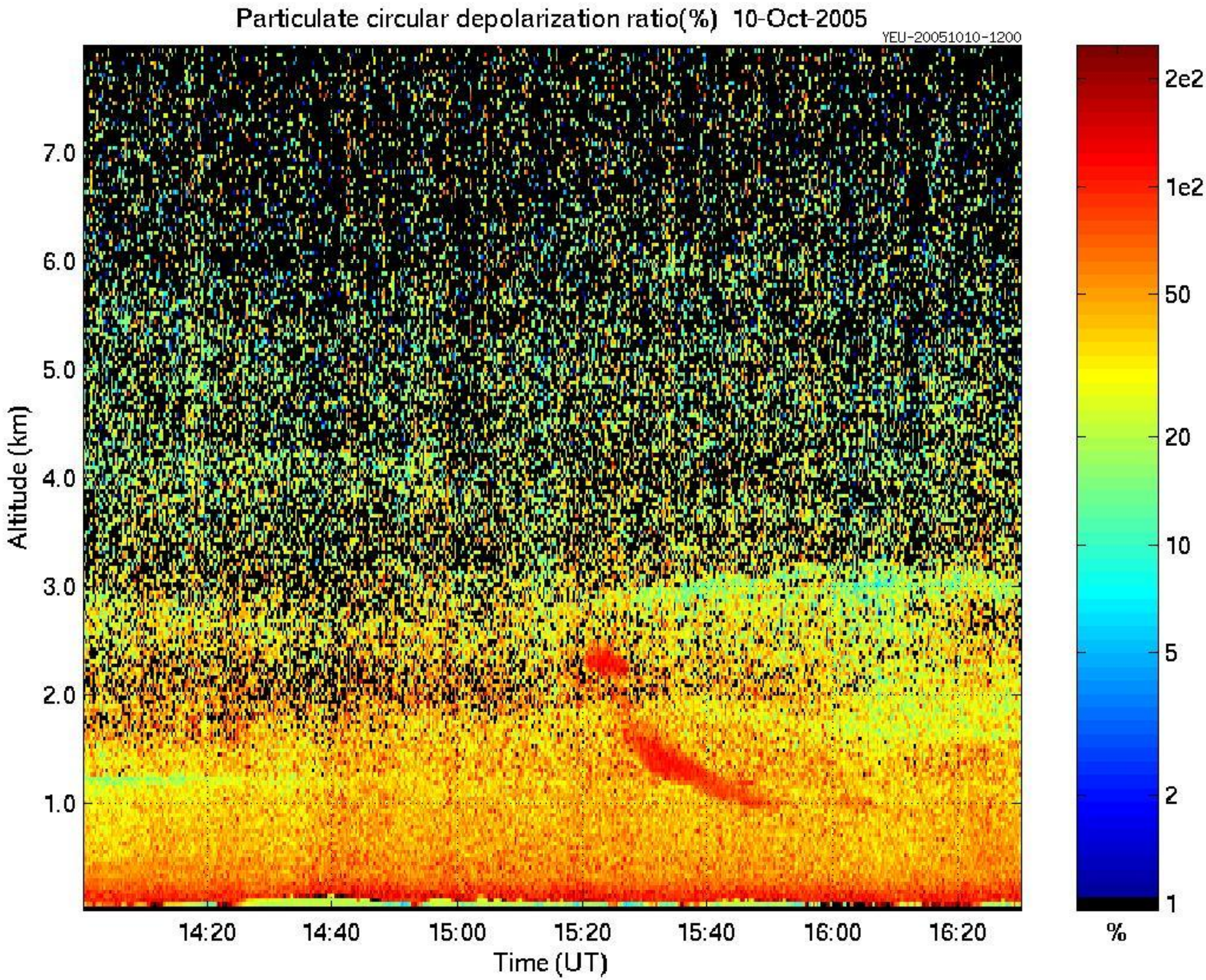
Aerosol backscatter cross section $m^{-1}str^{-1}$ 14-Jun-2004
GRB-20040614-1200
9.0
7.9
6.8
5.6
4.5
3.4
2.3
1.1
0.0
Altitude (km)
12:30
12:40
12:50
13:00
13:10
13:20
Time (UT)
1e-3
1e-4
1e-5
1e-6
1e-7
1e-8
1 / (m str)



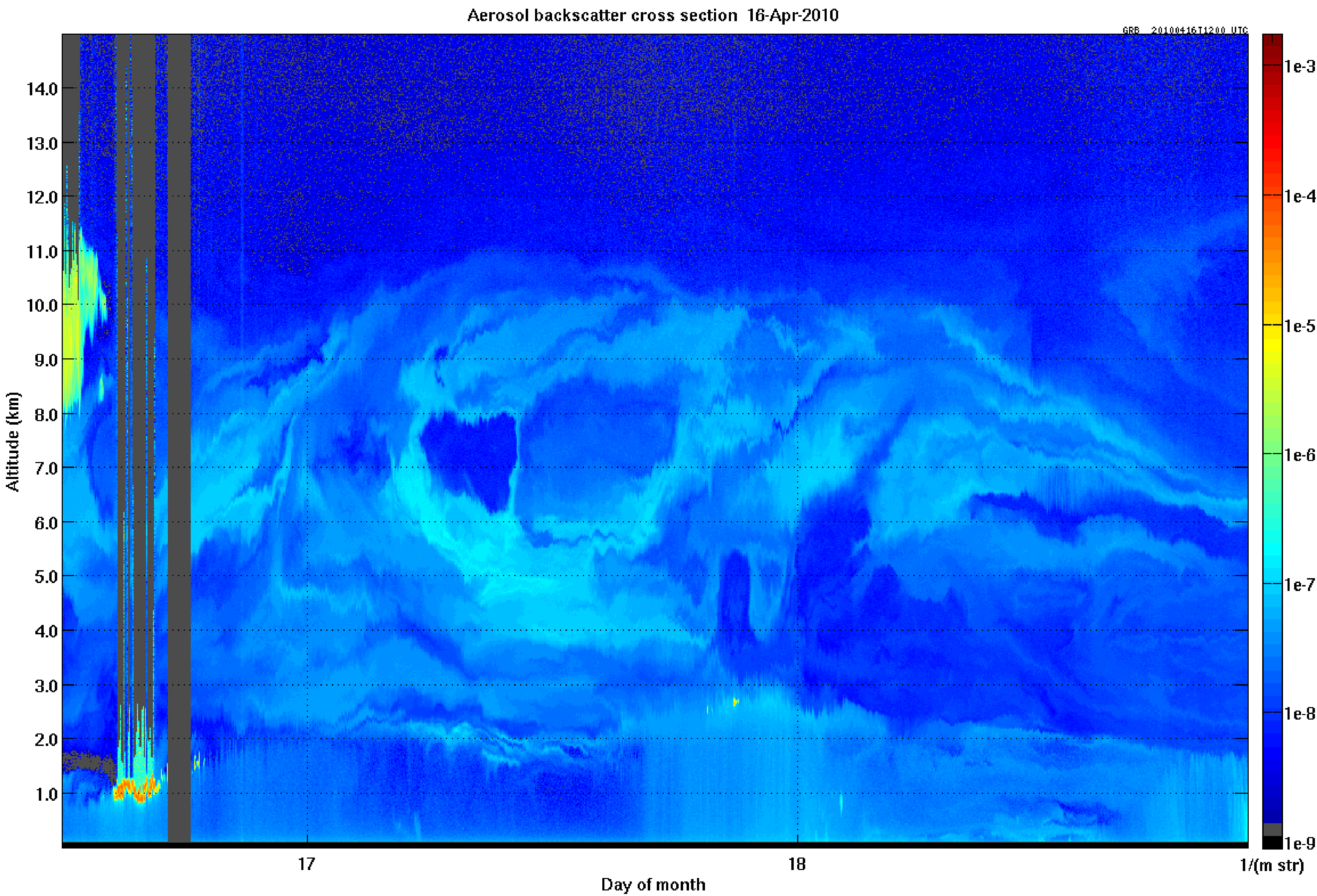
Attenuated backscatter (m^-1 str^-1) 10-Oct-2005
Altitude (km)
7.0
6.0
5.0
4.0
3.0
2.0
1.0
14:20
14:40
15:00
15:20
15:40
16:00
16:20
Time (UT)
1e-4
1e-5
1e-6
1e-7
1 / (m str)

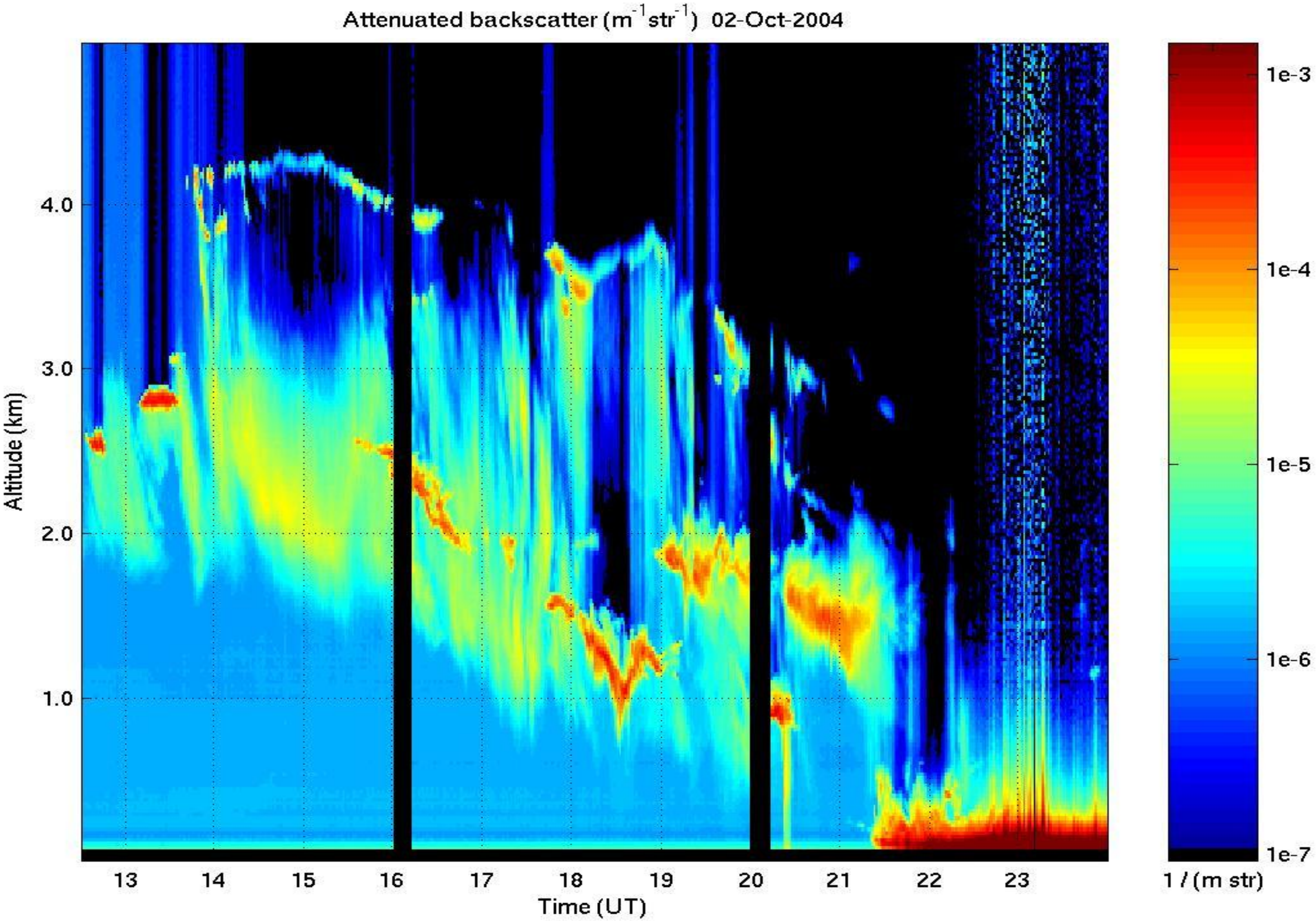


Aerosol backscatter cross section m^{-1}str^{-1} 10-Oct-2005
YEU-20051010-1200
Altitude (km)
7.0
6.0
5.0
4.0
3.0
2.0
1.0
14:20
14:40
15:00
15:20
15:40
16:00
16:20
Time (UT)
1e-4
1e-5
1e-6
1e-7
1e-8
1 / (m str)

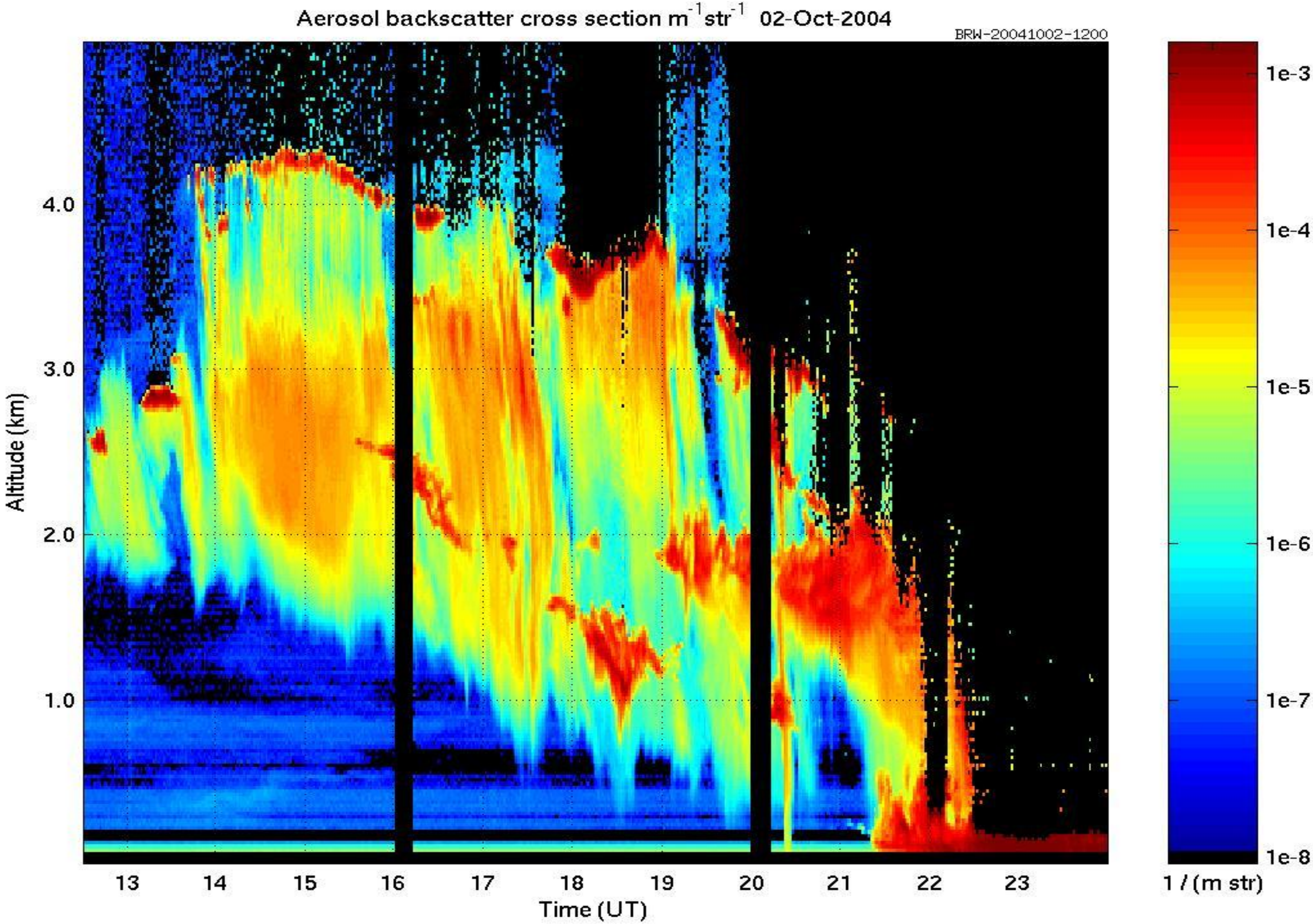


Particulate circular depolarization ratio(%) 10-Oct-2005
YEU-20051010-1200
Altitude (km)
7.0
6.0
5.0
4.0
3.0
2.0
1.0
14:20
14:40
15:00
15:20
15:40
16:00
16:20
Time (UT)
2e2
1e2
50
20
10
5
2
1
%

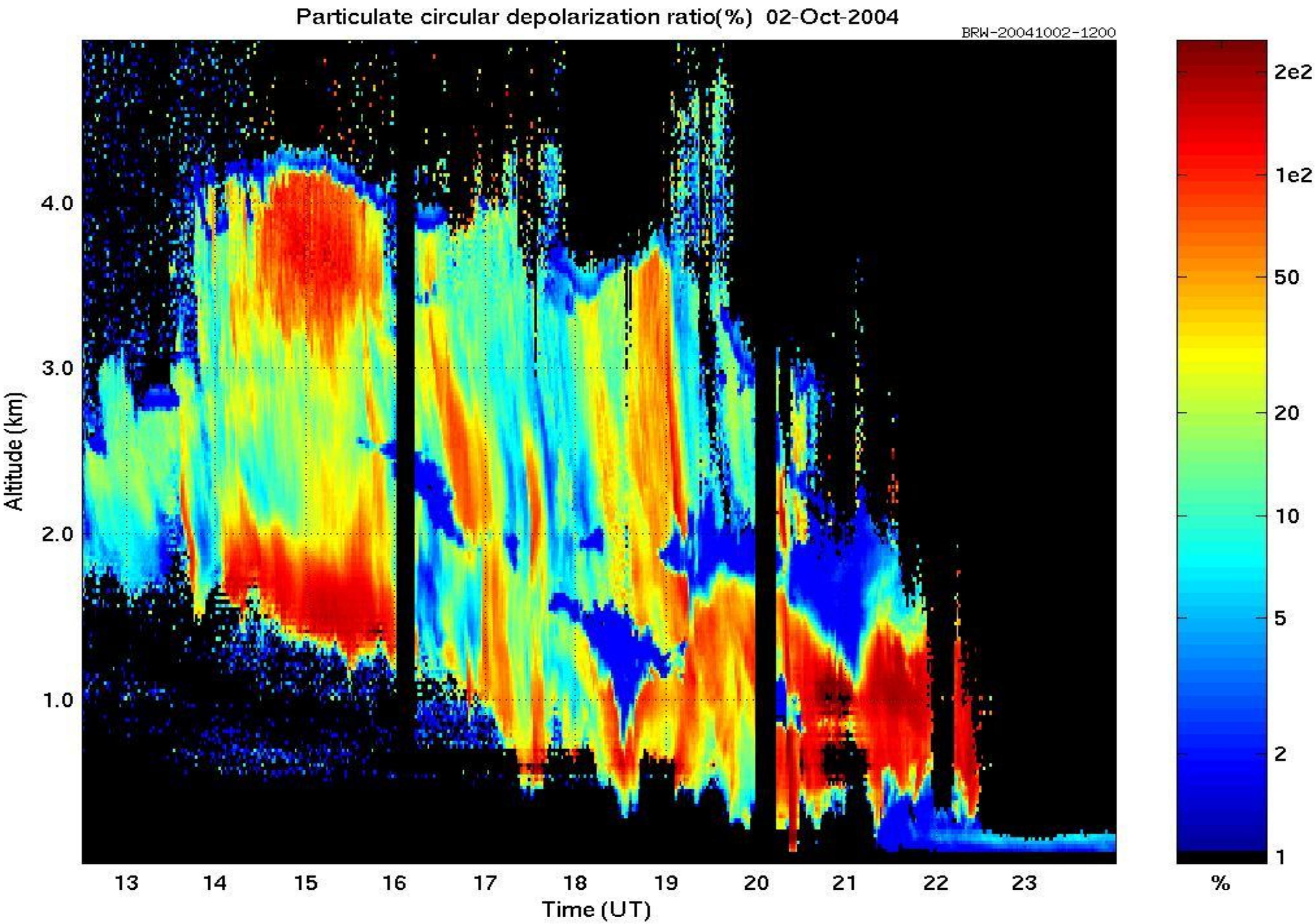

Aerosol backscatter cross section 16-Apr-2010
GRB 20100416T1200 UTC
Altitude (km)
14.0
13.0
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
17
18
Day of month
1e-3
1e-4
1e-5
1e-6
1e-7
1e-8
1e-9
1/(m str)

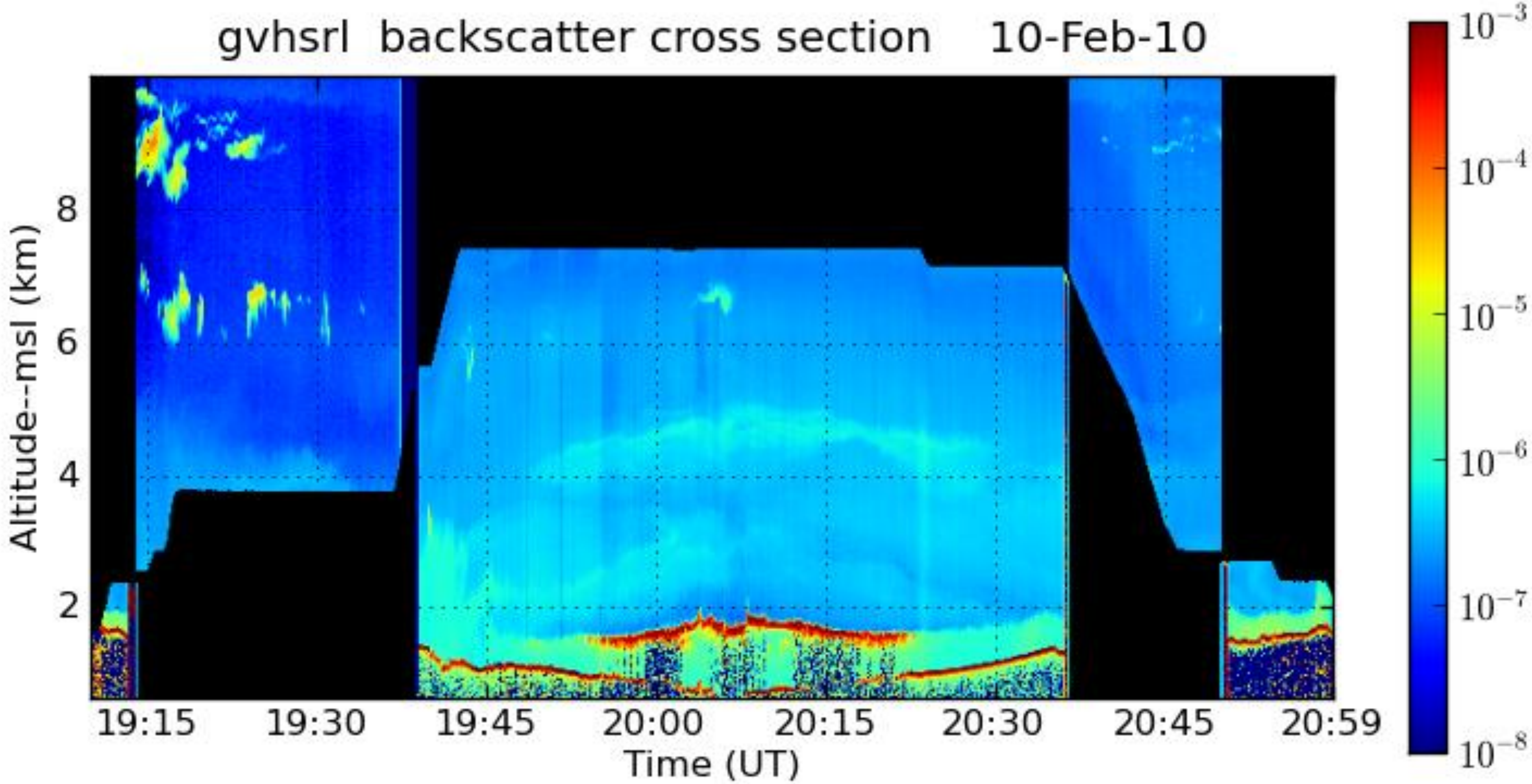


Attenuated backscatter (m^-1 str^-1) 02-Oct-2004
Altitude (km)
4.0
3.0
2.0
1.0
13
14
15
16
17
18
19
20
21
22
23
Time (UT)
1e-3
1e-4
1e-5
1e-6
1e-7
1 / (m str)

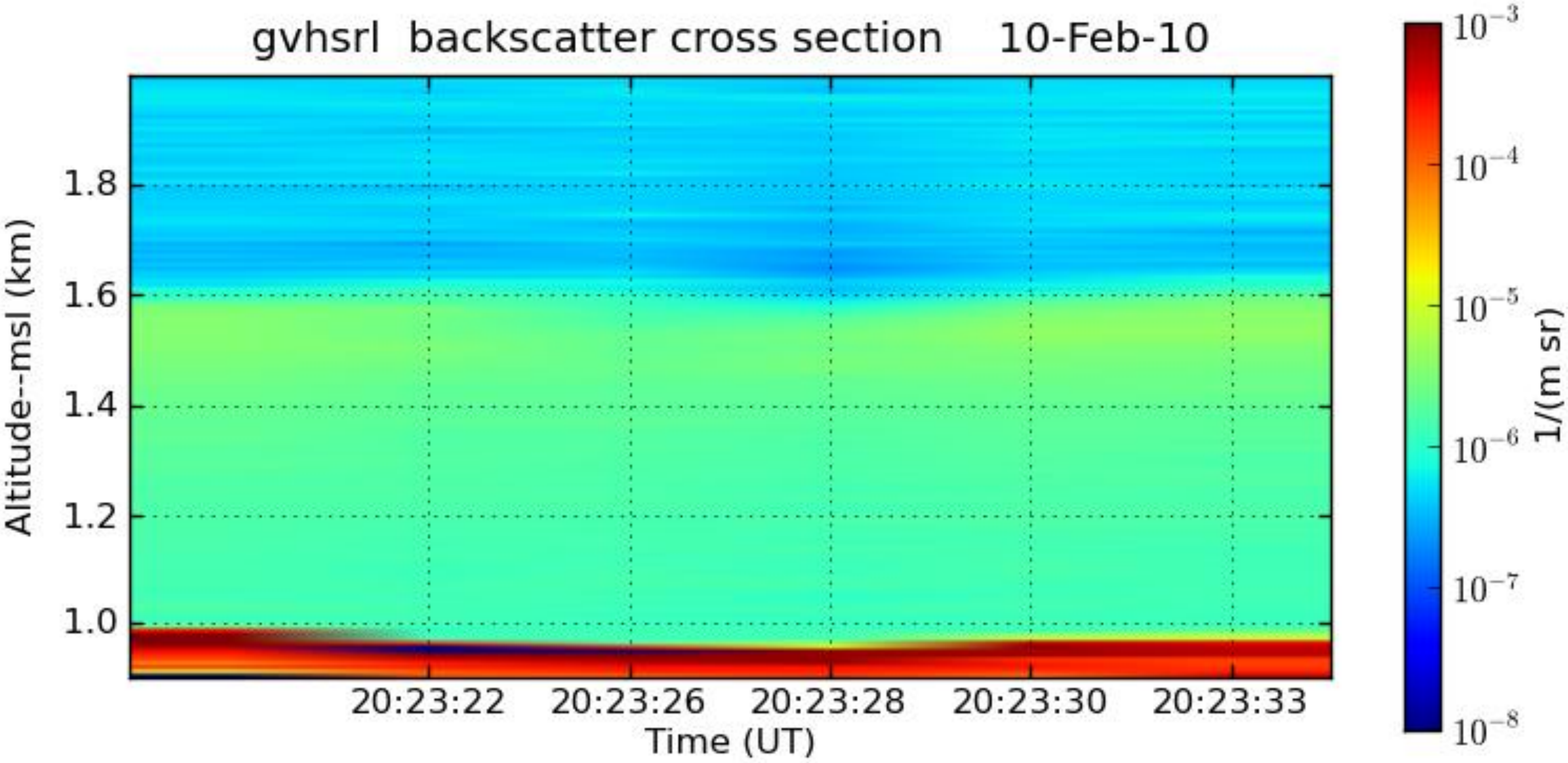


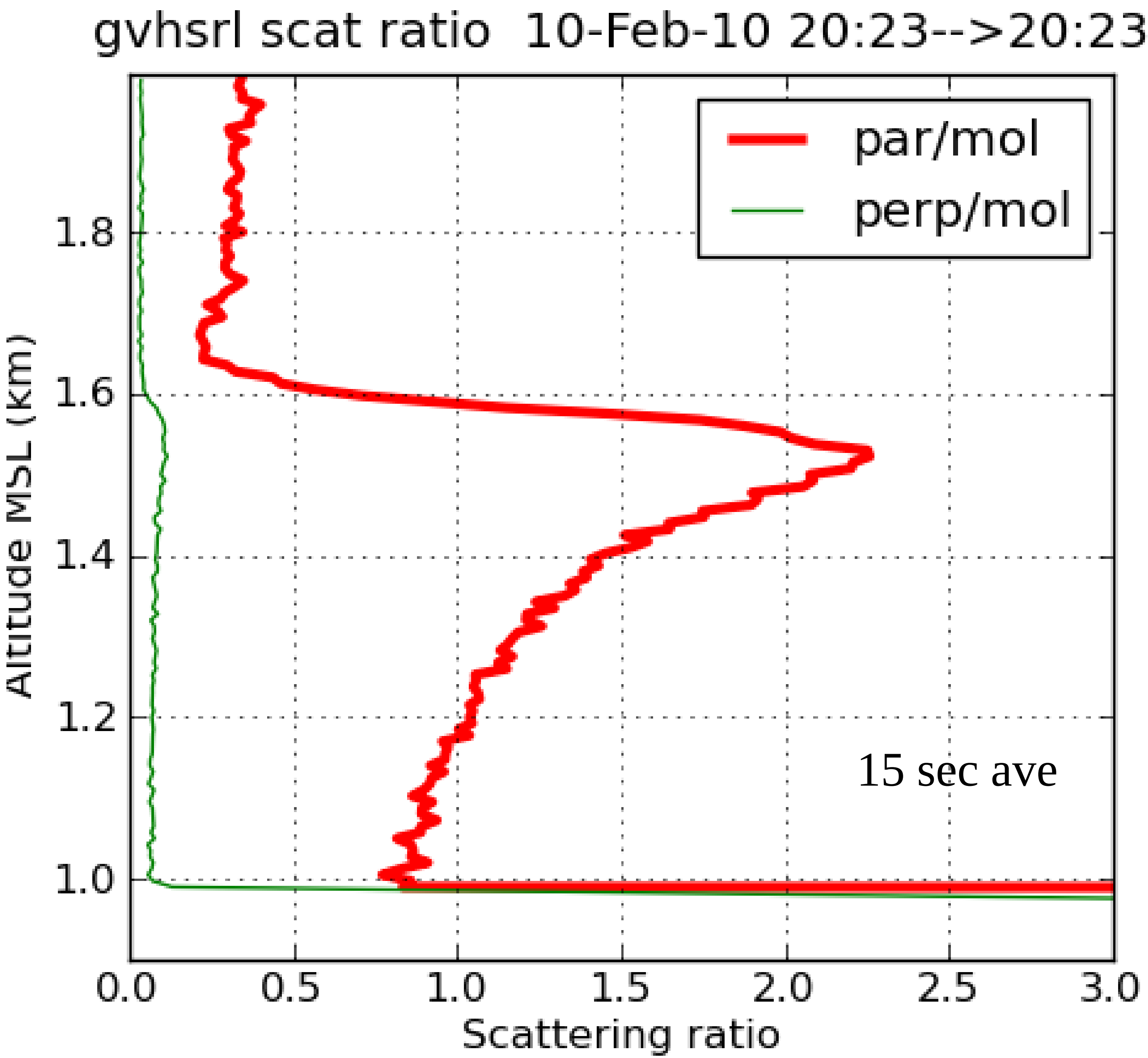
Aerosol backscatter cross section $m^{-1}str^{-1}$ 02-Oct-2004
BRW-20041002-1200
Altitude (km)
4.0
3.0
2.0
1.0
13
14
15
16
17
18
19
20
21
22
23
Time (UT)
1e-3
1e-4
1e-5
1e-6
1e-7
1e-8
1 / (m str)

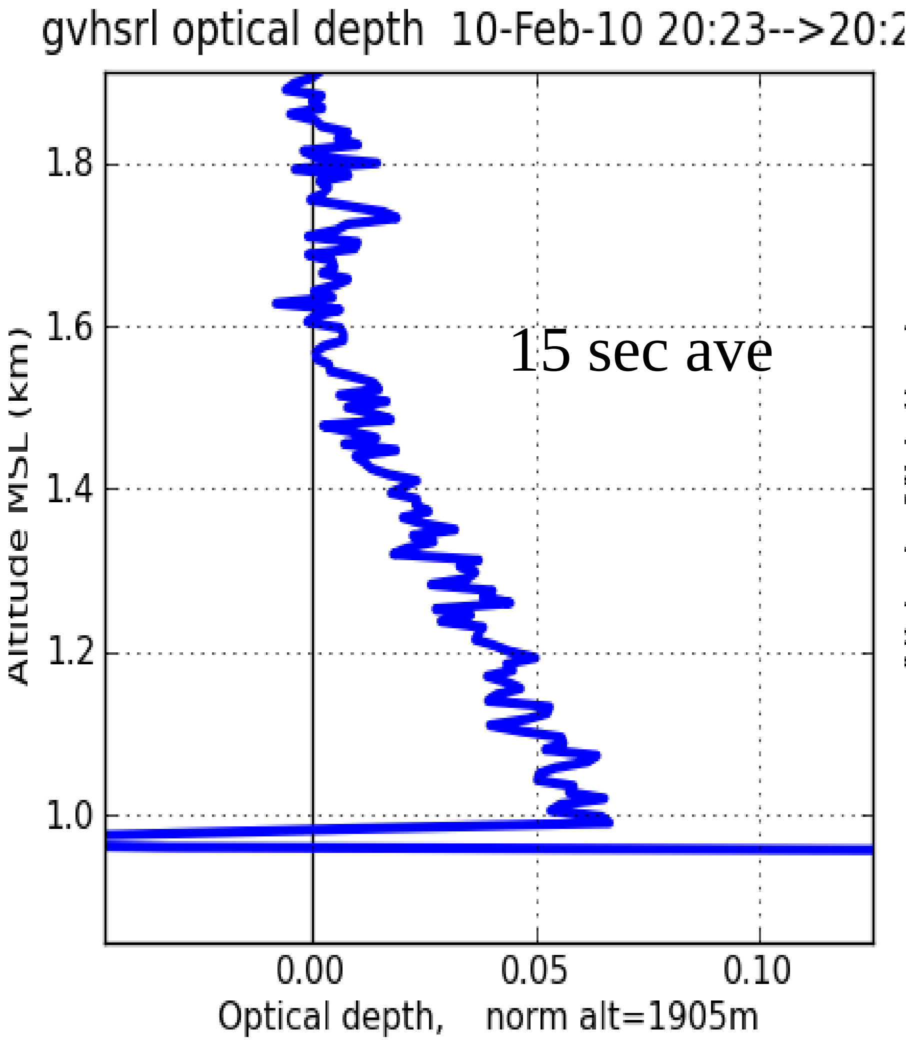

Particulate circular depolarization ratio(%) 02-Oct-2004
BRW-20041002-1200
Altitude (km)
4.0
3.0
2.0
1.0
13
14
15
16
17
18
19
20
21
22
23
Time (UT)
2e2
1e2
50
20
10
5
2
1
%

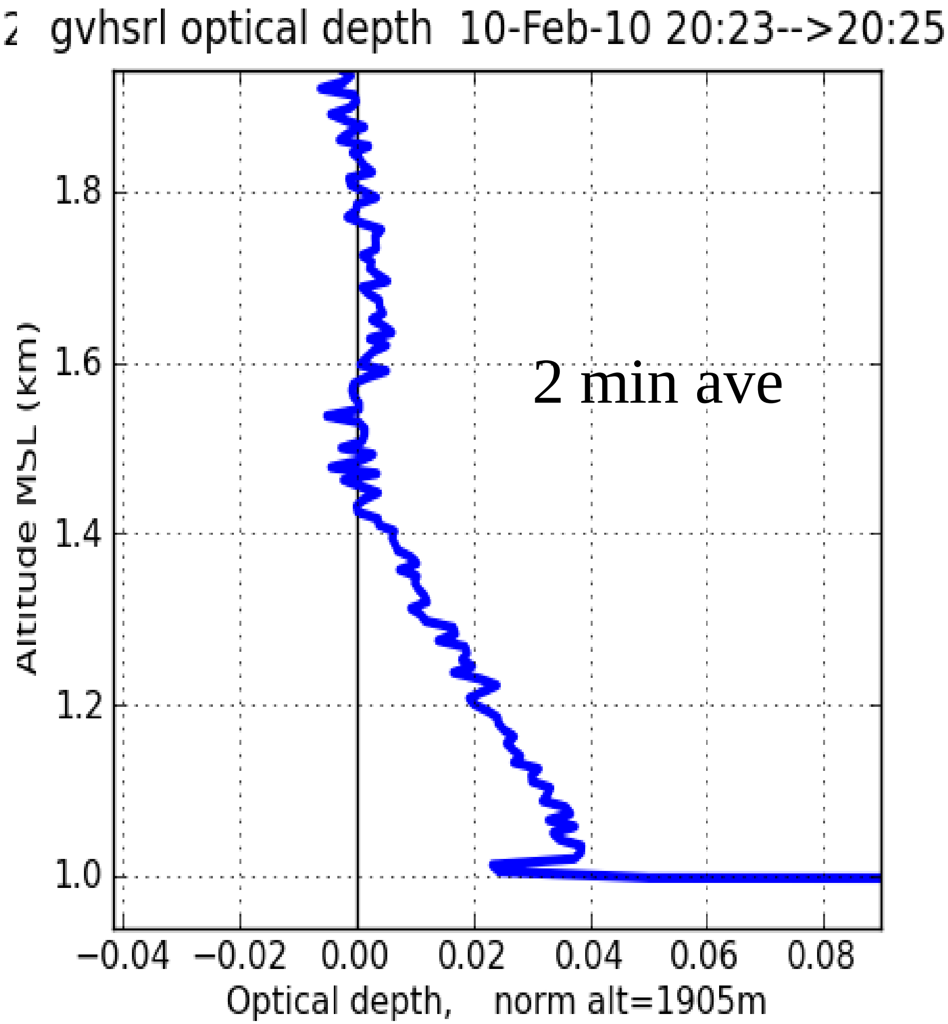

gvhsrl backscatter cross section 10-Feb-10
Altitude--msl (km)
2
4
6
8
19:15
19:30
19:45
20:00
20:15
20:30
20:45
20:59
Time (UT)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}

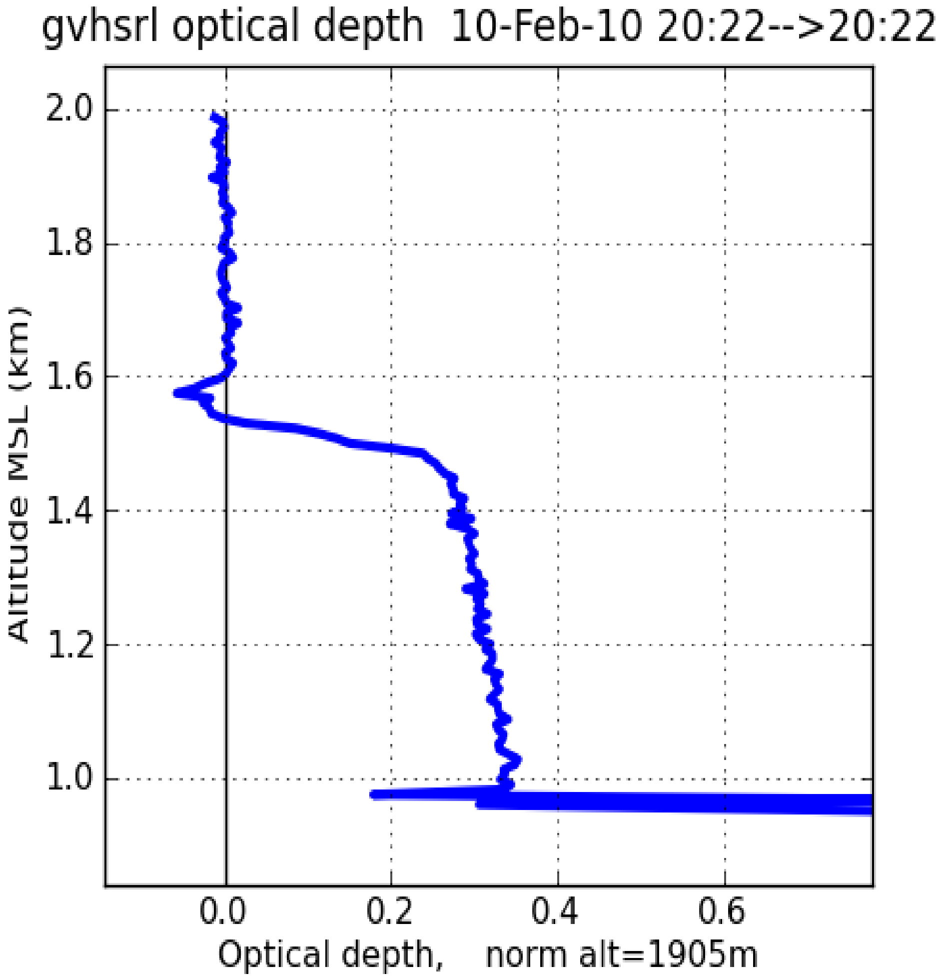
15-second observation of the the boundary layer

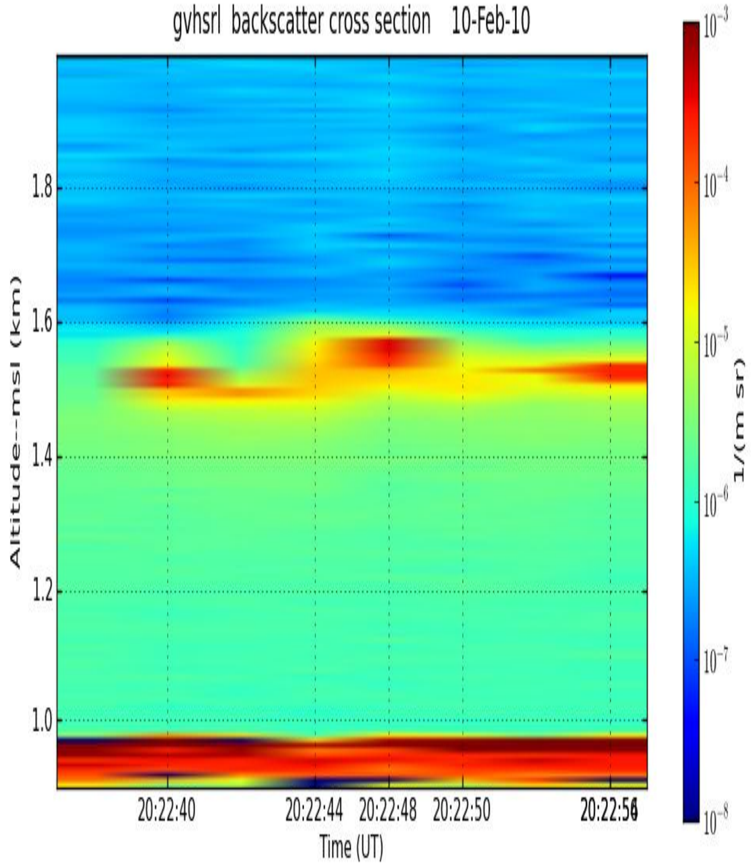



gvhsrl scat ratio 10-Feb-10 20:23-->20:23
par/mol
perp/mol
1.8
1.6
1.4
1.2
1.0
Altitude MSL (km)
15 sec ave
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Scattering ratio


gvhsrl optical depth 10-Feb-10 20:23-->20:2
15 sec ave
Altitude MSL (km)
1.8
1.6
1.4
1.2
1.0
0.00
0.05
0.10
Optical depth, norm alt=1905m

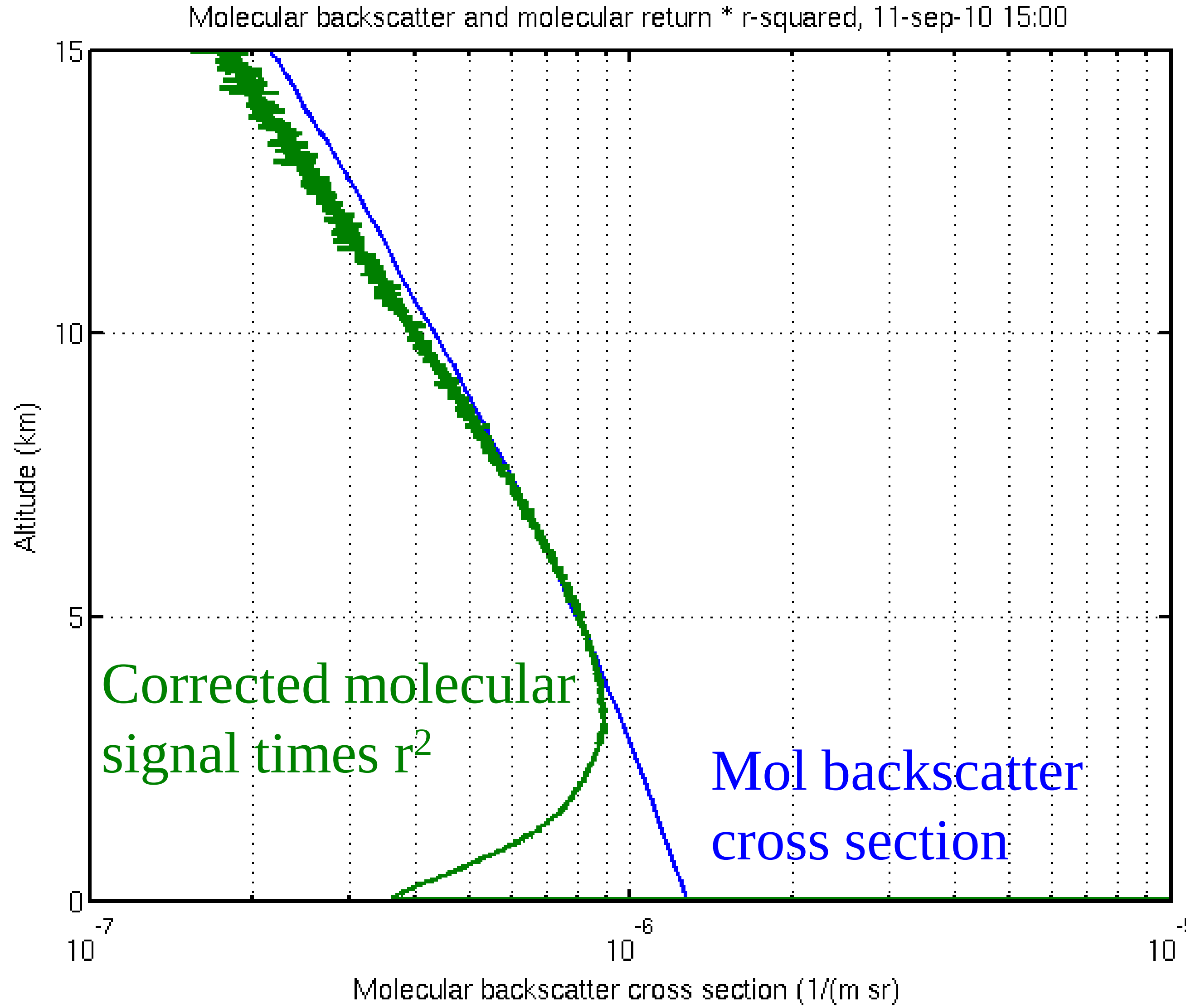

gvhsrl optical depth 10-Feb-10 20:23-->20:25
2 min ave
Altitude MSL (km)
1.8
1.6
1.4
1.2
1.0
−0.04
−0.02
0.00
0.02
0.04
0.06
0.08
Optical depth, norm alt=1905m

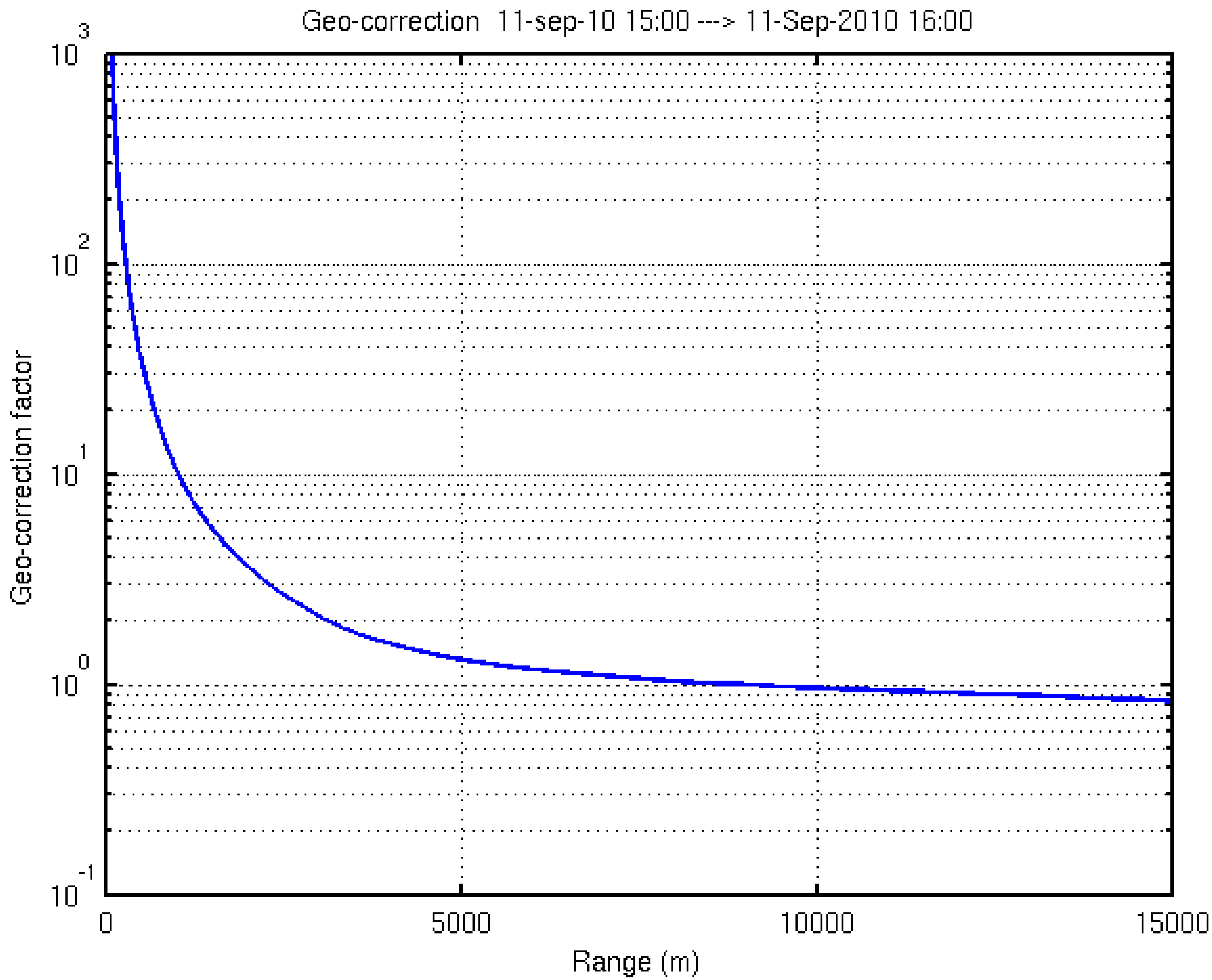




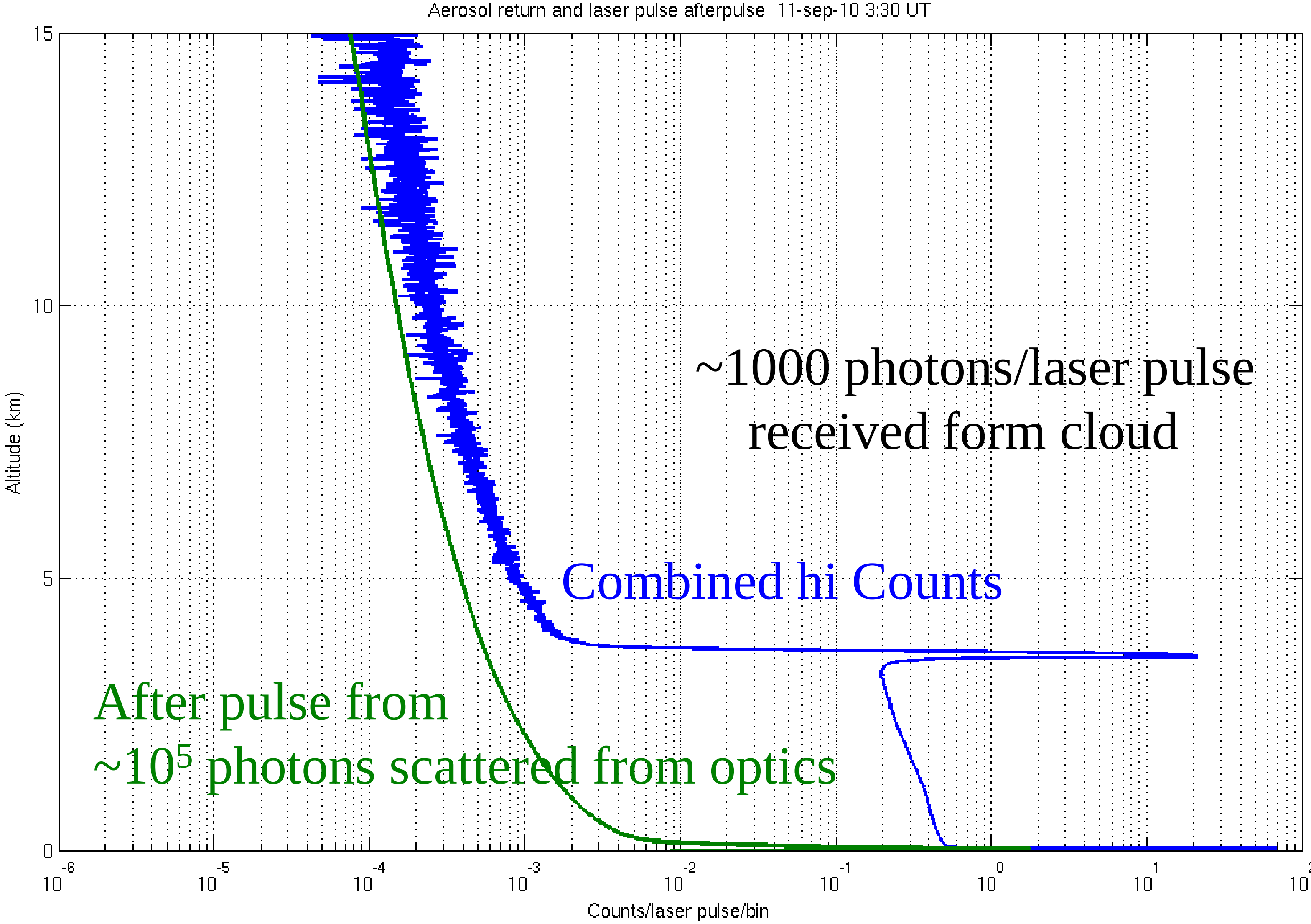
Optical depth profile for thin water cloud, 20 sec average

As the laser pulse propagates away from system the image size on the detector changes





Geo-correction 11-sep-10 15:00 ---> 11-Sep-2010 16:00
Geo-correction factor
Range (m)
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
0
5000
10000
15000



Aerosol return and laser pulse afterpulse 11-sep-10 3:30 UT
Altitude (km)
15
10
5
0
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
Counts/laser pulse/bin
~1000 photons/laser pulse
received form cloud
Combined hi Counts
After pulse from
~10^5 photons scattered from optics

Advantages of 532 nm operation

--Iodine adsorption line for filtering

--Important wavelength for radiative transfer

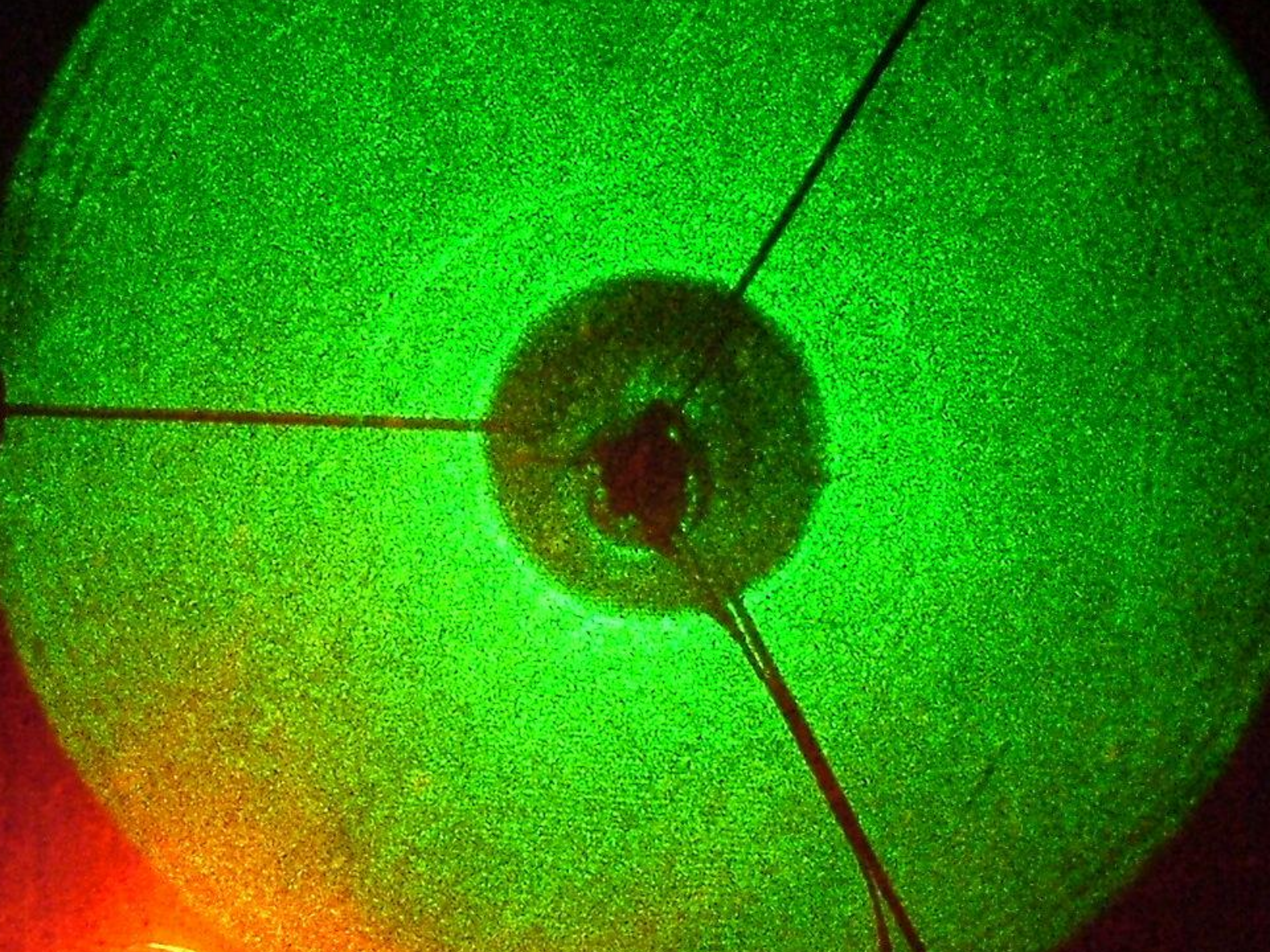
--Allows use of doubled Nd:YAG laser

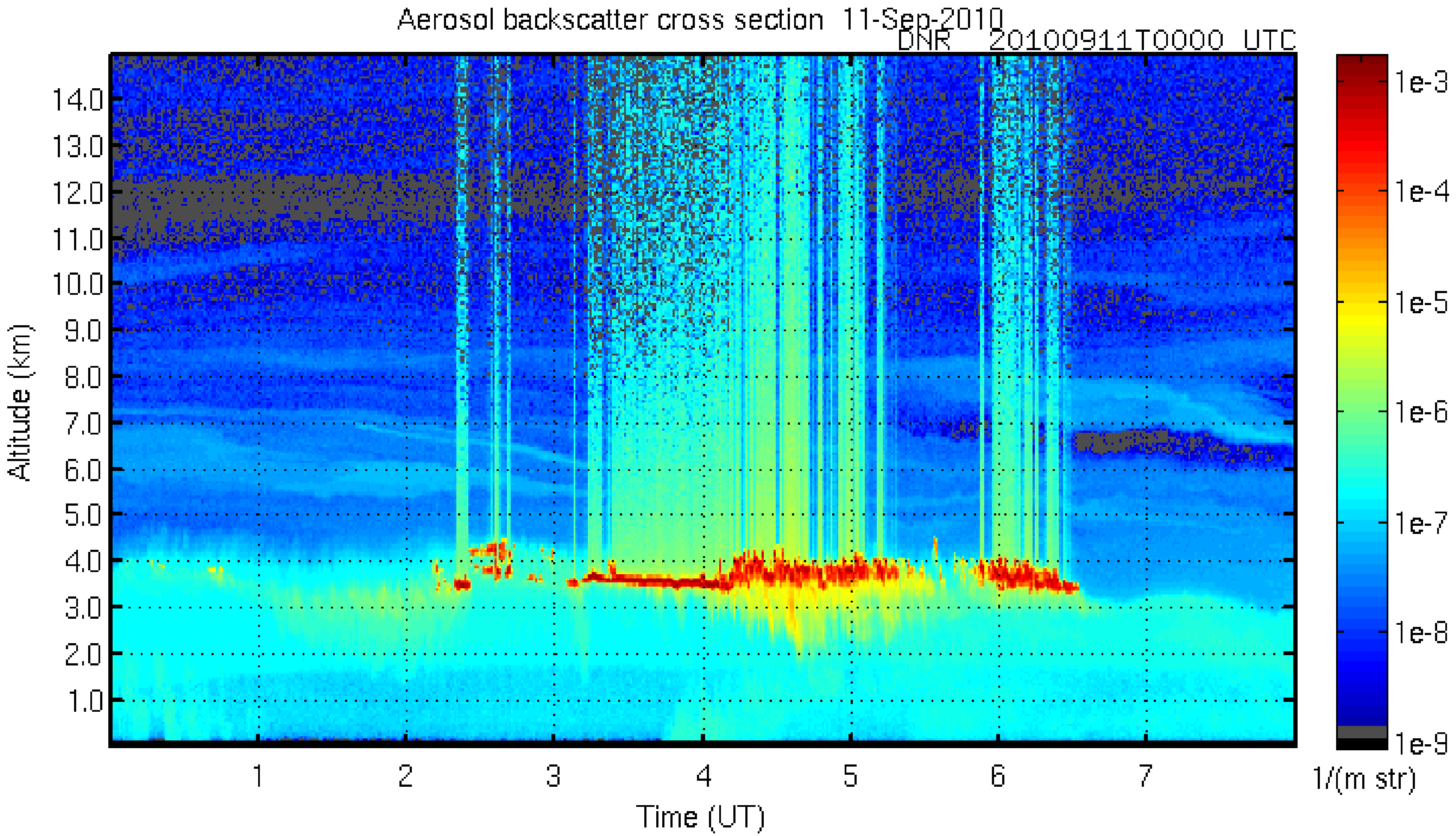
--Strong molecular scattering

Problem with 532 nm—eye safety

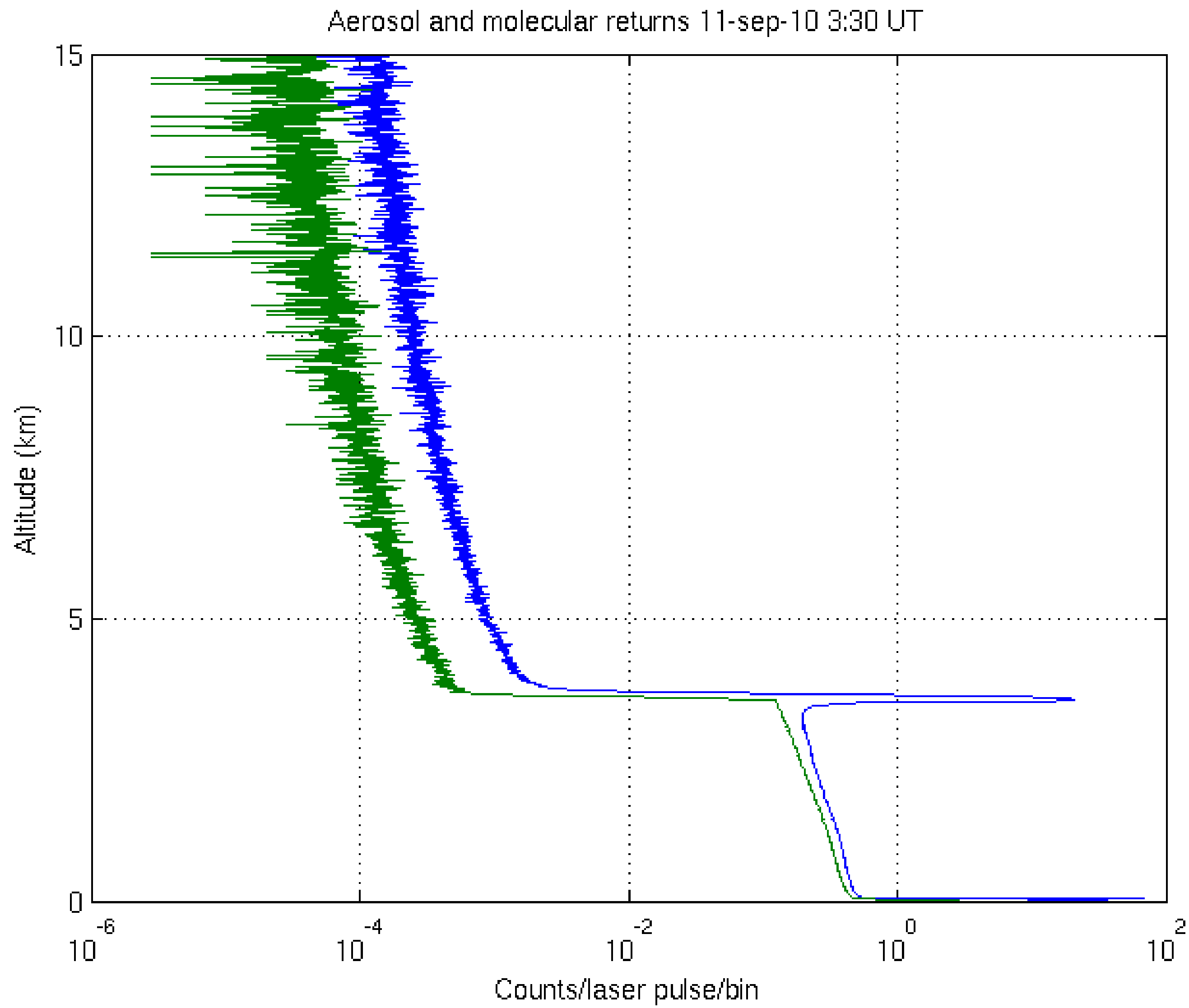
--Wavelength region with smallest permitted exposure

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



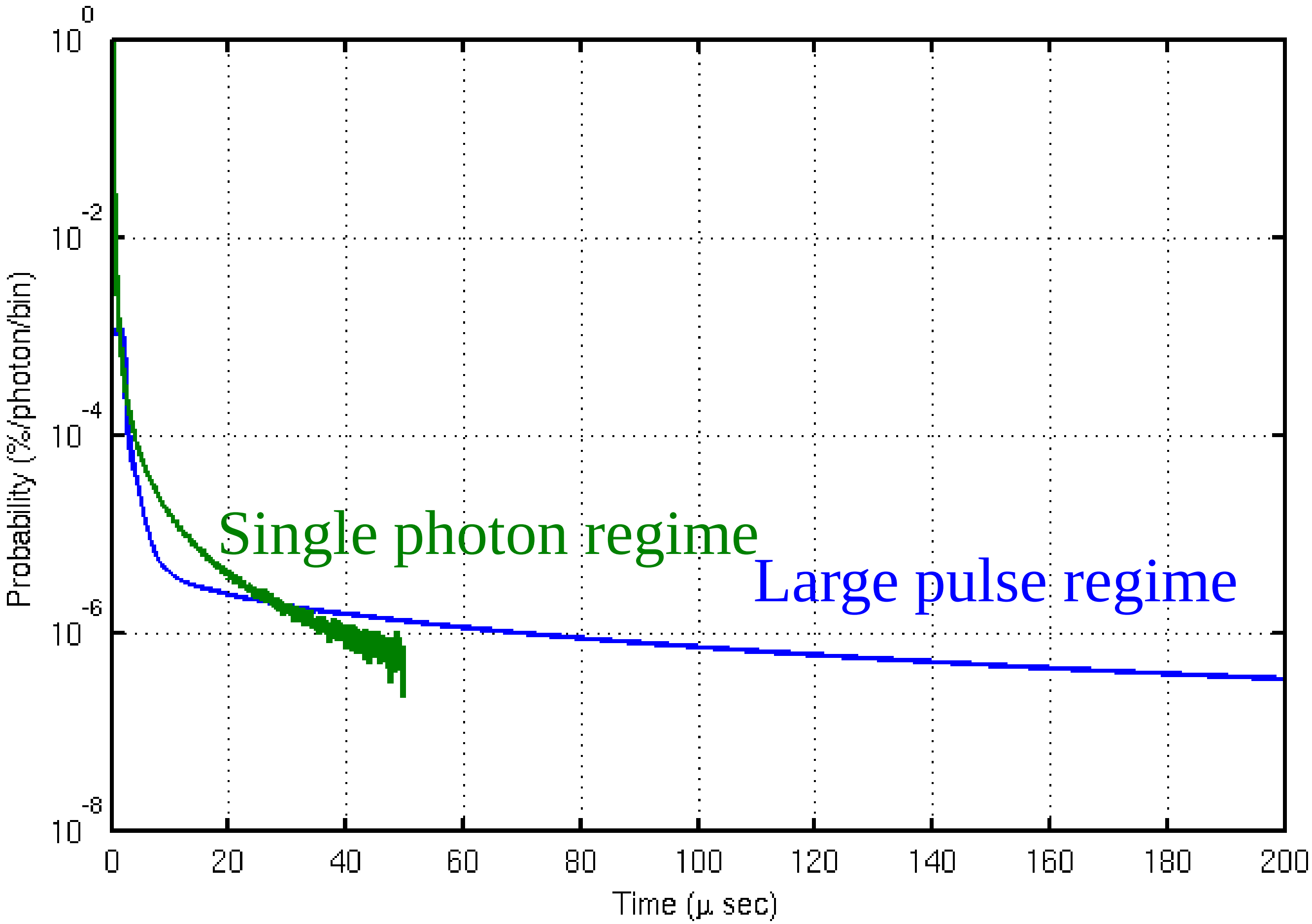


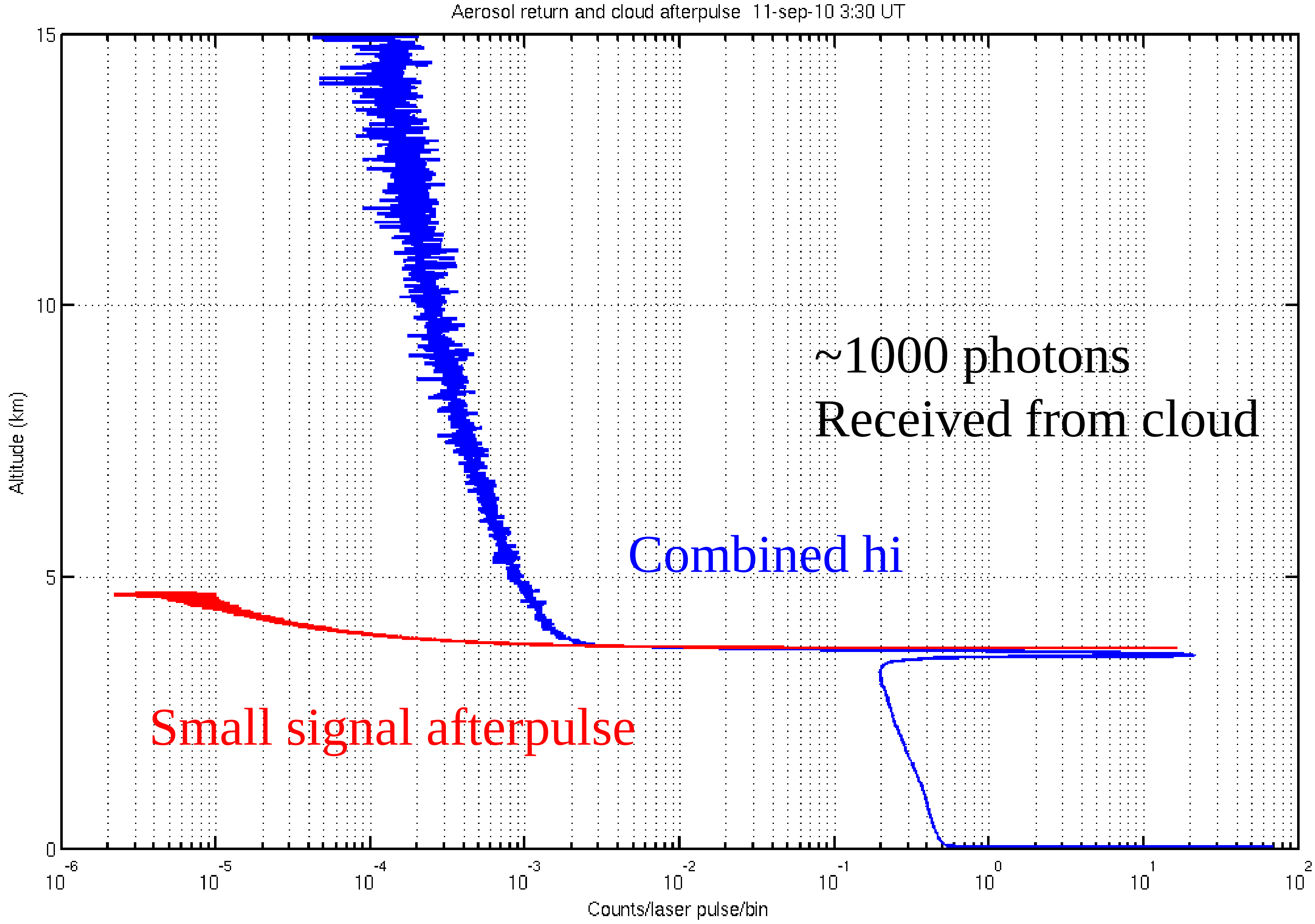
Aerosol backscatter cross section 11-Sep-2010
DNR 20100911T0000 UTC
Altitude (km)
14.0
13.0
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
1
2
3
4
5
6
7
Time (UT)
1e-3
1e-4
1e-5
1e-6
1e-7
1e-8
1e-9
1/(m str)

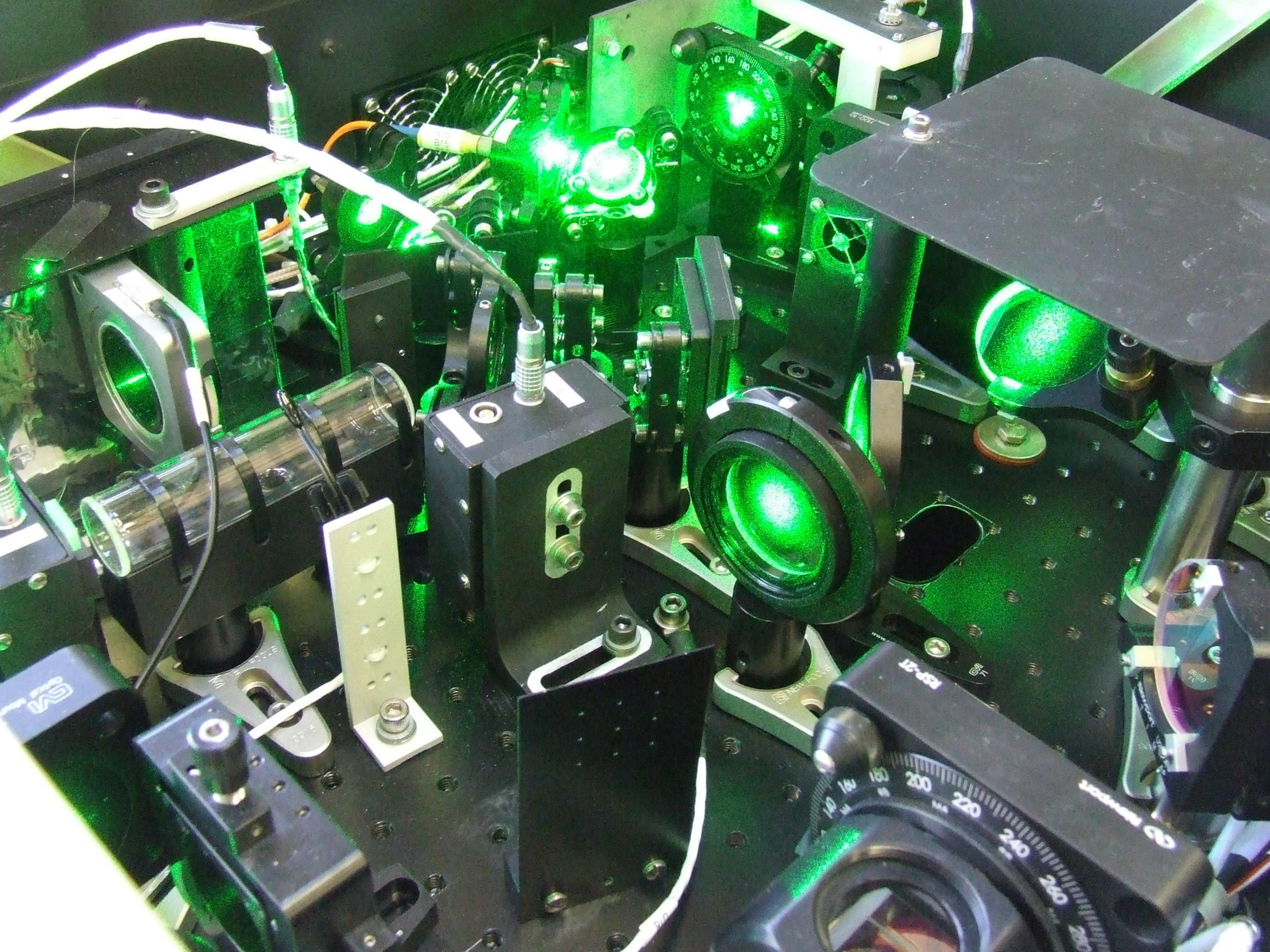


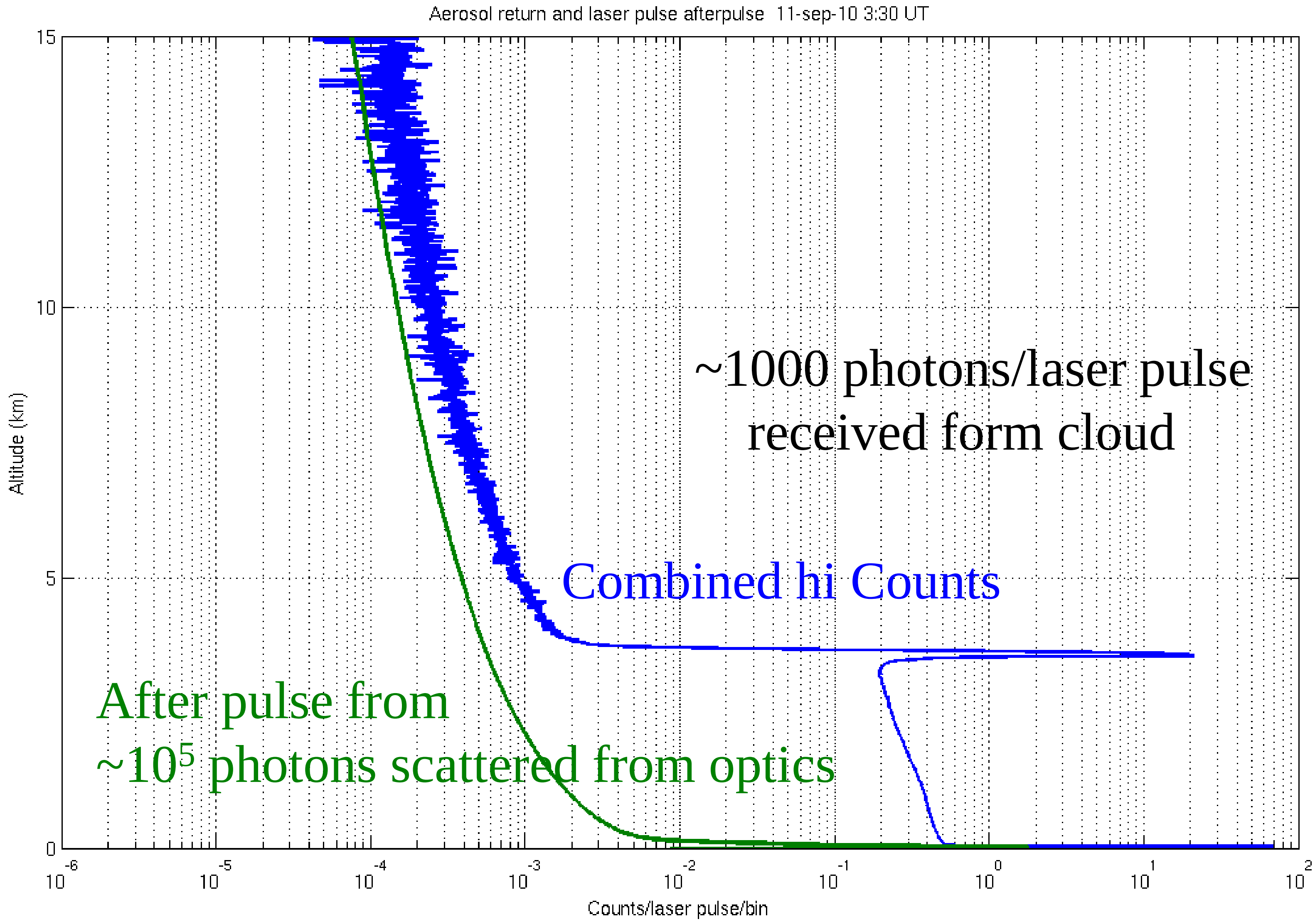
Aerosol and molecular returns 11-sep-10 3:30 UT
Altitude (km)
Counts/laser pulse/bin
15
10
5
0
10^-6
10^-4
10^-2
10^0
10^2

Geiger-mode APD afterpulse probability



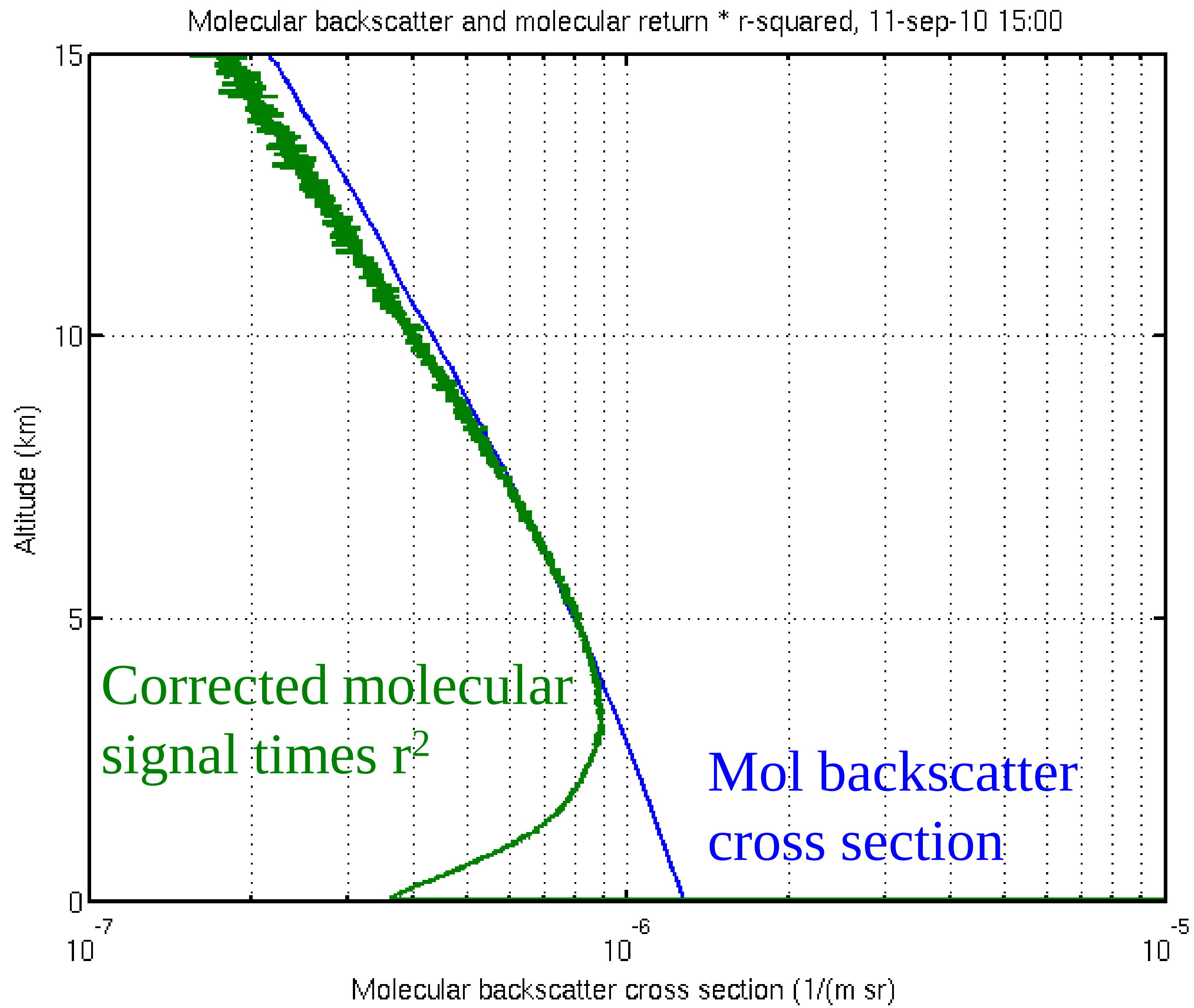

Aerosol return and cloud afterpulse 11-sep-10 3:30 UT
15
10
5
0
Altitude (km)
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
Counts/laser pulse/bin
~1000 photons
Received from cloud
Combined hi
Small signal afterpulse

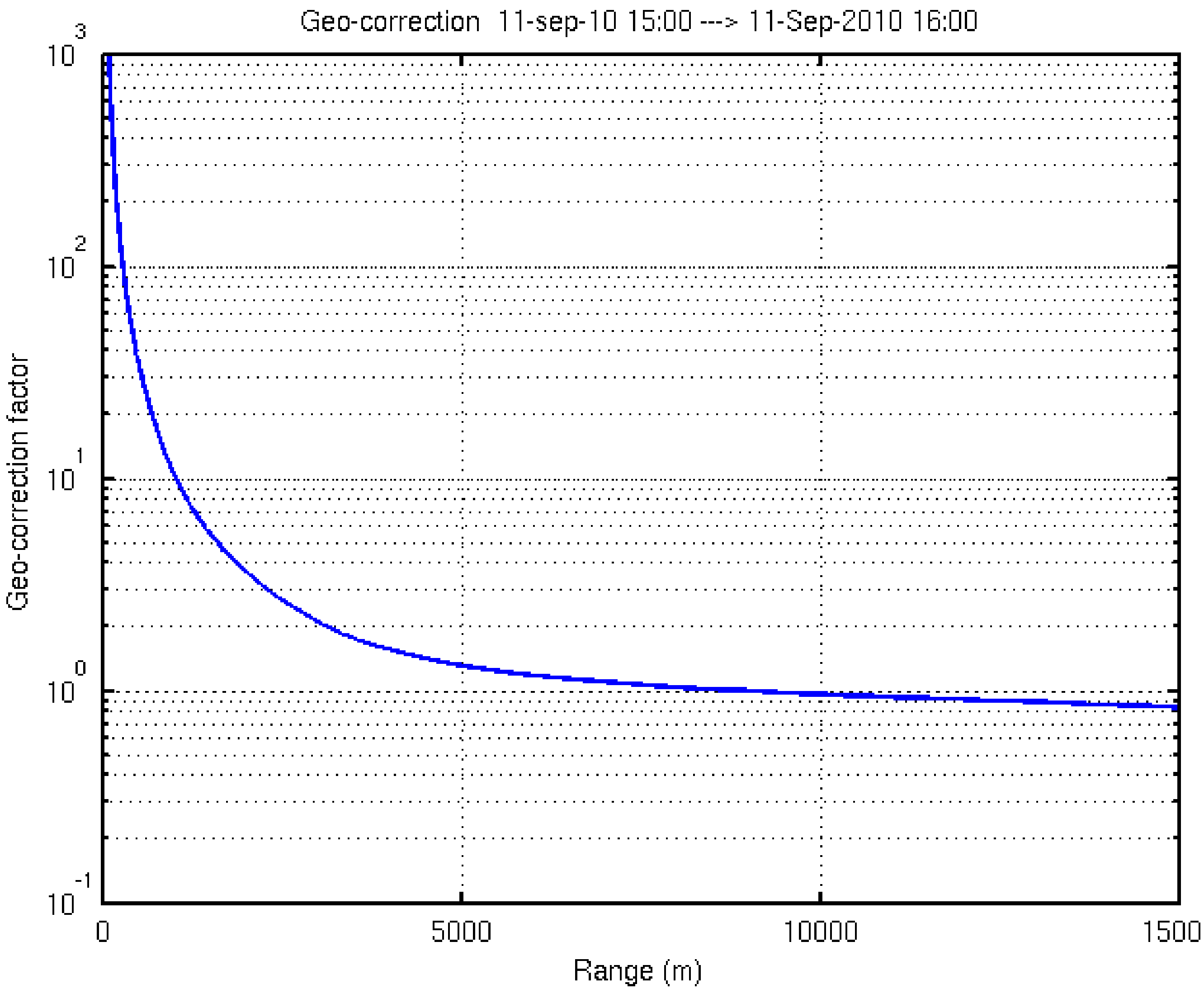

200
220
240
260



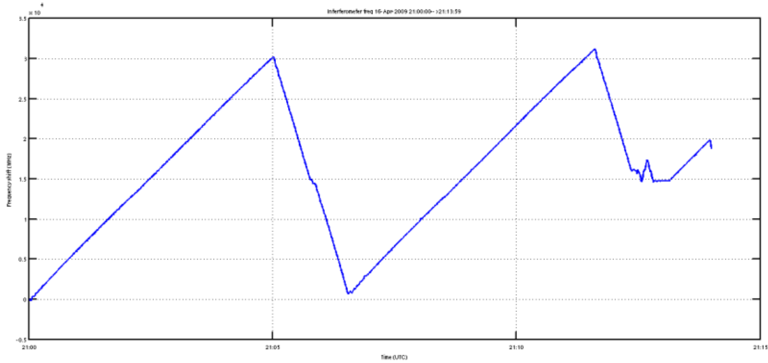
Aerosol return and laser pulse afterpulse 11-sep-10 3:30 UT
Altitude (km)
15
10
5
0
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
Counts/laser pulse/bin
~1000 photons/laser pulse
received form cloud
Combined hi Counts
After pulse from
~10^5 photons scattered from optics

As the laser pulse propagates away from system the image size on the detector changes

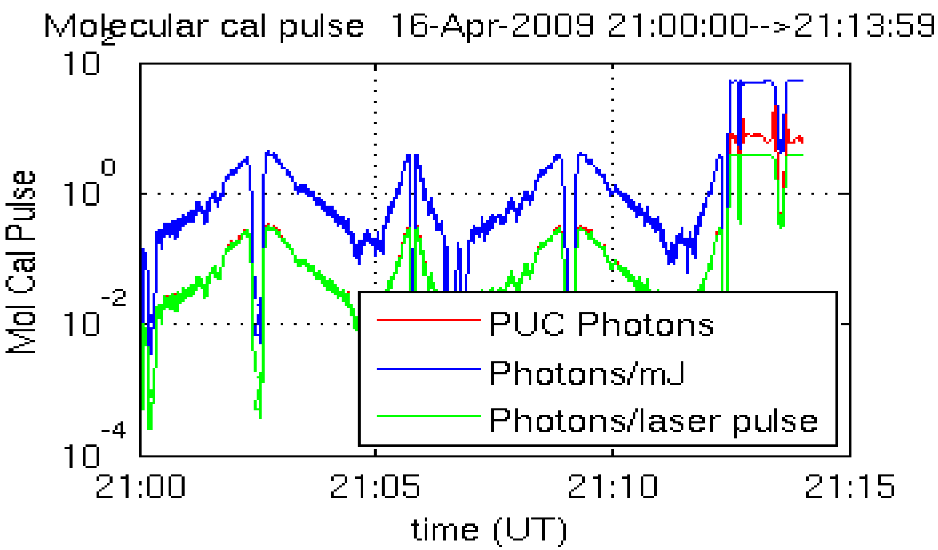




Geo-correction 11-sep-10 15:00 ---> 11-Sep-2010 16:00
Geo-correction factor
Range (m)
10^3
10^2
10^1
10^0
10^-1
0
5000
10000
15000

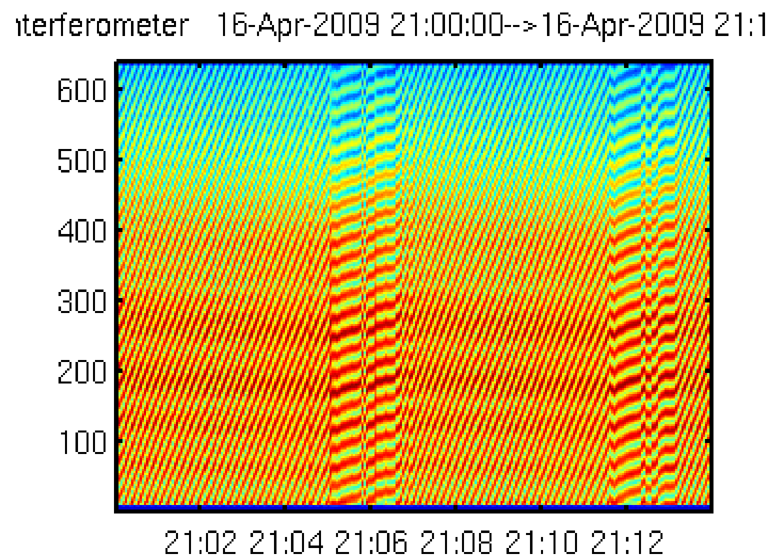


Frequency

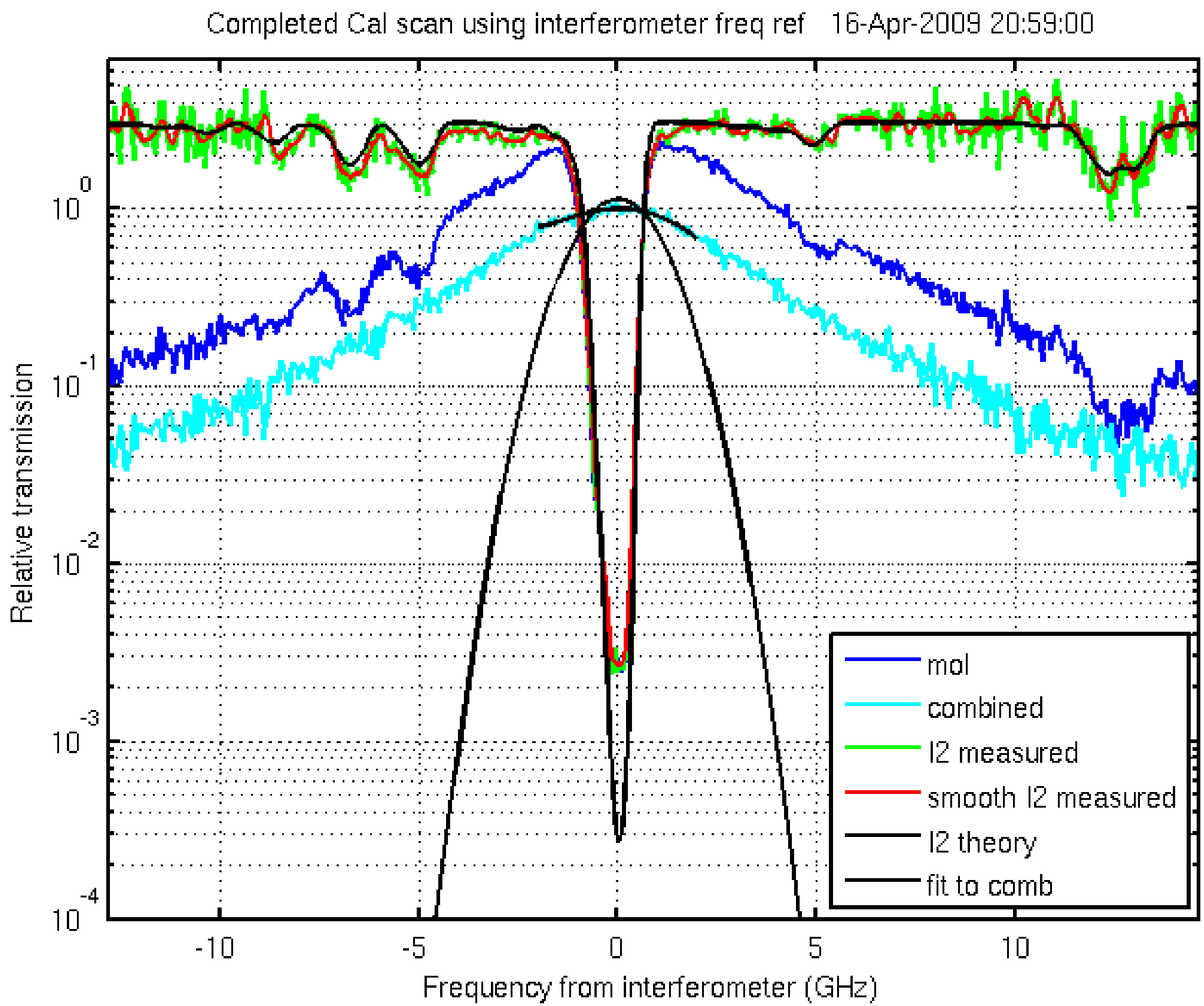


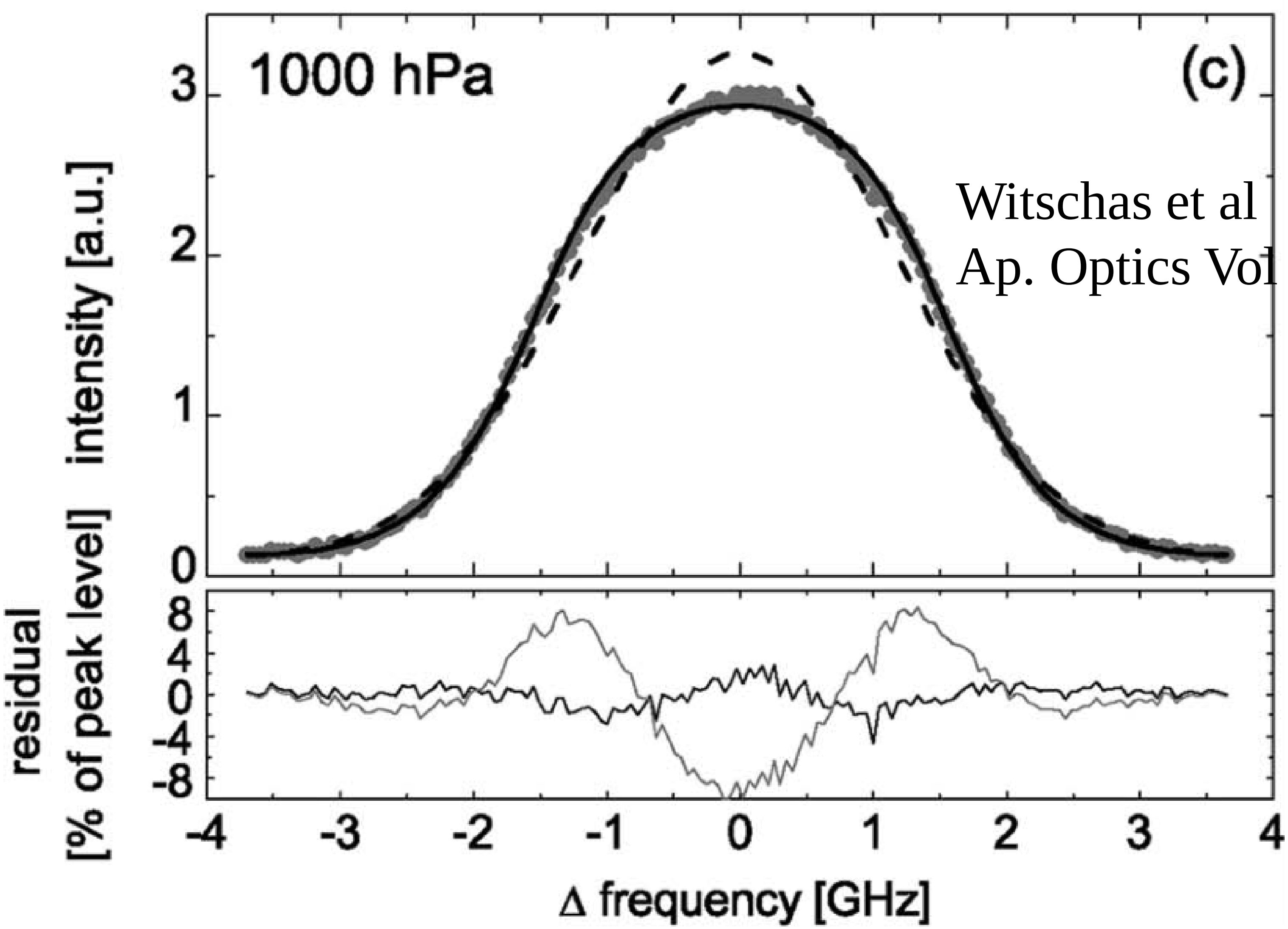
The transmitter frequency is scanned over ~20 GHz to measure the spectral bandpass of the receiver

Receiver bandpass calibration



An interferometer is used to determine frequency during the spectral scan

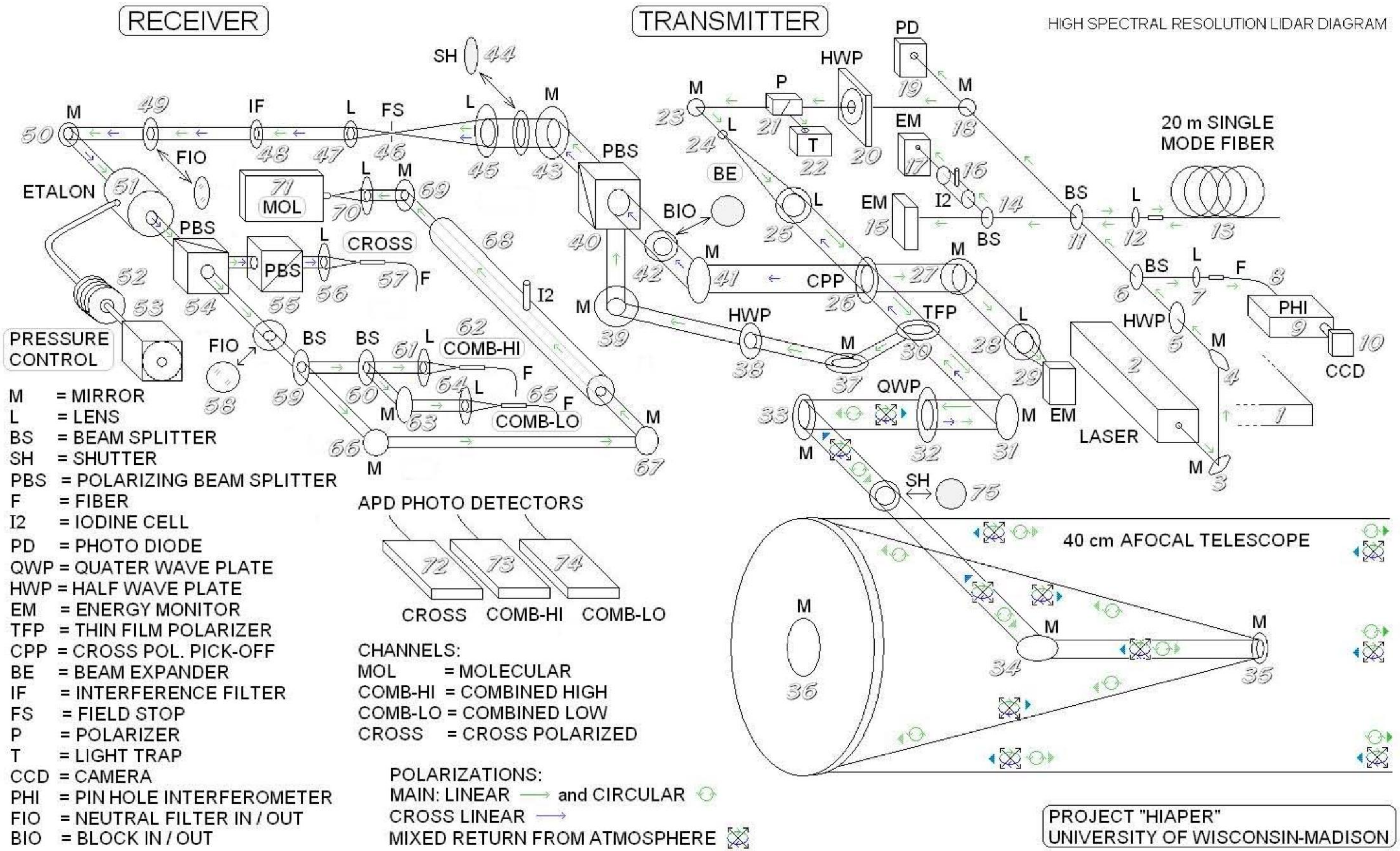

Completed Cal scan using interferometer freq ref 16-Apr-2009 20:59:00
Relative transmission
Frequency from interferometer (GHz)
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
-10
-5
0
5
10
mol
combined
I2 measured
smooth I2 measured
I2 theory
fit to comb

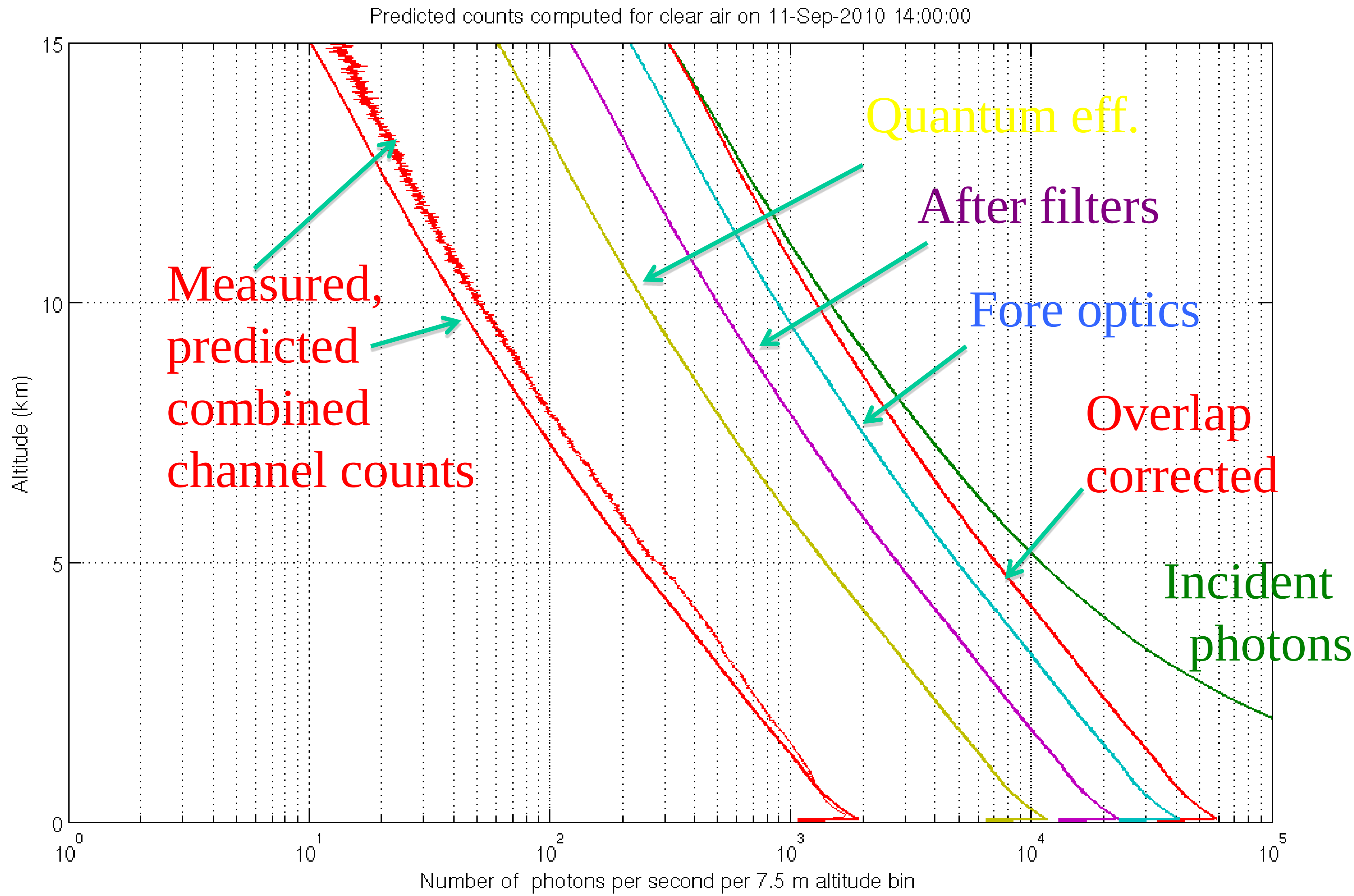


Witschas et al
Ap. Optics Vol 49, 2010

Brillouin line shape at 1000 hPa (solid), Rayleigh line shape (dashed) and deviations from measured values using Tenti S6 and Rayleigh shapes

HSRL schematic – NCAR HAIPER version





Predicted counts computed for clear air on 11-Sep-2010 14:00:00
Quantum eff.
After filters
Fore optics
Overlap corrected
Incident photons
Measured, predicted combined channel counts
Altitude (km)
Number of photons per second per 7.5 m altitude bin

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:

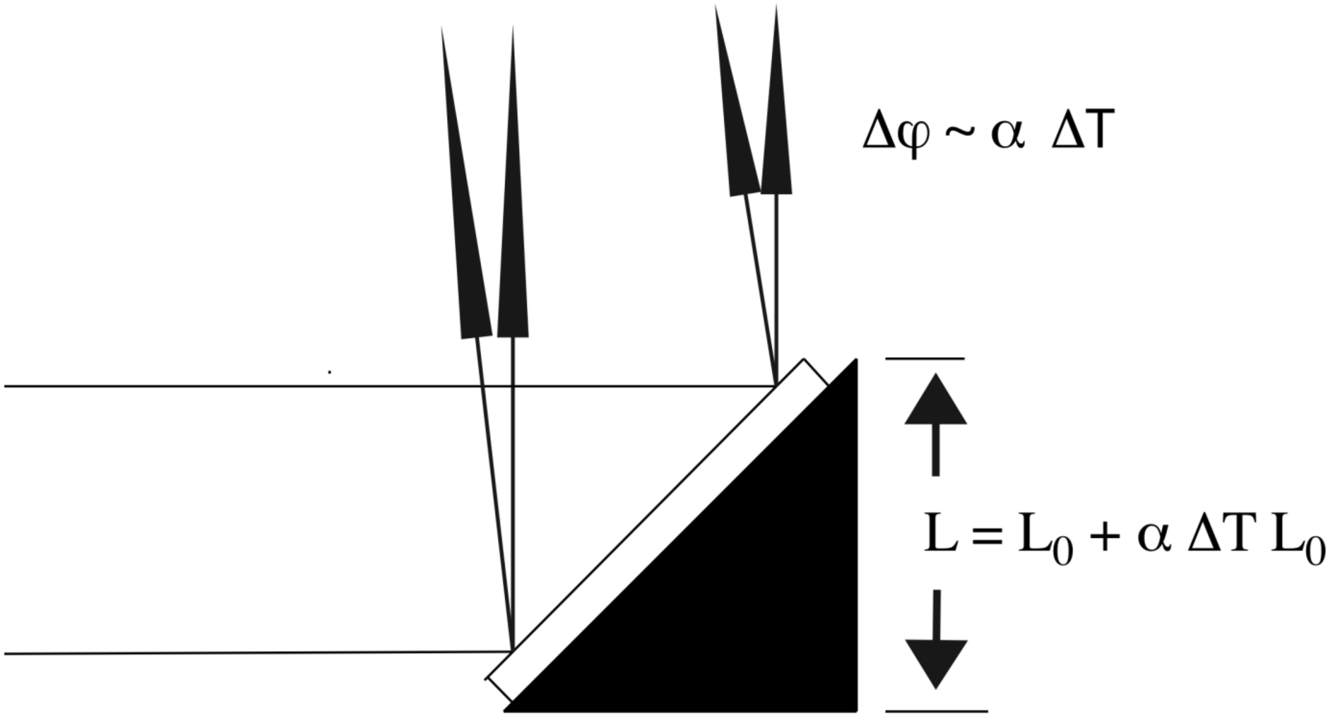
$\frac{N_a}{N_m} = \frac{C_{mm}S_c - C_{mc}S_m}{S_m - C_{am}S_c}$

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



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

Problem with 532 nm—eye safety

--Wavelength region with smallest permitted exposure

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

Where R = the pulse repetition rate

This forces high repetition rate and large apertures

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

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

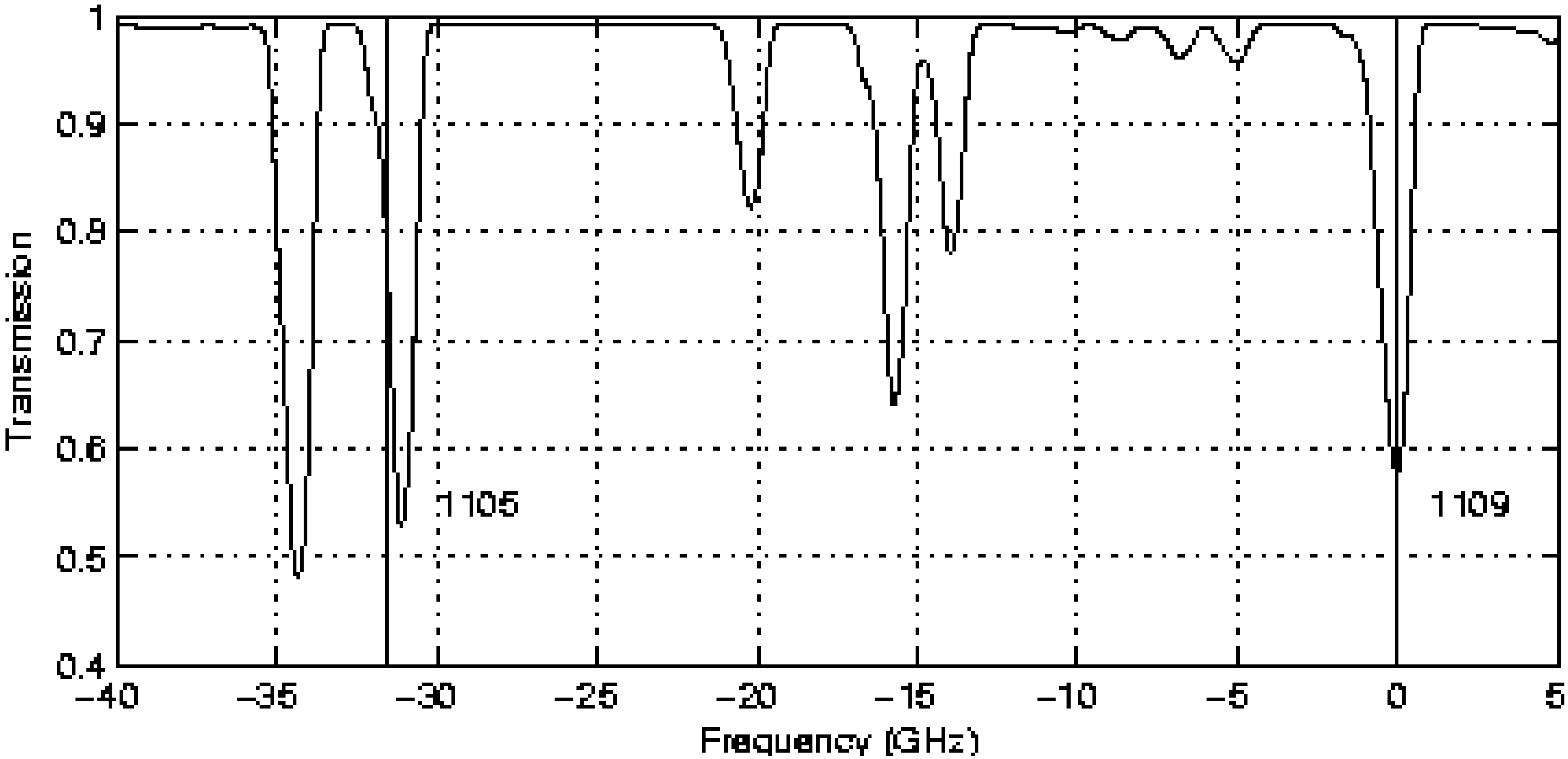
Thus max transmitted energy laser pulse is limited to:

$$\pi 25^2 * 5e\text{-}7 * 1000^{-1/4} = 0.174 \text{ mJ/pulse}$$

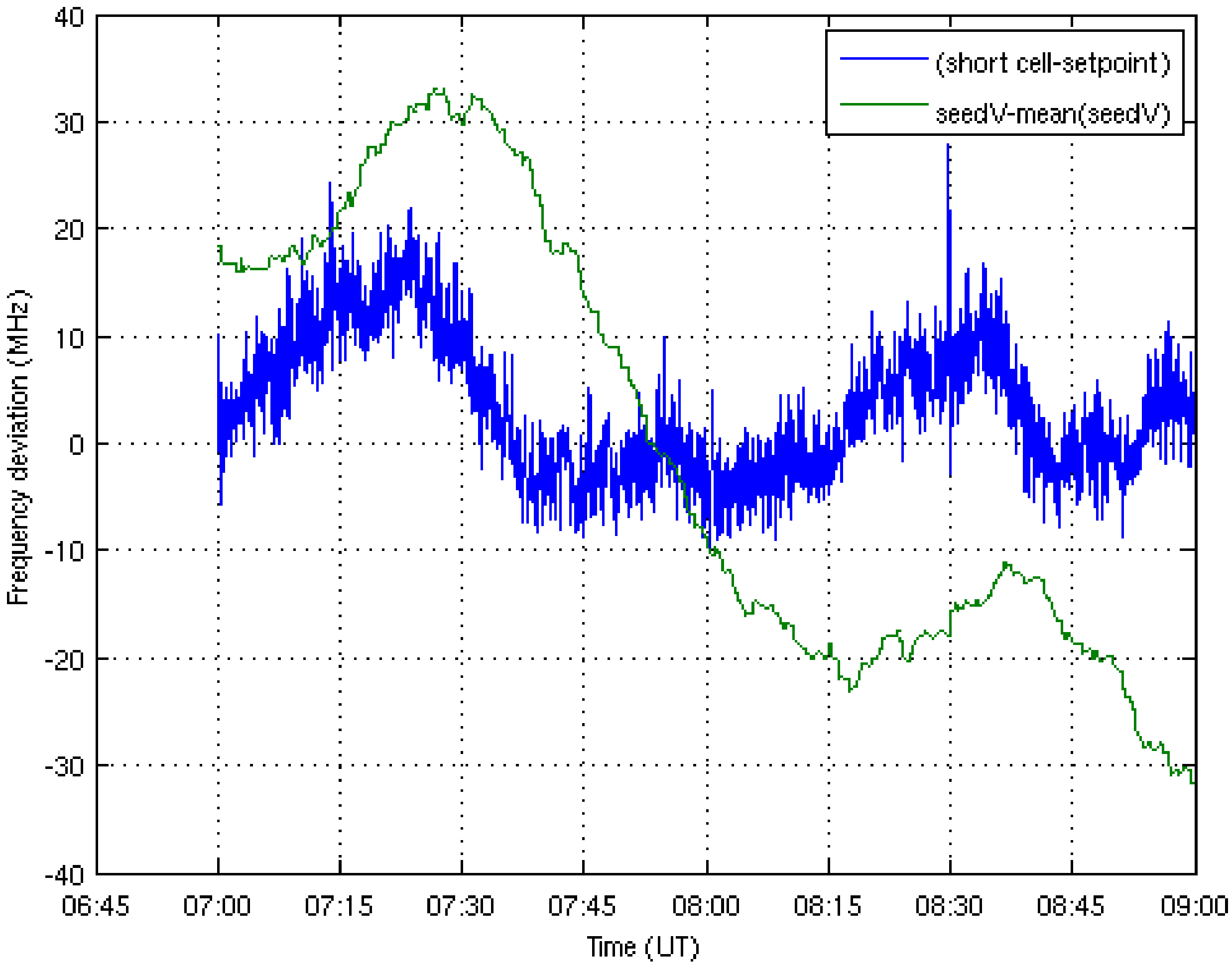
and the maximum transmitted power is:

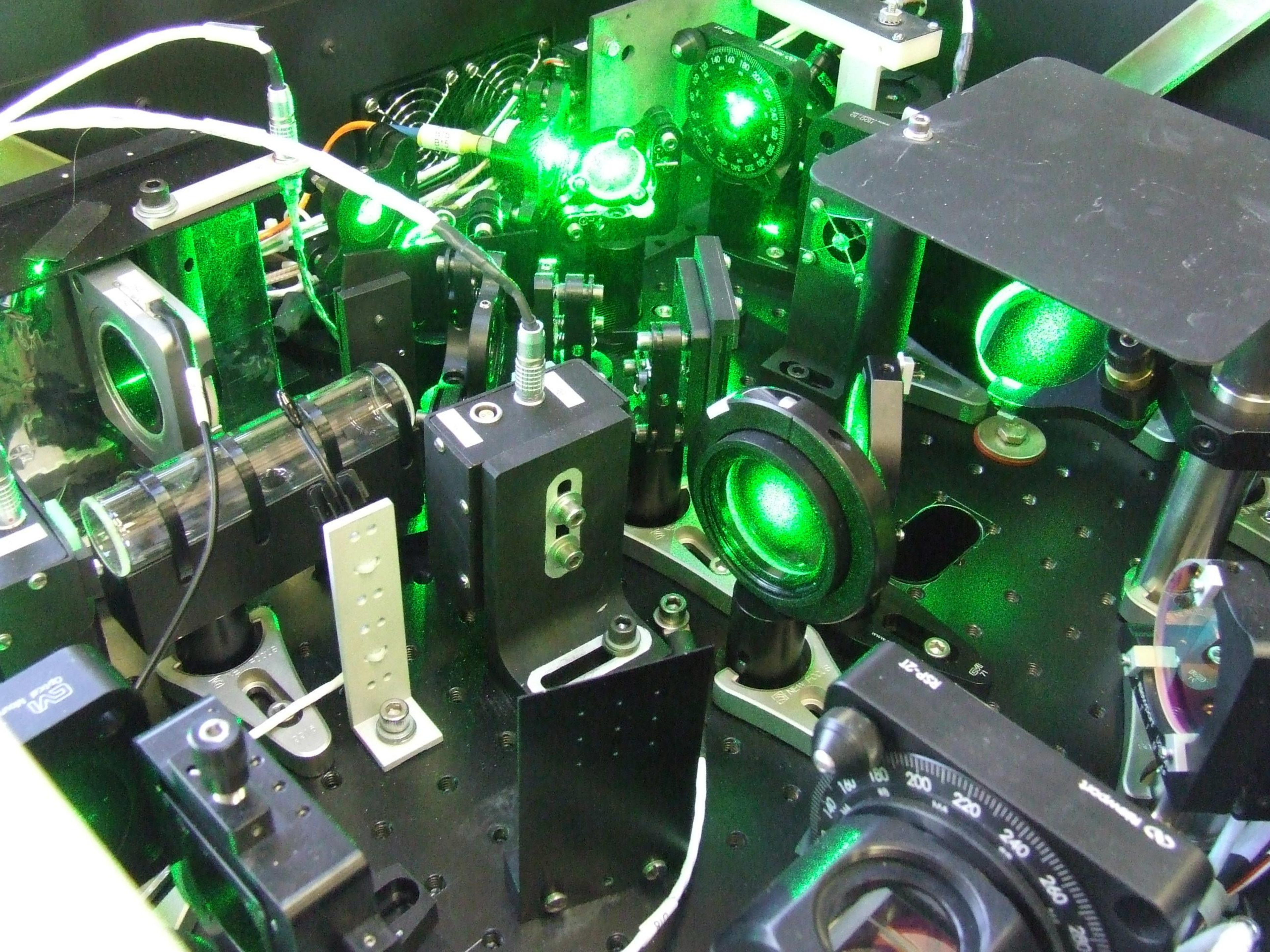
$$0.174e\text{-}3 * 4000 \text{ Hz} = 0.7 \text{ Watt}$$

Transmission of 2-cm iodine cell



Example of frequency locking




RSP-2T
Newport
180
200
220
240
260

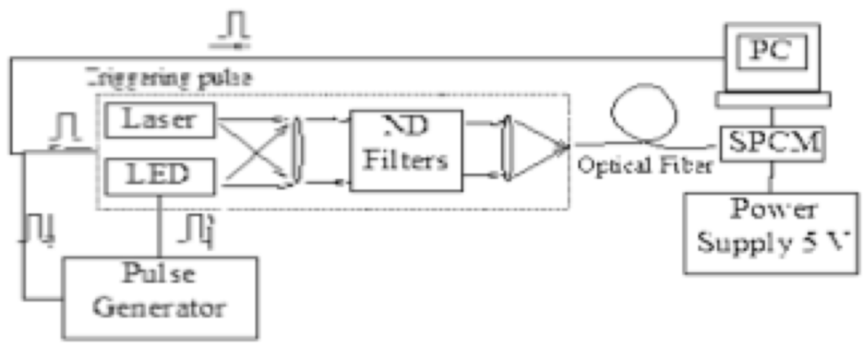
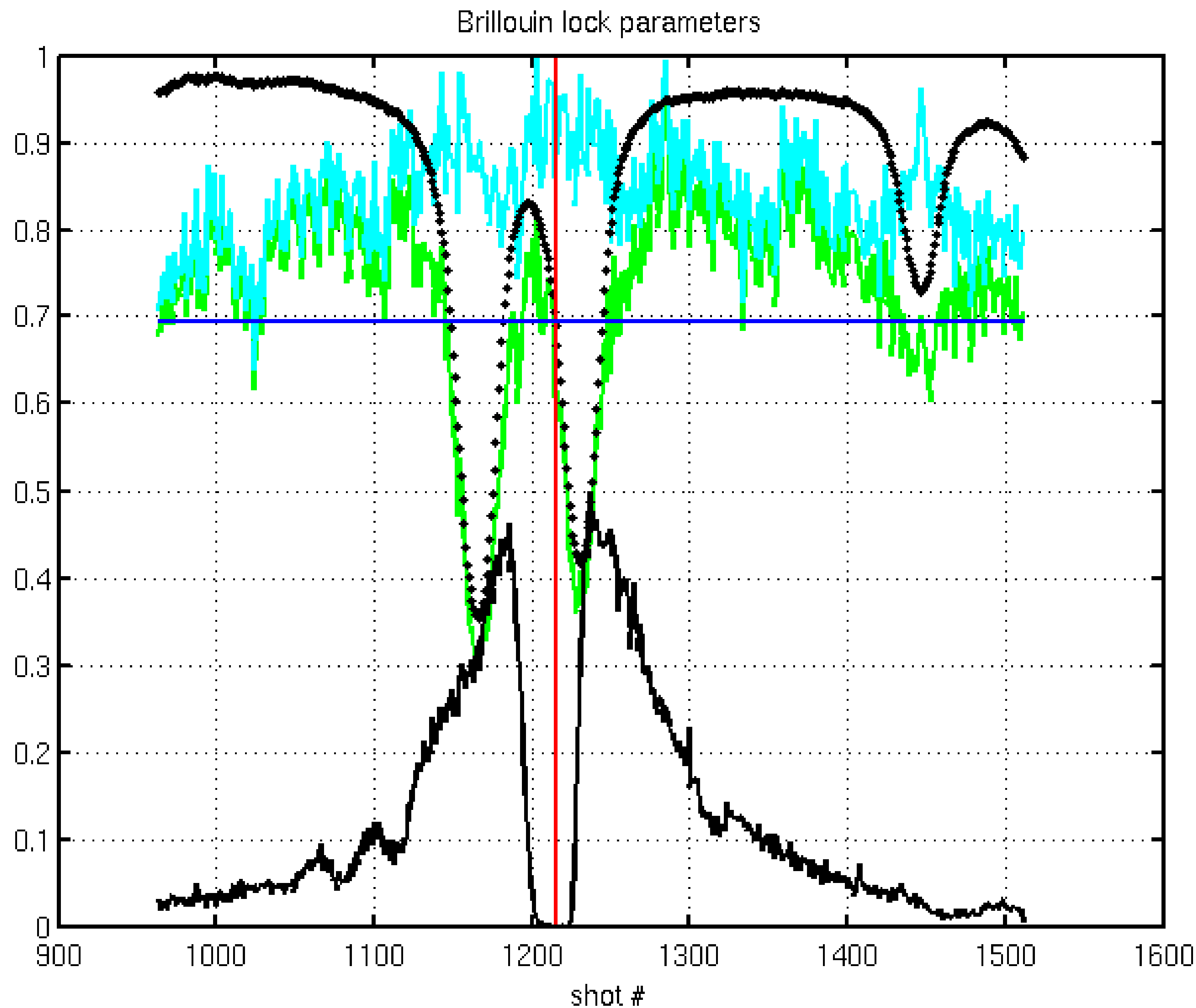


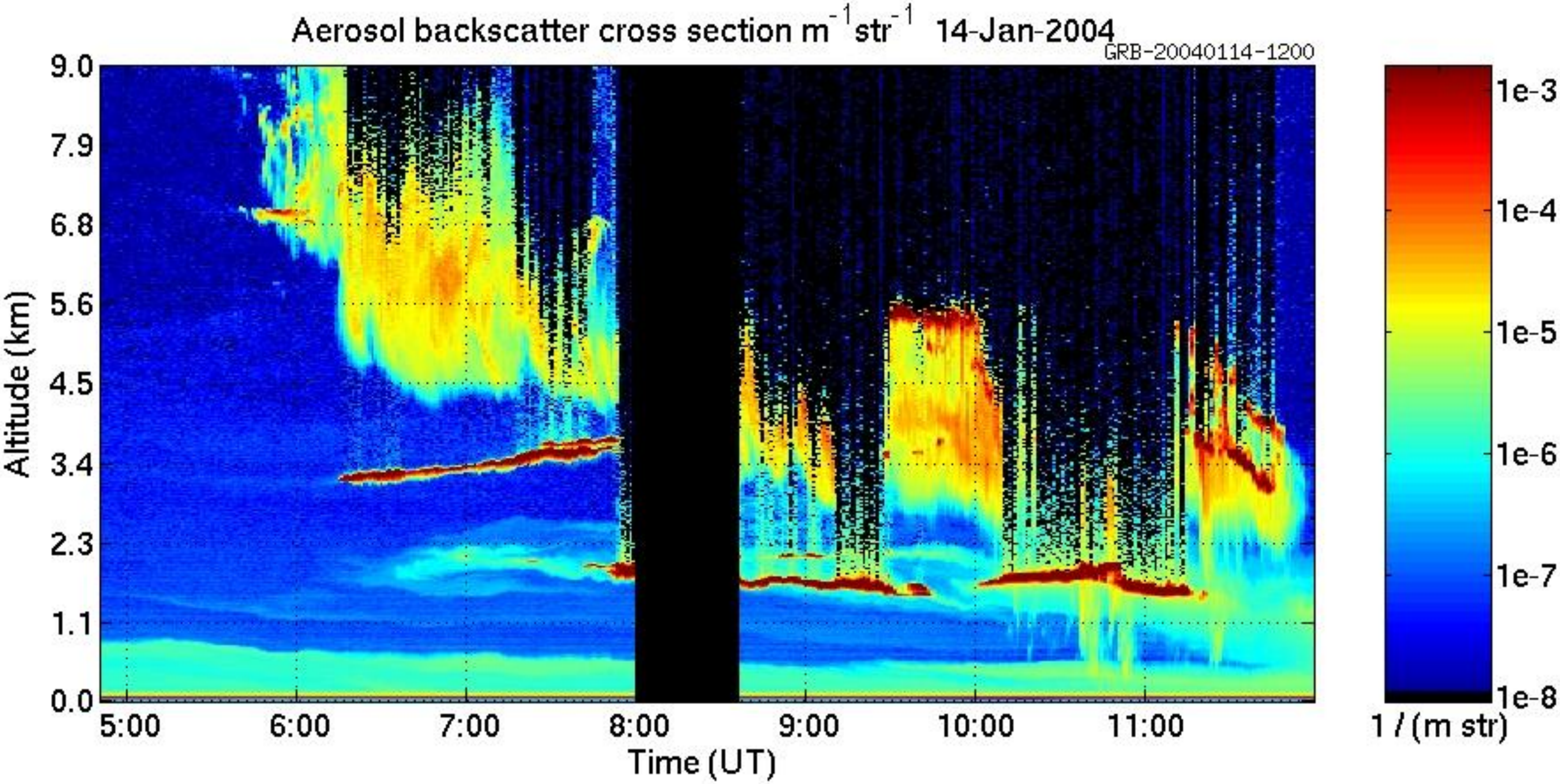
Figure 4. A block-diagram of the experimental setup.

3.2 Detector impulse response function



Brillouin lock parameters
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
900
1000
1100
1200
1300
1400
1500
1600
shot #


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
Newport
PERFORMAX

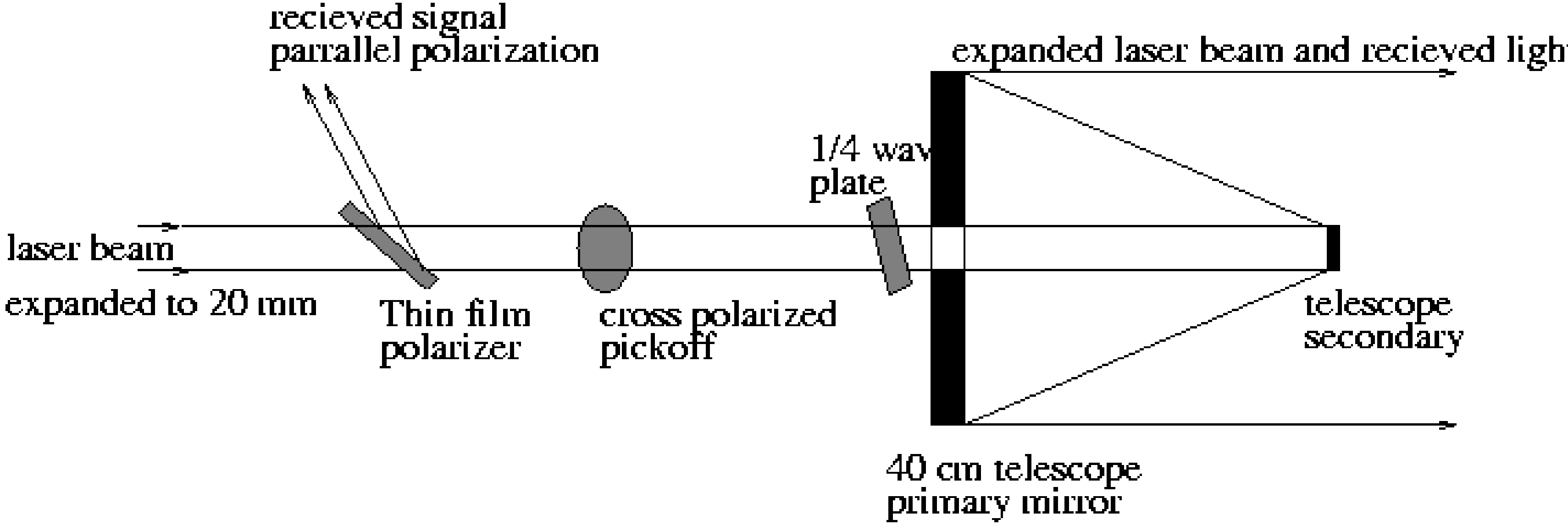


Aerosol backscatter cross section $m^{-1}str^{-1}$ 14-Jan-2004
GRB-20040114-1200
Altitude (km)
9.0
7.9
6.8
5.6
4.5
3.4
2.3
1.1
0.0
5:00
6:00
7:00
8:00
9:00
10:00
11:00
Time (UT)
1e-3
1e-4
1e-5
1e-6
1e-7
1e-8
1 / (m str)

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 μrad	250-1000 μrad
Optical trans	~34%	57%
Signal strength ~	1	0.27 (Area*Pwr*QE*η)
Sky Noise ~	0.24	3.4 (Area*BW*Ω*QE*η)

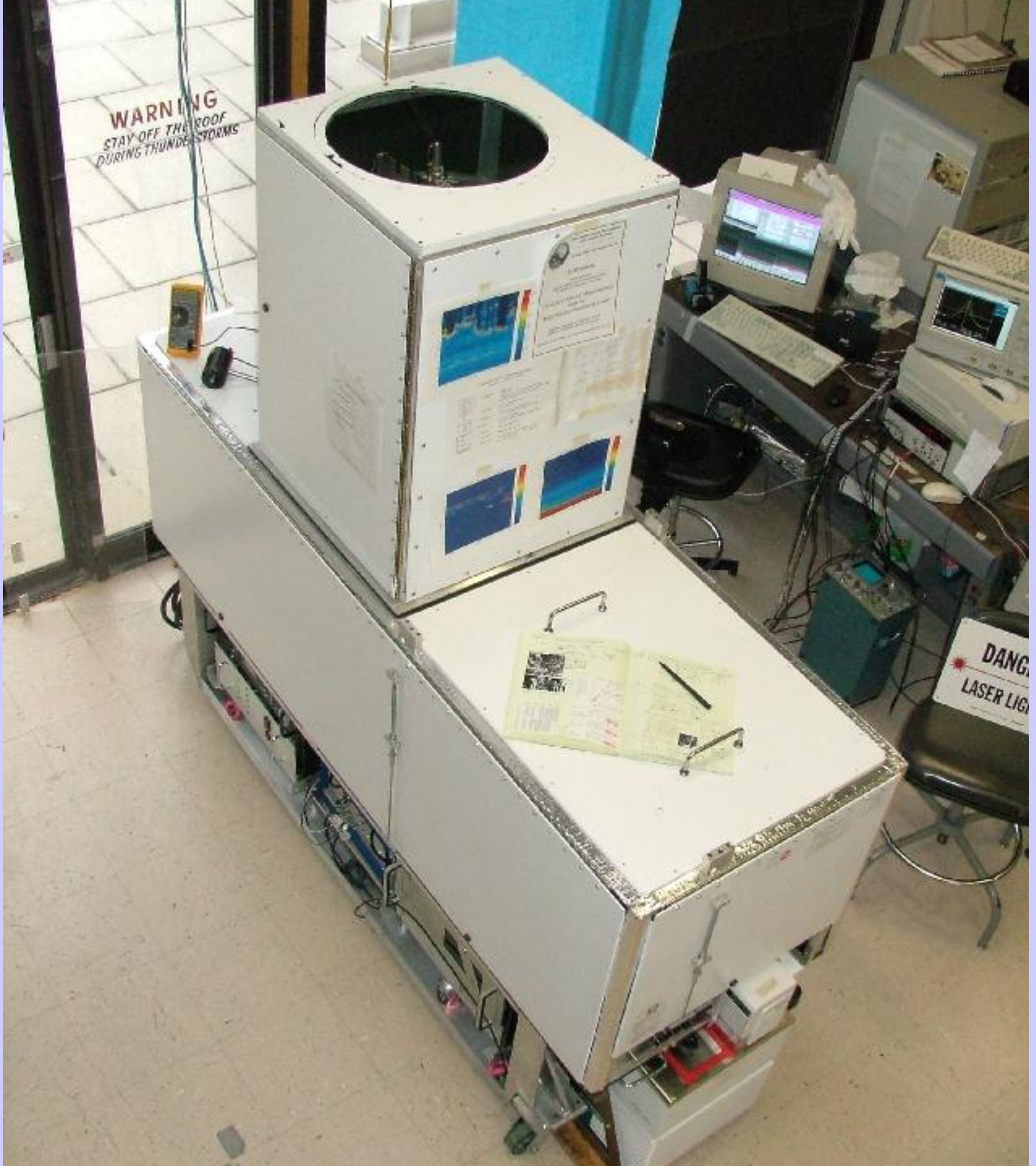
AHSRL transmit-receive telescope



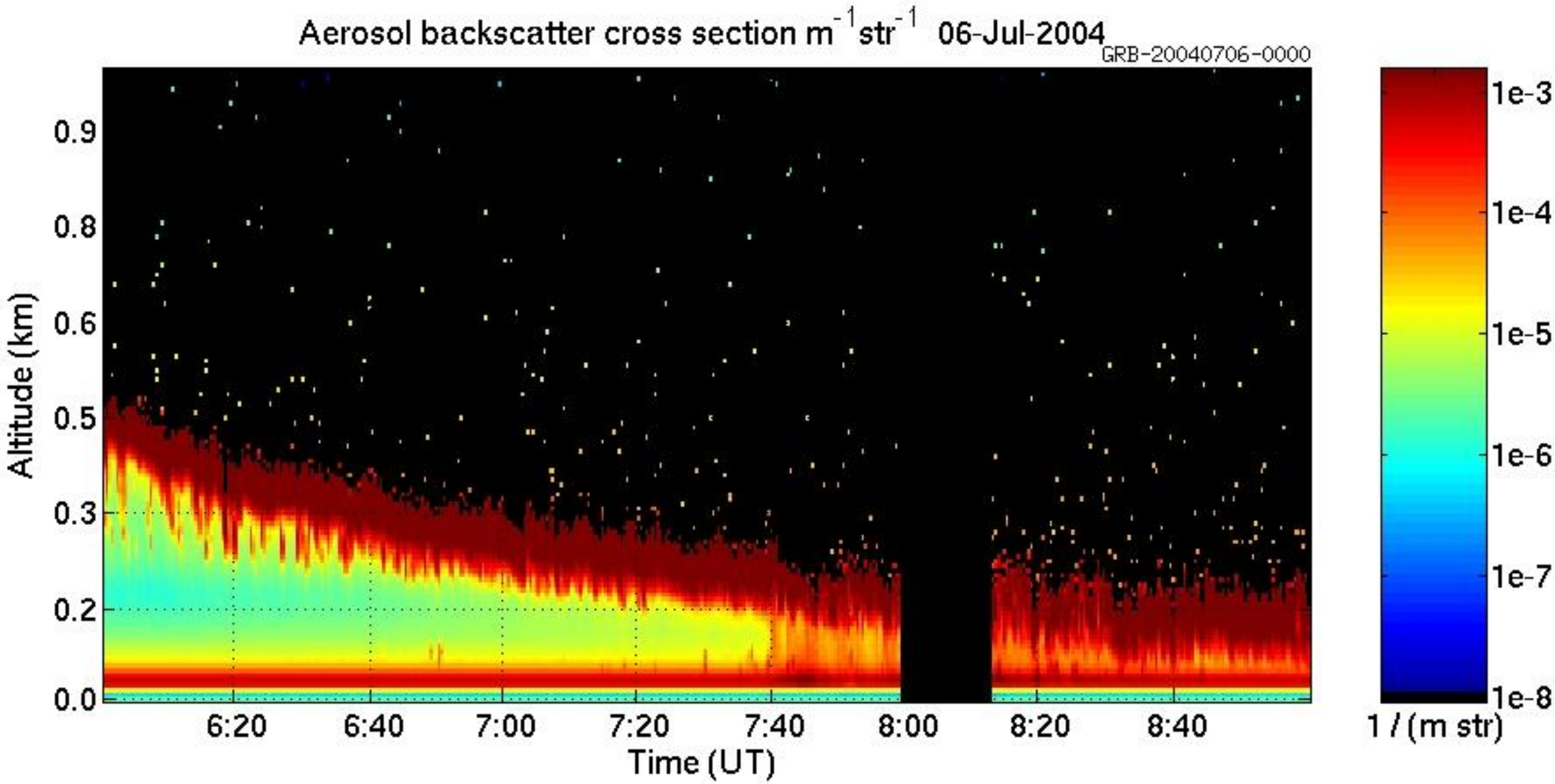
--The 20 mm diameter linearly-polarized laser beam is converted to circular polarization by ¼ wave plate before expansion 40 cm.

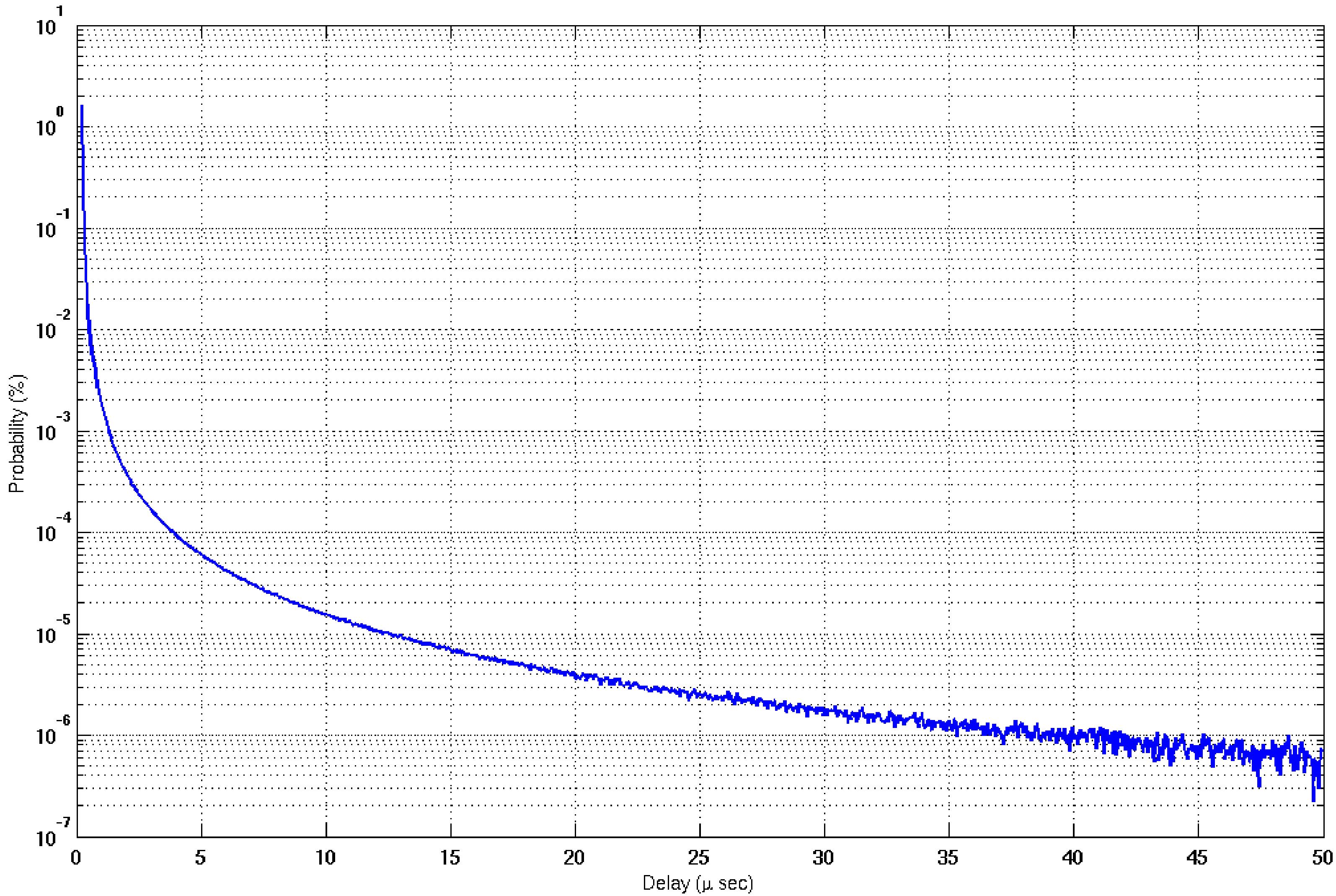
--The received signal is converted to linear polarization on return through the ¼ wave plate. Approx. 10% of the signal is separated to measure the cross-polarized component. The parallel-polarized component is separated from the transmit beam by the thin-film polarizer.


EXIT
CAUTION!


WARNING
STAY OFF THE ROOF
DURING THUNDERSTORMS
DANG
LASER LIGH

High Spectral Resolution Lidar at North Slope ARM site

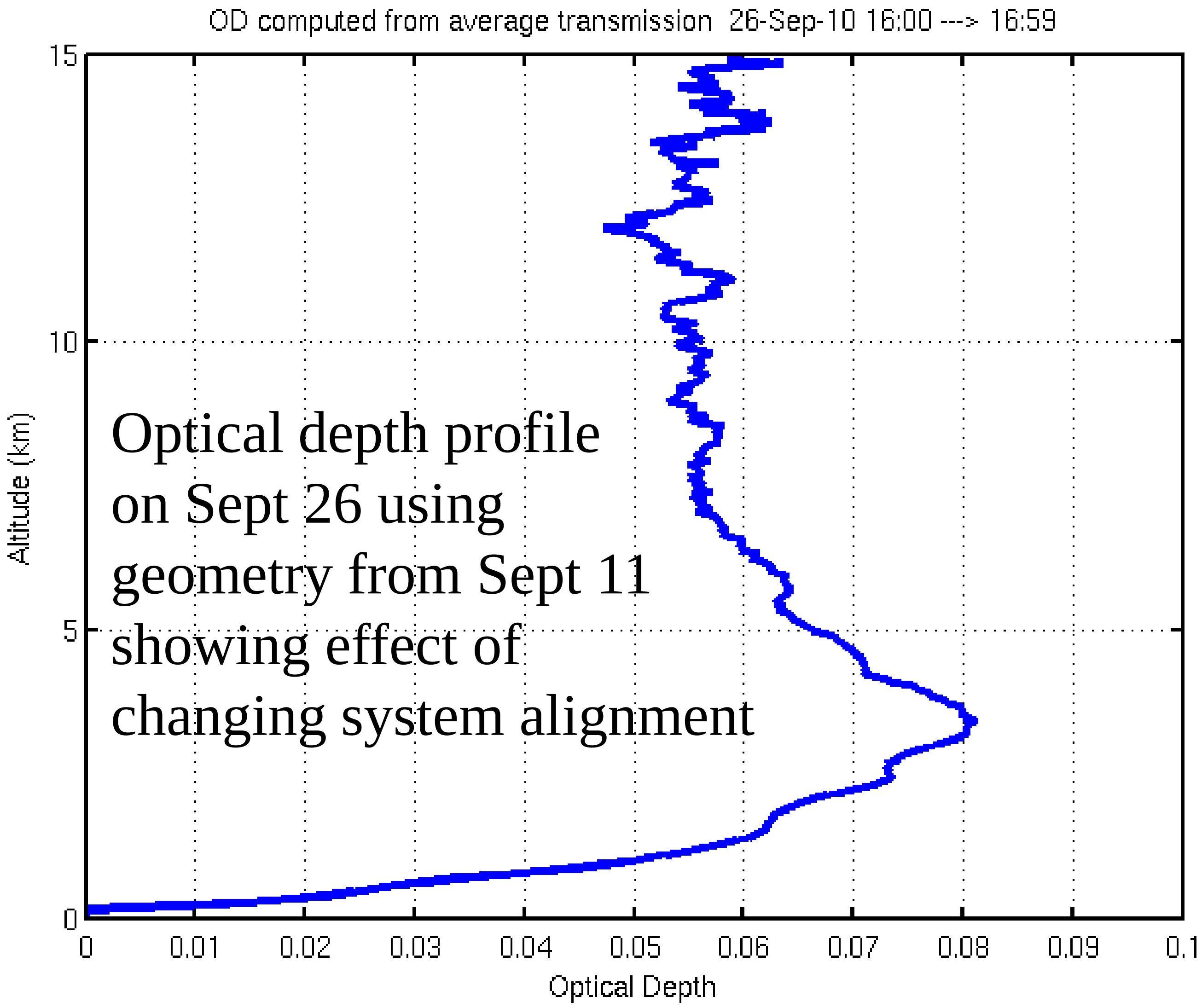

Aerosol backscatter cross section m^{-1}str^{-1} 06-Jul-2004
GRB-20040706-0000
Altitude (km)
0.0
0.2
0.3
0.5
0.6
0.8
0.9
6:20
6:40
7:00
7:20
7:40
8:00
8:20
8:40
Time (UT)
1e-3
1e-4
1e-5
1e-6
1e-7
1e-8
1 / (m str)



Probability (%)
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
0 5 10 15 20 25 30 35 40 45 50
Delay (µ sec)

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


OD computed from average transmission 26-Sep-10 16:00 ---> 16:59
Altitude (km)
15
10
5
0
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
Optical Depth
Optical depth profile
on Sept 26 using
geometry from Sept 11
showing effect of
changing system alignment


FM