Radiative Transport in Volcanic Plumes

DOAS Workshop 2015
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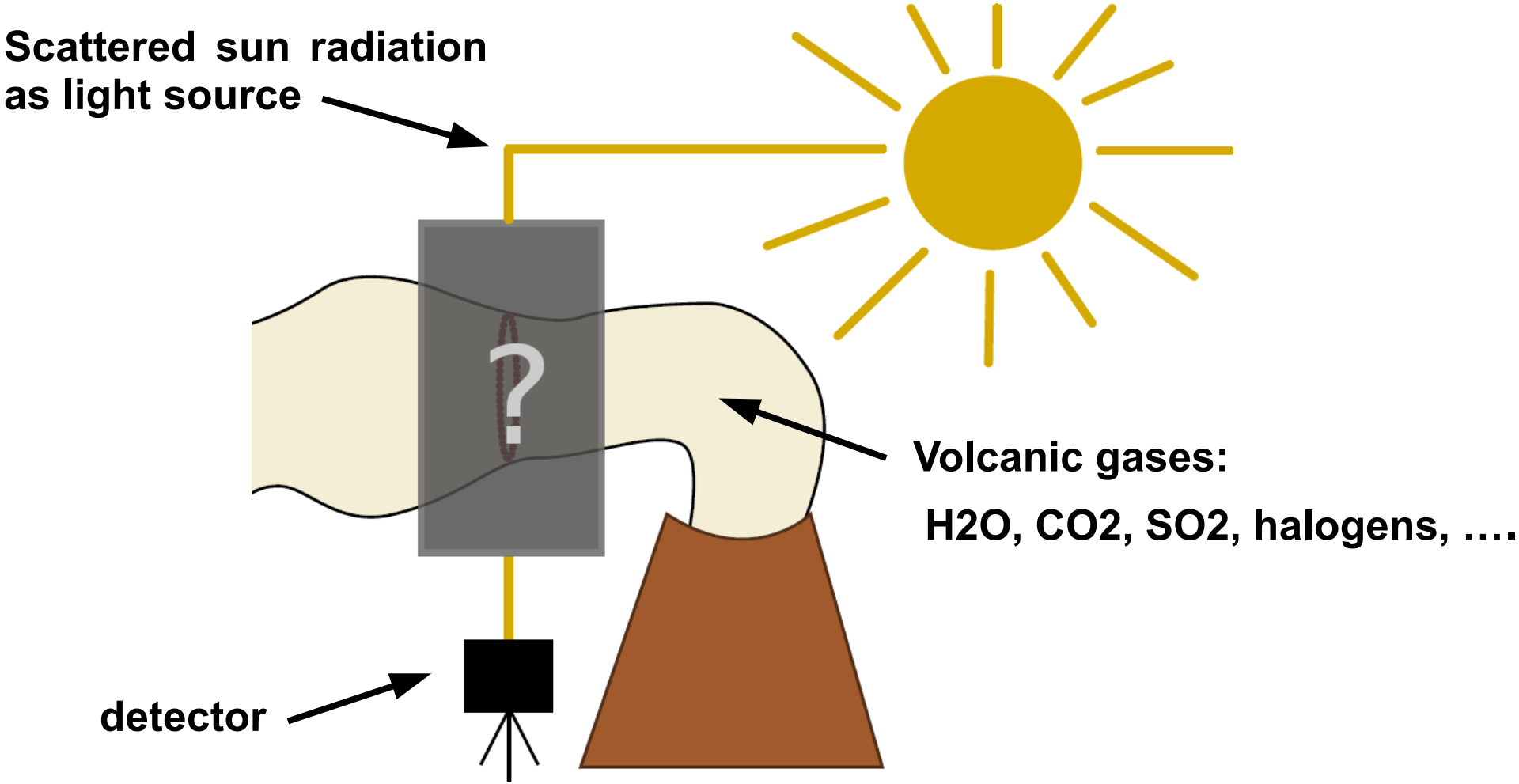
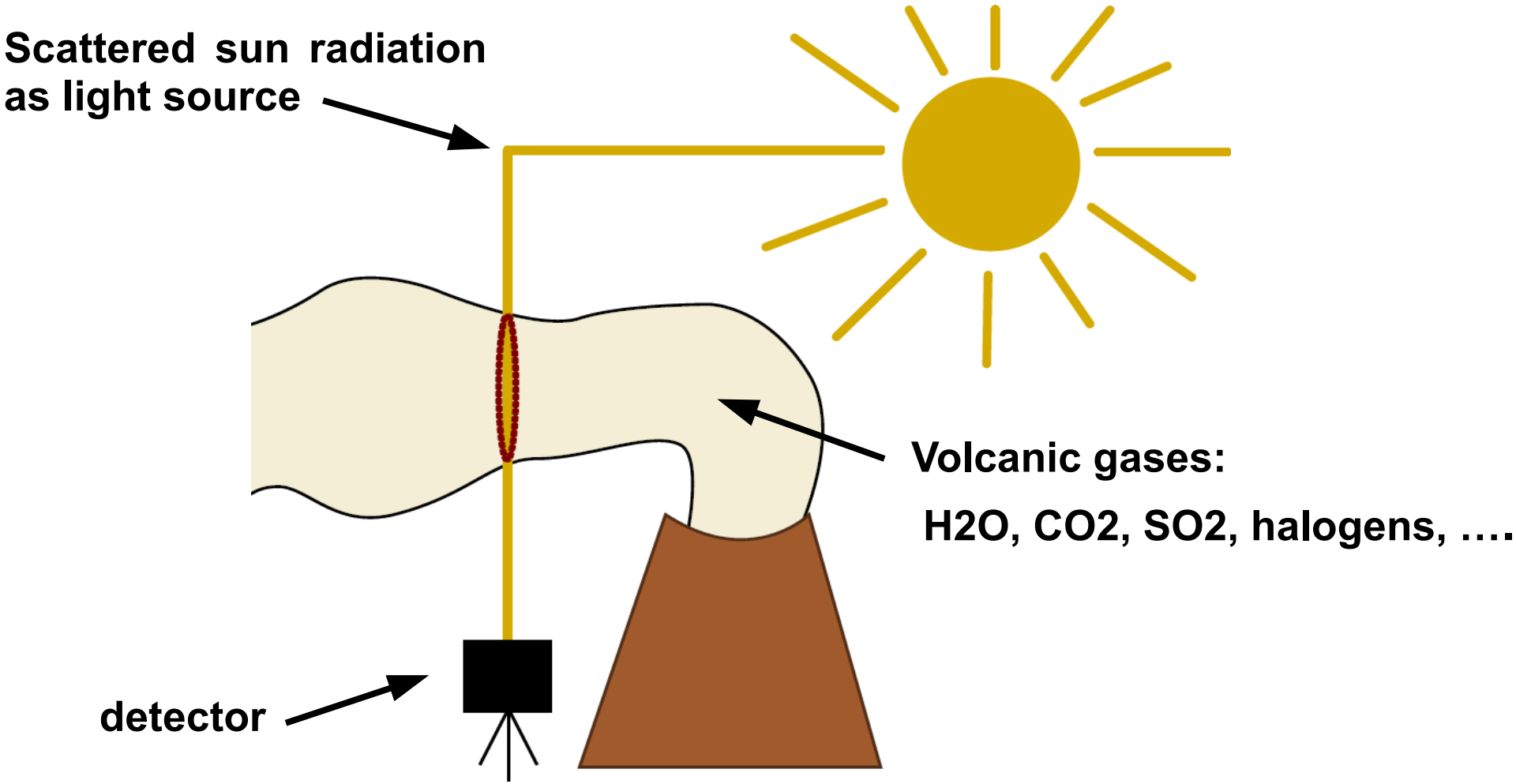
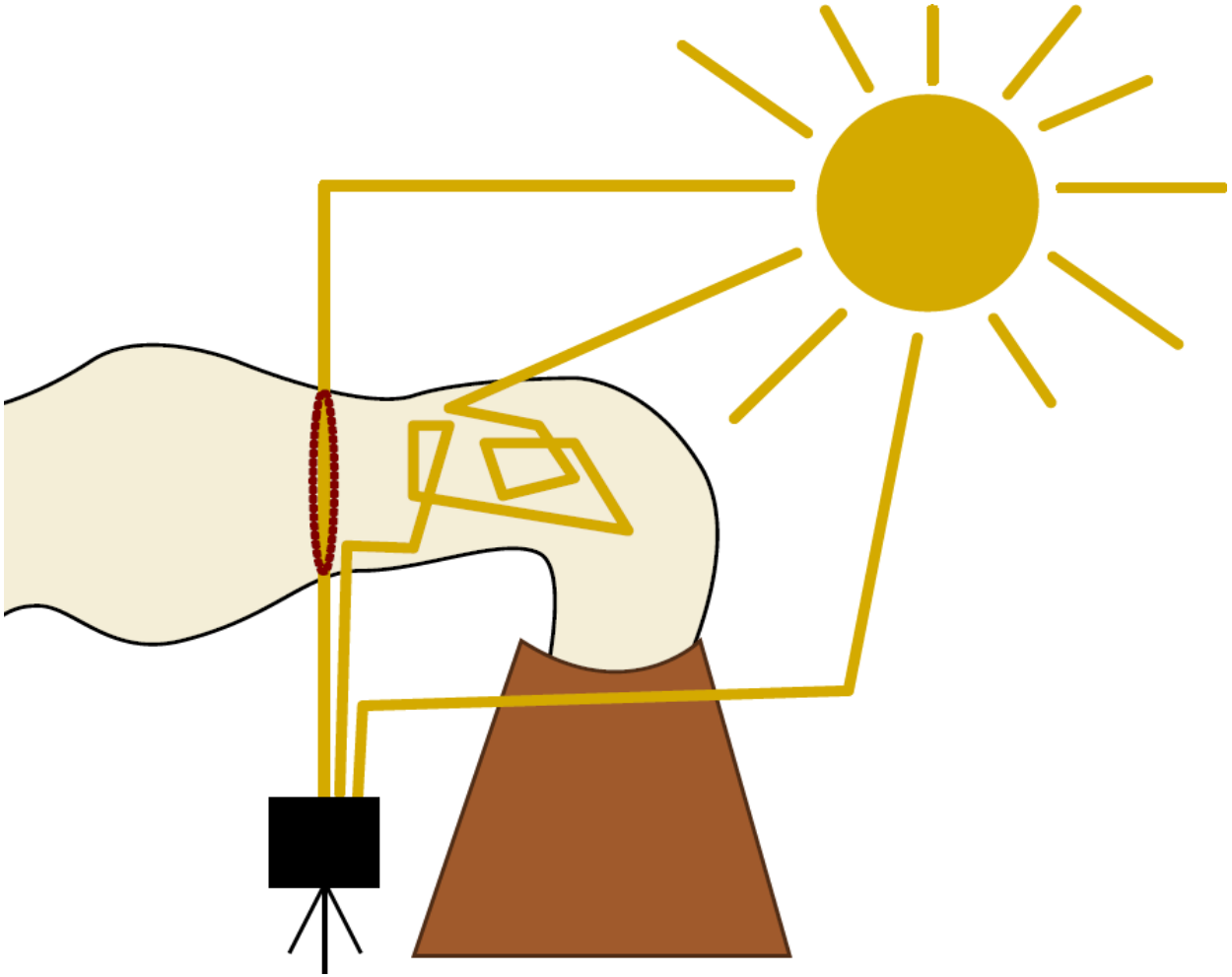
MAX-DOAS measurement



Simple Light Path Assumption



Radiative Transport



Radiative Transfer Theory

absorption and scattering coefficients

$$\frac{dI(\lambda)}{ds} = -(\epsilon_a(\lambda) + \epsilon_s(\lambda)) \cdot I(\lambda)$$

Lambert-Beer law

- attenuation by scattering and absorption

Radiative Transfer Theory

absorption and scattering coefficients

Lambert-Beer law

- attenuation by scattering and absorption

$$\frac{dI(\lambda)}{ds} = -(\epsilon_a(\lambda) + \epsilon_s(\lambda)) \cdot I(\lambda)$$

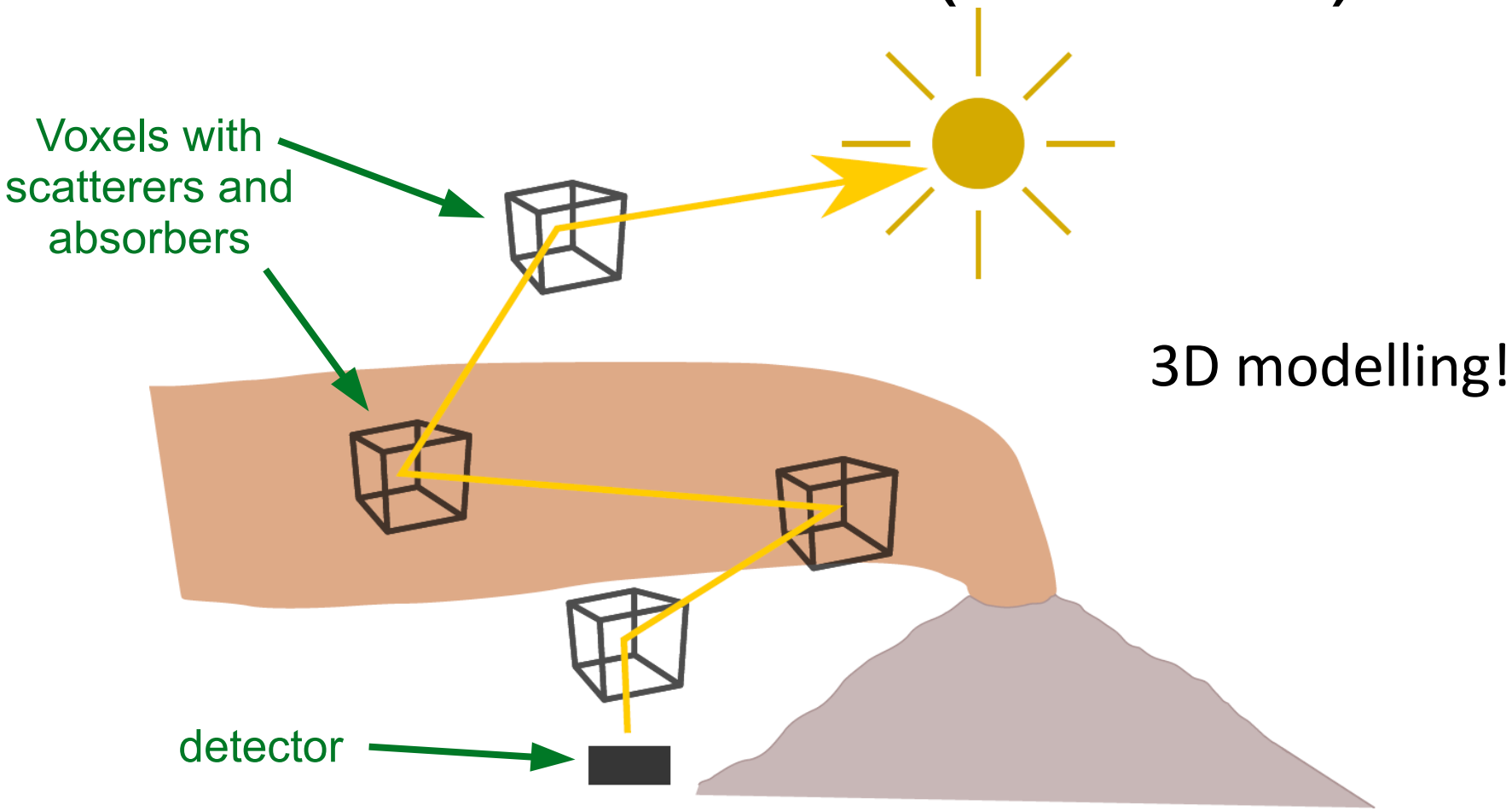
$$+ \epsilon_s(\lambda) \cdot \int_0^{\pi} \int_0^{2\pi} I^*(\lambda, \vartheta^*, \phi^*) \cdot \frac{S(\vartheta^*, \phi^*)}{4\pi} d\phi^* \cdot sin(\vartheta^*) d\vartheta^*$$

dimensionless scattering function

scattering into light path

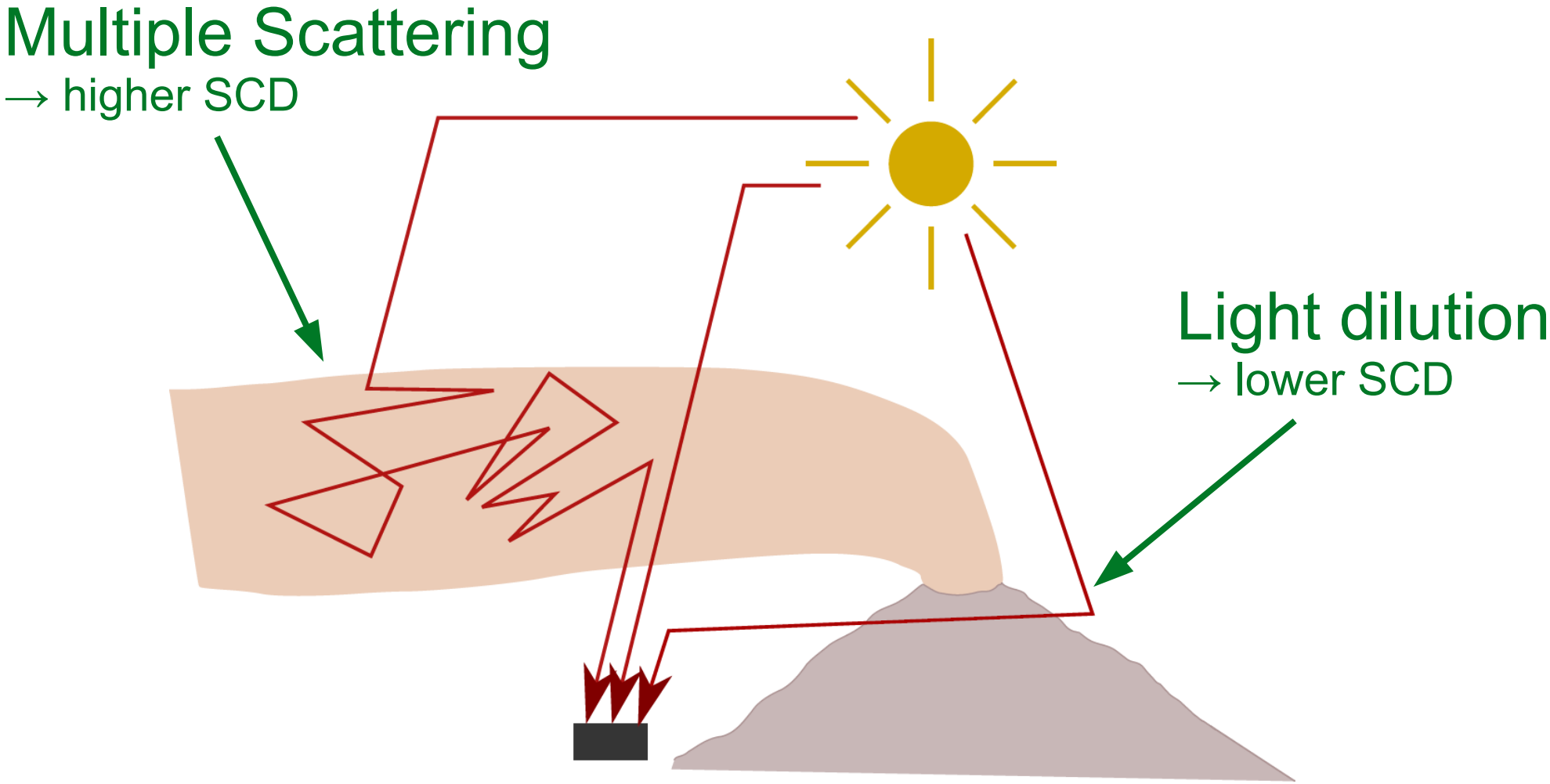
- Non-linear → only **numerically solvable**, inverse modelling

Monte Carlo Atmospheric Radiative Transfer Model (McArtim)



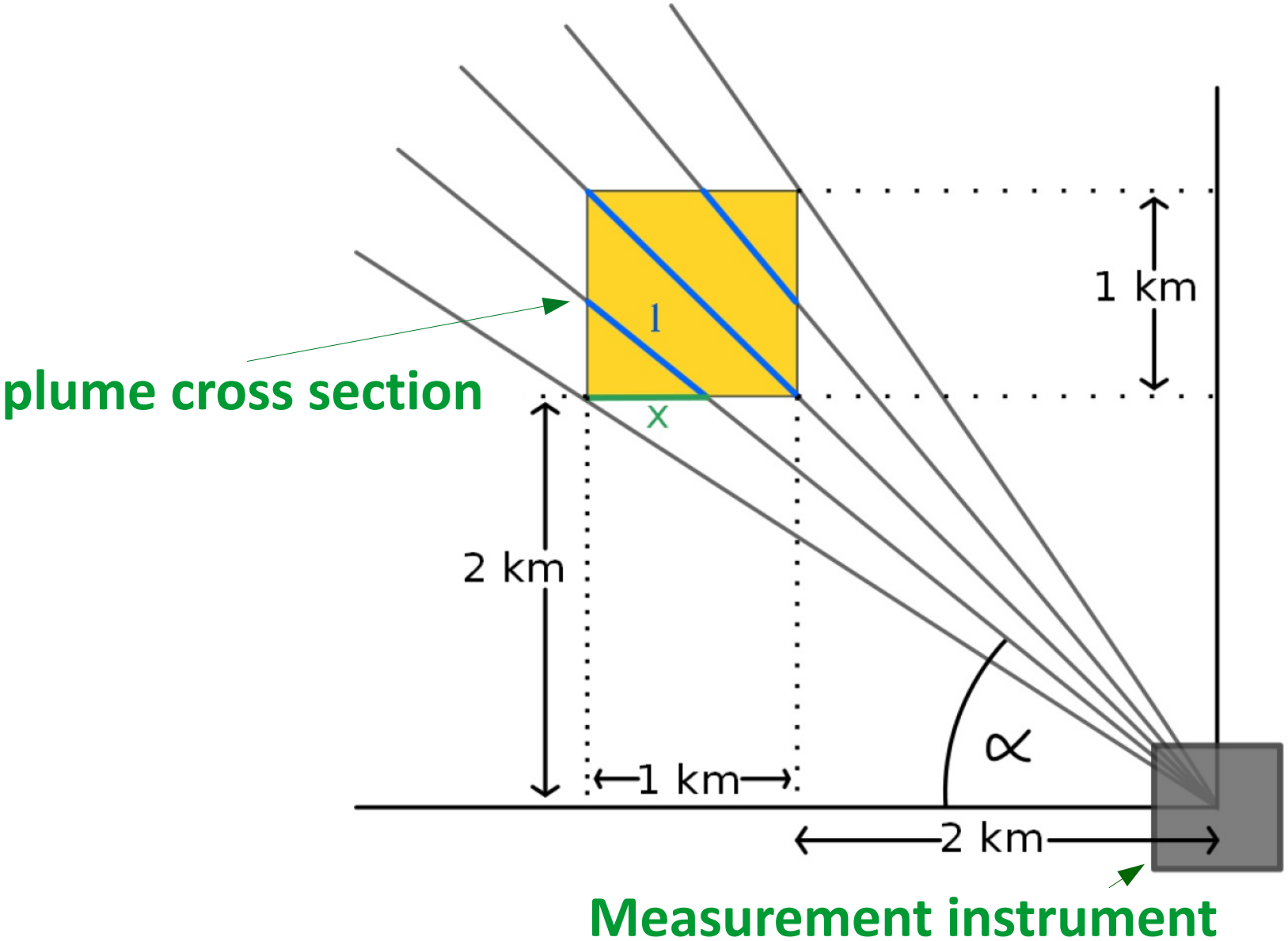
McArtim : *T. Deutschmann et al.:* ***The Monte Carlo atmospheric radiative transfer model McArtim: Introduction and validation of Jacobians and 3D features****. Journal of Quantitative Spectroscopy and Radiative Transfer, 112, 2011.*

Complications for RT in volcanic plumes



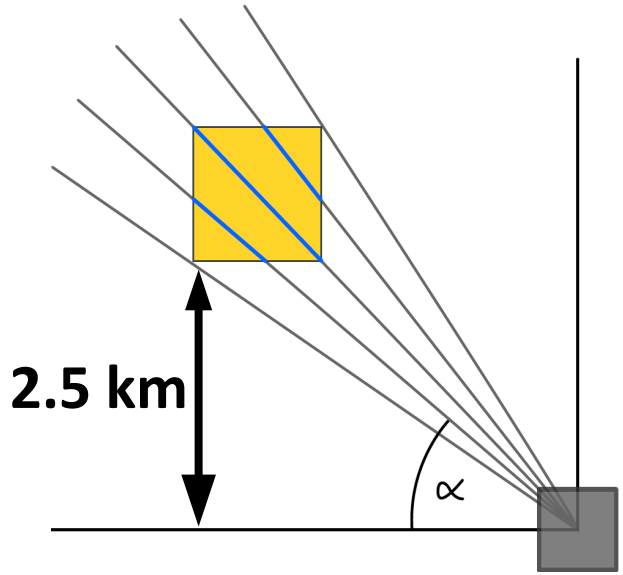
- Also, light path shortening due to high absorber load

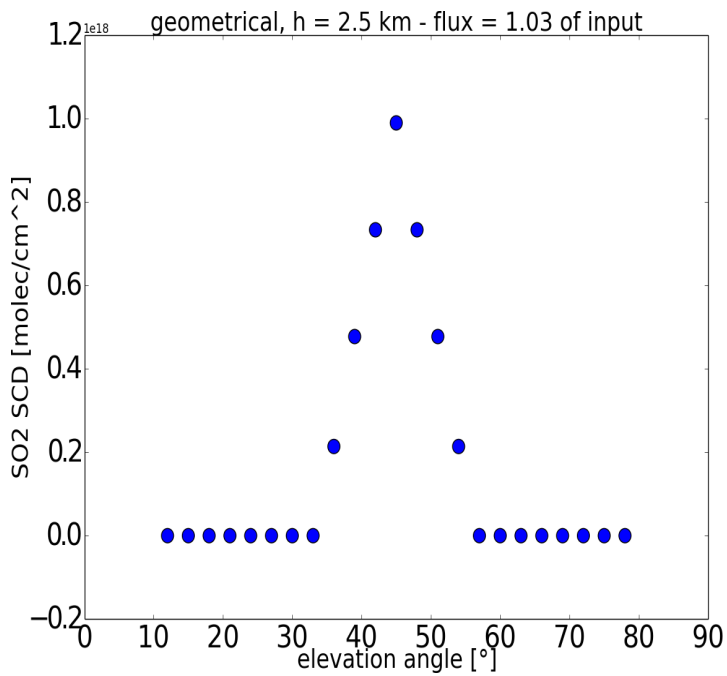
Examining a simple Plume



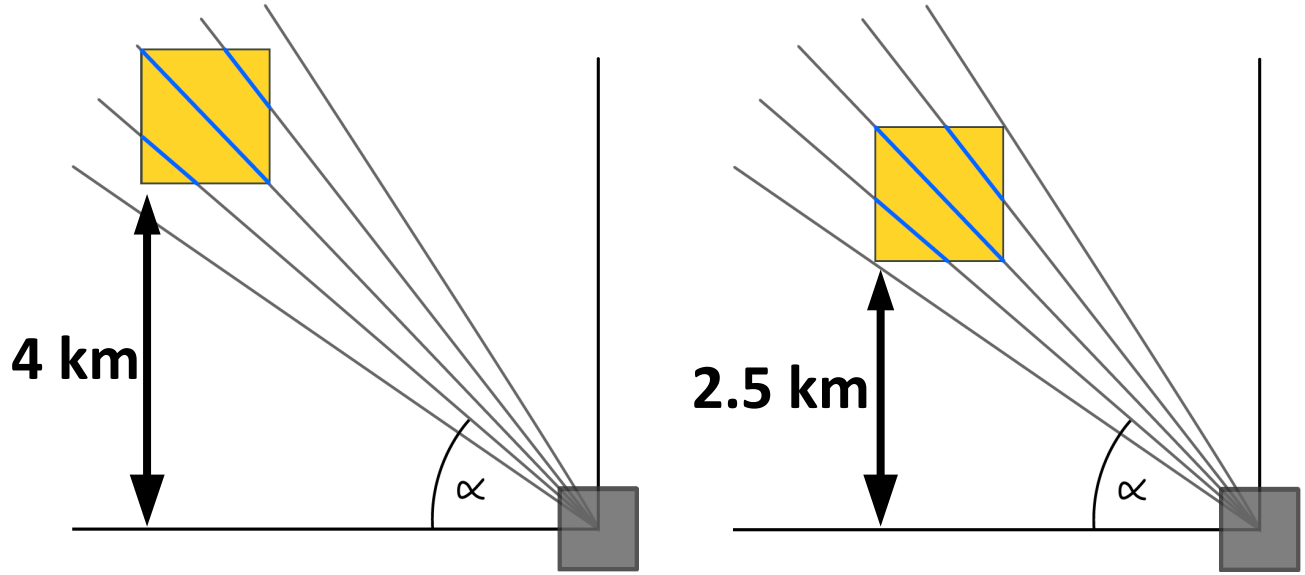
Plume extends several km perpendicular to image

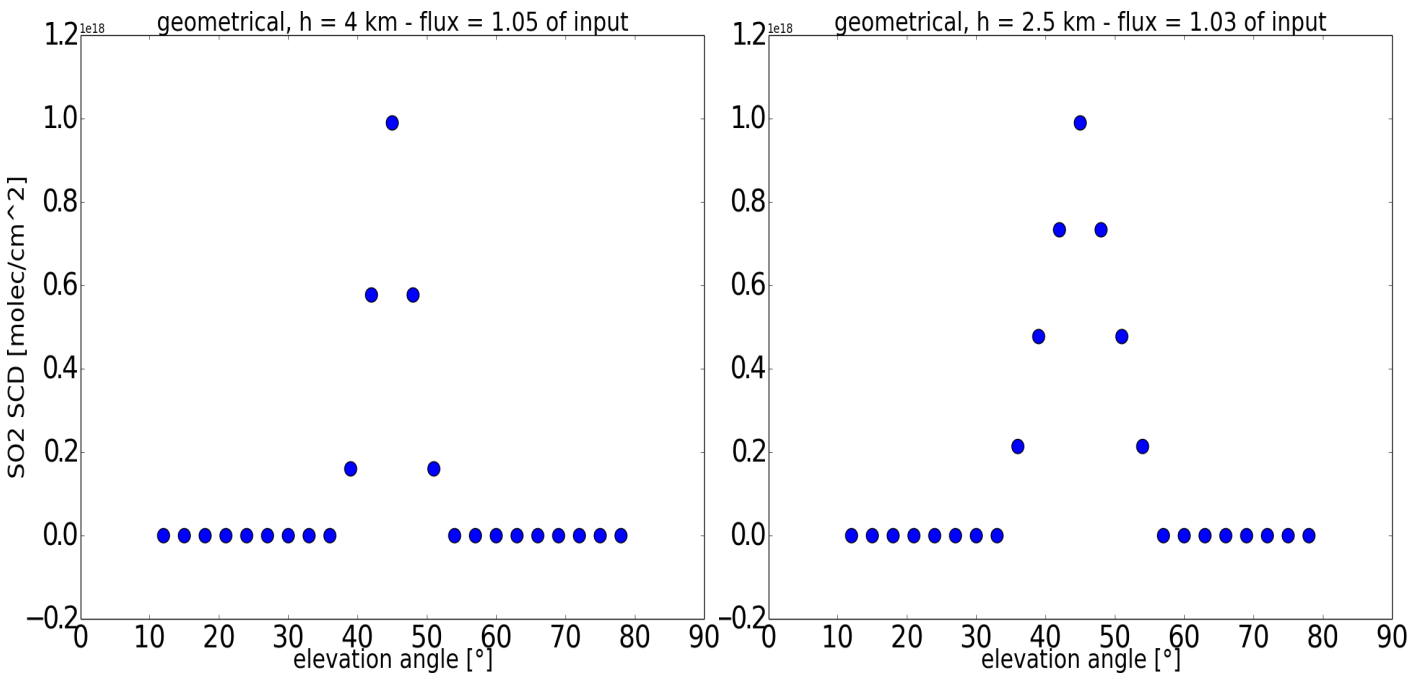
Geometrical considerations



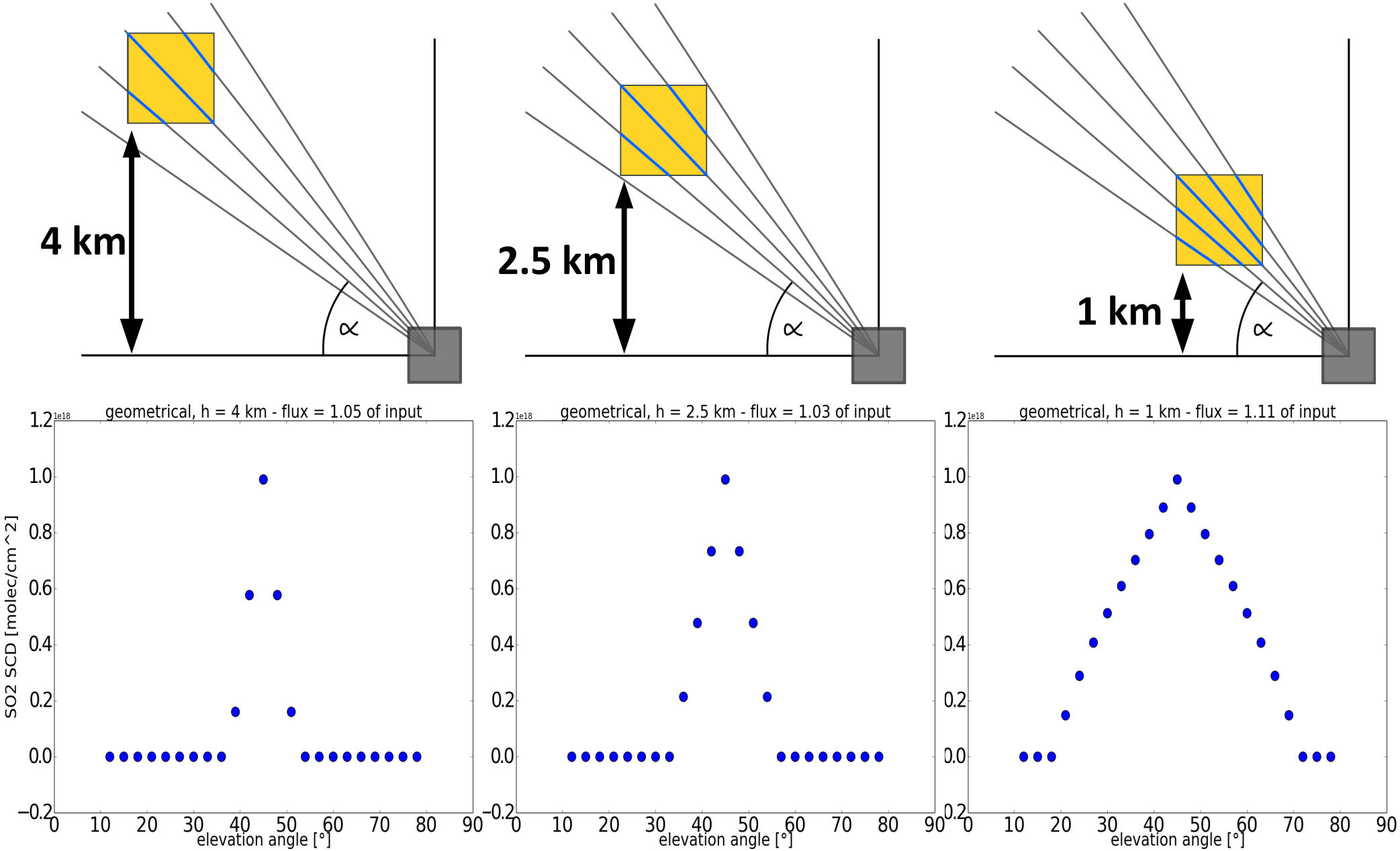


Geometrical considerations

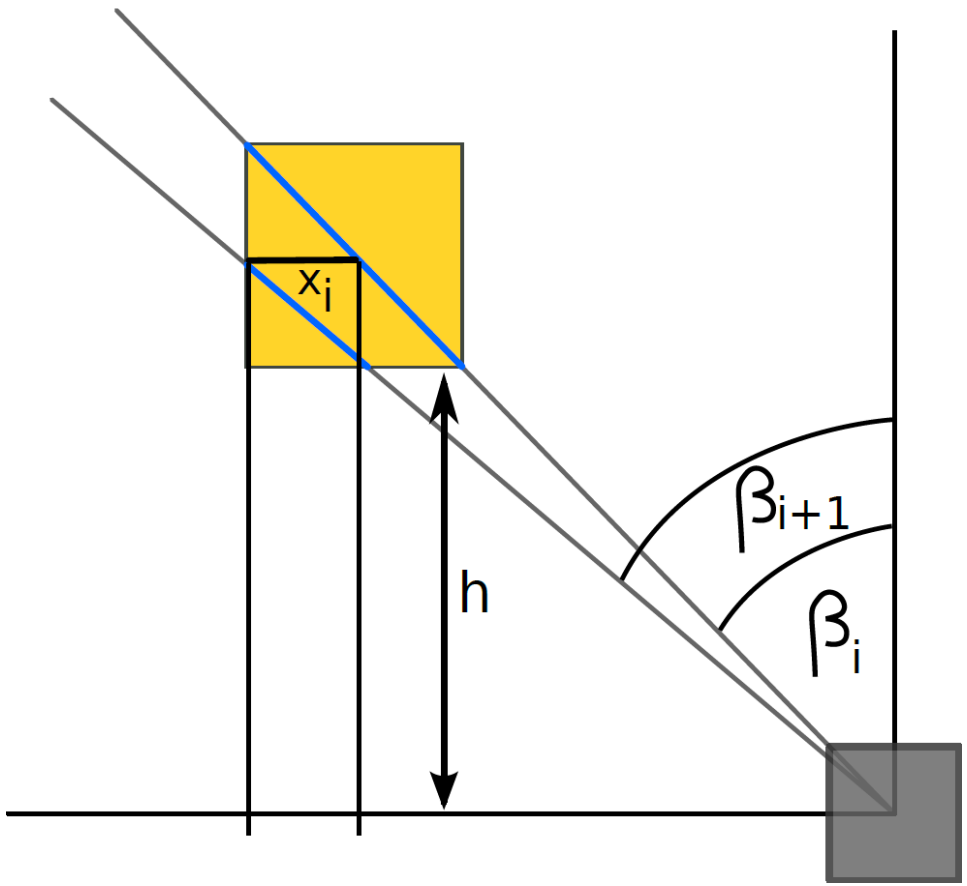




Geometrical considerations



From Scan to Flux (as done in NOVAC)

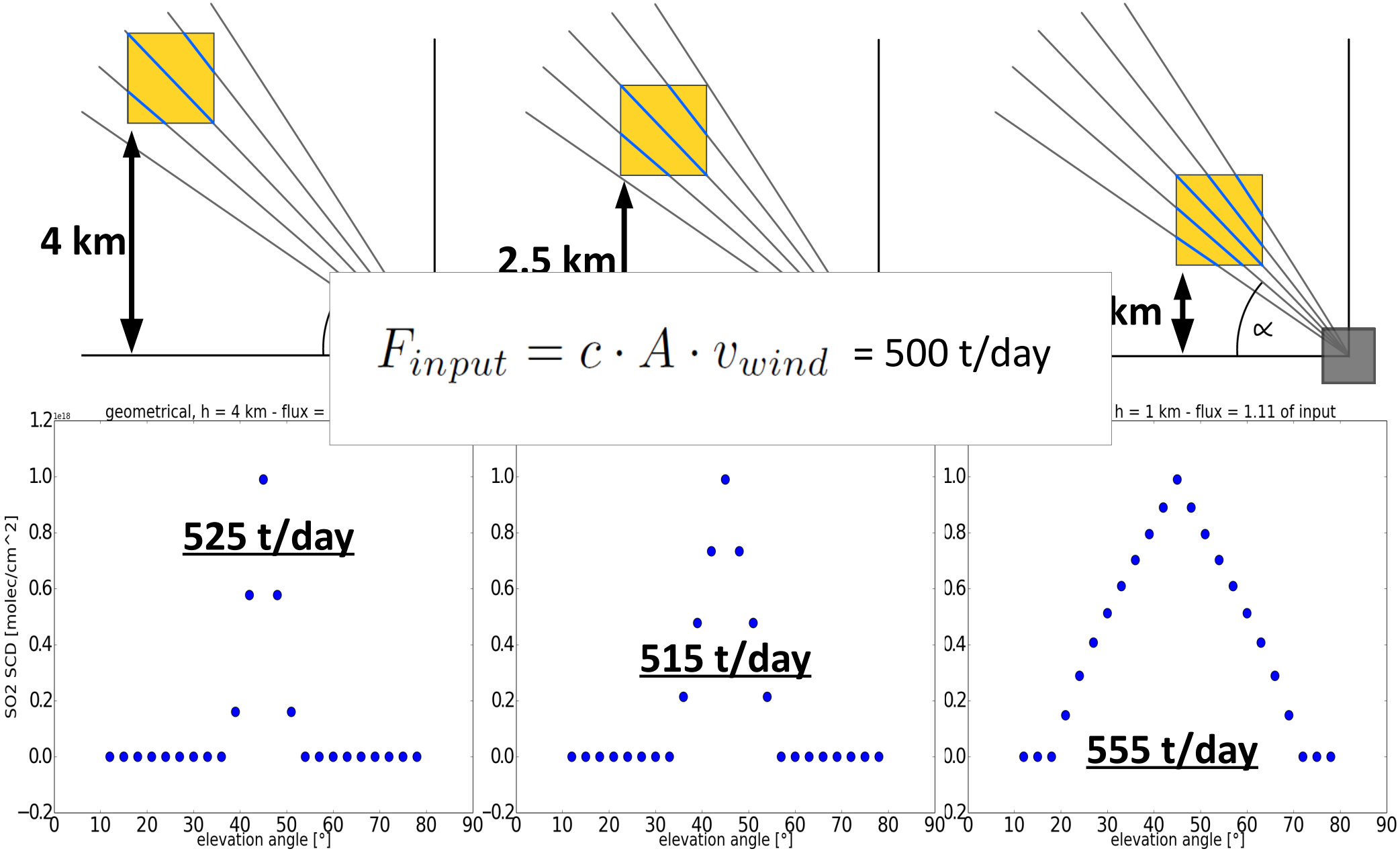


$$x_i = h \cdot (tan(\beta_i) - tan(\beta_{i+1}))$$

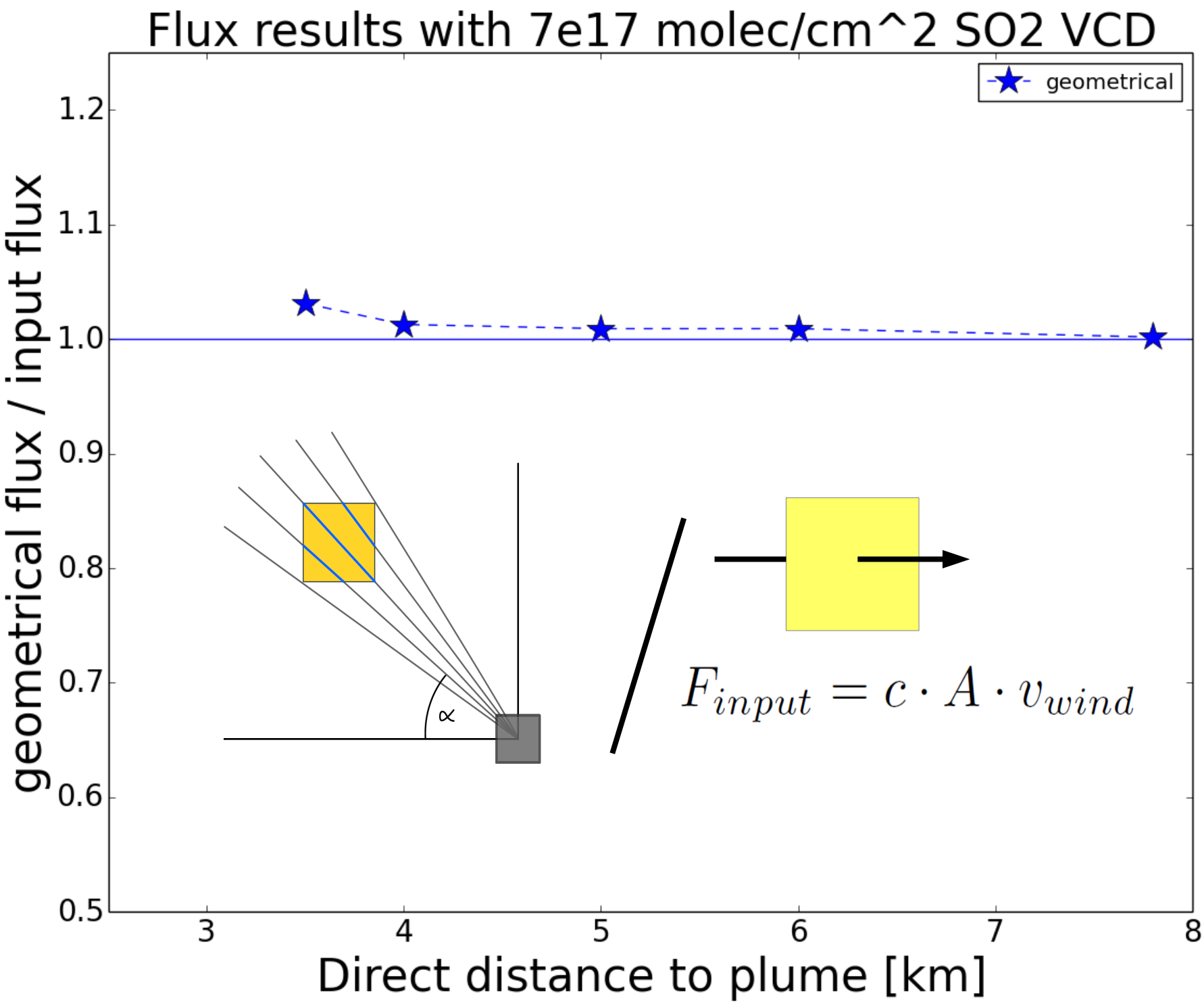
$$S_{corr} = x_i \cdot \frac{S_i \cdot cos(\beta_i) + S_{i+1} \cdot cos(\beta_{i+1})}{2}$$

→ high emphasis on signal seen at low angles
(problem is known and being worked on)

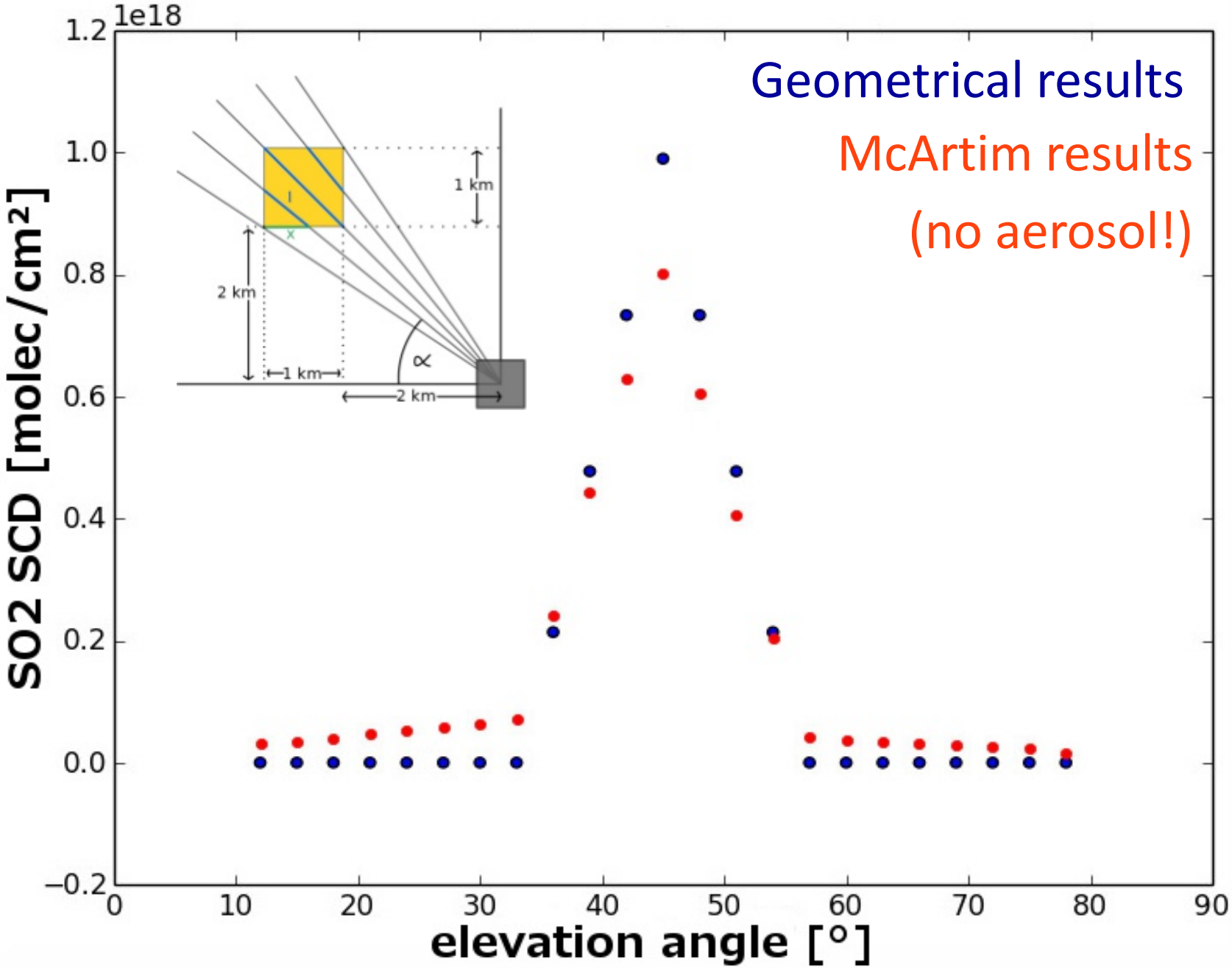
Geometrical considerations



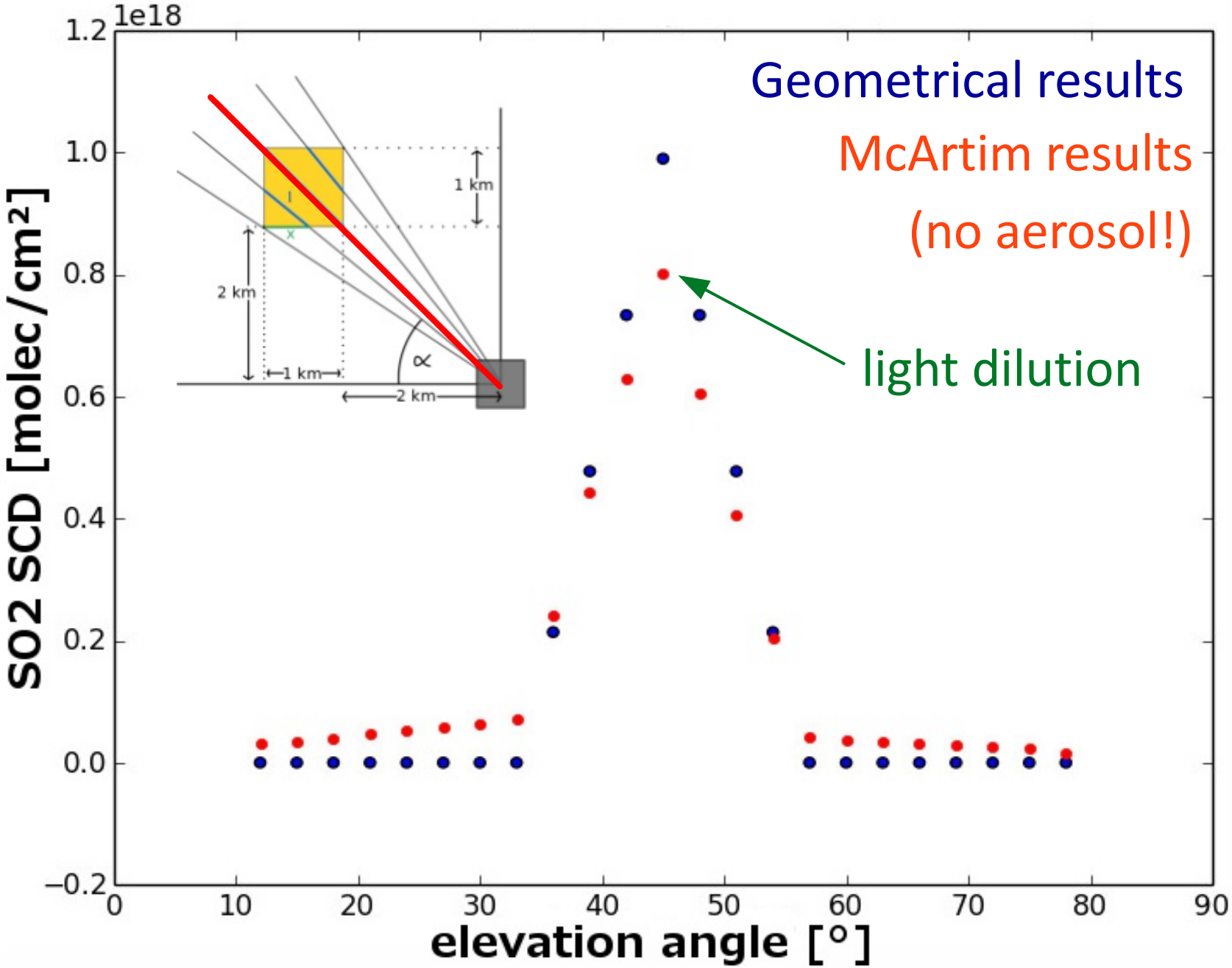
$$F_{input} = c \cdot A \cdot v_{wind} = 500 \text{ t/day}$$


Flux results with 7e17 molec/cm^2 SO2 VCD
geometrical
geometrical flux / input flux
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
3
4
5
6
7
8
Direct distance to plume [km]
∝
$F_{input} = c \cdot A \cdot v_{wind}$

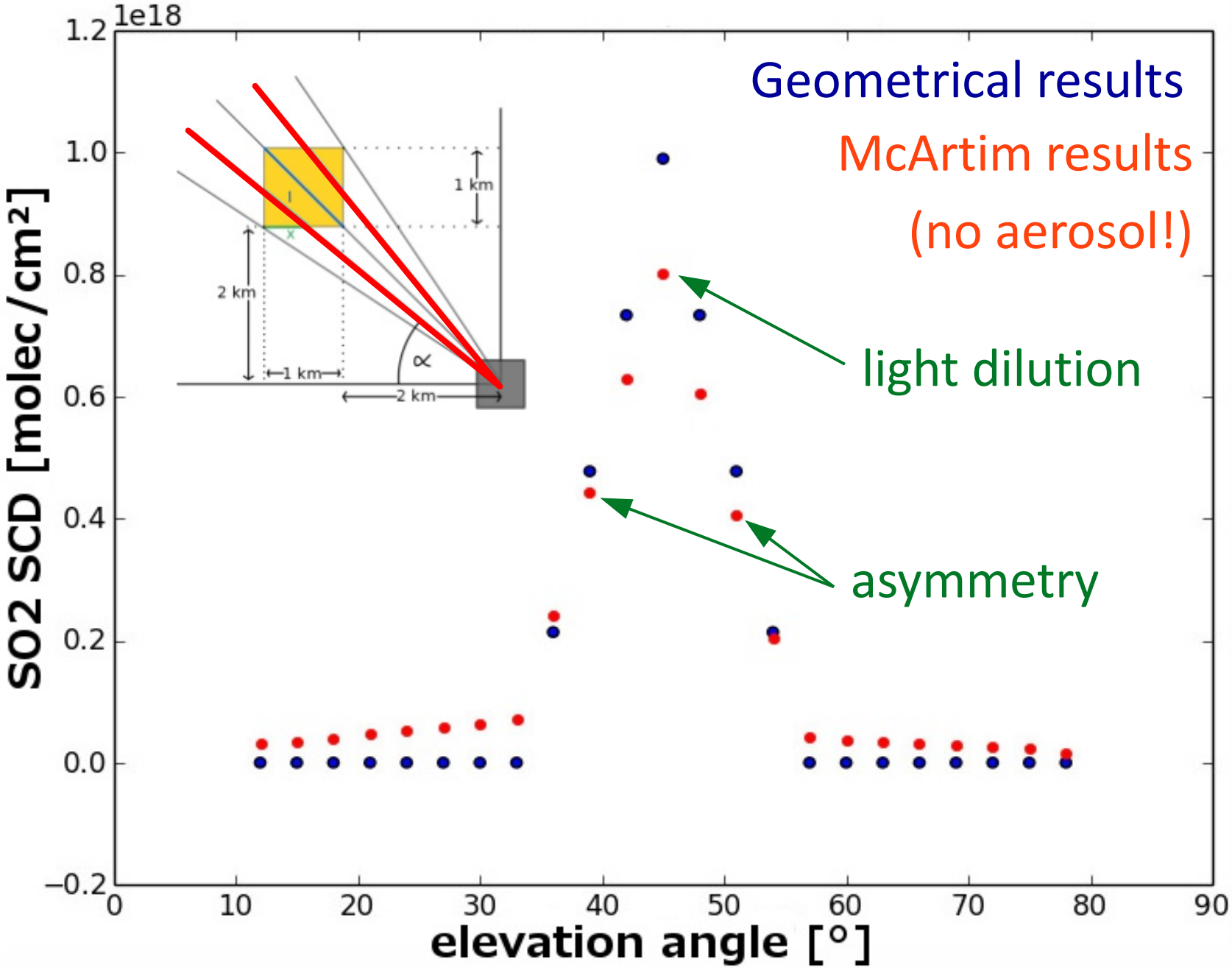
Examining a simple Plume



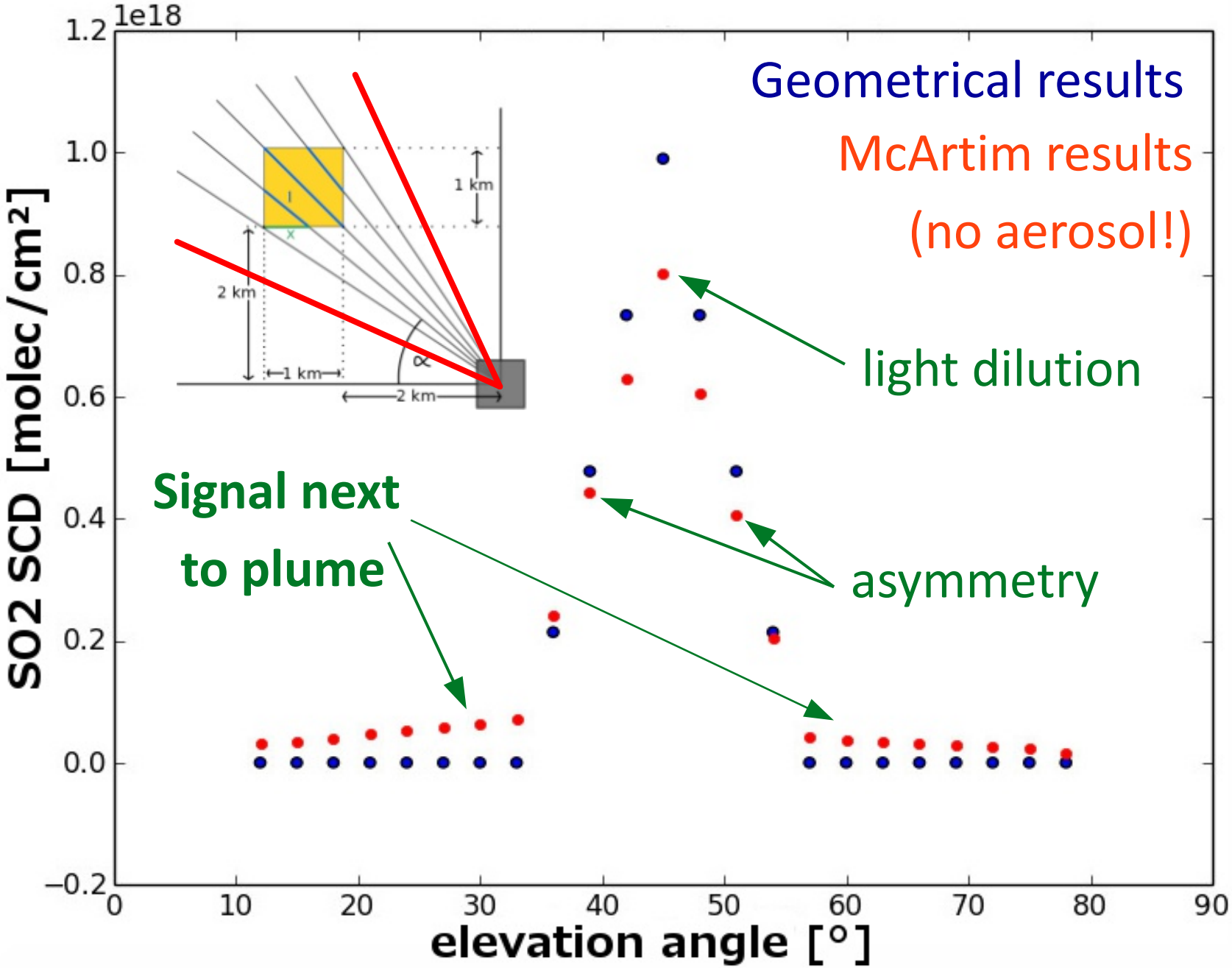
Examining a simple Plume



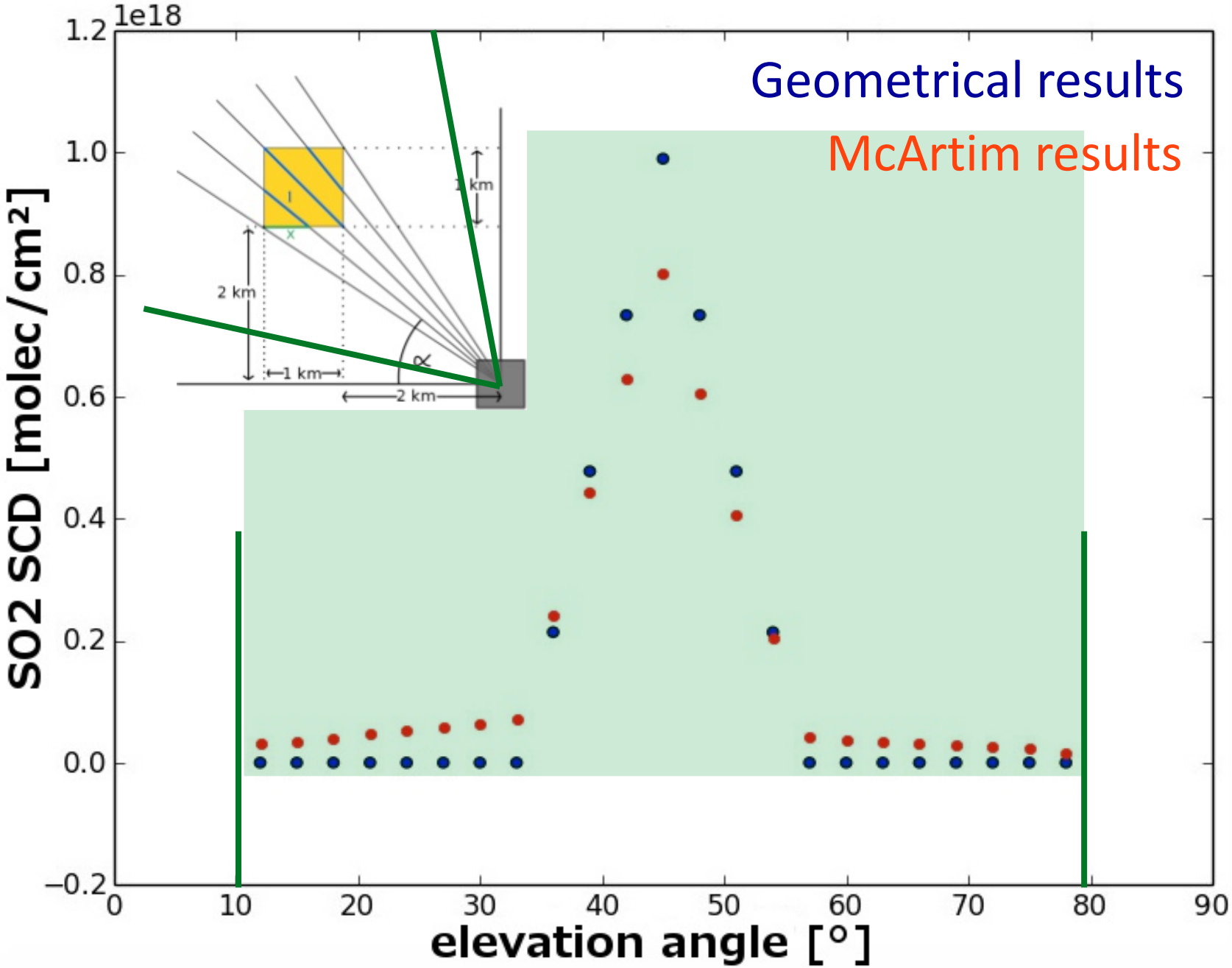
Examining a simple Plume

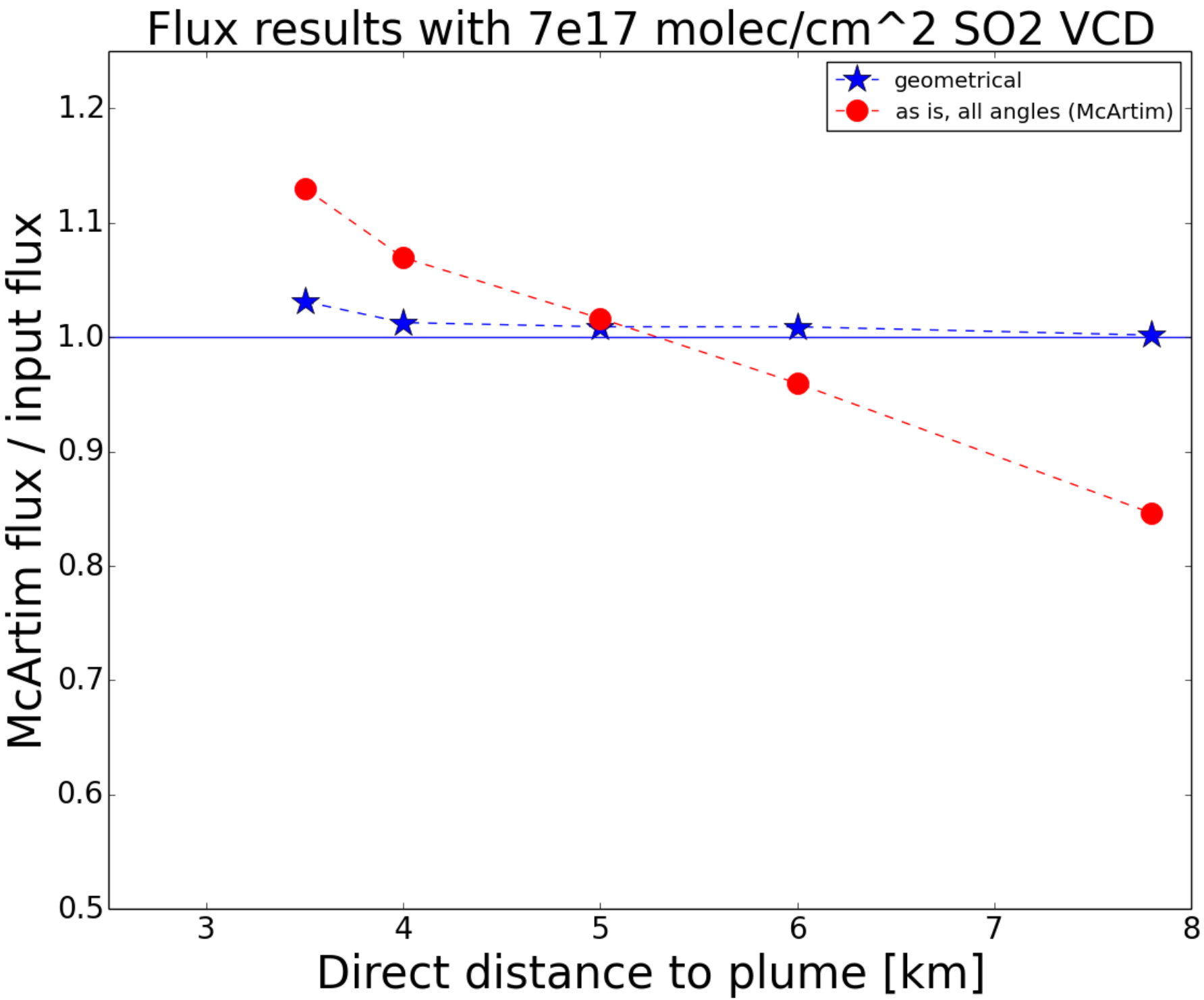


Examining a simple Plume

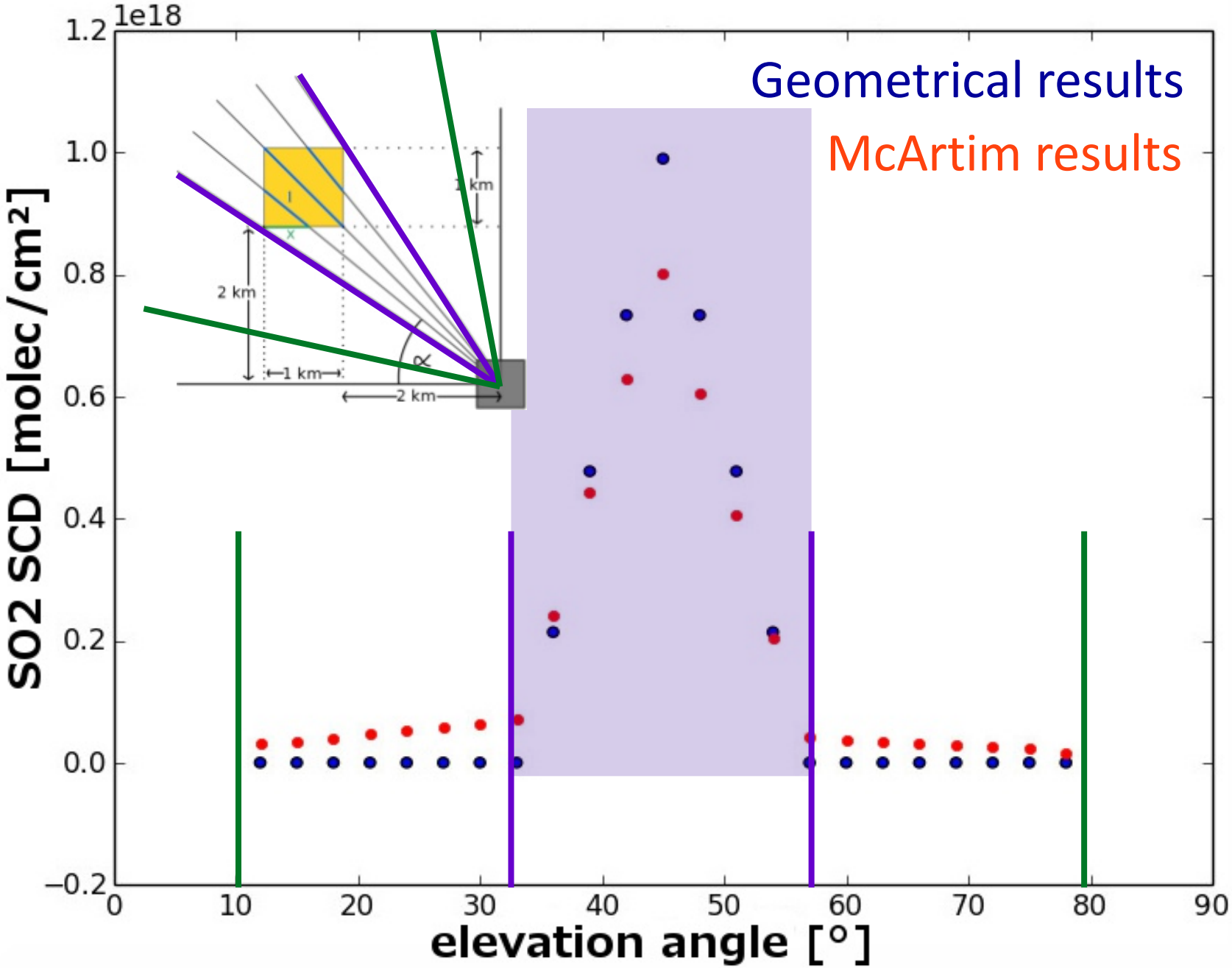


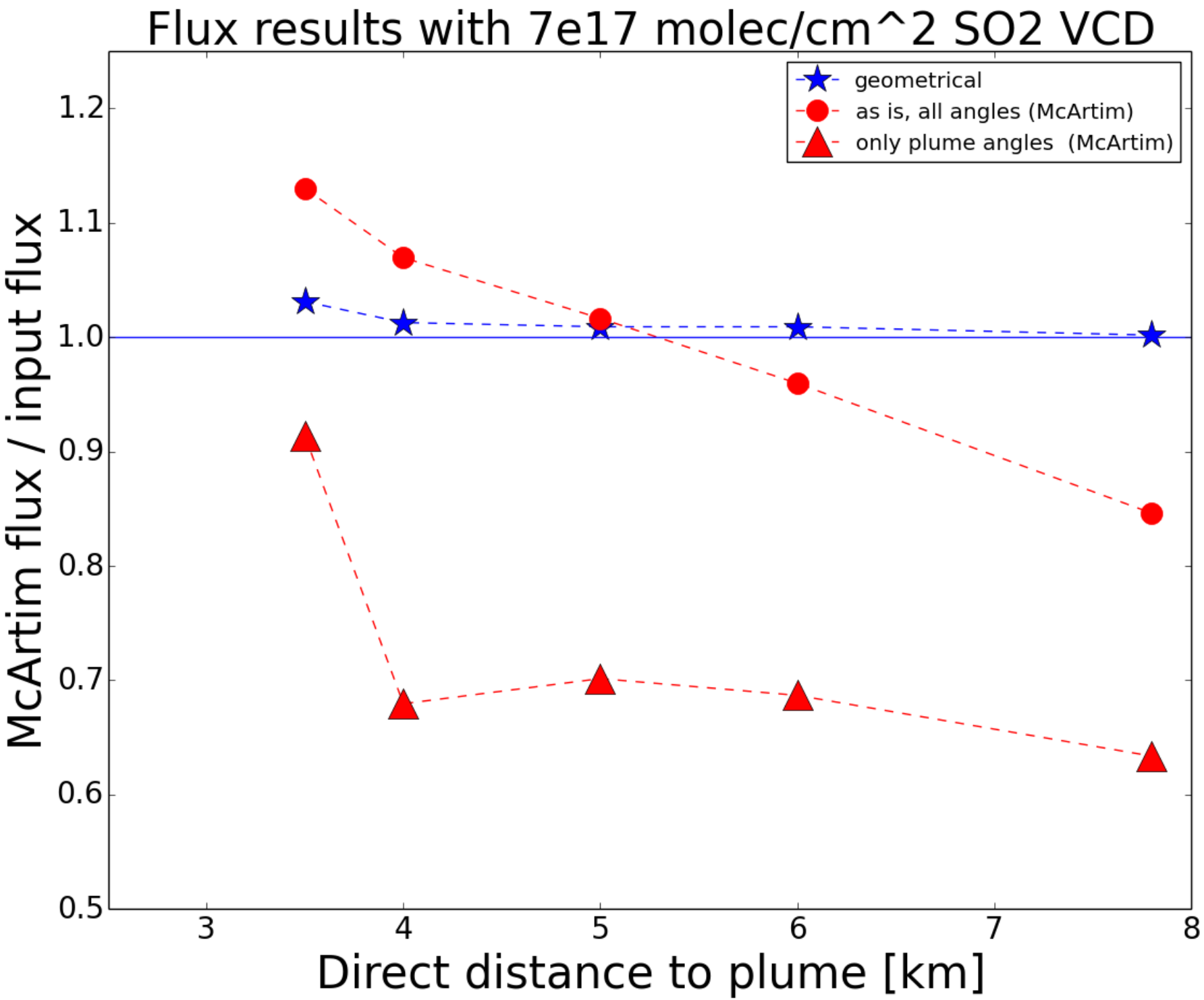
Choosing the Evaluation Region



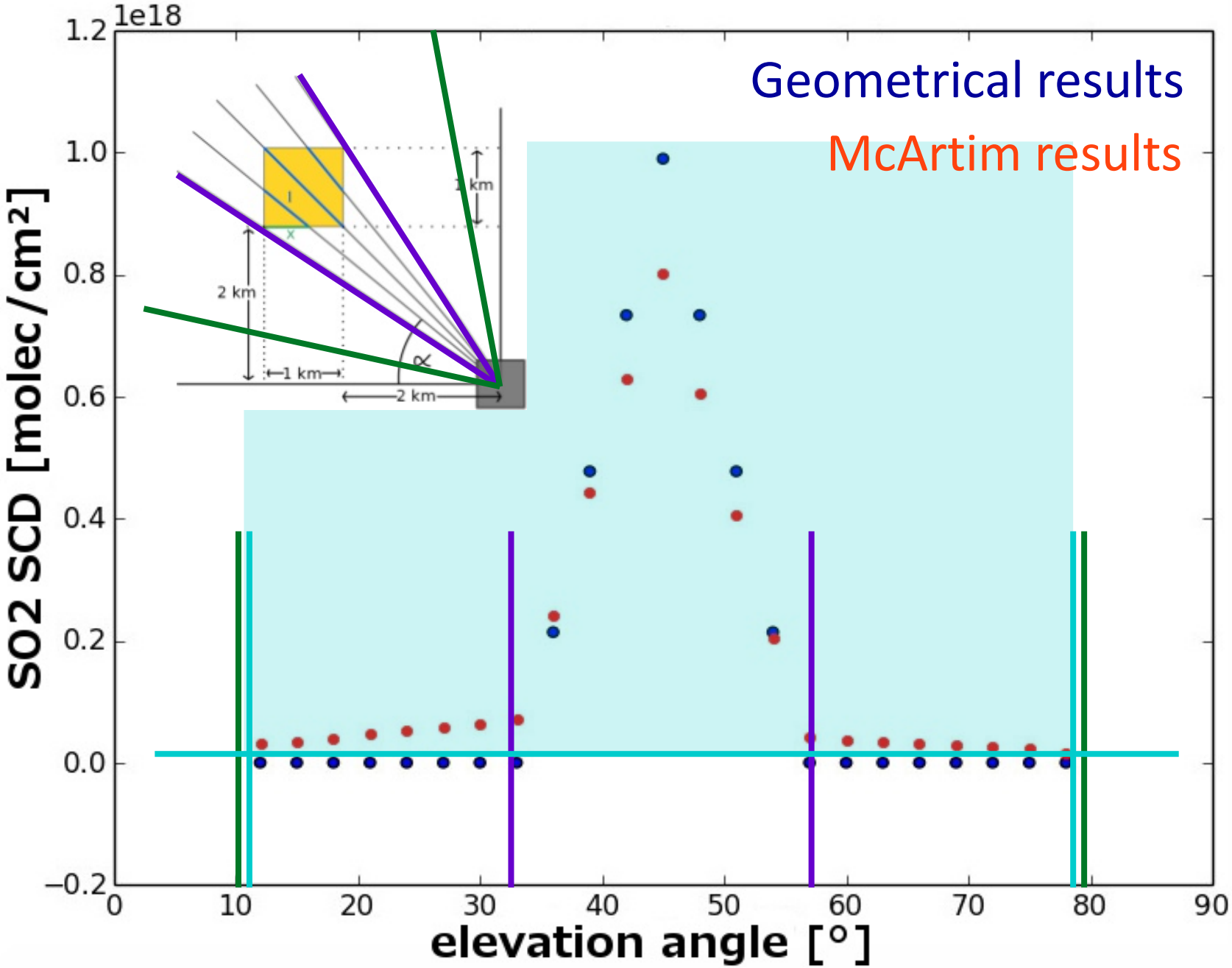

Flux results with 7e17 molec/cm^2 SO2 VCD
geometrical
as is, all angles (McArtim)
McArtim flux / input flux
Direct distance to plume [km]
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
3
4
5
6
7
8

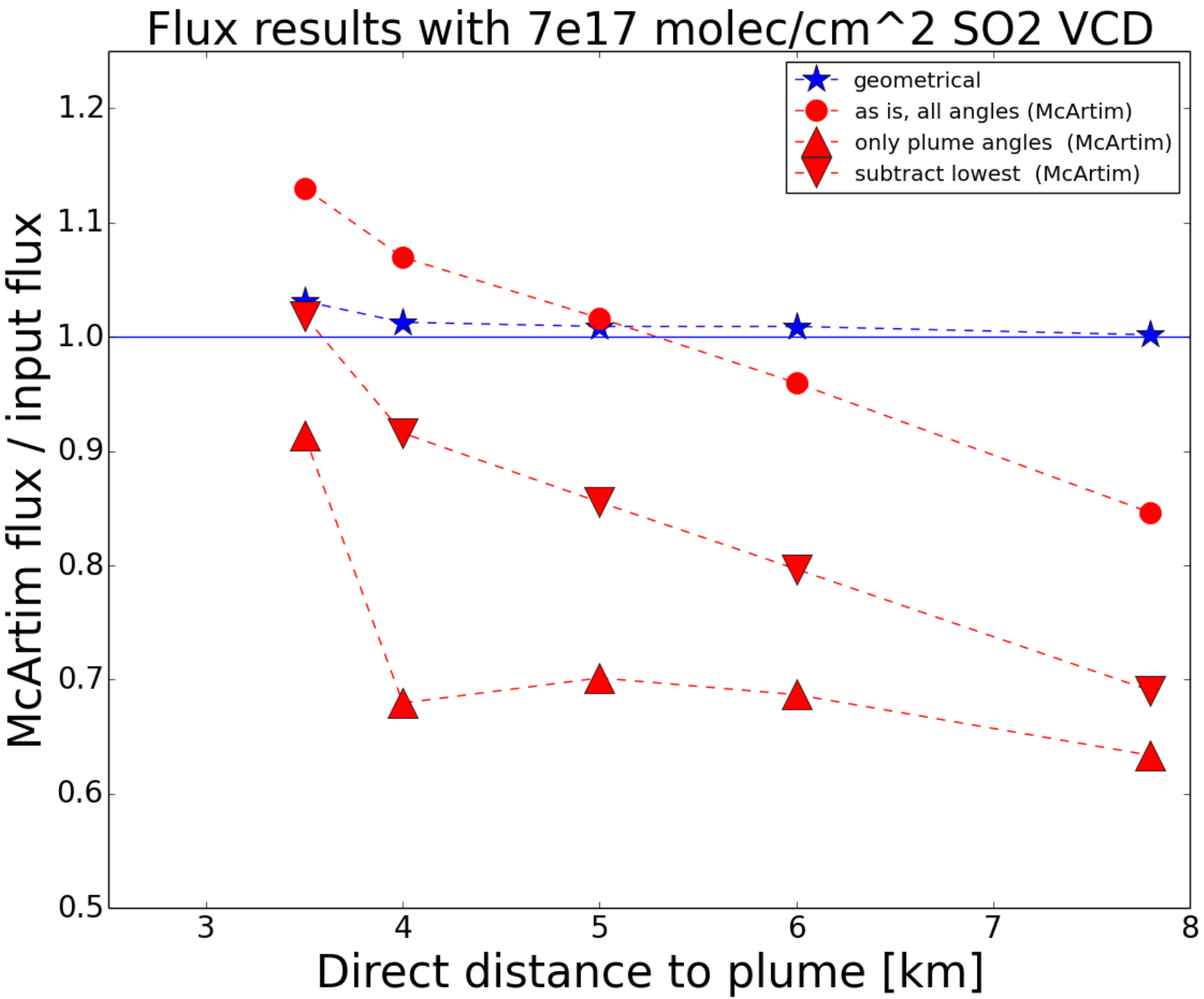
Choosing the Evaluation Region



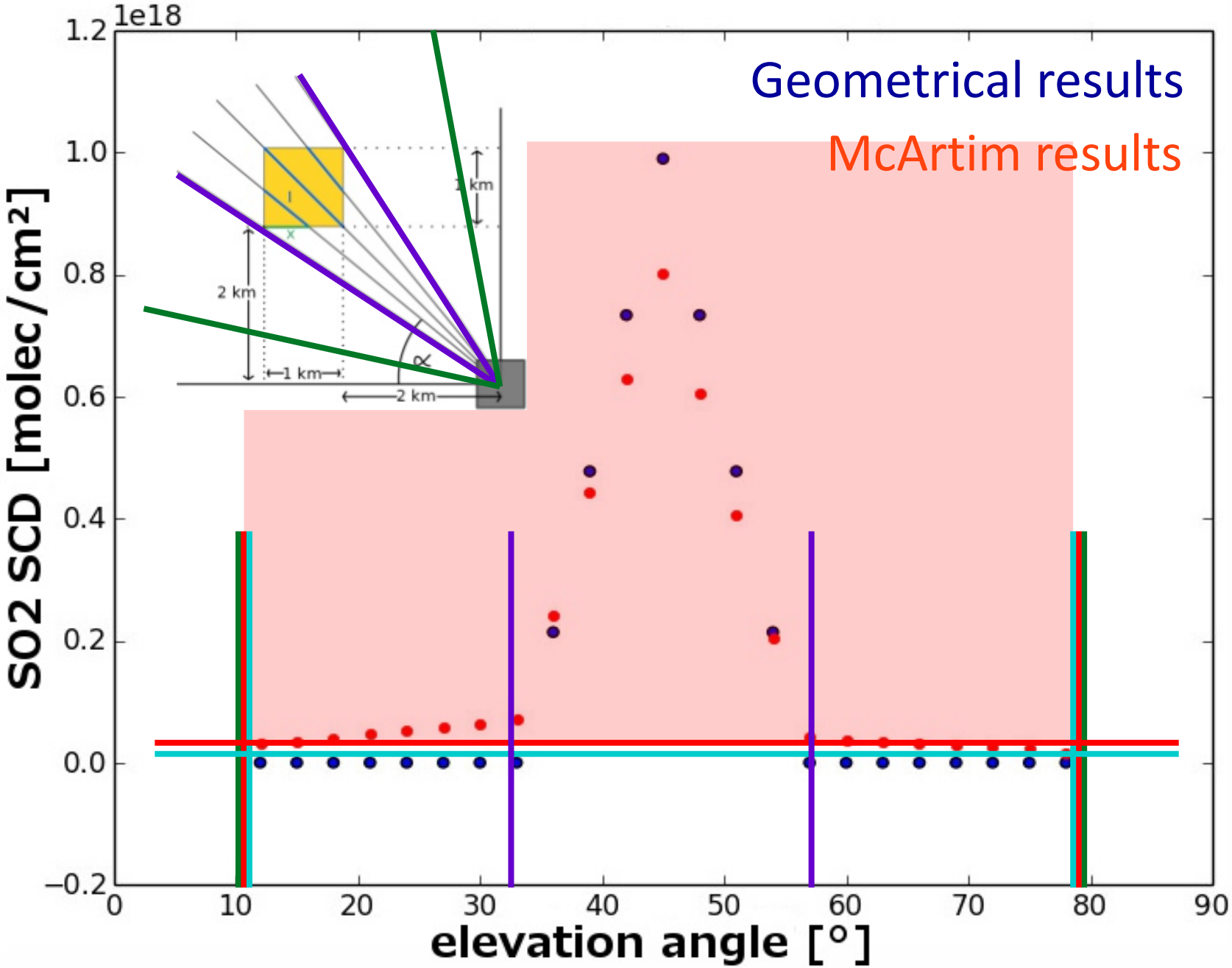

Flux results with 7e17 molec/cm^2 SO2 VCD
geometrical
as is, all angles (McArtim)
only plume angles (McArtim)
McArtim flux / input flux
Direct distance to plume [km]
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
3
4
5
6
7
8

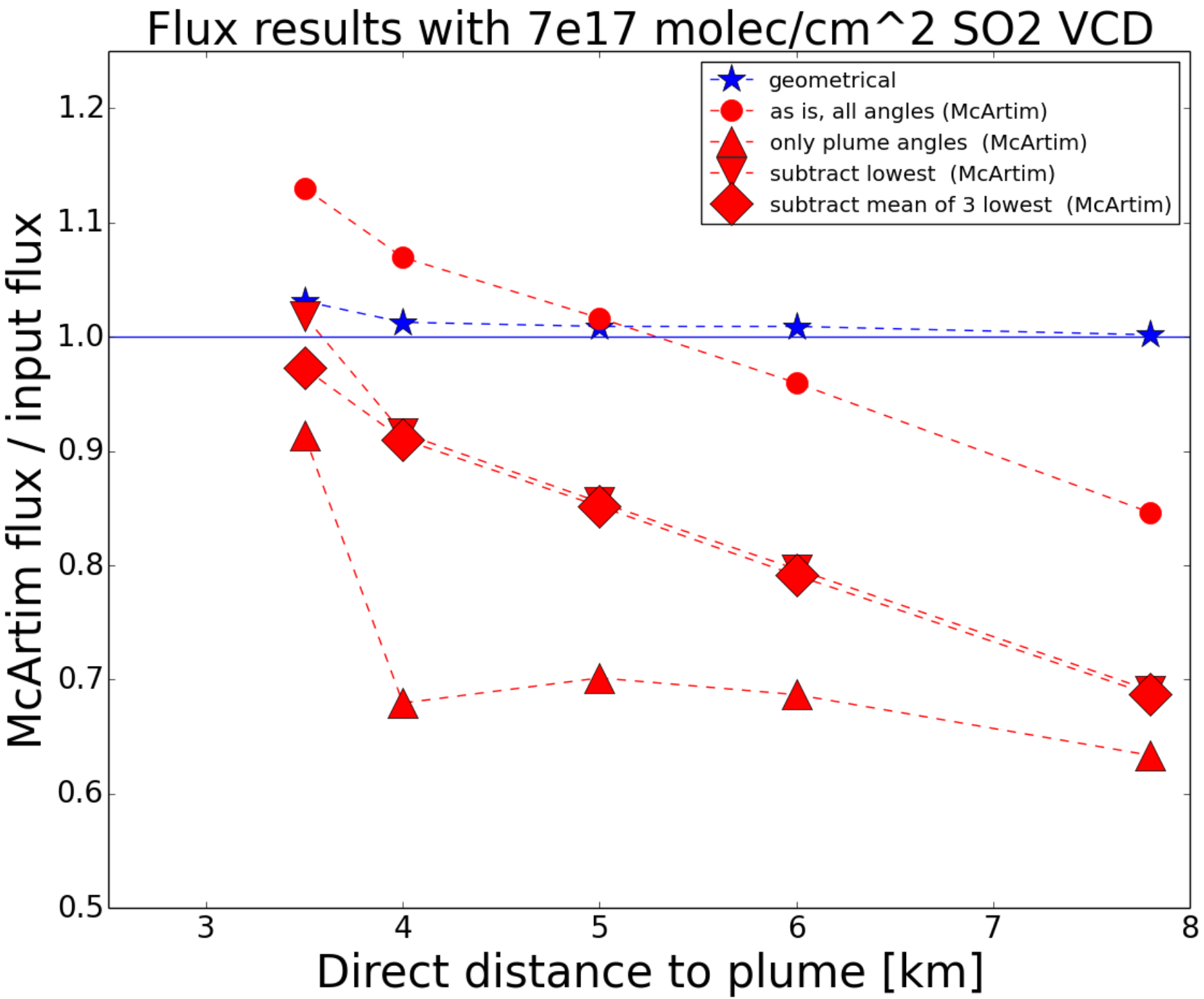
Choosing the Evaluation Region

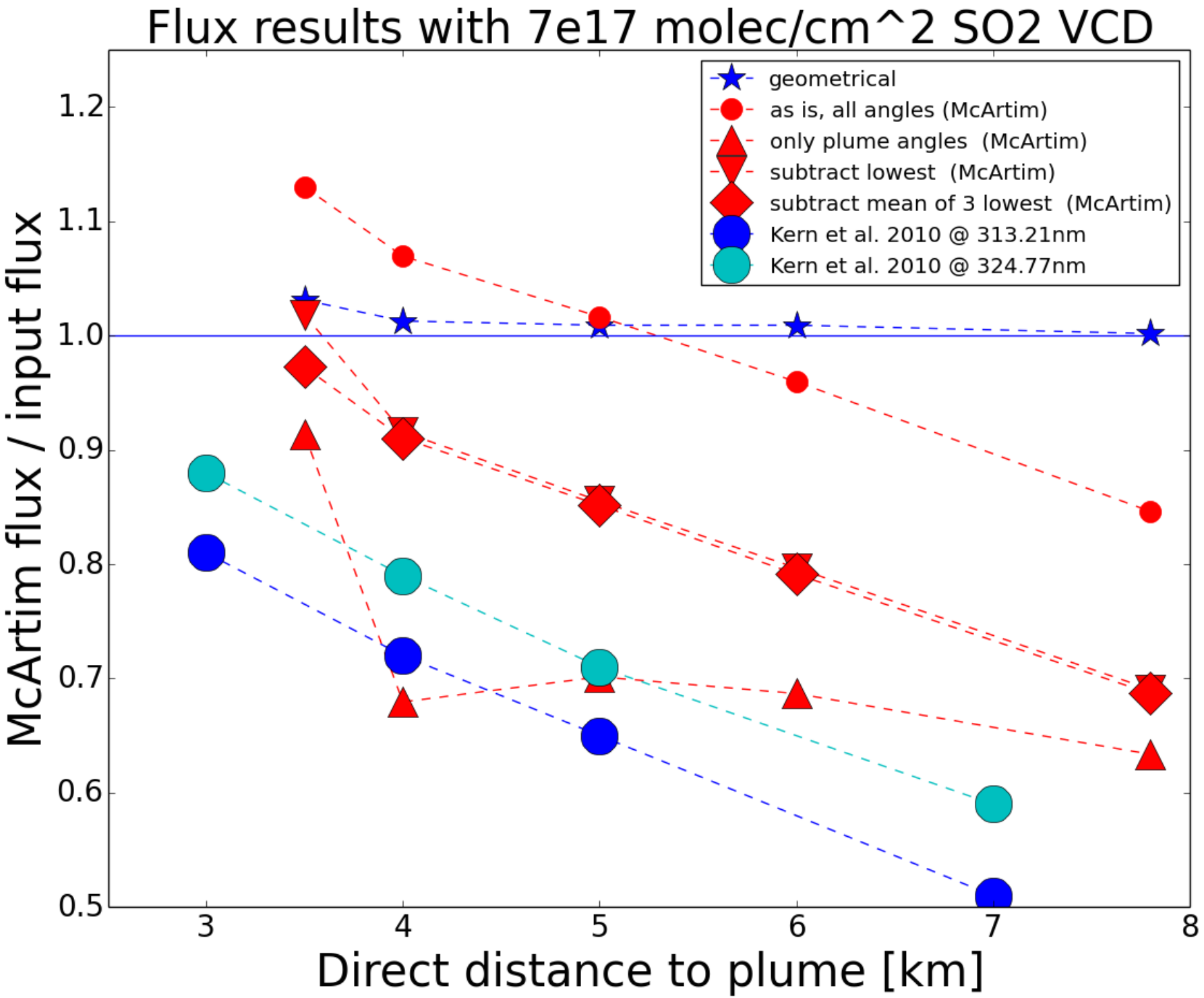


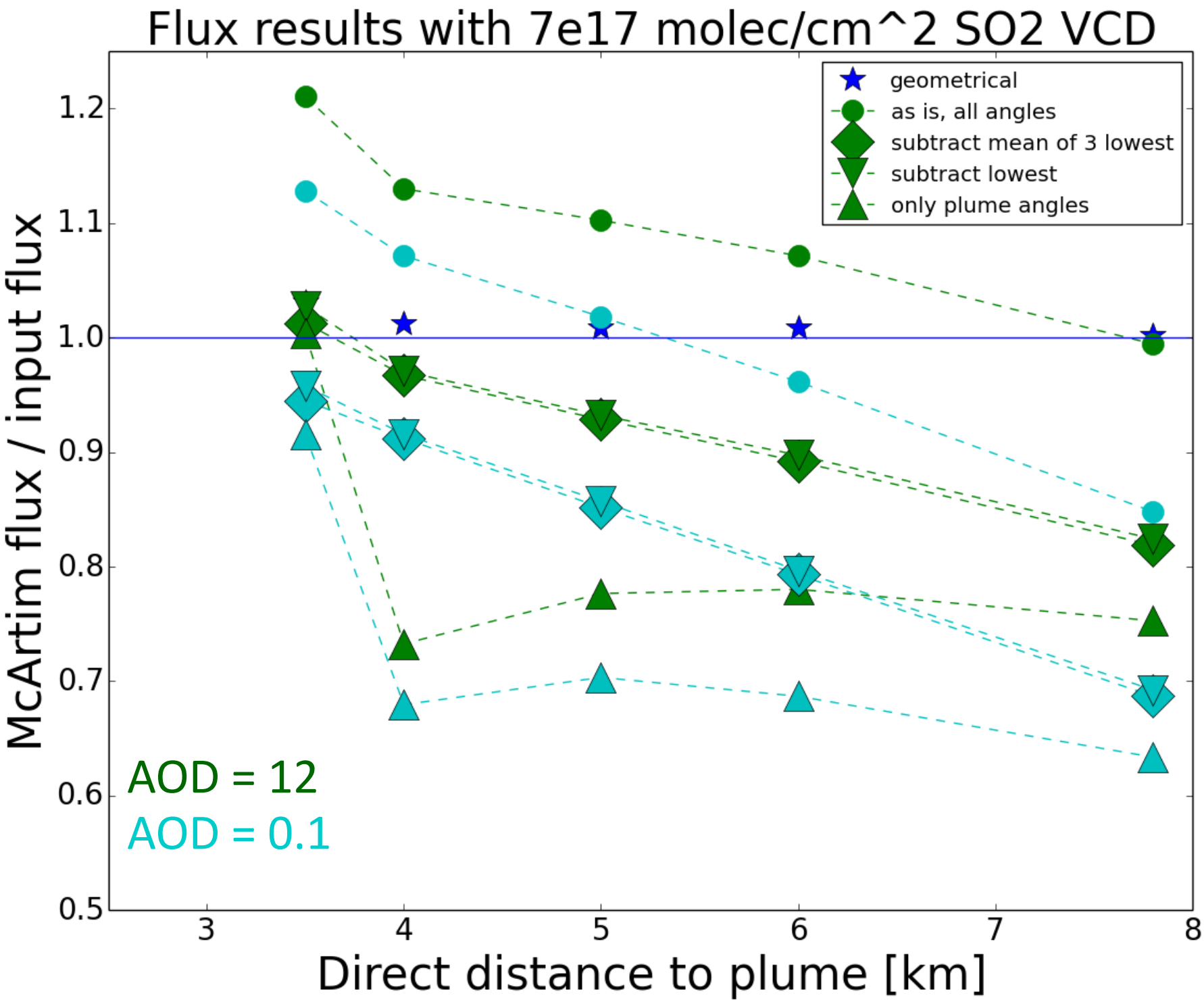

Flux results with 7e17 molec/cm^2 SO2 VCD
geometrical
as is, all angles (McArtim)
only plume angles (McArtim)
subtract lowest (McArtim)
McArtim flux / input flux
Direct distance to plume [km]
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
3
4
5
6
7
8

Choosing the Evaluation Region




Flux results with 7e17 molec/cm^2 SO2 VCD
geometrical
as is, all angles (McArtim)
only plume angles (McArtim)
subtract lowest (McArtim)
subtract mean of 3 lowest (McArtim)
McArtim flux / input flux
Direct distance to plume [km]
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
3
4
5
6
7
8


Flux results with 7e17 molec/cm^2 SO2 VCD
geometrical
as is, all angles (McArtim)
only plume angles (McArtim)
subtract lowest (McArtim)
subtract mean of 3 lowest (McArtim)
Kern et al. 2010 @ 313.21nm
Kern et al. 2010 @ 324.77nm
McArtim flux / input flux
Direct distance to plume [km]
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
3
4
5
6
7
8

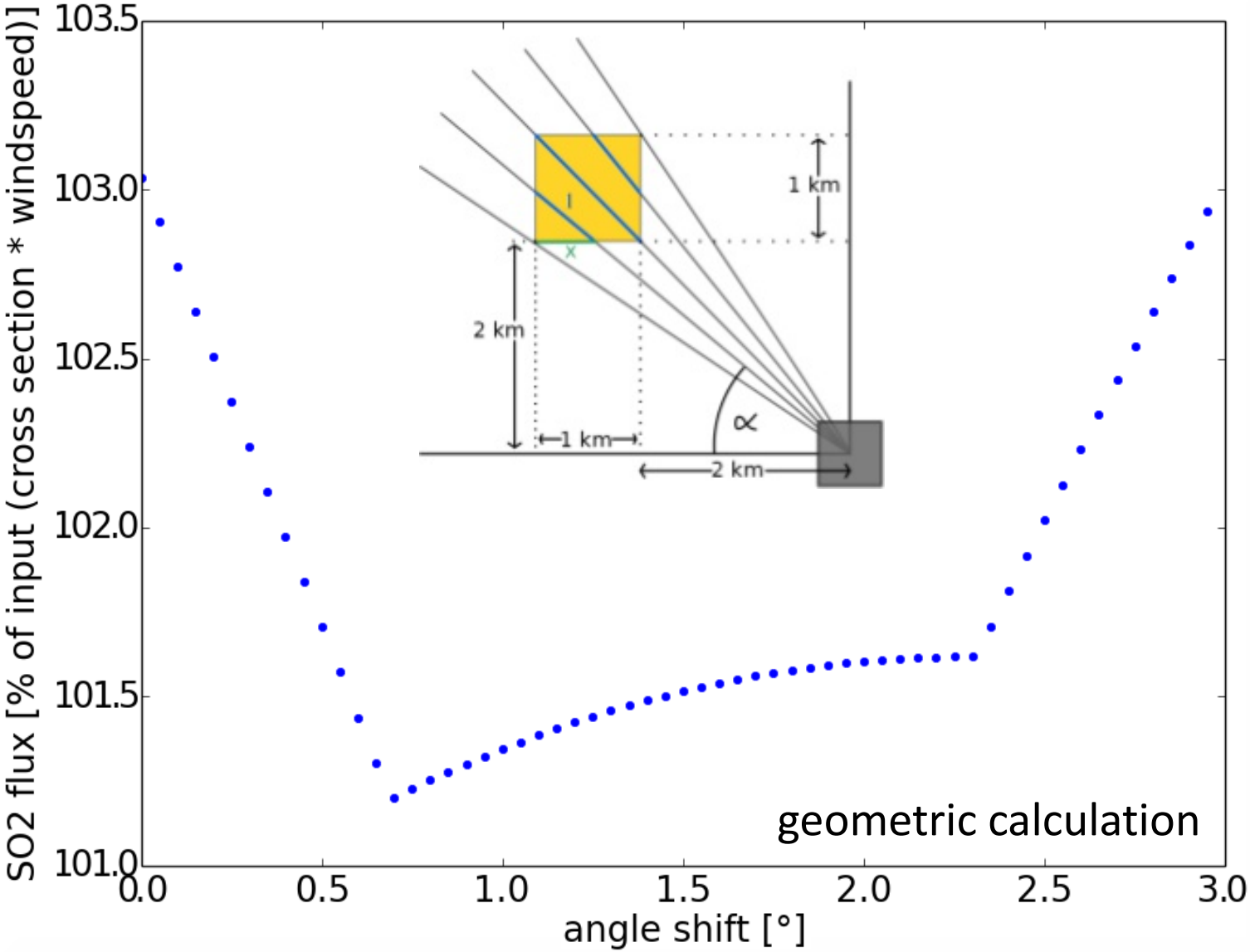

Flux results with 7e17 molec/cm^2 SO2 VCD
geometrical
as is, all angles
subtract mean of 3 lowest
subtract lowest
only plume angles
AOD = 12
AOD = 0.1
McArtim flux / input flux
Direct distance to plume [km]
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
3
4
5
6
7
8

Conclusions

- Need full plume modelling for RT investigation of flux measurements - ***contributions also from measurement angles not geometrically seeing the plume***!
- Multiple scattering can partly compensate light dilution (even without aerosols)
- Further modelling necessary – wider aerosol range, background aerosols, plume forms

Thank you for listening!

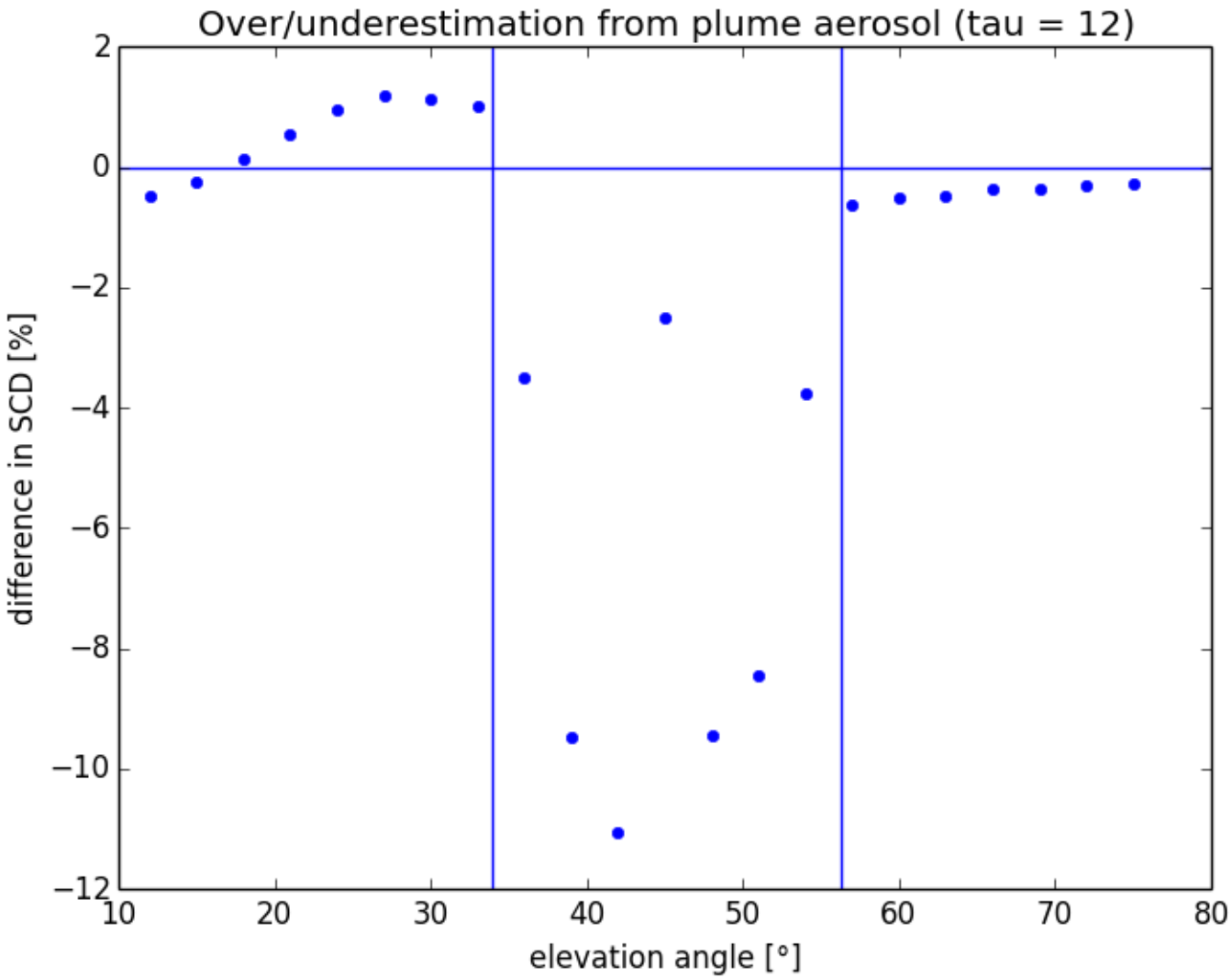
Influence of sampling positions

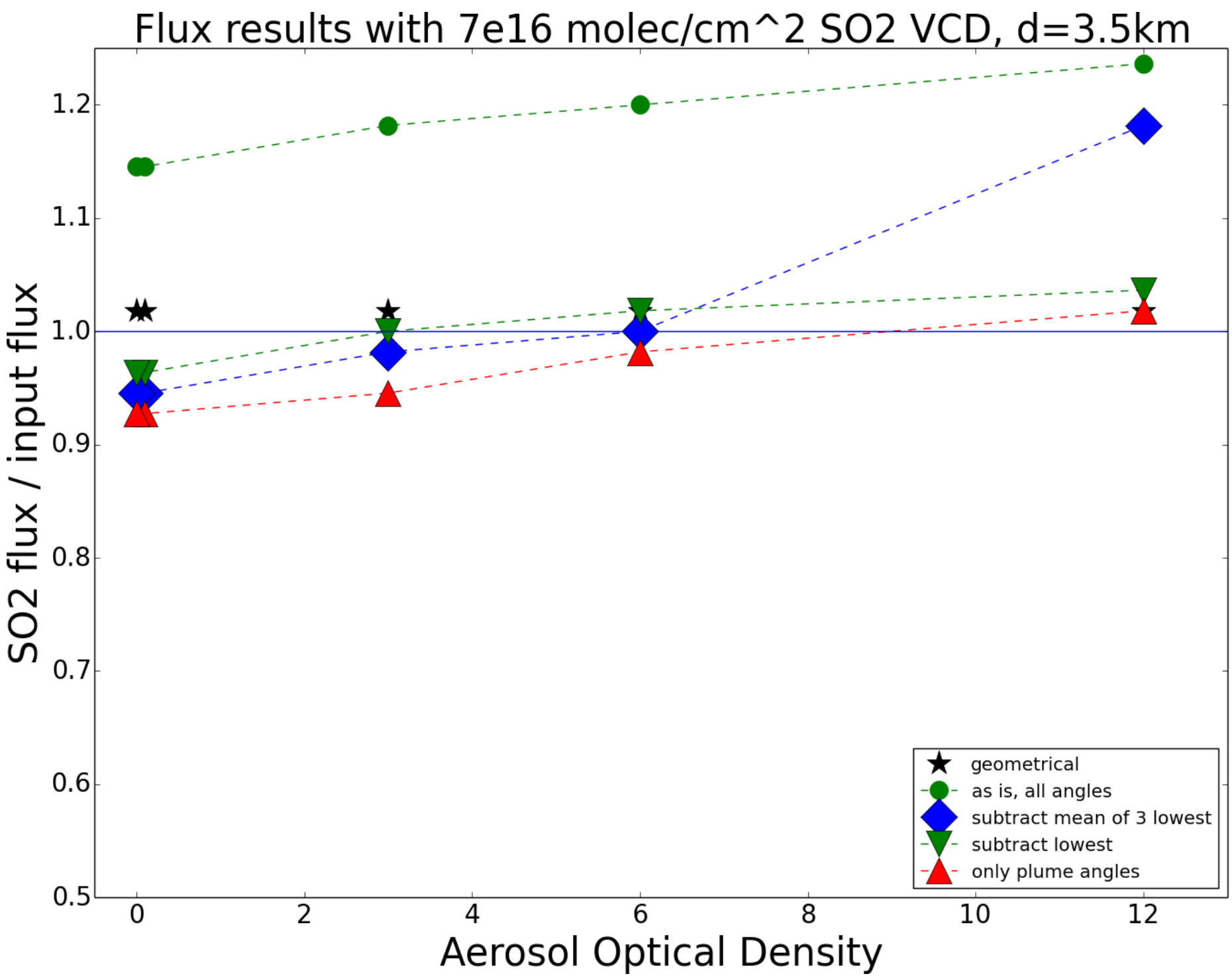


Sampling resolution of 3°, shifting by 0.05°, geometrical results

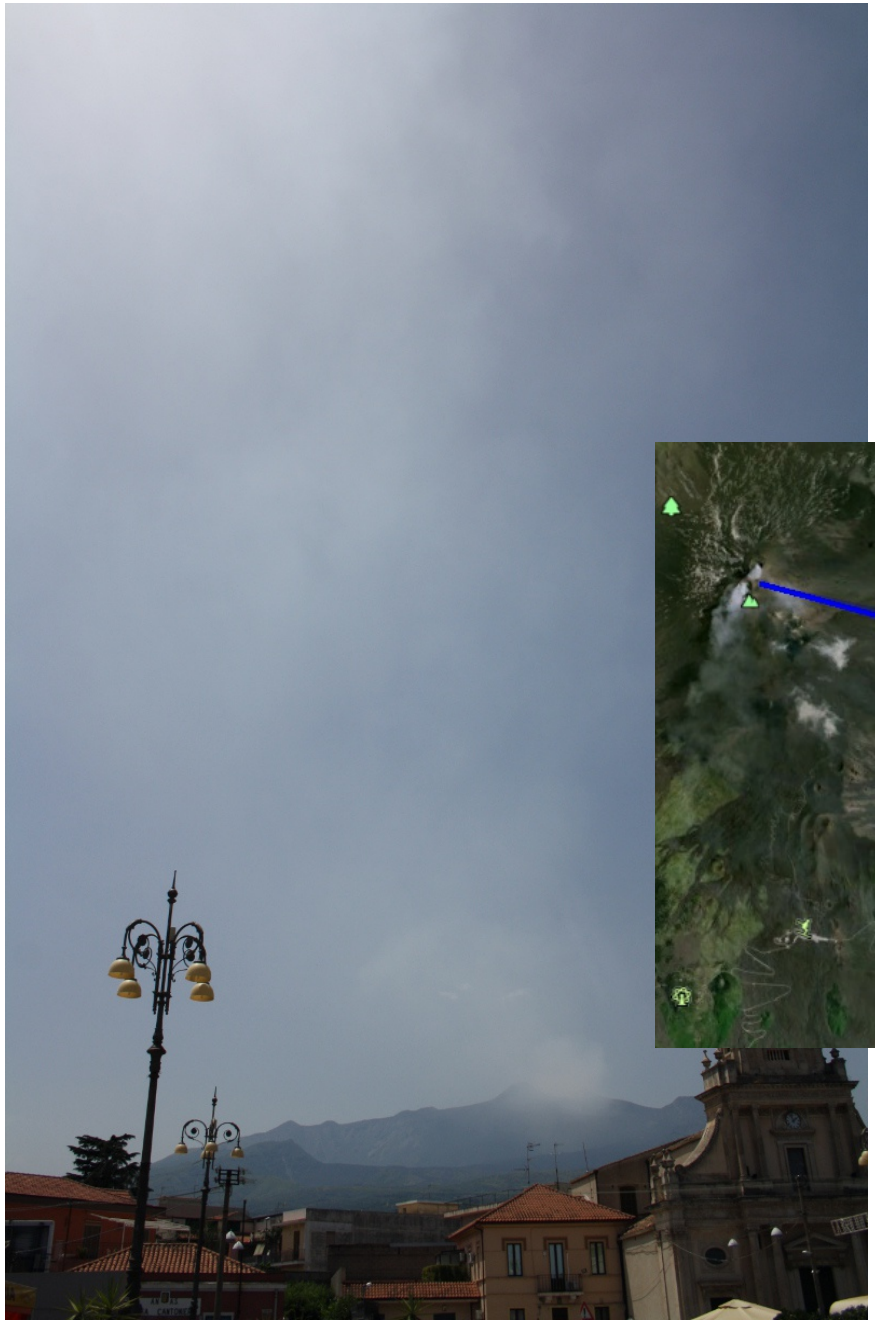
Input is 546 t/day (cross section * wind speed)

Percentage of McArtim results w.r.t. geometrical results

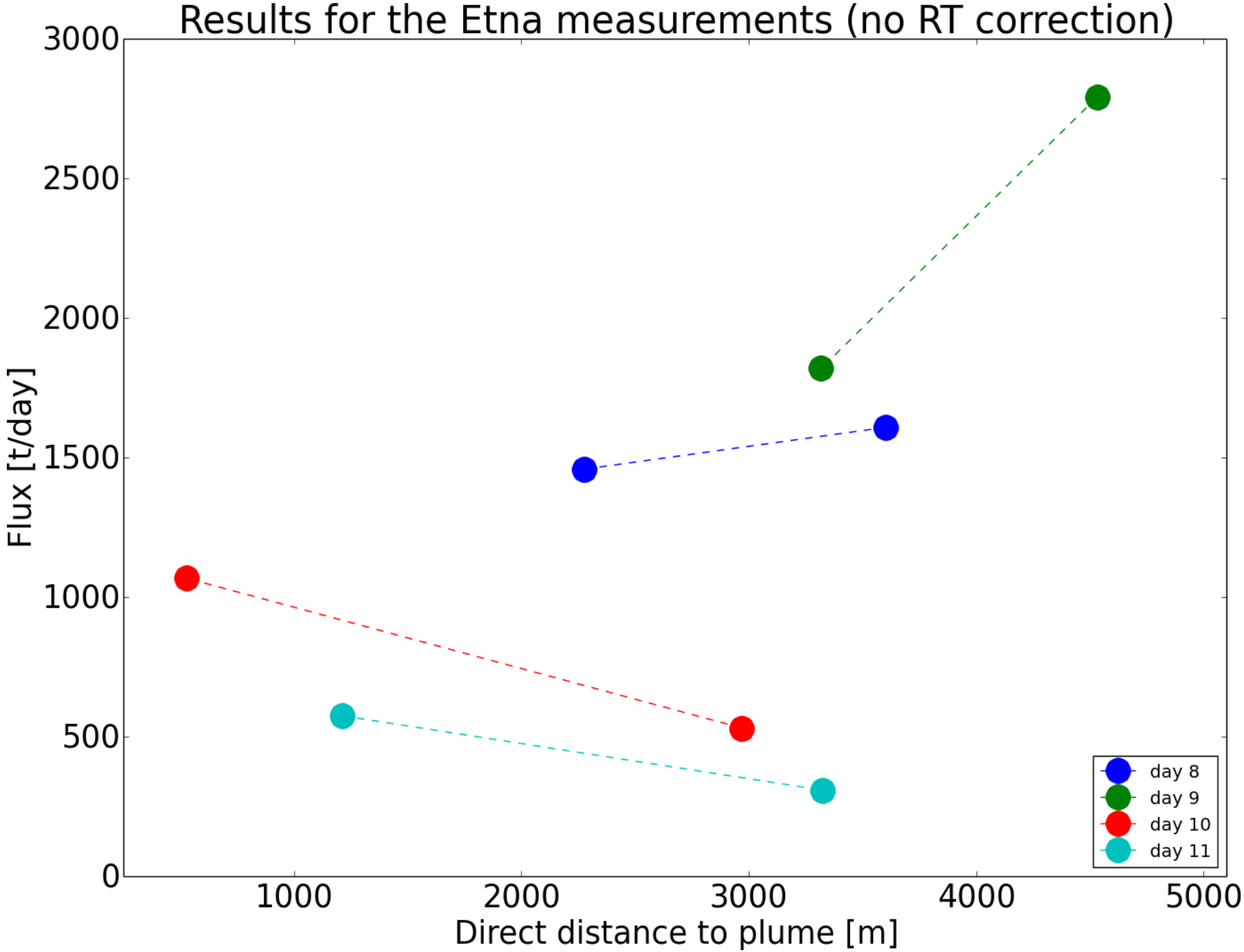


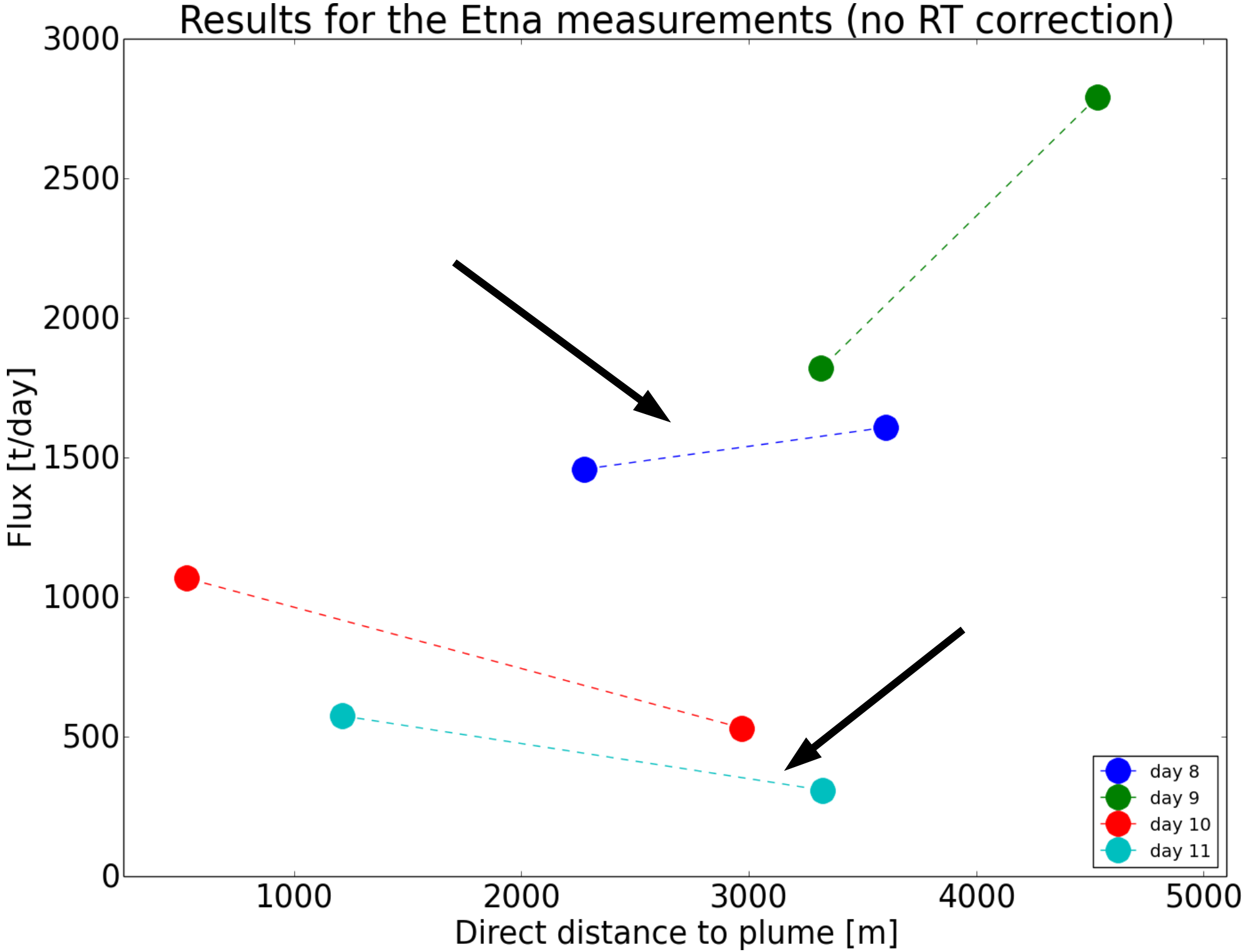

Flux results with 7e16 molec/cm^2 SO2 VCD, d=3.5km
SO2 flux / input flux
Aerosol Optical Density
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0
2
4
6
8
10
12
geometrical
as is, all angles
subtract mean of 3 lowest
subtract lowest
only plume angles

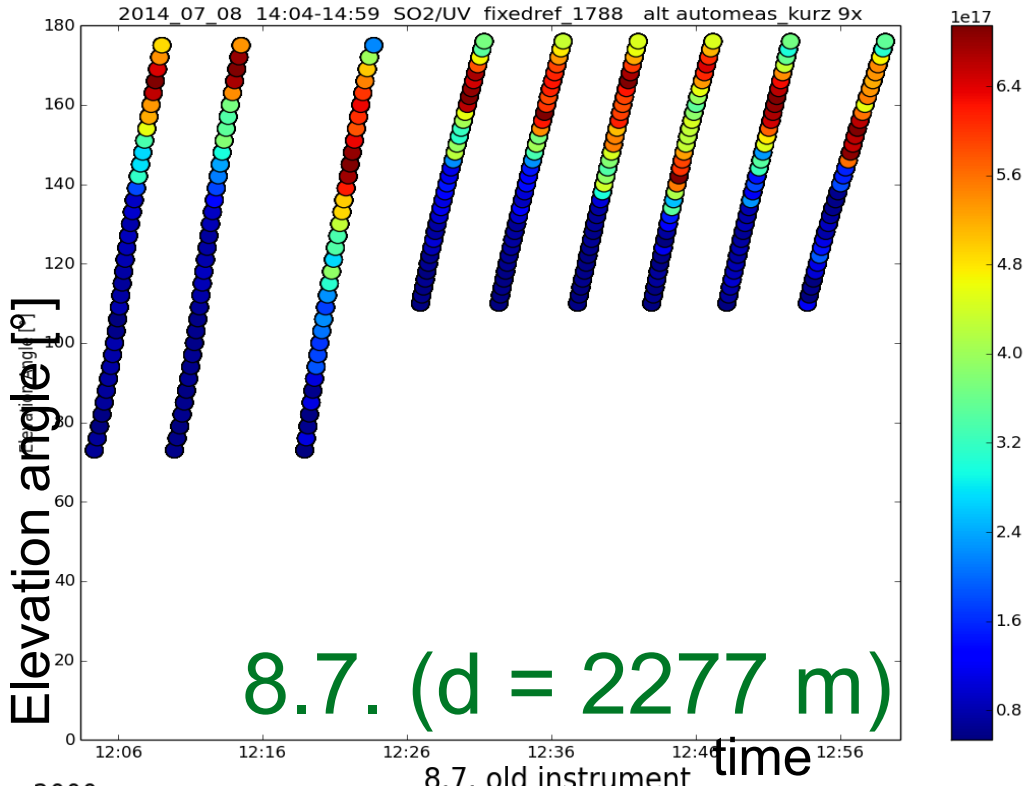
Measurements & Modelling

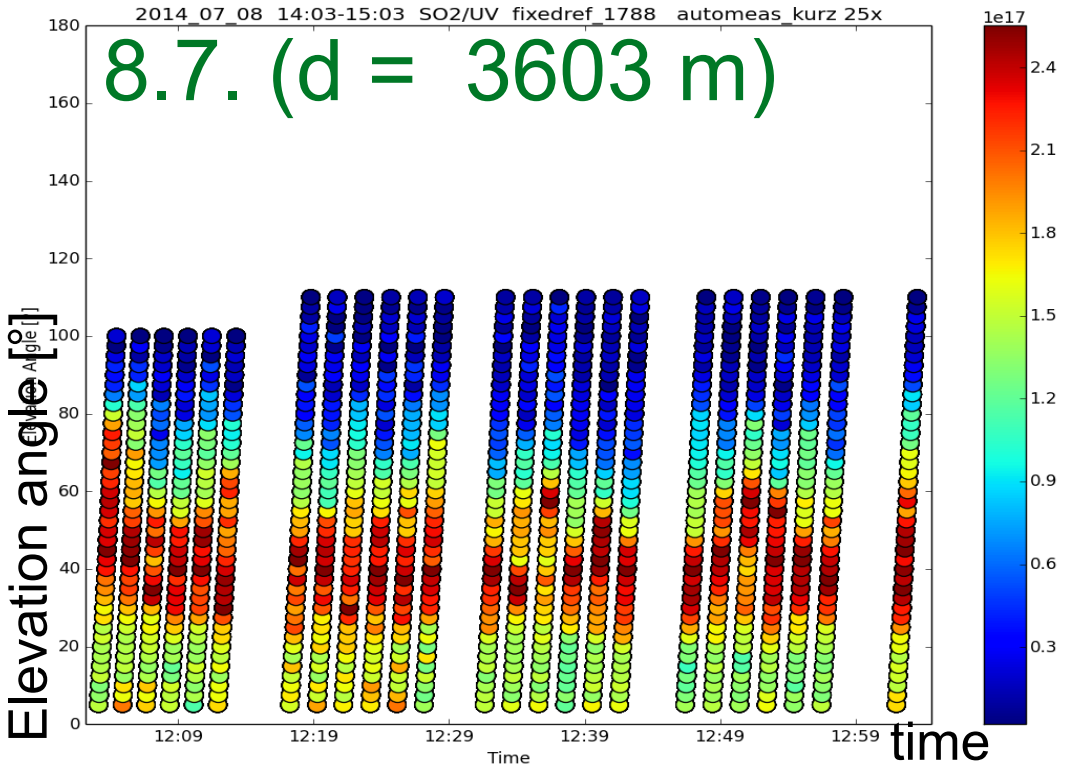


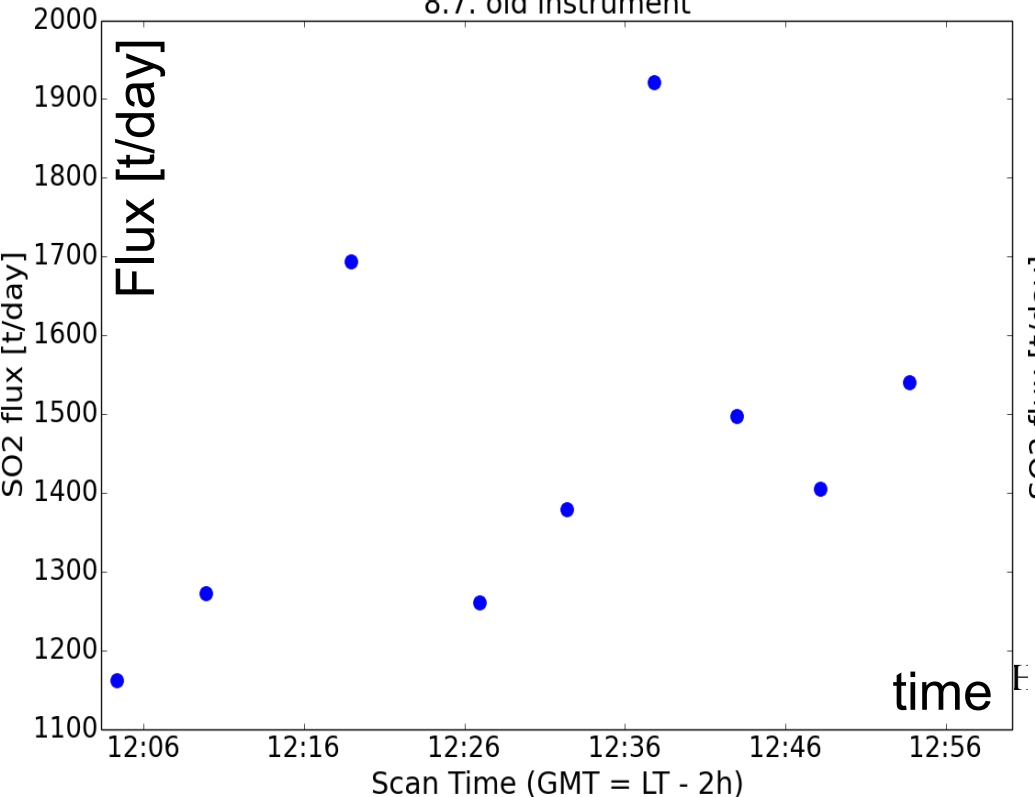
Campaign:
June 2014
Etna and Stromboli

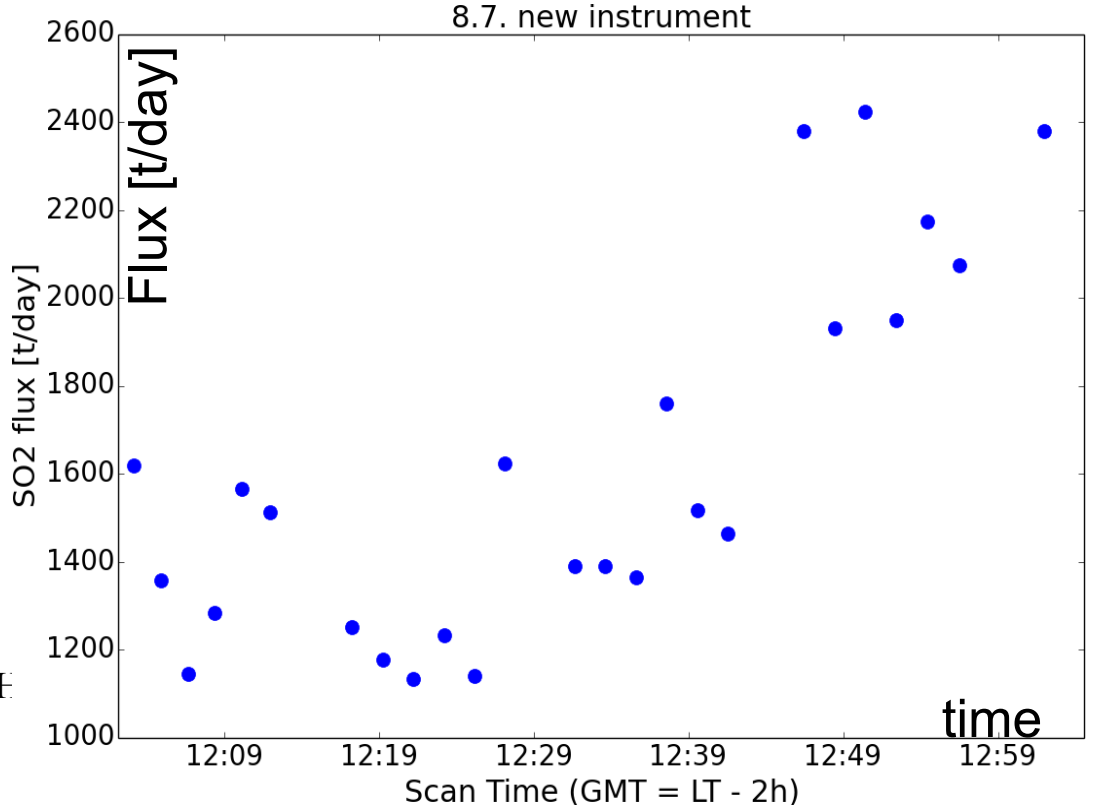

Results for the Etna measurements (no RT correction)
Flux [t/day]
Direct distance to plume [m]
0
500
1000
1500
2000
2500
3000
1000
2000
3000
4000
5000
day 8
day 9
day 10
day 11

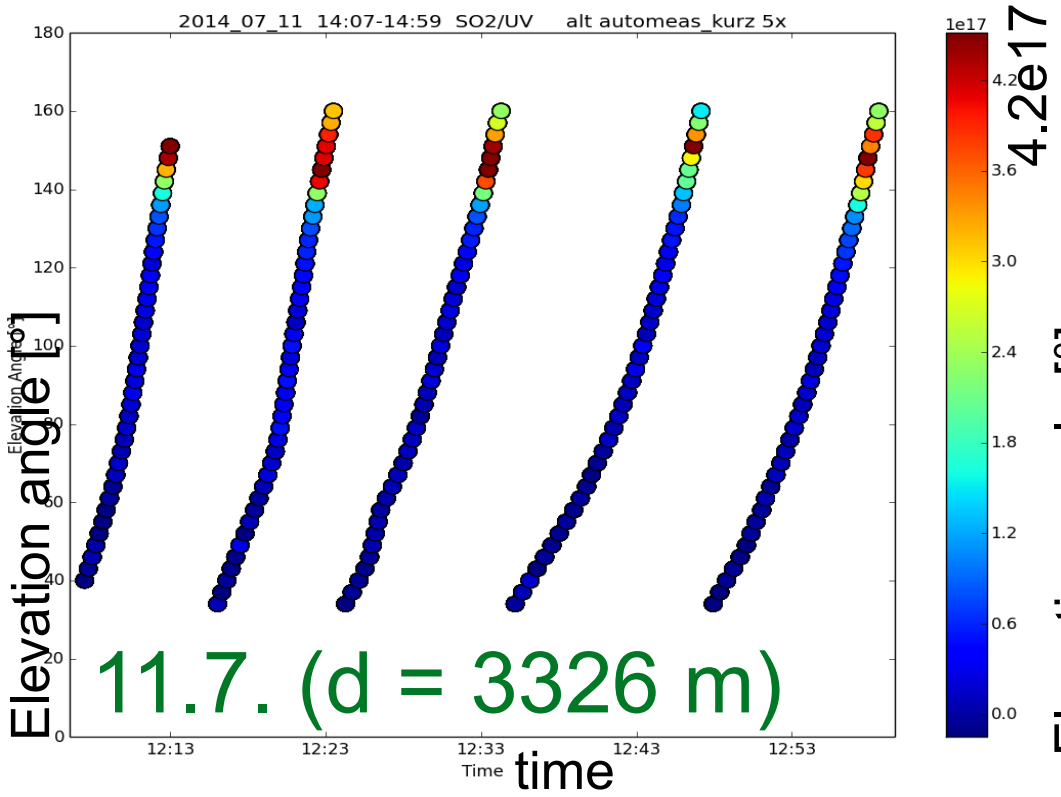

Results for the Etna measurements (no RT correction)
Flux [t/day]
Direct distance to plume [m]
0
500
1000
1500
2000
2500
3000
1000
2000
3000
4000
5000
day 8
day 9
day 10
day 11

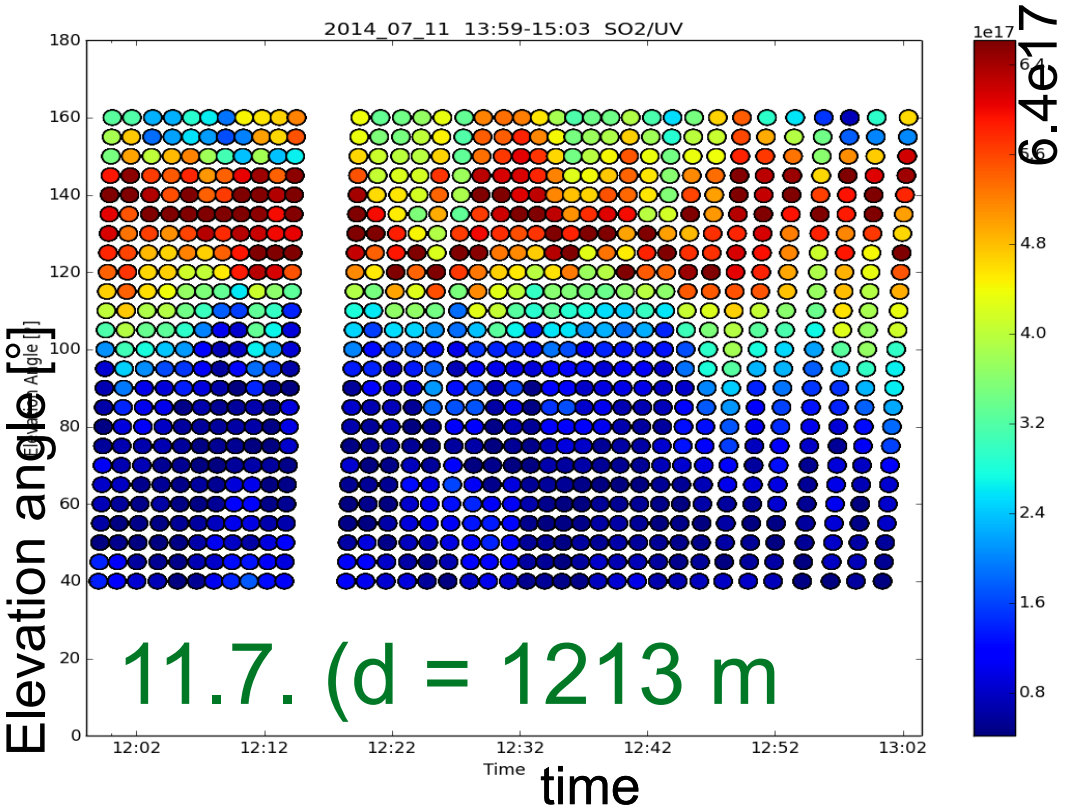

2014_07_08 14:04-14:59 SO2/UV fixedref_1788 alt automeas_kurz 9x
Elevation angle [°]
8.7. (d = 2277 m)
time
1e17

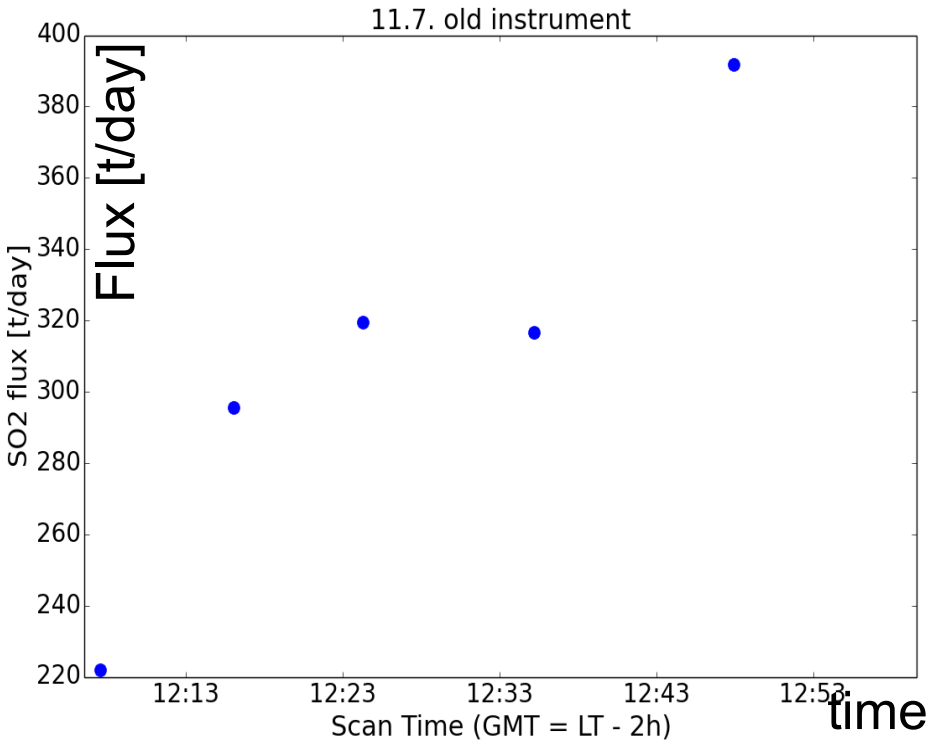

2014_07_08 14:03-15:03 SO2/UV fixedref_1788 automeas_kurz 25x
8.7. (d = 3603 m)
Elevation angle [°]
Time
time
1e17

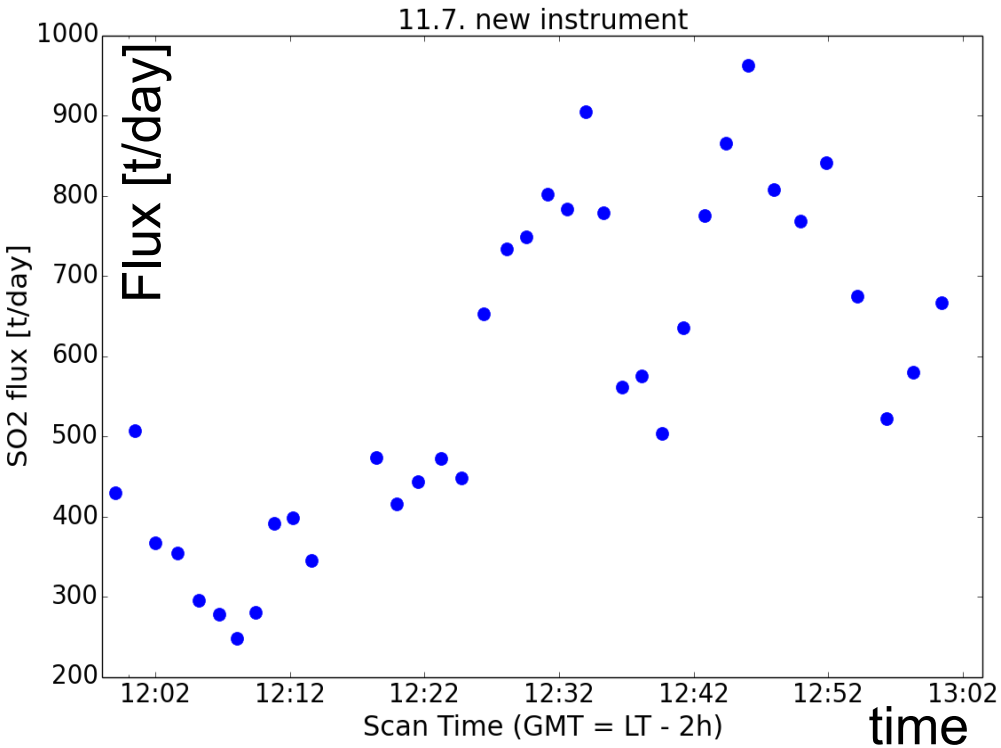

8.7. old instrument
Flux [t/day]
SO2 flux [t/day]
time
Scan Time (GMT = LT - 2h)

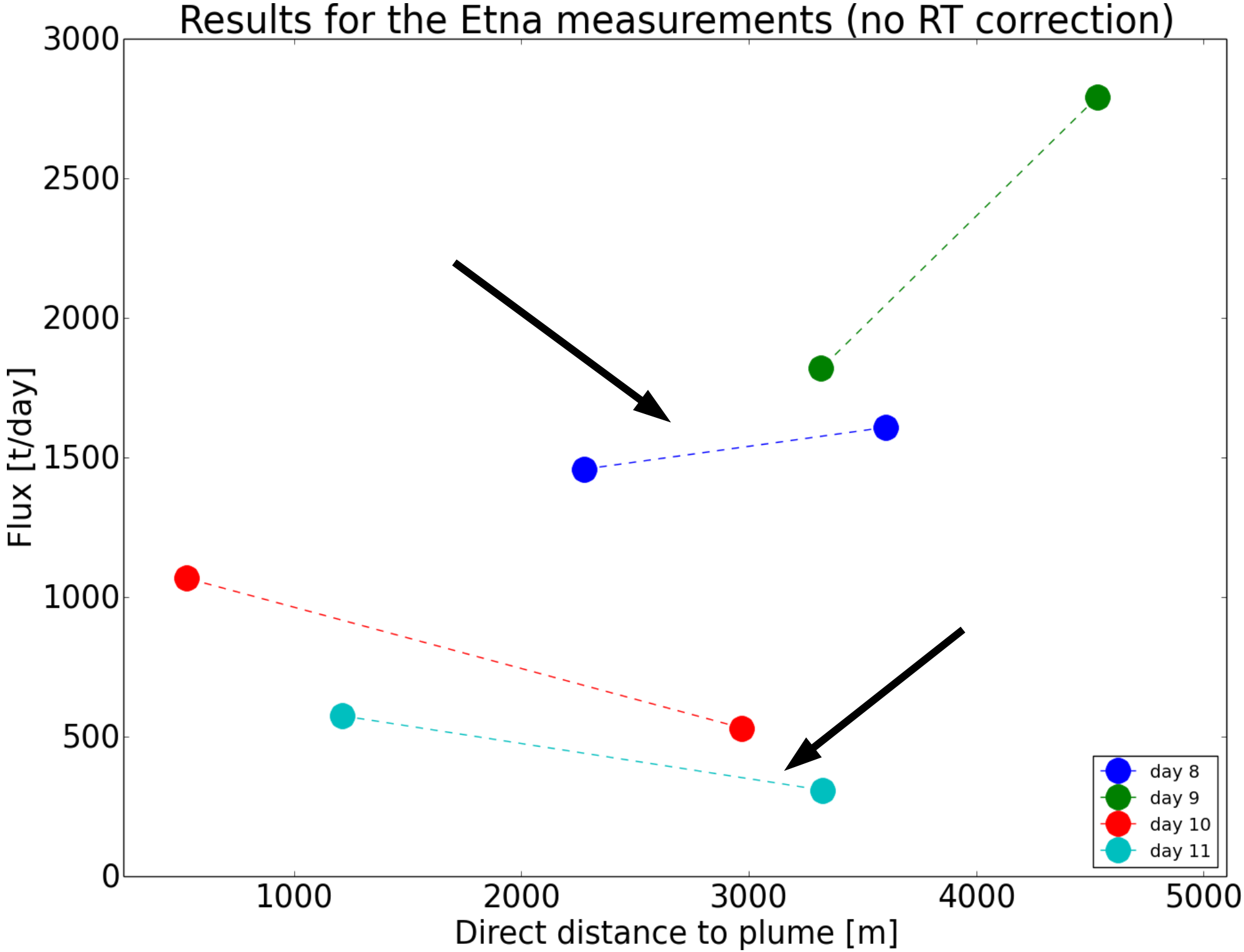

8.7. new instrument
Flux [t/day]
SO2 flux [t/day]
time
Scan Time (GMT = LT - 2h)


2014_07_11 14:07-14:59 SO2/UV alt automeas_kurz 5x
Elevation angle [°]
Time
time
11.7. (d = 3326 m)
1e17
4.2e17

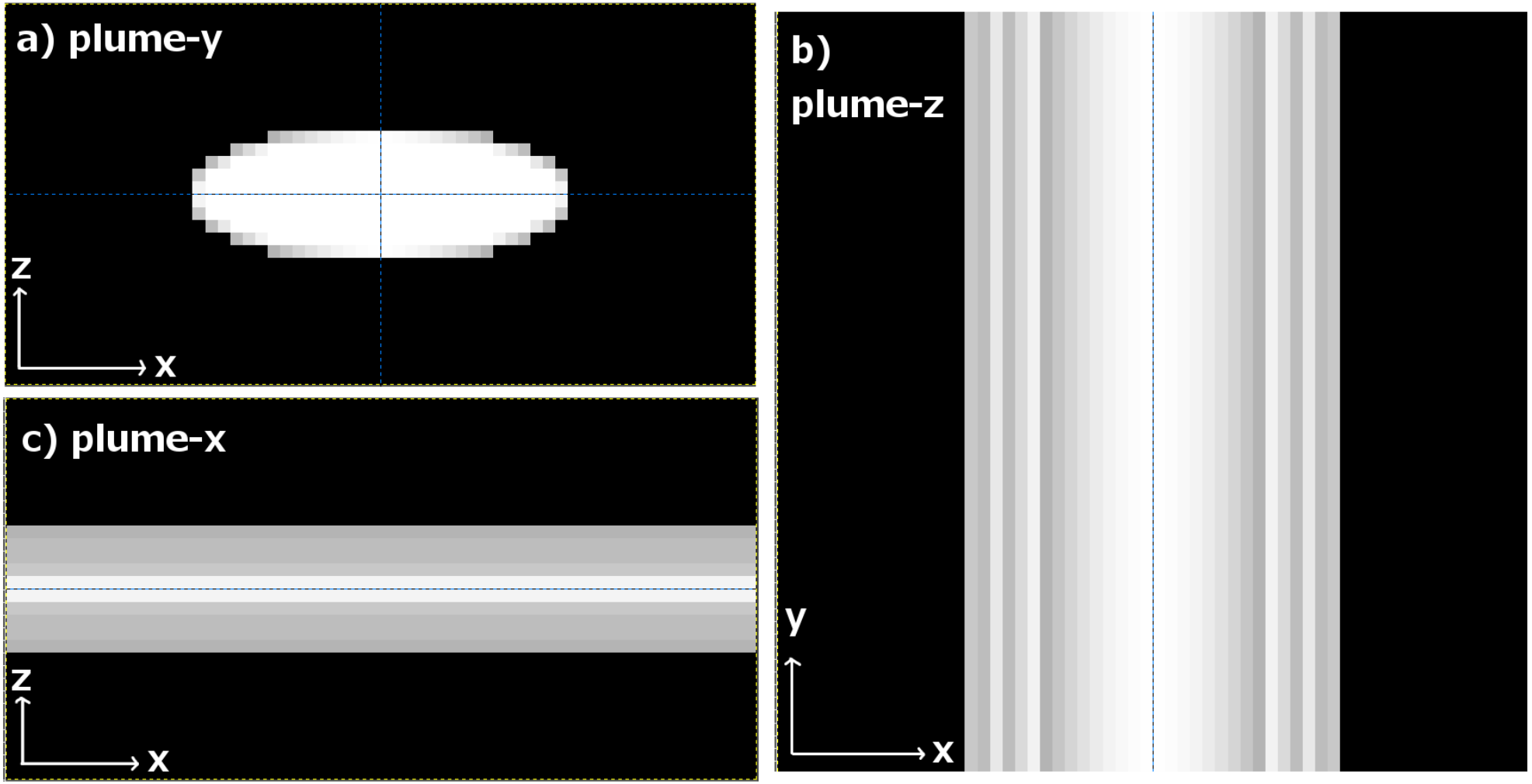

2014_07_11 13:59-15:03 SO2/UV
Elevation angle [°]
Time
time
11.7. (d = 1213 m
1e17
6.4e17

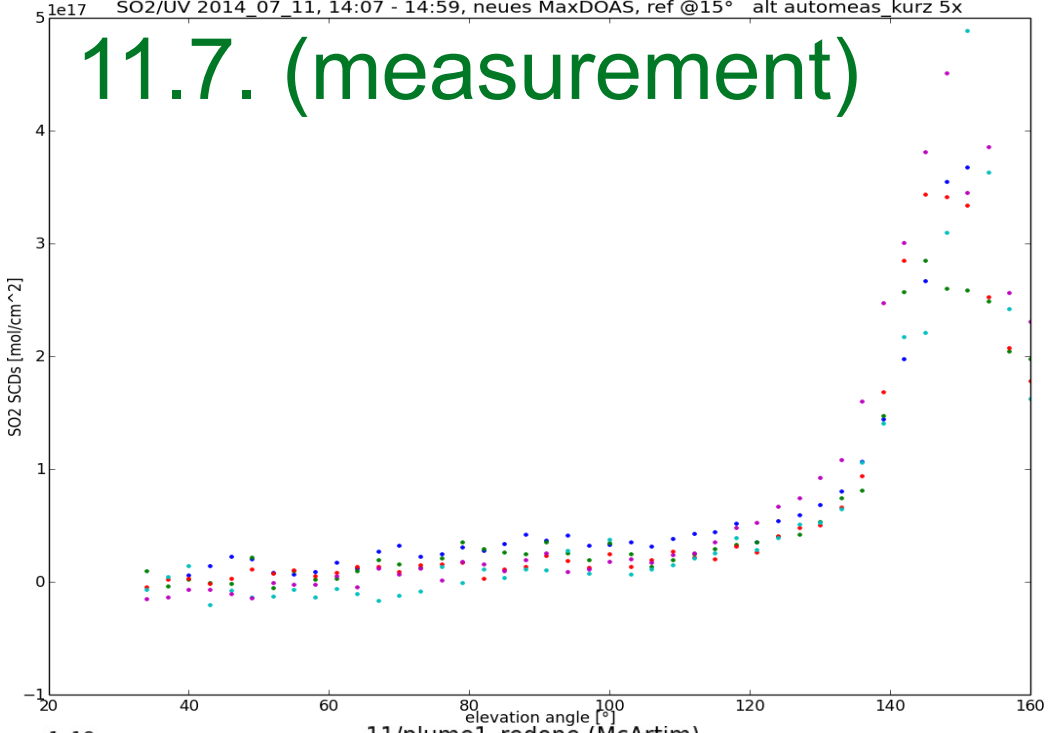

11.7. old instrument
Flux [t/day]
SO2 flux [t/day]
Scan Time (GMT = LT - 2h)
time

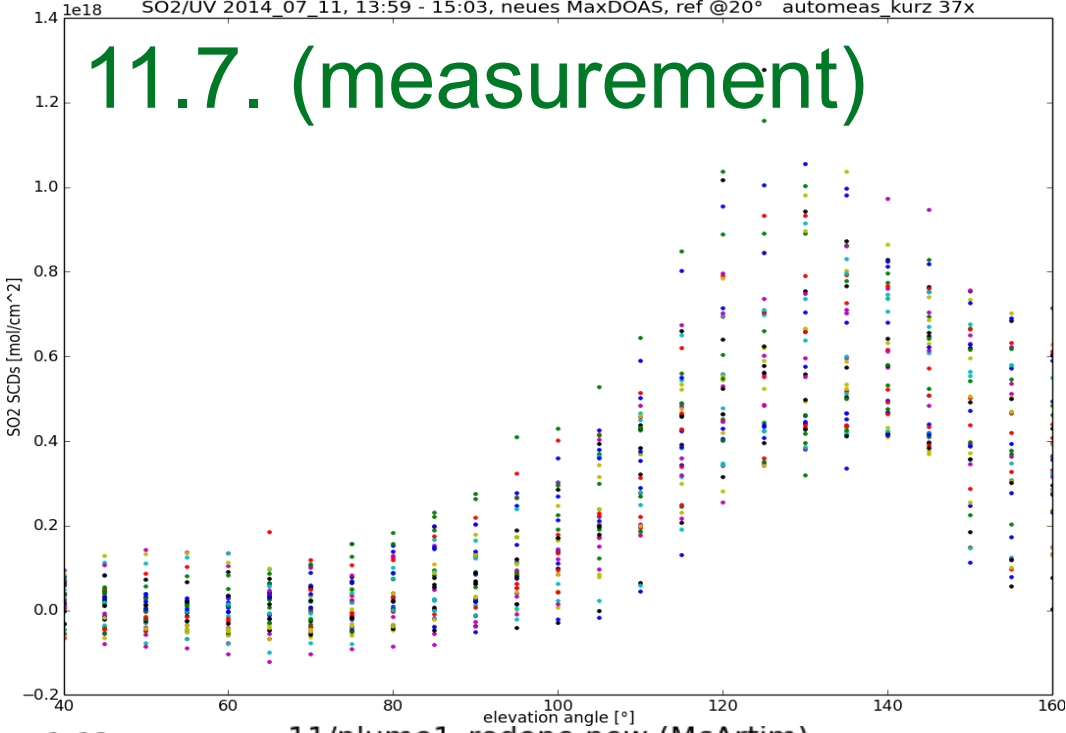

11.7. new instrument
Flux [t/day]
SO2 flux [t/day]
Scan Time (GMT = LT - 2h)
time

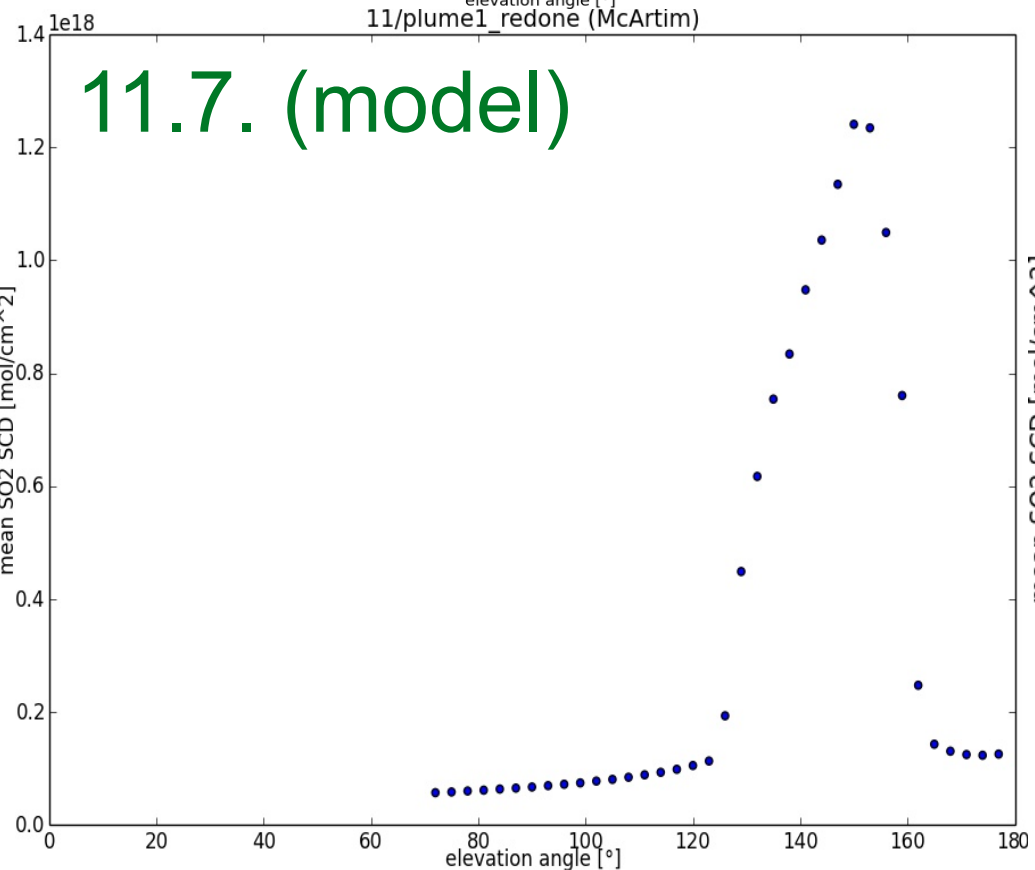

Results for the Etna measurements (no RT correction)
Flux [t/day]
Direct distance to plume [m]
0
500
1000
1500
2000
2500
3000
1000
2000
3000
4000
5000
day 8
day 9
day 10
day 11

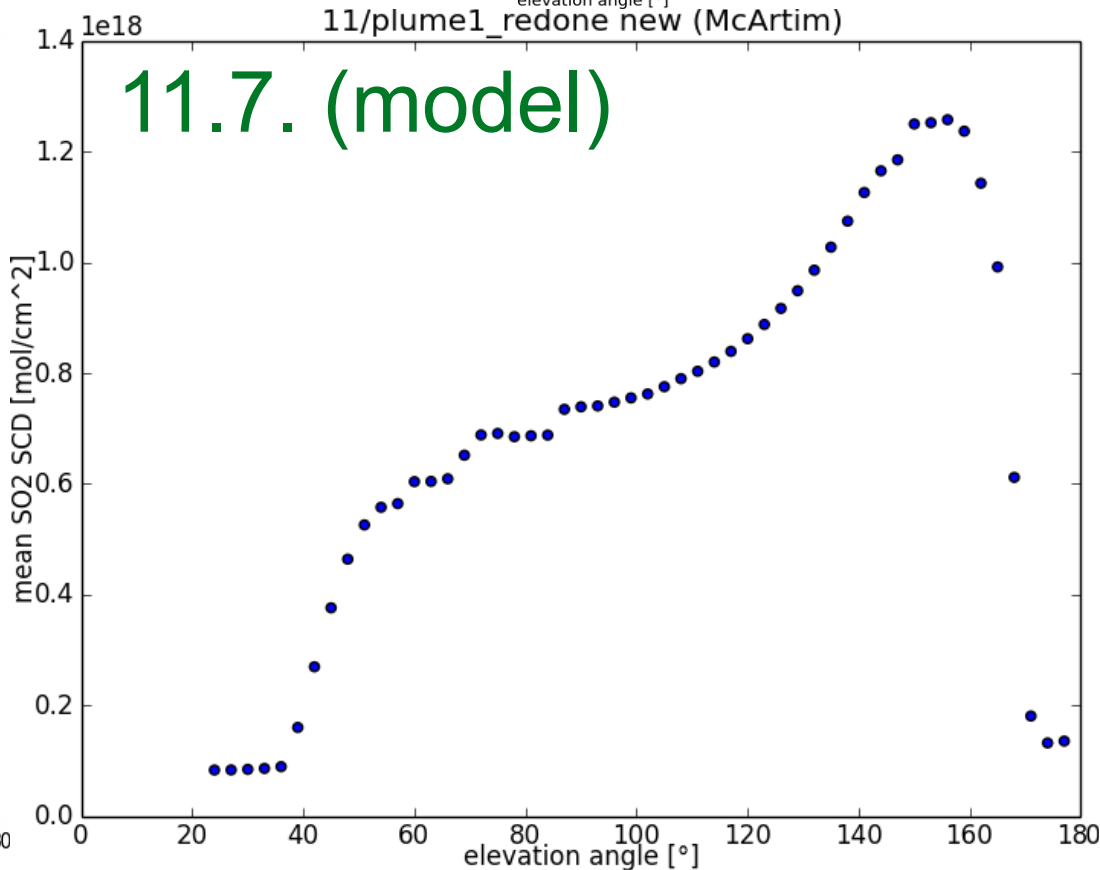
Plume Creator (for McArtim)




SO2/UV 2014_07_11, 14:07 - 14:59, neues MaxDOAS, ref @15° alt automeas_kurz 5x
11.7. (measurement)
1e17
SO2 SCDs [mol/cm^2]
elevation angle [°]

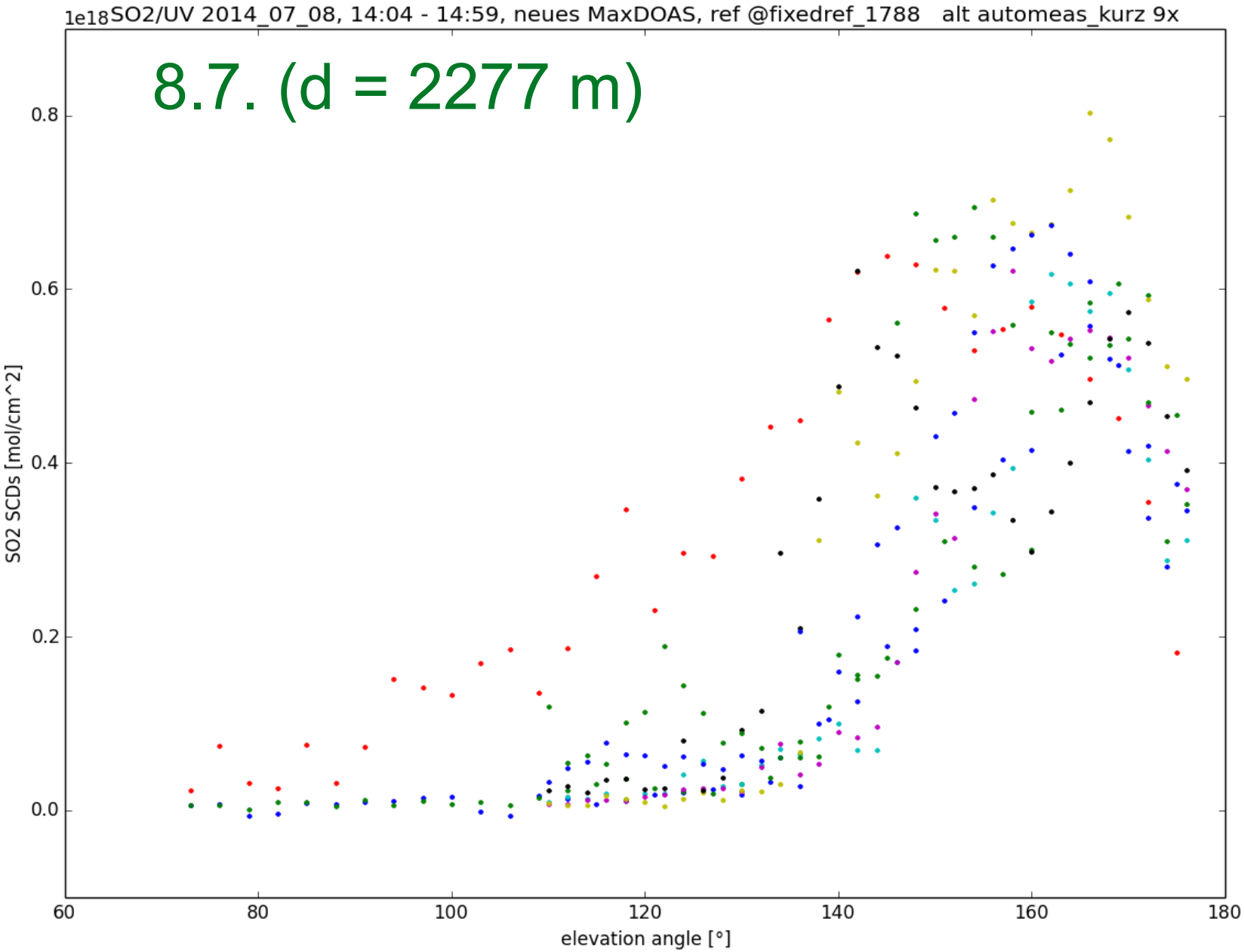

SO2/UV 2014_07_11, 13:59 - 15:03, neues MaxDOAS, ref @20° automeas_kurz 37x
11.7. (measurement)
1e18
SO2 SCDs [mol/cm^2]
elevation angle [°]

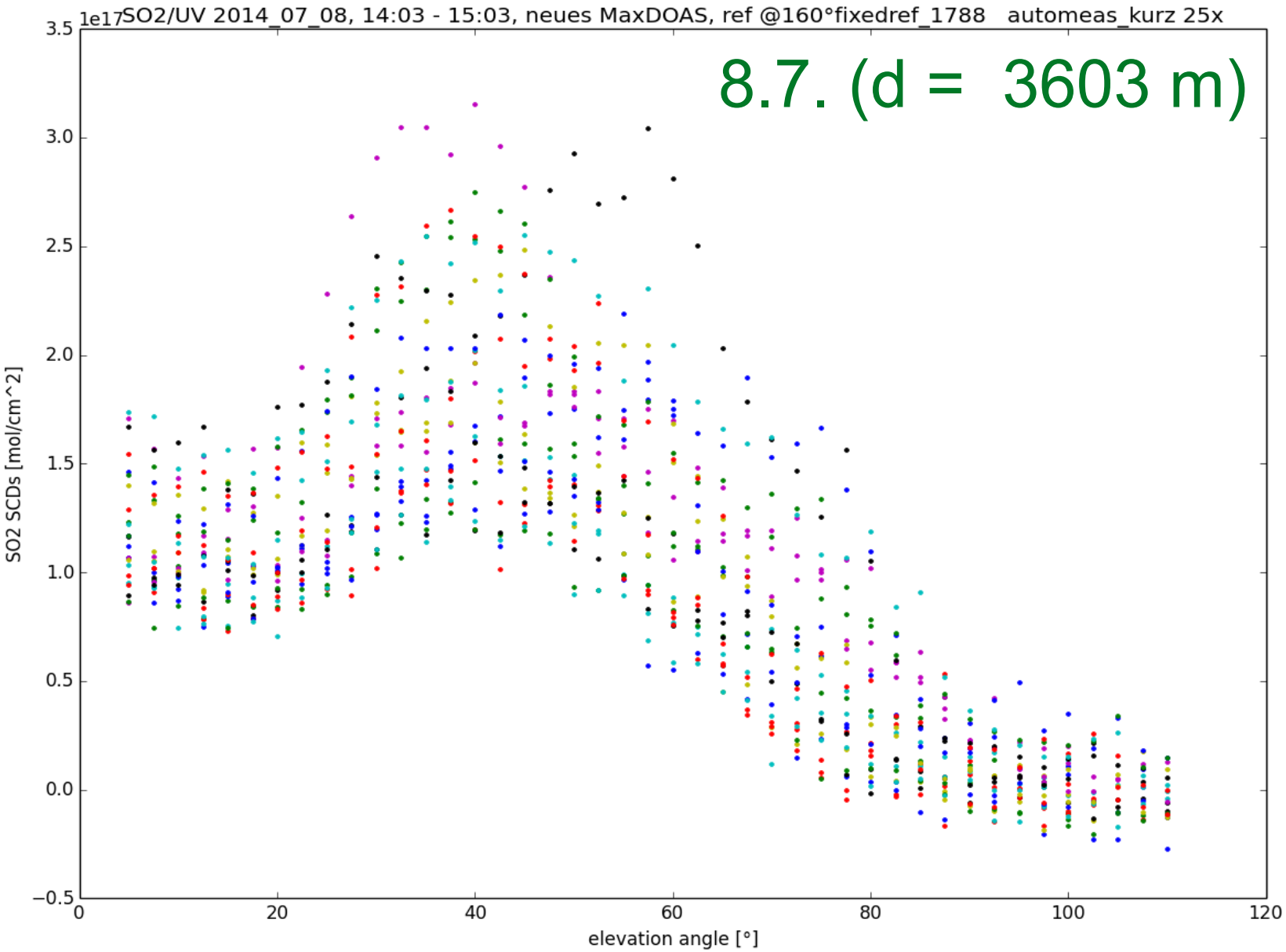

11/plume1_redone (McArtim)
11.7. (model)
1e18
mean SO2 SCD [mol/cm^2]
elevation angle [°]

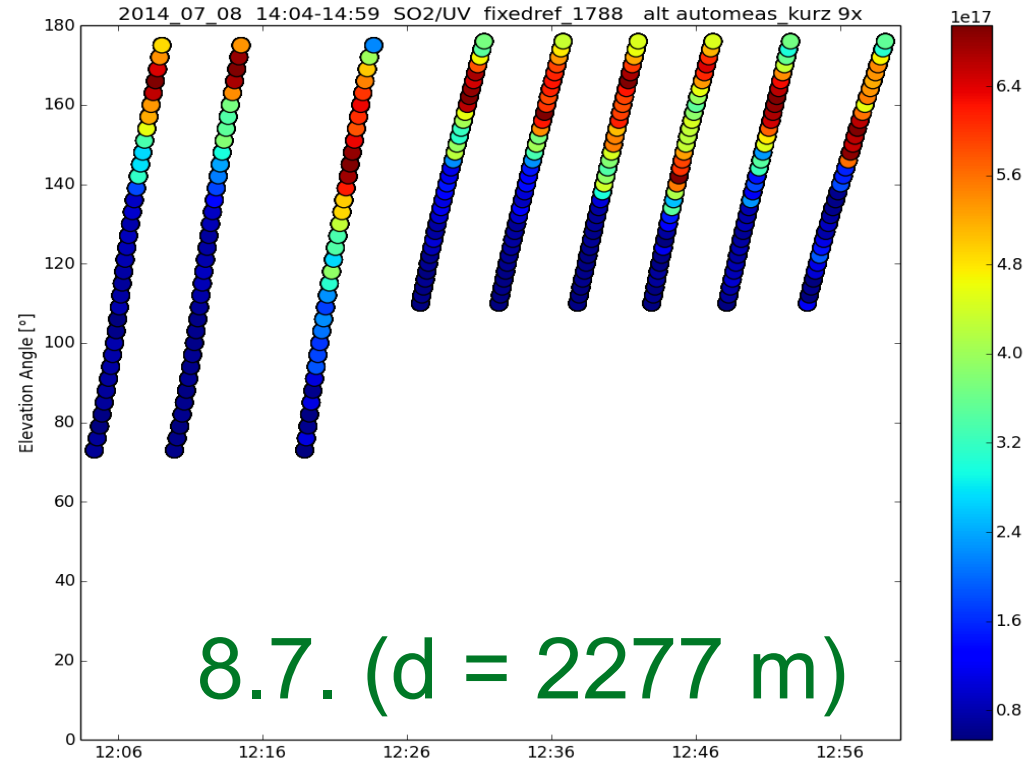

11/plume1_redone new (McArtim)
11.7. (model)
1e18
mean SO2 SCD [mol/cm^2]
elevation angle [°]

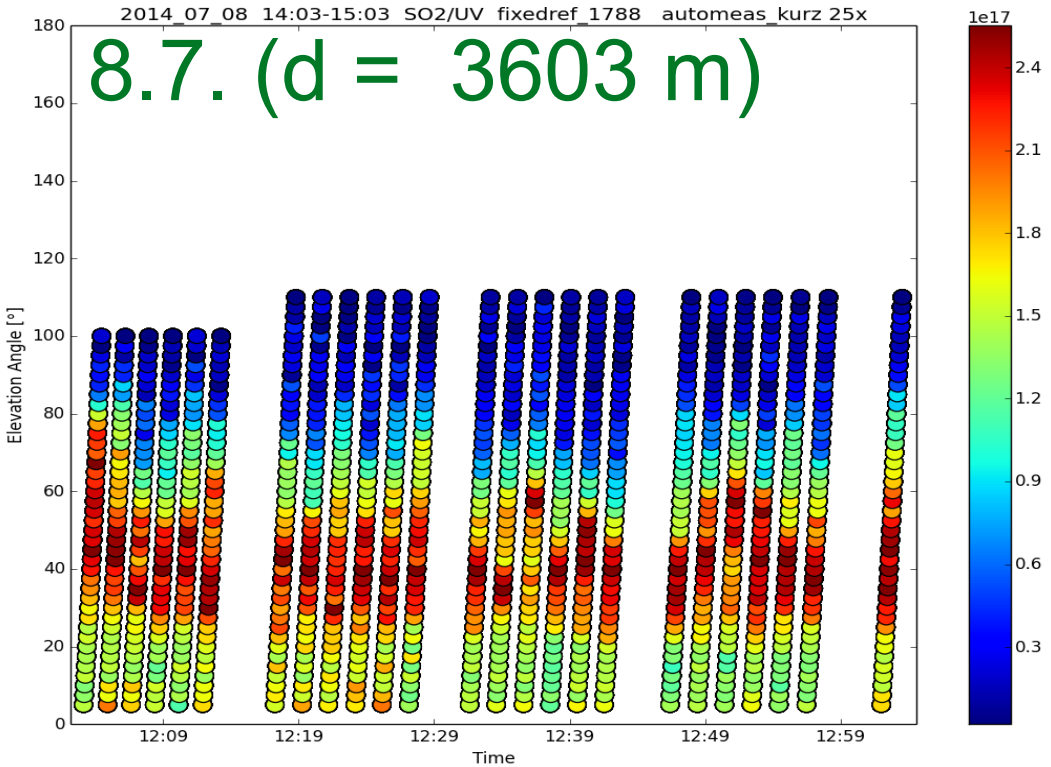
8.7.

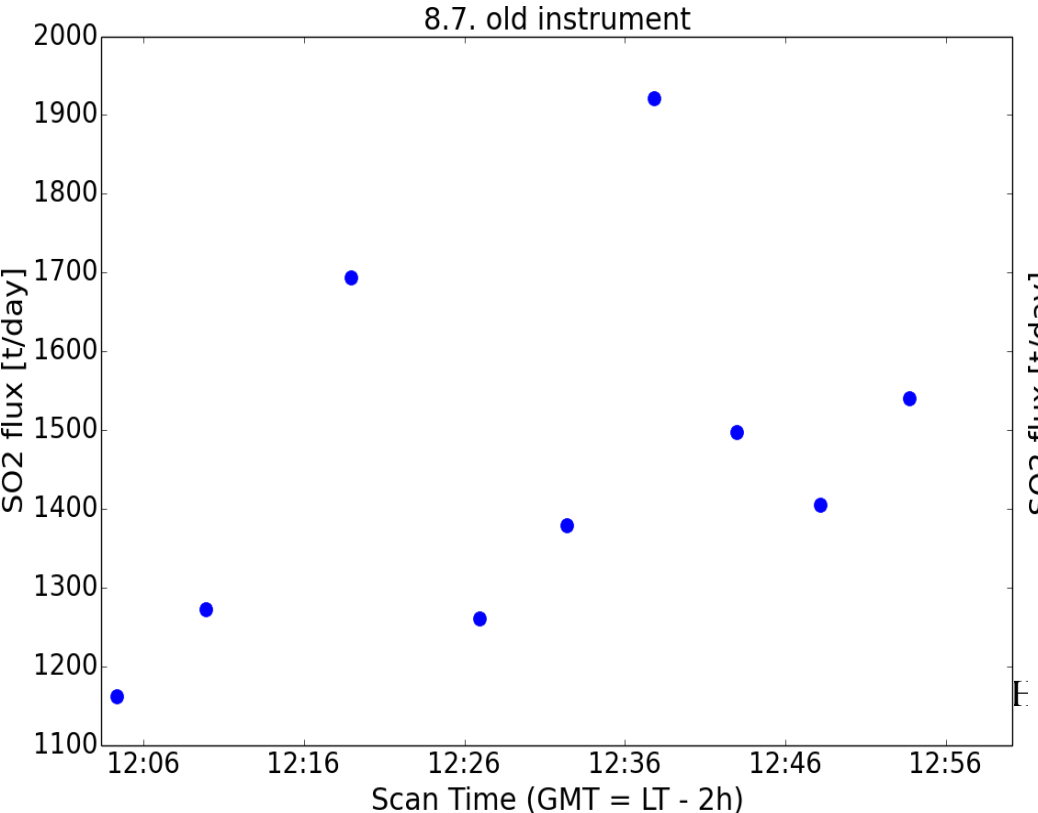
yellow: d = 2277 m red: d = 3603 m h plume a.s.l.: ~2300 m

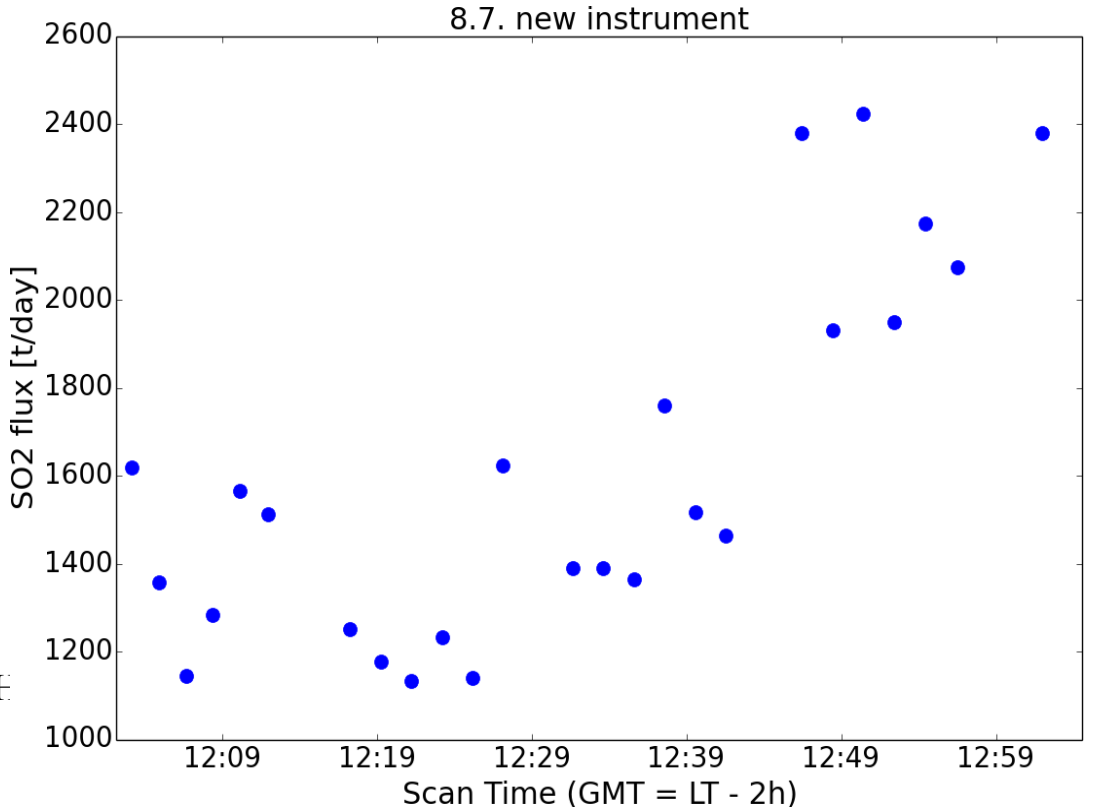

1e18SO2/UV 2014_07_08, 14:04 - 14:59, neues MaxDOAS, ref @fixedref_1788 alt automeas_kurz 9x
8.7. (d = 2277 m)
SO2 SCDs [mol/cm^2]
0.0
0.2
0.4
0.6
0.8
60
80
100
120
140
160
180
elevation angle [°]


SO2/UV 2014_07_08, 14:03 - 15:03, neues MaxDOAS, ref @160°fixedref_1788 automeas_kurz 25x
8.7. (d = 3603 m)
1e17
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
SO2 SCDs [mol/cm^2]
0
20
40
60
80
100
120
elevation angle [°]


2014_07_08 14:04-14:59 SO2/UV fixedref_1788 alt automeas_kurz 9x
Elevation Angle [°]
1e17
8.7. (d = 2277 m)


2014_07_08 14:03-15:03 SO2/UV fixedref_1788 automeas_kurz 25x
Elevation Angle [°]
Time
1e17
8.7. (d = 3603 m)


8.7. old instrument
SO2 flux [t/day]
Scan Time (GMT = LT - 2h)

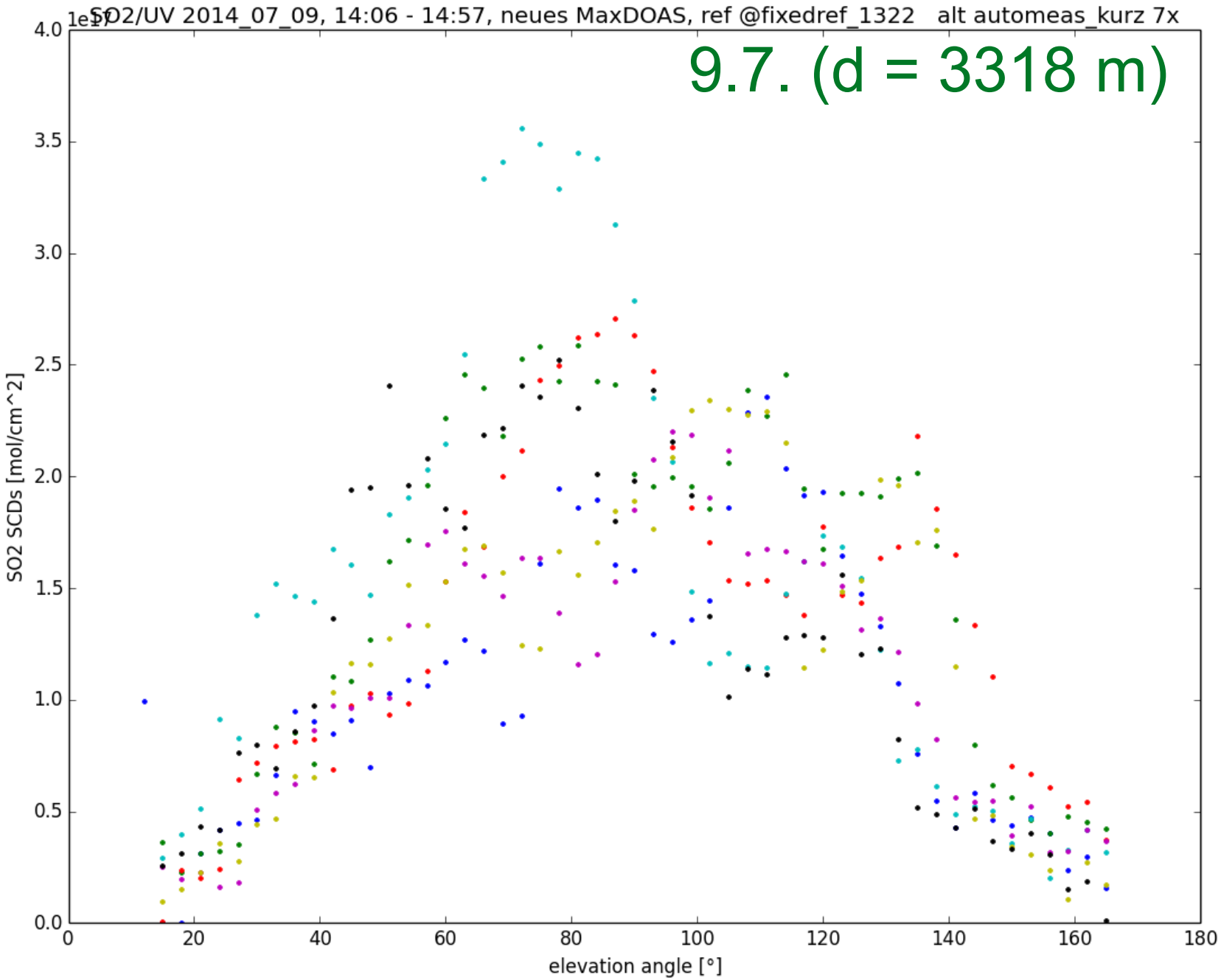

8.7. new instrument
SO2 flux [t/day]
Scan Time (GMT = LT - 2h)

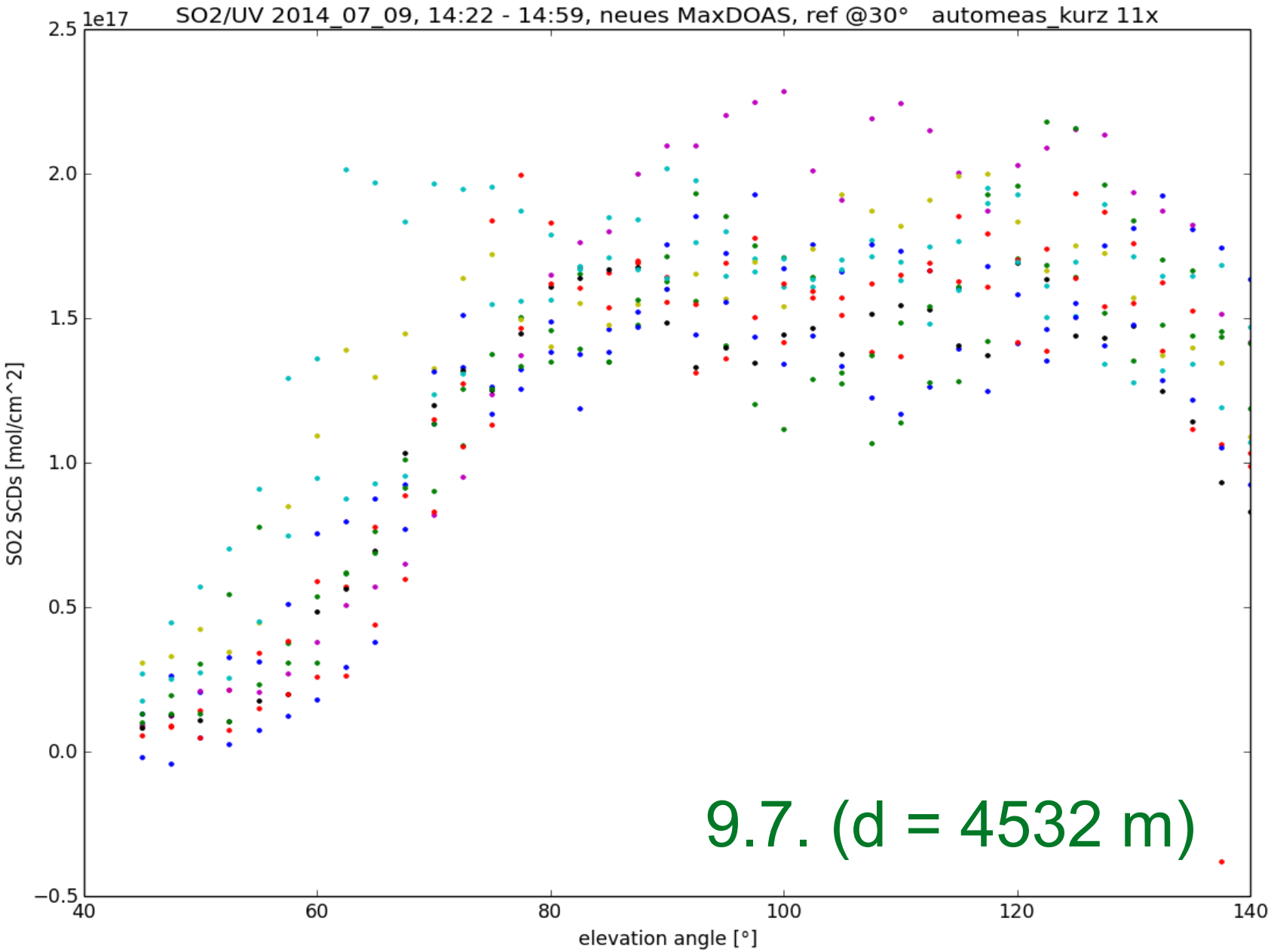
	plumeI	plumeII	measurement
input	1102	1801	?
old	1523 /138%	1758 /98%	-
old -	1431 /130%	1594 /89%	1459
old (plume)	1502 /136%	1729 /96%	-
new	1488 /135%	2472 /137%	-
new -	1307 /119%	2042 /113%	1609
new (plume)	1142 /104%	1926 /107%	-

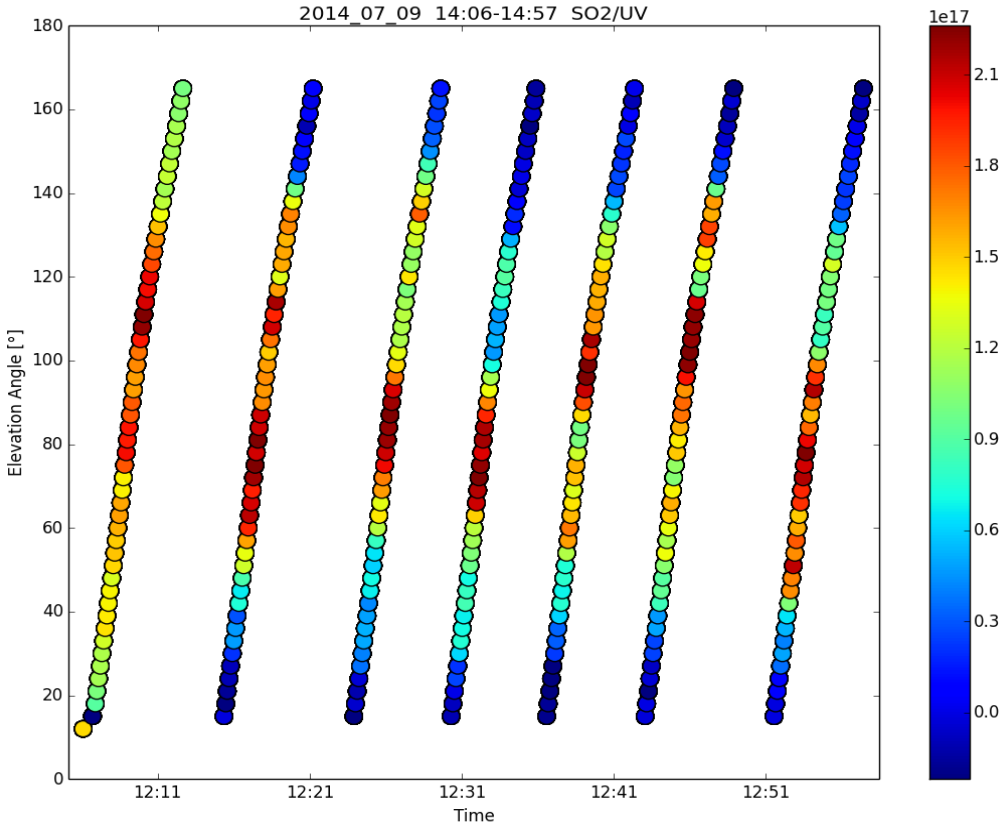
Table 6.16: Modeling results for the measurement geometries of 8.7., with wind speed v_{wind}=20 m/s. Values in t/day.

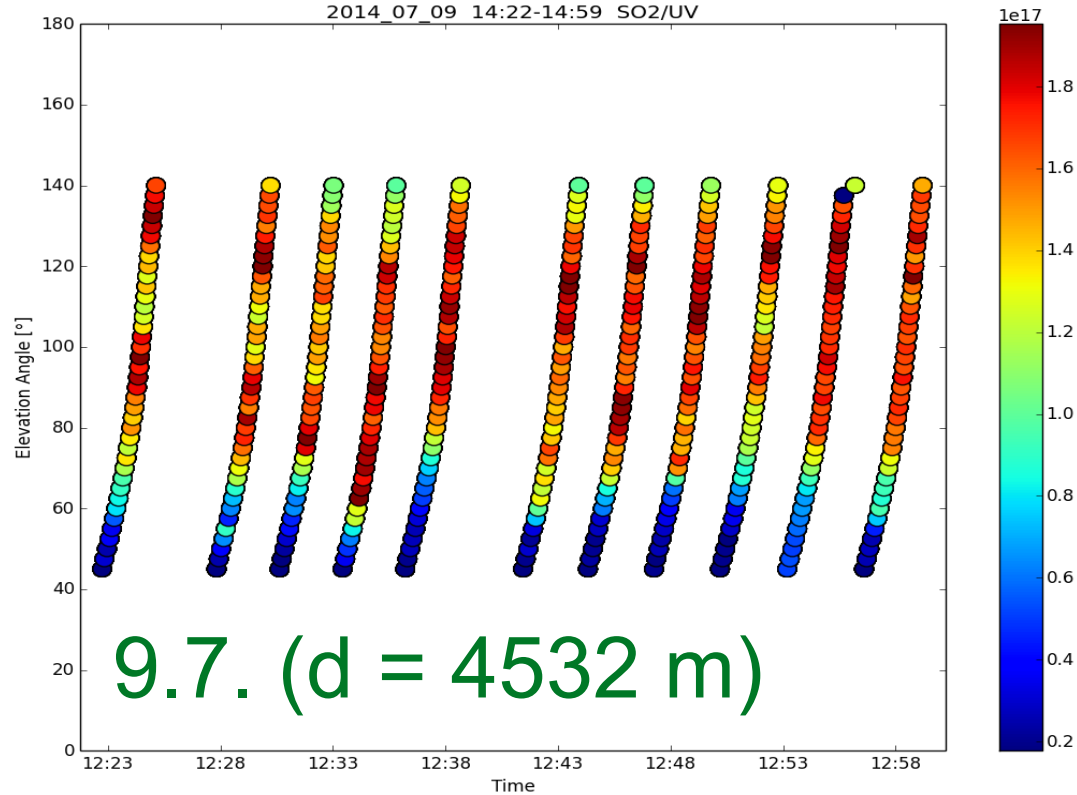
9.7.

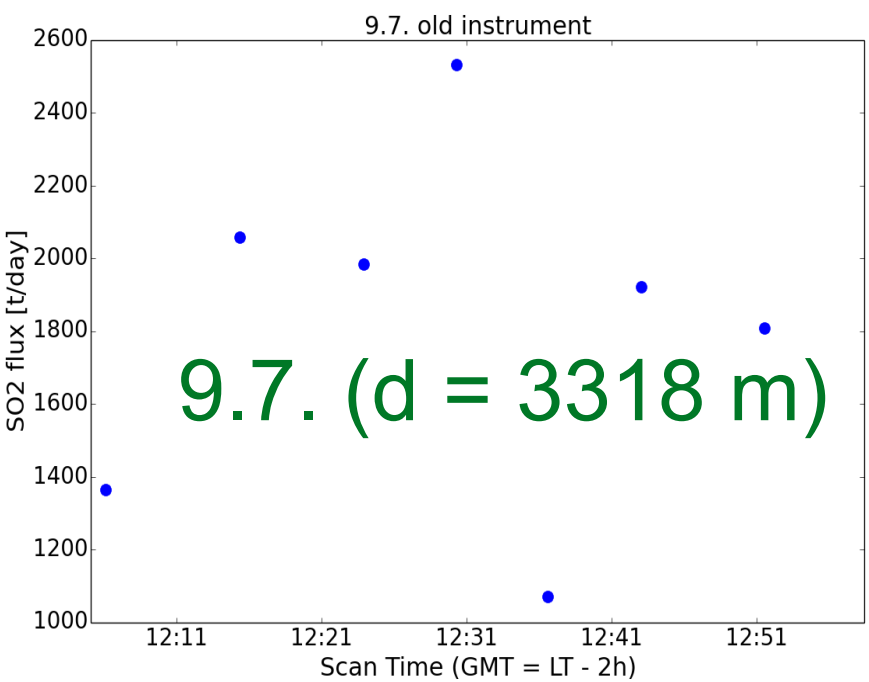
yellow: d = 3318 m red: d = 4532 m h plume a.s.l.: ~4000 m

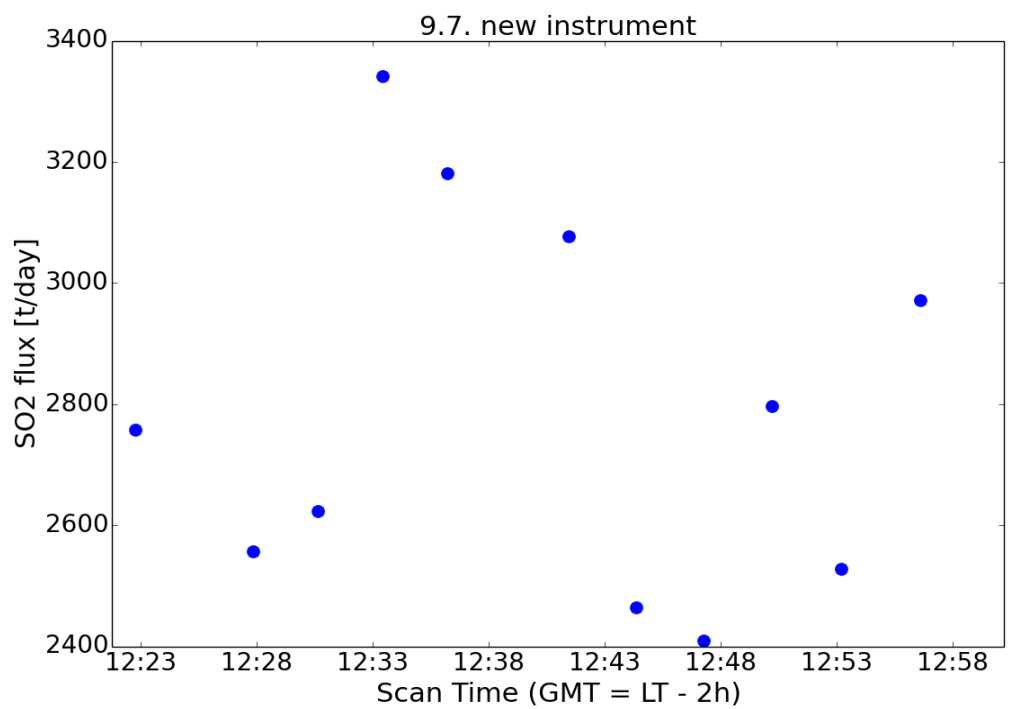

SO2/UV 2014_07_09, 14:06 - 14:57, neues MaxDOAS, ref @fixedref_1322 alt automeas_kurz 7x
9.7. (d = 3318 m)
1e17
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
SO2 SCDs [mol/cm^2]
0
20
40
60
80
100
120
140
160
180
elevation angle [°]


SO2/UV 2014_07_09, 14:22 - 14:59, neues MaxDOAS, ref @30° automeas_kurz 11x
1e17
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
SO2 SCDs [mol/cm^2]
40
60
80
100
120
140
elevation angle [°]
9.7. (d = 4532 m)


2014_07_09 14:06-14:57 SO2/UV
Elevation Angle [°]
Time
1e17


2014_07_09 14:22-14:59 SO2/UV
Elevation Angle [°]
Time
1e17
9.7. (d = 4532 m)

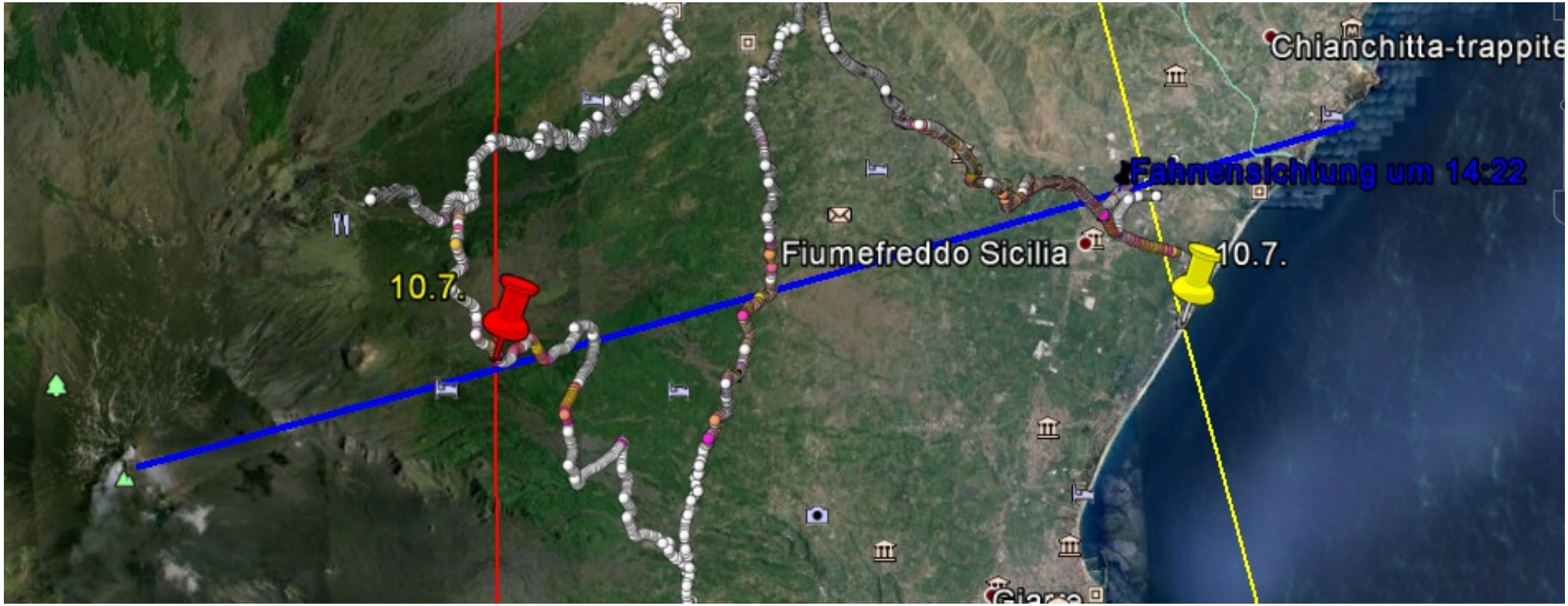

9.7. old instrument
SO2 flux [t/day]
Scan Time (GMT = LT - 2h)
9.7. (d = 3318 m)


9.7. new instrument
SO2 flux [t/day]
Scan Time (GMT = LT - 2h)

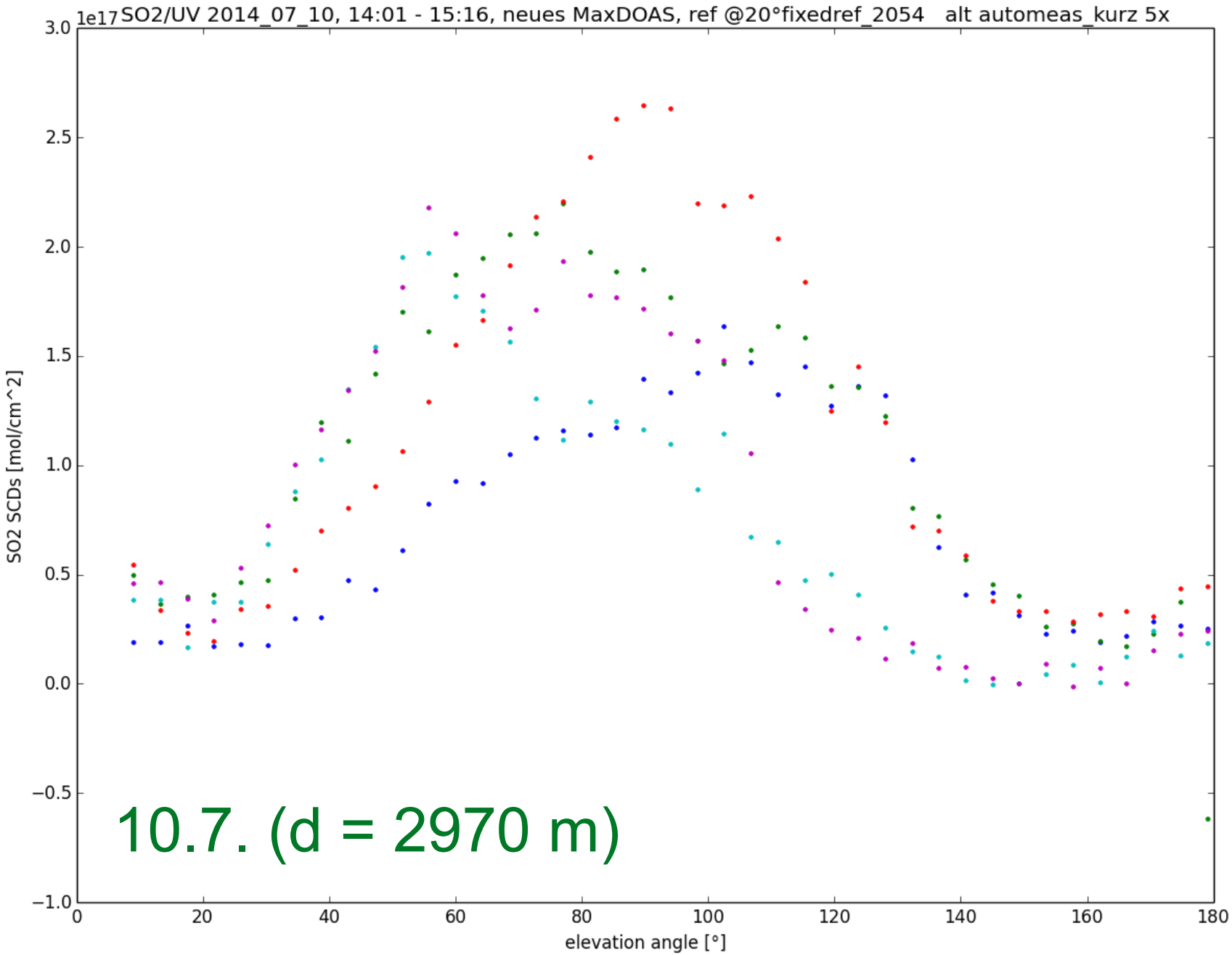
	plumeA (square)	plumeB	measurement
input	1212	1981	?
old	1624 /134%	2498 /126%	-
old -	1273 /105%	2066 /104%	1820
old (plume)	1184 /98%	1781 /90%	-
new	2163 /178%	1166 /59%	-
new -	1777 /147%	497 /25%	2791
new (plume)	1455 /120%	299 /15%	-

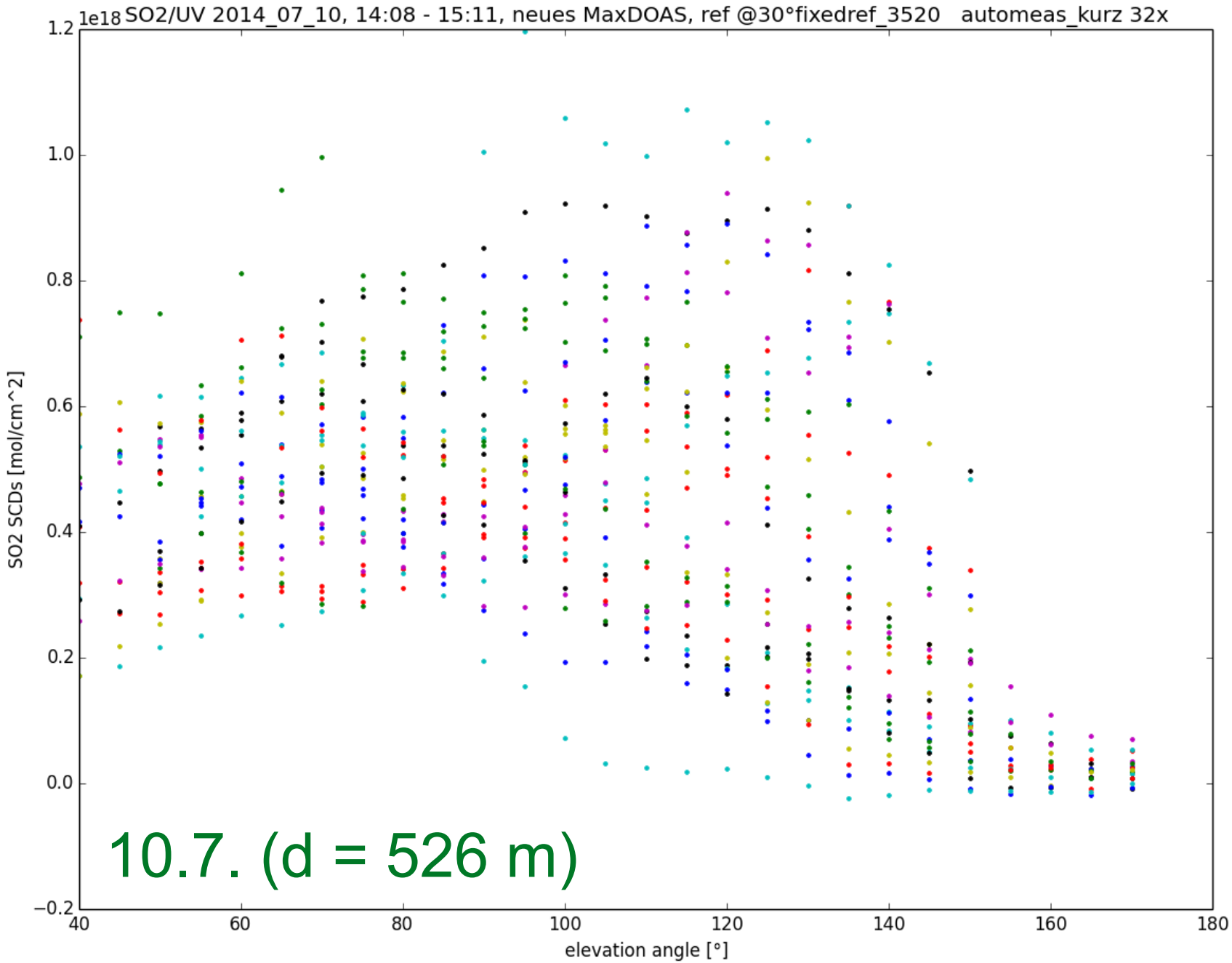
Table 6.17: Modeling results for the measurement geometries of 9.7., with wind speed v_{wind}=22 m/s. Values in t/day.

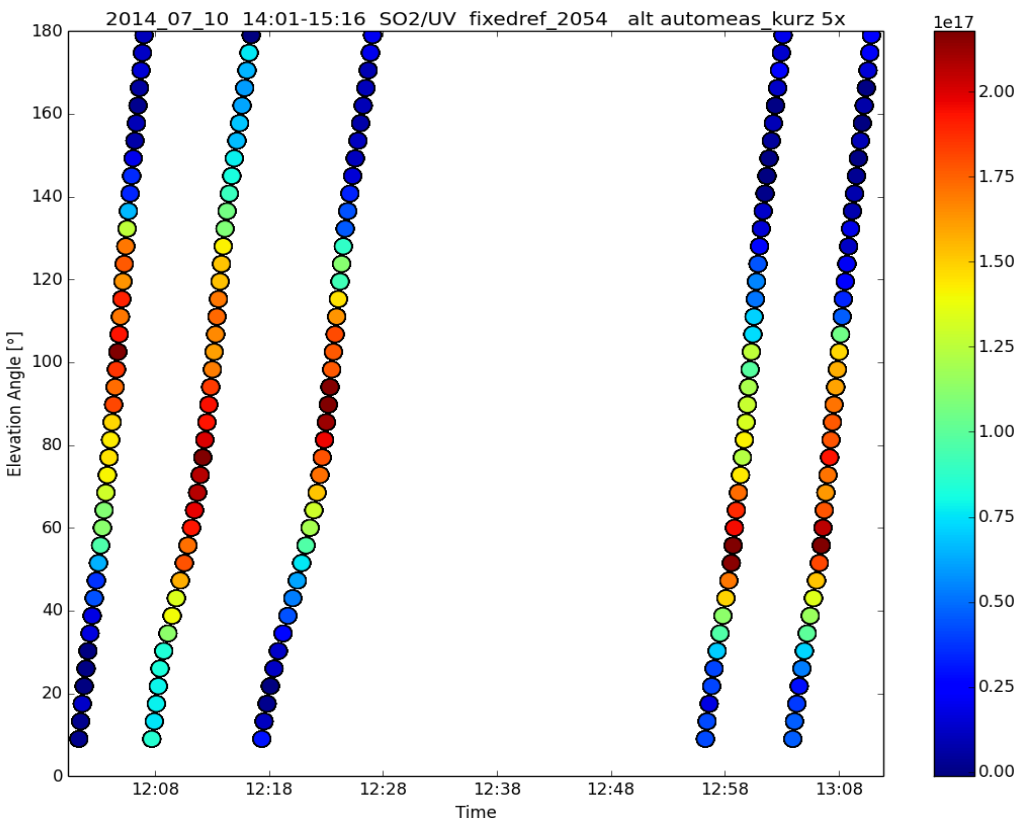
10.7.

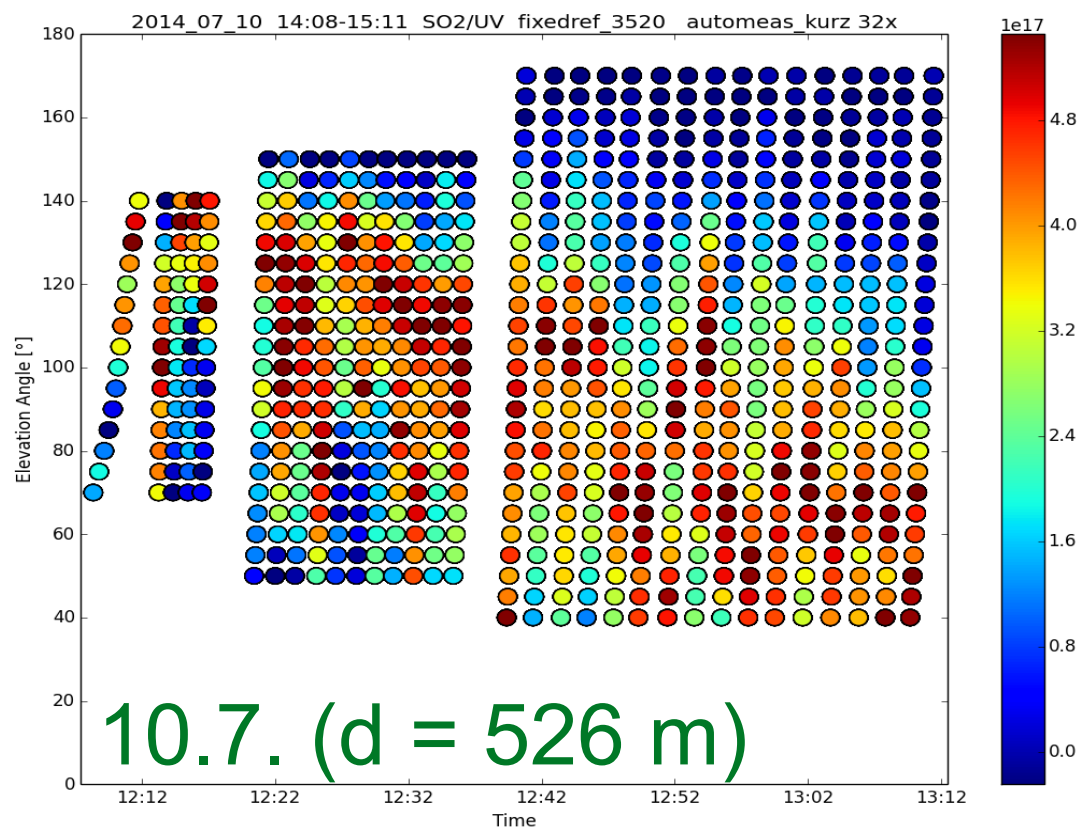


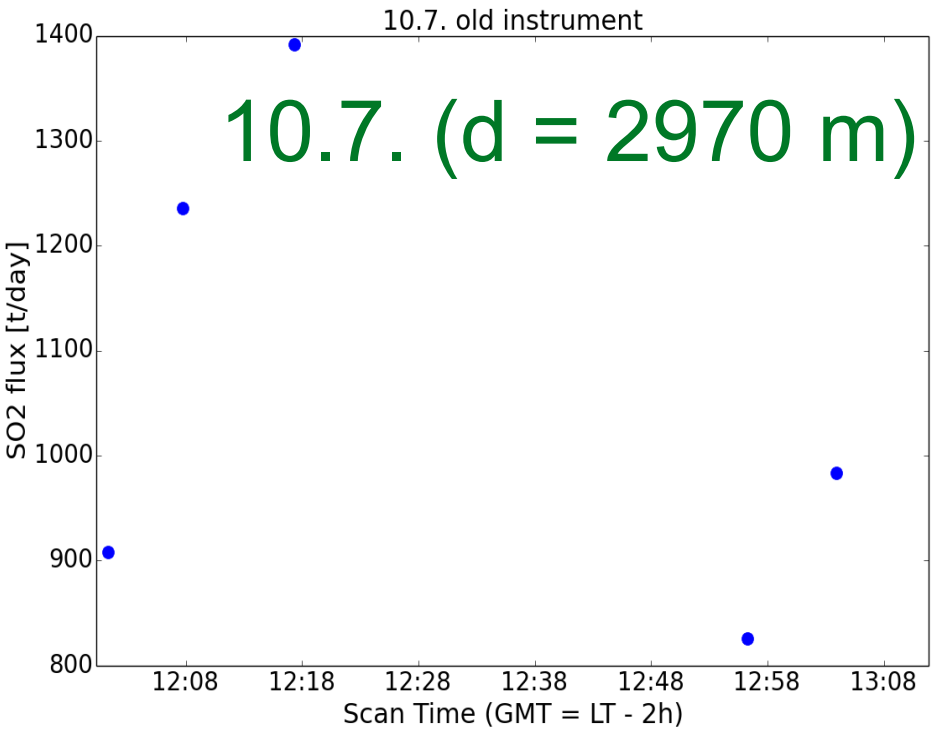
yellow: d = 2970 m red: d = 526 m h plume a.s.l.: ~2000 m

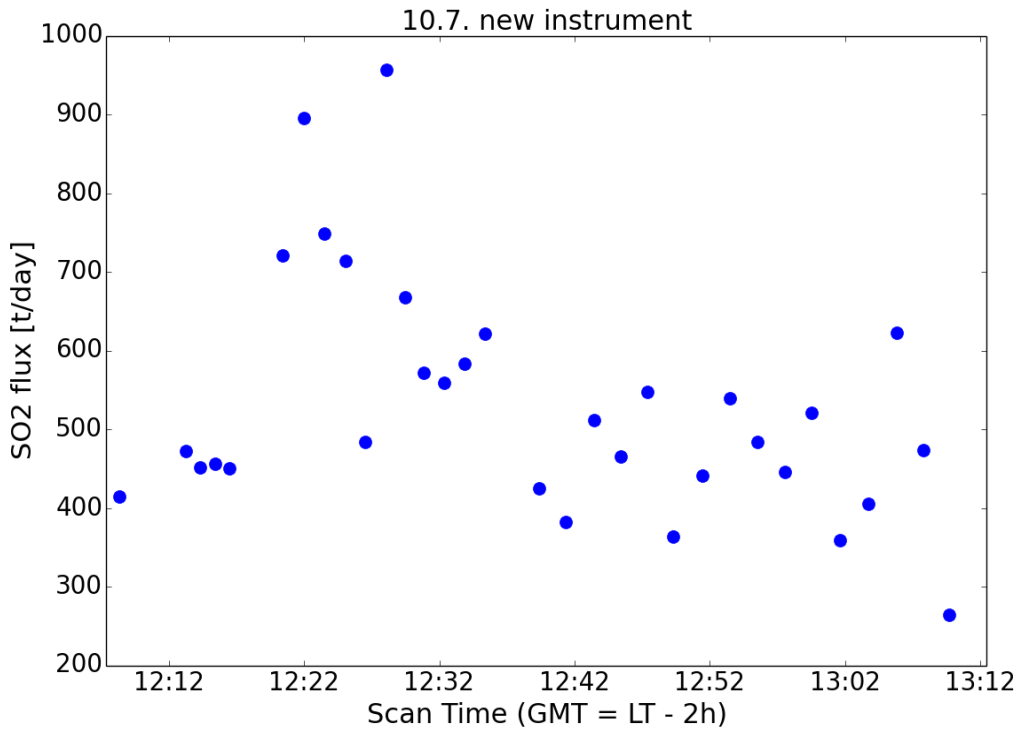

SO2/UV 2014_07_10, 14:01 - 15:16, neues MaxDOAS, ref @20°fixedref_2054 alt automeas_kurz 5x
1e17
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
SO2 SCDs [mol/cm^2]
0
20
40
60
80
100
120
140
160
180
elevation angle [°]
10.7. (d = 2970 m)


SO2/UV 2014_07_10, 14:08 - 15:11, neues MaxDOAS, ref @30°fixedref_3520 automeas_kurz 32x
1e18
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
SO2 SCDs [mol/cm^2]
40
60
80
100
120
140
160
180
elevation angle [°]
10.7. (d = 526 m)


2014_07_10 14:01-15:16 SO2/UV fixedref_2054 alt automeas_kurz 5x
Elevation Angle [°]
Time
1e17

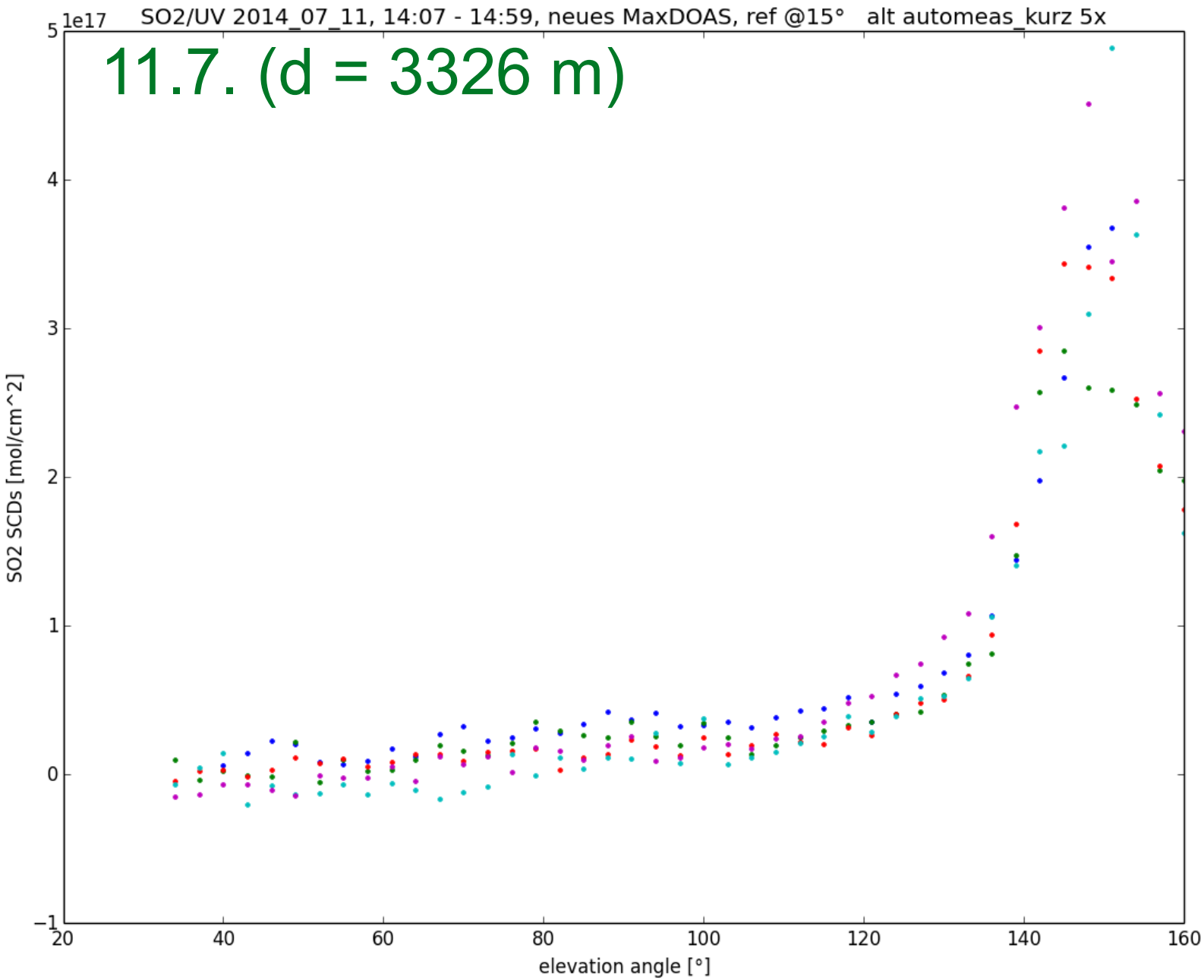

2014_07_10 14:08-15:11 SO2/UV fixedref_3520 automeas_kurz 32x
Elevation Angle [°]
Time
1e17
10.7. (d = 526 m)

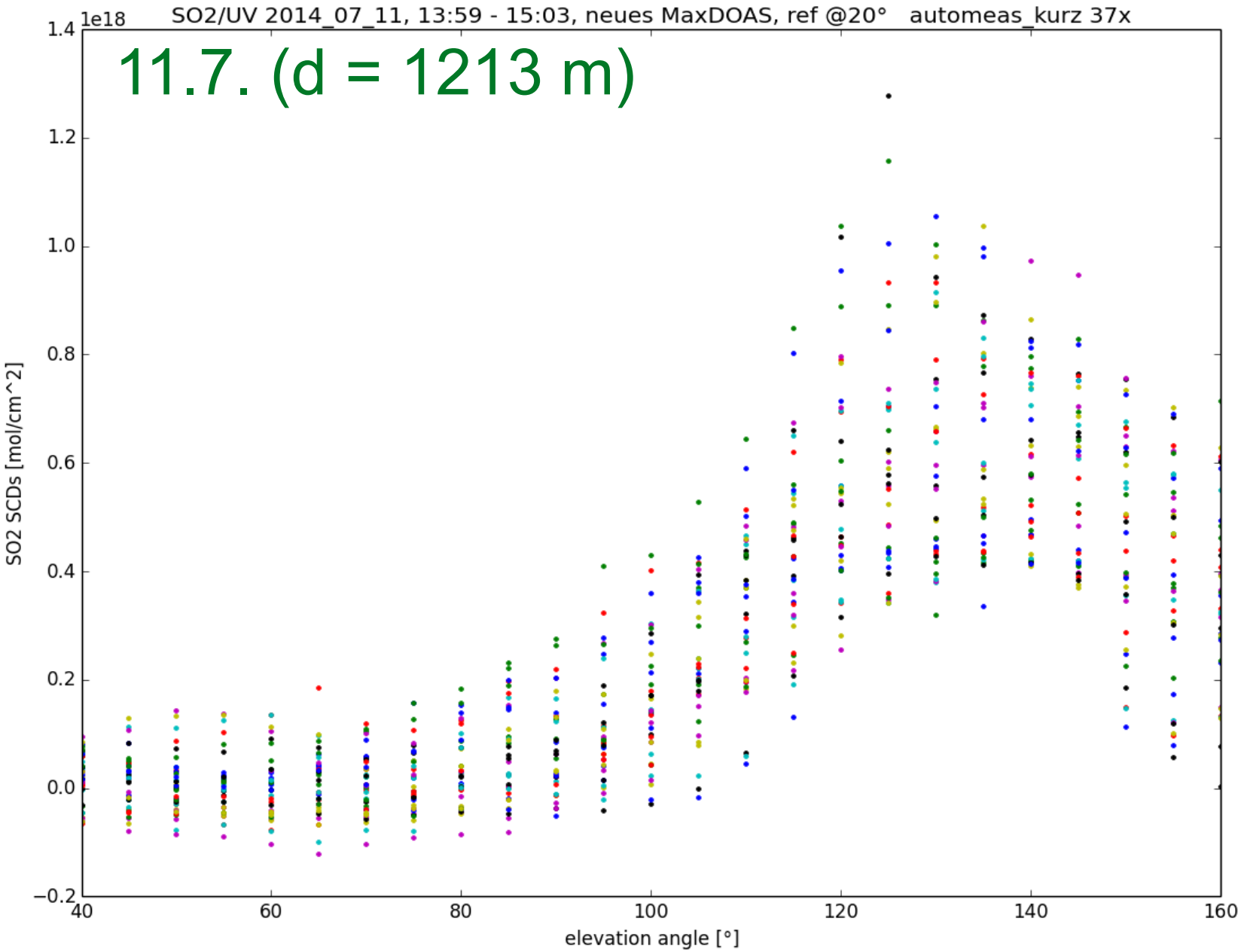

10.7. old instrument
10.7. (d = 2970 m)
SO2 flux [t/day]
Scan Time (GMT = LT - 2h)

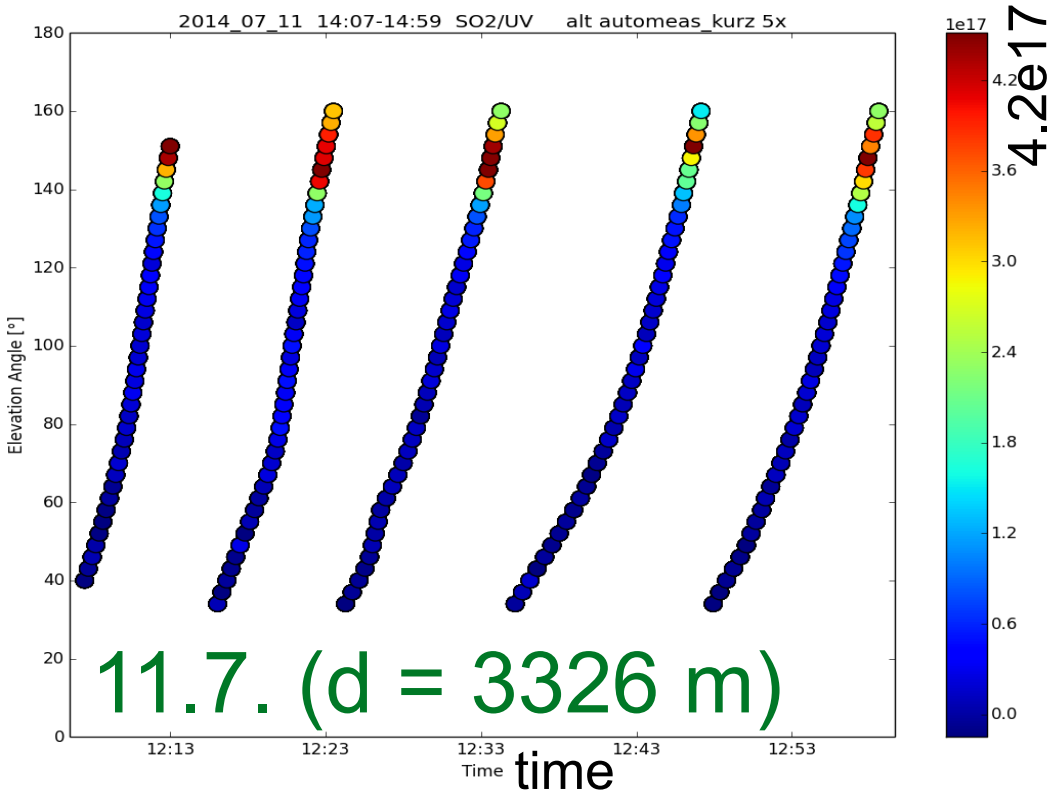

10.7. new instrument
SO2 flux [t/day]
Scan Time (GMT = LT - 2h)

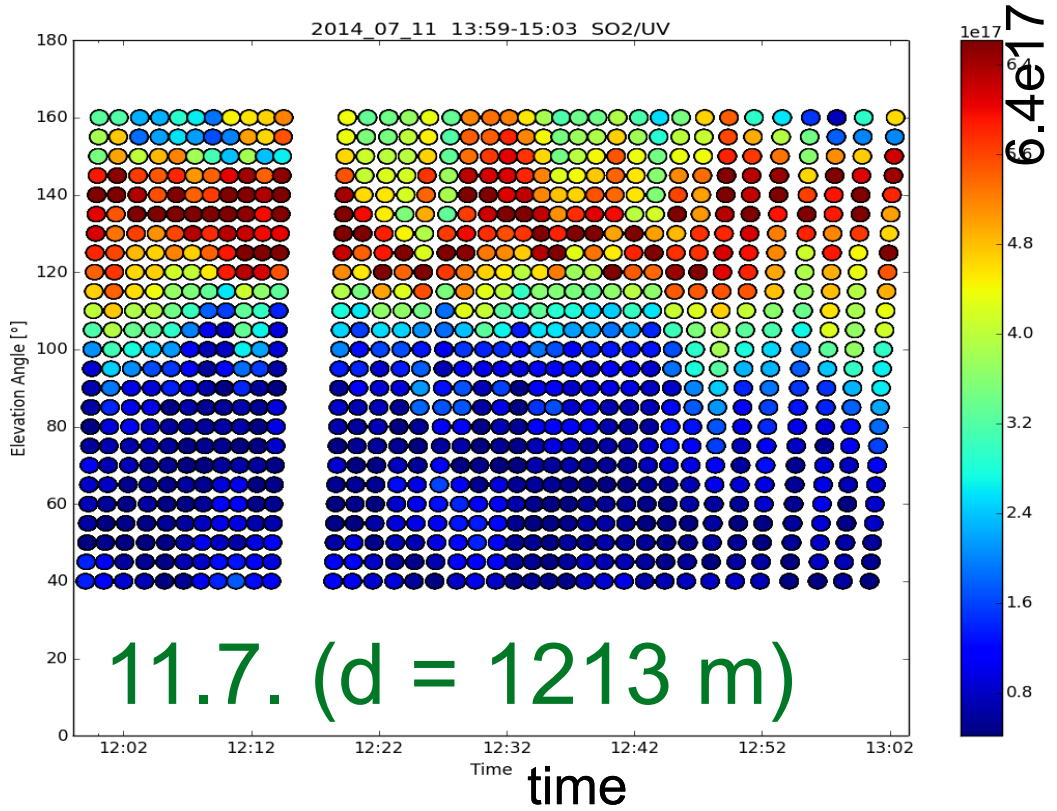
11.7.

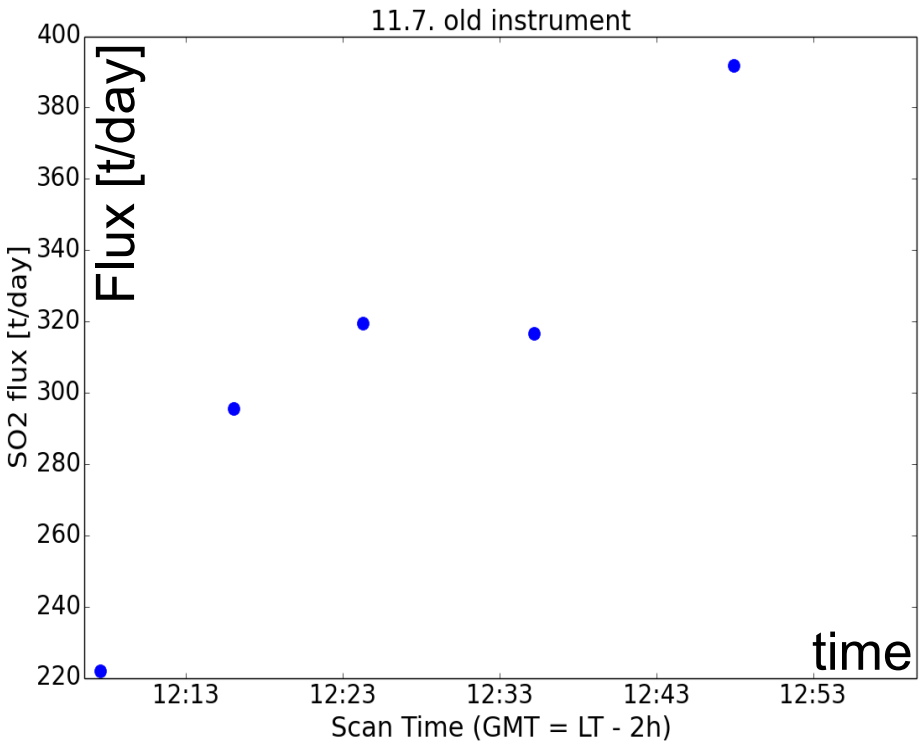
yellow: d = 3326 m red: d = 1213 m h plume a.s.l.: ~1700 m

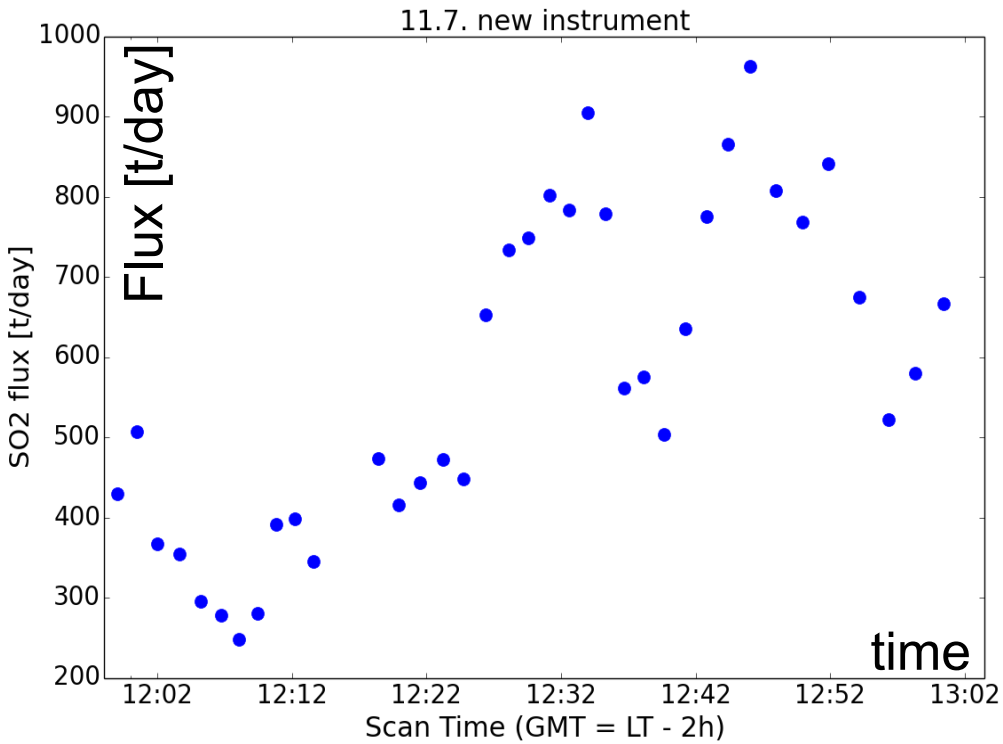

SO2/UV 2014_07_11, 14:07 - 14:59, neues MaxDOAS, ref @15° alt automeas_kurz 5x
1e17
11.7. (d = 3326 m)
SO2 SCDs [mol/cm^2]
elevation angle [°]
5
4
3
2
1
0
−1
20
40
60
80
100
120
140
160


SO2/UV 2014_07_11, 13:59 - 15:03, neues MaxDOAS, ref @20° automeas_kurz 37x
11.7. (d = 1213 m)
1e18
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
SO2 SCDs [mol/cm^2]
40
60
80
100
120
140
160
elevation angle [°]


2014_07_11 14:07-14:59 SO2/UV alt automeas_kurz 5x
Elevation Angle [°]
Time
time
11.7. (d = 3326 m)
1e17
4.2e17


2014_07_11 13:59-15:03 SO2/UV
Elevation Angle [°]
Time
time
11.7. (d = 1213 m)
1e17
6.4e17

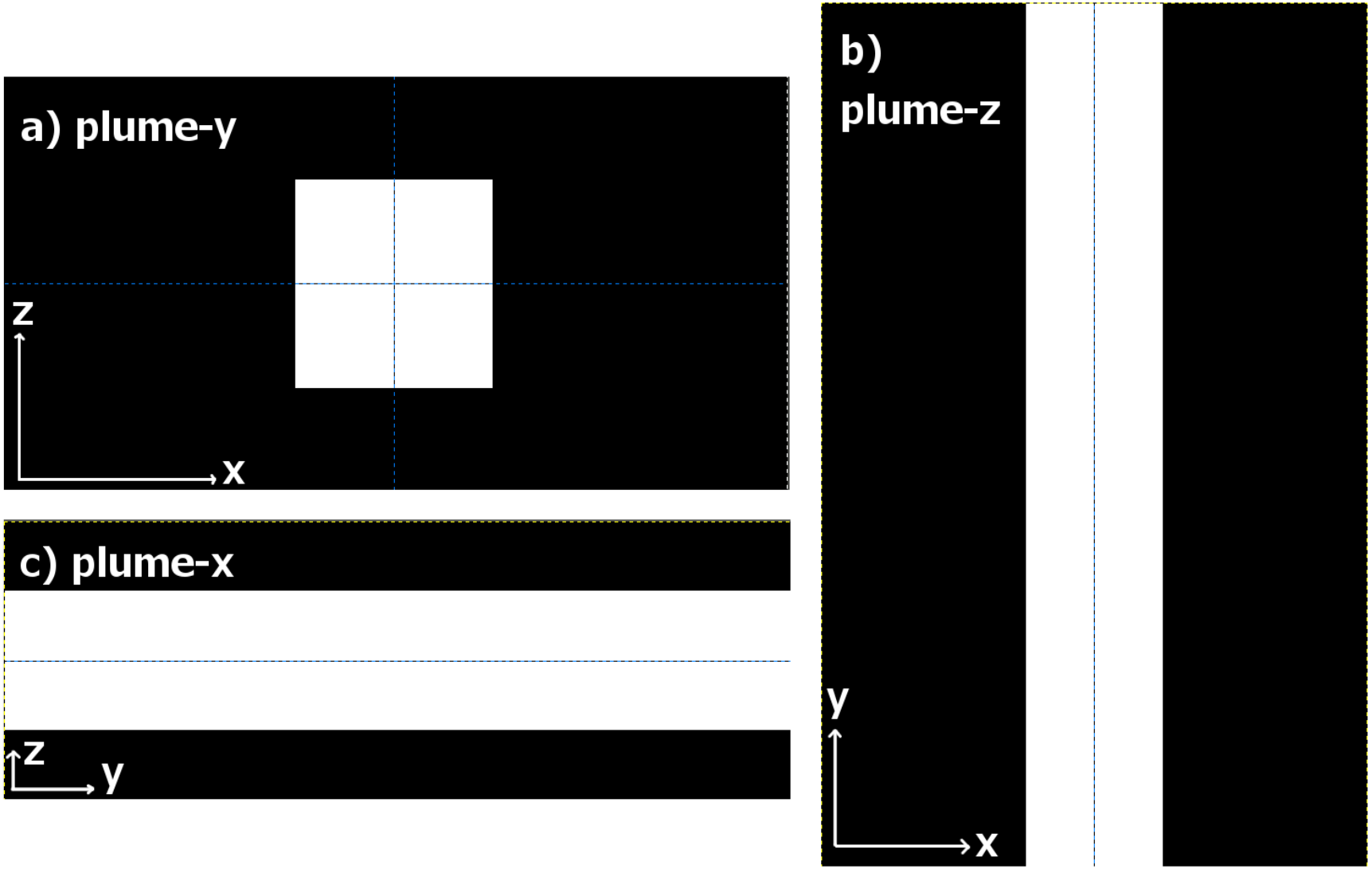

11.7. old instrument
Flux [t/day]
SO2 flux [t/day]
Scan Time (GMT = LT - 2h)
time


11.7. new instrument
Flux [t/day]
SO2 flux [t/day]
Scan Time (GMT = LT - 2h)
time

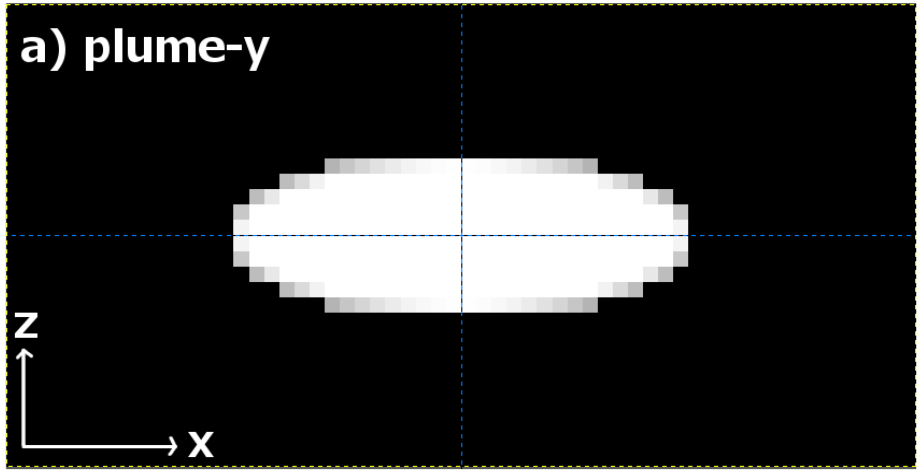
	plume3	plume2	plume2 /0.1	plume2 /1	plume2 /10	plume4	plume1 (square)	measurement
input	1377	893	893	893	893	481	546	?
old	1750 /127%	1185 /133%	1183 /132%	1178 /131%	1137 /127%	655 /136%	800 /147%	-
old -	1454 /106%	991 /111%	991 /111%	990 /111%	982 /110%	565 /117%	678 /124%	311
old (plume)	1110 /80%	901 /101%	901 /101%	901 /101%	909 /101%	493 /102%	587 /108%	-
new	1868 /136%	1160 /130%	1162 /130%	1172 /131%	1247 /140%	640 /133%	793 /145%	-
new -	1611 /117%	993 /111%	994 /111%	1007 /113%	1101 /123%	572 /119%	684 /125%	576
new (plume)	1749 /127%	1053 /118%	1155 /130%	1066 /119%	1150 /129%	595 /124%	750 /137%	-

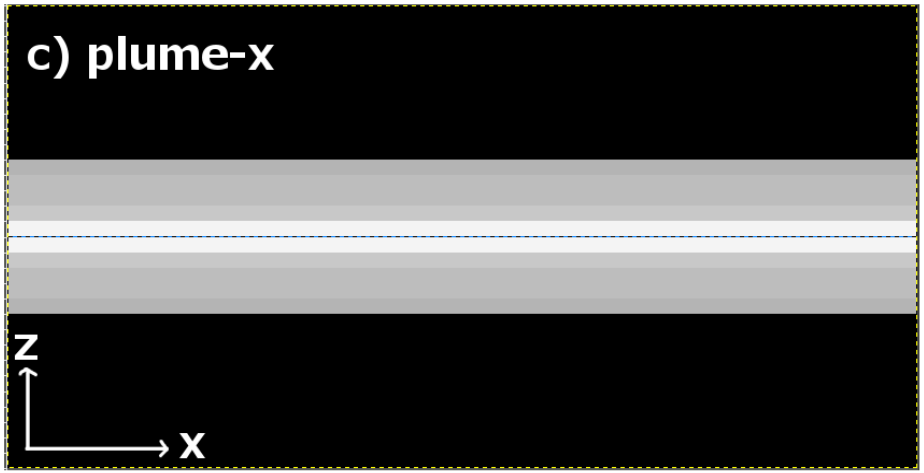
Table 6.18: Modeling results for the measurement geometries of 11.7., with wind speed v_{wind}=8.5 m/s. Values in t/day, percentages are with respect to the input value.

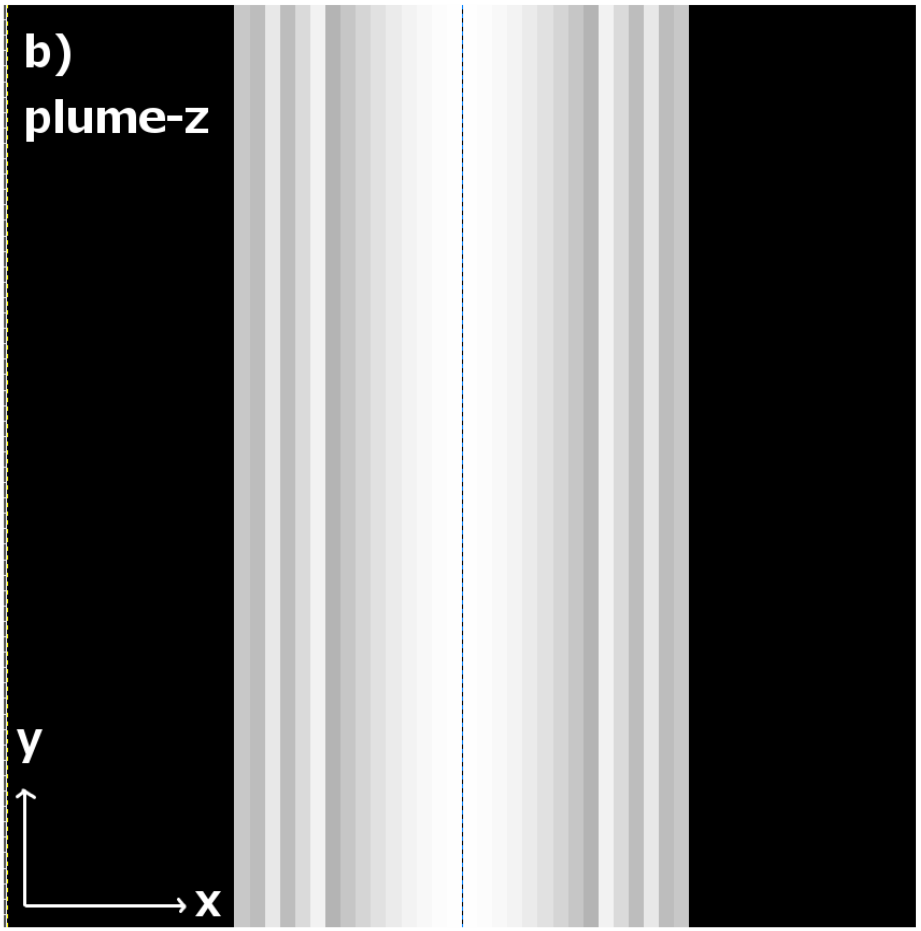
Plume 1/a/l



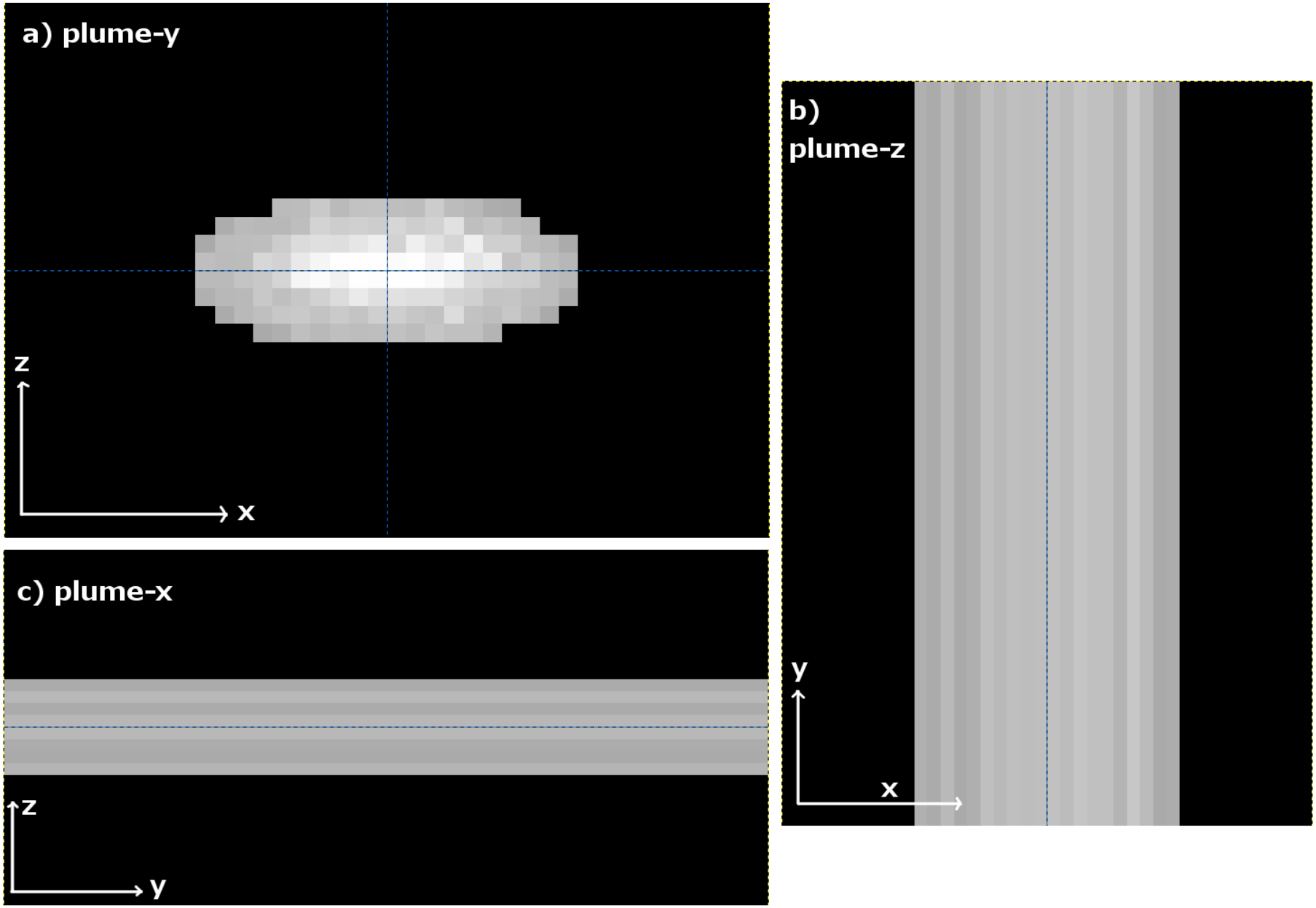
Plume 2/b/II



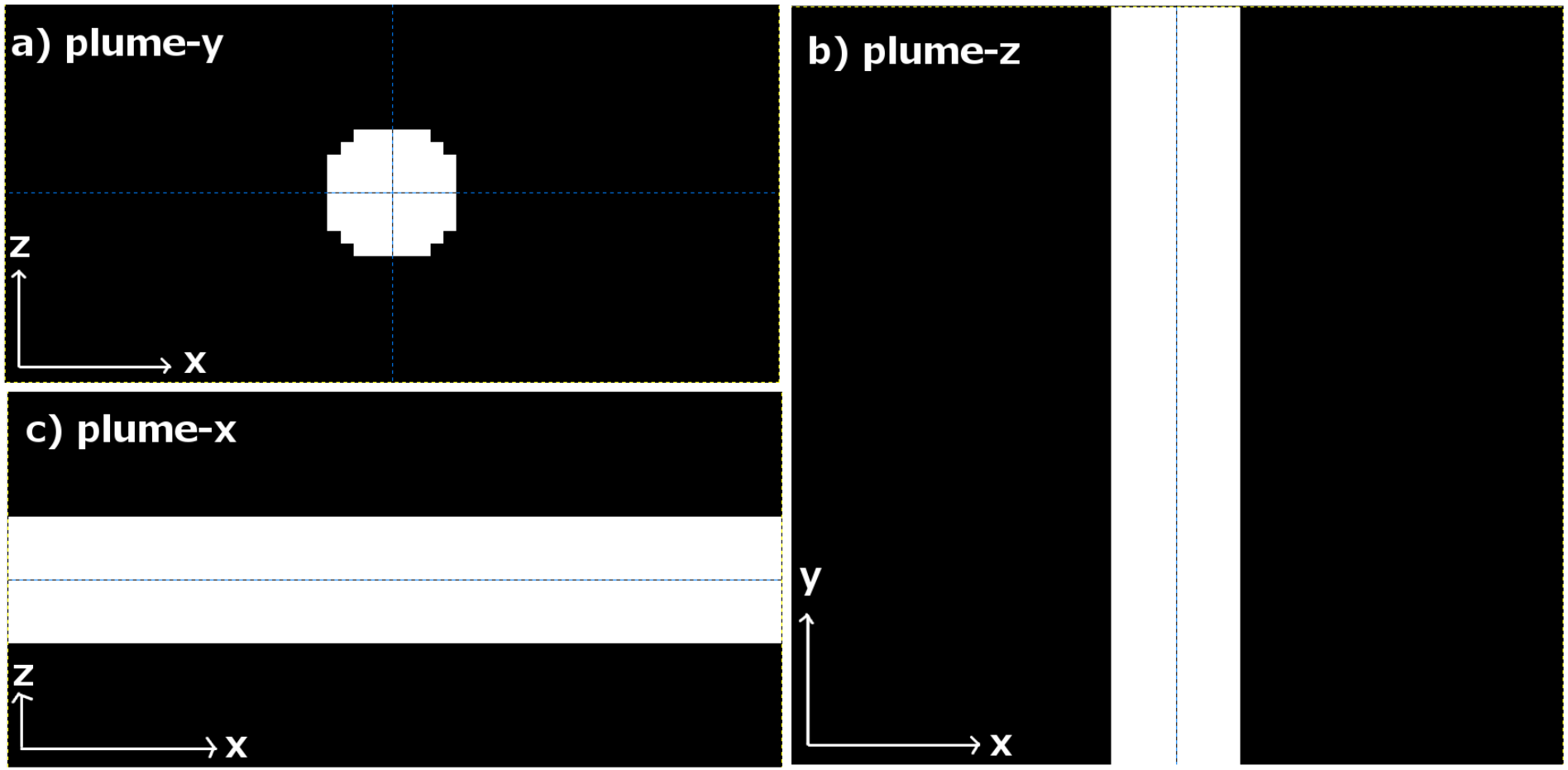


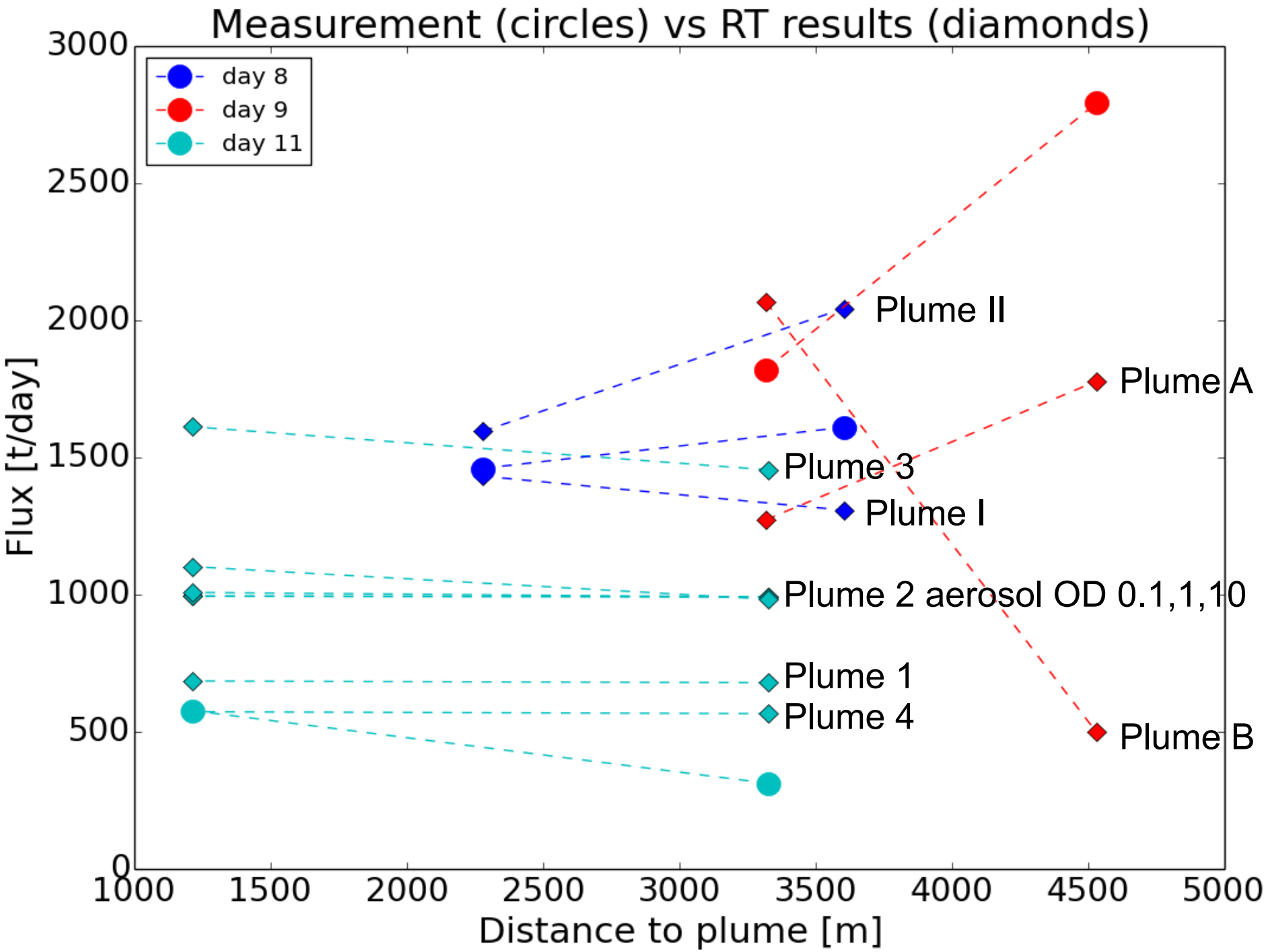


Plume 3



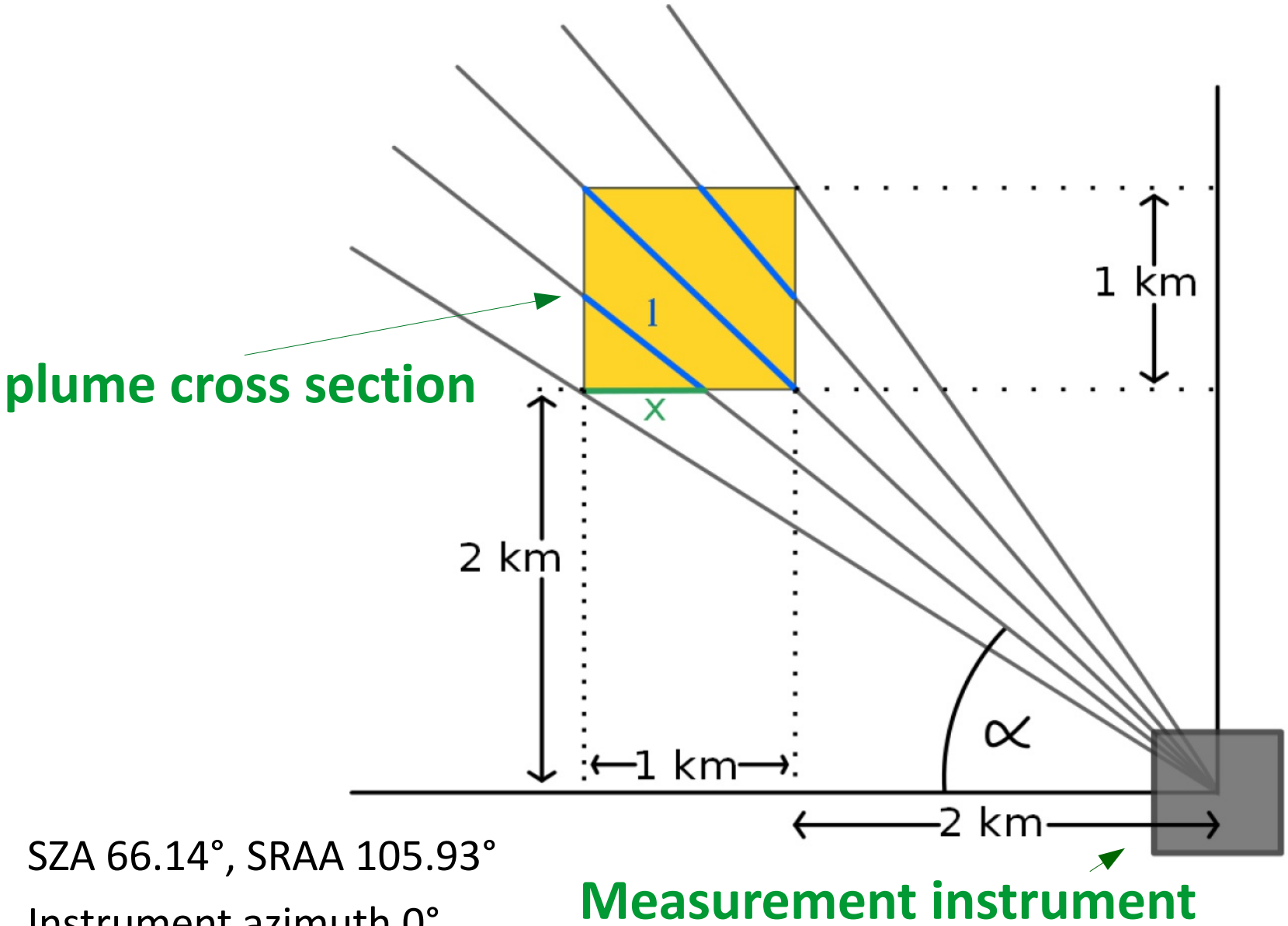
Plume 4




Measurement (circles) vs RT results (diamonds)
day 8
day 9
day 11
Plume II
Plume A
Plume 3
Plume I
Plume 2 aerosol OD 0.1,1,10
Plume 1
Plume 4
Plume B
Flux [t/day]
Distance to plume [m]
0
500
1000
1500
2000
2500
3000
1000
1500
2000
2500
3000
3500
4000
4500
5000

Mathematical Correction

Examining a simple Plume



SZA 66.14°, SRAA 105.93°

Instrument azimuth 0°

Plume extends several km perpendicular to image