An hour for the atmosphere…

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7/15.

Start with Atmospheric Optical Depth

Two basic measurement methods

1) Sunphotometers (handheld or autonomous): 2 degree field of view around sun (which subtends 0.5 degree full angle).

Most popular handheld now with our crowd, Microtops…you have seen already.

http://aeronet.gsfc.nasa.gov/new_web/maritime_aerosol_network.html

Atmospheric Optical depth

- Another method: Shadowband radiometer

Shadowband rotates and either provides a total downwelling irradiance E_s (no shadow) or the diffuse irradiance, E_{ds}. Direct solar irradiance, E_d, is roughly the difference:

$$E_d = (E_s - E_{ds})/\cos(\text{solar zenith})$$

J. Michalsky and J. Berndt. "Automated Multifilter Rotating Shadow-band Radiometer: an Instrument for Optical Depth and Radiation Measurements." *Applied Optics, Vol.33, No.22*. pp 5118-5125.

Either way

$$E_d = E_o \exp(-m\tau)$$

$$or$$

$$\ln(E_d) = \ln(E_o) - \tau m$$

$$or$$

$$\tau = -\frac{1}{m}\ln\left(\frac{E_d}{E_o}\right)$$

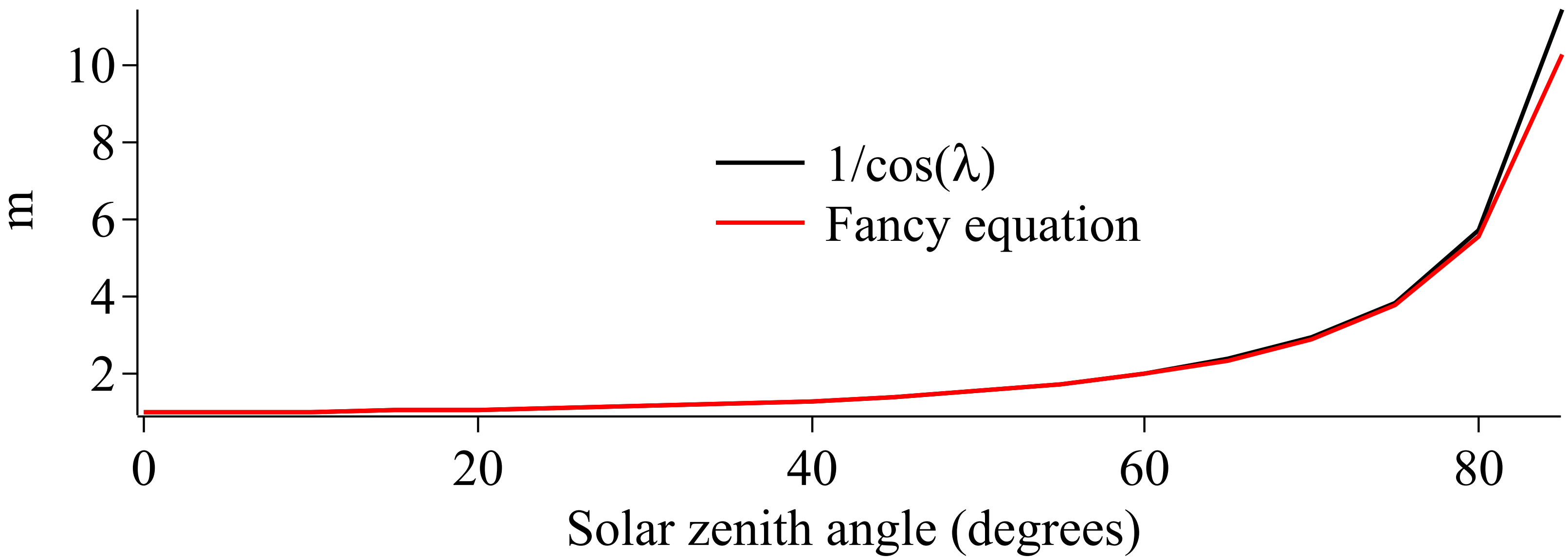
Either need E_o in terms of instrument units or have a stable day and take measurements with varying m and slope is $-\tau$.

E_o is the extraterrestrial solar irradiance in instrument units.

Calculate Air mass from solar ephemeris program (or tables) given date, time, location

- $m = 1.0 / [\cos(Z) + 0.50572 * (96.07995 - Z)^{-1.6364}]$
- Or m = 1/cos(z) NOTE z is solar zenith angle in degrees

Only matters above 70 degrees differenece is due to earth curvature



What should you expect for Optical depth

$$\tau_{total} = \tau_R + \tau_g + \tau_a$$

τ_R is rayleigh (molecular scattering) optical depth
τ_g is absorption by molecular gases (ozone, water vapor, etc).
τ_a is aerosol optical depth (scattering and absorption….).

For aerosol information choose spectral region where most gas absorption is avoided.
water vapor, choose good water vapor absorption band…
ozone, choose good ozone absorption band….

Rayleigh Optical depth

- Falls off as λ^{-4}

Full blown equation, from Bodhaine et al. 1999, supposed to be accurate in the visible to within 0.02%......

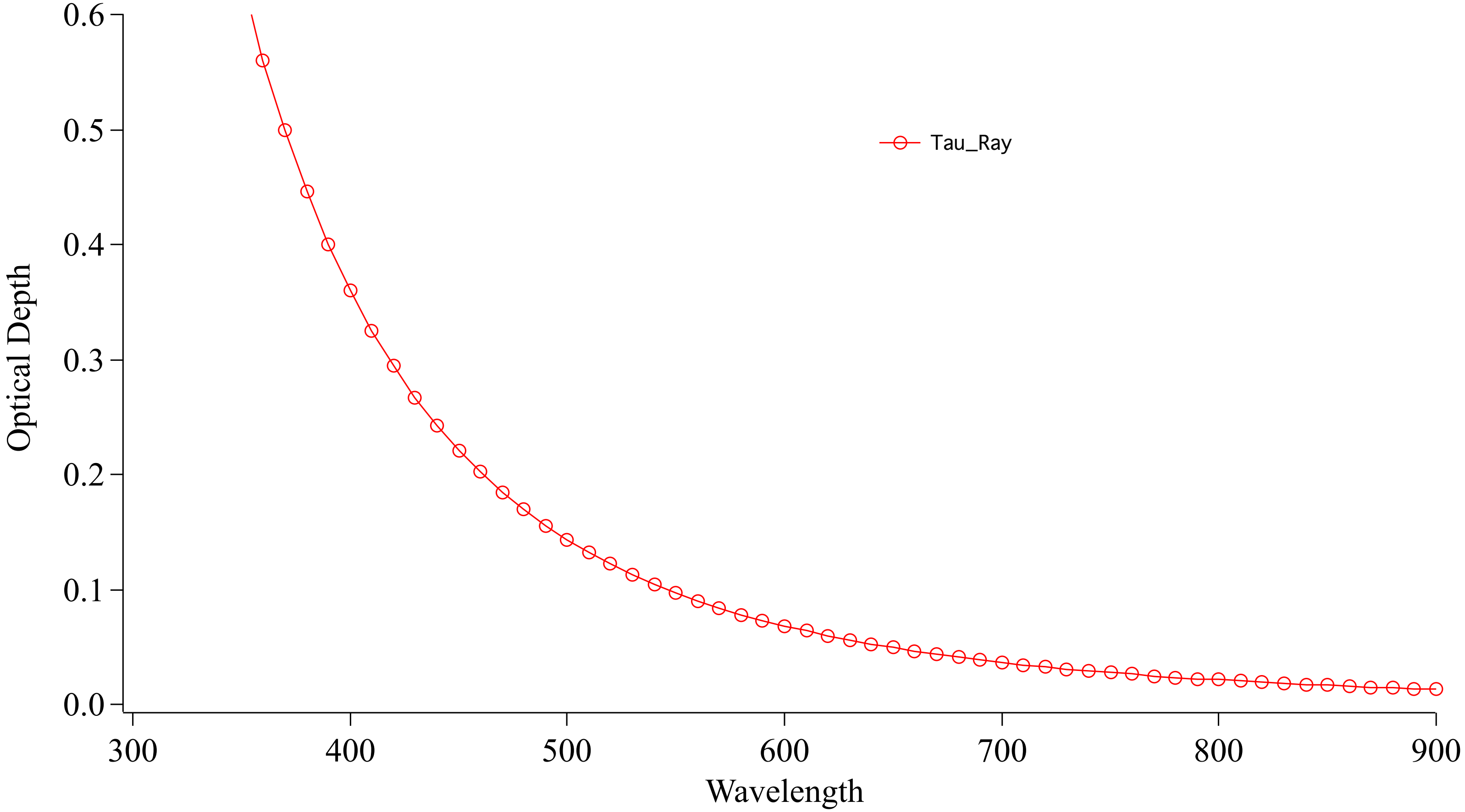
$$\tau_R = 0.0021520\left(\frac{1.0455996 - 341.29061\lambda^{-2} - 0.90230850\lambda^2}{1 + 0.0027059889\lambda^{-2} - 85.968563\lambda^2}\right)$$

At sea level, 45 deg latitude, 1013.25 mb Scale by pressure on that day

For microtops

Wavelength	τ_R
380	0.446
440	0.243
500	0.143
675	0.042
870	0.015

Rayleigh Optical Depth



Ozone

- In UV very strong, to measure ozone, differential UV bands are used (300, 305.5, 312.5 nm)
- In visible still evident. Ozone varies over the globe, so need to get column ozone value at measurement site from climatology or from some other source (TOMS, etc.). Typically reported in Dobson Units which are milli atm-cm. Get ozone optical depth by multiplying ozone absorption coefficient by DU/1000

Ozone climatology, Ziemke et al. 2011 (need to add tropospheric ozone, around 40DU, in paper)…MLS is Microwave Limb Sounder

Table 3. Global stratospheric column ozone zonal mean monthly mean climatology (in Dobson Units) derived from MLS integrated ozone
profiles at 5 latitude resolution.

Latitudes	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
85 N–90 N	311	350	352	340	324	297	269	253	243	246	267	279
75 N–80 N	319	363	363	359	330	301	272	254	248	254	275	287
65 N–70 N	330	359	359	355	332	304	280	269	262	265	280	299
55 N–60 N	332	355	354	347	329	307	291	277	270	270	282	309
50 N–55 N	329	349	348	340	325	306	290	276	267	267	279	308
45 N–50 N	321	338	338	331	318	299	280	269	262	260	273	302
40 N–45 N	307	320	324	318	304	286	266	259	254	252	265	289
35 N–40 N	284	292	300	298	286	271	256	252	248	243	252	269
30 N–35 N	257	262	272	275	269	259	251	248	244	237	237	247
25 N–30 N	234	238	248	255	256	252	248	246	242	234	229	230
20 N–25 N	221	224	234	242	246	246	245	244	240	232	224	219
15 N–20 N	215	218	227	235	240	242	244	245	241	232	223	215
10 N–15 N	214	216	224	232	237	240	244	245	242	232	223	214
5 N–10 N	215	217	223	230	234	237	240	242	240	231	224	216
0–5 N	219	221	226	231	232	233	236	238	237	229	225	219

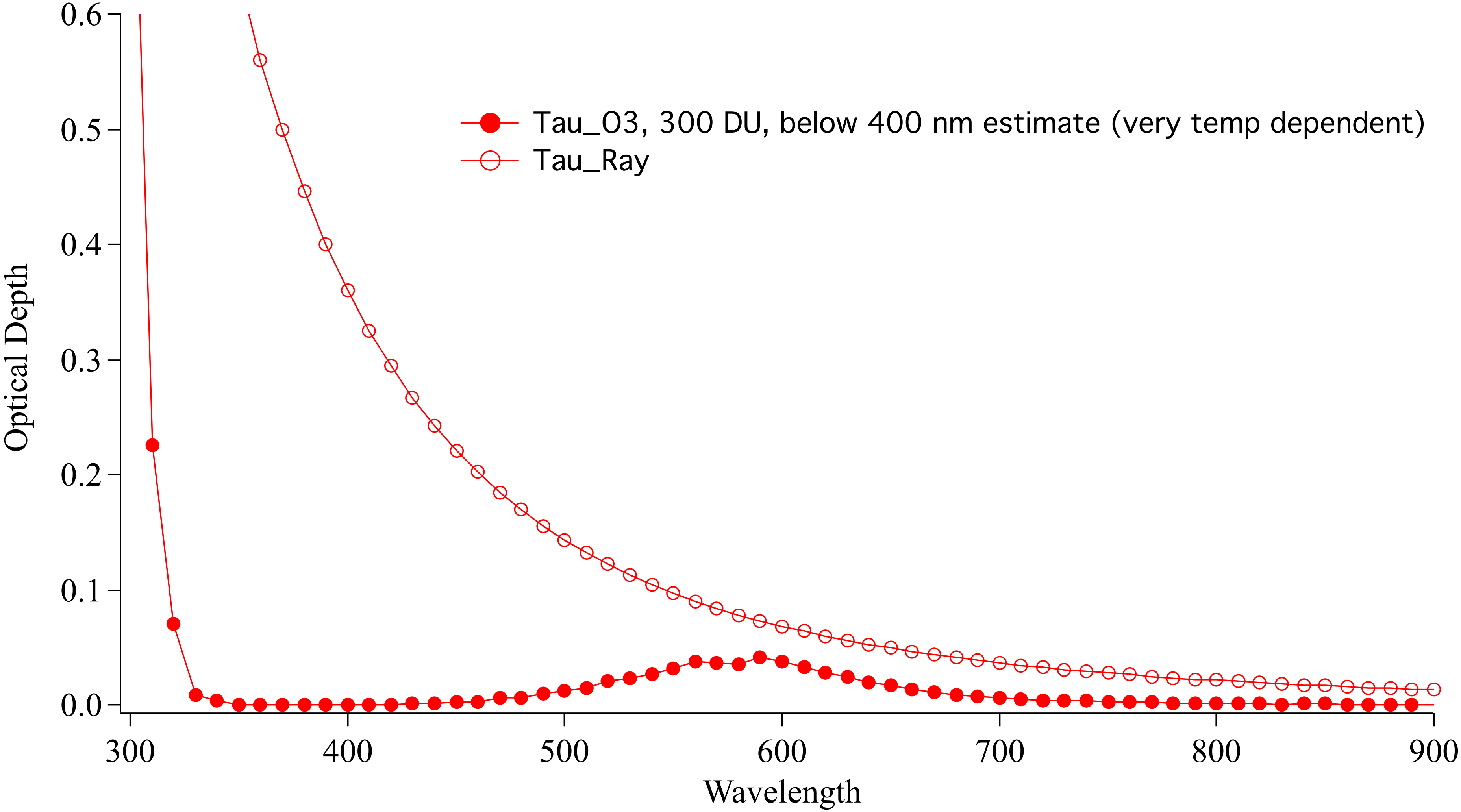
NOTE: I TRUNCATED TABLE>>>>HAS SOUTHERN HEMISPHERE ALSO

Ozone (308 DU, estimate for our cruise)

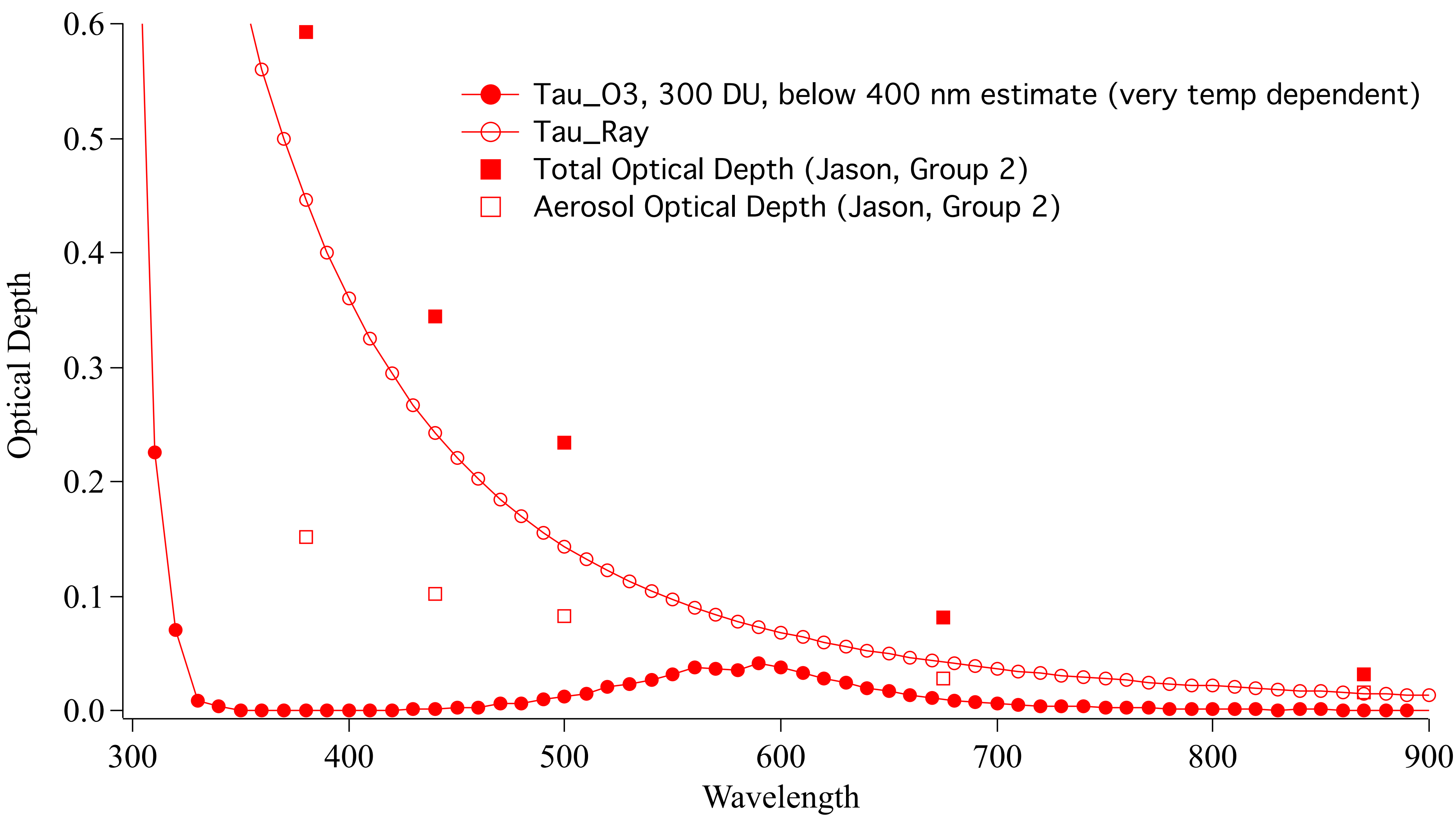
Wavelength	absorption coeff.	tauO3
380	0	0.000
440	0.0021	0.001
500	0.0320	0.010
675	0.0401	0.012
870	0.0013	0.000

308 DU from Ziemke et al. 2011, absorption coefficients from doe-sc-arm-tr-129.pdf and Gorshelev et al. 2014 (associated tables)

Ozone and Rayleigh

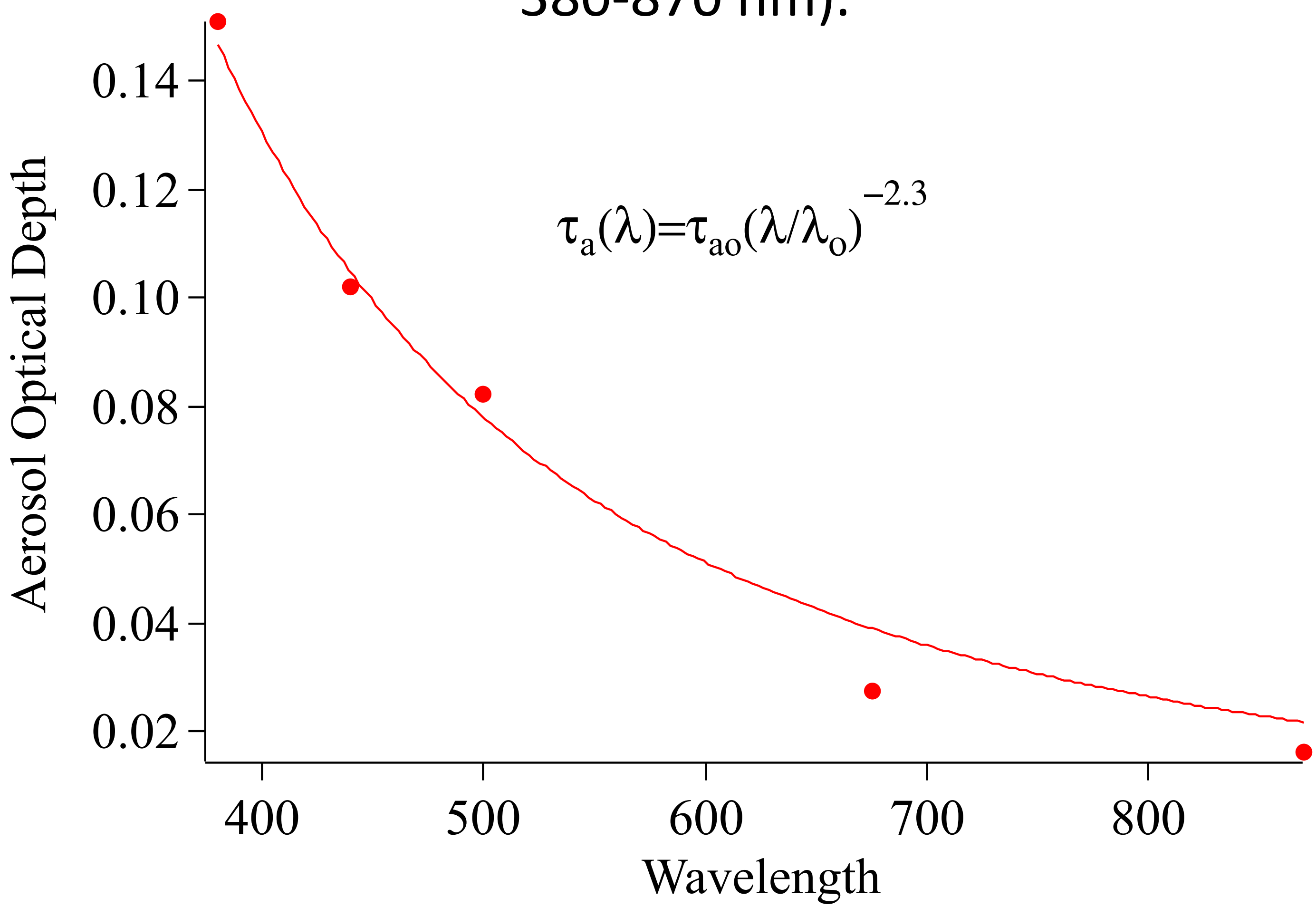


Your data



0.6
0.5
0.4
0.3
0.2
0.1
0.0
Optical Depth
300
400
500
600
700
800
900
Wavelength
Tau_O3, 300 DU, below 400 nm estimate (very temp dependent)
Tau_Ray
Total Optical Depth (Jason, Group 2)
Aerosol Optical Depth (Jason, Group 2)

Expect aerosol to follow angstrom law, with angstrom coeff. around 1. (lower often for maritime atmosphere and larger in polluted atmospheres…often follows different angstrom exponent over different ranges…so need to specify (Below is 380-870 nm).



For completeness, NO_2

- Shaw, 1976..discusses in respect to optical depth
- Peak at 390 nm, falls off to half this value at 325 nm and 480 nm
- Shaw estimated the optical depth could vary between 0.008 and 0.087 at 390 nm for values of NO^2 of 5×10^{-3} to 0.4 atm-cm (note 0.4 atm-cm = 400 DU, 5×10^{-3} is 5 DU.

More recent data (derived from AERONET data) From Rublev et al 2014.

Table 1. Types of Regions in Dependence on Column NO_2

#	Region type	Description and Examples	Q_{NO2}, DU	τ_{NO2} (380 nm)	F_{NO2}, W/m^2 Sum.	Wint.
1	Oceanic and Remote - continental	Without own sources, no any NO_2 advection due to transfer within troposphere (East Pacific; Northern Caucasia; Oklahoma, the US)	0.1 ÷ 0.4	0.002 ÷ 0.007	0.5 ÷ 1.9	0.7 ÷ 2.6
2	Continental	Without own anthropogenic sources, some NO_2 advection from remote industrial areas; (Northern Europe; some parts of Russia)	0.4 ÷ 0.8	0.007 ÷ 0.014	1.9 ÷ 3.8	2.6 ÷ 5.2
3	Suburban	Without own powerful anthropogenic sources of NO_2, but a site is nearby the air plume of city or big industrial area (Northern part of West Siberia, nearby Norilsk steel mill)	0.8 ÷ 3.0	0.014 ÷ 0.051	3.8 ÷ 13.4	5.2 ÷ 18.5
4	Urban	There are own powerful sources of NO_2 (Moscow; Hamilton)	1 ÷ 15	0.017 ÷ 0.253	4.7 ÷ 58.7	6.5 ÷ 78.6

Extinction in the atmosphere

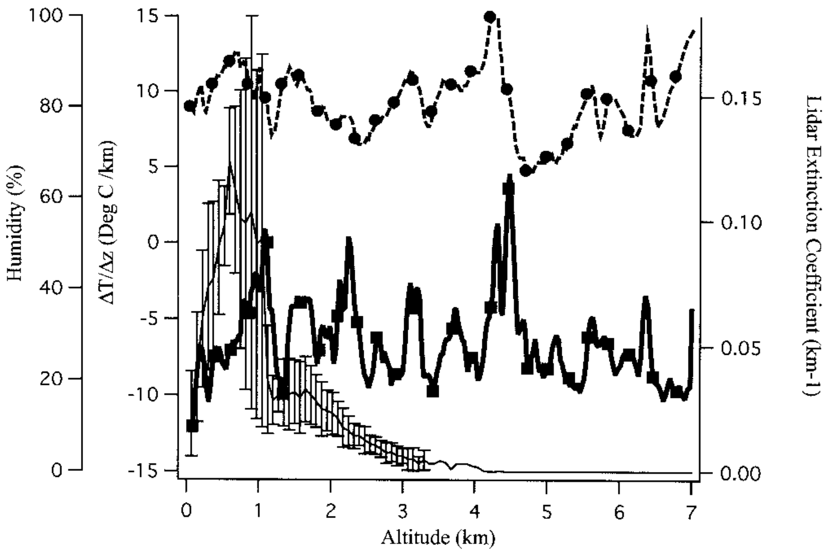


Figure 7. Radiosonde and lidar-derived profiles typical for region 2, Northern Hemisphere clean (31°N–15.5°N). This specific case was for DOY 18.5, 27.7°N. LIDAR extinction is shown as the fine line with no symbols. This is an average of the nearest three profiles (each of which is a 10 min cloud-free

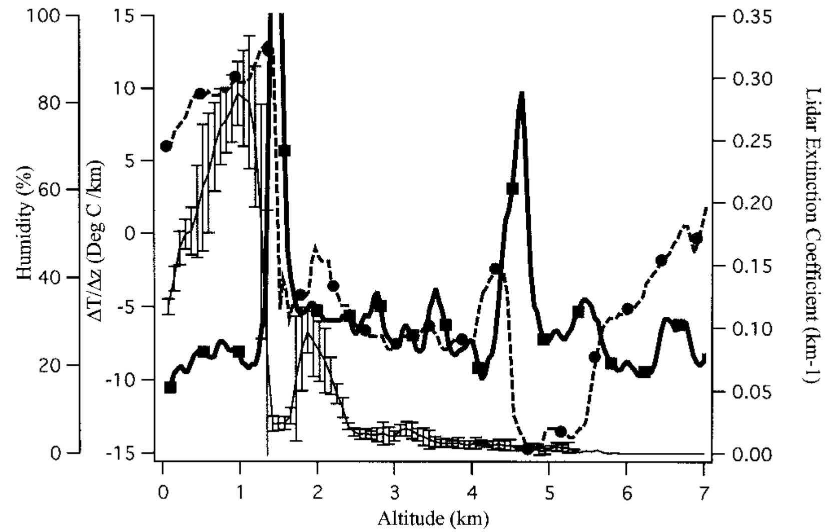


Figure 8. Region 3: dust (15.5°N–8°N). This specific case was for DOY 24.5, 11.2°N. Symbols and error bars are as in Figure 7. Extinction has increased from region 2, and there is another aerosol layer above the first temperature inversion (positive $\Delta T/\Delta z$).

To get frame of reference, extinction is the thin line, note units…km-1! Low density allows sky radiance to contain more information (more SS, less multiple scattering).

From Voss et al. JGR 2001

Methods to measure extinction

- Long pathlength (between mountains, etc) beam transmissometers.
- Lidars :Light Detection and Ranging…sort of like Radars….

Light backscattered by
Aerosols and molecules

Lidar signal attenuated by aerosols and gas going down

Lidar signal travels up at speed of light (3 nsec/meter)

Lidar signal attenuated by aerosols and gas going up

Lidar signal travels up at speed of light (3 nsec/meter)

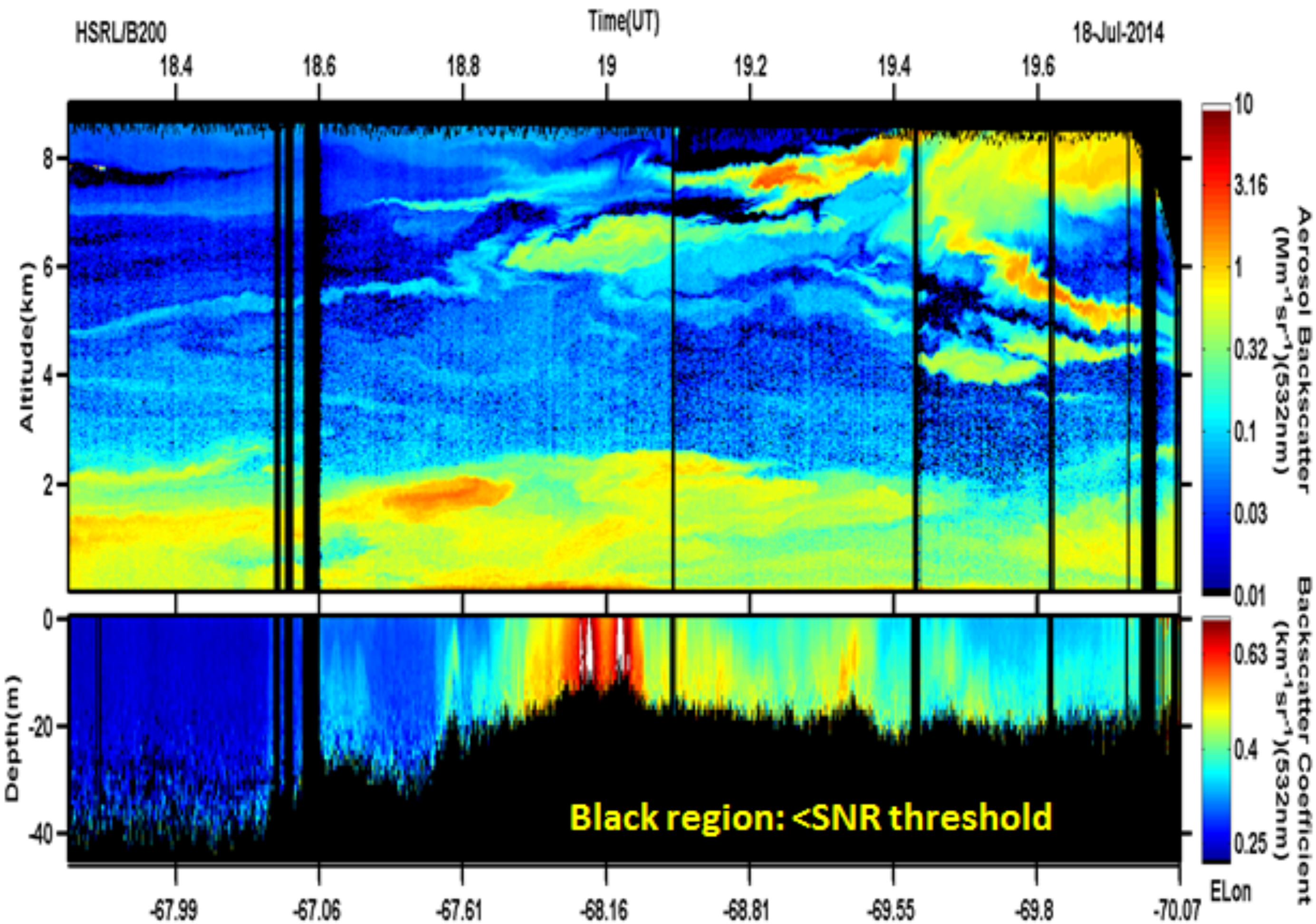
Signal is convolved extinction and Backscattering.

LIDAR

Lidar signal proportional to backscattering/attenuation
Takes 2*(3 nsec)*altitude (in meters)

25m resolution Is 0.15 usec for Transmit and receive

Lidars are hot topic…from SABOR, High Resolution Spectral Lidar (HRSL)

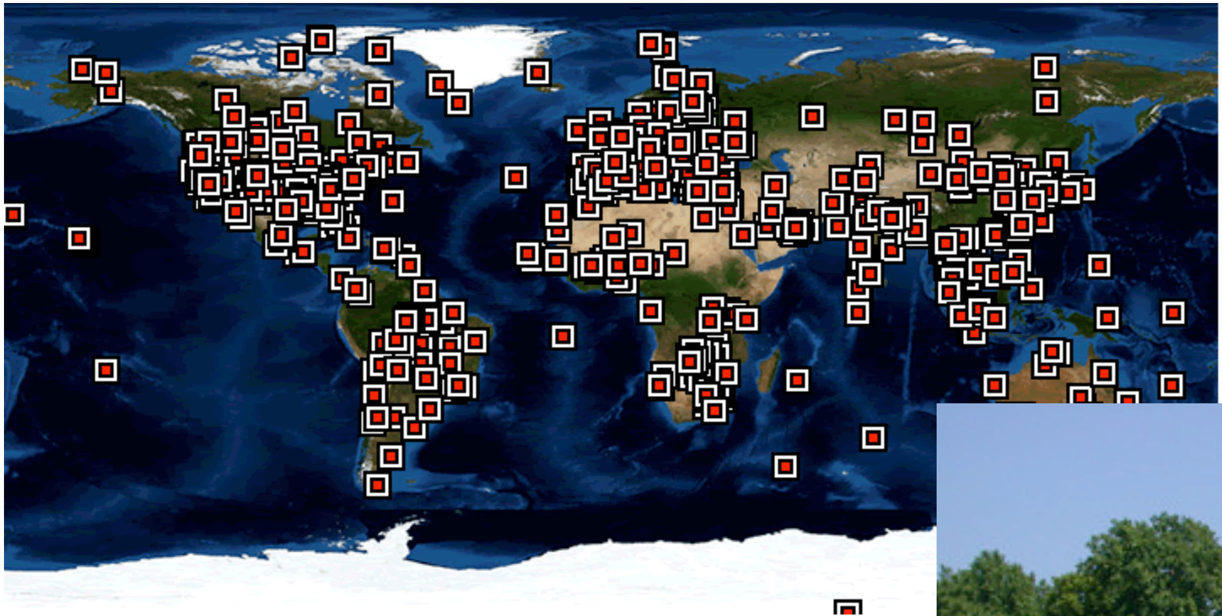


Aerosol Absorption….really hard to measure (think about value of extinction)

- Techniques:
- Capture aerosols on filters using high volume (filter all day) and measure reflectance, or transmittance through filter….
- Measure direct/diffuse sky irradiance and calculate missing part in diffuse…..
- Ring lasers (absorbing cavity inside laser)
- Photoacoustics

Lots of variability between techniques……really a relative mess

AERONET (Brent Holben, GSFC/NASA)



From
Aeronet.gsfc.nasa.gov

Note….not all stations are active

Based on CIMEL sunphotometers

- Standard: 1020-870-675-440-936-500-340-380 nm channels
- Measures direct solar irradiance and almucantor and principal plane sky radiance

Measurement frequency

- Direct solar irradiance at 0.25 AM intervals at large solar zenith angles, and 15 minute intervals at small solar zenith angles (high sun) with the 8 wavelengths (to get spectral aerosol optical depth)
- Principal plane and almucantor measurements at 440, 670, 870 and 1020 nm at air mass 4,3,2,1.7 in morning and afternoon.

Sky radiance inversions

- Does simultaneous inversion using AOD(4 λ) and sky radiance along almucantor at all 4 λ.
- If solar zenith angle is 60 deg, max scattering angle is 120 deg.

Dubovik and King (2000)

Retrieves, m ($1.33<n<1.6$, $0.0005<k<0.5$)

$0.05<r<15$ um, 22 sizes of dV/dln(r), Δln(r) constant

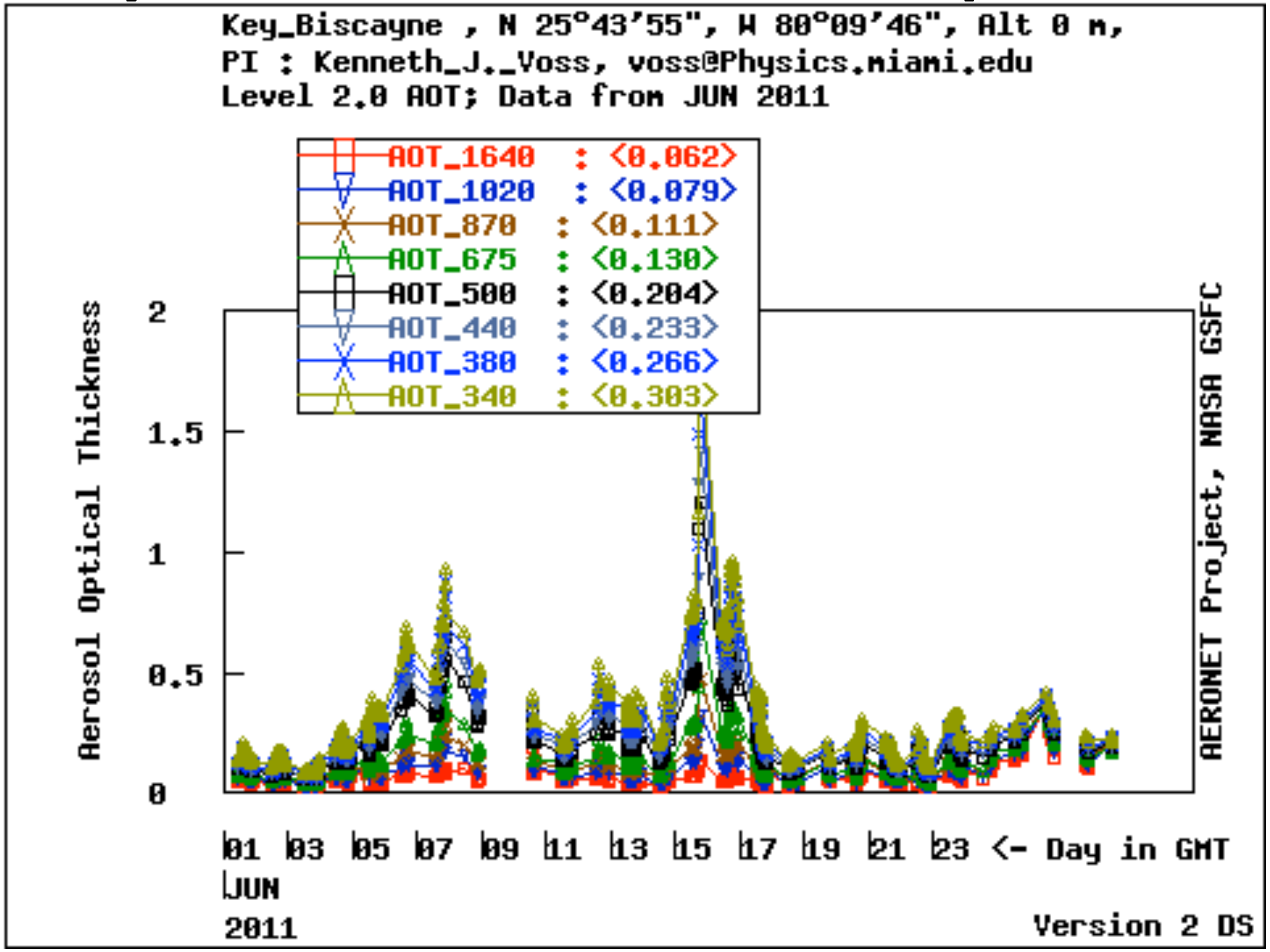
Estimated inversion acuarcy (version 1)

Table 4. Errors in the Size Distribution, Complex Refractive Index, and Single-Scattering Albedo

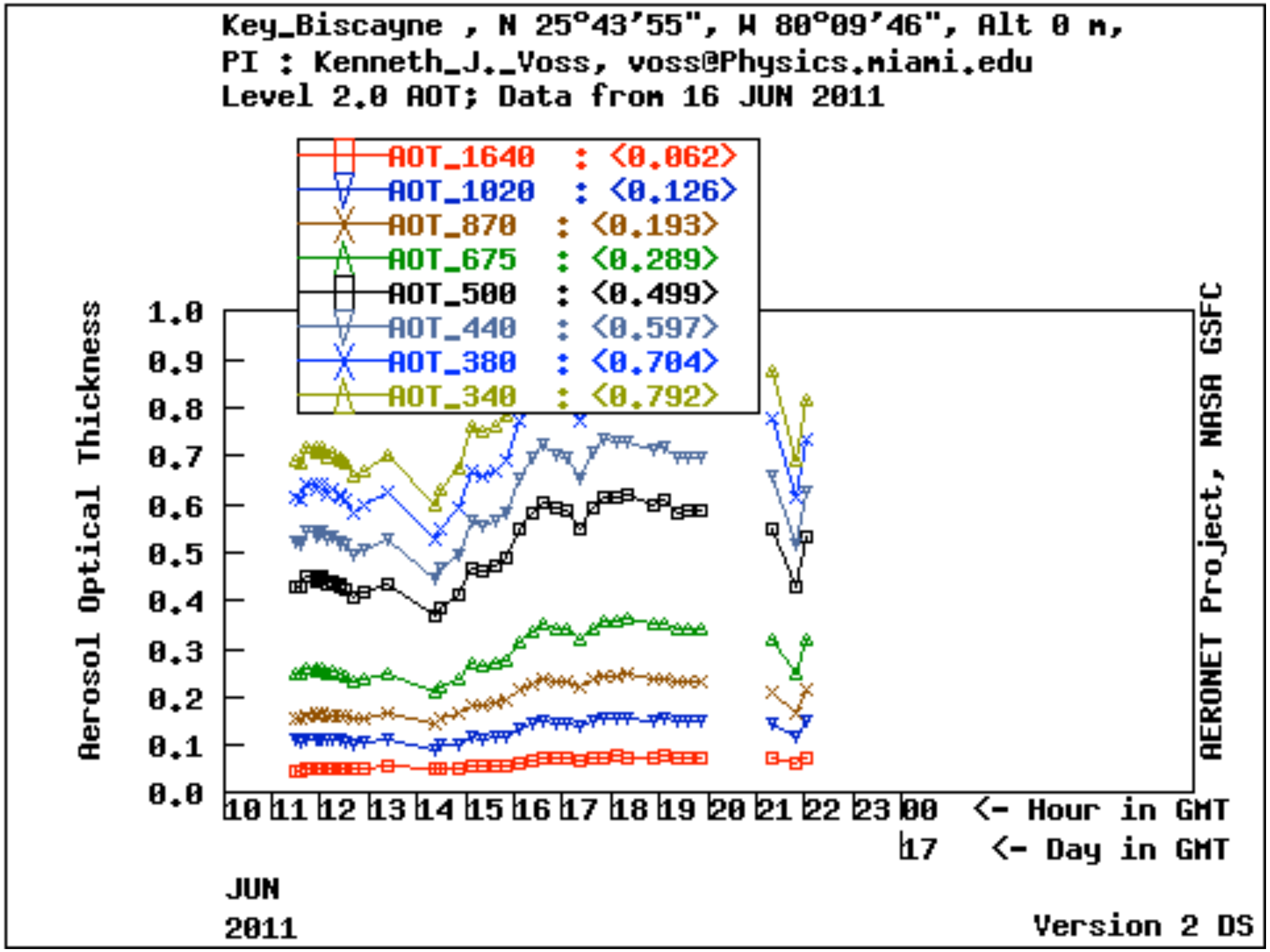
	Water-Soluble	Dust	Biomass Burning
$dV/d\ \ln r(r_i)$, %			
$0.1\ \mu m < r < 7\ \mu m$	15	35	25
$r < 0.1\ \mu m$ and $r > 7\ \mu m$	15–100	35–100	25–100
$n(\lambda)$			
$\tau_a(440) \leq 0.2$	0.05		
$\tau_a(440) > 0.2$	0.025		
$\tau_a(440) \geq 0.5$		0.04	0.04
$k(\lambda)$			
$\tau_a(440) \leq 0.2$	80–100%		
$\tau_a(440) > 0.2$	50%		
$\tau_a(440) \geq 0.5$		50%	30%
$\omega_0(\lambda)$			
$\tau_a(440) \leq 0.2$	0.05–0.07		
$\tau_a(440) > 0.2$	0.03		
$\tau_a(440) \geq 0.5$		0.03	0.03

Dubovik et al, 2000

Example inversions (from aeronet.gsfc.nasa.gov)….note always use Level 2.0 if possible!

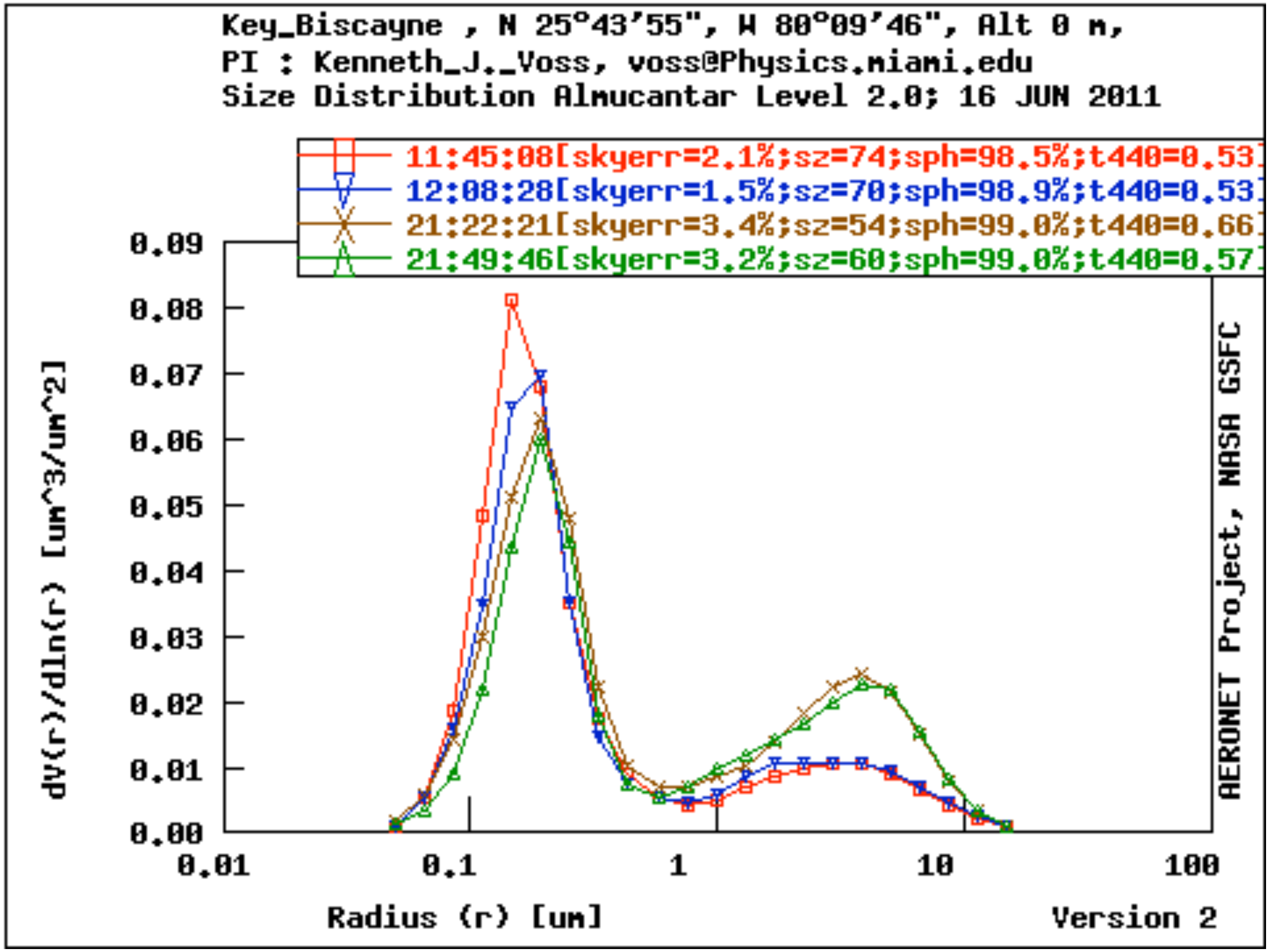


During Day



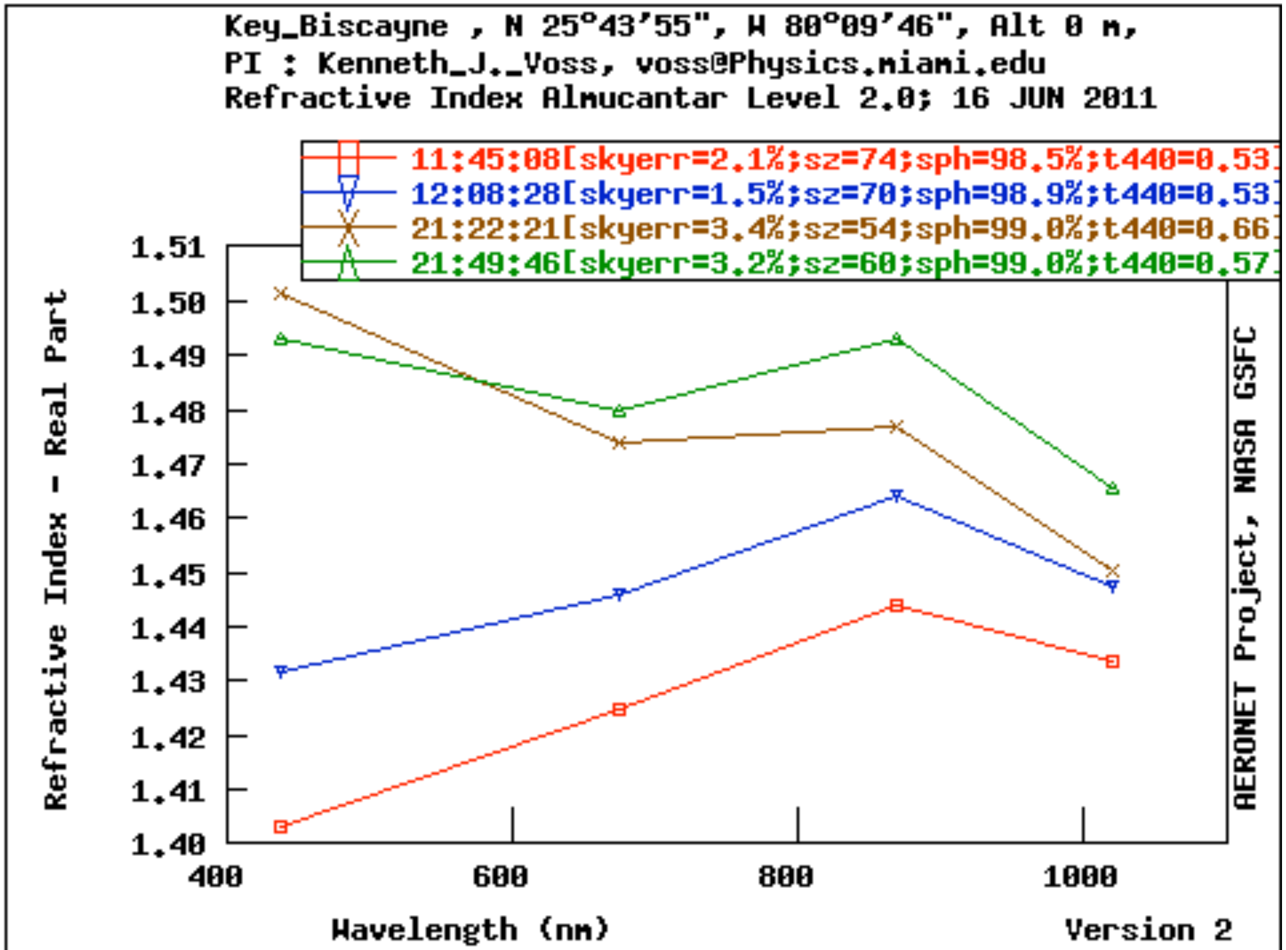
Key_Biscayne , N 25°43'55", W 80°09'46", Alt 0 m,
PI : Kenneth_J._Voss, voss@Physics.miami.edu
Level 2.0 AOT; Data from 16 JUN 2011
AOT_1640 : <0.062>
AOT_1020 : <0.126>
AOT_870 : <0.193>
AOT_675 : <0.289>
AOT_500 : <0.499>
AOT_440 : <0.597>
AOT_380 : <0.704>
AOT_340 : <0.792>
Aerosol Optical Thickness
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
10 11 12 13 14 15 16 17 18 19 20 21 22 23 00 <- Hour in GMT
17 <- Day in GMT
JUN
2011
AERONET Project, NASA GSFC
Version 2 DS

size

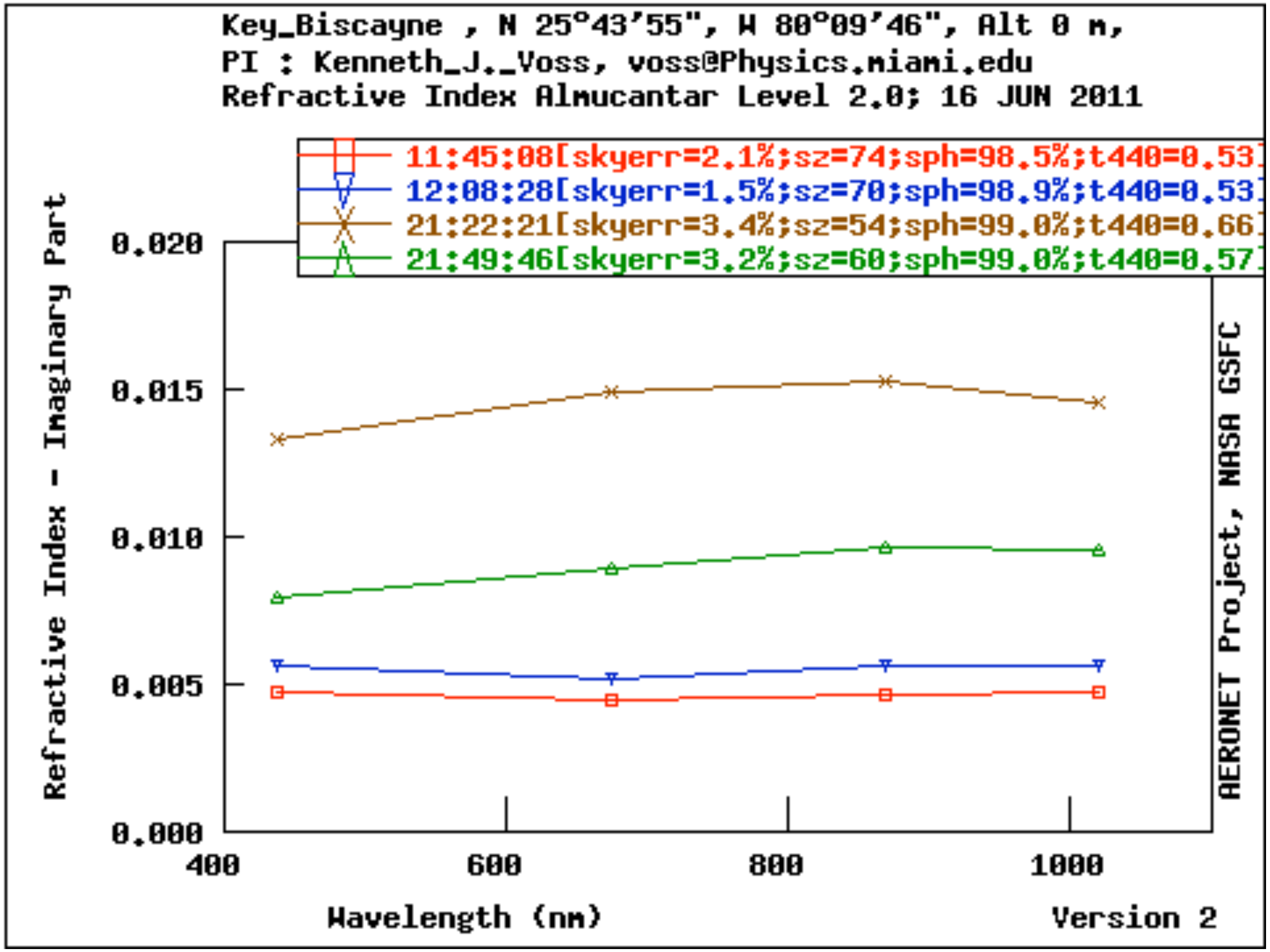


Key_Biscayne , N 25°43'55", W 80°09'46", Alt 0 m,
PI : Kenneth_J._Voss, voss@Physics.miami.edu
Size Distribution Almucantar Level 2.0; 16 JUN 2011
11:45:08[skyerr=2.1%;sz=74;sph=98.5%;t440=0.53]
12:08:28[skyerr=1.5%;sz=70;sph=98.9%;t440=0.53]
21:22:21[skyerr=3.4%;sz=54;sph=99.0%;t440=0.66]
21:49:46[skyerr=3.2%;sz=60;sph=99.0%;t440=0.57]
dV(r)/dln(r) [um^3/um^2]
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
0.01
0.1
1
10
100
Radius (r) [um]
Version 2
AERONET Project, NASA GSFC

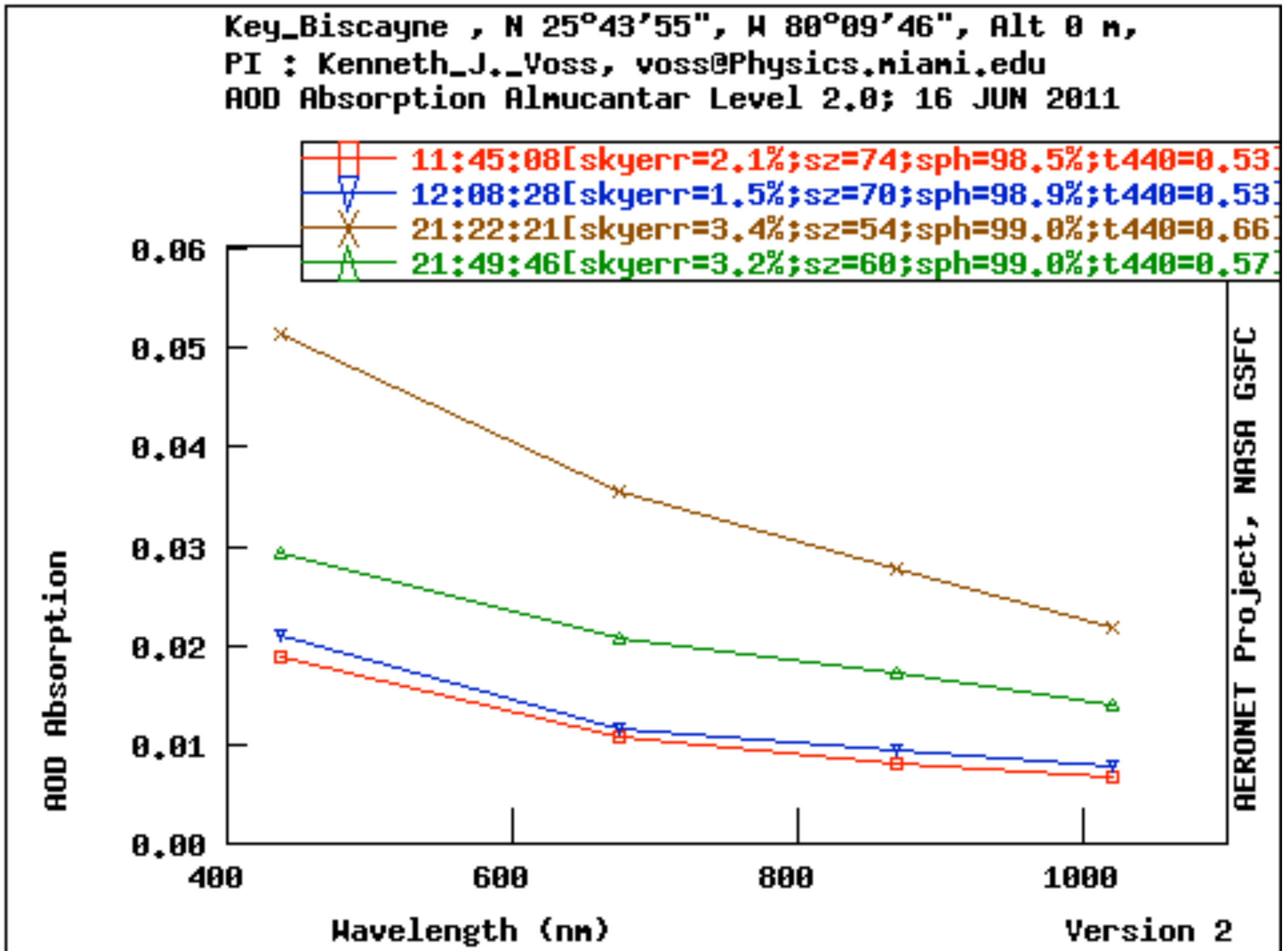
Real index of refraction (remember accuracy 0.05)



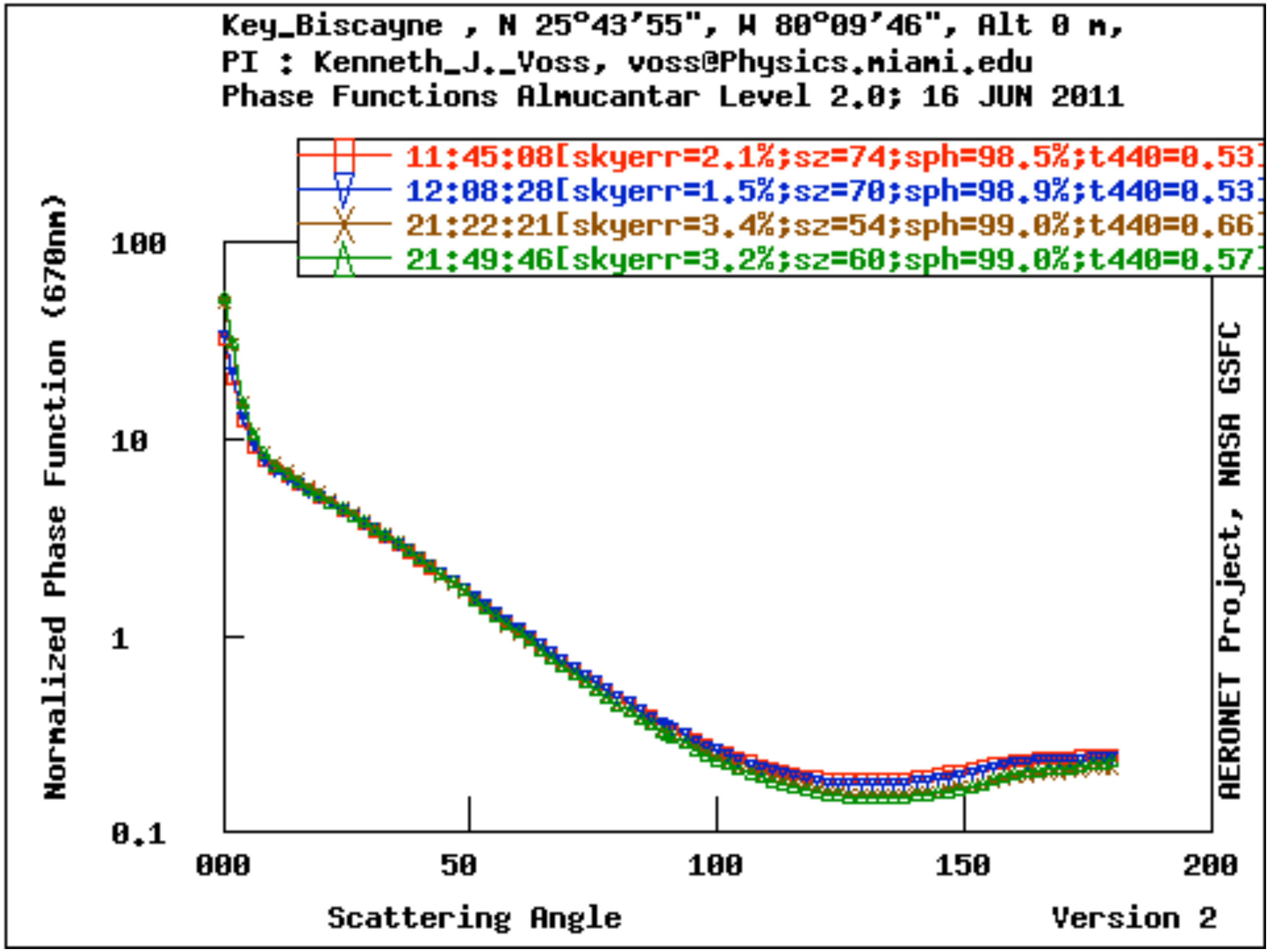
Imaginary index of refraction accuracy 50%



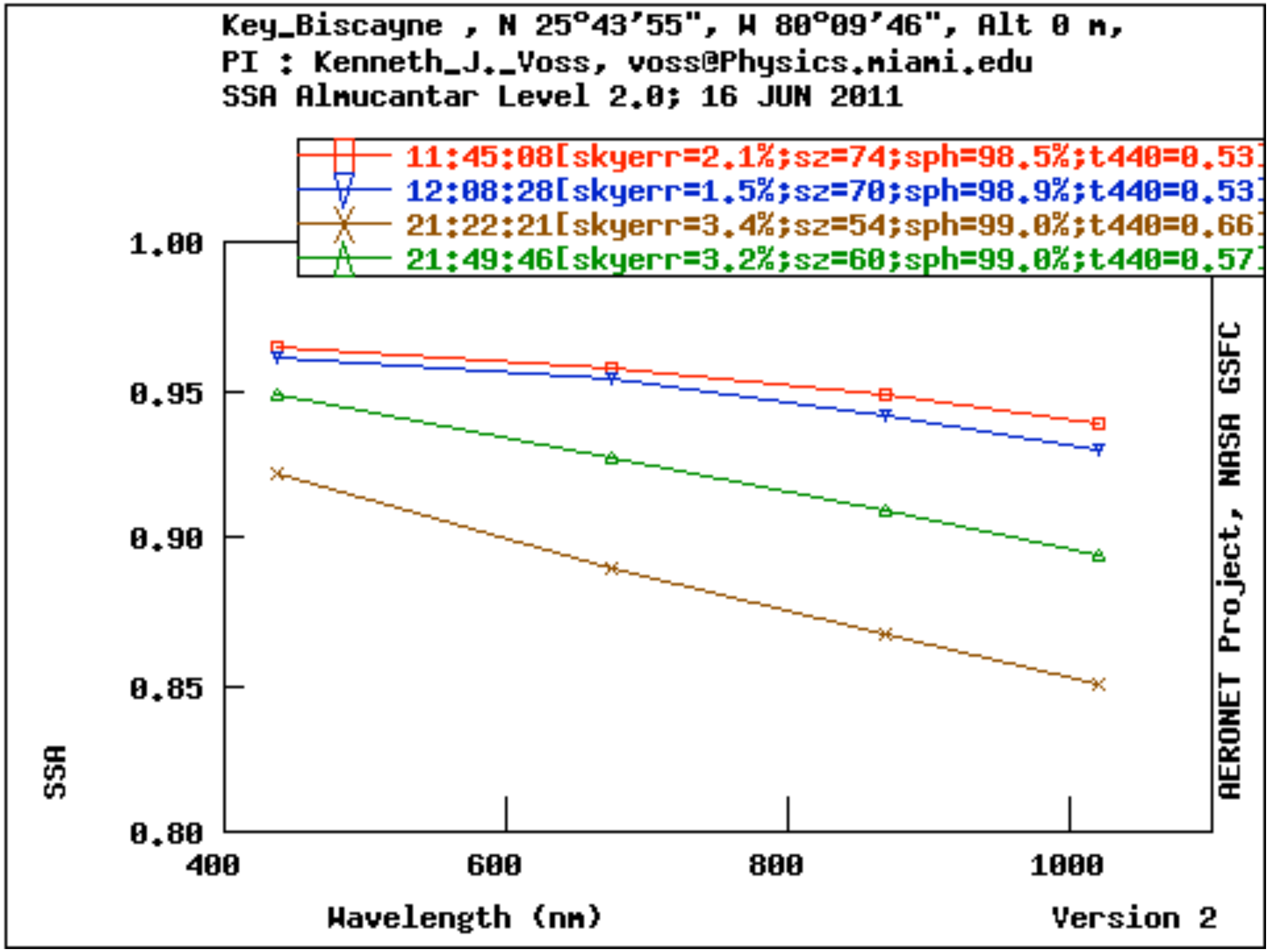
Absorption optical depth



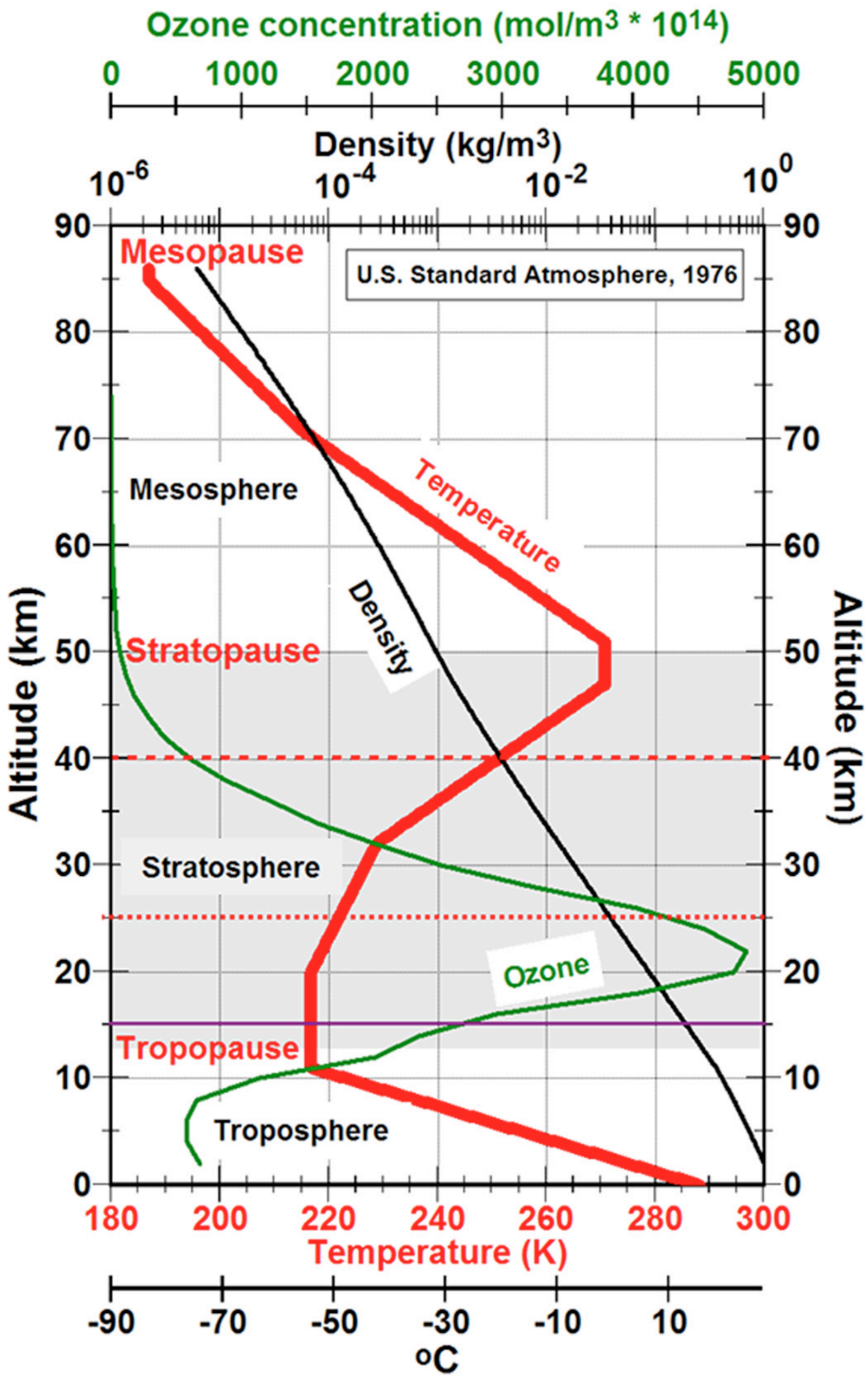
Phase function (at 670 nm)



Single scattering albedo



Why do we worry about absorbing aerosols for Atmospheric Correction? Rayleigh backscattering proportional to density.



How do we currently handle vertical structure?

- Typical…2 layers…Rayleigh overlaying aerosols (aerosols packed in bottom).
- There is a rayleigh-aerosol interaction term….
- But lots of work has shown that for non absorbing aerosols vertical structure doesn't matter….
- But what about absorbing aerosols?

- For absorbing aerosols matters where they are relative to the molecular scattering optical depth.
- How about absorbing gasses?
  - Ozone above aerosols and much of molecular scattering.
  - NO_2, mostly tropospheric….hence the problem….

All the techniques I know of for absorbing aerosols are spectral optimization techniques of some sort… i.e. require a model ocean and models for atmosphere. Problem in polluted coastal regions, or dusty regions.