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Title: Aerosol optical depth measurements by airborne sun photometer in SOLVE II: Comparisons to SAGE III, POAM III and airborne spectrometer measurements

Authors: P. Russell, J. Livingston, B. Schmid, J. Eilers, R. Kolyer, J. Redemann, S. Ramirez, J.-H. Yee, W. Swartz, R. Shetter, C. Trepte, A. Risley Jr., B. Wenny, J. Zawodny, W. Chu, M. Pitts, J. Lumpe, M. Fromm, C. Randall, K. Hoppel, and R. Bevilacqua

General author comment: We thank the anonymous referees for their efforts in reading the ms and offering comments that have helped us improve it. Our specific responses follow each referee comment below.

Anonymous Referee #1

Referee's General Comments

This paper discusses at length and in great detail, aerosol optical depth measurements made by the NASA Ames sun photometer mounted aboard a DC-8 during the SOLVE II campaign. In particular it compares these multi-wavelength measurements with those of the DIAS instrument and the SAGE III and POAM III satellites. Most of the paper is devoted to a detailed consideration of the differences in the sets of results and an examination of possible causes for the discrepancies - in particular between the sun photometer (AATS) and SAGE III. Although it seems that some of the observed differences might be explained by differences in viewing path, in timing and in solar zenith angle, for the most part these cannot explain all the differences observed. The authors then examine other possible causes one by one.

The paper is well-written, clear and very thorough. I have no doubt as to its accuracy and the scientific methodology employed, and the paper is fundamentally very sound. It presents new data and new results, which are scientifically interesting.

Response: We appreciate the positive comments.

Referee: Its major weakness stems from the nature of its conclusion that significant differences exist between the SAGE III and AATS measurements which are unresolved. This may indeed be the case, but in order to make a useful contribution to this problem, the authors need to at least state what they intend to investigate next as the cause, or what further experiment or data would be needed in order to resolve the problem. Although there is a valid and significant scientific contribution made by stating that a problem exists and that they have examined umpteen different possible causes, which have not led to a resolution - this is not enough. The authors need to state either where they intend to look next for an explanation, what further data or calculations are necessary, or what further experiments must be carried out.

Response: We agree that a valid and significant scientific contribution has been made by stating that a problem exists and that we have examined many different possible causes, which have not led to a resolution. To address the statement that this is not enough, we have added a short discussion of possible future work that would help to resolve the discrepancies. Specifically, just before Appendix A we have inserted:

“The analysis presented here clearly reveals that more work must be done to understand even the satellite comparisons themselves. This will require quantitative comparisons of both aerosol extinction and transmission profiles from the SAGE III, SAGE II, and POAM III instruments, and is the subject of future work. The POAM-SAGE differences shown in Figures 21 and 22, including their seasonal evolution, provide important context for the AATS-POAM and AATS-SAGE comparisons, as well as potentially important clues and a data set that can be studied in search of a resolution of the AATS-SAGE differences.”

Referee: My other general comment for resolution is the size of the figures. I cannot read them even with a magnifying lens. All the figures need to be printed at least twice as big as their current size in the pdf manuscript.

Response: We also were concerned by the small size of the figures in the ACPD version—much smaller than the versions we submitted. We raised this concern with the EGU Production Office, which said that figure size can be enlarged when the paper is converted to two-column style for the final ACP version. The Production Office thought the small figure size in the ACPD one-column style was big enough since readers can use the zoom tool of the Acrobat Reader to enlarge the figures. We feel this is not an adequate solution for ACPD readers who print pages in ACPD size (two ACPD pages per printed sheet). The referee’s difficulty reading the figures bears out our concern. We will work with the Production Office to be sure figures are fully legible in the final ACP version.

Referee’s Specific Comments

There is an enormous amount of detail in the paper, including 4 pages of Tables and 24 figures. I am not sure that quite as much detail needs to be presented. The fact that the figures are far too small made it impossible for me to examine them in much detail. I would suggest making the paper more readable by eliminating some of the figures - although I do not have specific recommendations. Many of the discussion points can be made without reference to a figure, and it would certainly help to reduce the length of the paper were this done.

Response: Referee #2 has made some specific recommendations on which figures to drop, and we have done some of this, along with some other deletions. See our response to Referee #2 below.

Referee: I also think that the Appendix is unnecessary.

Response: Here we disagree—we feel the Appendix is necessary to demonstrate clearly that the window was frost-free during the measurements reported here. In fact, Referee #2 has pointed to the need to assure that the measurements were not affected by deposits on other parts of the instrument optical path. Providing this assurance is similar to what we have provided regarding window frost. We now provide this in a slightly expanded Appendix, with brief mention in the main text.

Referee: One other comment - is “airmass” a common term? I found its use quite confusing because I would not normally consider the ratio of the slant path optical depth to the vertical optical depth to be an “airmass” but more of an optical path difference (or ratio).

Response: “Air mass” or “airmass” is the terminology used by Thomason et al. (1983), Reagan et al. (1986) and most of the rest of the atmospheric Sun photometry community to describe the ratio of line-of-sight (LOS) optical thickness (OT) to vertical OT. The referee is certainly correct that it is a ratio. That is why Kasten (1966) calls it “relative optical airmass” and why we have introduced the terminology as “relative optical airmass (here called airmass for brevity)” on p. 7294, line 4, carefully defining it as “the ratio of LOS optical thickness (OT) to vertical OT”.

Kondratyev (1969, p. 162) calls the same quantity “atmospheric mass” but hastens to add “It should be emphasized in this connection that the concept of atmospheric mass has nothing in common with the general idea of mass. Atmospheric mass in the given case is a dimensionless quantity indicating by how many times the optical thickness in the direction of inclination exceeds the optical thickness in the direction of the vertical.”

Hence we certainly empathize with the referee for questioning the use of the term “airmass” for an optical thickness ratio. It’s not very intuitive terminology. But it is quite standard, and we don’t think we should attempt to change it at this point. We think our introducing it as we have on p. 7294 is the best way to go.

Technical Corrections

Referee: pg 7297, line 21. Figsures should be replaced by Figures.

Response: Correction made.

Referee: pg 7298, line 20. “more-transmission oriented” should be replaced by “more transmission-oriented”

Response: Change made.

Anonymous Referee #2

Referee’s General Comments

This is an excessively long and detailed intercomparison of AOD measurements made during SOLVE 2. Four different instruments are involved: AATS and DIAS on board the DC-8 aircraft, and SAGE3 and POAM3 satellite instruments.

Response: See below for the deletions of figures and text we have made to shorten the paper.

Referee: The challenge is that the instruments on board the DC-8 typically measure only half the full limb path that the SAGE3 and POAM3 instruments see though. This leaves a high potential for systematic biases between the air- and space-borne sensors, since the conversion of the partial-limb-path AODs to full limb path AODs is critically dependent on the assumed solar zenith angle, refraction, aircraft altitude, and the aerosol extinction profile.

Response: Actually, the conversion from half limb to full limb is a separate issue from the dependence of airmass on solar zenith angle, refraction, aircraft altitude, and the aerosol extinction profile. First, note that the conventional AATS analyses involve no conversion from half limb to full limb. As shown in Figure 10 and noted in the text, these conventional analyses yield AATS results virtually identical to those from the transmission-oriented analyses, which make the half-limb to full-limb conversion for ease of comparisons to SAGE III transmissions. Second, in this paper the conversion of the half-limb-path AODs to full limb path AODs is done simply by multiplying by a factor two, or, equivalently, by squaring the corresponding transmissions. This is stated clearly on p. 7300, along with the fact that “This squaring assumes that transmission is equal in the two limb halves (i.e., from DC-8 to the Sun and from DC-8 away from the Sun).” Equal transmission in the two limb halves is just a special case of the homogeneity in spherical shells that is assumed by satellite limb inversion algorithms. We have now added mention of this in the text. We do not claim that this equality is exactly true, and, indeed, in Section 6 we are careful to note that:

“Differences in viewing path (including the major difference between full limb and half limb), in timing, and in SZA each occurred at some time for the AATS-satellite comparisons.... However, the systematic nature of the AATS-satellite differences, in which satellite AOD (especially SAGE)

is always less than AATS AOD for $\lambda > 755$ nm, suggests strongly that differences in viewing path, timing, or SZA cannot explain all the AATS-satellite differences.”

The dependence mentioned by the referee “on the assumed solar zenith angle, refraction, aircraft altitude, and the aerosol extinction profile” occurs in the calculation of airmass (ratio of LOS OT to vertical OT), not in the conversion from half limb to full limb. As we clearly state on p. 7315, “Systematic underestimation of aerosol airmass factors in the AATS analyses could explain the larger AATS AODs, but we have to reject such airmass errors on three grounds: the airmass sensitivity study discussed in conjunction with Figures 4–5, the success of the Yee LOS integrator (which is used by the Yee airmass algorithm) in the comparisons reported by Swartz et al. (2004), and, most of all, the fact that the AATS-satellite differences are apparent in transmissions and LOS AOTs at refracted SZA 90°, which do not depend on airmass values.”

Referee: A major problem is that the paper unearths significant biases between the DC-8 and the satellite instruments, but never satisfactorily explains/resolves any of them. The authors try several different ways of comparing the data (transmission, vertical OD, slant OD, etc) but they all exhibit the same behavior. To add to the sense of confusion and futility, the authors tell us that SAGE3 and POAM3 disagree with each other during the period of the DC-8 measurements, but are in agreement before and after.

Response: First of all, we think that the phrase “significant biases between the DC-8 and the satellite instruments” which lumps the AATS-SAGE and AATS-POAM comparisons together, misses an important distinction that is made clearly in the paper. The AATS-POAM differences, shown in Figure 19 and Table 4, and also described in the text (“RMS percentage differences in AOD ([AATS-POAM]/AATS) <31% for all λ , 442–1018nm”) are markedly smaller than for AATS-SAGE (RMS percentage differences in AOD, ([AATS-SAGE]/AATS), of 59% for 1020nm and 66% at 1545 nm). The AATS-POAM agreement, to 31% or better, may be as good as one can expect, given the very small AODs during the experiment, the half-vs-full limb path difference, and the other sources of error described in the paper. The 59% AATS-SAGE difference at 1020 nm, shown in Figure 10 and Table 2, is nearly twice as large.

This difference between POAM and SAGE, revealed by the respective comparisons with AATS, is consistent with the POAM-SAGE differences shown in Figures 21 and 22. We don’t see why this consistency causes a “sense of confusion and futility” in the referee. On the contrary, we feel the POAM-SAGE differences shown in Figures 21 and 22, including their seasonal evolution, provide important context for the AATS-POAM and AATS-SAGE comparisons, as well as potentially important clues and a data set that can be studied in search of a resolution of the AATS-SAGE differences. Text added just before Appendix A now emphasizes this point.

Referee: The authors go to great lengths to prove that there was no ice on the window of the AATS instrument, adding an appendix, but they don’t say anything about non-ice crud on their optics. The SAGE3 and POAM3 instruments can take a solar spectrum high above the atmosphere to establish a “baseline” exo-atmospheric spectrum. But for the DC-8 instruments this is much more difficult. How does AATS distinguish crud on its optics from atmospheric aerosol?

Response: The optical path of each AATS channel has very few optical elements: the AATS entrance window, an interference filter, and a photodiode detector. Of these, the entrance window was the coldest optical surface during the DC-8 flight segments reported in this paper. The detectors for wavelengths 354-1241 nm are in tight thermal contact with a mounting block maintained at an elevated temperature of 45 ± 1 C, and the interference filters are in a mounting block with temperature that is continuously measured and found to stay within the range 30 to 42 C. Although the detector for wavelength 1558 nm has an internal chip thermoelectrically maintained at 0 C, its case and detector entrance window are warm, mounted in tight thermal contact with a block that is in conductive contact with the 45 C hot-detector block and radiatively heated by the 30-40 C filter block. Hence, the temperatures of all detector cases and filters

greatly exceeded the AATS entrance window temperature during the DC-8 flight segments reported in this paper. As a consequence, any “non-ice crud” available to deposit on optical surfaces would deposit on the window, not a filter or detector (the only other optical elements). This is the reason our tests for reduced optical transmission in the instrument focused on the window. Moreover, if one were to postulate a deposit on an interference filter or detector, it would be revealed by the tests described in the Appendix, especially the plot of AOD difference vs airmass shown in Figure A2. As noted, the measured dependence on airmass is just the opposite of what would be caused by a deposit on any surface in the instrument optical path.

We have slightly modified the Appendix to make these points.

Referee: The paper has a lot of duplication. For example, lines 4-10 of the abstract are virtually identical to lines 14-21 of the introduction. I strongly recommend that the authors try to shorten the text and try to reduce the number of figures. Although there are “only” 24 figures, most of these are multi-panel. I counted a total of 111 figure-panels! The problem with this excessive detail is that readers “burn out” half-way through the paper, before reaching the important stuff. So I recommend that the number of figure-panels be reduced by at least a factor 2. This will allow more space for the remaining figures (improving their legibility) and will allow the text to be trimmed since the deleted figures don’t have to be discussed. A few suggestions: figures 6-9 are very similar. Is it really necessary to show this same information for all 4 DC-8 flights? Why not simply choose one typical flight? And figures 14 and 15 are really very similar – there is no need for both.

Response: We have shortened lines 4-10 of the abstract. We have also deleted Figures 7 and 9. (Figure 8 is needed with Figure 6 to show the range of SZAs encountered on flights, along with the corresponding variation in airmasses.) And we have deleted Figures 14 and 17.

Referee’s Specific Comments

The authors say nothing about the spectral resolution of the AATS-14 instrument. Their equations implicitly assume that its spectral resolution is much higher than any structure in the incident solar spectrum. They should comment on the validity of this assumption.

Response: Actually, the spectral resolution is noted on p. 7302, line 20: “Typical channel full widths at half maximum (FWHM) are 5 nm.” To make this clearer, we have now inserted in the second paragraph of Section 1: “The AATS-14 channels used in this paper have full width at half maximum (FWHM) of 2.0 to 5.6 nm, with most channel FWHMs ~5 nm.”

Regarding the effect of solar spectral variations on the validity of our equations, it is certainly true that the incident solar spectrum (e.g., Kurucz, 1995) has a lot of fine structure within the AATS channel widths. Specifically, solar irradiance can vary by nearly an order of magnitude over ~0.1 nm within some of these channels, as illustrated in [Figure R1 \(http://geo.arc.nasa.gov/sqg/SOLVE2-website/papers/FACACPD-2004-si01017Russell_fr01.gif\)](http://geo.arc.nasa.gov/sqg/SOLVE2-website/papers/FACACPD-2004-si01017Russell_fr01.gif). However, the relevant equations, (1)-(6), which are exact for monochromatic radiation, also apply with sufficient accuracy to the AATS channels used, and the constituents addressed, in this paper--despite this solar fine structure.

To show this, we start by writing the exact equation for $T_j(\text{SZA})$, the transmission of the LOS path from Sun to airborne photometer for channel j :

$$T_j(\text{SZA}) = \frac{\int S(\lambda) \exp\left[-\sum_i m_i(\text{SZA}) OD_i(\lambda)\right] F_j(\lambda) d\lambda}{\int S(\lambda) F_j(\lambda) d\lambda} = \frac{V_j}{V_{0,j}} \frac{K_j}{K_j}, \quad (6A)$$

where $S(\lambda)$ is the extraterrestrial solar spectral irradiance and $F_j(\lambda)$ is the channel filter transmission function. V_j and $V_{0,j}$ are the channel j output voltages at the photometer's location and above the atmosphere, respectively, and are given by

$$V_j(SZA) = K_j \int S(\lambda) \exp\left[-\sum_i m_i(SZA) OD_i(\lambda)\right] F_j(\lambda) d\lambda \quad (6B)$$

$$V_{0,j}(SZA) = K_j \int S(\lambda) F_j(\lambda) d\lambda, \quad (6C)$$

where K_j is the channel j calibration constant.

The key to obtaining Eqs. (1)-(6) for AATS channels is the limited variation within each channel of the optical depths $OD(\lambda)$ and transmissions $T(\lambda)$ for the constituents relevant to this paper. This small variation of constituent OD within each channel allows the exponentials in Eqs. (6A)-(6B) to be extracted from the integrals, yielding

$$T_j^{approx}(SZA) = \frac{\exp\left[-\sum_i m_i(SZA) OD_{i,j}\right] \int S(\lambda) F_j(\lambda) d\lambda}{\int S(\lambda) F_j(\lambda) d\lambda} = \prod_i \hat{T}_{i,j}, \quad (6D)$$

where $OD_{i,j}$ is a representative OD of constituent i for channel j . In the AATS data processing routines, this "representative" OD is computed differently for different constituents i . For the calculations reported here we used

$$OD_{i,j} = \int OD_i(\lambda) F_j(\lambda) d\lambda / \int F_j(\lambda) d\lambda, \quad \text{for } i = R, NO_2, O_3, O_2-O_2, \dots \quad (6E)$$

$$OD_{i,j} = OD_i(\lambda_j), \quad \text{for } i = a \quad (6F)$$

where λ_j is the center wavelength of channel j , a stands for aerosol and R for Rayleigh (as also noted under Eq. (1)). For all constituents i ,

$$\hat{T}_{i,j} = \exp[-m_i(SZA) OD_{i,j}]. \quad (6G)$$

Note that Eqs. (6D) and (6G) are equivalent to Eqs. (1)-(6) (apart from the factor 2 used in converting from the sunphotometer-viewed path to the full limb path).

To assess quantitatively the differences between the exact and approximate channel transmissions T_j and T_j^{approx} in Eqs. (6A) and (6D), we have used the Kurucz (1995) solar spectrum, absorbing gas spectra from MODTRAN (Kneizys et al., 1996), the Rayleigh scattering results of Bucholtz et al. (1995), and aerosol extinction spectra typical of those in Figures 8, 10-12, and 15, to calculate the ratios T_j^{approx}/T_j (i.e., Eq. (6D)/Eq. (6A)) for the range of channel wavelengths, filter functions, $m(SZA)$ and constituent optical depths $OD_i(\lambda)$ covered in this paper (see, e.g., Figs. 6-18).

[Figure R1](#) illustrates the relevant quantities for two typical AATS channels.

We find the ratios T_j^{approx}/T_j differ from 1.00 by at most 1%. Differences are largest at the shortest wavelengths and are all <0.3% for $\lambda > 519$ nm.

Since Eq. (2) or (6A) yields $dOD = -(1/m)dT/T$, the typical airmass values of 20 to 40 in the DC-8 measurements yield OD values derived from (6E) (or equivalently (1)-(6)) that differ from those derived from an exact transmission formulation by less than $\sim 0.01/20$ to $\sim 0.003/40$, or 5×10^{-4} to 7×10^{-5} . These differences are negligible for the OD values of interest in this paper (cf. Figures 8 and 15).

To address potential similar questions from other readers, we have now inserted at the end of the third paragraph after Eq. (6):

“Although the absorbing gas optical depth and transmission values in Figure 10 do not account for solar spectral variations within the AATS channel widths, we have performed other calculations that do account for these variations and found that transmissions calculated by the two methods differ by less than 1%. These more detailed calculations use the Kurucz (1995) solar spectrum, absorbing gas spectra from MODTRAN (Kneizys et al., 1996), the Rayleigh scattering results of Bucholtz et al. (1995), and aerosol extinction spectra typical of those in Figures 8, 10-12, and 15. The reason for the small differences is the limited variation within each AATS channel of the optical depths $OD(\lambda)$ for the constituents relevant to this paper. These same comparisons also show that Eqs. (1)-(6), which are exact for monochromatic radiation, also apply with similar accuracy to the AATS channels used, and the constituents addressed, in this paper--despite the solar fine structure within each channel.”

Referee: P. 7292, line 2: Why is "Second" capitalized? Is this the "S" in SOLVE?

Response: We have now changed “Second” to “second”.

Referee: P. 7292, line 4-5: I prefer "multi-wavelength" to "mul-tiwavelength".

Response: This was the result of an automatic hyphenator. We've changed it back to "multiwavelength" (with no hyphen) and hope it stays that way!

Referee: P. 7292, line 27: It seems redundant to use the word "percentage" when it says "%" after each value.

Response: We've now changed "percentage" to “relative”.

Referee: P. 7292, line 28: Is the 1020nm channel mentioned here the same as the 1019nm channel cited in Table 2, or are they different?

Response: “1020 nm” is used in the text to refer to the collection of AATS, POAM III, and SAGE III channels near 1020 nm. In tables and figures, where only one or two sensors are involved, more exact wavelengths are used.

AATS, POAM III, and SAGE III archive aerosol products at the following channel-center wavelengths near 1020 nm:

AATS: 1019.3 nm

POAM III: 1018.3 nm

SAGE III: 1021.6 nm

In addition, SAGE provides transmission products for several Pixel Groups with centers near 1020 nm, including Pixel Group 81 centered at 1019.3 nm. The different sensor wavelengths are shown in tables and figures as follows:

Table 2: Wavelengths shown are SAGE III aerosol-archive wavelengths, except that 1019.3 nm (SAGE III transmission Pixel Group 81) is shown in place of 1021.6 nm to accommodate our SAGE III transmission-derived results at wavelength 1019.3 nm. (The 1019.3 nm transmission-derived and 1021 nm conventionally derived SAGE III AODs are very similar, as shown in Figure 10 and noted in the text.) In calculating AATS-SAGE differences, AATS results are interpolated to SAGE wavelengths.

Table 3: Both AATS and POAM III wavelengths are shown, as labeled.

Figure 2: Wavelengths shown are SAGE III aerosol extinction and AOD archive wavelengths.

Figure 3: Wavelengths shown are POAM III aerosol extinction and AOD archive wavelengths.

Figure 11: Both AATS and SAGE III transmission Pixel Group wavelengths are shown, as labeled.

Figure 20: Both AATS and POAM III wavelengths are shown, as labeled.

To help reduce any confusion, we have now added a footnote to Table 2 stating the material labeled Table 2 above.

Referee: P. 7294, line 6: The authors state that "airmass is defined as the LOS optical thickness (OT) to the vertical OT". Is this the vertical OT above the observer or above the lowest point along the LOS?

Response: It's vertical OT above the observer. We've now inserted this on p. 7294, line 4 to answer the question for all readers.

Referee: P. 7324: Table 2: I don't understand how the rms values are calculated for this table. Take the right-most column (1545nm) in Table 2(a). The values are 10.1, 15.3, 16.8, and 19.4. By my calculation, the mean value is 15.4 and the rms is 3.4. So where does the tabulated rms value of 15.8 come from? Ditto for all the other rms values in Table 2 and for Table 4. Obviously, I'm completely missing the point here.

Response: The mean and rms values given in the tables are correct. The value 3.4 obtained by the referee is not the rms of the given values, but instead their standard deviation. For a set of numbers, the rms, or root-mean-square, is the square root of the mean of the squared elements (Weisstein, <http://mathworld.wolfram.com/Root-Mean-Square.html>). The standard deviation is the square root of the mean of the squared difference of each element from the mean (Weisstein, <http://mathworld.wolfram.com/StandardDeviation.html>). In other words, the standard deviation is the rms deviation from the mean. In an effort to avoid similar confusion among other readers, we have added a footnote defining rms to Tables 2-4.

Referee: P. 7324: Table 2: Why do the wavelengths in Table 2a have 5 significant figures, but only 4 in Table 2b? Ditto for 2c & 2d.

Response: This was an inadvertent result of a spreadsheet column width change coupled with a general format. The values are now all displayed to resolution 0.1 nm.

Referee: P. 7335: What is the significance of the left-pointing arrows in figures 6, 7, 8, and 18?

Response: They mean "Use the left scale". This is rather standard graphing practice. We are willing to change each left-pointing arrow to the words "(left scale)", but we will leave the decision to the ACP editorial staff.

Referee: P. 7339: Change "Aerosol" to "Aerosol" (y-axis annotation). Ditto for figure 19.

Response: Changes made.

Referee: P. 7341: Panels are not labelled (a), (b), (c).

Response: We have changed "a", "b", and "c" to "Top frame", "Middle frame", and "Bottom frame", respectively.

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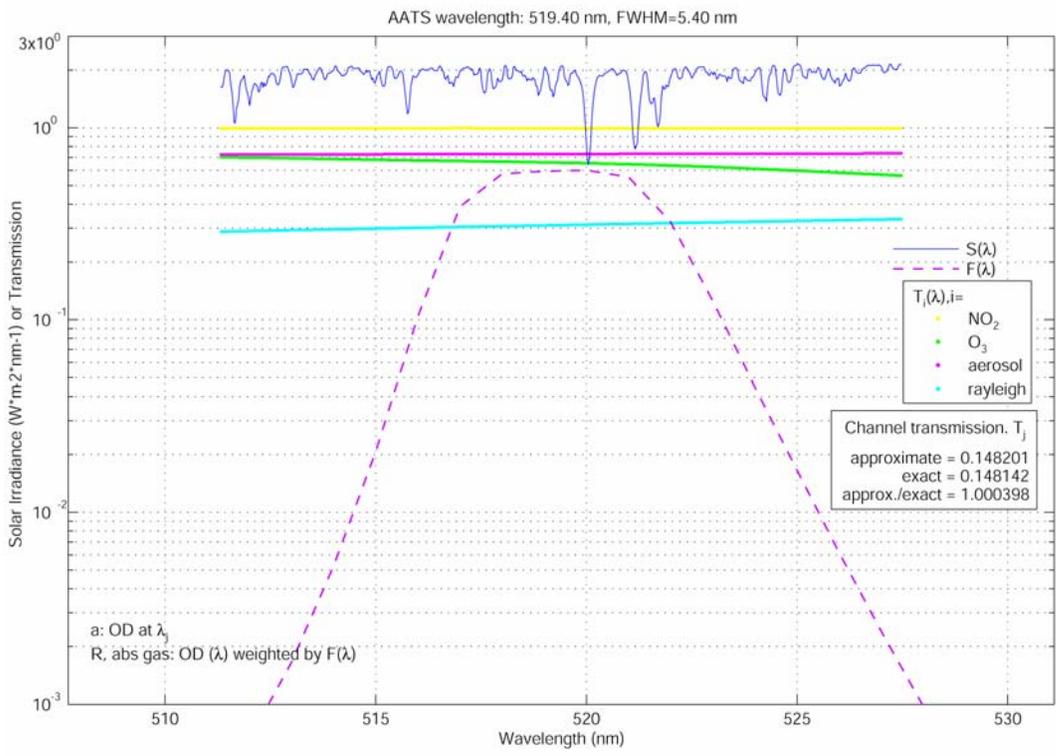
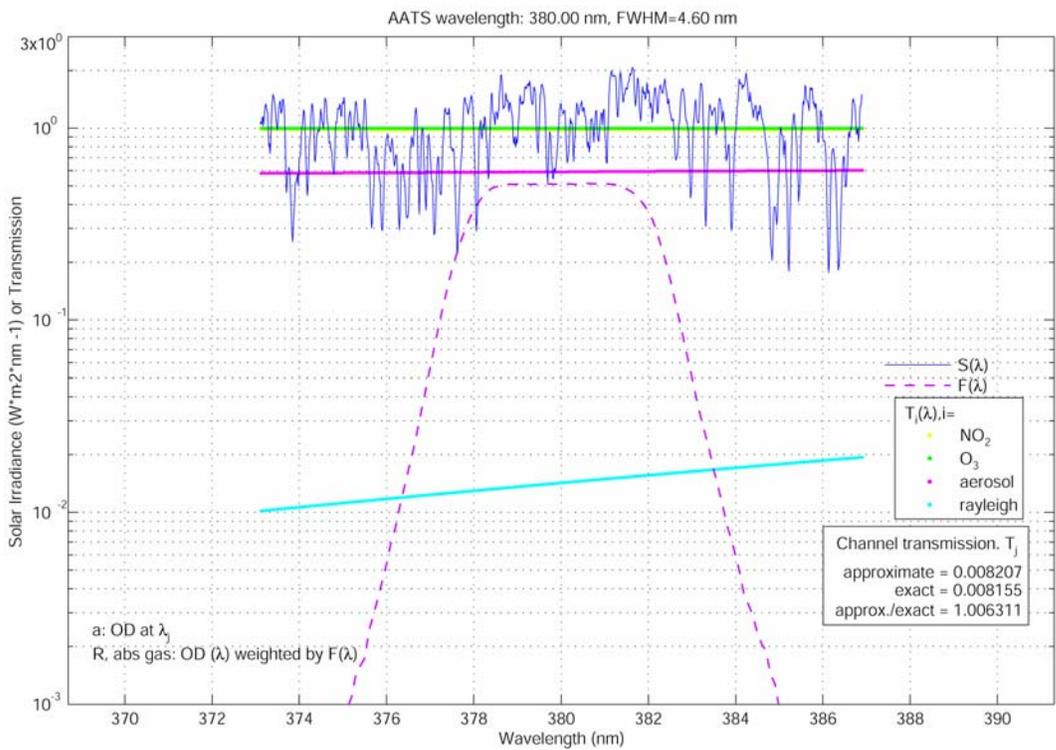


Fig. R1. Illustration of the variation of solar spectral irradiance $S(\lambda)$, constituent transmissions $T_i(\lambda)$ and filter transmissions $F(\lambda)$ for typical AATS channels with FWHM ~ 5 nm. Channel transmissions T_j , exact and approximate, are as defined by Eqs. (6A) and (6D).