The Aerosol Limb Imager: Acousto-Optic 2D Measurements of Limb Scattered Sunlight for Stratospheric Aerosol Profiling

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September 16, 2015

Abstract

1 Introduction

Kiehl1993 (*Kiehl and Briegleb*, 1993)
Stocker2013 (*Stocker et al.*, 2013)
Solomon2011 (*Solomon et al.*, 2011)
Haywood2014 (*Haywood et al.*, 2014)
Fyfe2013 (*Fyfe et al.*, 2013)
Rieger2015 (*Rieger et al.*, 2015)
Ridley2014 (*Ridley et al.*, 2014)
Junge1961 (*Junge et al.*, 1961)
Deshler2003 (*Deshler et al.*, 2003)
Deshler2006 (*Deshler et al.*, 2006)
Deshler2015 (**?**)
Beuttell1949 (*Beuttell and Brewer*, 1949)
Charlson1969 (*Charlson et al.*, 1969)
Murphy2014 (**?**)
Chazette1995 (*Chazette et al.*, 1995)
Sawamura2012 (*Sawamura et al.*, 2012)
Hofmann2009 (*Hofmann et al.*, 2009)
Vernier2011b (*Vernier et al.*, 2011b)
Hofmann2009 (*Hofmann et al.*, 2009)
Russell1989 (*Russell and McCormick*, 1989)
Thomason2003 (*Thomason and Taha*, 2003)
Russell1989 (*Russell and McCormick*, 1989)
Deshler2015 (**?**)

Damadeo2013 (*Damadeo et al.*, 2013)
McElroy2007 (*McElroy et al.*, 2007)
Gilbert2007 (*Gilbert et al.*, 2007)
Vanhellemont2008 (*Vanhellemont et al.*, 2008)
Sioris2010 (*Sioris et al.*, 2010)
Cisewski2014 (*Cisewski et al.*, 2014)
Llewellyn2004 (*Llewellyn et al.*, 2004)
Bourassa2007 (*Bourassa et al.*, 2007)
Bourassa2012a (*Bourassa et al.*, 2012b)
Rieger2015 (*Rieger et al.*, 2015)
Bovensmann1999 (*Bovensmann et al.*, 1999)
Ernst2012 (*Ernst et al.*, 2012)
VonSavigny2015 (*von Savigny et al.*, 2015)
Rault2013 (*Rault and Loughman*, 2013)
Ridley2014 (*Ridley et al.*, 2014)
Andersson2015 (*Andersson et al.*, 2015)
Bourassa2012c (*Bourassa et al.*, 2012)
Bourassa2013 (*Bourassa et al.*, 2013)
Vernier2013 (*Vernier et al.*, 2013)
Fromm2013 (*Fromm et al.*, 2013)
Fairlie2014 (*Fairlie et al.*, 2014)
Clarisse2014 (*Clarisse et al.*, 2014)
Fromm2014 (*Fromm et al.*, 2014)
Vernier2011a (*Vernier et al.*, 2011a)
Neely2014 (*Neely et al.*, 2014)
Thomason2013 (*Thomason and Vernier*, 2013)
Winker2007 (*Winker et al.*, 2007)
Vernier2011b (*Vernier et al.*, 2011b)
Rogers2011 (*Rogers et al.*, 2011)
Rieger2014 (*Rieger et al.*, 2014)
Dekemper2012 (*Dekemper et al.*, 2012)

2 ALI Instrument

Georgiev2002 (*Georgiev et al.*, 2002)
Voloshinov2007 (*Voloshinov et al.*, 2007)
Voloshinov2006 (*Voloshinov and Mosquera*, 2006)
Voloshinov1996 (*Voloshinov*, 1996)
Uchida1971 (*Uchida*, 1971)
Suhre2004 (*Suhre et al.*, 2004)

Smith2000 (*Smith*, 2000)
Fischer2008 (*Fischer et al.*, 2008)
Dekemper2012 (*Dekemper et al.*, 2012)
Dekemper2012 (*Dekemper et al.*, 2012)

3 Calibration

Xu1992 (*Xu and Stroud*, 1992)
Xu1992 (*Xu and Stroud*, 1992)
Kosch2003 (*Kosch et al.*, 2003)

4 Balloon Flight

Dee2011 *Dee et al.* (2011)
Bourassa2012a(*Bourassa et al.*, 2012b)
Wiscombe1980 (*Wiscombe*, 1980)
Bourassa2008a (*Bourassa et al.*, 2008)
Zawada2015 (*Zawada et al.*, 2015)
Dueck2015 (*Dueck S. and Degenstein*)
Bourassa2012a(*Bourassa et al.*, 2012b)
Bourassa2007(*Bourassa et al.*, 2007)
Rodgers2000 (*Rodgers*, 2000)
Bourassa2012b (*Bourassa et al.*, 2012a)
Rodgers2000 (*Rodgers*, 2000)
Rault2013 (*Rault and Loughman*, 2013)
Berthet2002 (*Berthet et al.*, 2002)
Bourassa2012a (*Bourassa et al.*, 2012b)
Rieger2015 (*Rieger et al.*, 2015)
Deshler2003 (*Deshler et al.*, 2003)
Rieger2014 (*Rieger et al.*, 2014)

References

Andersson, S. M., B. G. Martinsson, J.-P. Vernier, J. Friberg, C. A. Brenninkmeijer, M. Hermann, P. F. van Velthoven, and A. Zahn (2015), Significant radiative impact of volcanic aerosol in the lowermost stratosphere, *Nature communications*, *6*.

Berthet, G., J.-B. Renard, C. Brogniez, C. Robert, M. Chartier, and M. Pirre (2002), Optical and physical properties of stratospheric aerosols from balloon measurements in the visible

and near-infrared domains. i. analysis of aerosol extinction spectra from the amon and salomon balloonborne spectrometers, *Applied optics*, *41*, 7522–7539.

Beuttell, R. G., and A. W. Brewer (1949), Instruments for the measurement of the visual range, *Journal of Scientific Instruments*, *26*, 357.

Bourassa, A. E., D. A. Degenstein, R. L. Gattinger, and E. J. Llewellyn (2007), Stratospheric aerosol retrieval with optical spectrograph and infrared imaging system limb scatter measurements, *Journal of Geophysical Research (Atmospheres)*, *112*, D10217, doi: 10.1029/2006JD008079.

Bourassa, A. E., D. A. Degenstein, and E. J. Llewellyn (2008), SASKTRAN: A spherical geometry radiative transfer code for efficient estimation of limb scattered sunlight, *Journal of Quantitative Spectroscopy and Radiative Transfer*, *109*, 52–73, doi:10.1016/j.jqsrt.2007.07.007.

Bourassa, A. E., C. A. McLinden, A. F. Bathgate, B. J. Elash, and D. A. Degenstein (2012a), Precision estimate for Odin-OSIRIS limb scatter retrievals, *Journal of Geophysical Research (Atmospheres)*, *117*, D04303, doi:10.1029/2011JD016976.

Bourassa, A. E., L. A. Rieger, N. D. Lloyd, and D. A. Degenstein (2012b), Odin-OSIRIS stratospheric aerosol data product and SAGE III intercomparison, *Atmospheric Chemistry & Physics*, *12*, 605–614, doi:10.5194/acp-12-605-2012.

Bourassa, A. E., A. Robock, W. J. Randel, T. Deshler, L. A. Rieger, N. D. Lloyd, E. T. Llewellyn, and D. A. Degenstein (2012), Large volcanic aerosol load in the stratosphere linked to asian monsoon transport, *Science*, *337*, 78–81.

Bourassa, A. E., A. Robock, W. J. Randel, T. Deshler, L. A. Rieger, N. D. Lloyd, E. Llewellyn, and D. A. Degenstein (2013), Response to comments on" large volcanic aerosol load in the stratosphere linked to asian monsoon transport", *Science*, *339*, 647–647.

Bovensmann, H., J. Burrows, M. Buchwitz, J. Frerick, S. Noël, V. Rozanov, K. Chance, and A. Goede (1999), Sciamachy: Mission objectives and measurement modes, *Journal of the Atmospheric Sciences*, *56*, 127–150.

Charlson, R. J., N. Ahlquist, H. Selvidge, and P. MacCready Jr (1969), Monitoring of atmospheric aerosol parameters with the integrating nephelometer, *Journal of the Air Pollution Control Association*, *19*, 937–942.

Chazette, P., C. David, J. Lefrere, S. Godin, J. Pelon, and G. Mégie (1995), Comparative lidar study of the optical, geometrical, and dynamical properties of stratospheric post-volcanic aerosols, following the eruptions of el chichon and mount pinatubo, *JOURNAL OF GEOPHYSICAL RESEARCH-ALL SERIES-*, *100*, 23–195.

Cisewski, M., J. Zawodny, J. Gasbarre, R. Eckman, N. Topiwala, O. Rodriguez-Alvarez, D. Cheek, and S. Hall (2014), The stratospheric aerosol and gas experiment (sage iii) on the international space station (iss) mission, 924,107–924,107.

Clarisse, L., P.-F. Coheur, N. Theys, D. Hurtmans, and C. Clerbaux (2014), The 2011 nabro eruption, a so_2 plume height analysis using iasi measurements, *Atmospheric Chemistry and Physics*, *14*, 3095–3111, doi:10.5194/acp-14-3095-2014.

Damadeo, R. P., J. M. Zawodny, L. W. Thomason, and N. Iyer (2013), Sage version 7.0 algorithm: application to sage ii, *Atmospheric Measurement Techniques*, *6*, 3539–3561, doi:10.5194/amt-6-3539-2013.

Dee, D. P., S. M. Uppala, A. J. Simmons, P. Berrisford, P. Poli, S. Kobayashi, U. Andrae, M. A. Balmaseda, G. Balsamo, P. Bauer, P. Bechtold, A. C. M. Beljaars, L. van de Berg, J. Bidlot, N. Bormann, C. Delsol, R. Dragani, M. Fuentes, A. J. Geer, L. Haimberger, S. B. Healy, H. Hersbach, E. V. Hlm, L. Isaksen, P. Kllberg, M. Khler, M. Matricardi, A. P. McNally, B. M. Monge-Sanz, J.-J. Morcrette, B.-K. Park, C. Peubey, P. de Rosnay, C. Tavolato, J.-N. Thpaut, and F. Vitart (2011), The era-interim reanalysis: configuration and performance of the data assimilation system, *Quarterly Journal of the Royal Meteorological Society*, *137*, 553–597, doi:10.1002/qj.828.

Dekemper, E., N. Loodts, B. V. Opstal, J. Maes, F. Vanhellemont, N. Mateshvili, G. Franssens, D. Pieroux, C. Bingen, C. Robert, L. D. Vos, L. Aballea, and D. Fussen (2012), Tunable acousto-optic spectral imager for atmospheric composition measurements in the visible spectral domain, *Applied Optics*, *51*, 6259–6267, doi:10.1364/AO.51.006259.

Deshler, T., M. Hervig, D. Hofmann, J. Rosen, and J. Liley (2003), Thirty years of in situ stratospheric aerosol size distribution measurements from laramie, wyoming (41 n), using balloon-borne instruments, *Journal of Geophysical Research: Atmospheres (1984–2012)*, *108*.

Deshler, T., R. Anderson-Sprecher, H. Jger, J. Barnes, D. J. Hofmann, B. Clemesha, D. Simonich, M. Osborn, R. G. Grainger, and S. Godin-Beekmann (2006), Trends in the nonvolcanic component of stratospheric aerosol over the period 19712004, *Journal of Geophysical Research: Atmospheres*, *111*, n/a–n/a, doi:10.1029/2005JD006089.

Dueck S., A. E., Bourassa, and D. A. Degenstein (), SASKTRAN-HR Polarization Module, *In Preperations*.

Ernst, F., C. von Savigny, A. Rozanov, V. Rozanov, K.-U. Eichmann, L. A. Brinkhoff, H. Bovensmann, and J. P. Burrows (2012), Global stratospheric aerosol extinction profile retrievals from sciamachy limb-scatter observations, *Atmospheric Measurement Techniques Discussions*, *5*, 5993–6035, doi:10.5194/amtd-5-5993-2012.

Fairlie, T. D., J.-P. Vernier, M. Natarajan, and K. M. Bedka (2014), Dispersion of the nabro volcanic plume and its relation to the asian summer monsoon, *Atmospheric Chemistry and Physics*, *14*, 7045–7057, doi:10.5194/acp-14-7045-2014.

Fischer, H., M. Birk, C. Blom, B. Carli, M. Carlotti, T. v. Clarmann, L. Delbouille, A. Dudhia, D. Ehhalt, M. Endemann, et al. (2008), Mipas: an instrument for atmospheric and climate research, *Atmospheric Chemistry and Physics*, *8*, 2151–2188.

Fromm, M., G. Nedoluha, and Z. Charvt (2013), Comment on "large volcanic aerosol load in the stratosphere linked to asian monsoon transport", *Science*, *339*, 647, doi:10.1126/science.1228605.

Fromm, M., G. Kablick, G. Nedoluha, E. Carboni, R. Grainger, J. Campbell, and J. Lewis (2014), Correcting the record of volcanic stratospheric aerosol impact: Nabro and sarychev peak, *Journal of Geophysical Research: Atmospheres*, *119*, 10,343–10,364, doi:10.1002/2014JD021507.

Fyfe, J. C., N. P. Gillett, and F. W. Zwiers (2013), Overestimated global warming over the past 20 years, *Nature Climate Change*, *3*, 767–769.

Georgiev, G., D. A. Glenar, and J. J. Hillman (2002), Spectral characterization of acousto-optic filters used in imaging spectroscopy, *Appl. Opt.*, *41*, 209–217, doi:10.1364/AO.41.000209.

Gilbert, K., D. Turnbull, K. Walker, C. Boone, S. McLeod, M. Butler, R. Skelton, P. Bernath, F. Chateauneuf, and M.-A. Soucy (2007), The onboard imagers for the canadian ace scisat-1 mission, *Journal of Geophysical Research: Atmospheres (1984–2012)*, *112*.

Haywood, J. M., A. Jones, and G. S. Jones (2014), The impact of volcanic eruptions in the period 20002013 on global mean temperature trends evaluated in the hadgem2-es climate model, *Atmospheric Science Letters*, *15*, 92–96, doi:10.1002/asl2.471.

Hofmann, D., J. Barnes, M. O'Neill, M. Trudeau, and R. Neely (2009), Increase in background stratospheric aerosol observed with lidar at mauna loa observatory and boulder, colorado, *Geophysical Research Letters*, *36*, n/a–n/a, doi:10.1029/2009GL039008, l15808.

Junge, C. E., C. W. Chagnon, and J. E. Manson (1961), Stratospheric Aerosols., *Journal of Atmospheric Sciences*, *18*, 81–108, doi:10.1175/1520-0469(1961)018⟨0081:SA⟩2.0.CO;2.

Kiehl, J. T., and B. P. Briegleb (1993), The relative roles of sulfate aerosols and greenhouse gases in climate forcing, *Science*, *260*, 311–314, doi:10.1126/science.260.5106.311.

Kosch, M., S. Mäkinen, F. Sigernes, and O. Harang (2003), Absolute optical calibration using a simple tungsten light bulb: Experiment, *Proceedings of the 30th Annual European Meeting on Atmospheric Studies by Optical Methods*, 50–54.

Llewellyn, E., N. D. Lloyd, D. A. Degenstein, R. L. Gattinger, S. V. Petelina, A. E. Bourassa, J. T. Wiensz, E. V. Ivanov, I. C. McDade, B. H. Solheim, J. C. McConnell, C. S. Haley, C. von Savigny, C. E. Sioris, C. A. McLinden, E. Griffioen, J. Kaminski, W. F. J. Evans, E. Puckrin, K. Strong, V. Wehrle, R. H. Hum, D. J. W. Kendall, J. Matsushita, D. P. Murtagh, S. Brohede, J. Stegman, G. Witt, G. Barnes, W. F. Payne, L. Piche, K. Smith, G. Warshaw, D. L. Deslauniers, P. Marchand, E. H. Richardson, R. A. King, I. Wevers, W. McCreath, E. Kyrola, L. Oikarinen, G. W. Leppelmeier, H. Auvinen, G. Megie, A. Hauchecorne, F. Lefevre, J. de La Noe, P. Ricaud, U. Frisk, F. Sjoberg, F. von Scheele, and L. Nordh (2004), The OSIRIS instrument on the Odin spacecraft, *Canadian Journal of Physics*, *82*, 411–422, doi:10.1139/p04-005.

McElroy, C. T., C. R. Nowlan, J. R. Drummond, P. F. Bernath, D. V. Barton, D. G. Dufour, C. Midwinter, R. B. Hall, A. Ogyu, A. Ullberg, D. I. Wardle, J. Kar, J. Zou, F. Nichitiu, C. D. Boone, K. A. Walker, and N. Rowlands (2007), The ace-maestro instrument on scisat: description, performance, and preliminary results, *Appl. Opt.*, *46*, 4341–4356, doi:10.1364/AO.46.004341.

Neely, R. R., P. Yu, K. H. Rosenlof, O. B. Toon, J. S. Daniel, S. Solomon, and H. L. Miller (2014), The contribution of anthropogenic so2 emissions to the asian tropopause aerosol layer, *Journal of Geophysical Research: Atmospheres*, *119*, 1571–1579, doi:10.1002/2013JD020578.

Rault, D. F., and R. P. Loughman (2013), The omps limb profiler environmental data record algorithm theoretical basis document and expected performance, *Geoscience and Remote Sensing, IEEE Transactions on*, *51*, 2505–2527.

Ridley, D. A., S. Solomon, J. E. Barnes, V. D. Burlakov, T. Deshler, S. I. Dolgii, A. B. Herber, T. Nagai, R. R. Neely, A. V. Nevzorov, C. Ritter, T. Sakai, B. D. Santer, M. Sato, A. Schmidt, O. Uchino, and J. P. Vernier (2014), Total volcanic stratospheric aerosol optical depths and implications for global climate change, *Geophysical Research Letters*, *41*, 7763–7769, doi:10.1002/2014GL061541, 2014GL061541.

Rieger, L. A., A. E. Bourassa, and D. A. Degenstein (2014), Stratospheric aerosol particle size information in odin-osiris limb scatter spectra, *Atmospheric Measurement Techniques*, *7*, 507–522, doi:10.5194/amt-7-507-2014.

Rieger, L. A., A. E. Bourassa, and D. A. Degenstein (2015), Merging the osiris and sage ii stratospheric aerosol records, *Journal of Geophysical Research: Atmospheres*, n/a–n/a, doi:10.1002/2015JD023133, 2015JD023133.

Rodgers, C. (2000), *Inverse Methods for Atmospheric Sounding: Theory and Practice*, Series on atmospheric, oceanic and planetary physics: 1999, World Scientific.

Rogers, R. R., C. A. Hostetler, J. W. Hair, R. A. Ferrare, Z. Liu, M. D. Obland, D. B. Harper, A. L. Cook, K. A. Powell, M. A. Vaughan, and D. M. Winker (2011), Assessment of the calipso lidar 532 nm attenuated backscatter calibration using the nasa larc airborne high spectral resolution lidar, *Atmospheric Chemistry and Physics*, *11*, 1295–1311, doi: 10.5194/acp-11-1295-2011.

Russell, P., and M. McCormick (1989), Sage ii aerosol data validation and initial data use: An introduction and overview, *Journal of Geophysical Research: Atmospheres (1984–2012)*, *94*, 8335–8338.

Sawamura, P., J. P. Vernier, J. E. Barnes, T. A. Berkoff, E. J. Welton, L. Alados-Arboledas, F. Navas-Guzmn, G. Pappalardo, L. Mona, F. Madonna, D. Lange, M. Sicard, S. Godin-Beekmann, G. Payen, Z. Wang, S. Hu, S. N. Tripathi, C. Cordoba-Jabonero, and R. M. Hoff (2012), Stratospheric aod after the 2011 eruption of nabro volcano measured by lidars over the northern hemisphere, *Environmental Research Letters*, *7*, 034,013.

Sioris, C. E., C. D. Boone, P. F. Bernath, J. Zou, C. T. McElroy, and C. A. McLinden (2010), Atmospheric chemistry experiment (ace) observations of aerosol in the upper troposphere and lower stratosphere from the kasatochi volcanic eruption, *Journal of Geophysical Research: Atmospheres*, *115*, n/a–n/a, doi:10.1029/2009JD013469, d00L14.

Smith, W. J. (2000), *Modern Optical Engineering*, New York: McGraw-Hill.

Solomon, S., J. S. Daniel, R. R. Neely, J.-P. Vernier, E. G. Dutton, and L. W. Thomason (2011), The persistently variable background stratospheric aerosol layer and global climate change, *Science*, *333*, 866–870, doi:10.1126/science.1206027.

Stocker, T. F., D. Qin, G.-K. Plattner, M. M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley (2013), *Climate Change 2013 The Physical Science Basis*.

Suhre, D. R., L. J. Denes, and N. Gupta (2004), Telecentric confocal optics for aberration correction of acousto-optic tunable filters, *Applied Optics*, *43*, 1255–1260, doi:10.1364/AO. 43.001255.

Thomason, L. W., and G. Taha (2003), Sage iii aerosol extinction measurements: Initial results, *Geophysical research letters*, *30*.

Thomason, L. W., and J.-P. Vernier (2013), Improved sage ii cloud/aerosol categorization and observations of the asian tropopause aerosol layer: 1989-;2005, *Atmospheric Chemistry and Physics*, *13*, 4605–4616, doi:10.5194/acp-13-4605-2013.

Uchida, N. (1971), Optical properties of single-crystal paratellurite (teo_2), *Phys. Rev. B*, *4*, 3736–3745, doi:10.1103/PhysRevB.4.3736.

Vanhellemont, F., C. Tetard, A. Bourassa, M. Fromm, J. Dodion, D. Fussen, C. Brogniez, D. Degenstein, K. L. Gilbert, D. N. Turnbull, P. Bernath, C. Boone, and K. A. Walker (2008), Aerosol extinction profiles at 525 nm and 1020 nm derived from ace imager data: comparisons with gomos, sage ii, sage iii, poam iii, and osiris, *Atmospheric Chemistry and Physics*, *8*, 2027–2037, doi:10.5194/acp-8-2027-2008.

Vernier, J.-P., L. Thomason, and J. Kar (2011a), Calipso detection of an asian tropopause aerosol layer, *Geophysical Research Letters*, *38*.

Vernier, J.-P., L. W. Thomason, T. D. Fairlie, P. Minnis, R. Palikonda, and K. M. Bedka (2013), Comment on "large volcanic aerosol load in the stratosphere linked to asian monsoon transport", *Science*, *339*, 647, doi:10.1126/science.1227817.

Vernier, J.-P., L. W. Thomason, J.-P. Pommereau, A. Bourassa, J. Pelon, A. Garnier, A. Hauchecorne, L. Blanot, C. Trepte, D. Degenstein, and F. Vargas (2011b), Major influence of tropical volcanic eruptions on the stratospheric aerosol layer during the last decade, *Geophysical Research Letters*, *38*, n/a–n/a, doi:10.1029/2011GL047563, l12807.

Voloshinov, V. (1996), Spectral and polarization analysis of optical images by means of acousto-optics, *Optics Laser Technology*, *28*, 119–127, doi:10.1016/0030-3992(95)00079-8.

Voloshinov, V. B., and J. C. Mosquera (2006), Wide-aperture acousto-optic interaction in birefringent crystals, *Optics and Spectroscopy*, *101*, 635–641, doi:10.1134/S0030400X06100225.

Voloshinov, V. B., K. B. Yushkov, and B. B. J. Linde (2007), Improvement in performance of a TeO_2 acousto-optic imaging spectrometer, *Journal of Optics A: Pure and Applied Optics*, *9*, 341–347, doi:10.1088/1464-4258/9/4/006.

von Savigny, C., F. Ernst, A. Rozanov, R. Hommel, K.-U. Eichmann, V. Rozanov, J. P. Burrows, and L. W. Thomason (2015), Improved stratospheric aerosol extinction profiles from sciamachy: validation and sample results, *Atmospheric Measurement Techniques Discussions*, *8*, 8353–8383, doi:10.5194/amtd-8-8353-2015.

Winker, D. M., W. H. Hunt, and M. J. McGill (2007), Initial performance assessment of caliop, *Geophysical Research Letters*, *34*.

Wiscombe, W. J. (1980), Improved mie scattering algorithms, *Applied optics*, *19*, 1505–1509.

Xu, J., and R. Stroud (1992), *Acousto-optic devices: principles, design, and applications*, vol. 12, Wiley-Interscience.

Zawada, D. J., S. R. Dueck, L. A. Rieger, A. E. Bourassa, N. D. Lloyd, and D. A. Degenstein (2015), High resolution and monte carlo additions to the sasktran radiative transfer model, *Atmospheric Measurement Techniques Discussions*, *8*, 3357–3397, doi:10.5194/amtd-8-3357-2015.