The Meteor3M/ Stratospheric Aerosol and Gas Experiment III: A bridge to the future for long-term records of ozone and aerosol

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OUTLINE

- Introduction
- SAGE II Accomplishments
- SAGE III
  - Solar
  - Lunar
  - Limb Scatter
- Limb Scatter Challenges & Potential
- Summary

SAGE III Science Objectives

The SAGE III science objectives can be summarized as follows:

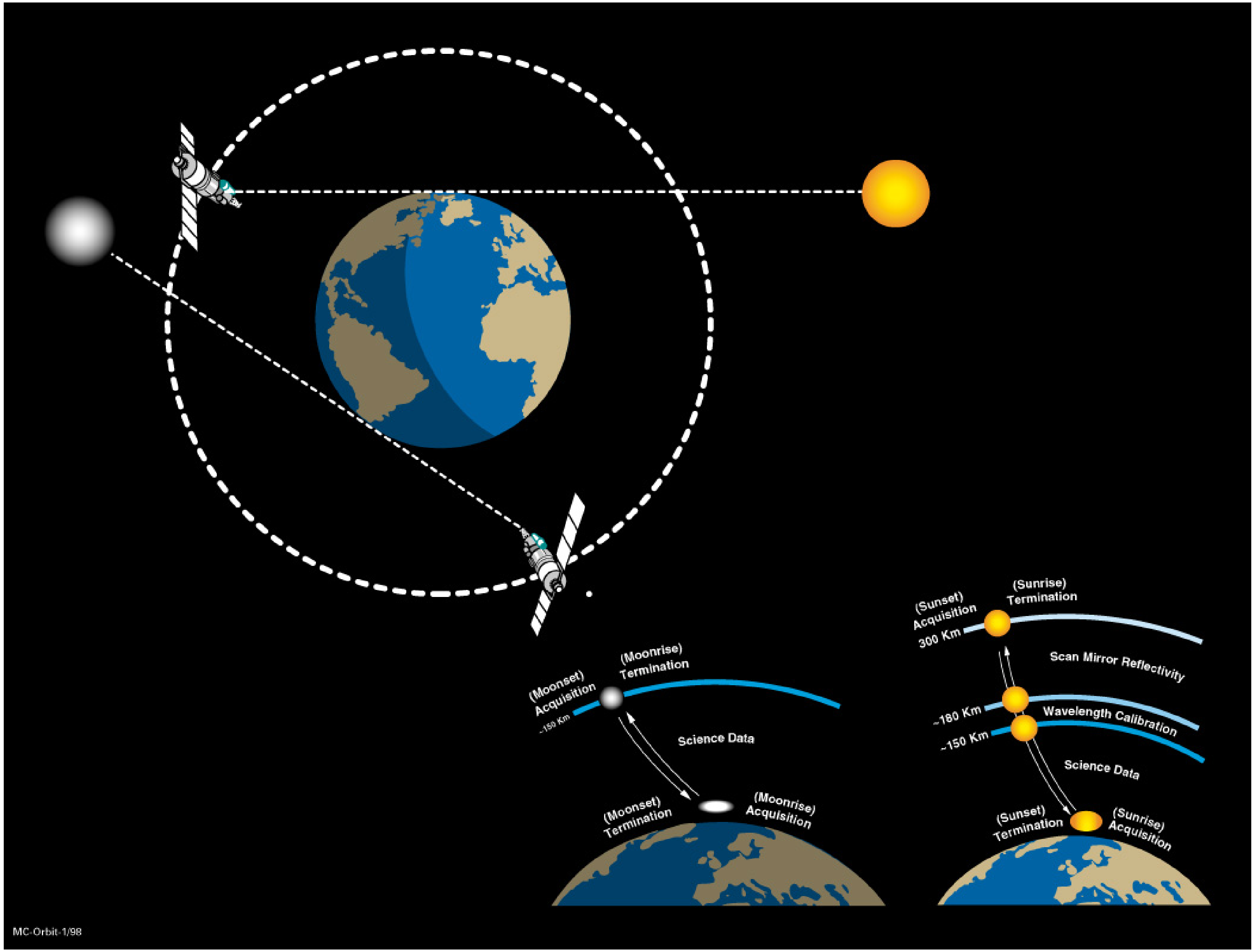
- Provide global profiles of atmospheric aerosols, ozone (O_3), water vapor (H_2O), nitrogen dioxide (NO_2), nitrogen trioxide (NO_3), air density, and chlorine dioxide (OClO) in the mesosphere, stratosphere, and troposphere.
- Investigate the spatial and temporal variability of the measured species in order to determine their role in climatological processes, biogeochemical cycles, the hydrologic cycle, and atmospheric chemistry.
- Characterize tropospheric as well as stratospheric aerosols and upper tropospheric and stratospheric clouds, and investigate their effects on the Earth's environment including radiative, microphysical, and chemical interactions.
- Extend the SAM II, SAGE I, and SAGE II data sets enabling the detection of long-term trends.
- Provide atmospheric data essential for the calibration and interpretation or correction of other satellite sensors, including EOS and ground-based networks.

SAGE III INSTRUMENT HERITAGE

INSTRUMENT	MISSION	NO. CHANNELS	ALTITUDE RESOLUTIUON	SAMPLE RATE	ORBIT	GEOGRAPHIC COVERAGE	STATUS
SAM	ASTP 1975	1 (200 nm)	7 KM	10 SPS	223 KM 51.8°	4 Profiles 39°N & 43°S	Successful; Technology Demonstration Flight
SAM II	Nimbus 7 1978 to 1994	1 (50 nm)	1 KM	50 SPS	955 KM 99.3° Noon Crossing	64 - 80°N 64 - 80°S	Highly Successful; 14+ Yrs Data Archived
SAGE	AEM-2 1979 to 1981	4 (20 nm)	1 KM	64 SPS	600 KM 55°	79°N - 79°S	Successful; S/C Battery Failure Terminated Operation After 3 Yrs
SAGE II	ERBS 1984 to 2005	7 (20 nm)	1 KM	64 SPS	610 KM 57°	80°N - 80°S	Highly Successful; Mission Retired; 21+ Yrs Data Archived
SAGE III METEOR 3(M)	2001 to 2006	12 (1 nm)	1 KM	64 SPS	1040 KM 99.5 9:15 AM	*64 - 80°N *64 - 80°S	Successful; S/C Failure; V4 release imminent
FOO	TBD	12 (1 nm)	1 KM	64 SPS	TBD	TBD	Delivered 6/99
SAGE III ISSA	TBD Launch	12 (1 nm)	1 KM	64 SPS	TBD	GLOBAL	Delivered 12/98

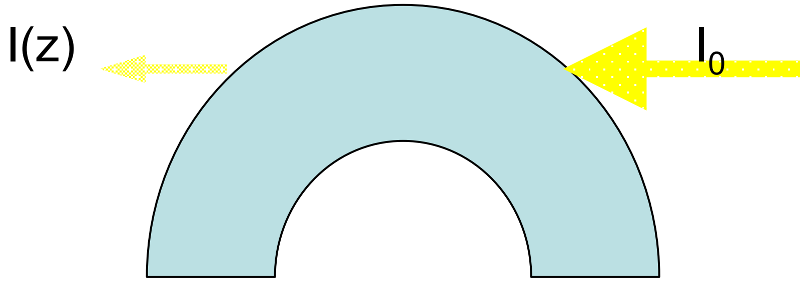
* SOLAR MODE

Measurement Technique



Occultation & Atmospheric Tranmission

- Fundamental equation is the transmission of light as it travels from the source to through the atmosphere.



$I(z) = I_0 T(z)$

where:

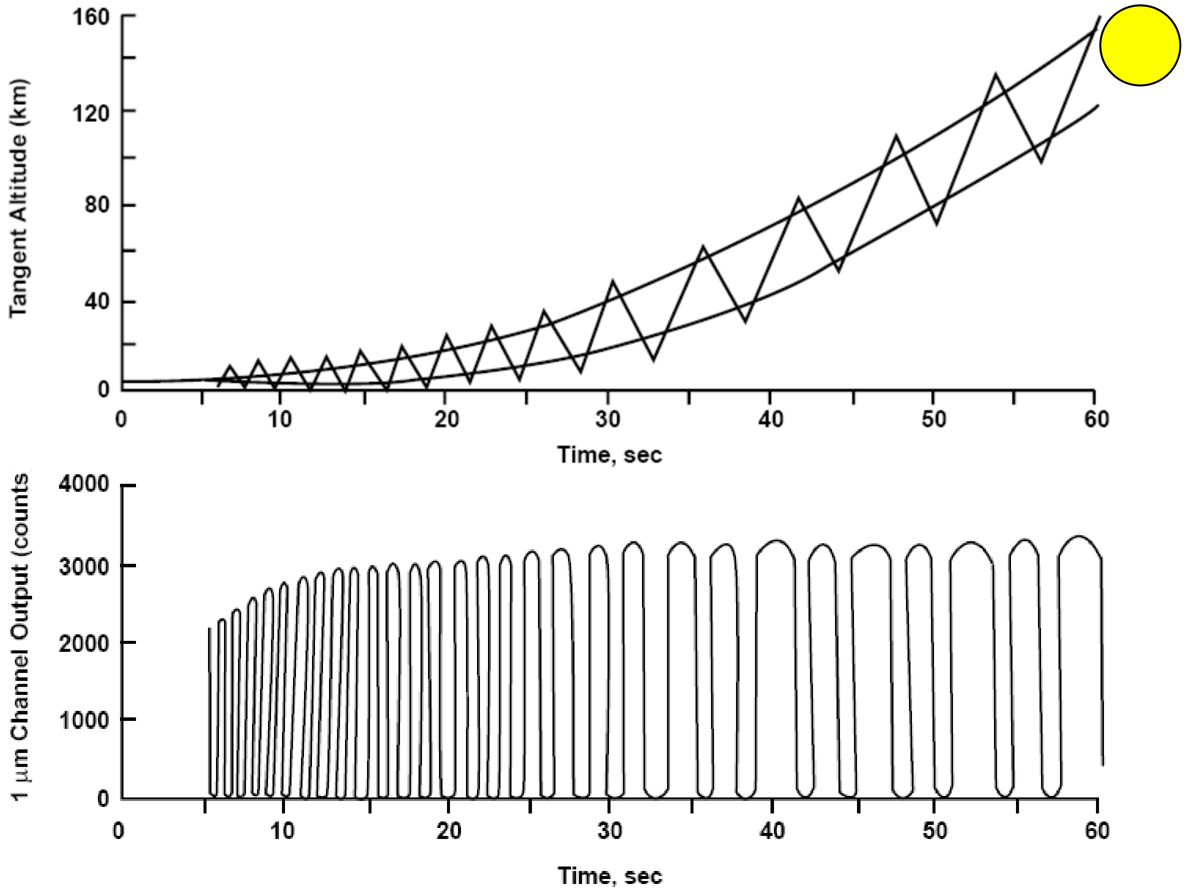
I_0 incident light outside atmosphere

$T(z)$ = Transmission = $e^{-\int k \cdot ds}$

k = ext. cross section x number density = c·n

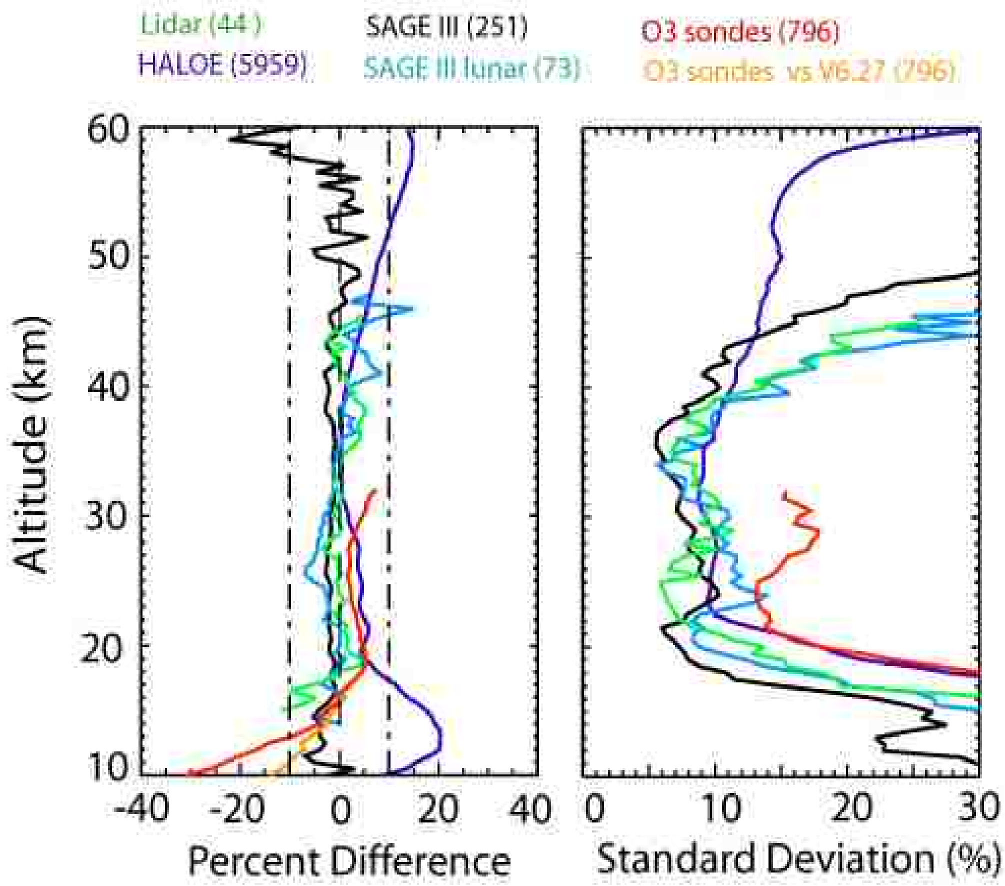
SAGE Scanning Technique

- Scan 0.5 km IFOV over the 30km source.
- Resolve stratified layers and scale height in rapidly changing UTLS.



Science Accomplishments – O_3

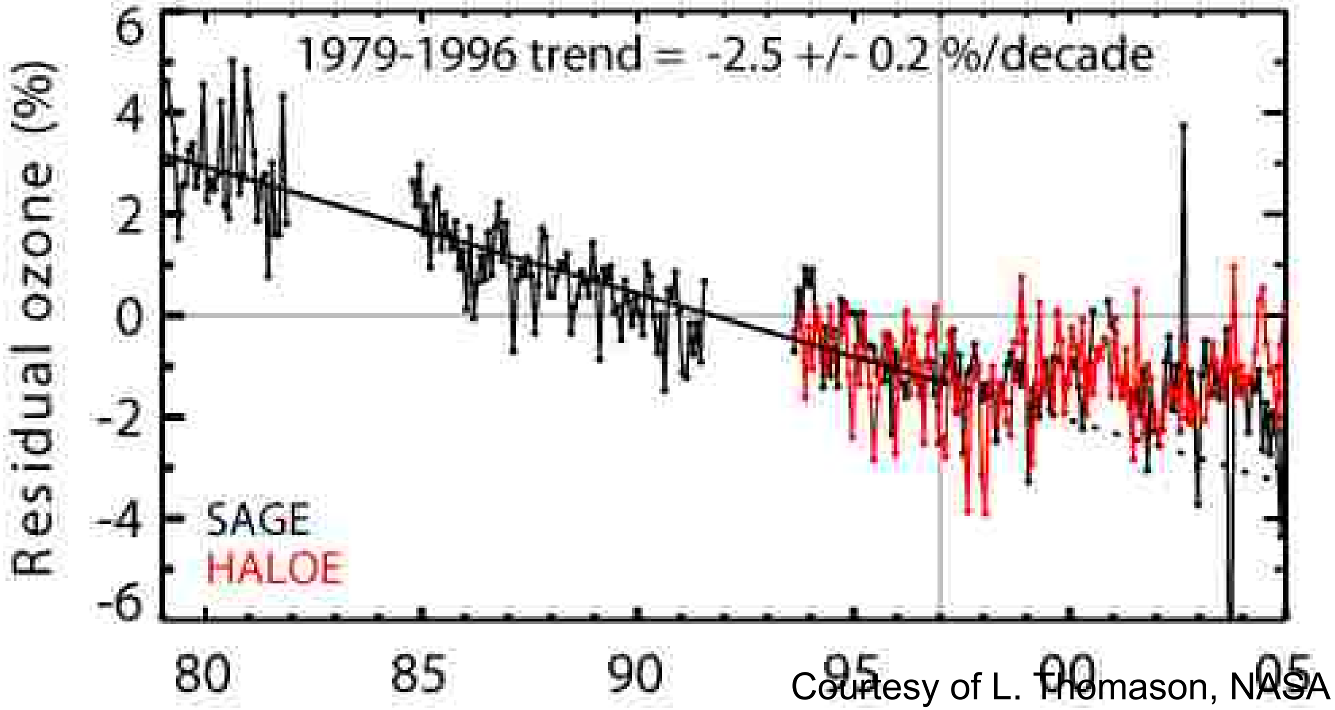
SAGE ozone retrievals are robust down to the tropopause and statistically indistinguishable from ozonesondes [Borchi et al., 2004; Cunnold et al, 2004]



Courtesy of L. Thomason, NASA
Langley Research Center, Hampton, VA

Science Accomplishments – O_3

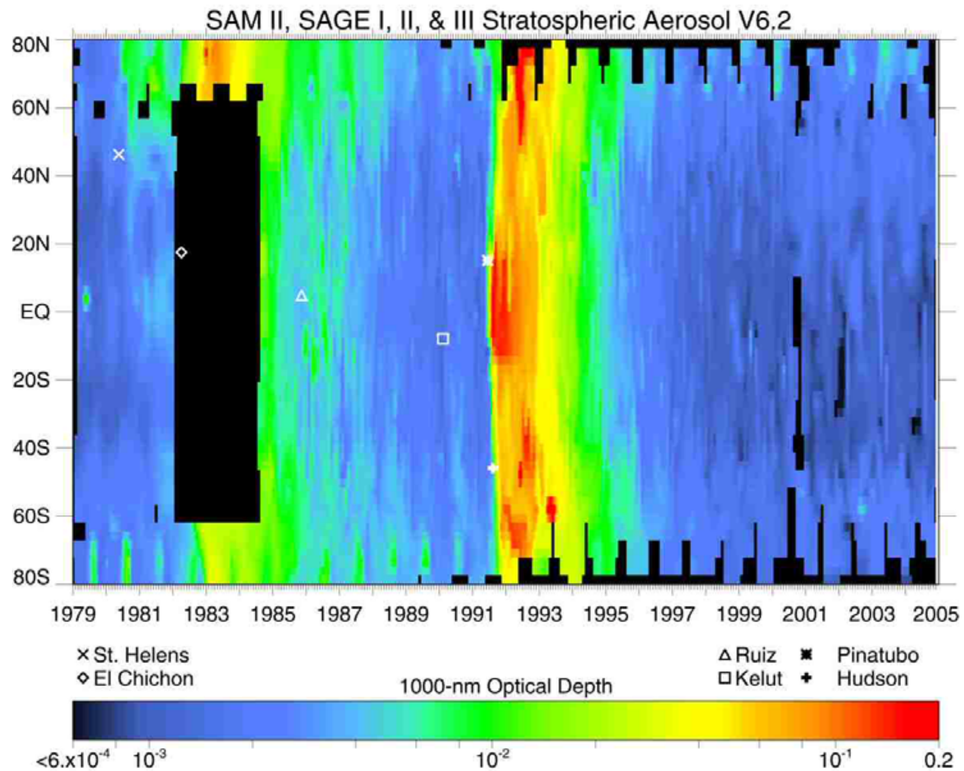
- *SAGE data has allowed the transition from quantifying ozone change to the attribution of those changes to physical processes [Newchurch et al., 2003; Yang et al., 2005]*



Courtesy of L. Thomason, NASA
Langley Research Center, Hampton, VA

Science Accomplishments - Aerosol

- ***SAGE aerosol extinction and surface area density measurements are a key input to modeling of climate and stratospheric chemical/dynamical processes related to ozone destruction***
- ***SAGE is the focus of the current SPARC (WCRP) Assessment of Stratospheric Aerosol Properties [Thomason and Peter 2004]***



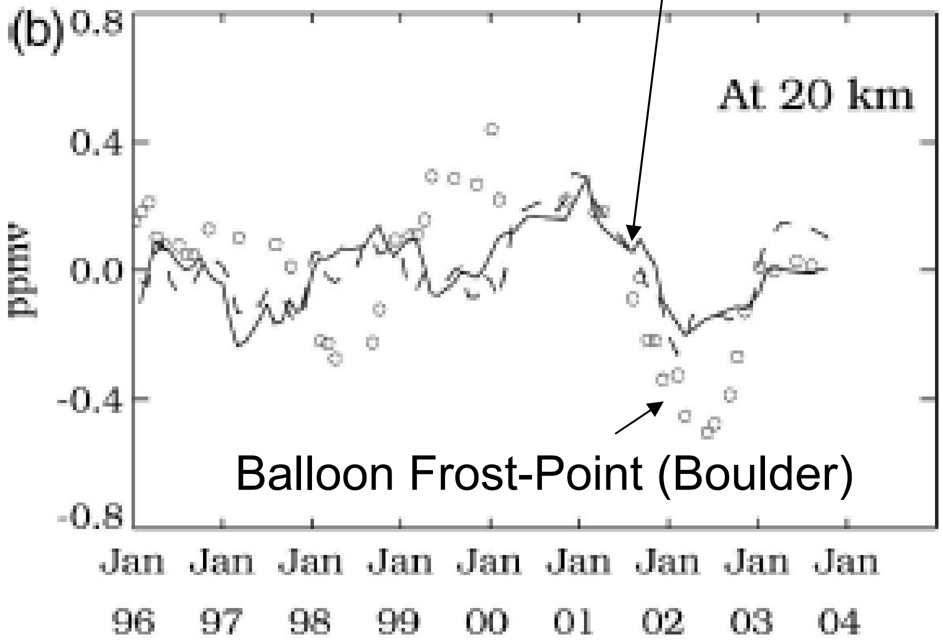
Courtesy of L. Thomason, NASA
Langley Research Center, Hampton, VA

SAGE II H2O Record

(Chiou, et al., J. Climate, 2006)

H2O from SAGE II, HALOE & Balloon Frost-Point @ Boulder, CO

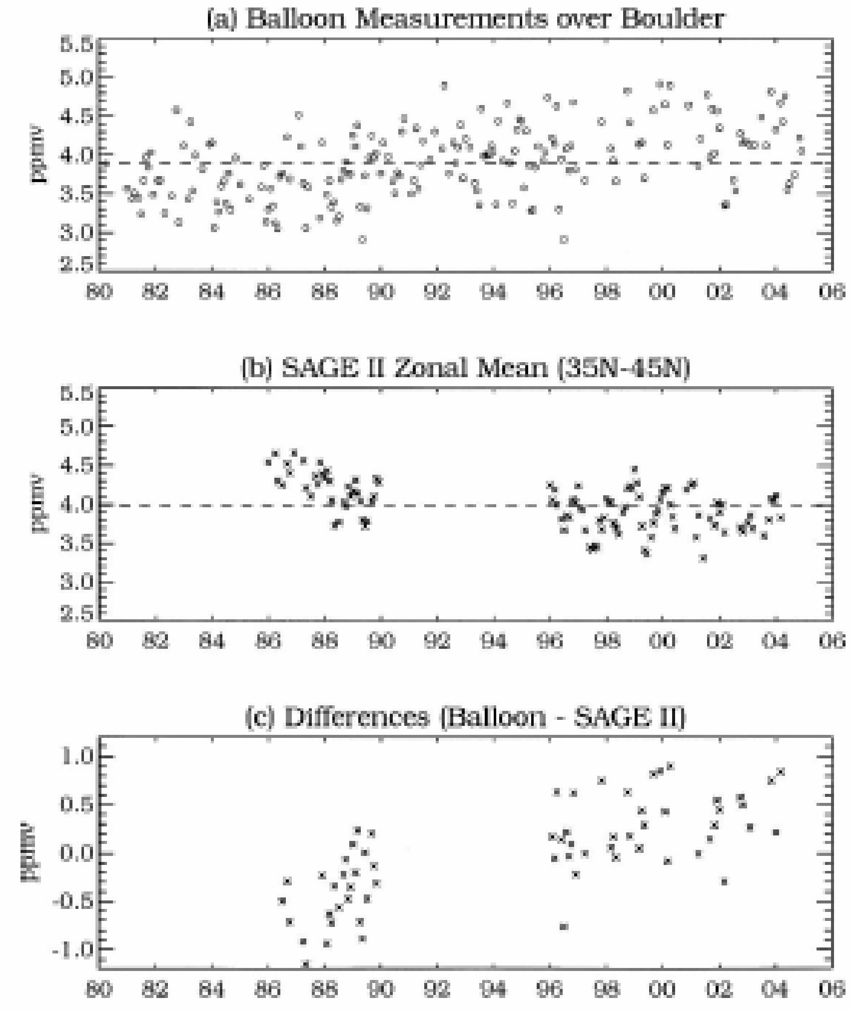
Zonal Mean SAGE II & HALOE are consistent



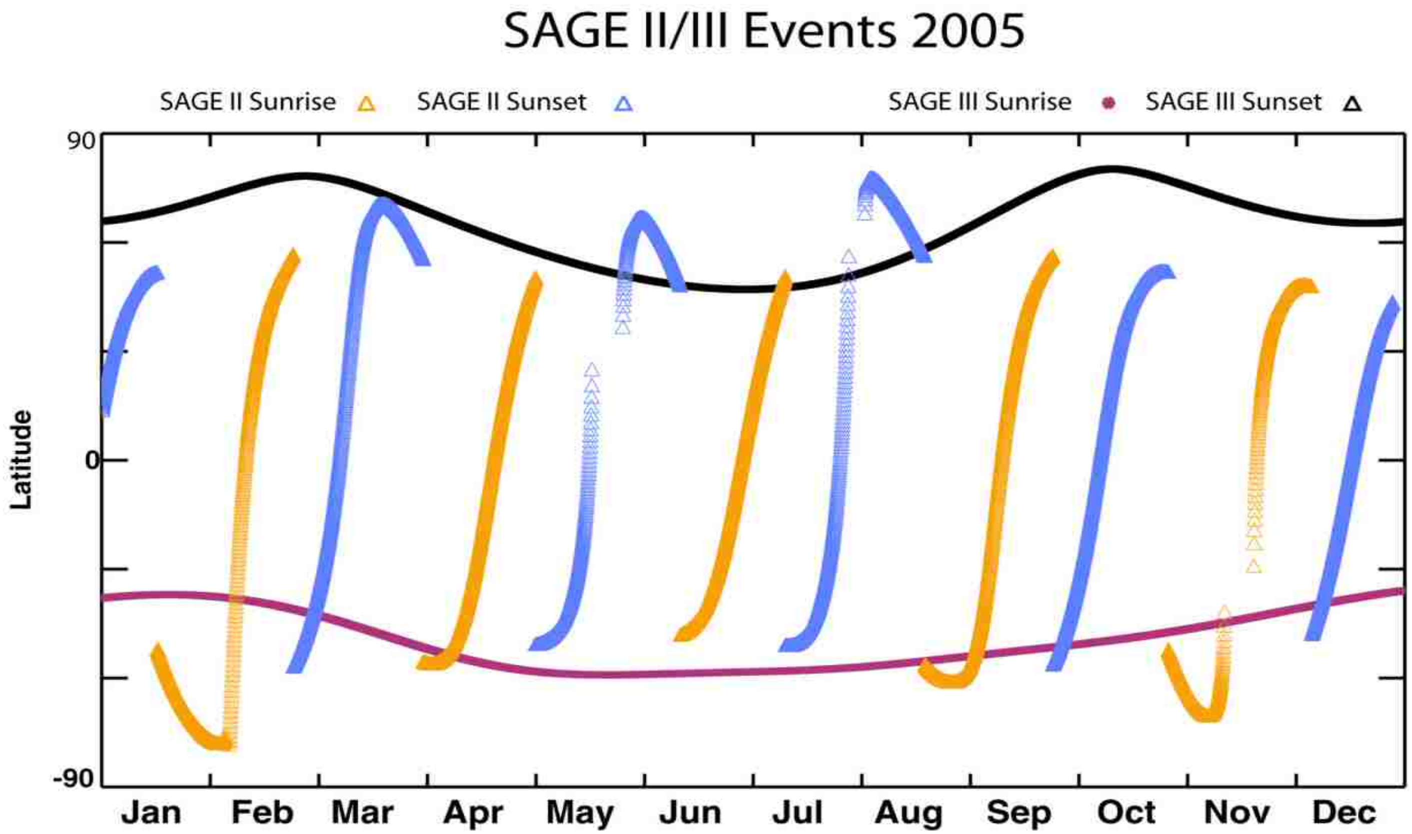
Balloon Frost-Point (Boulder)

Deseasonalized Anomalies

(18 km)



SAGE Spatial Coverage



Courtesy of L. Thomason, NASA
Langley Research Center, Hampton, VA

Facts about SAGE III/Meteor 3M

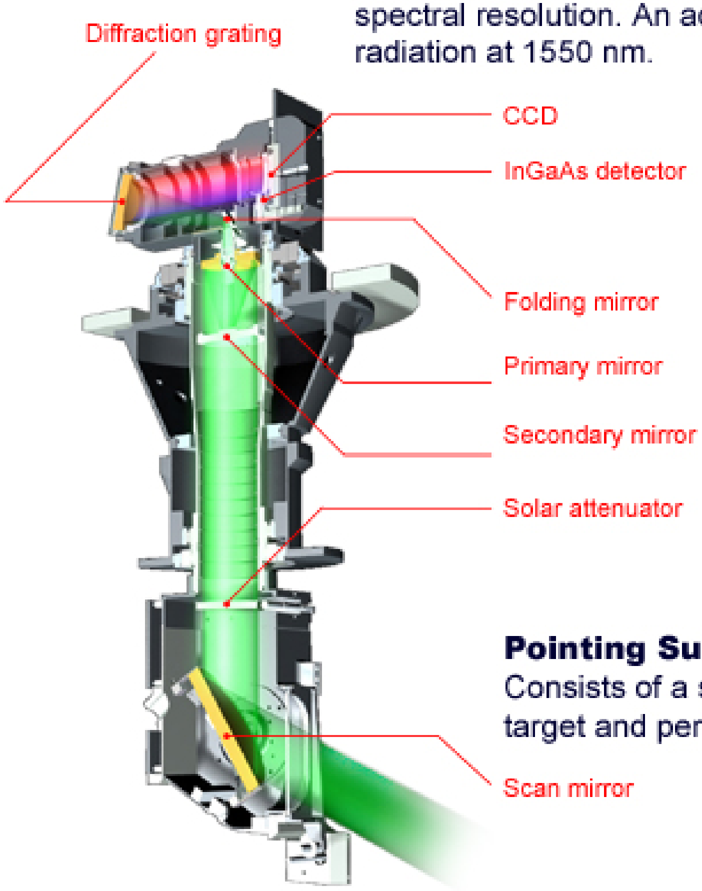
- Sept 1989 -- selection for Phase B
- November 1994 -- Authority to Proceed phase C/D
- September 1998 -- SAGE III Meteor Instrument delivered from Ball to LaRC
- April 2000 -- SAGE III Meteor Instrument shipped to Russia
- January 2001 -- SAGE III Meteor Instrument developed Azimuth Motor anomaly, shipped back to US
- July 2001 -- SAGE III Meteor (R) Instrument shipped to Baikonur. (R) stands for replacement, using the backup FOO instrument
- December 2001 -- Launch (Delay from original planned launch date of August 1998)

SAGE 3 mission milestones

• Launch:	Dec. 10, 2001
• SAGE III Power ON:	Dec. 17, 2001
• First Data Transmission to WFF:	Dec. 19, 2001
• 1.7 GHz Transmitter anomaly:	Jan. 1, 2002
• Resume operations:	Feb. 18, 2002
• First Solar Measurements:	Feb. 27, 2002
• First Lunar Measurements:	March 4, 2002
• First ILRS Orbit Products:	May 7, 2002
• First Limb Scan Measurement:	June 30, 2002
• Space-craft Hermetic Seal Breached:	July 2005
• Space-craft Charging System Failed:	March 2006

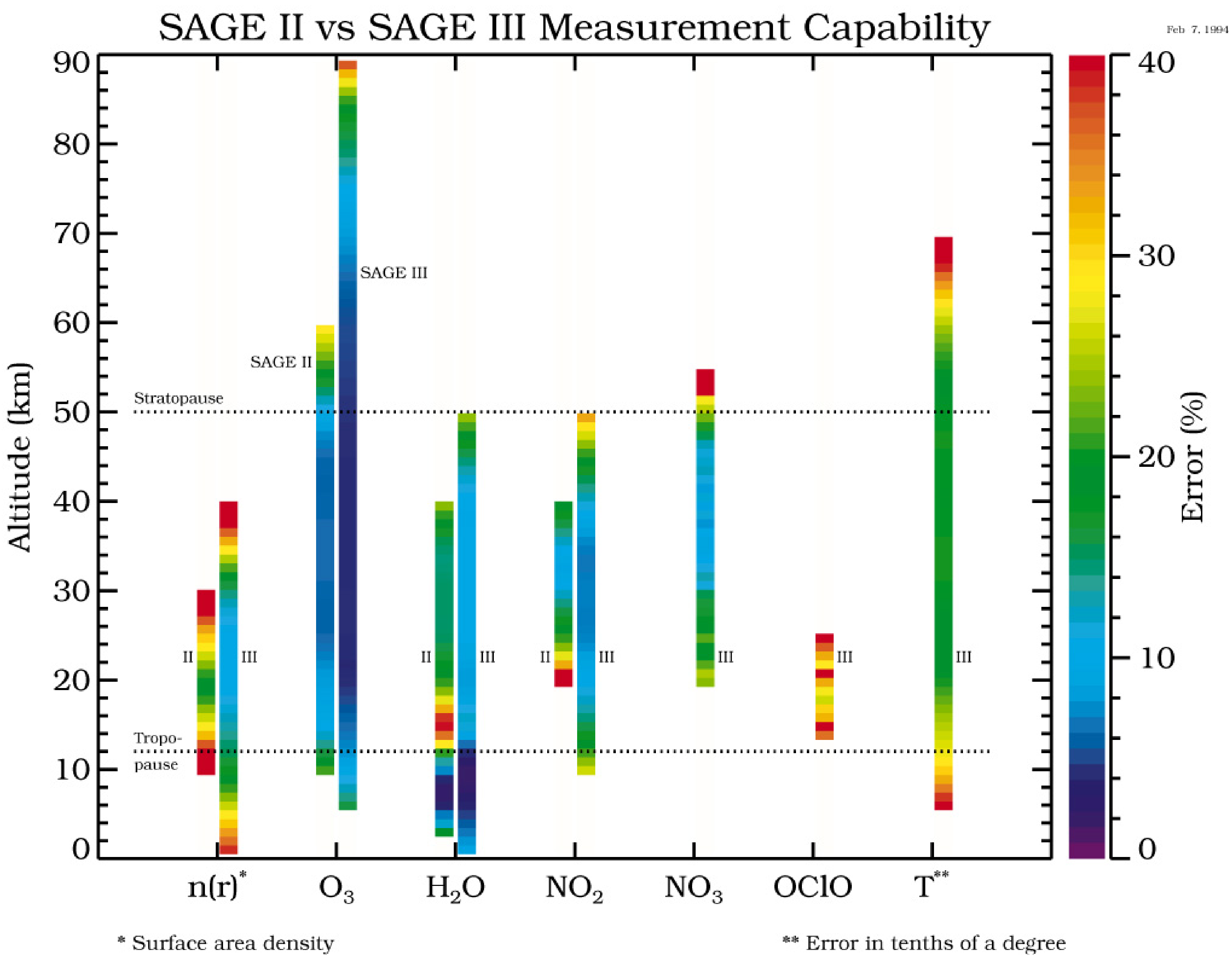
SAGE III INSTRUMENT

Spectrometer Subsystem
Measures solar radiation from 280 to 1040 nm and 1 to 2 nm spectral resolution. An additional photodetector measures radiation at 1550 nm.



Imaging Subsystem
Produces a focused image of the target at a focal plane where the instrument's field of view is situated.

Pointing Subsystem
Consists of a scan mirror which acquires the radiant target and performs vertical scanning across the target.



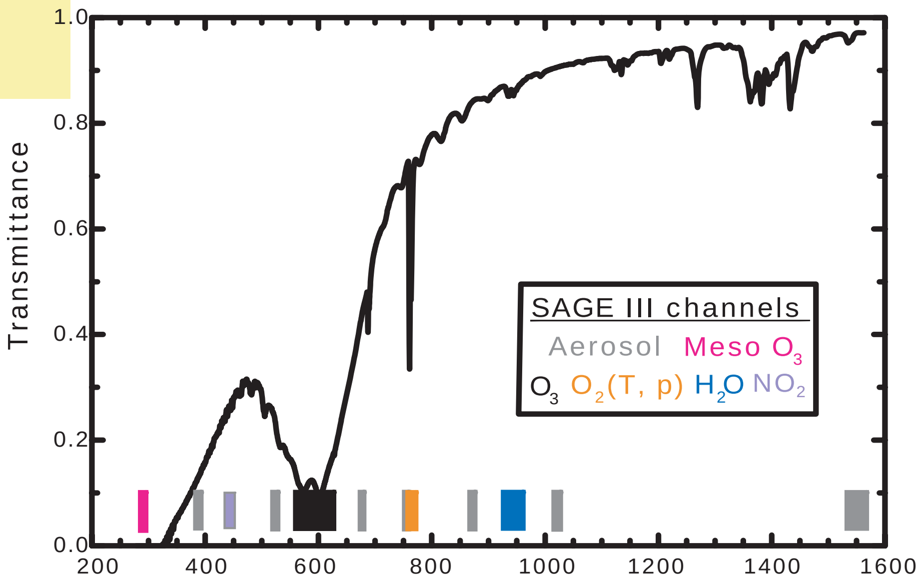
SAGE II vs SAGE III Measurement Capability
Feb 7, 1994
Altitude (km)
90
80
70
60
50
40
30
20
10
0
Stratopause
Tropo-
pause
SAGE II
SAGE III
II
III
n(r)*
O_3
H_2O
NO_2
NO_3
OClO
T**
Error (%)
40
30
20
10
0
* Surface area density
** Error in tenths of a degree

Solar Channel Map

Channel	Wavelength (nm)	Subchannels	Species
S1	287.2-292.9	1	Mesospheric O_3
S2	381.9-386.6	1	Aerosol
S3	432.6-450.4	19	NO_2, Aerosol
S4	518.0-522.7	1	Aerosol
S5	560.2-622.5	10	O_3
S6	673.3-678.0	1	Aerosol
S7	753.1-757.8	1	Aerosol
S8	757.8-770.9	14	T/P
S9	867.0-871.1	1	Aerosol
S10	933.0-959.9	29	H_2O
S11	1018.9-1024.5	1	Aerosol
S12	1530.1-1560.2	1	Aerosol

84 spectral pixels
are down-linked

Analysis using:
-Broad-band, aka SAGE II
-Narrow-band, aka Multiple Linear Regression



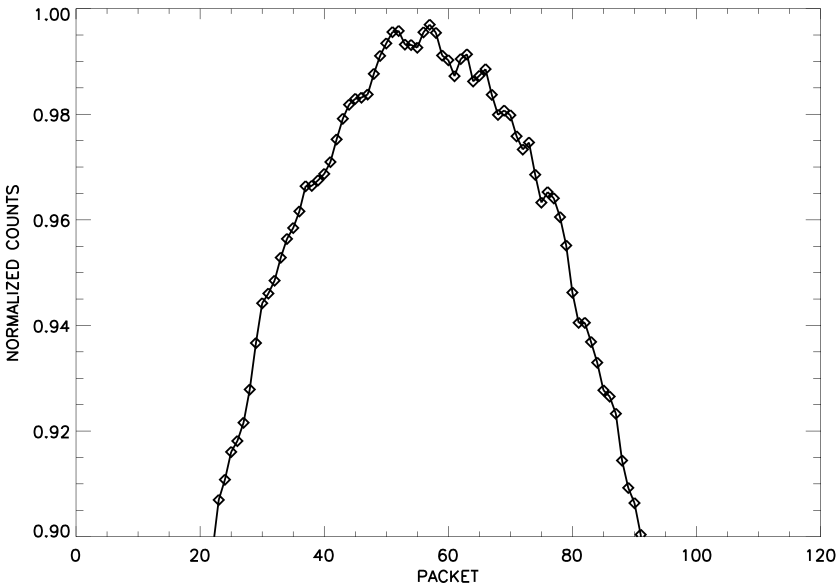
SAGE III V4 Key Items

- **Initial water vapor release (Thomason & Chiou)**
- **Revised ozone cross sections**
- **Level 1 transmission algorithms standardized between SAGE I/II/III**
- **Improvements in the Level 1 transmission product have resulted in reduced noise in ozone and aerosol retrievals. Key improvements include:**
  - **Revised ephemeris calculation**
  - **Improved data binning algorithm**
  - **Exoatmospheric data filtering**
  - **Time dependent I0 correction (Solar rotation)**
  - **Revised refraction algorithm**

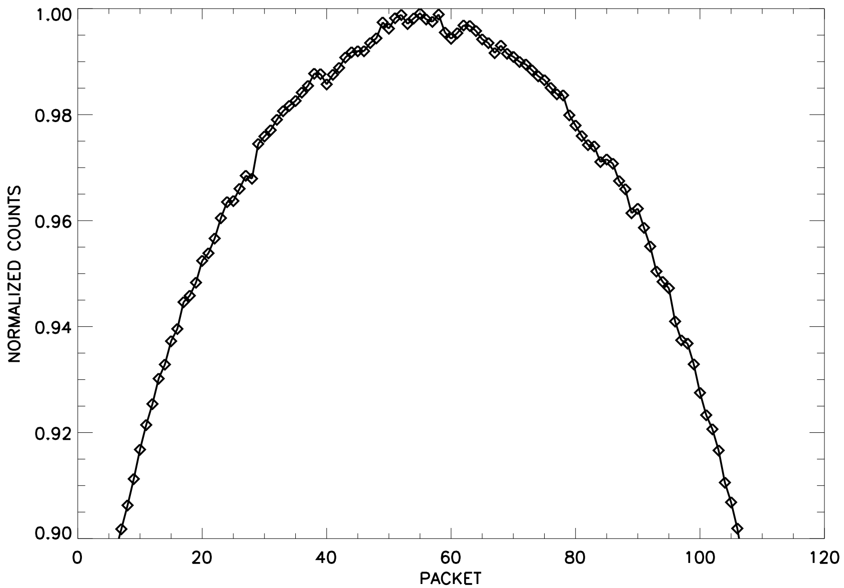
Solar Target Challenges

- Sun appears different at each wavelength
- Sun is not a uniform source

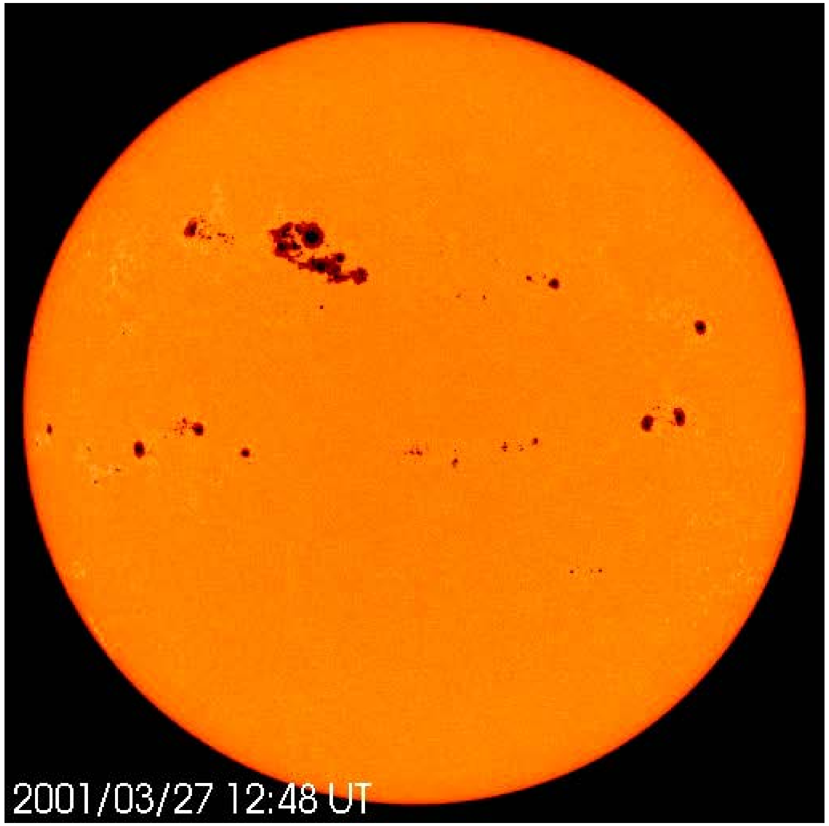
UV



Near-IR



Sun Spots

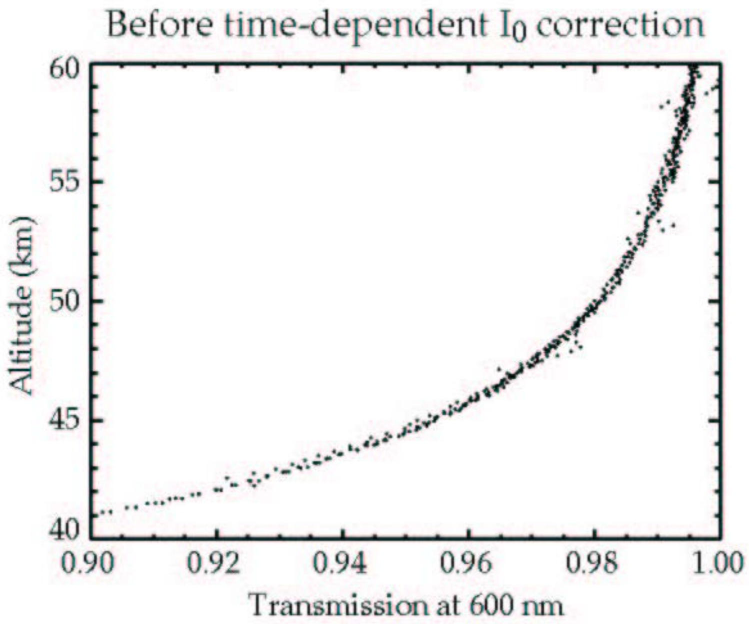


http://sohowww.nascom.nasa.gov/gallery/Movies/sunspots.html

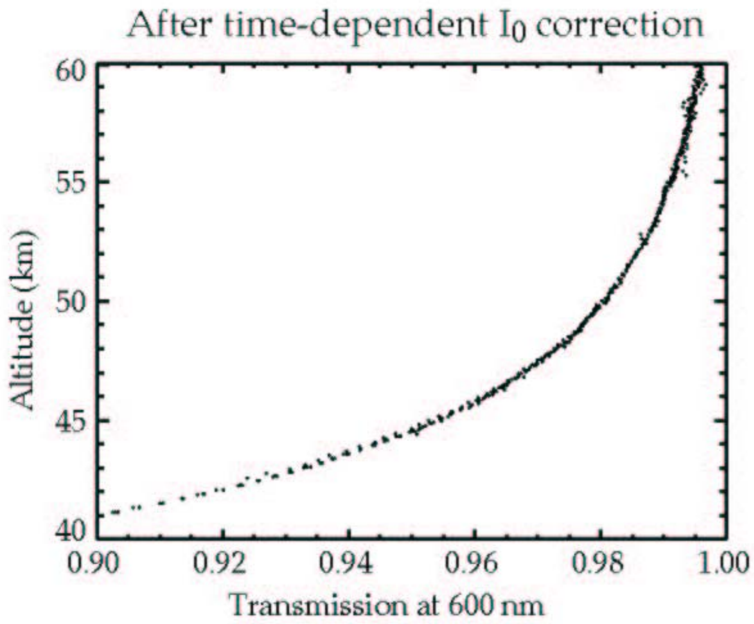
Refinements in Data Processing substantially increase SNR

SAGE II

Tranmission



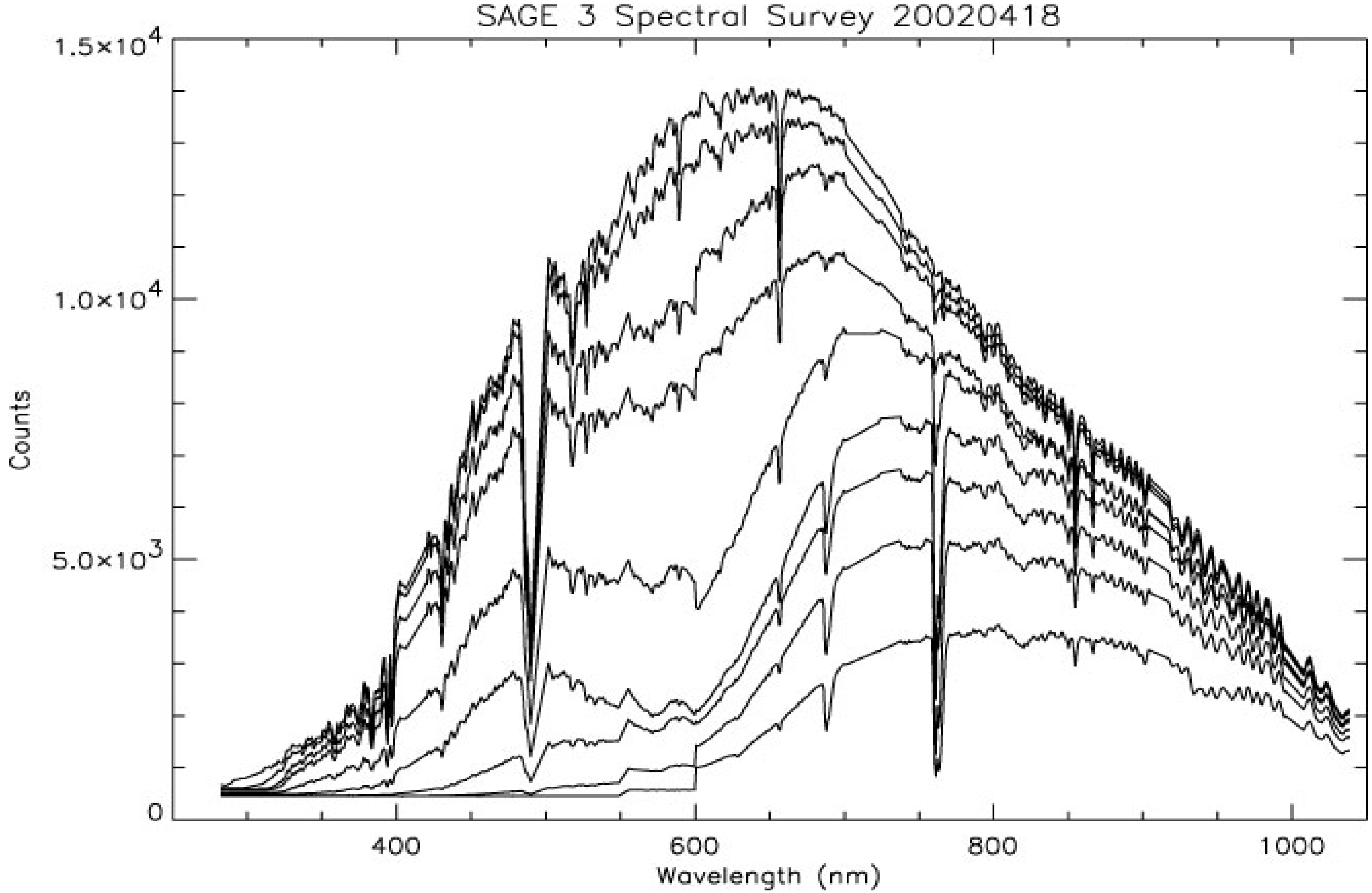
Transmission measurements are shown for the primary ozone channel for a sunset observation on 21 July 2001, at altitudes where attenuation by Rayleigh scattering and ozone absorption begins to be detectable. After the improved I_0 calibration (discussed at left) and other corrections, much of the remaining scatter is due to time dependence of the solar limb darkening.



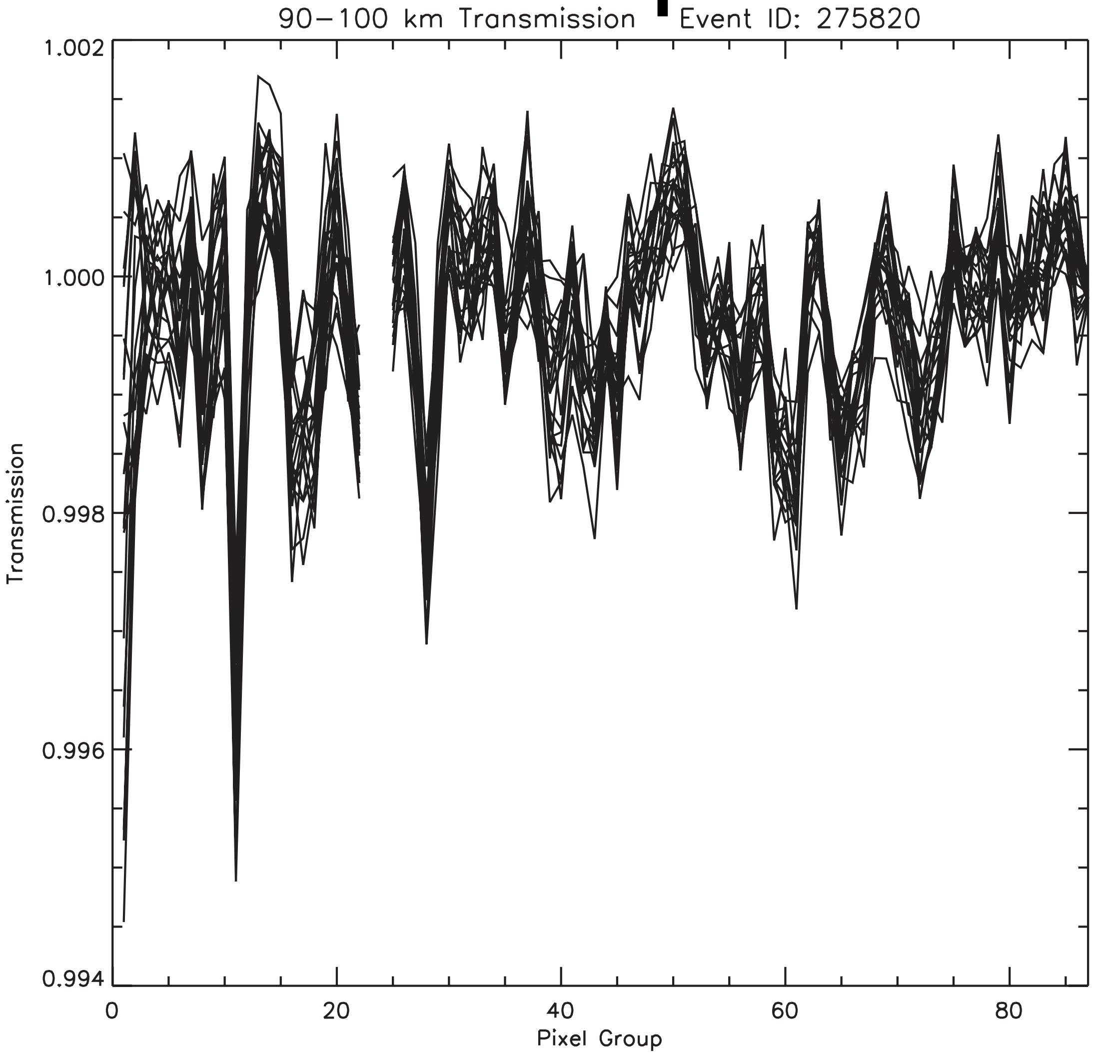
The time dependence of the solar limb darkening is a combination of rotation of the scan plane and real-time variability of the photosphere. Correcting for apparent time dependence in the limb darkening decreases the scatter in the normalized transmission by approximately 40%.

(Sharron Burton, 2005)

SAGE III Instrument performance

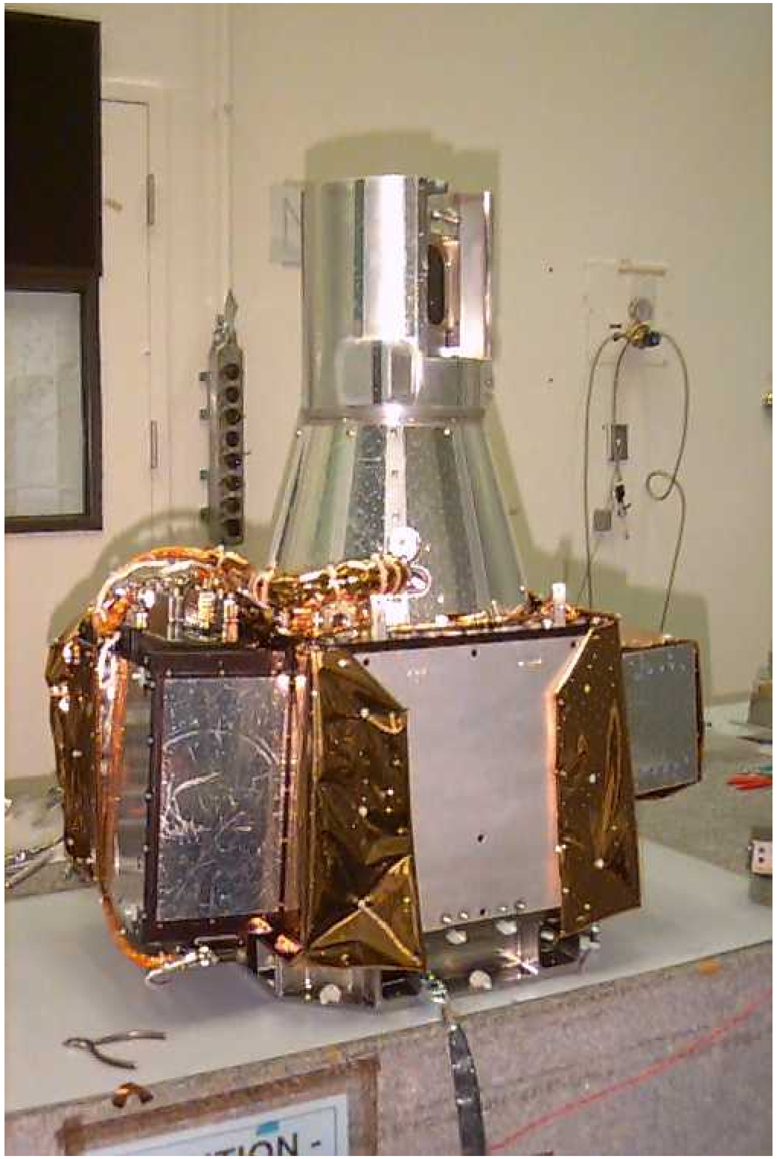


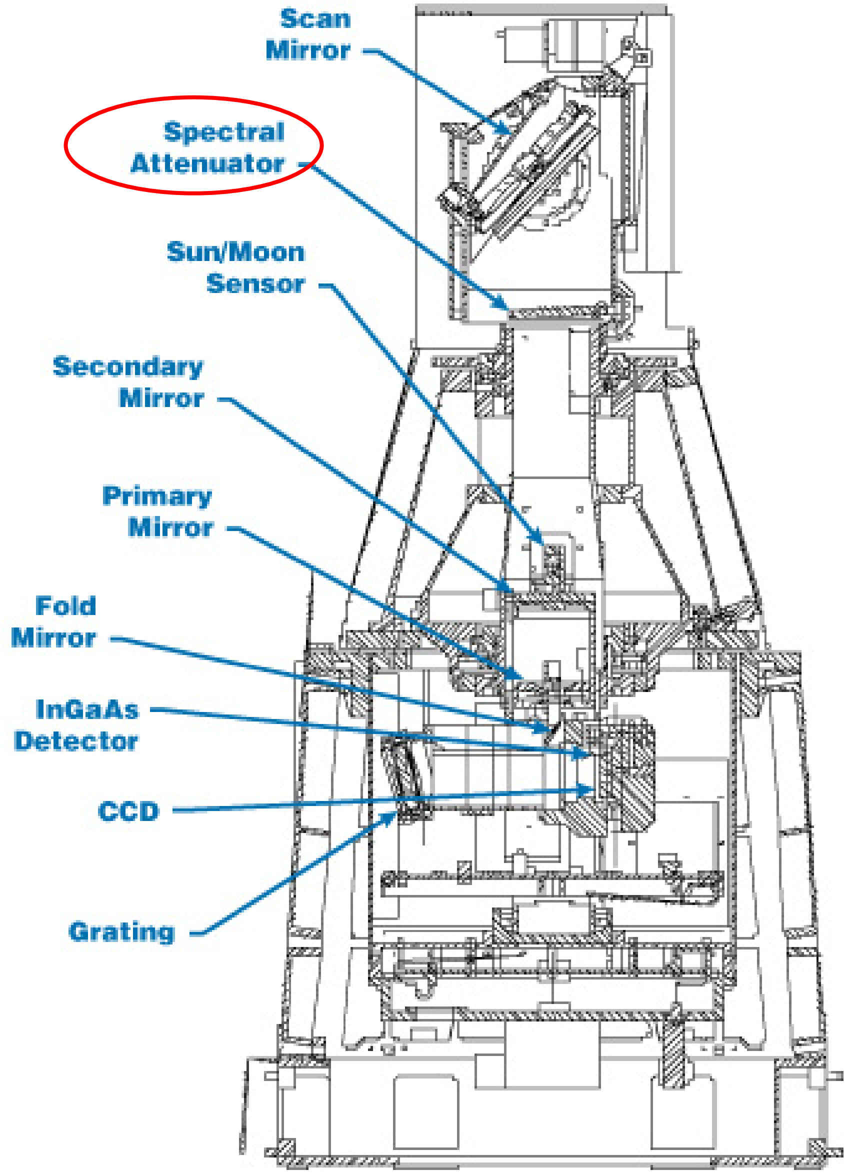
Anomalous Spectral Features



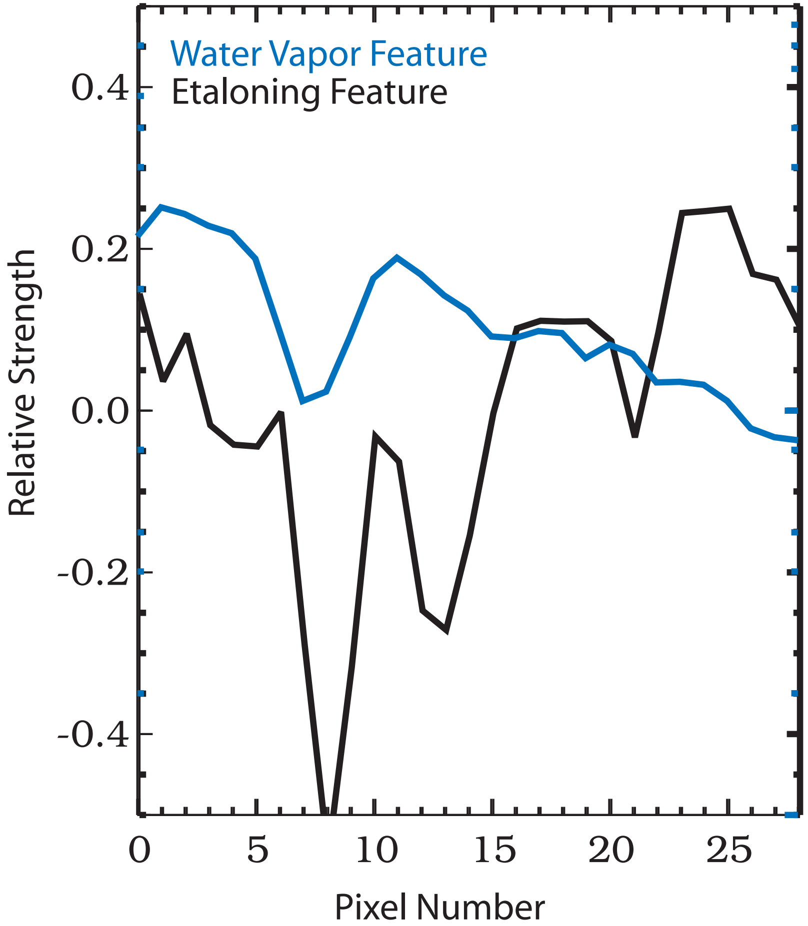
High altitude transmission exhibits anomalous but consistent spectral features

SAGE III Instrument





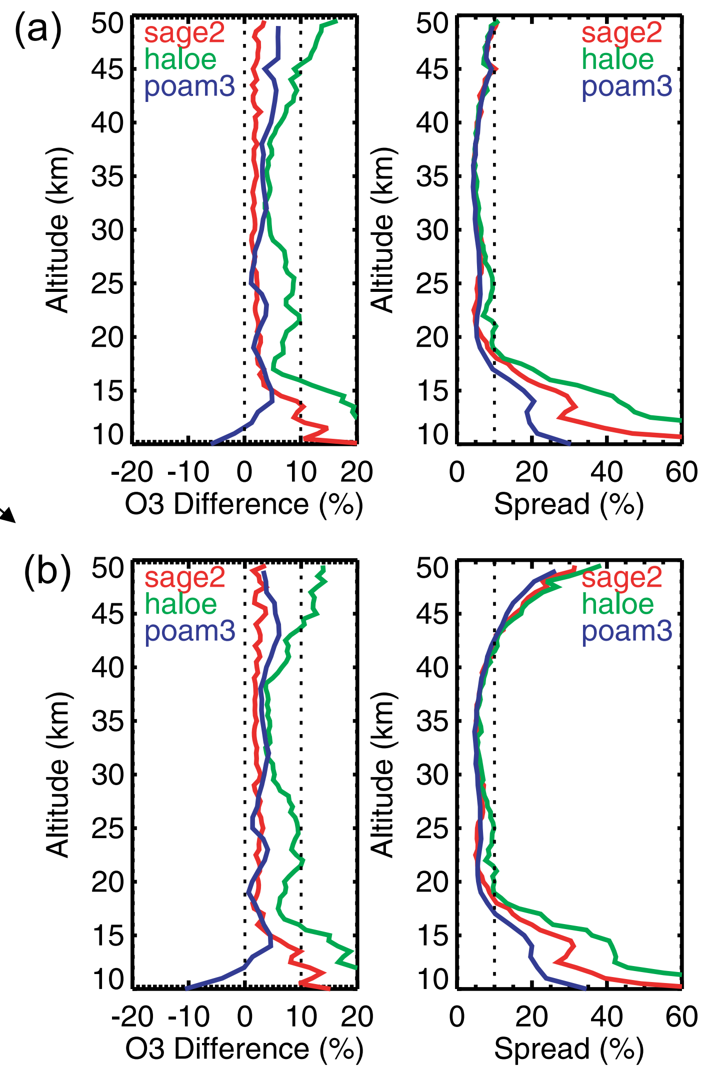
Comparison of Water Vapor and Etaloning Feature



Different View of Same Thing

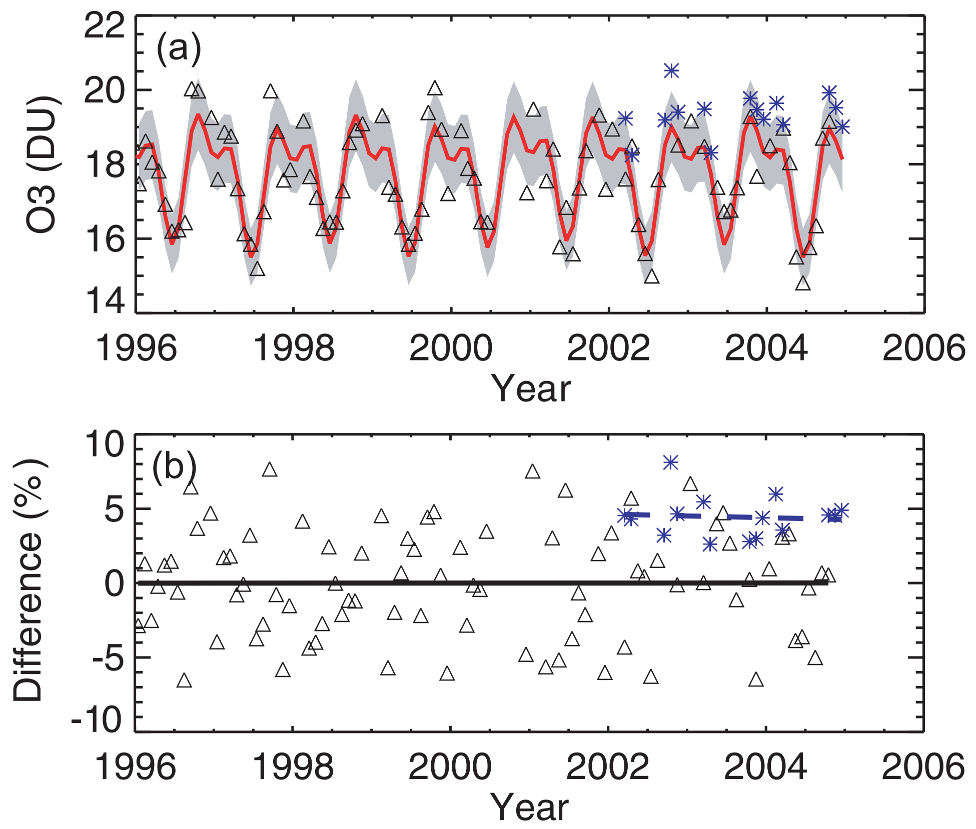
- Different analysis of solar data (Broad-band vs. Multiple Linear Regression, MLR) yield similar results

SAGE III vs. SAGE II, HALOE, POAM3



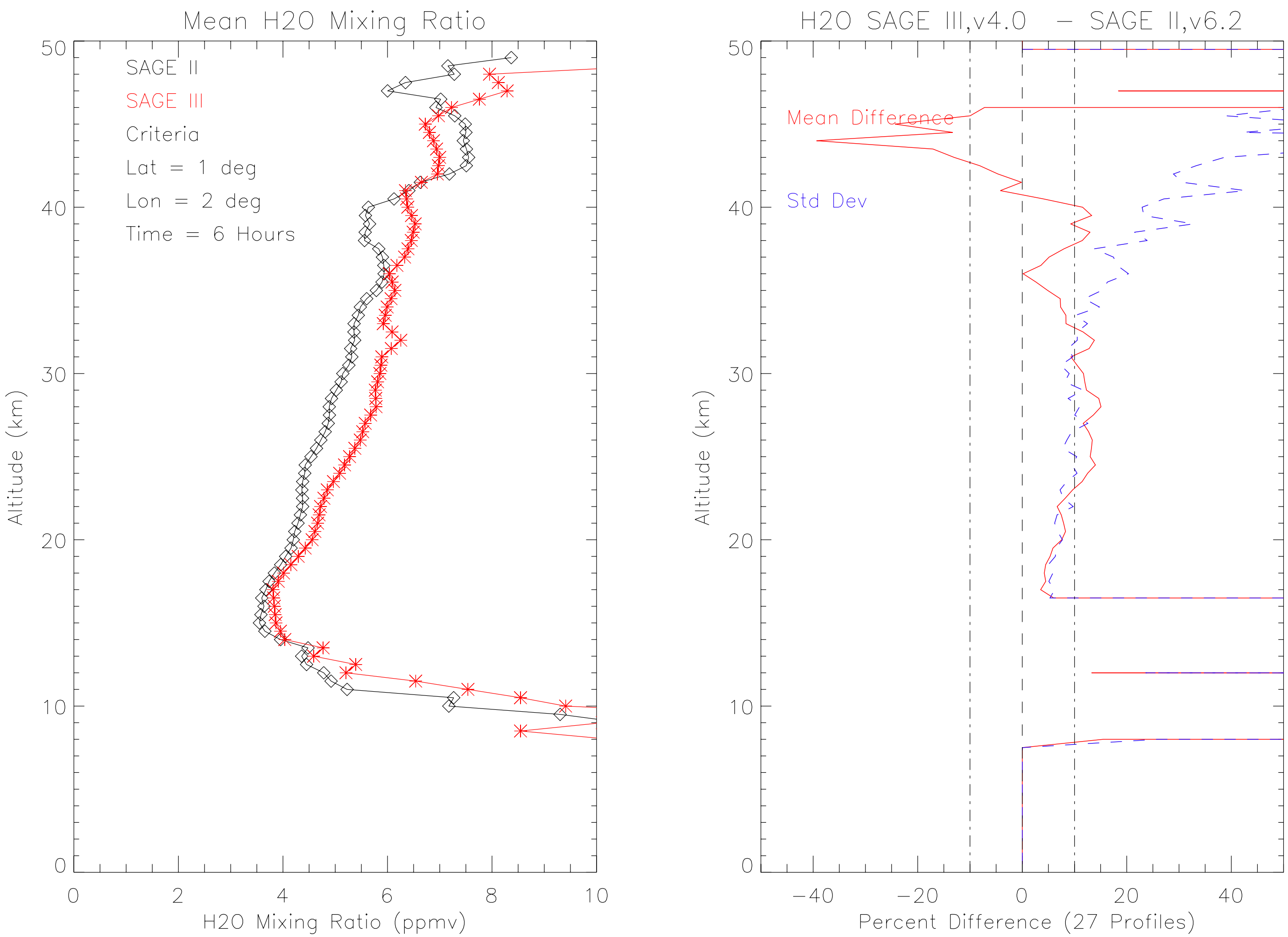
(Wang et al., 2006)

Consistency of SAGE II & SAGE III O3 Records

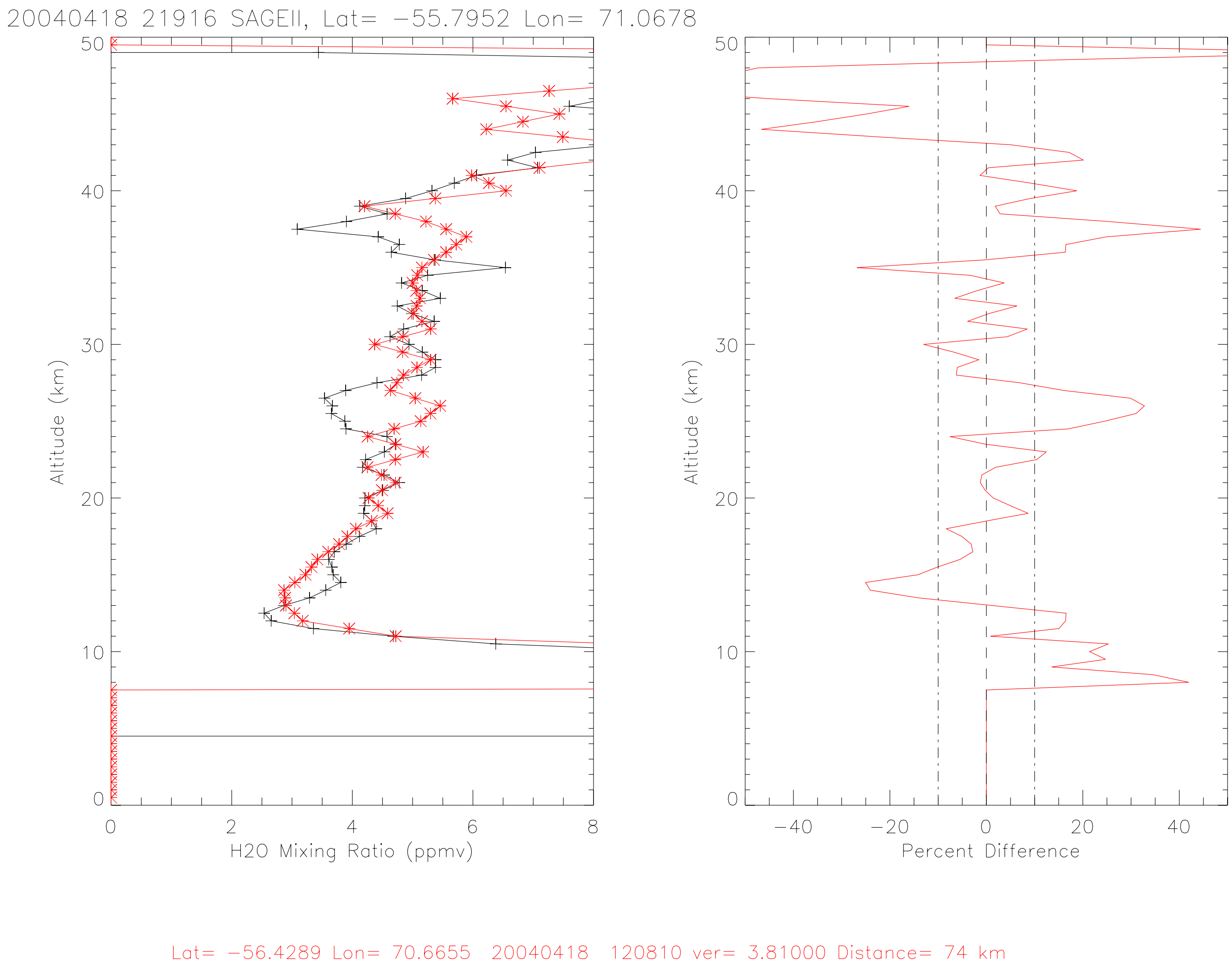


Wang et al., GRL, 2005

SAGE III V4: Water Vapor

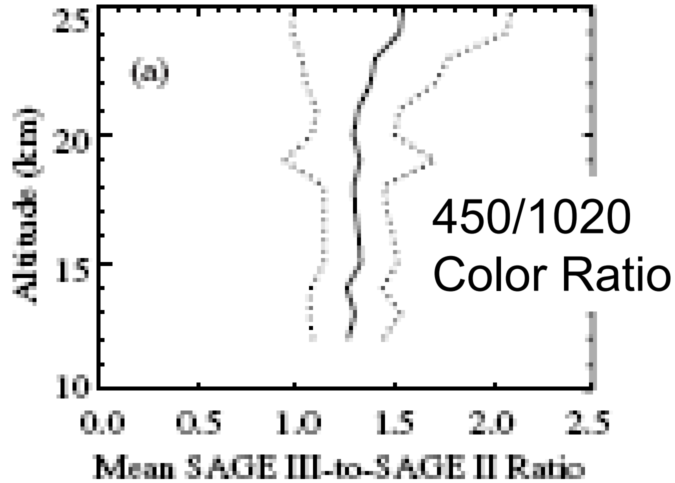


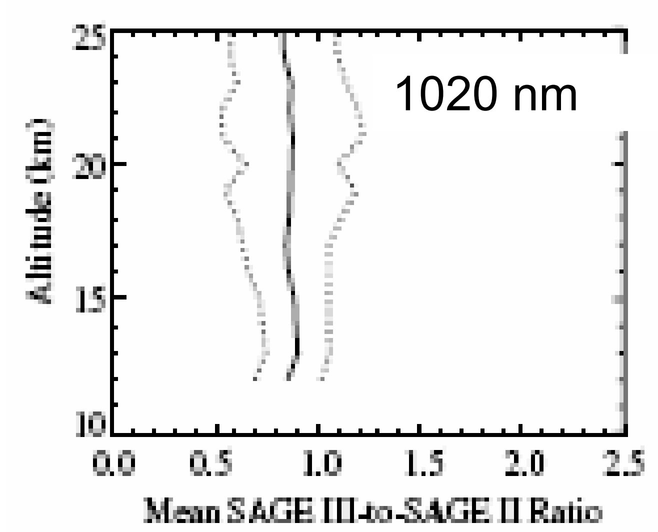
SAGE III V4: Water Vapor (2)



SAGE III Aerosol

- SAGE III Aerosol extinction has systematic biases compared to SAGE II, but vary with wavelength
- 1025 nm is 15% lower than SAGE II

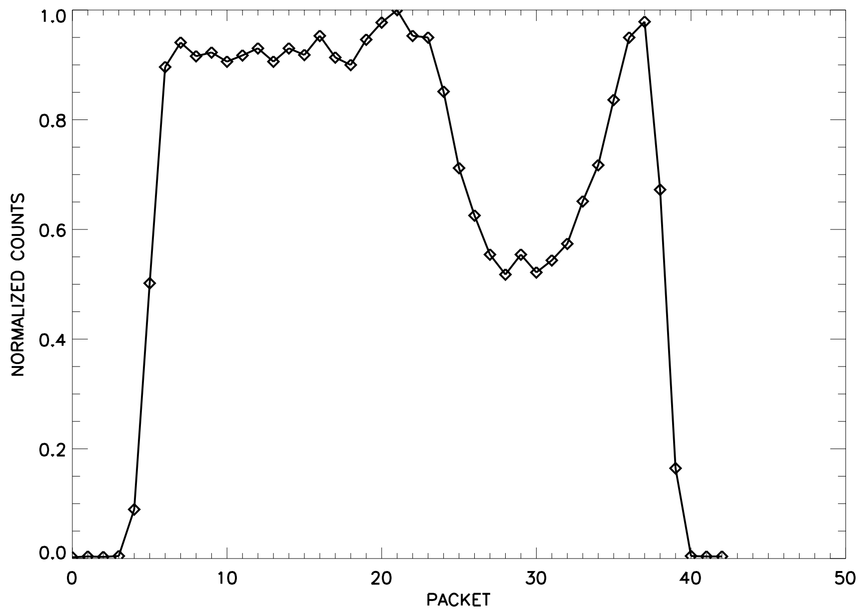




Lunar vs Solar

- Low Signal Strength (10-6 solar)
  - Integration Time 62.5ms vs 15.6ms
  - Increase FOV width
  - Process 294 pixels simultaneously
- Non-uniform albedo
- No baseline I0
  - No ratio I/I0
  - Use differential MLR for O3, NO2, NO3, OClO

Lunar Target More Challenging Than Solar



Lunar Inversion Algorithm

- Create optical depth curve with scan data and mean exoatmospheric lunar scan
- Filter optical depth curve to remove low frequency component
- Filter absorption cross sections
- Multiple Linear Regression fit of filtered OD curve and cross sections

Differential MLR for lunar

$I = aI_0\, e^{-T}\, e^{-\tau}$

- I= Observed lunar radiance
- aI_0= Scaled solar spectrum
- e^{-T}= Low frequency components
- $e^{-\tau}$= High frequency components

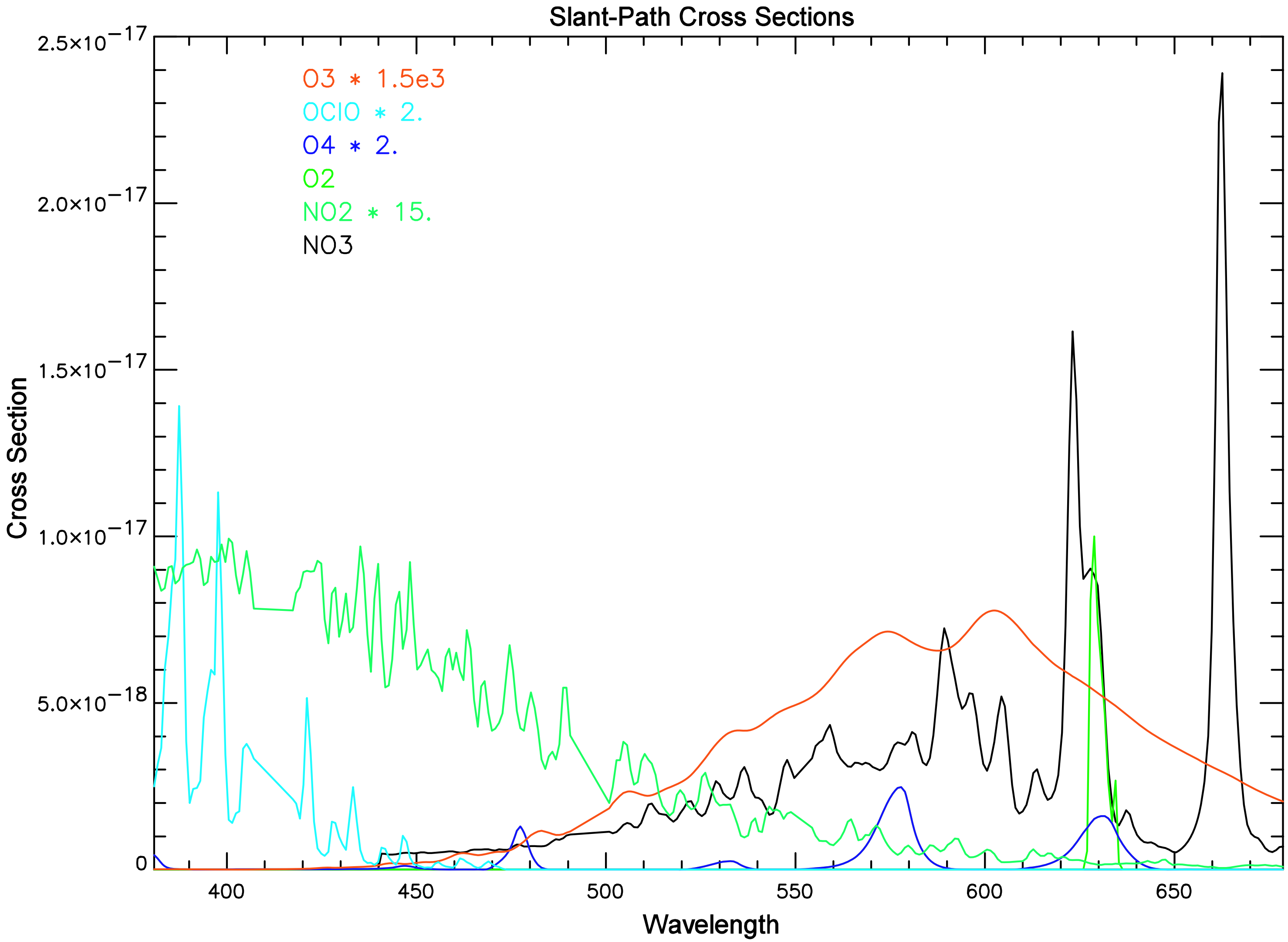
$\ln(I / \bar{A}\, I_0) = \ln(Ae^{-T}) - \tau.$

- $\bar{A}$= Mean albedo
- A= Albedo (λ)

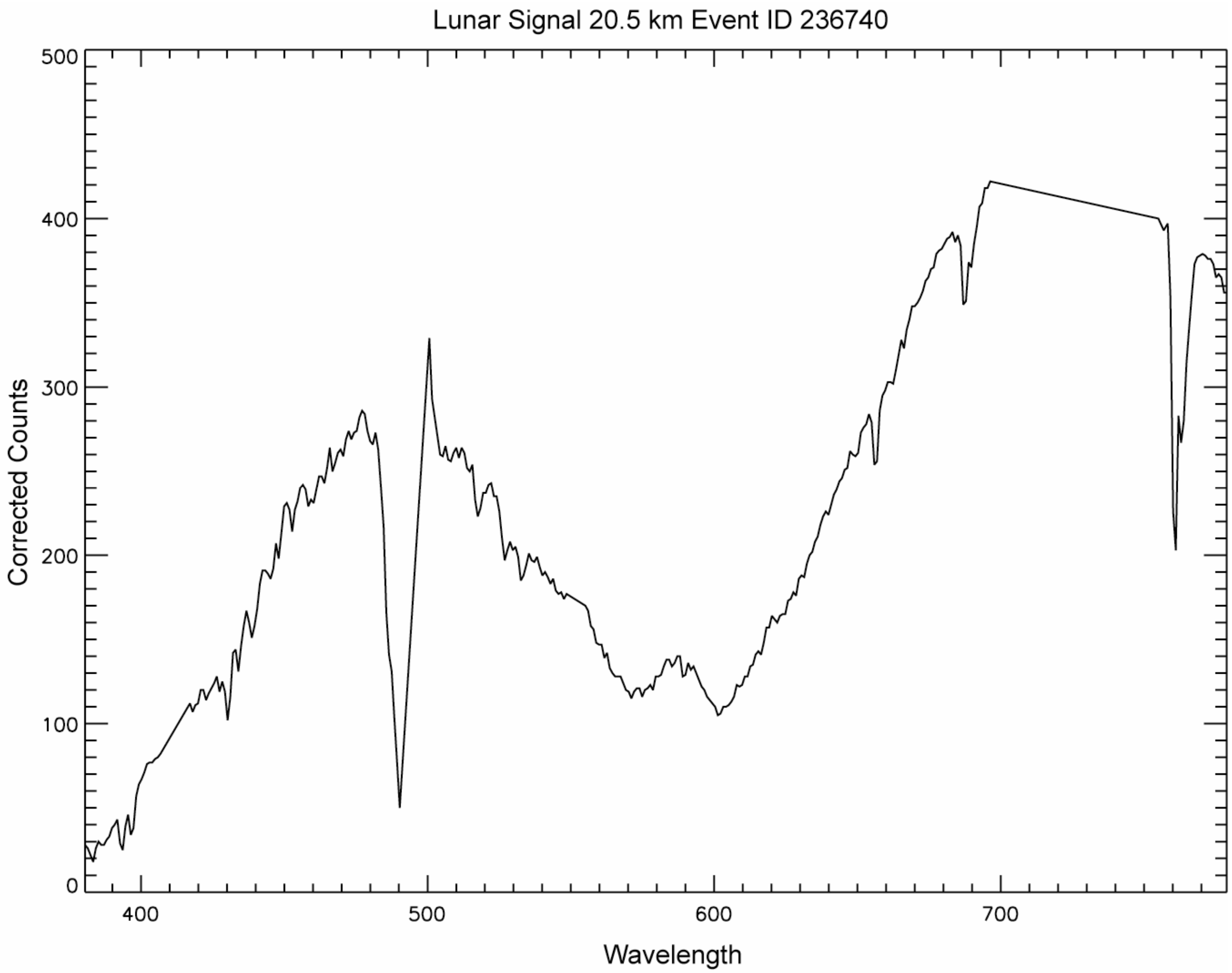
$$\tau(\lambda_i) = n_{O_3}\sigma_i(\lambda i, O_3) + n_{NO_2}\,\sigma_i(\lambda_i, NO_2)$$

$$n_{NO_3}\,\sigma_i(\lambda_i, NO_3) + n_{OClO}\,\sigma_i(\lambda_i, OClO)$$

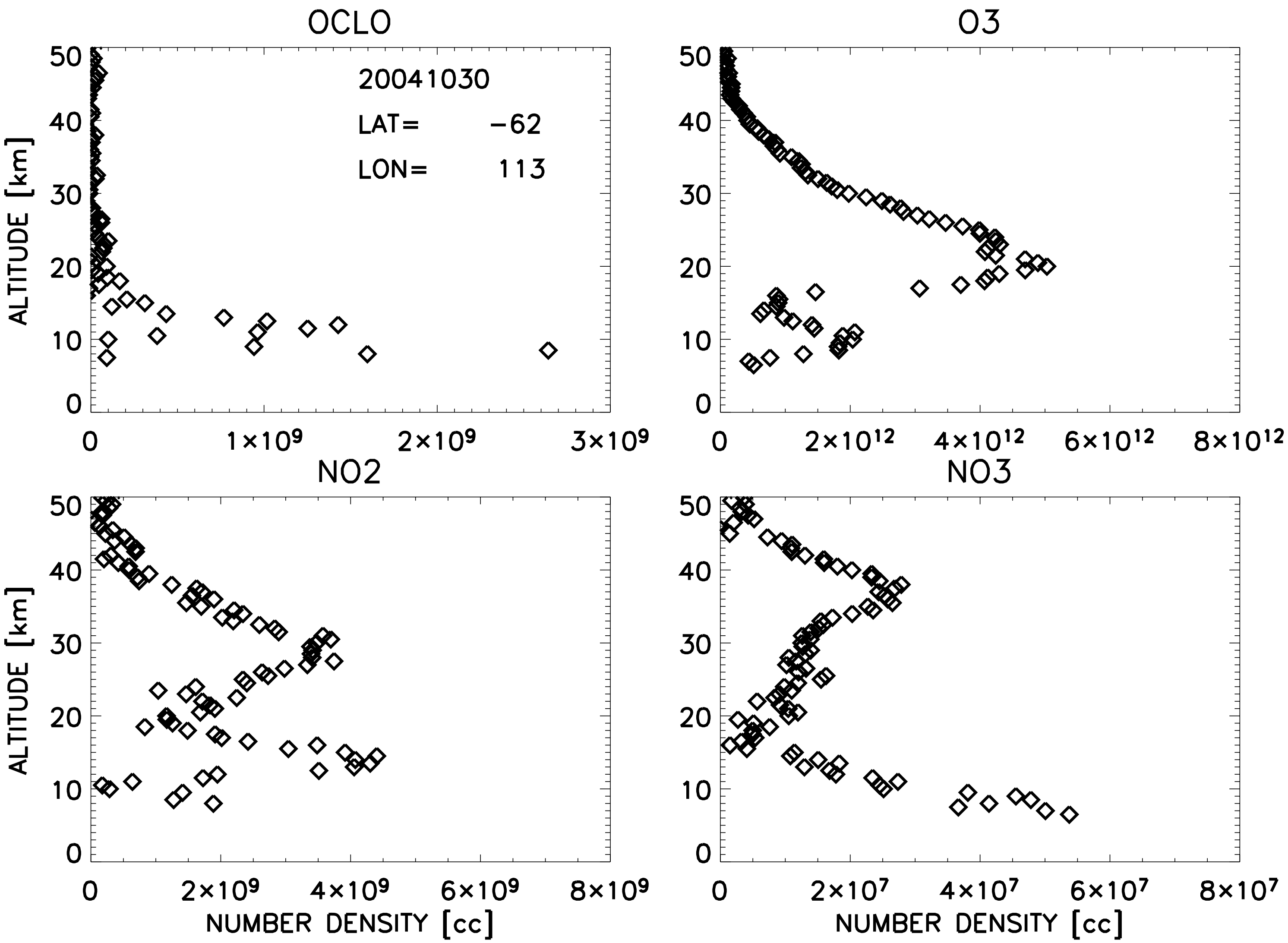
Slant-Path Cross Sections



Lunar signal @ 21 km

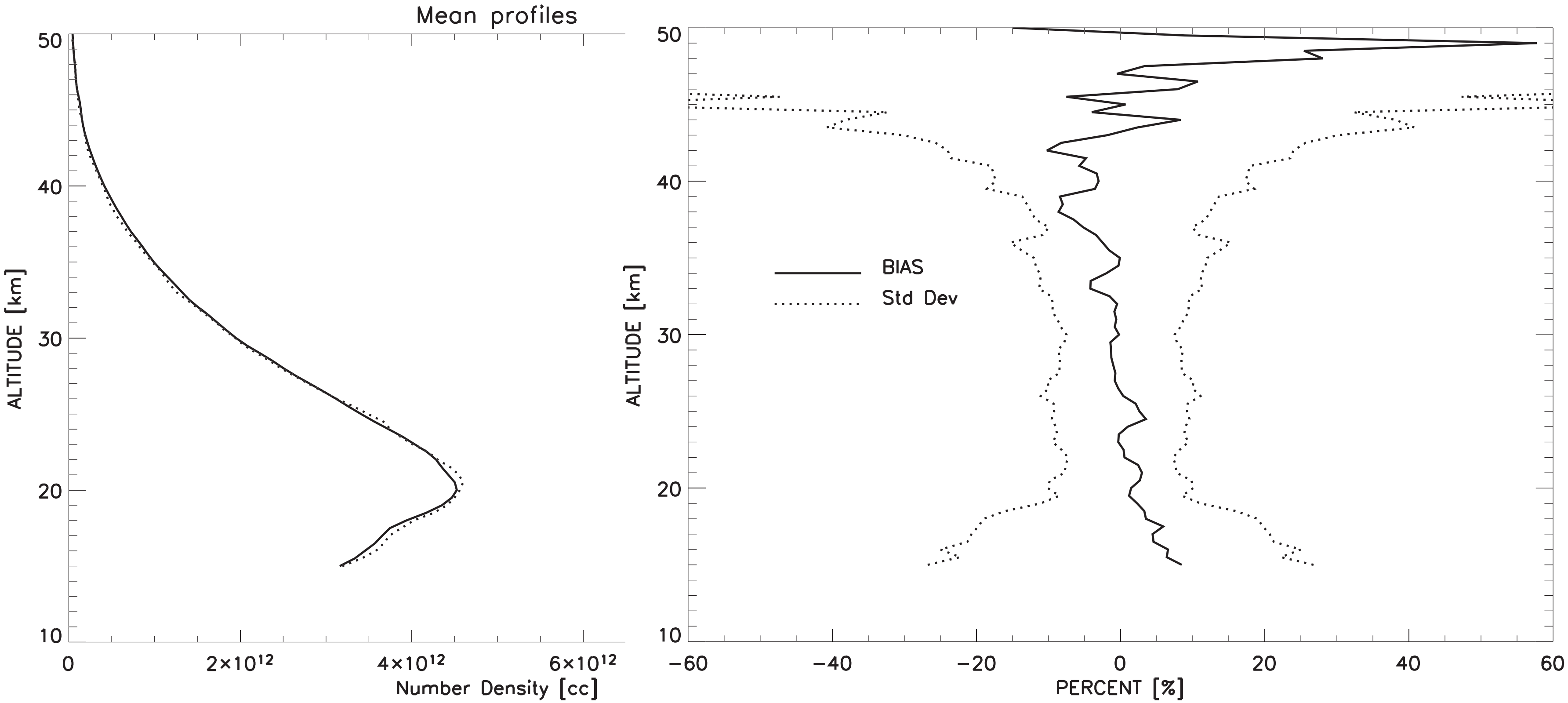


Lunar Results

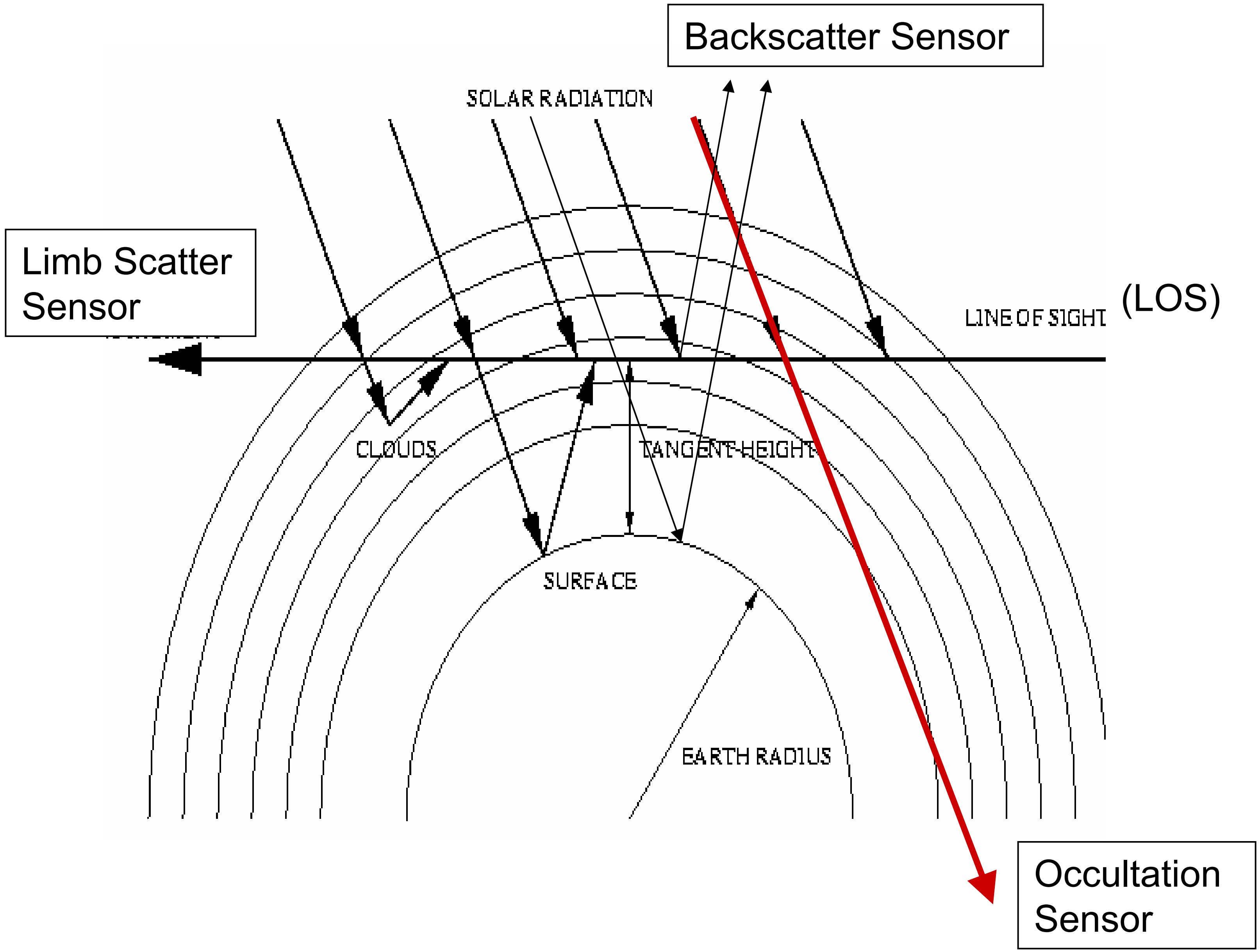


SAGE III Lunar vs SAGE II Solar

OZONE

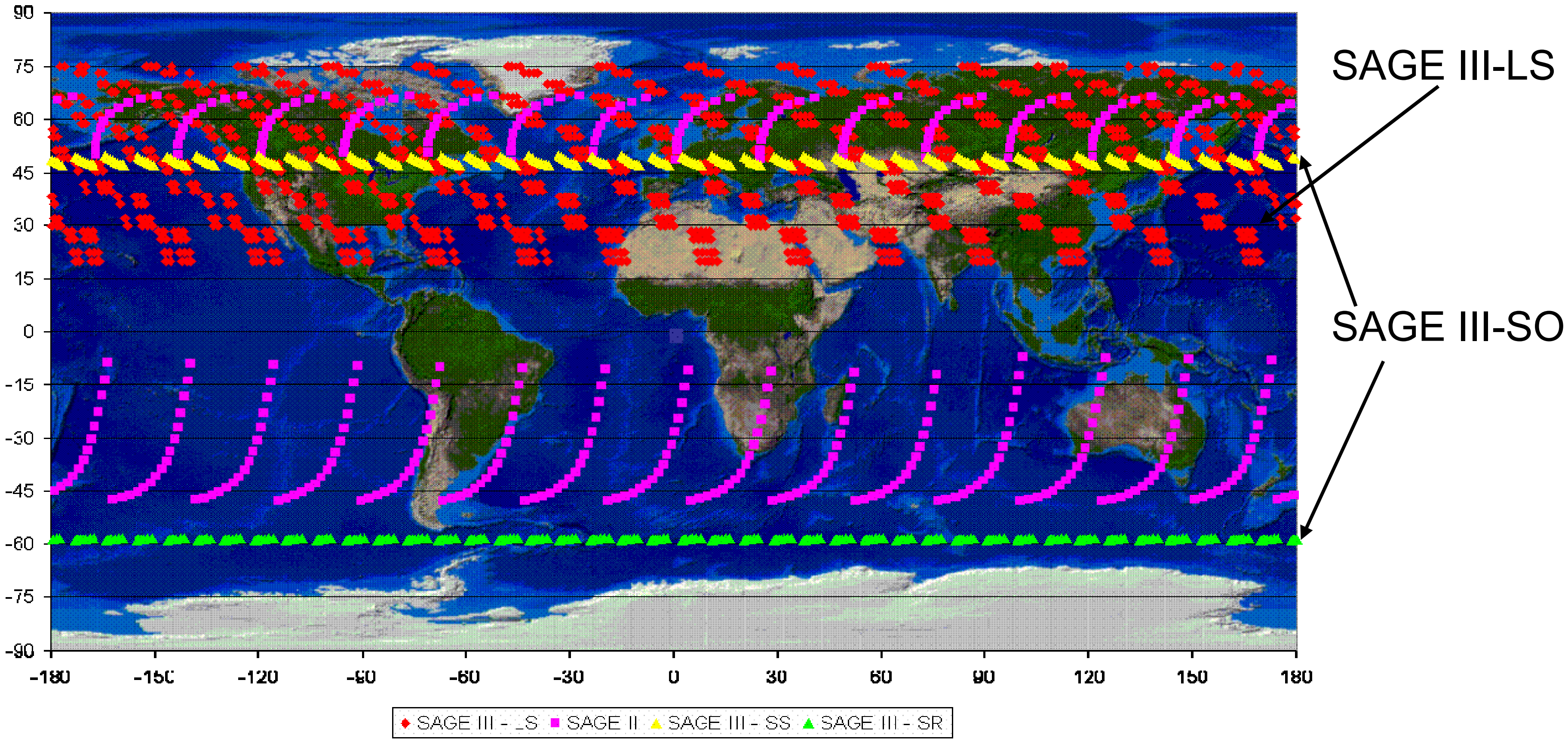


What is Limb Scatter



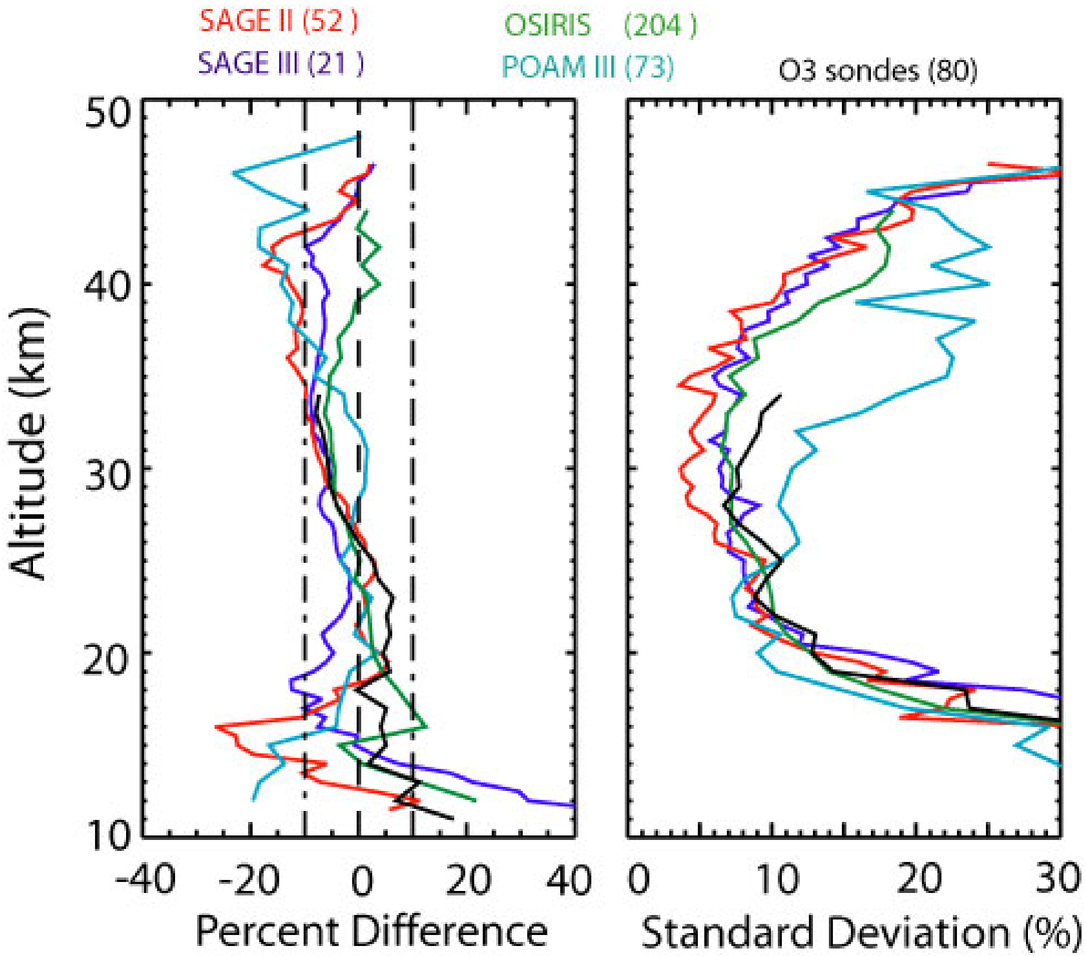
SAGE II/III Measurements

June 2005



Courtesy of L. Thomason, NASA
Langley Research Center, Hampton, VA

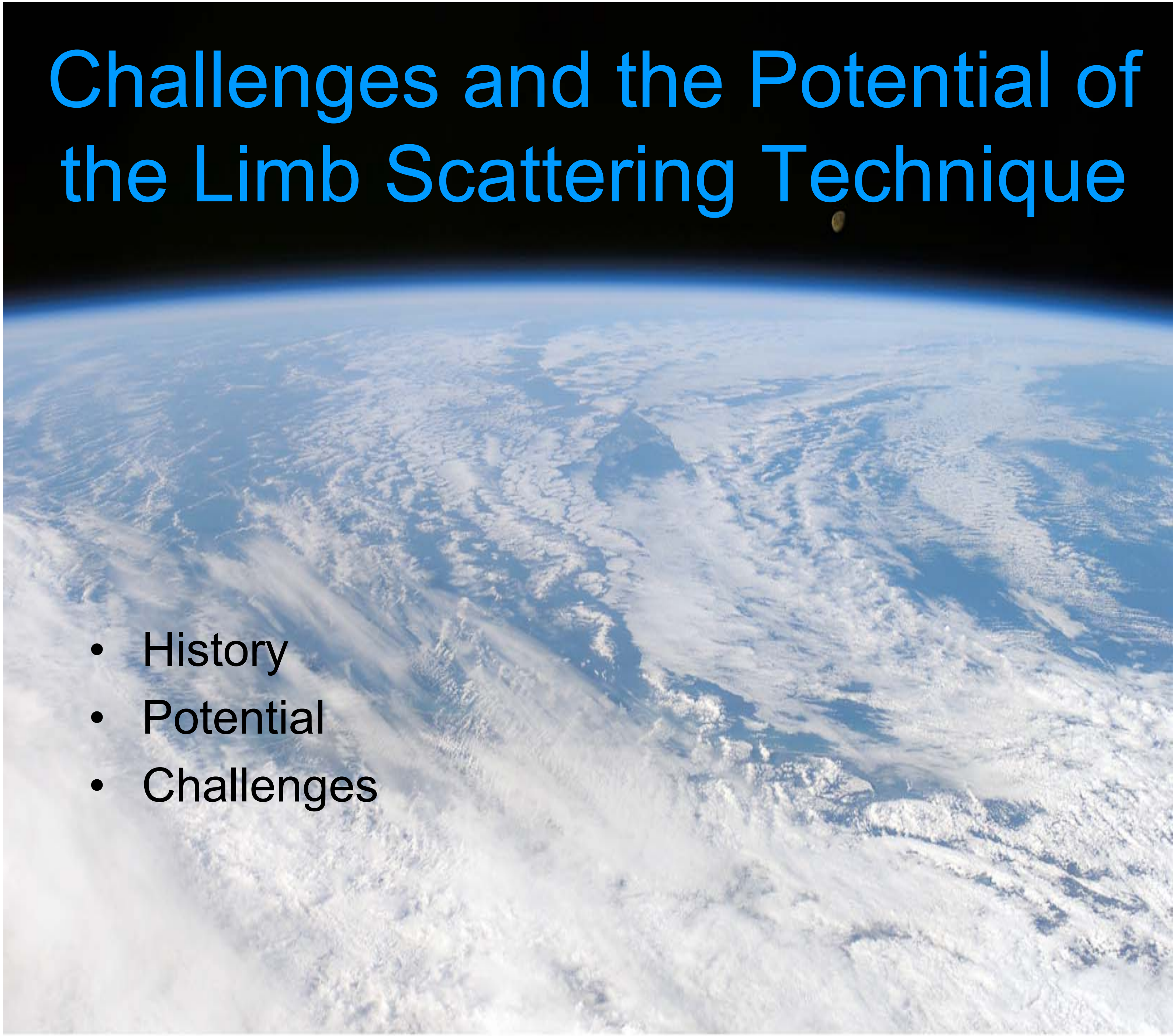
Limb Scattering



Comparison of SAGE III Limb Scatter O3 with correlative data.

Courtesy of D. Rault, NASA Langley Research Center, Hampton, VA

Challenges and the Potential of the Limb Scattering Technique



- History
- Potential
- Challenges

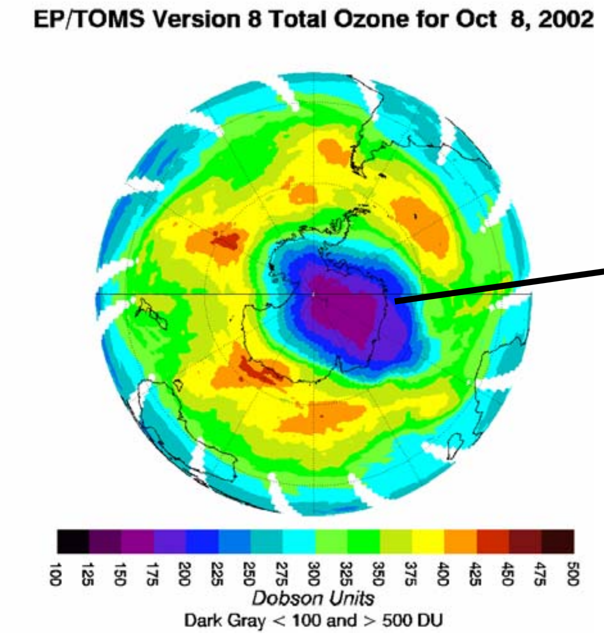
S107E05316

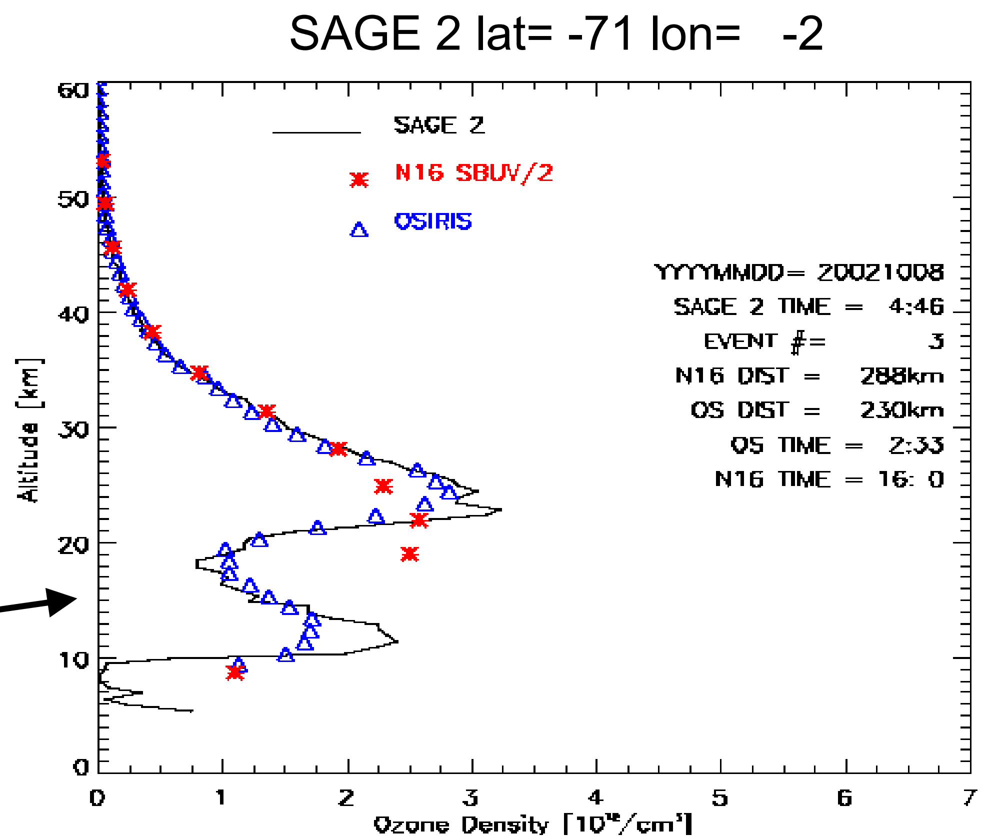
Limb Scatter Time Line

- **1960s – Early 70s**: While racing to the moon both USA & USSR make limb scatter observations.
- **Late 1970s – Early 80s**:
  - Theoretical stratospheric retrievals of ozone and aerosol profiles - (Malchow & Whitney, 1977; Deepak & Wang, 1983; Aruga & Heath, 1982)
  - Solar Mesospheric Explorer Mission (Rauch et al.)
    - Mesospheric ozone, stratospheric nitrogen dioxide & aerosol
    - Did much to advance LS experience and theory
- **1980s – Mid 1990s**: Theoretical work upon Radiative Transfer in a Spherical Atmosphere
- **1990s McPeters Effort to rekindle Aruga & Heath**
  - Demonstration of lower stratospheric retrievals:
    - Shuttle Ozone Limb Scanning Experiment (SOLSE) & Limb Ozone Retrieval Experiment (LORE) on Columbia in 1997 & 2003.
- **Late 1990s – Present:**
  - Space-based instruments with dedicated limb scatter measurements:
    - OSIRIS
    - SCIAMACHY
    - GOMOS
    - SAGE III
- **Future:**
  - National Polar-orbiting Operational Environmental Satellite System (NPOESS) Preparatory Project (NPP) will carry onboard the Ozone Mapping Profiling Suite (OMPS) by Ball Aerospace
    - Utilizes limb scatter technique in UV/Visible/Near IR for high resolution ozone and aerosol profiling
    - Launch in late 2009

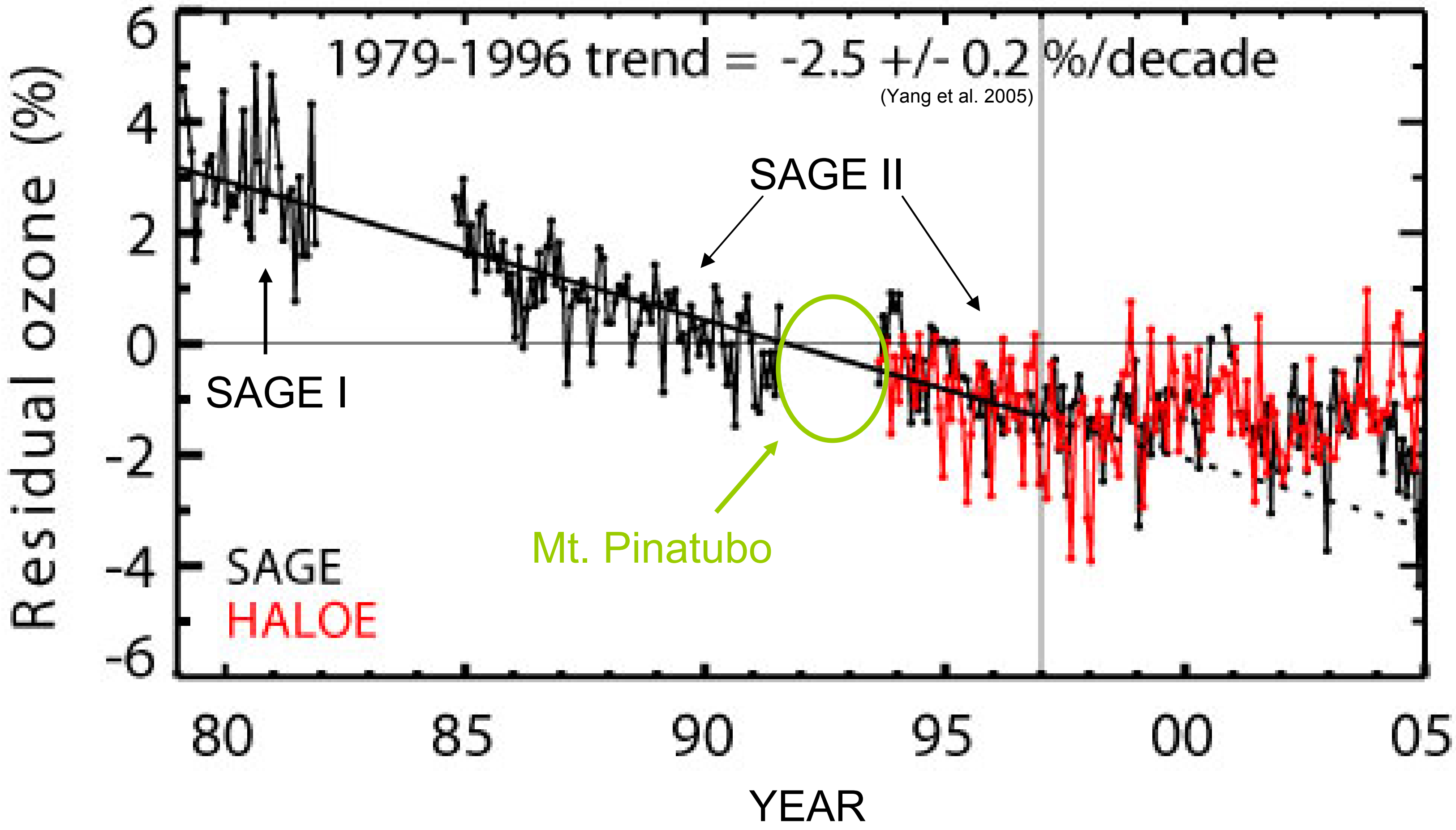
Vertical Resolution

- LS Method can directly observe variations in lower stratospheric ozone that can only be speculated when using nadir total column mapper (TOMS) and profile data (SBUV/2)





Limb Scatter has the *potential* to carry forward the long-term record of stratospheric *ozone* and *aerosol* begun by solar occultation sensors



Stratospheric O3 Column

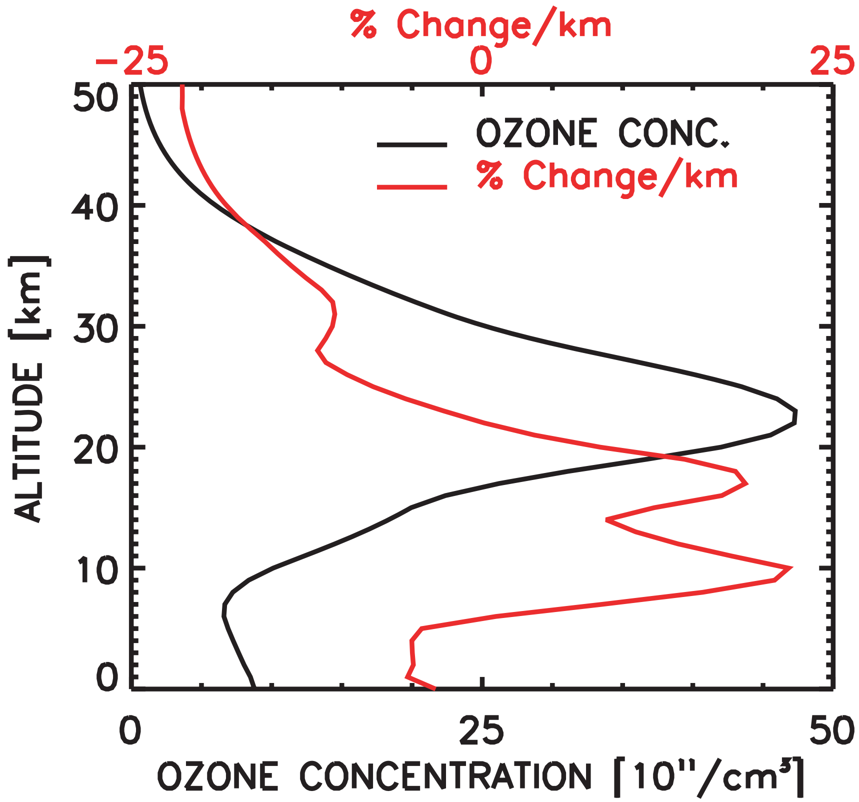
Limb Scatter Challenges

- Stray Light
- Altitude Registration
- Aerosol Scattering/Extinction
- Broken Clouds
- Horizontal Variations in Ozone

Many of these occur while probing the Upper Troposphere/Lower Stratosphere

Challenges: Altitude Registration

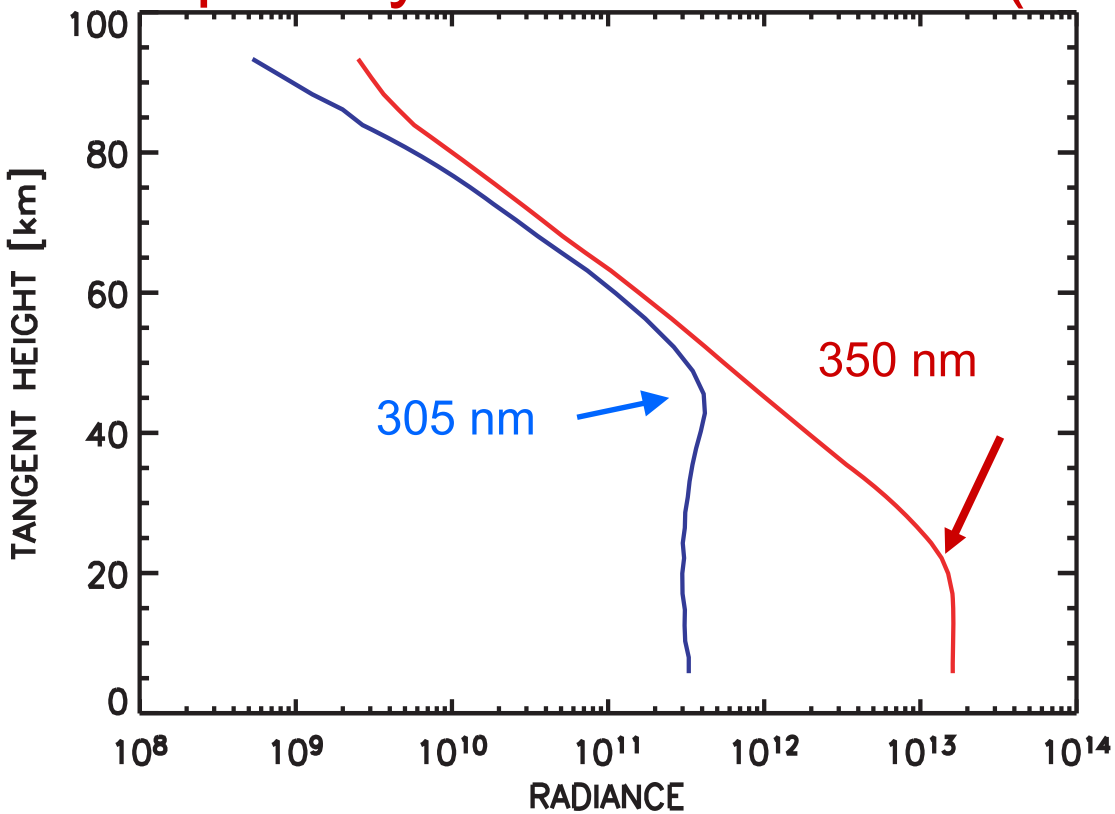
- Large vertical gradients exists in the typical ozone profile
- Altitude registration errors of 1 km can lead to retrieval errors of >20%.
- Space-craft based knowledge ~ 0.3-2.0 km.
- Need scene based method, i.e. using limb scatter radiance profile, for altitude registration to better than **0.1 km.**
- However, limb scattering has an ill defined target, unlike solar occultation.



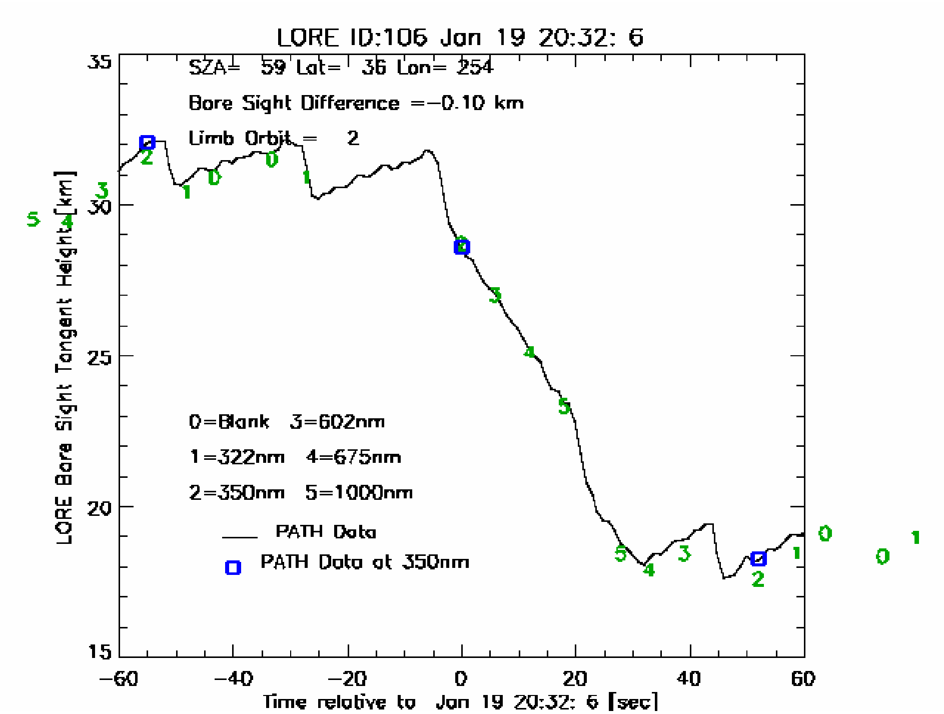
Altitude Registration

Two scene based methods currently used are:

- Radiance peak in absorbing channel (aka UV Knee)
- Switch between optically thin & thick LOS (aka RSAS)

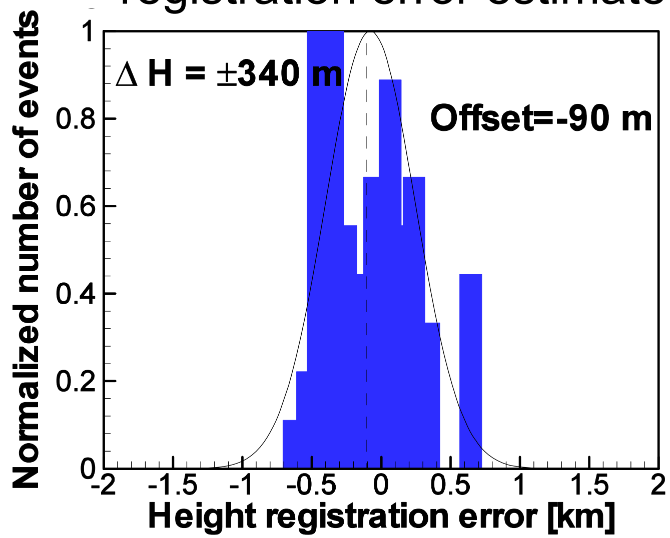


Altitude Registration



(Rault & Taha, *JGR*, 2006)

SAGE III LS Height registration error estimate



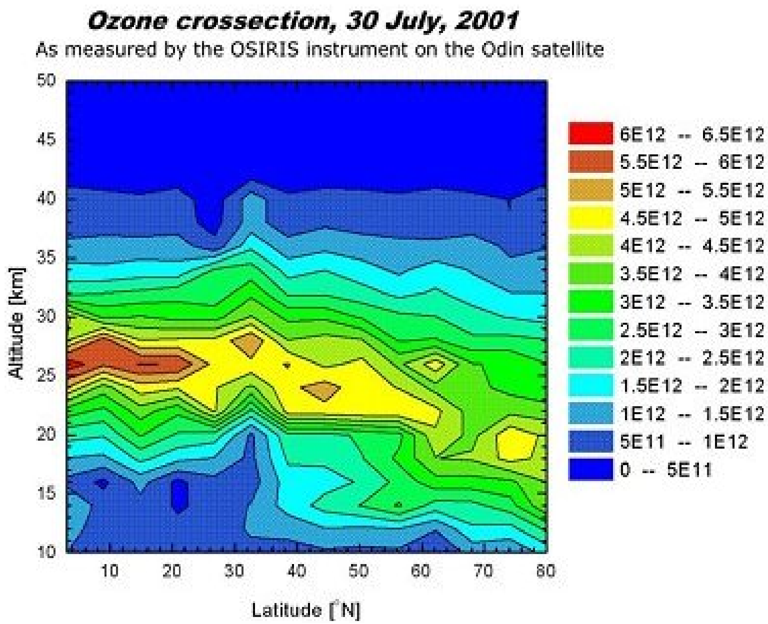
- Scene based methods can track large changes in pointing.
- Demonstrated Standard Deviation in offset is 0.3 – 0.5 km.
- Can this method be refined or another scene based technique be developed to attain the 0.1 km goal of OMPS?

Challenges: Heterogeneity

Two Kinds of Heterogeneity

- **Reflecting Surface Heterogeneity**
  – Scattering from the surface/clouds below contribute to the limb signal.
- **Atmospheric Heterogeneity**
  – Since the Limb Scatter method views the limb, observations are sensitive to horizontal variations in the atmospheric composition.
  – This is shared with all limb viewing techniques, e.g. occultation, thermal emission.
  – Can be handled in retrieval to some extent:
    - Tomography [Degenstein et al., 2002, Livesey & Read, 2000]
    - Data Assimilation [Syndergaard et al., 2002]

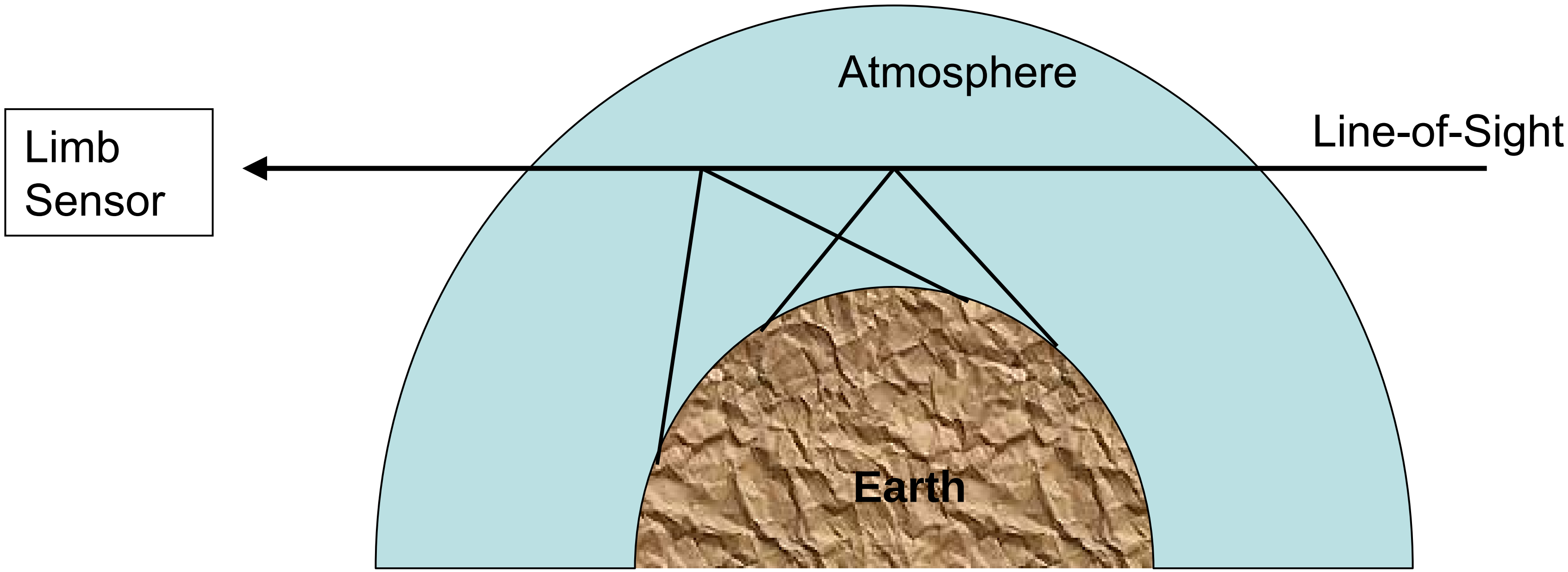
www.ssc.se/ssd/indexmainodinresultsX.html



Heterogeneity

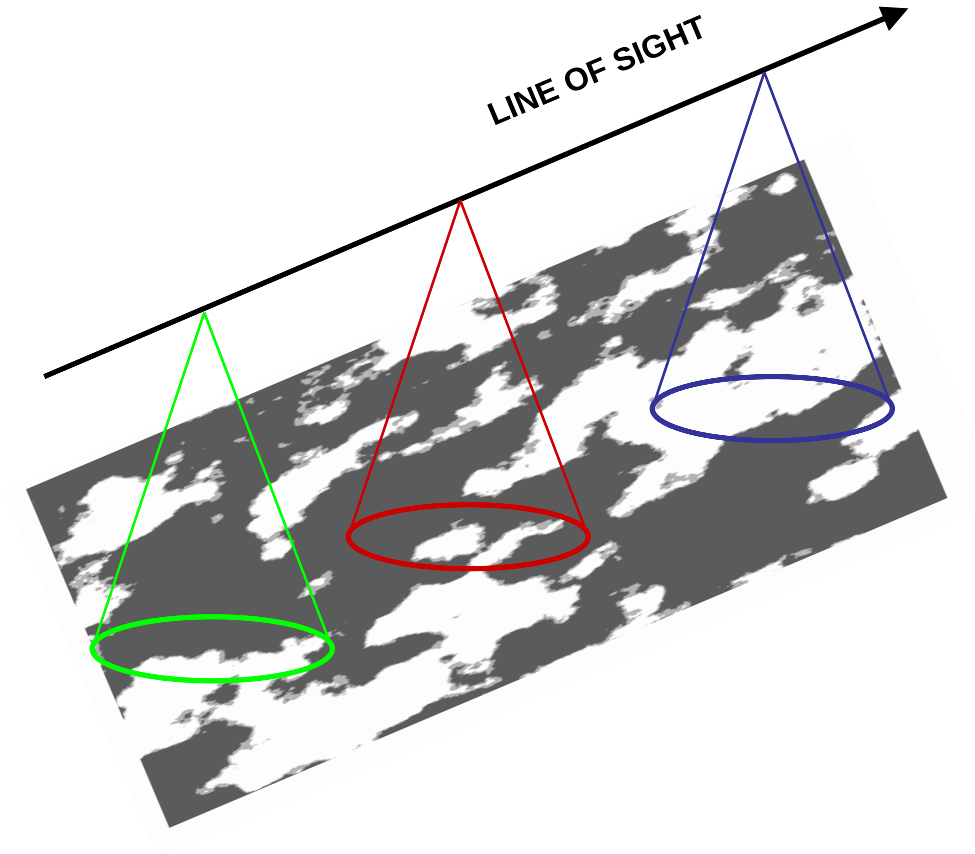
Different Views and Illuminations

- **The radiance from the limb of the atmosphere is due to scattering from points all along the Line of Sight (LOS). In turn, each point along the LOS is illuminated by two sources:**
  - **Direct Solar Beam, Js**
  - **Diffuse Radiance Field, Je**
- **The surface albedo can influence the diffuse radiance field which illuminates each point, can be ~ 50% of total radiance. (reflecting surface hetero.)**
- **The both radiance sources are attenuated along the LOS (atmo. hetero.)**

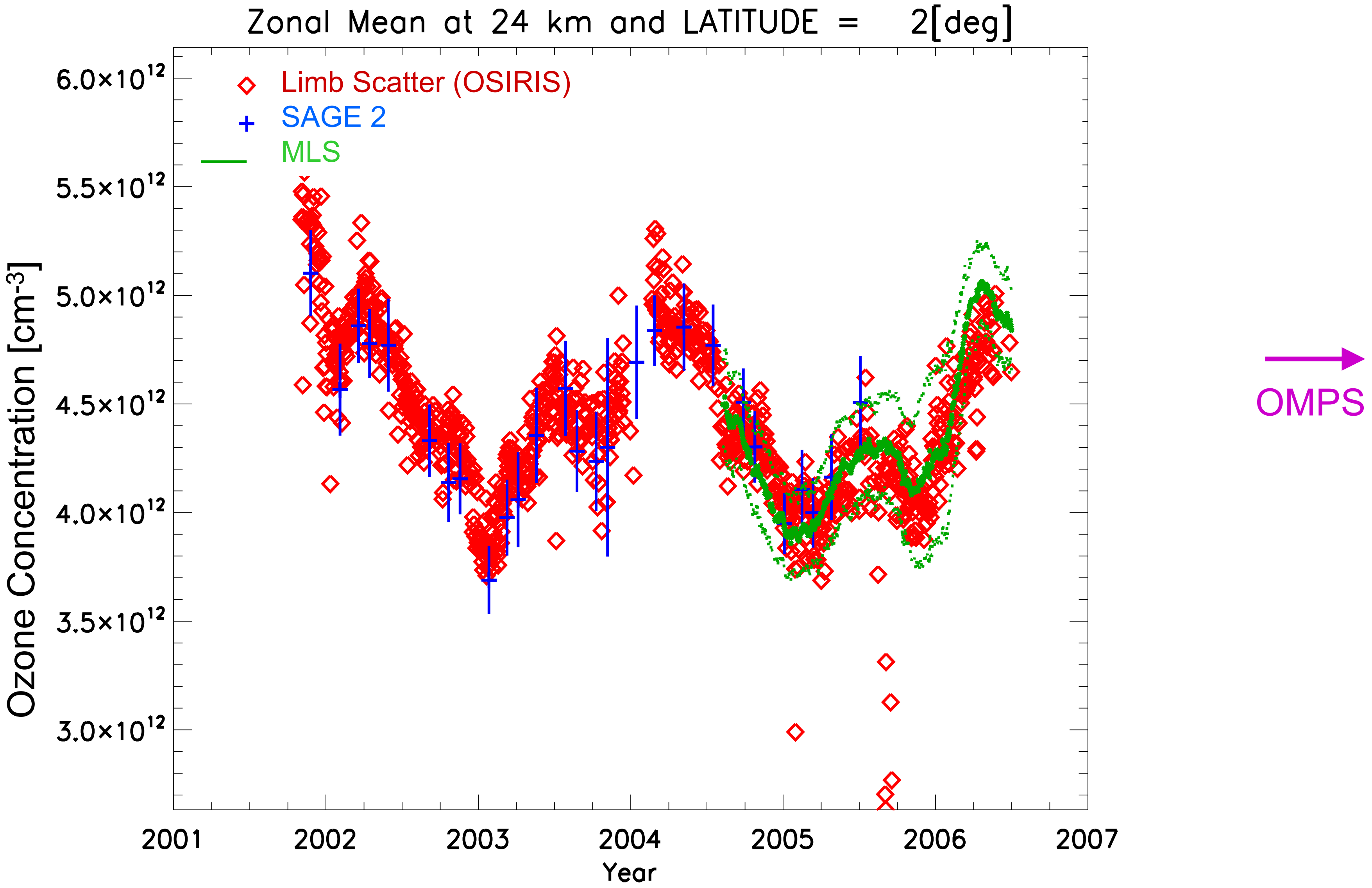


Reflecting Surface Heterogeneity (aka Broken Clouds)

- **Difference in effective path-lengths for absorption between uniform cloud case (assumed in retrieval) and broken cloud case (reality) can produce errors of 5% in ozone.**
- **Errors are nearly, but not exactly, symmetric with viewing direction.**
- **When averaged over orbit, bias and standard deviation of the bias is 0.5 – 1 % in the lower stratosphere.**



Potential Realized Yet?



Summary

- SAGE III/Meteor 3M mission has successfully:
  - Utilized new technology (CCD array)
  - Validated alternative analysis (MLR)
  - Demonstrated lunar occultation for “night-time” species
  - Provided a data set for refinement of limb scatter analysis and address challenges for OMPS
- These accomplishments are aiding in linking the historic records of ozone and aerosol with those of the present and future.

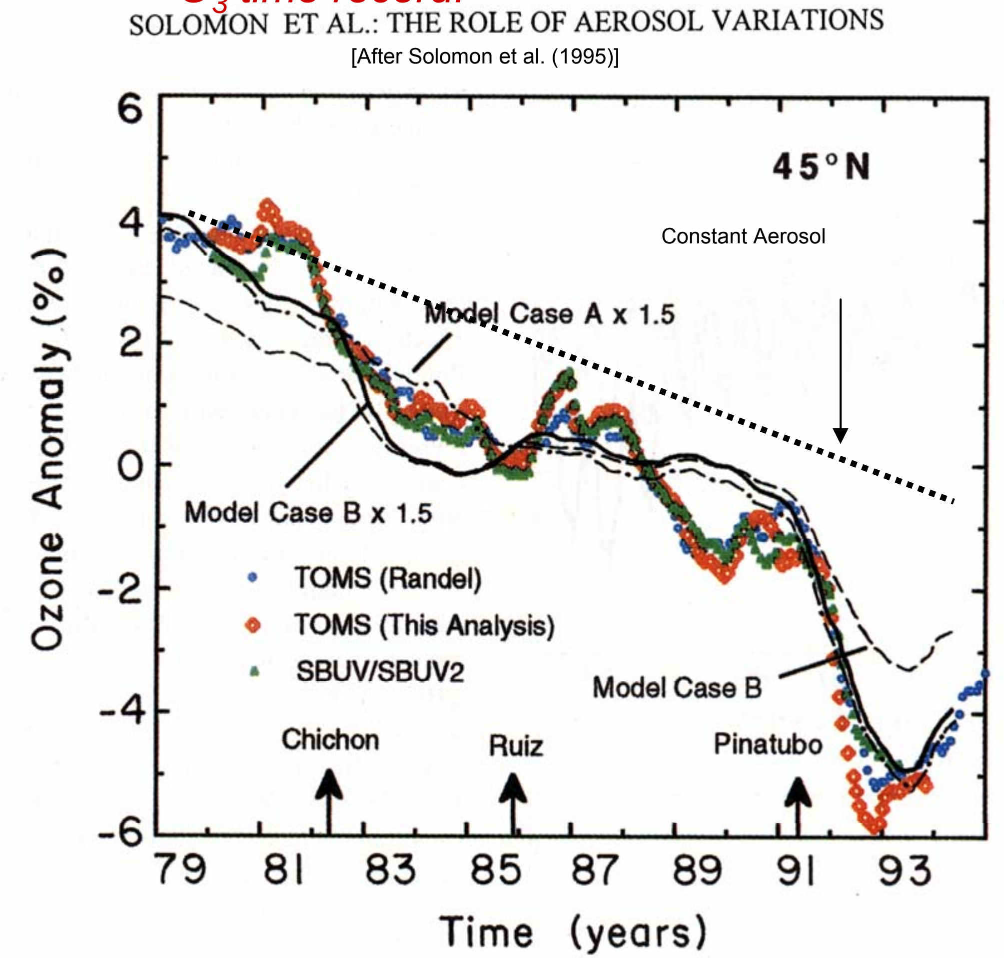
Acknowledgments

- Dr. Bill Chu for leading the SAGE III effort.
- Funding from:
  - NASA Science Directorate, Atmospheric Composition Program
  - NASA NPOESS Preparatory Project (NPP) Science Team

Aerosol Scattering/Extinction

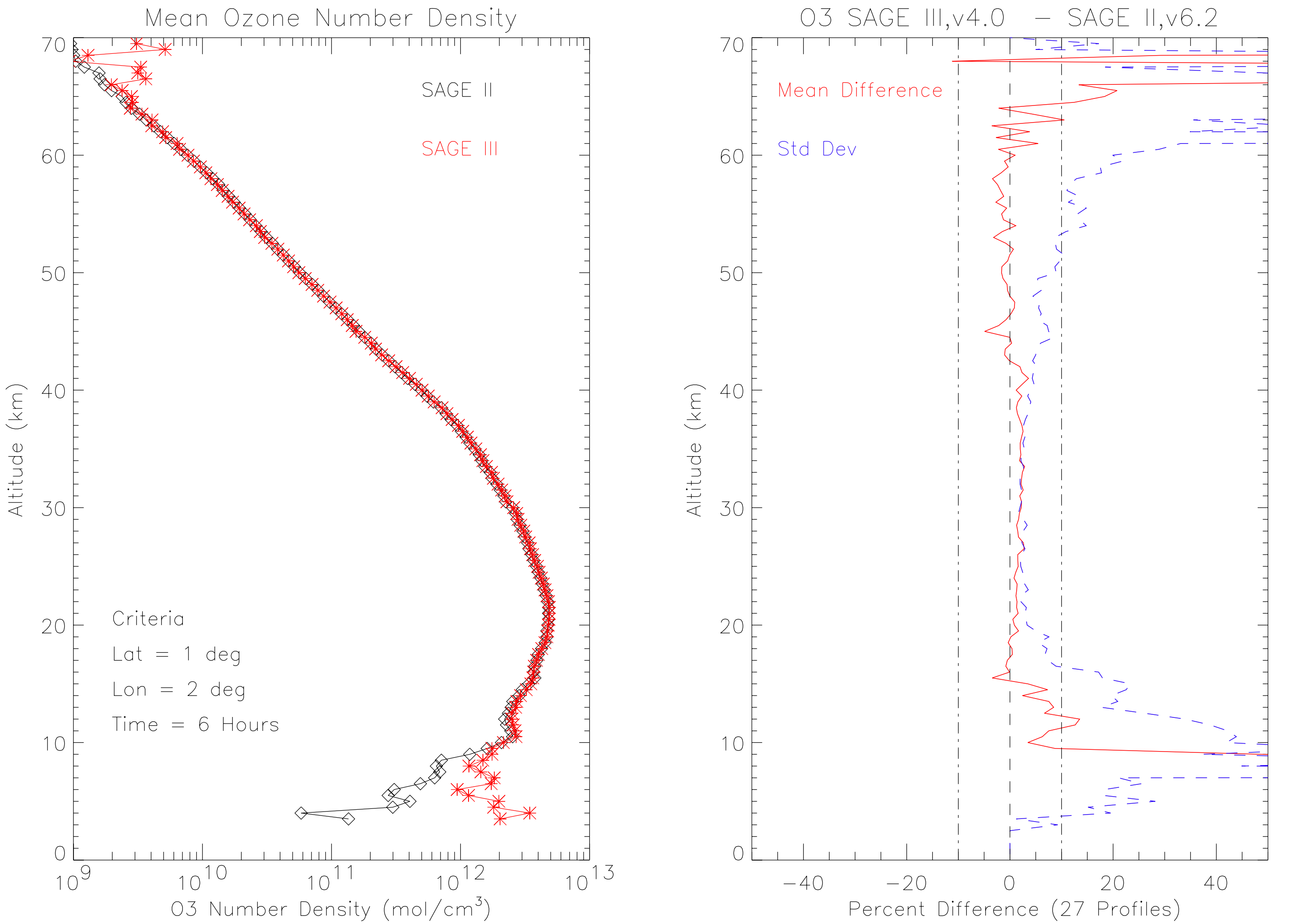
- Estimate of aerosol loading/size for improvement of ozone profiles,
- And determination of surface area density for chemical modeling and scientific understanding of the ozone time series.

Knowledge of stratospheric aerosol surface area density is critical to understanding the O_3 time record.



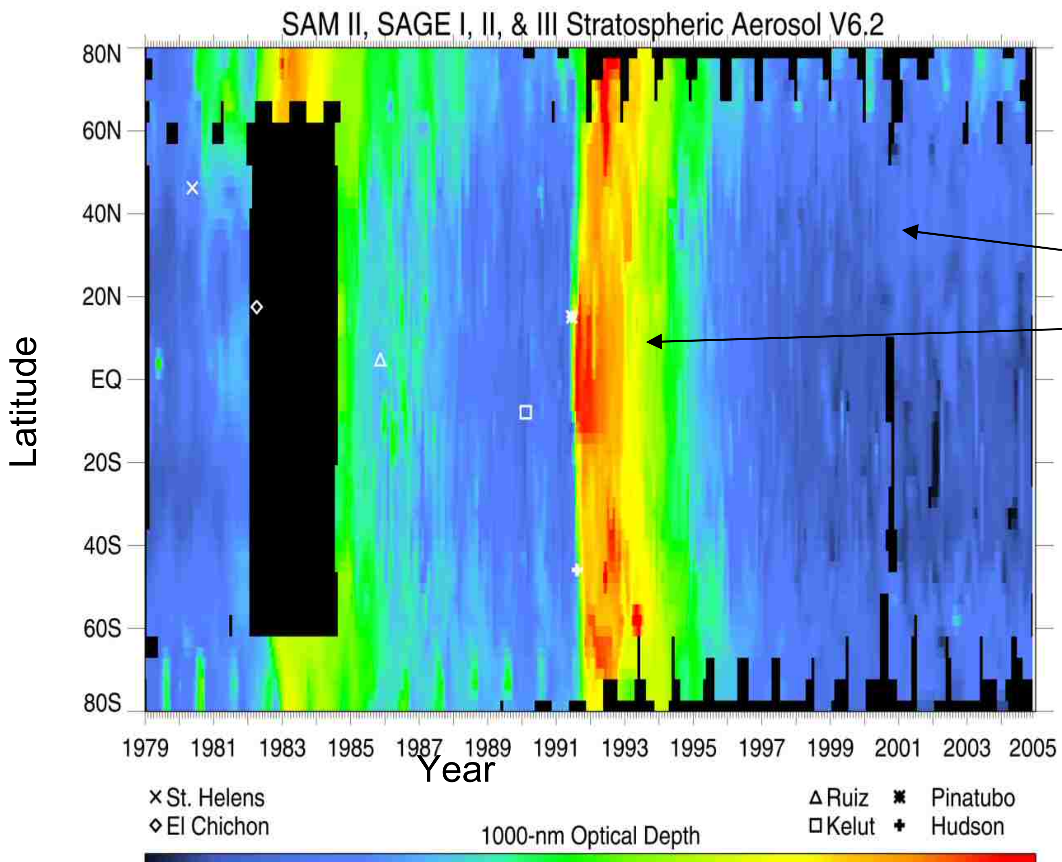
[After Solomon et al. (1995)]

SAGE III V4: Ozone



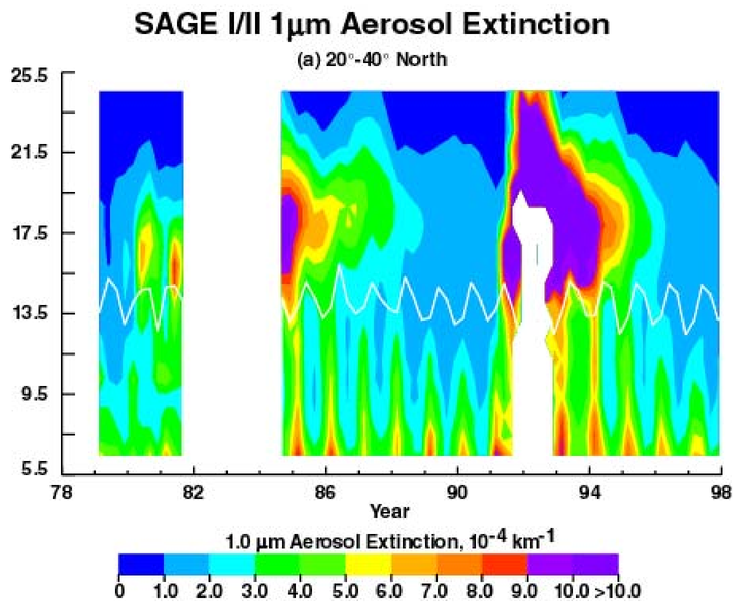
Aerosol Scattering/Extinction

Stratospheric Aerosol



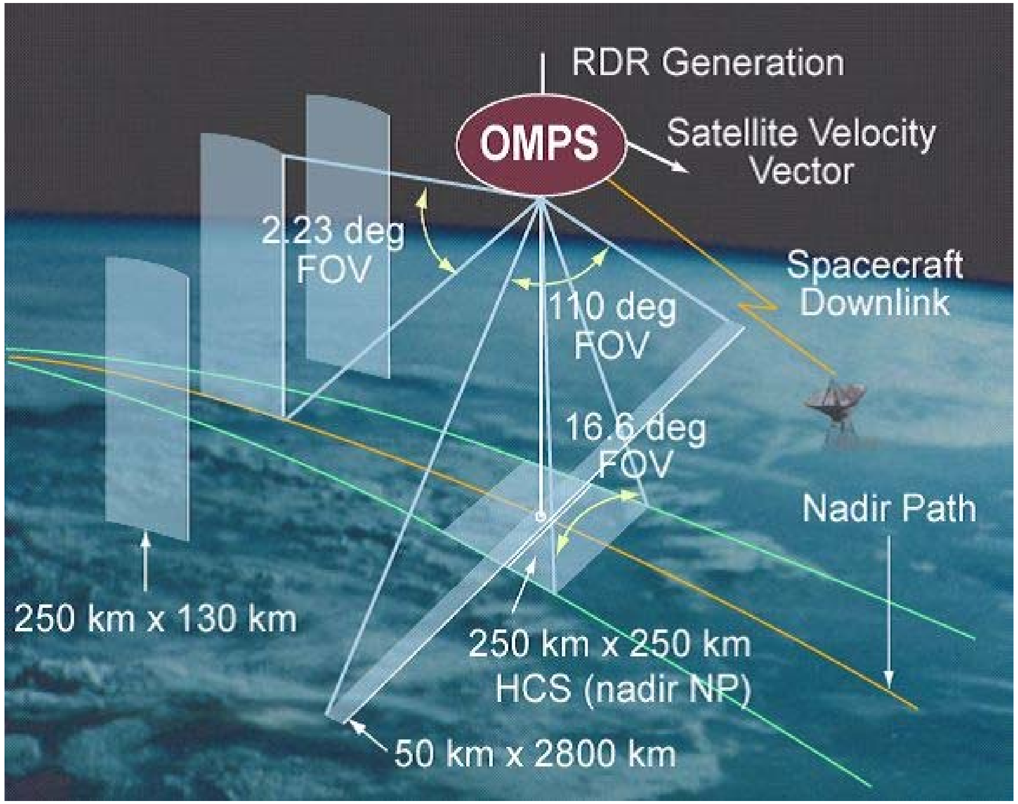
Courtesy of L. Thomason

- Can imagine at least two different situations:
  - Background
  - Post-volcanic



Ozone Mapping Profiler Suite: OMPS

- Next generation of US space-based ozone measurements onboard National Polar-orbiting Operational Environmental Satellite System & NPOESS Preparatory Project (NPP).
  - Nadir Total Ozone Mapper: TOMS
  - Nadir Profiler: SBUV
  - Limb Profiler (LP)
- Limb scatter measurements to provide primary ozone product.
  - 290-1000 nm spectral range
  - 2 km vertical resolution
  - 3 vertical slits across-track
- Aerosol extinction profile is an intermediate product.



Courtesy of Ball Aerospace