The History of Solar Occultation Satellite Science

M. Patrick McCormick

CENTER FOR ATMOSPHERIC SCIENCES
Hampton University

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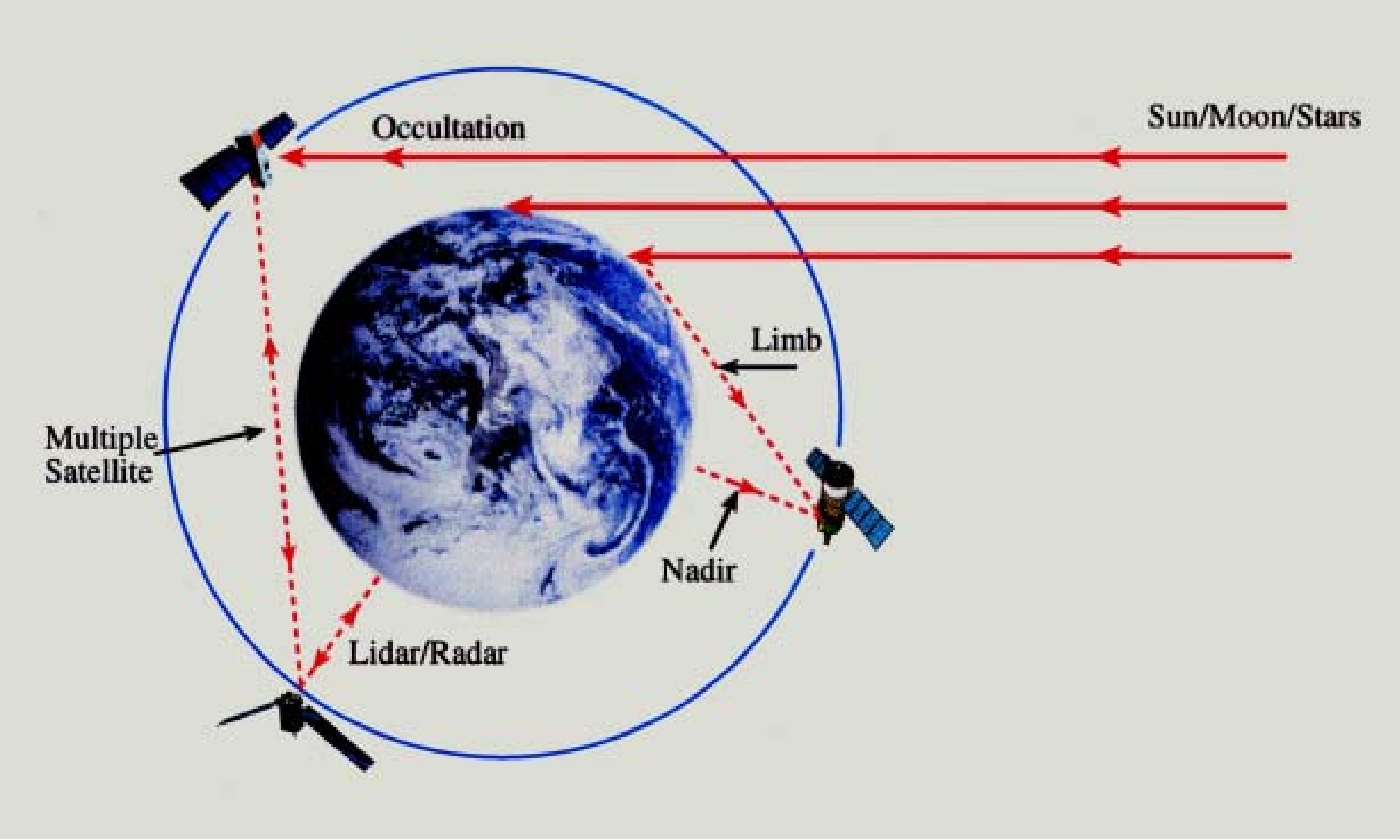
Outline

- **Remote Sensing Techniques**
  - Passive/Active
  - Advantages
- **Occultation**
  - Plus/minus
  - Coverage
  - Native Products
  - Validation
- **History**
  - Solar/Lunar/Stellar
  - Instruments
  - Measurements
- **SAM II/SAGE Series**
  - Examples
- **Summary**

Satellite Remote Sensing Approaches

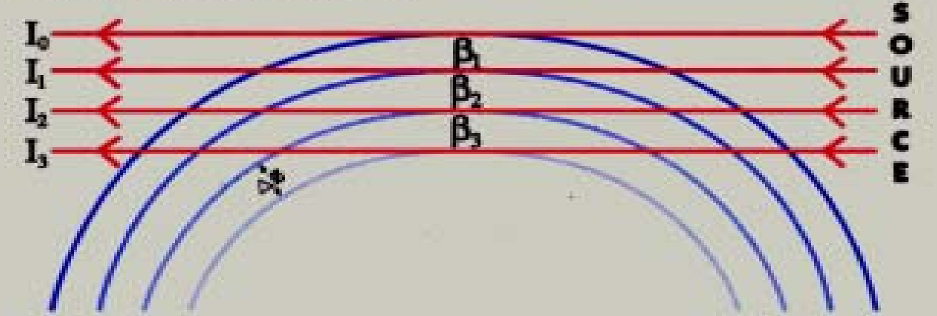


Occultation

$I = I_0 e^{-\delta}$ where δ = optical depth

$\delta = \int_0^{l'} \beta \, dl$ where β = extinction coeff. (km^{-1})

$\beta = \beta_{AER.} + \beta_{MOL.} + \beta_{ABS.}$

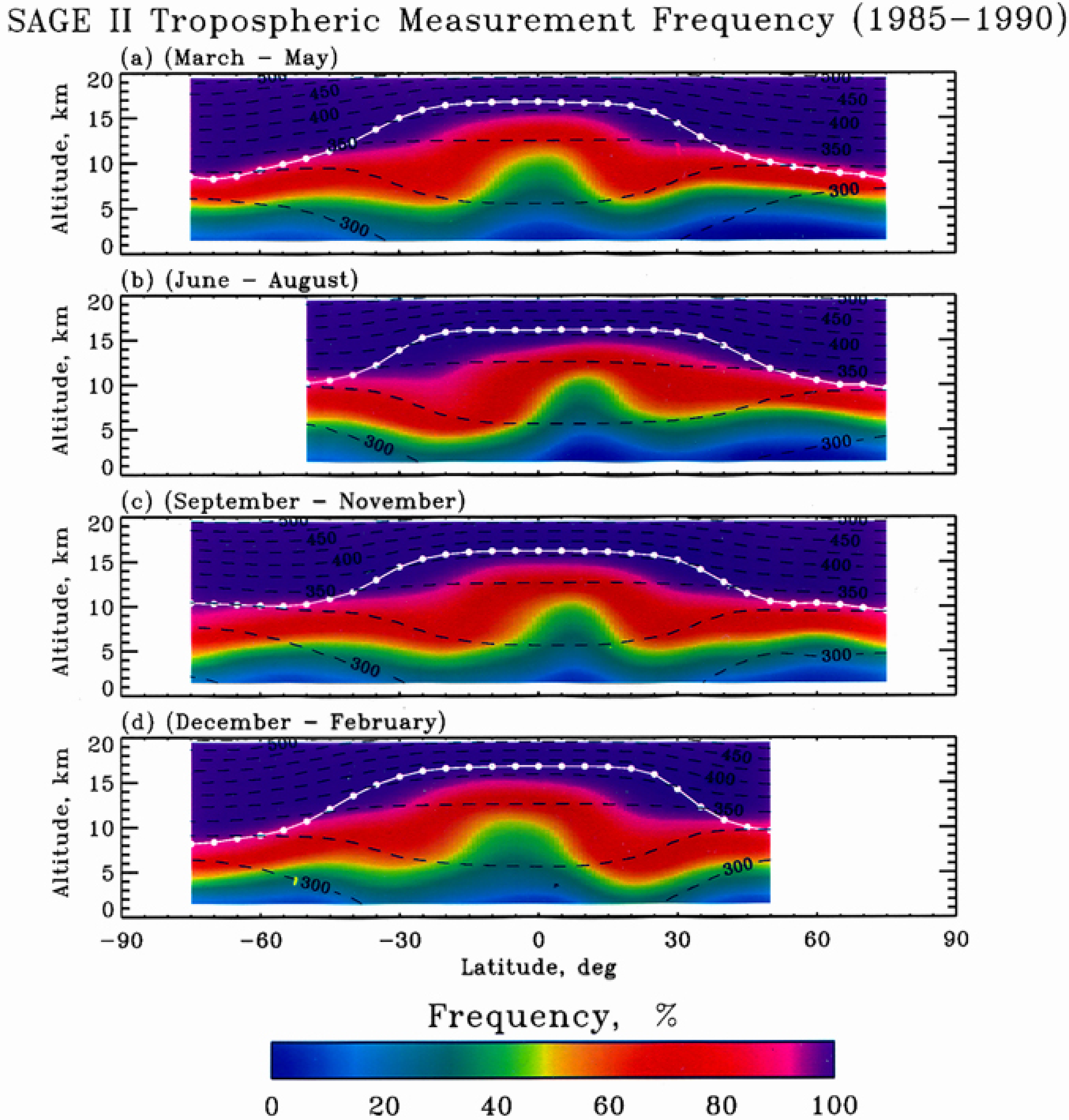


Pluses

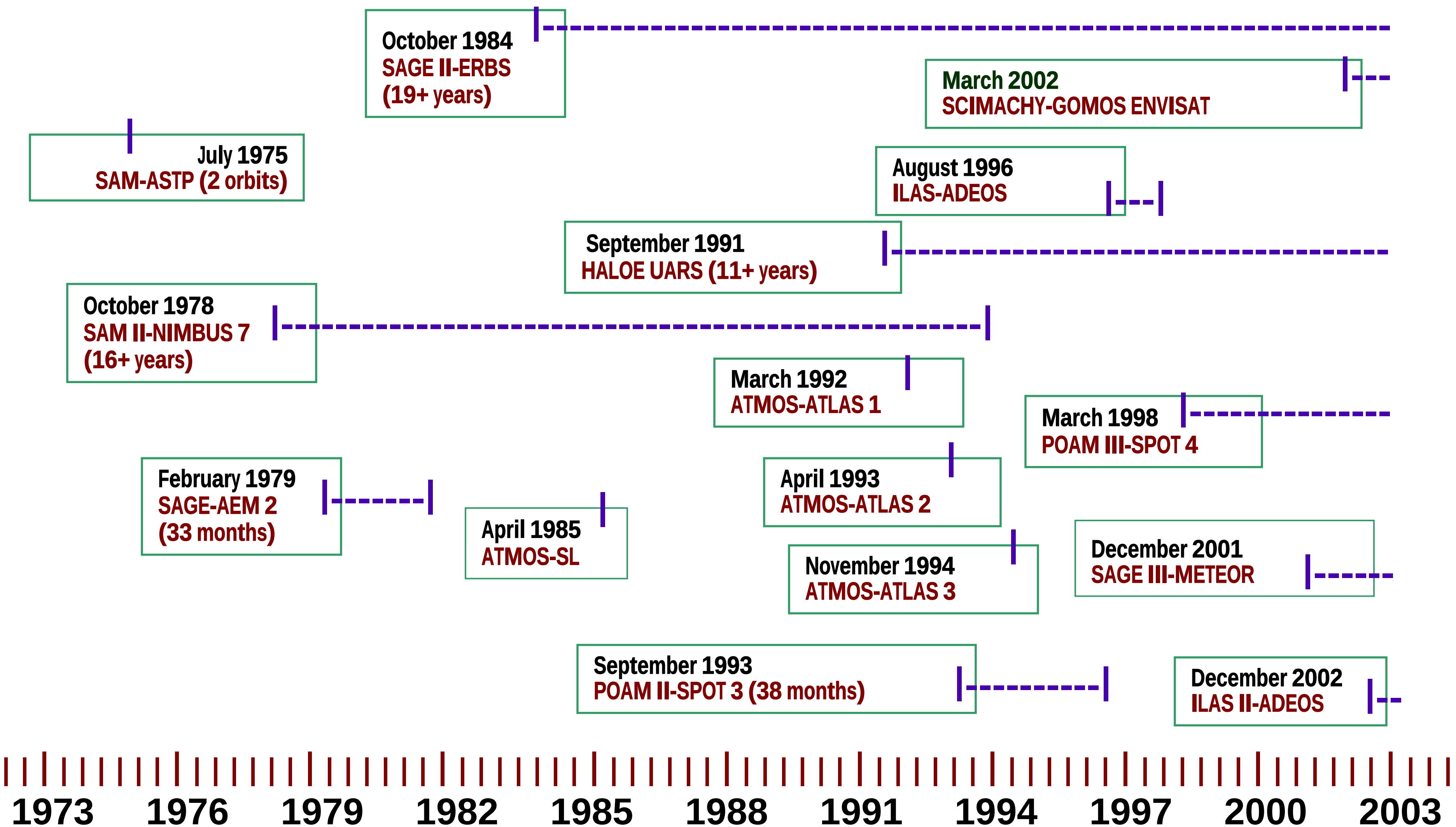
- High vertical resolution (~1.0km)
- High S/N (bright source over background)
- Self-calibrating with Exoatmospheric measurement for each event
- Long limb path and high S/N provides measurements of tenuous gases
- Well behaved inversion/retrievals
- Smaller instruments required

Minuses

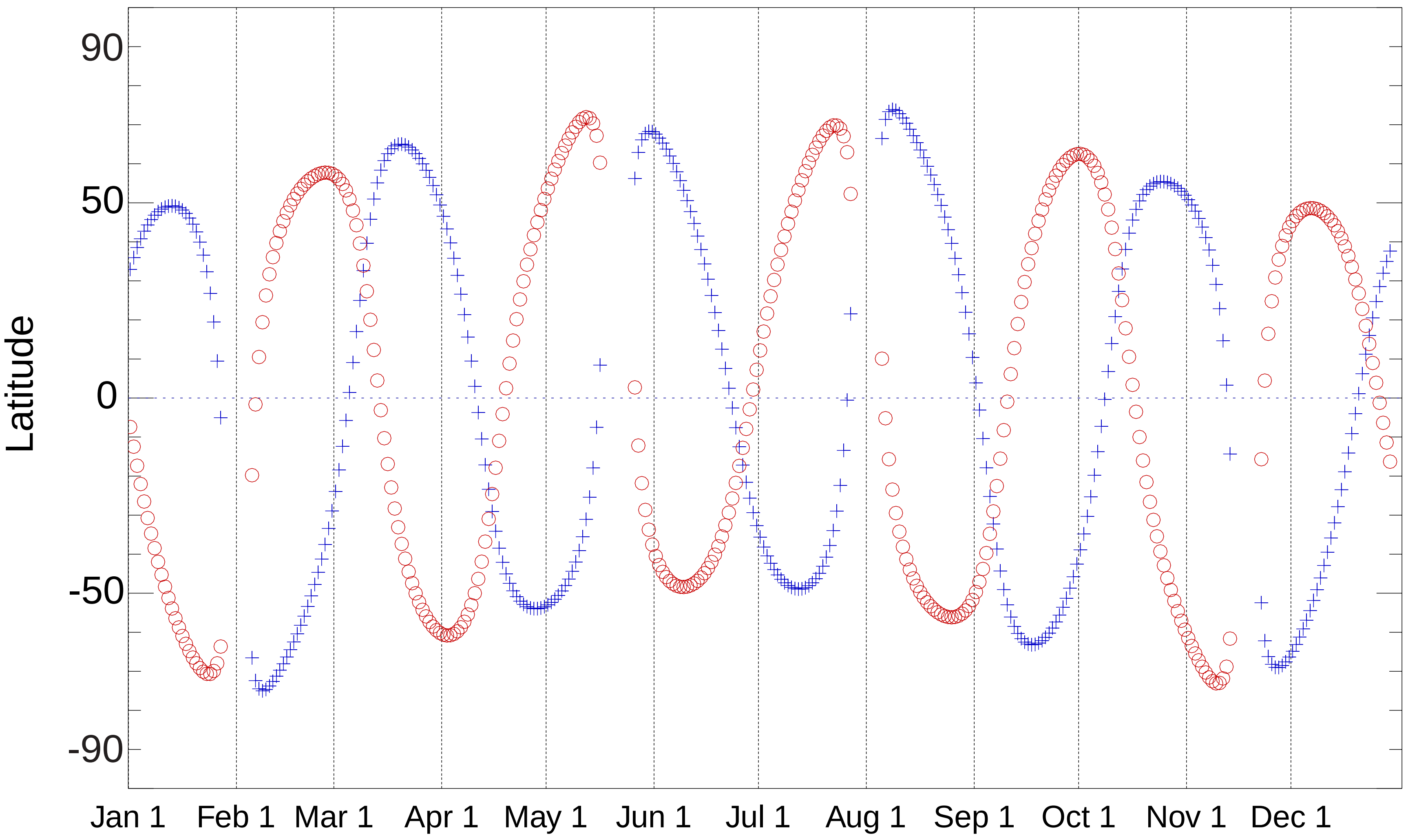
- Low sampling frequency (two profiles per orbit for solar and lunar occultation)
- Integrative over several hundreds of kilometers

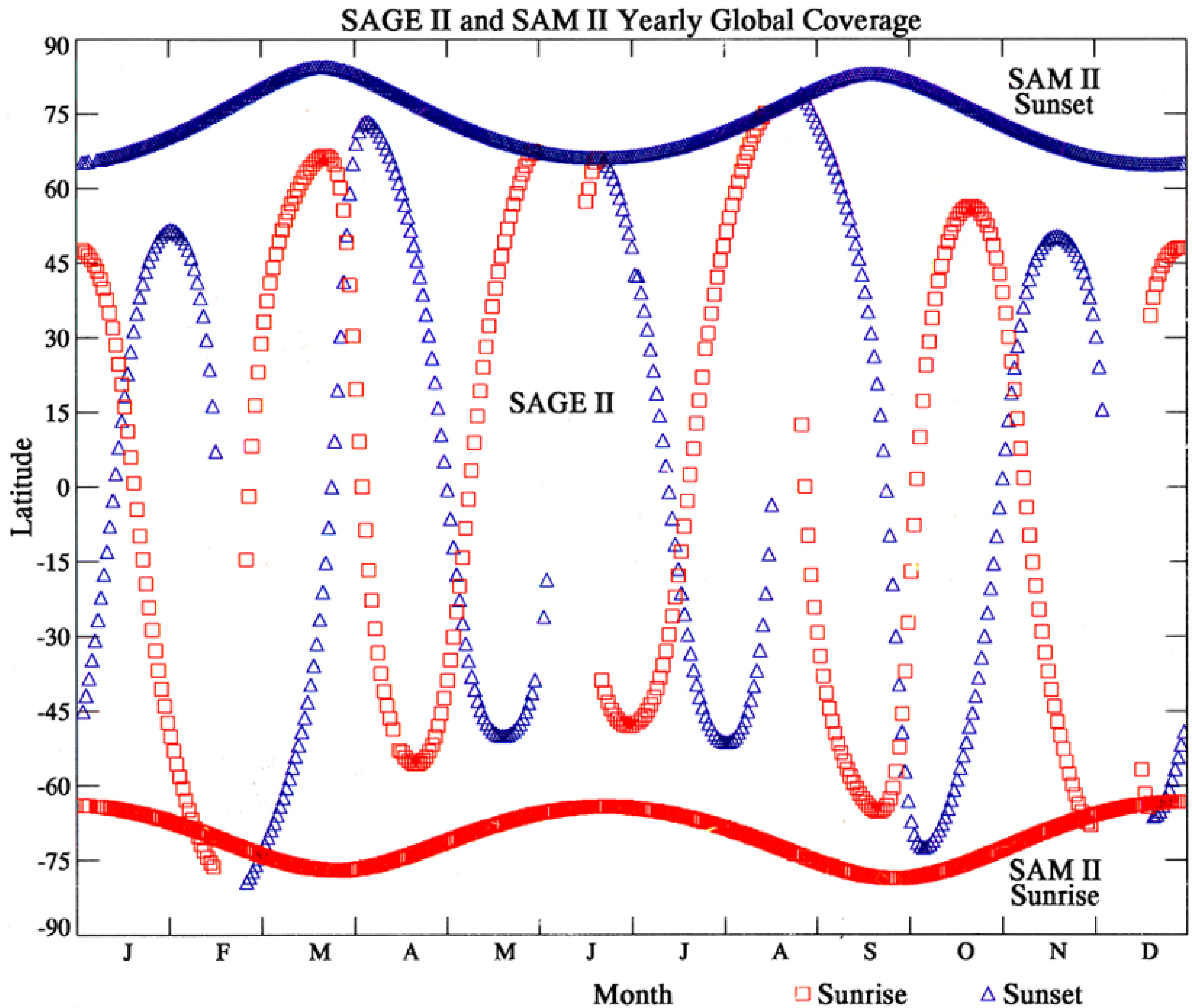

SAGE II Tropospheric Measurement Frequency (1985–1990)
(a) (March – May)
(b) (June – August)
(c) (September – November)
(d) (December – February)
Altitude, km
Latitude, deg
300
350
400
450
500
Frequency, %
0
20
40
60
80
100

The History of Earth-Orbiting Occultation Experiments

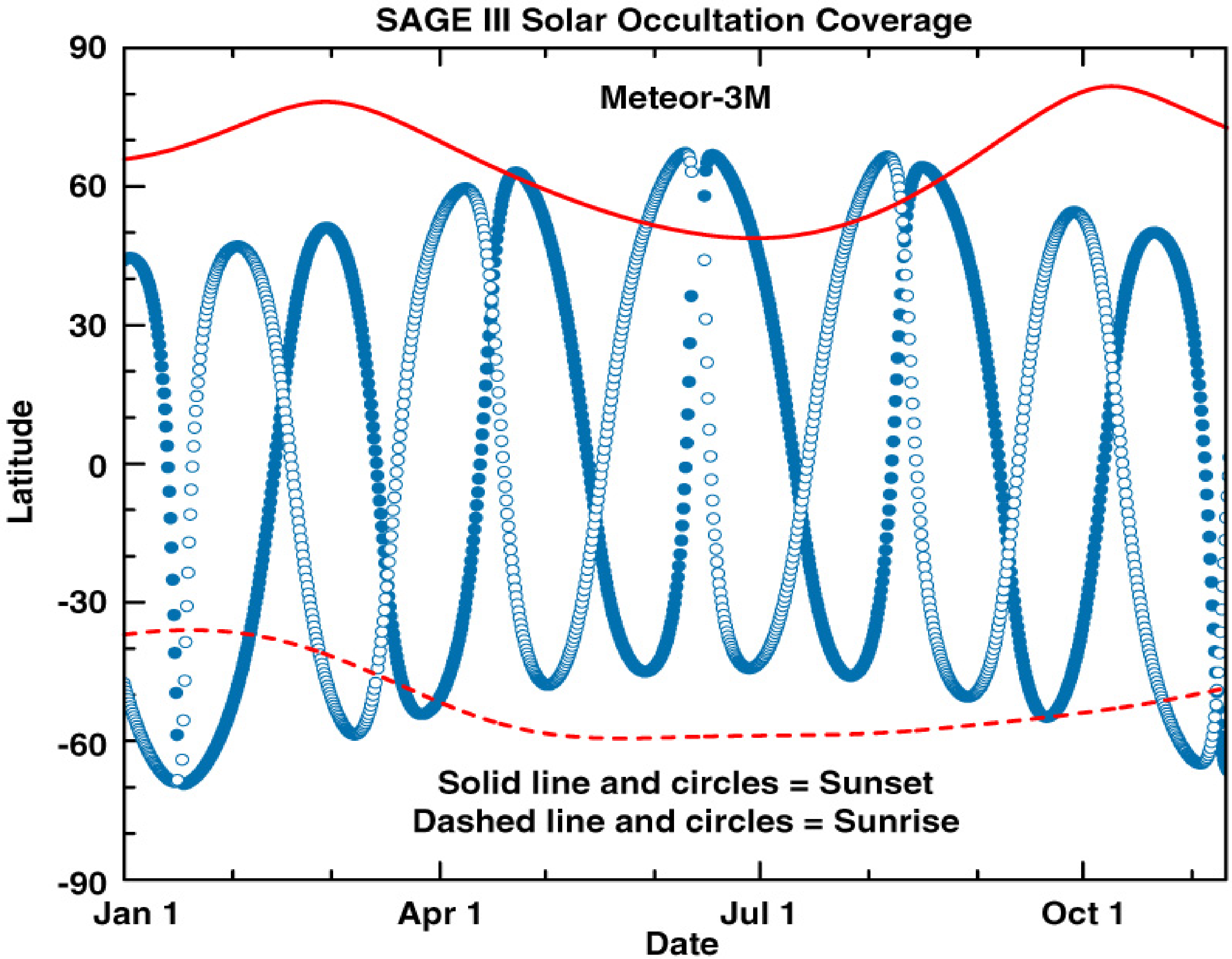


Latitude versus time coverage for 57º orbit

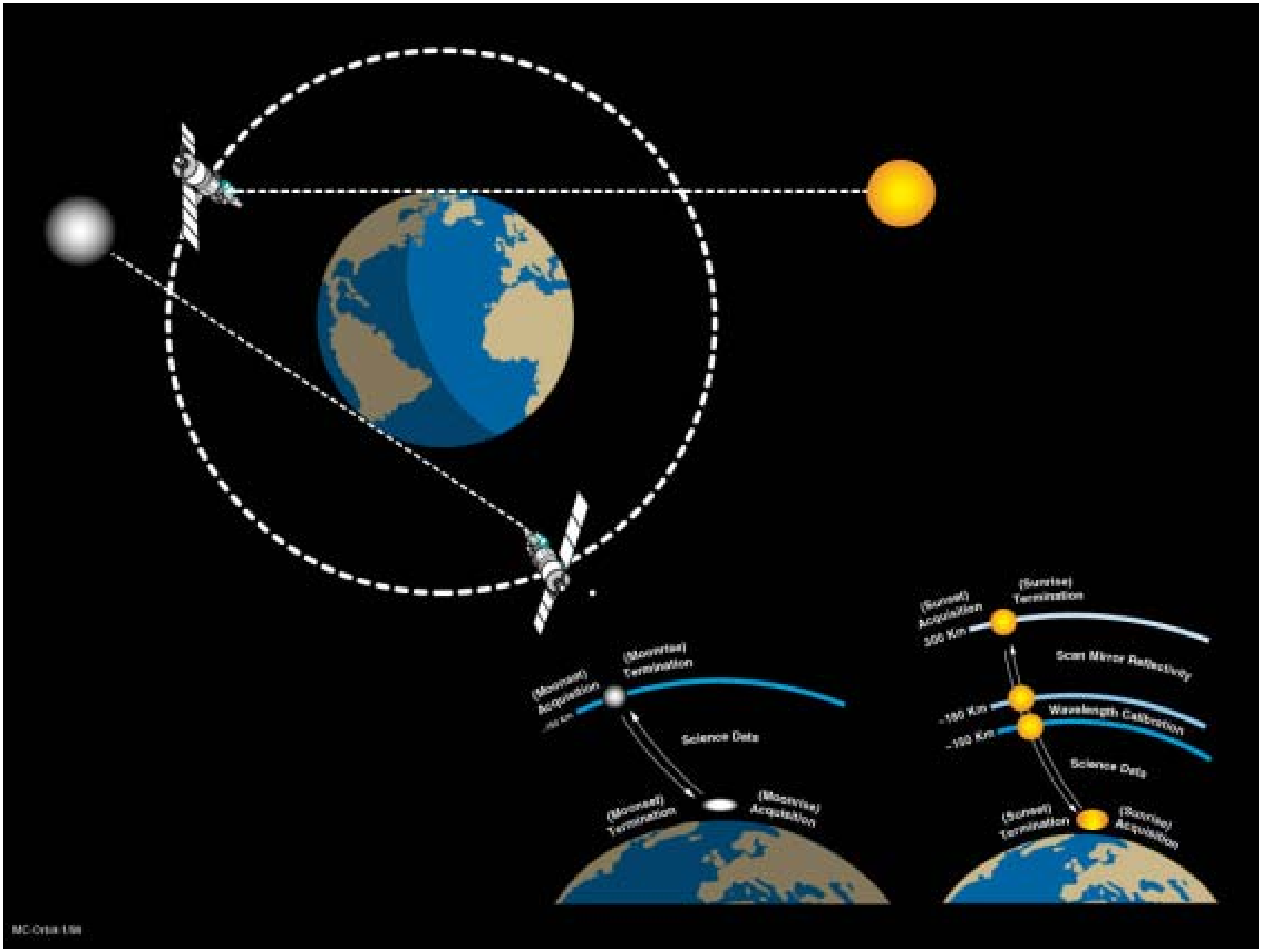



SAGE II and SAM II Yearly Global Coverage
SAM II Sunset
SAGE II
SAM II Sunrise
Latitude
90
75
60
45
30
15
0
-15
-30
-45
-60
-75
-90
J
F
M
A
M
J
J
A
S
O
N
D
Month
Sunrise
Sunset

SAGE III Measurement Coverage

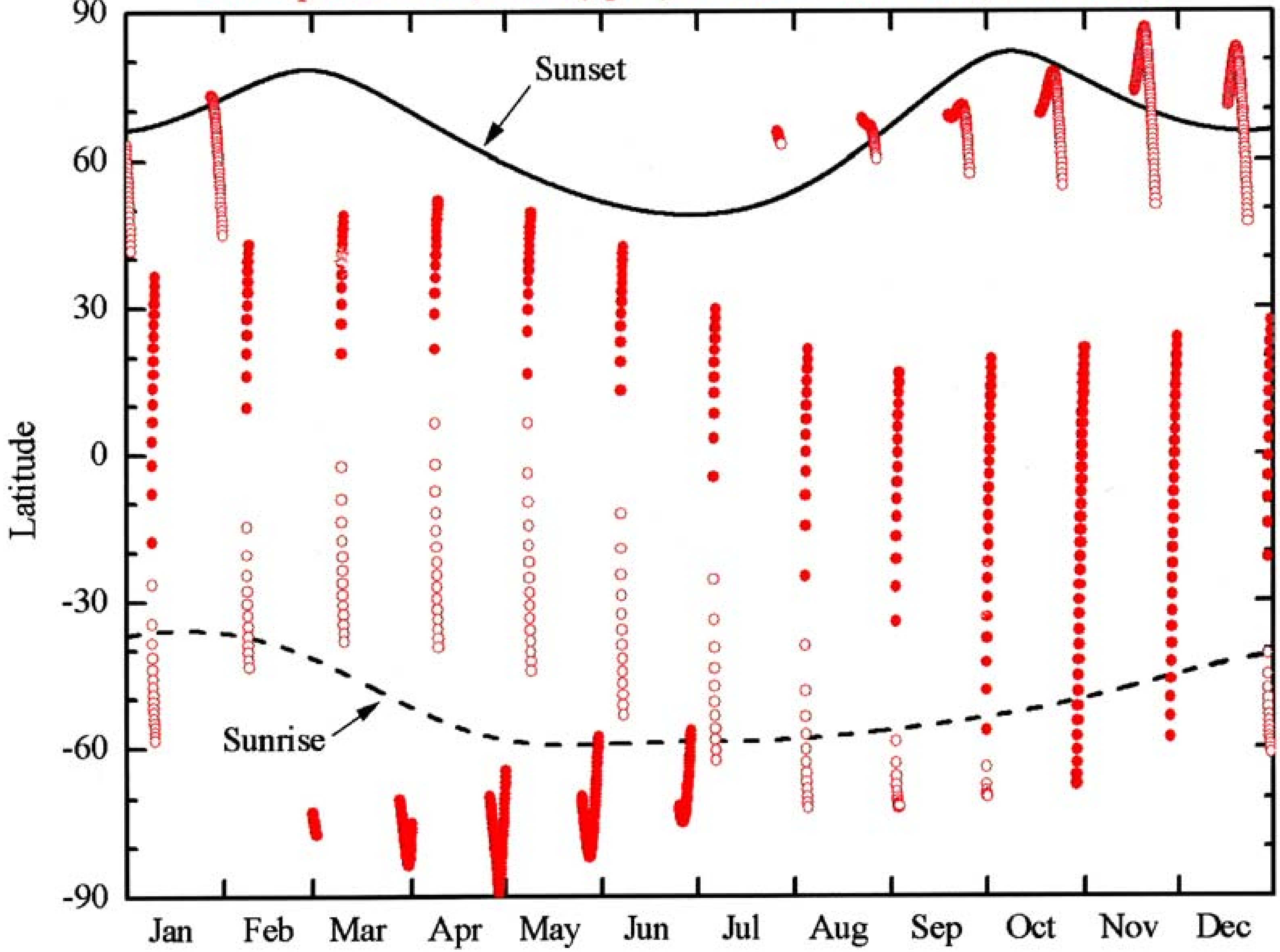


SAGE III Measurement Technique

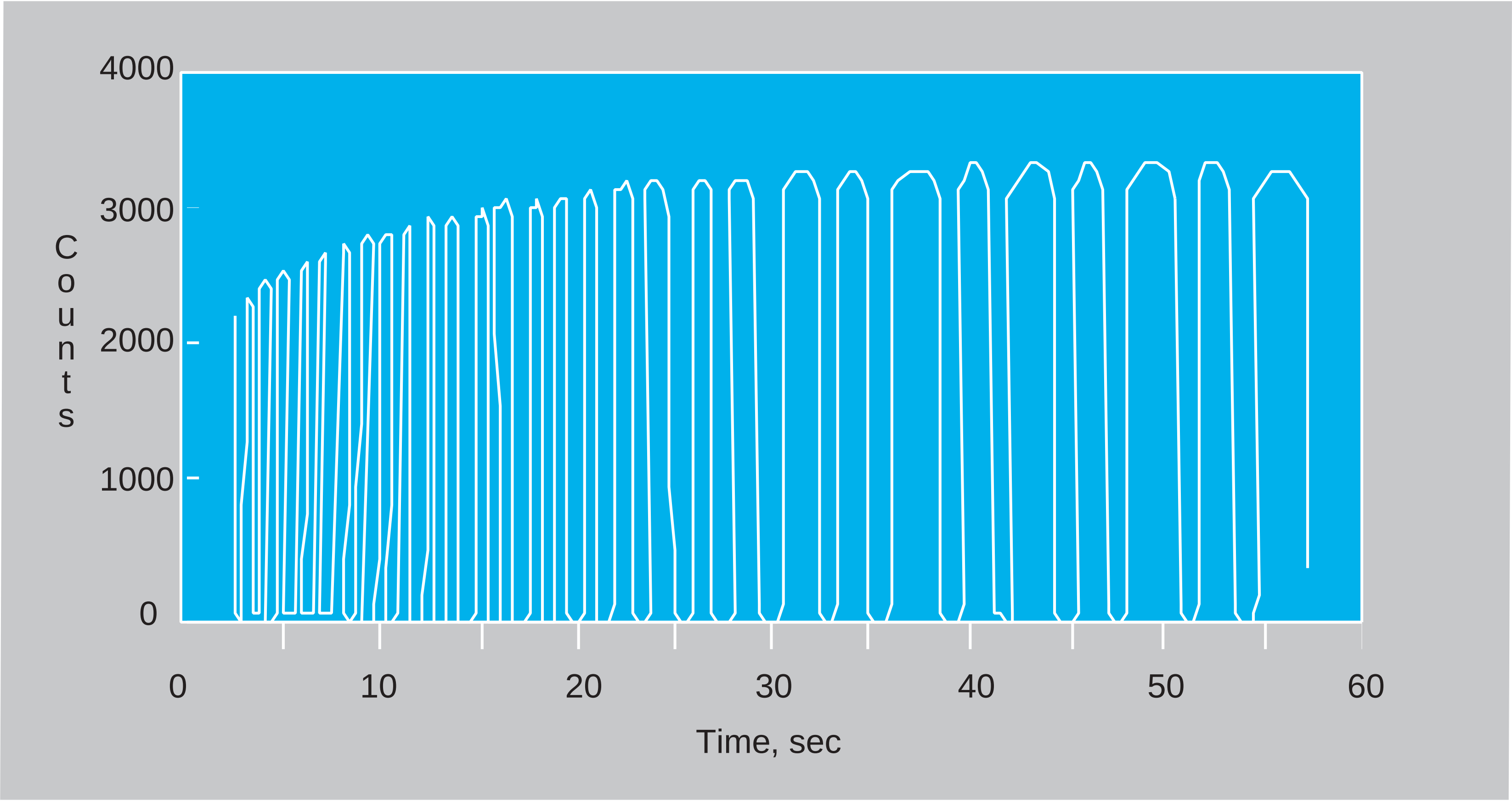


SAGE III Meteor-3M Solar and Lunar Occultation Coverage

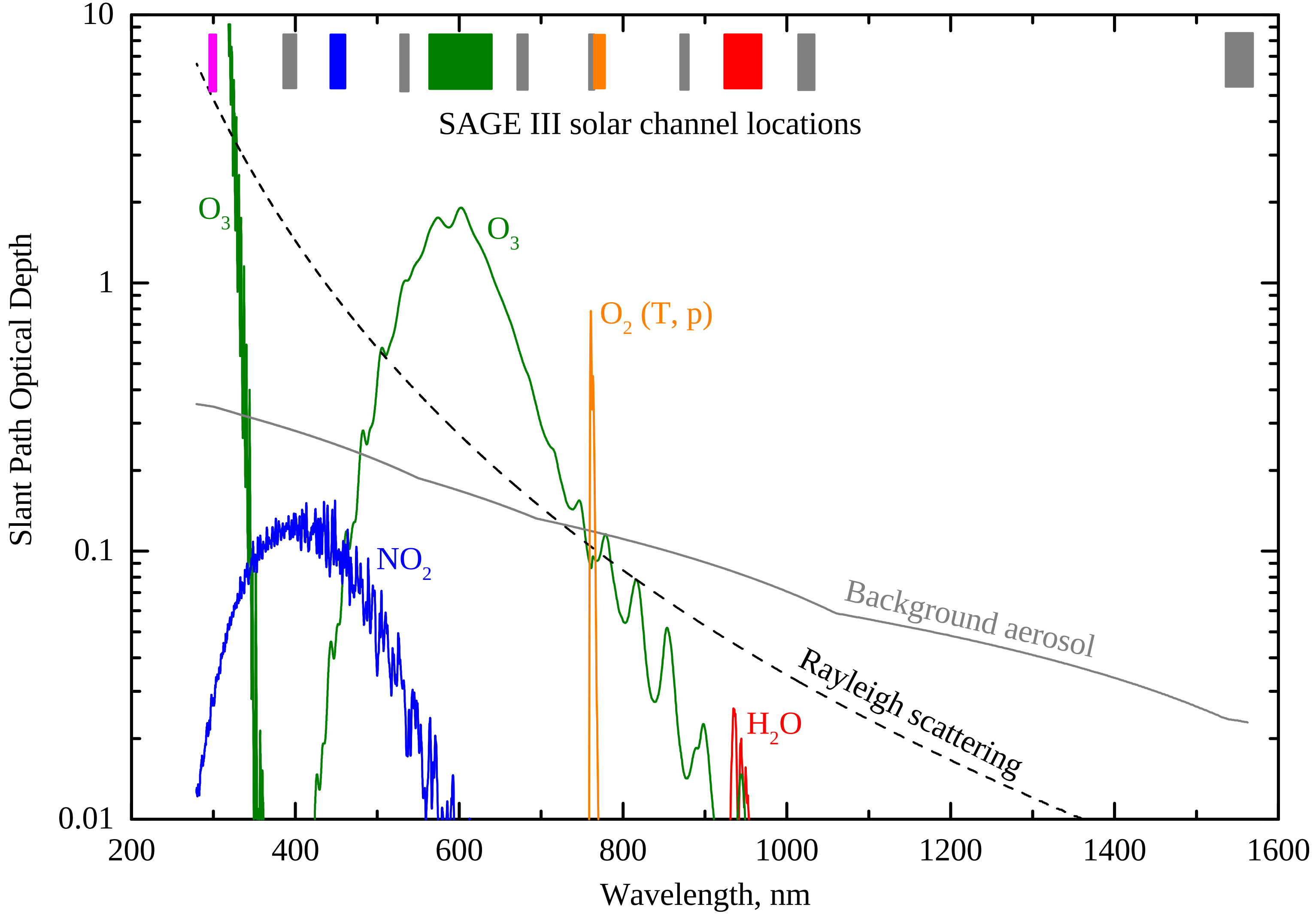
Lunar phase > 0.5; solid (open) circles = moonsets (moonrises)



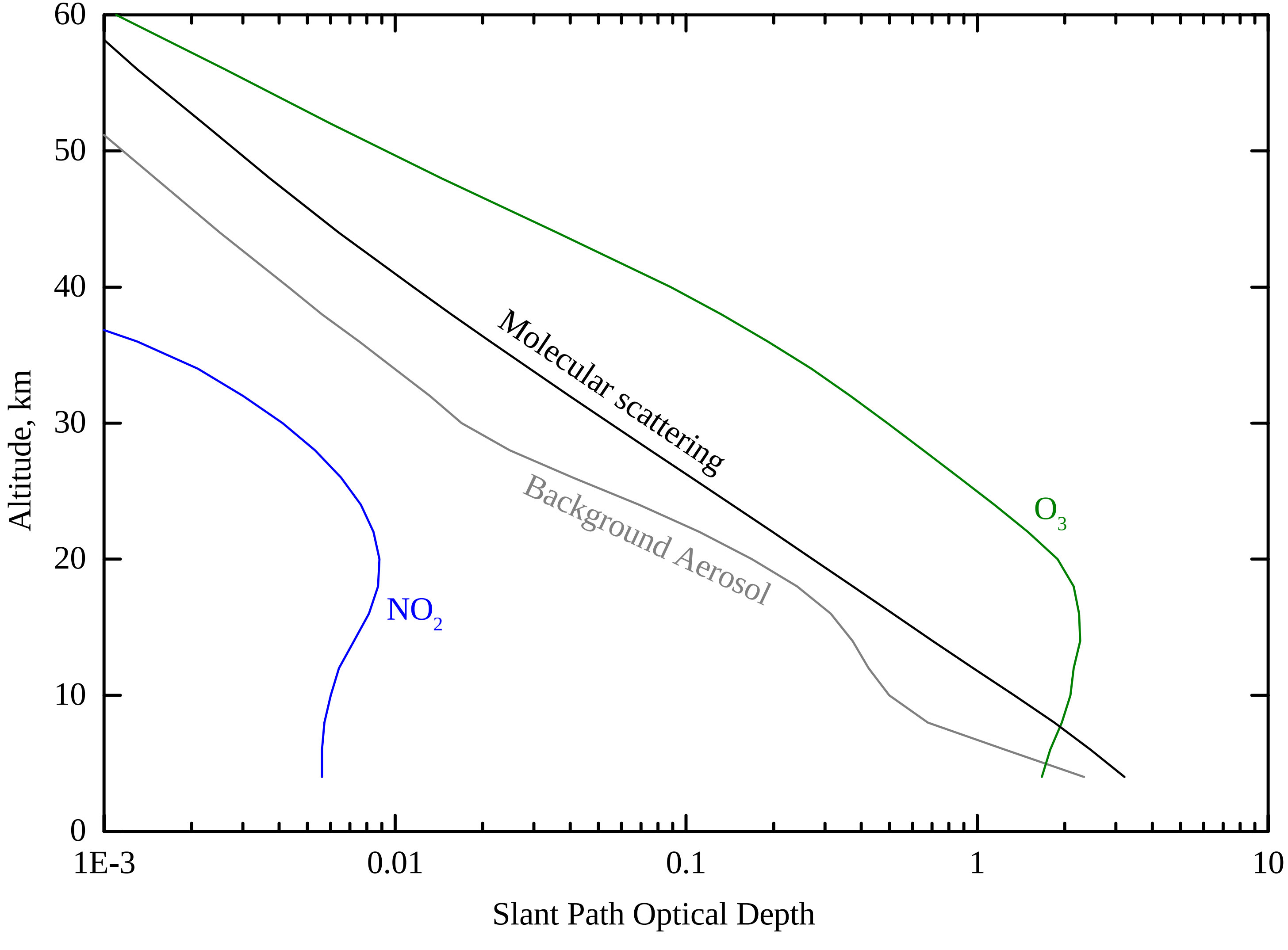
SAGE Data Stream (Sunrise Event)



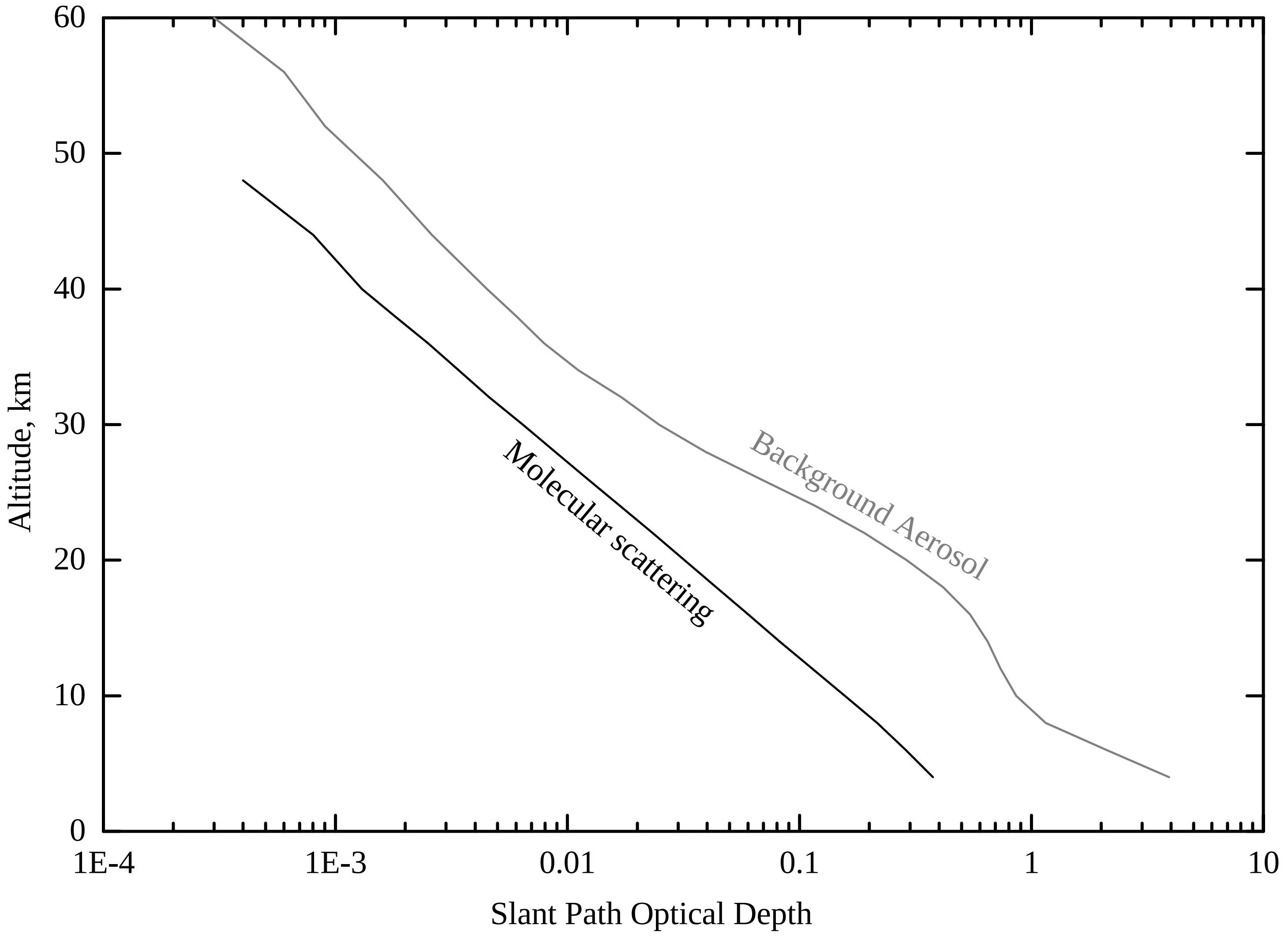
Slant Path Optical Depth at 20 Km



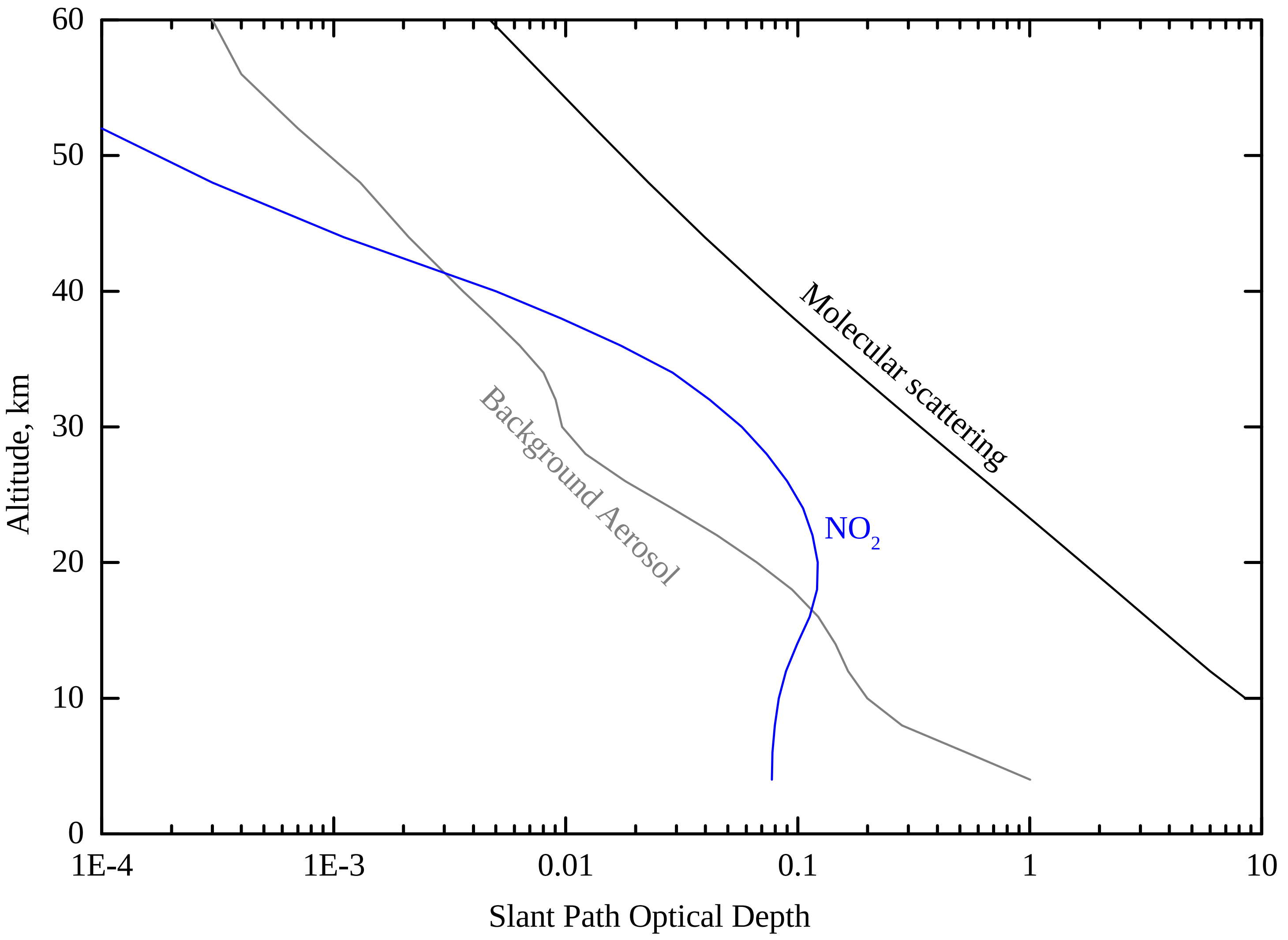
Slant Path Optical Depth at 600 nm



Slant Path Optical Depth at 1020 nm

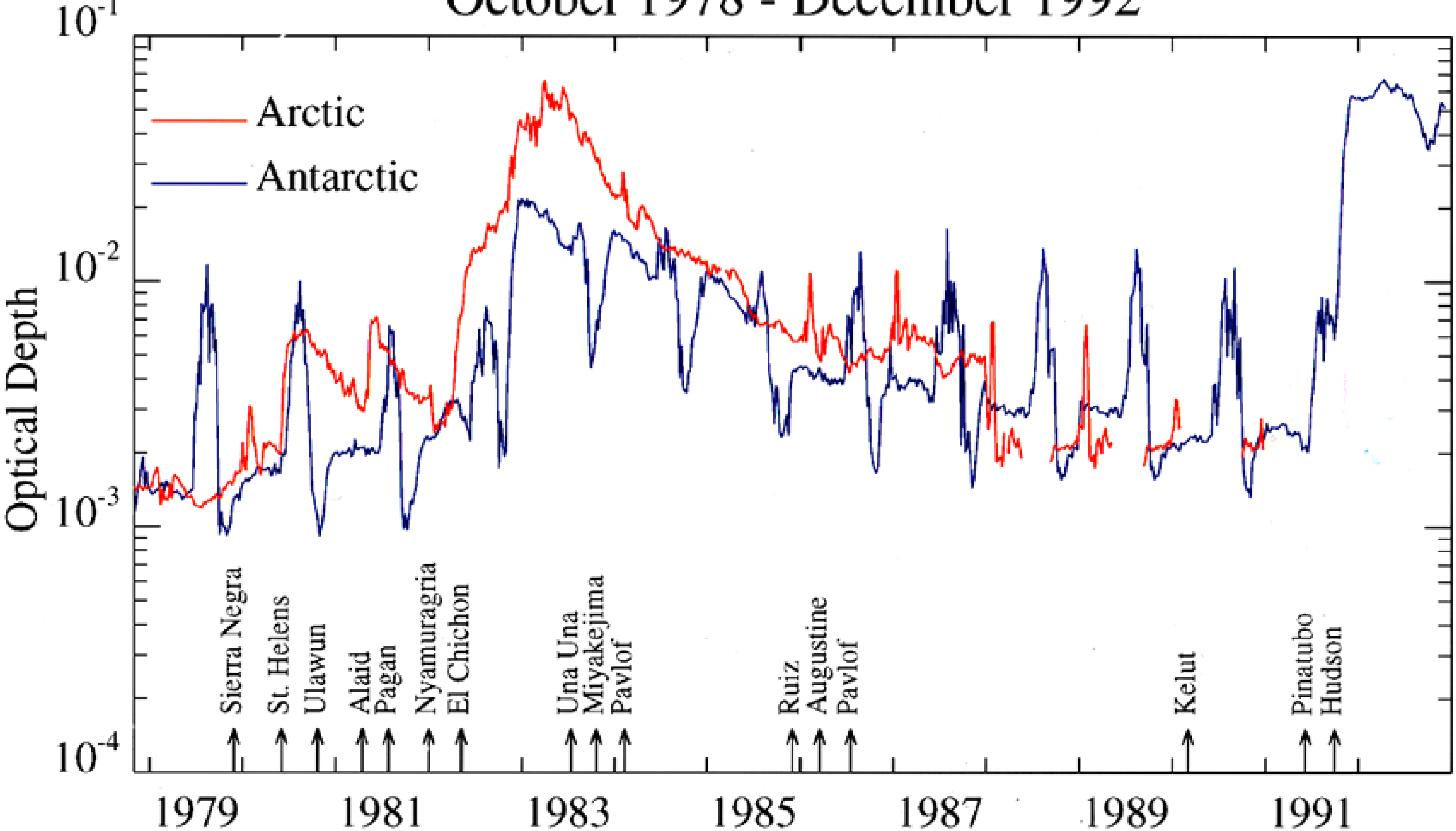


Slant Path Optical Depth at 385 nm

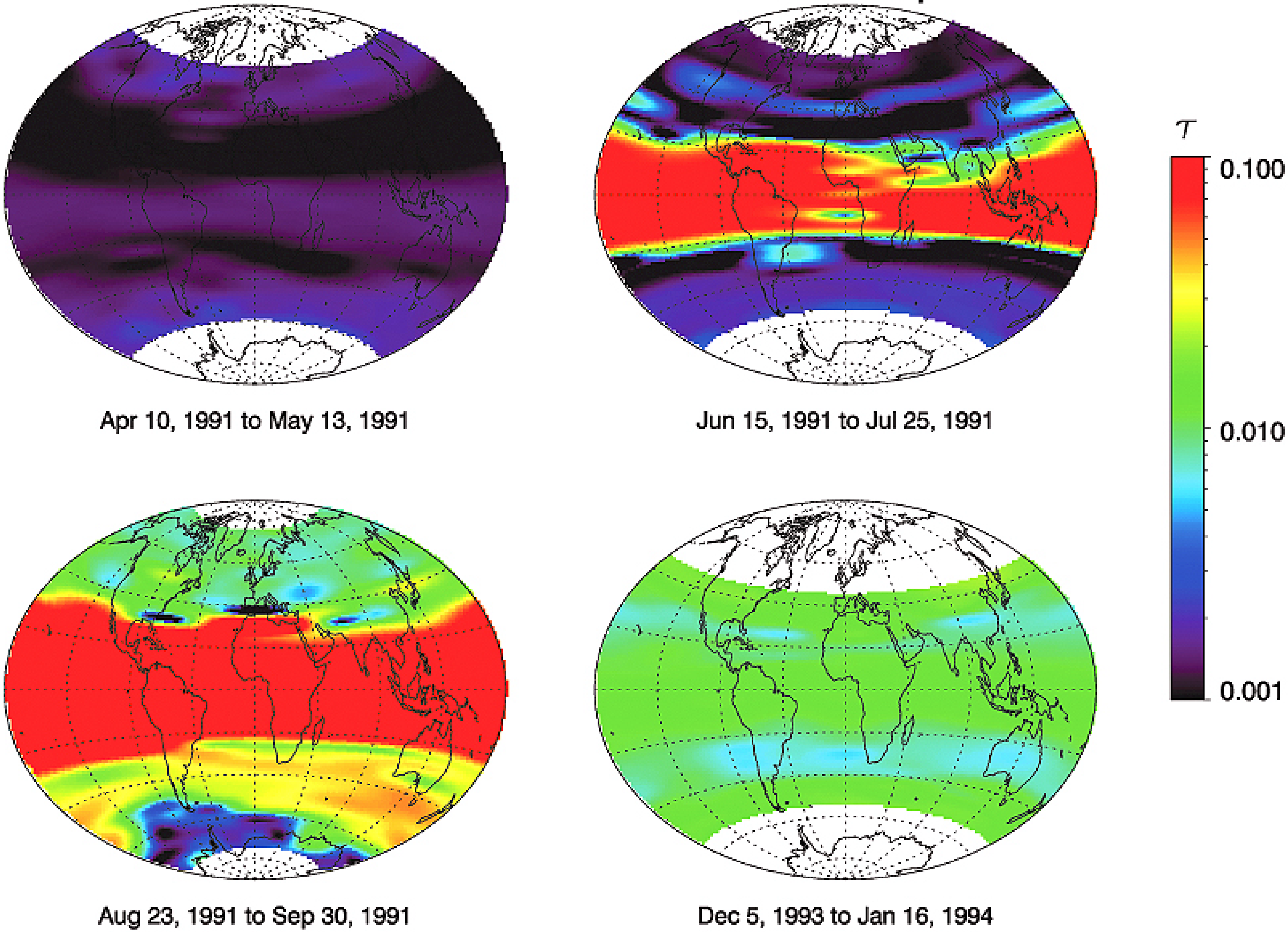


SAM II Polar Stratospheric Optical Depth

October 1978 - December 1992

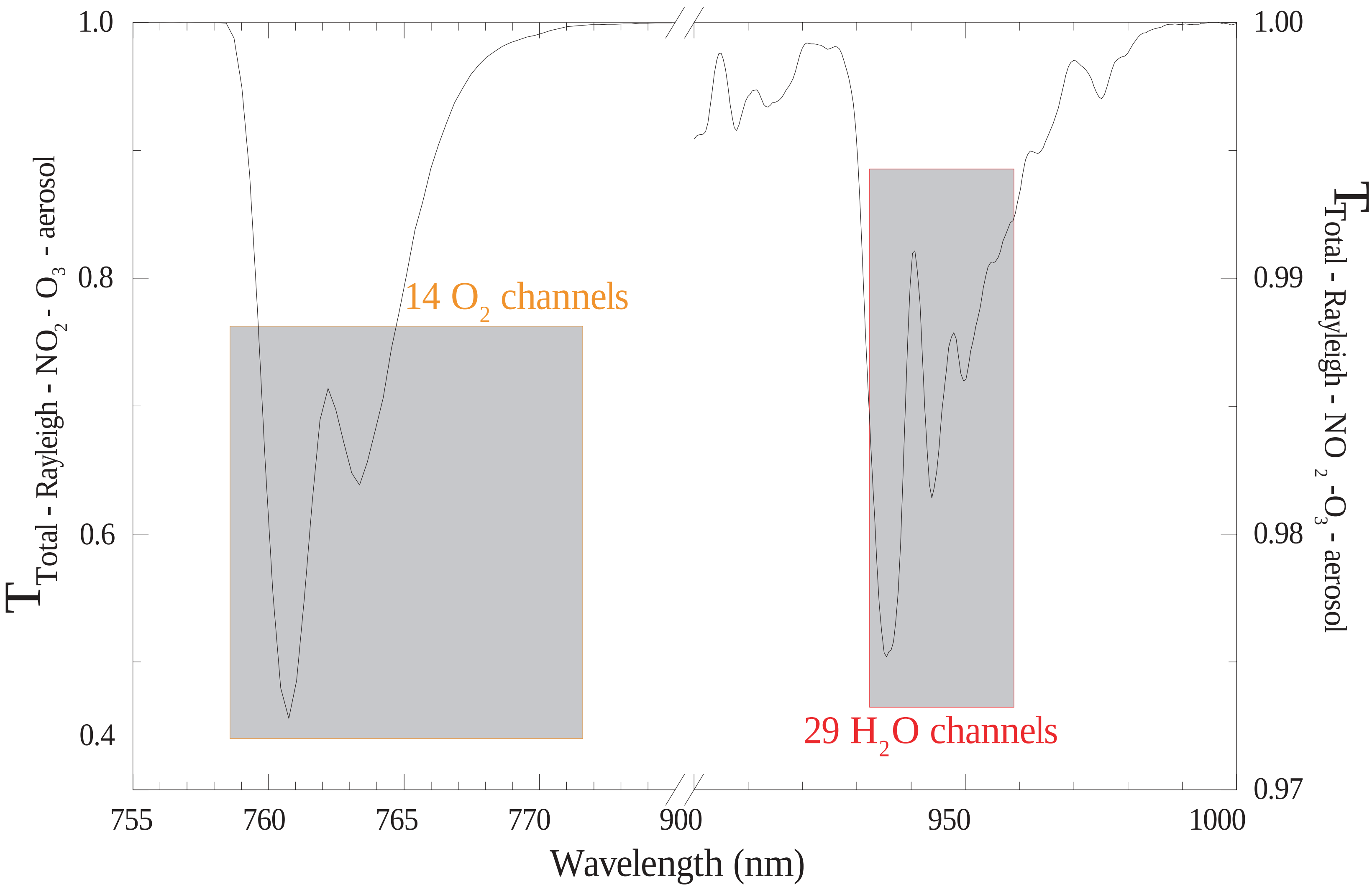


Stratospheric Optical Depth
Before and After 6/15/91 Pinatubo Eruption



May/2002
6.10
T+2

H_2O & T/P Channels

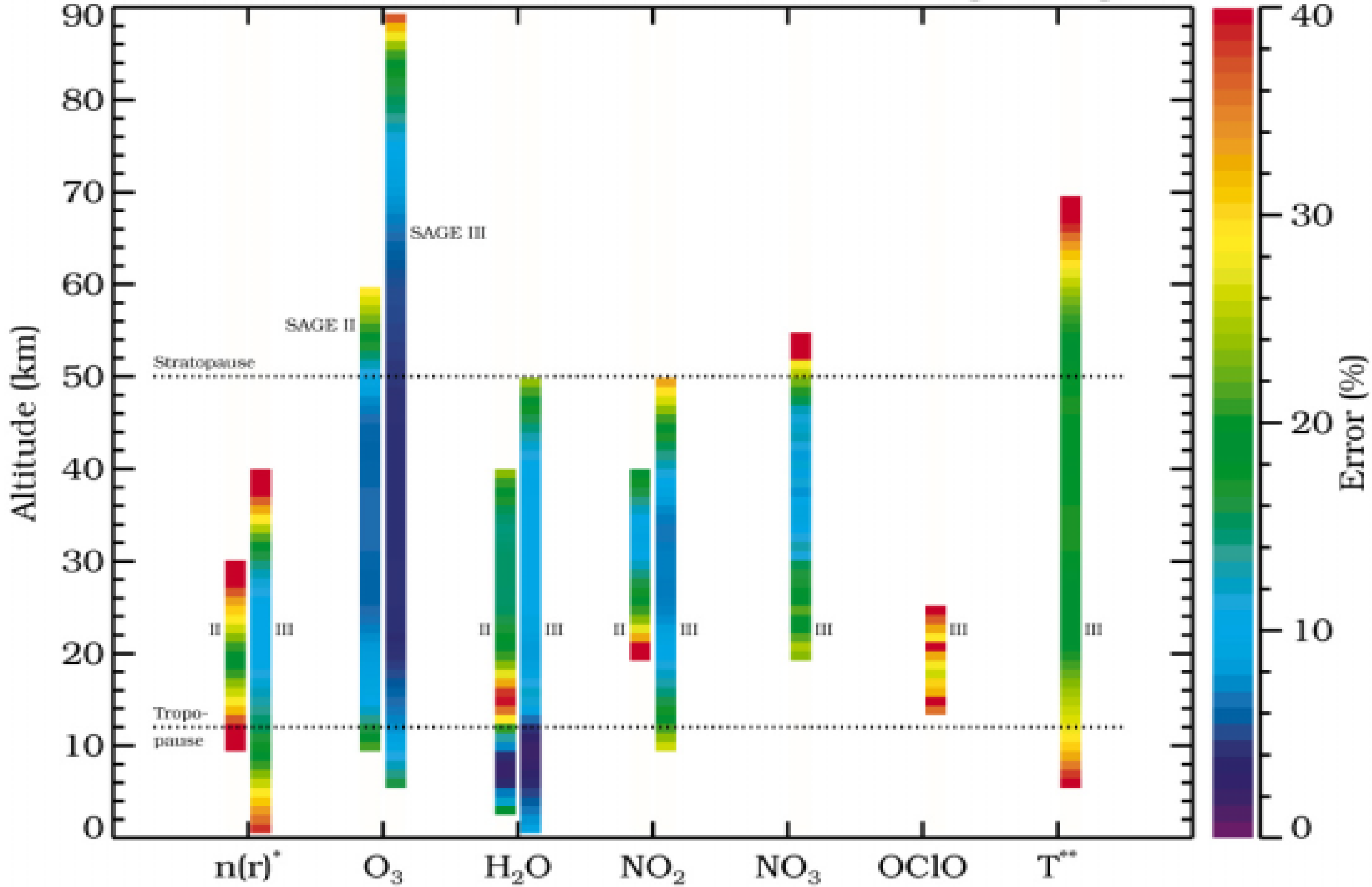


Solar and Lunar Measurement Wavelengths

Solar			
Channel	Wavelength Range (nm)	Subchannels	Species
S1	288-293	1	Mesospheric O_3
S2	382-387	1	Aerosol
S3	433-451	19	NO_2, Aerosol
S4	519-523	1	Aerosol
S5	561-622	10	O_3
S6	674-678	1	Aerosol
S7	754-758	1	Aerosol
S8	759-771	14	T/P
S9	867-871	1	Aerosol
S10	933-960	29	H_2O
S11	1017-1023	1	Aerosol
S12	1540	1	Aerosol

Lunar			
Channel	Wavelength Range (nm)	Subchannels	Species
L1	380-680	300	O_3, NO_2, NO_3, OClO
L2	739-780	22	T/P
L3	920-961	22	H_2O

SAGE II vs SAGE III Measurement Capability

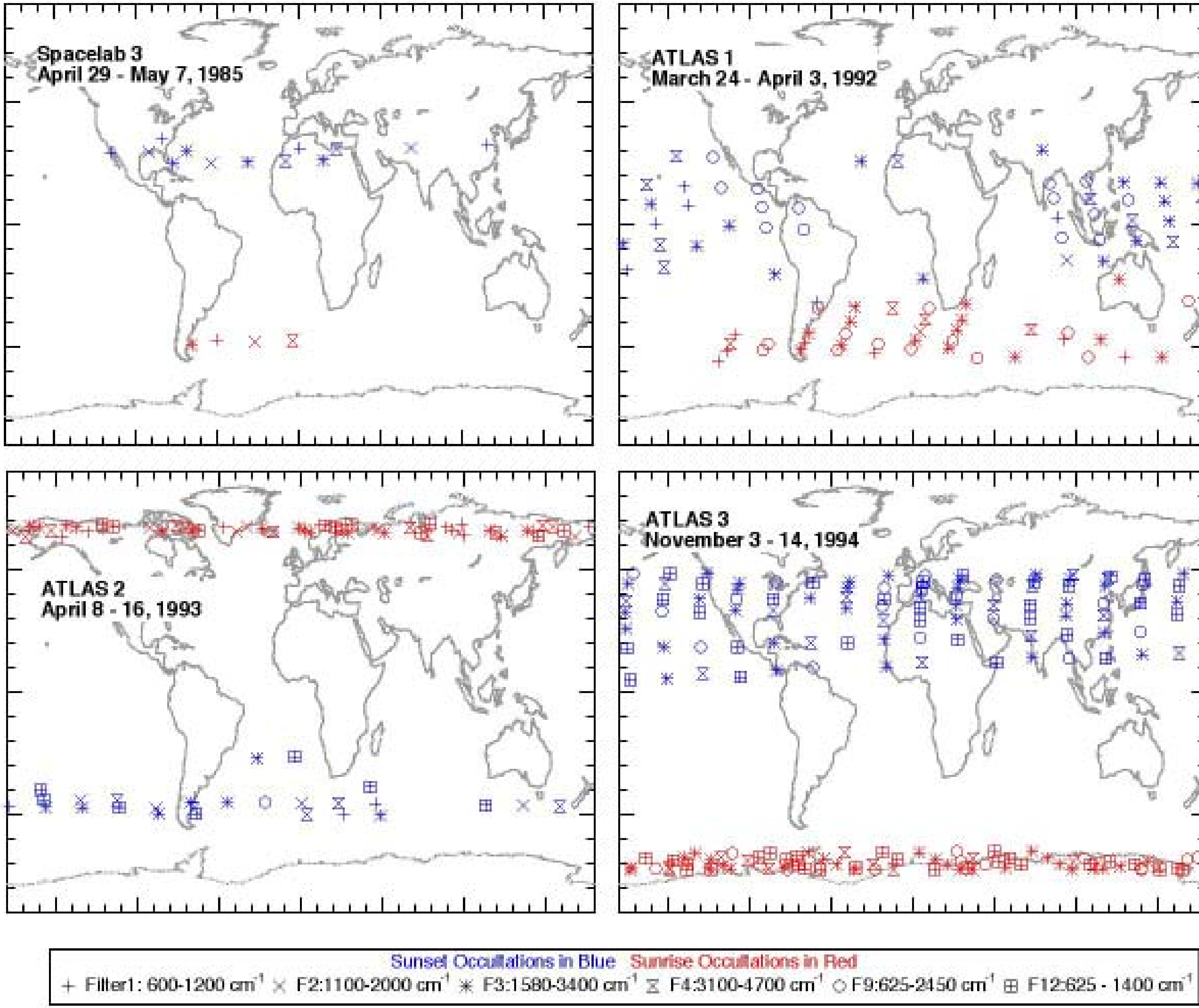


* Surface area density

** Error in tenths of a degree

SAGE III Science Team

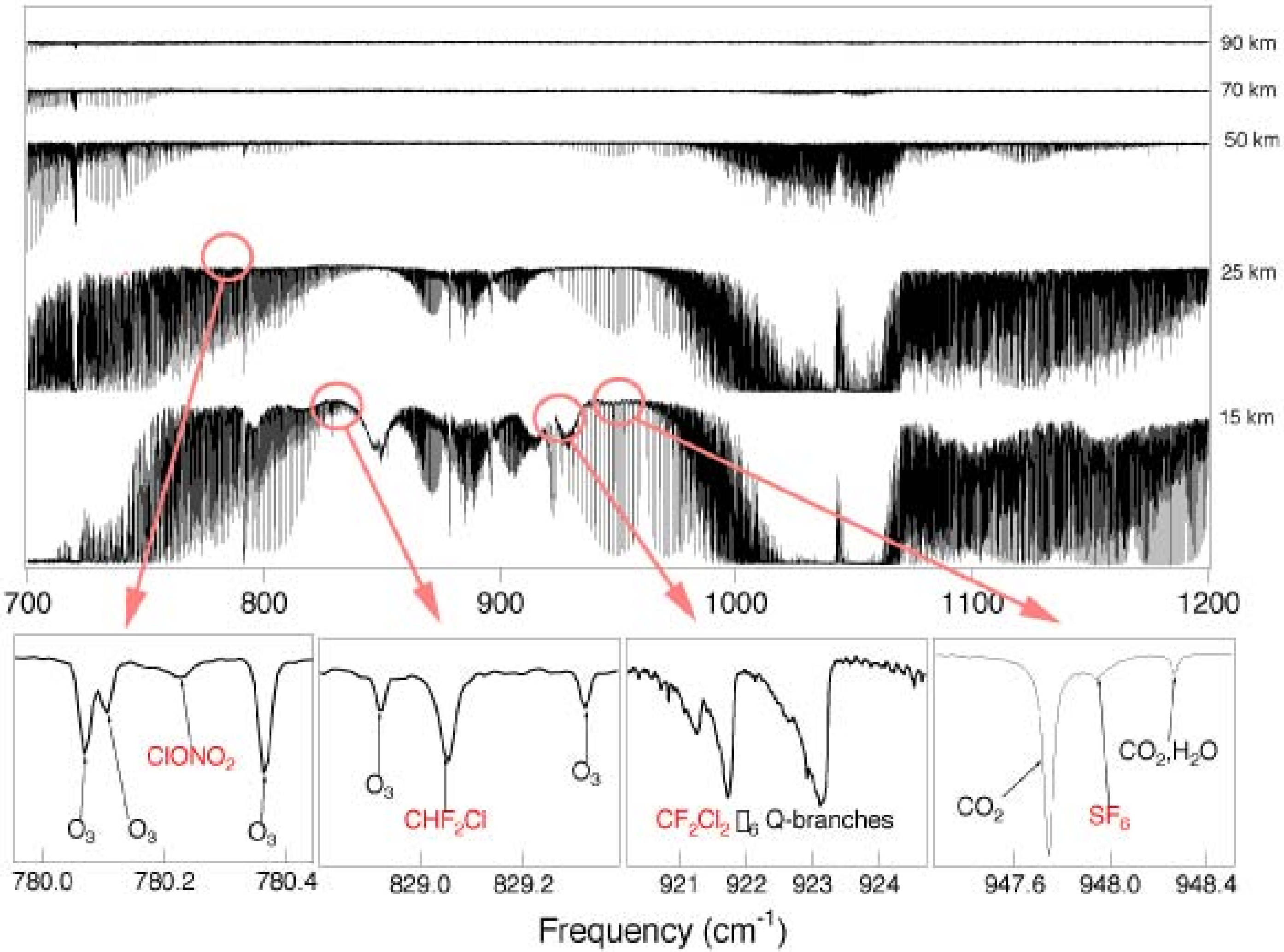
INVESTIGATORS	AFFILIATION
M. P. McCormick, Principal Investigator	Hampton University
W. P. Chu, Project Scientist	NASA Langley
A. A. Chernikov	Central Aerological Observatory
D. M. Cunnold	Georgia Institute of Technology
J. DeLuisi	NOAA/ERL
P. A. Durkee	Naval Postgraduate School
N. P. Elanski	Russian Academy of Sciences
B. M. Herman	University of Arizona
P. V. Hobbs	University of Washington
G. Kent	Science and Technology Corp.
J. Lenoble/C. Brogniez	University of Lille
A. J. Miller	NOAA NCEP
V. Mohnen	New York State University
V. Ramaswamy	Princeton University
D. Rind	NASA GISS
P. B. Russell	NASA Ames
V. Saxena	North Carolina State University
E. P. Shettle	Naval Research Lab.
L. Thomason	NASA Langley
C.Trepte	NASA Langley
G.Vali	University of Wyoming
S. C. Wofsy	Harvard University
J. M. Zawodny	NASA Langley



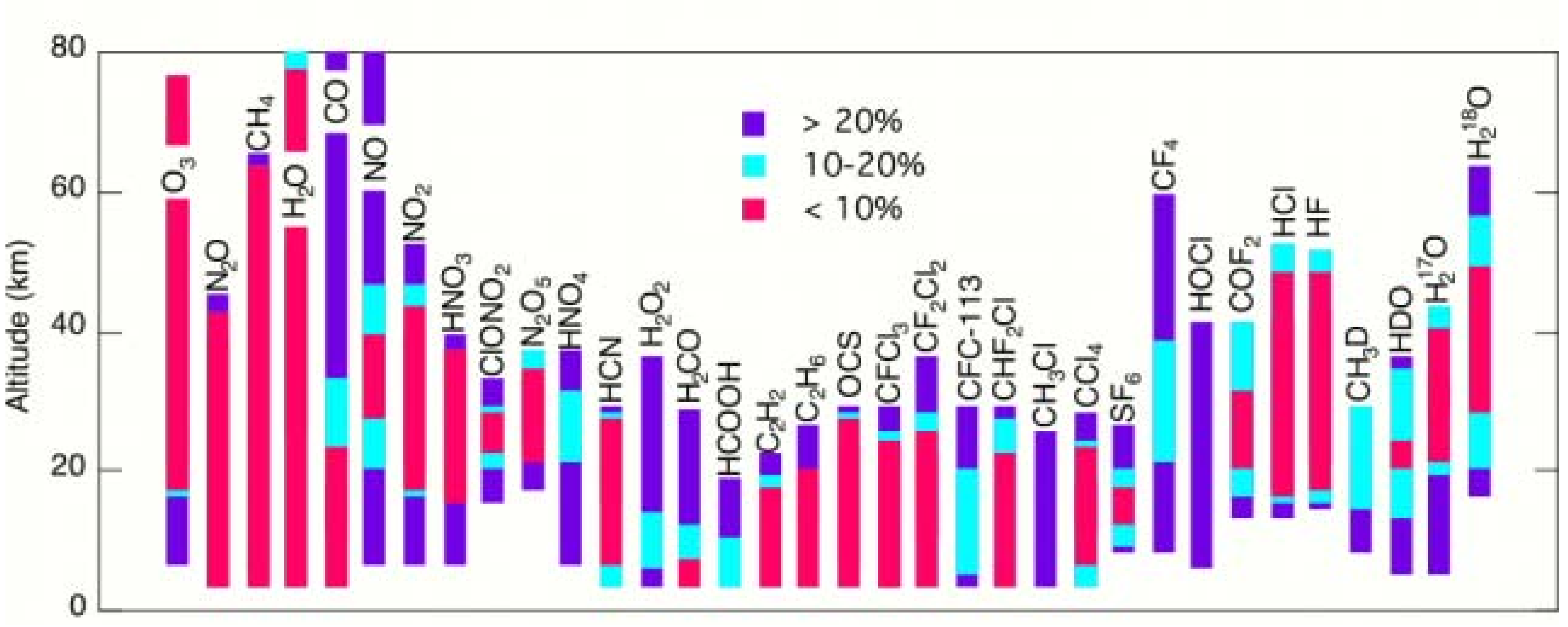
Spacelab 3
April 29 - May 7, 1985
ATLAS 1
March 24 - April 3, 1992
ATLAS 2
April 8 - 16, 1993
ATLAS 3
November 3 - 14, 1994
Sunset Occultations in Blue Sunrise Occultations in Red
+ Filter1: 600-1200 cm^{-1} F2:1100-2000 cm^{-1} F3:1580-3400 cm^{-1} F4:3100-4700 cm^{-1} F9:625-2450 cm^{-1} F12:625 - 1400 cm^{-1}

Typical ATMOS Spectra

The upper figure shows the decreasing absorption with altitude, while the bottom figures illustrate spectral features used for trace gas profile retrievals. For clarity, vertical scales differ among the displayed spectra.



ATMOS



Altitude (km)
0
20
40
60
80
> 20%
10-20%
< 10%
O_3
N_2O
CH_4
H_2O
CO
NO
NO_2
HNO_3
$ClONO_2$
N_2O_5
HNO_4
HCN
H_2O_2
H_2CO
HCOOH
C_2H_2
C_2H_6
OCS
$CFCl_3$
CF_2Cl_2
CFC-113
CHF_2Cl
CH_3Cl
CCl_4
SF_6
CF_4
HOCl
COF_2
HCl
HF
CH_3D
HDO
$H_2^{17}O$
$H_2^{18}O$

ATMOS

Principal Investigators: Barney Farmer, Michael Gunson

Key Contributors: Mian Abbas, Mark Abrams, Mark Allen, Reinhard Beer, Linda Brown, Albert Chang, Annmarie Eldering, Murray Geller, Bo-Cai Gao, Aaron Goldman, Bill Irion, Brian Kahn, Jack Kaye, Zhming Kuang, Bill Mankin, Gloria Manney, Hope Michelsen, Liz Moyer, Michael Newchurch, Robert Norton, Jae Park, Odell Raper, Curtis Rinsland, Jim Russell, Ross Salawitch, Bhaswar Sen, John Shaw, Gabrielle Stiller, Geoffrey Toon, Robert Toth, Yuk Yung, and Rodolphe Zander

Polar Ozone and Aerosol Measurement (POAM) Program

POAM III is a 9-channel visible/near infrared photometer for making measurements of stratospheric constituents using solar occultation techniques.

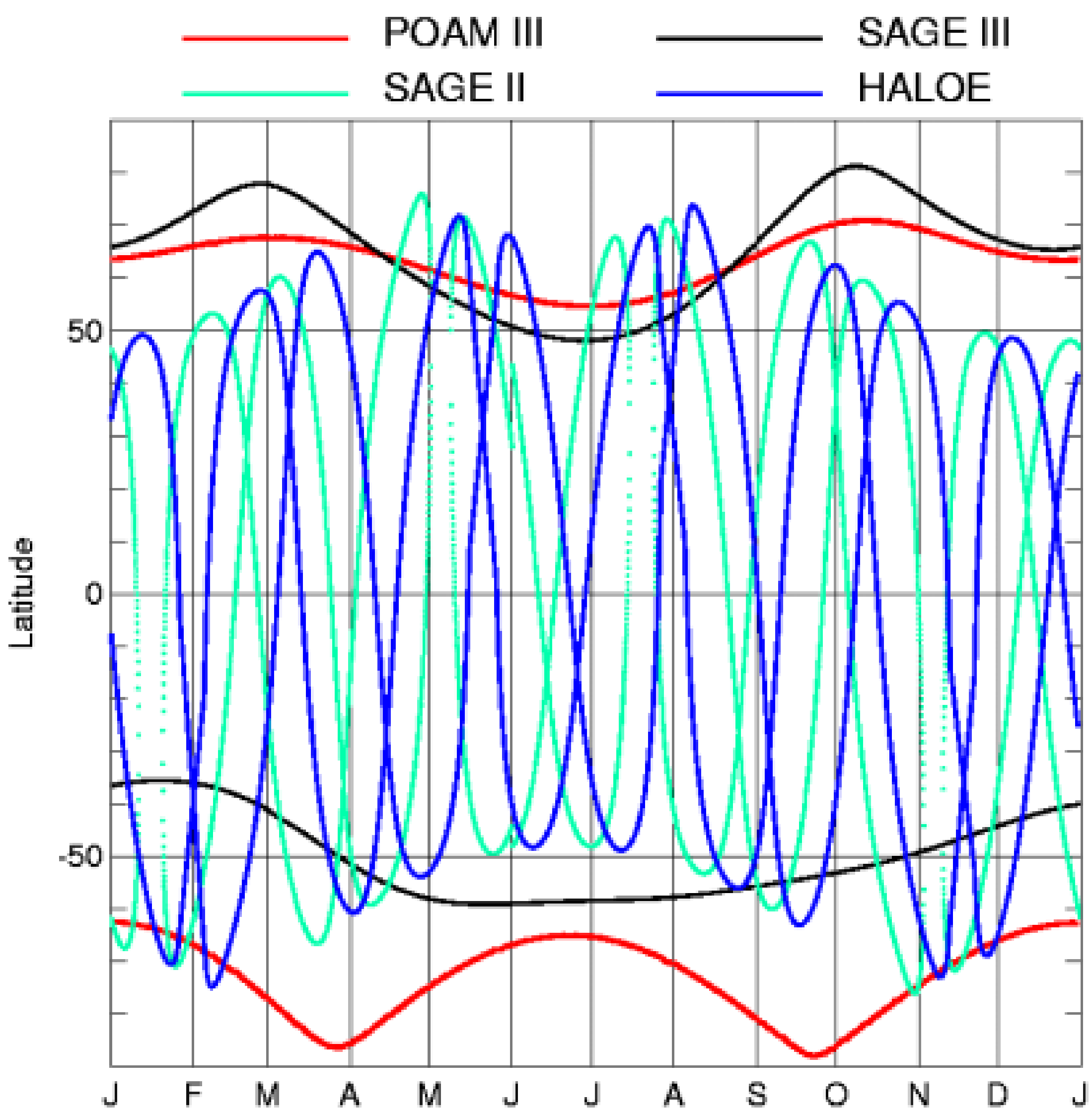
- POAM II was launched on 26 Sep., 1993 on the French SPOT 3 spacecraft into a polar sun synchronous orbit (98.7° inclination, 10:30 equatorial crossing) and operated until the satellite failed in Nov. 1996.

- The POAM II measurement complement includes:
  Ozone (10-60 km)
  Aerosol Extinction (10-30)
  Nitrogen Dioxide (20-40 km)

- POAM III was launched on SPOT 4 (orbit identical to that of POAM II) on 23 March 1998. The instrument is currently operational.

- The POAM III measurements:
  Ozone (5-60 km)
  Aerosol Extinction (5-30 km)
  Nitrogen Dioxide (20-45 km)
  Water Vapor (5-45 km)
  Atmospheric Density (30-60 km)

Polar Ozone and Aerosol Measurement (POAM) Program



- POAM II and III measurement coverage is identical, and are both annually periodic.

- The POAM measurements provide continuous coverage of the polar regions.

- POAM is complementary to SAGE III, which measures to higher latitudes in the north, but lower latitudes in the south.

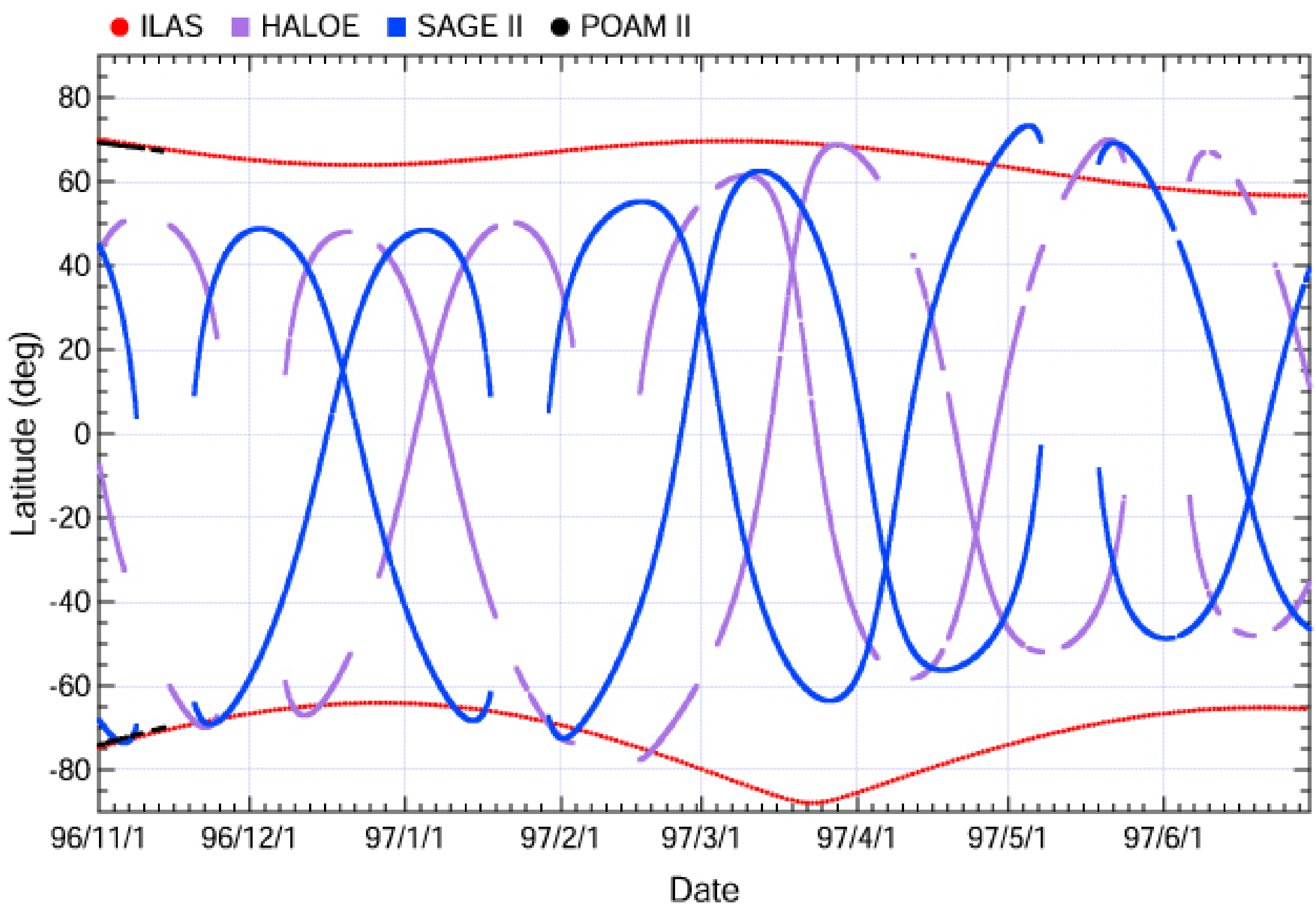
- The POAM measurement coverage is nearly identical to that of ILAS I and II

POAM Science Team:

R Bevilacqua (PI,NRL)	K. Hoppel (NRL)
J. Lumpe (CPI)	M. Fromm (CPI)
C. Randall (CU)	G. Nedoluha (NRL)
D. Allen (NRL)	E. Shettle (NRL)
J. Hornstein (NRL)	A. Prados (NRL)
C. Benson (NRL)	J. Alfred (CPI)
R. Salawitch (JPL)	M. Santee (JPL)
G. Manney (JPL)	D. Rusch (CU)
A. Strawa (NARC)	K. Drdla (NARC)
C. Brogniez (Lille)	H. Steele (CSUN)
B. Connor (NIWA)	K. Kreher (NIWA)
S. Massie (NCAR)	L. Pan (NCAR)

Data Archival information:

POAM II: Archived on Langley DAAC
POAM III: Publicly available (http://wvms.nrl.navy.mil/POAM/
and http://www.cpi.com/products/poam)



ILAS
HALOE
SAGE II
POAM II
80
60
40
20
0
-20
-40
-60
-80
Latitude (deg)
96/11/1
96/12/1
97/1/1
97/2/1
97/3/1
97/4/1
97/5/1
97/6/1
Date

The SCIAMACHY Instrument on ENVISAT

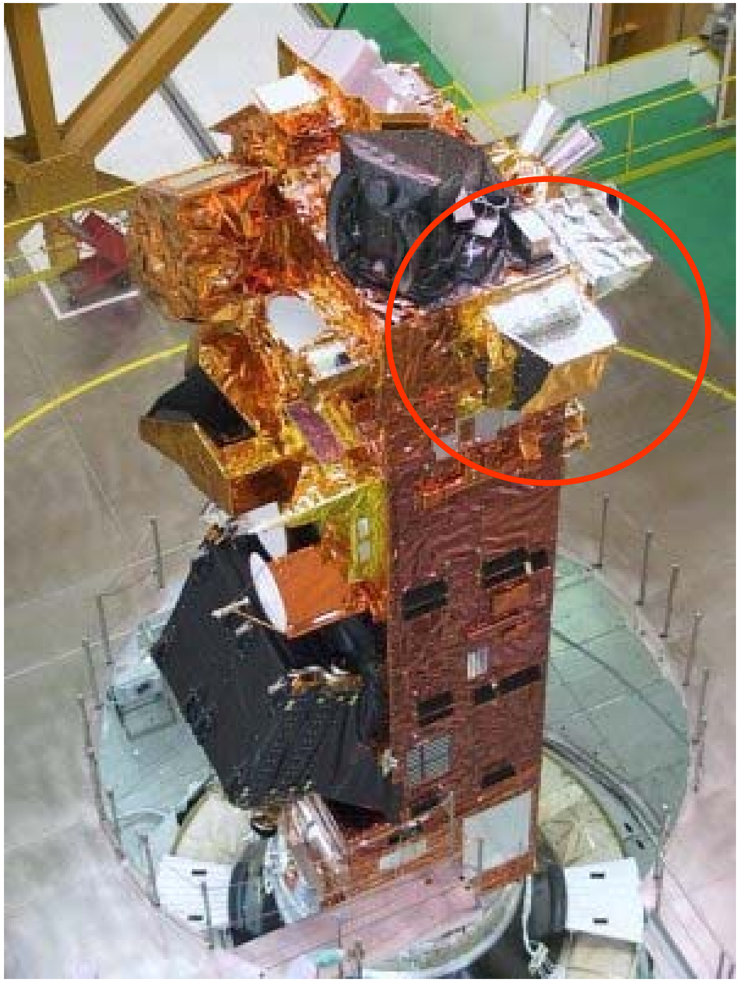


Fig.:ESA

- Spectrometer (214-2384 nm)
- Proposed in July 1988 as an AO for Envisat by German led international team
- German, Dutch and Belgian contribution to the ESA Envisat
- Science Team:
  - PI: J. P. Burrows, IFE/IUP Bremen, Germany
  - Co-PIs: A. Goede, SRON, The Netherlands; C. Mueller, BIRA/IASB, Belgium
  - International Science Team from Europe and several American groups.
- Envisat Launch: 1 March 2002
- Data Policy and Availability:
  - Still in commissioning activities - all data products starting from July 2002 will be made available for ENVISAT Validation and Data User PIs and the wider community via the ESA EO C1 procedure.

SCIAMACHY on Envisat

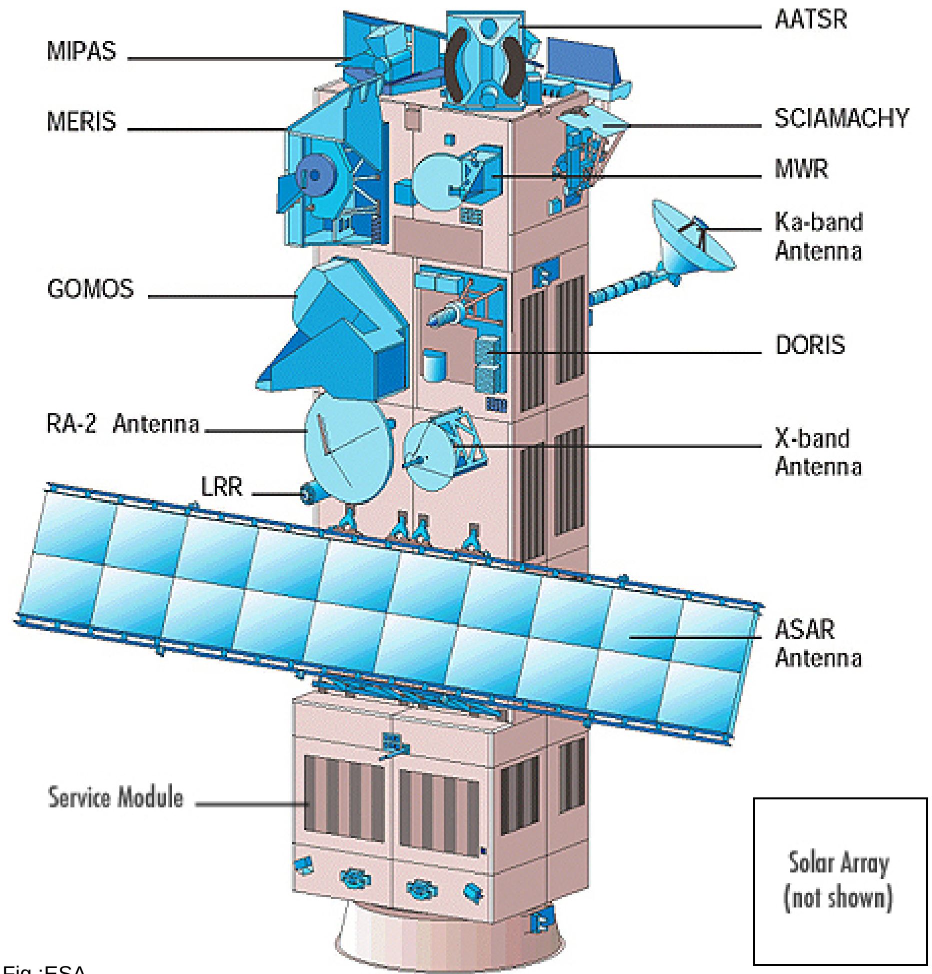
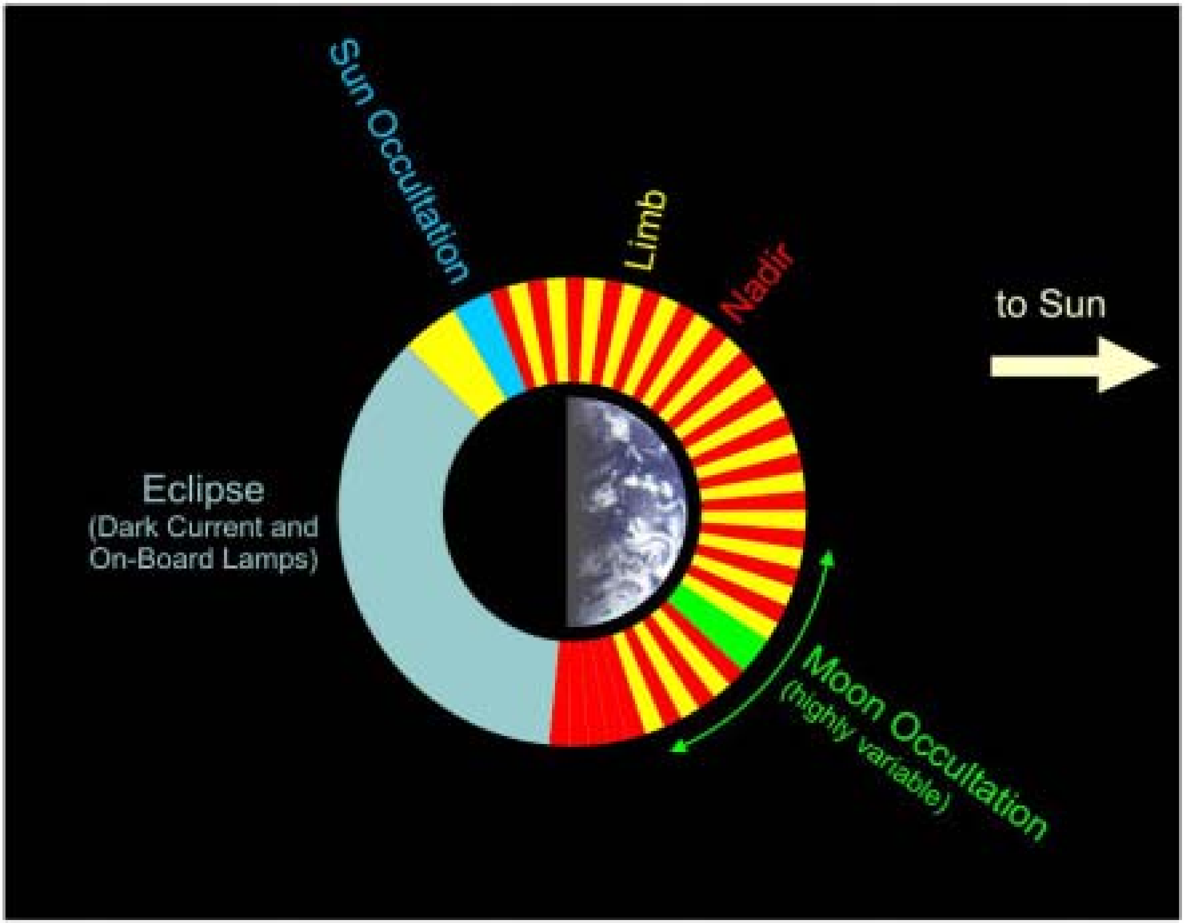


Fig.:ESA

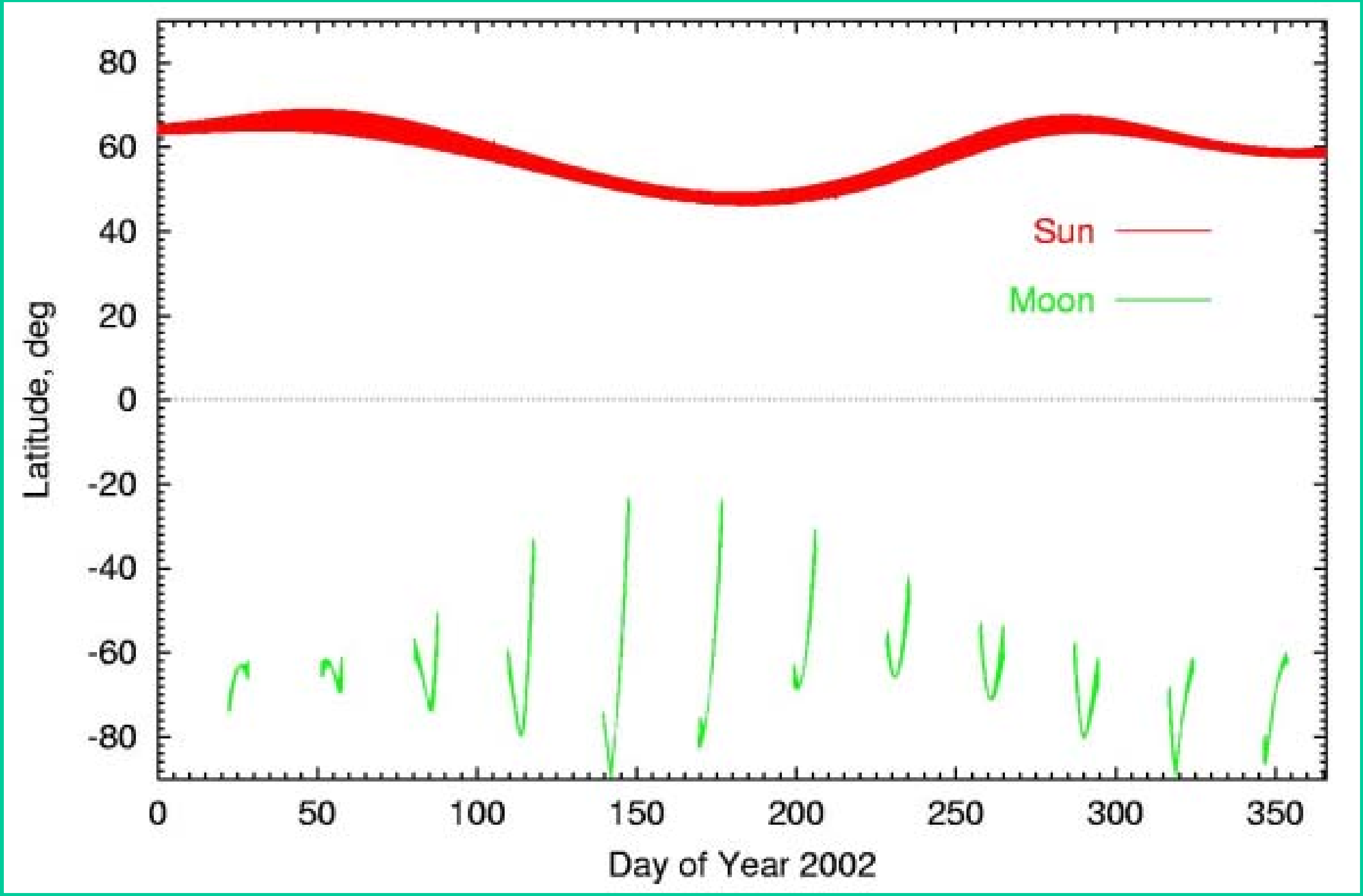
Envisat Launch: 1 March 2002

Typical Orbit

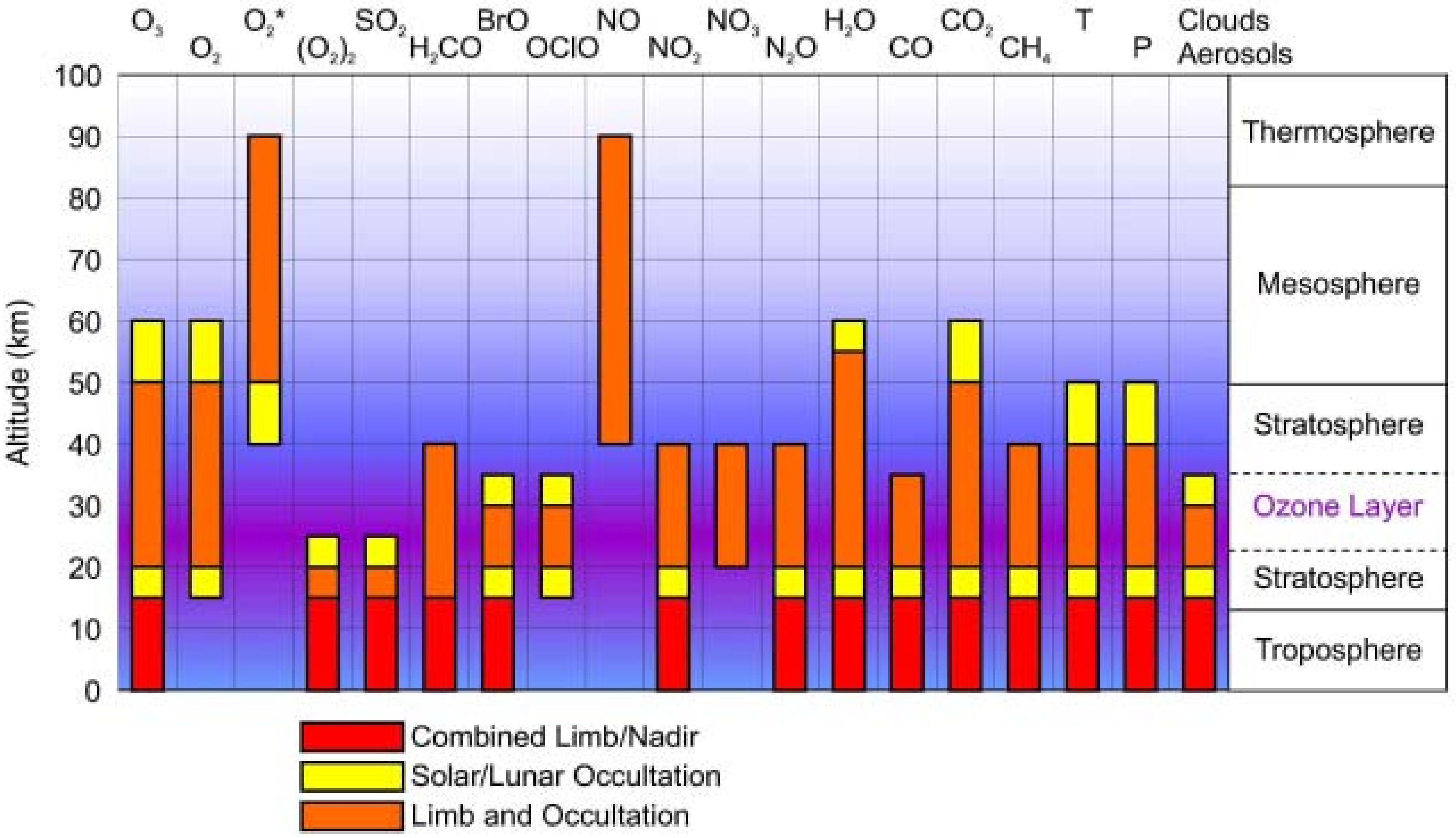


- Sun-synchronous orbit descending node having equator crossing at 10:00 AM)
- Altitude ~ 800 km ground speed 7 kms^{-1}
- Alternating Nadir and Limb measurements on dayside
- Solar occultation close to the terminator during sunrise every orbit in the NH.
- Lunar occultation made for about one week/month in the SH, provided that the tangent point is on night side.
- Calibration measurements during eclipse and in dedicated orbits
- Global coverage in 6 days

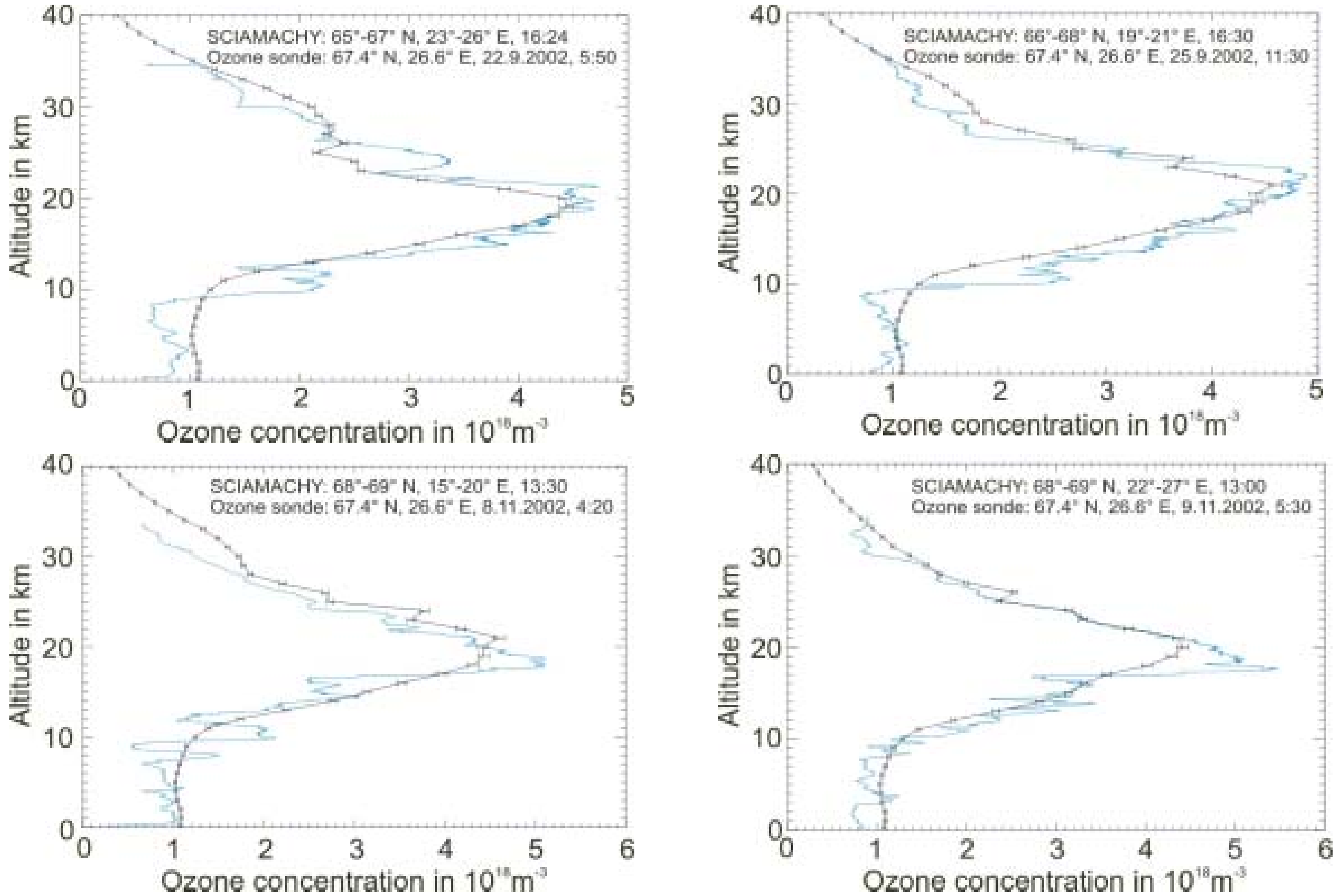
SCIAMACHY: Latitude Coverage for Solar and Lunar Occultation over the year



SCIAMACHY: Altitude Ranges for the Targeted Products



SCIAMACHYFirst Results: O_3 from Solar Occultation Comparisons with Ozone Sondes



Earth Orbiting Occultation Experiments

INSTRUMENT	λ (#, nm)	DETECTION SCHEME	Δ λ (nm)	ORBIT (LAT. COV.)
SAM	1 (1000)	Radiometer filter/diode	200	26°
SAM II	1 (1000)	Radiometer filter/diode	50	SS (noon)
SAGE	4 (1020, 600, 450, 380)	Spectrometer grating/diodes	20	56°
SAGE II	7 (1020, 940, 600, 525, 448, 453, 380)	Spectrometer grating/diodes	20	56°
ATMOS	700-1200 cm^{-1}	FTI	0.125 cm^{-1}	56^0
HALOE	8 (2.5-10.5mm)	Gas filter cells and broadband radio	≈ 80cm-1	57°
POAM II	9 (353.4-1018)	Radiometer	2-12	SS (10:30)
ILAS-ADEOS	753-874 1024	Vis. spect. MOS photodiode Pyroectron det.	 0.15nm 0.13nm	SS/57°- 71°N + 64°-89°S
SAGE III†	12 (290-1020, 1500)	Spectrometer gration/linear array (3) + 1 diode	1-1.5	SS (9:30)
GOMOS*	3 (250-675, 756-773, 926, 952)	Spectrometer		SS
SCIMACHY†	214-2384	Spectrometer-Si, Im Ga As	0.21-1.56	SS (10:00 a.m.)

*stellar occultation †lunar and solar occultation

Experiment Constituent Measurements

EXPERIMENT	CONSTITUENT MEASUREMENTS
SAM	A_E
SAM II	A_E
SAGE	A, O_3, NO_2
SAGE II	A, O_3, NO_2, H_2O
HALOE	HCl, HF, H_2O, CH_4, O_3, A, T, NO, NO_2
ATMOS	0_3, N_2O, CH_4, H_2O, CO, NO, NO_2, HNO_3, $ClONO_2$, N_20_5, HNO_4, HCN, HDO, $H_2{}^{17}O$, $H_2{}^{18}O$, H_2O_2, HCOOH, C_2H_2, OCS, $CFCl_3$, $CFCl_3$, CF_2, Cl_2, CFC-113, CHF_2, Cl, CCL_4, $5F_6$, CF_4, HOCl, COF_2, HCl, HF, CH_3D
POAM	O_3, A_E, NO_2, H_2O, Atm. Density
ILAS-ADEOS	O_3, HNO_3, NO_2, N_2O, CH_4, H_2O, A (780mm), CFC-11, CCFC-12, COF_2, N_2O_5, $ClONO_2$, A (7.12, 8.27, 10.6, 11.76mm)
SAGE III†	A, 0_3, NO_2, T, P, H_2O, OClO†, NO_3†
GOMOS*	O_3, NO_3, OClO, B_rO, A, H_2O, T
SCIMACHY†	A_E, Clouds, O_3, O_2, $(O_2)_2$, H_2CO, SO_2, BrO, OCLO, ClO, NO, NO_2, NO_3, H_2O, CO, CO_2, CH_4, N_2O

The SAGE Experience: Lessons Learned

- You can’t plan for >17 year lifetime, but you try hard to capitalize on it.
- Maintaining continuity over lifetime of mission is critical to long-term success, especially reprocessing
  - Made major contribution to assessment
- Focus on validation/intercomparison over lifetime of mission has important benefits to mission
- Team recompetition approach allowed for bringing in new views while providing for long-term stability

The SAGE Experience: Lessons Learned, cont.

- Nature sometimes provides unanticipated challenges and opportunities
  - e.g., Pinatubo eruption
- Creative data usage by scientists provides new scientific opportunities - consider some examples
  - PMC observations
  - TOMS/SAGE residual for tropospheric ozone
  - QBO effect studies
  - Upper stratospheric temperatures
  - Upper tropospheric water vapor transport mechanisms
  - Subvisible cirrus clouds

Summary

- **Solar occultation sensors have been making routine measurements since late 1978 (25 years) with exceedingly robust instrument and measurement lifetimes.**
- **Provides the high precision and high vertical resolution required for study of long-term changes.**
- **Stratospheric aerosol and ozone measurements have become primary global source for climatologies and trends:**
  - **"Gold-Standard" for 0_3 profiling.**
  - **Life-time and stability provides possibilities for 0_3 and A trends.**
- **Contributed significantly to:**
  - **Polar and near-global chemistry and dynamics.**
  - **Confirming evidence of effectiveness of international protocols regulating chlorine.**
  - **Volcanic impacts and use in GCMs.**