Improvements to Ozone Measurements Expected from the Ozone Mapping and Profile Suite for Weather and Climate

Maria Caponi[1], Lawrence Flynn[2], John Hornstein[3], Craig Long[2], Didier Rault[4]

1. JPSS program office /The Aerospace Corporation, 2. NOAA, 3. NRL, 4. NASA LaRC

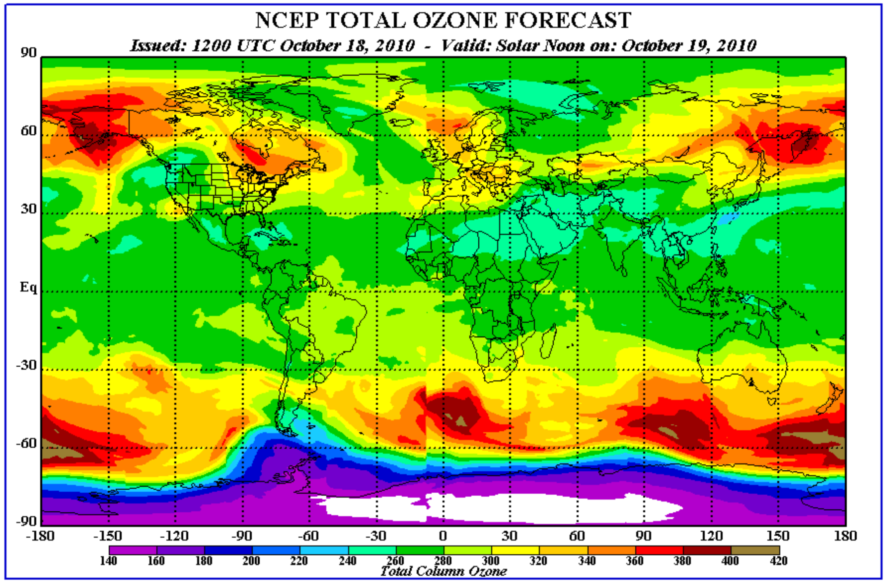
Outline

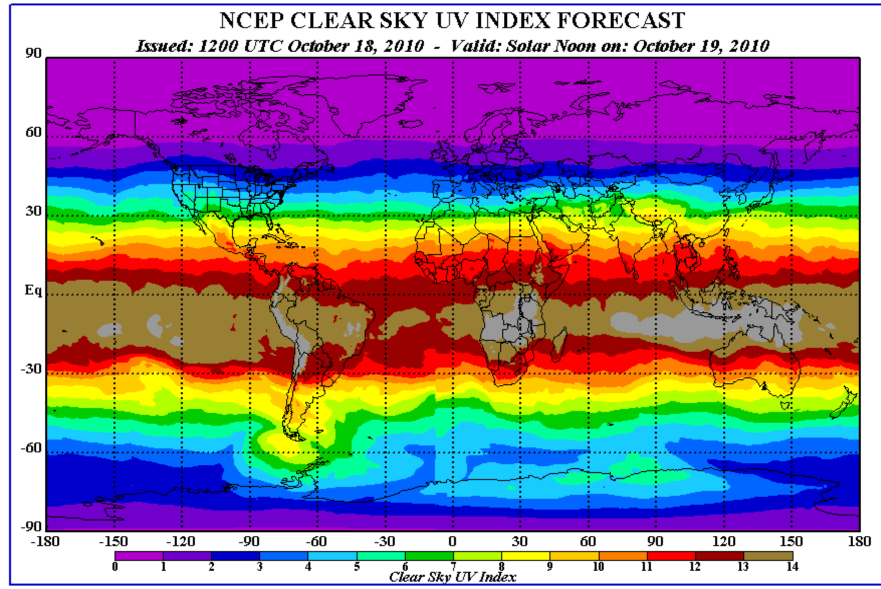
- Introduction
- OMPS profile suite description
- Observations – Heritage UV sensors
- Overview of Remote Limb Sensing
  - OMPS Improvements
  - Potential applications
- Conclusions

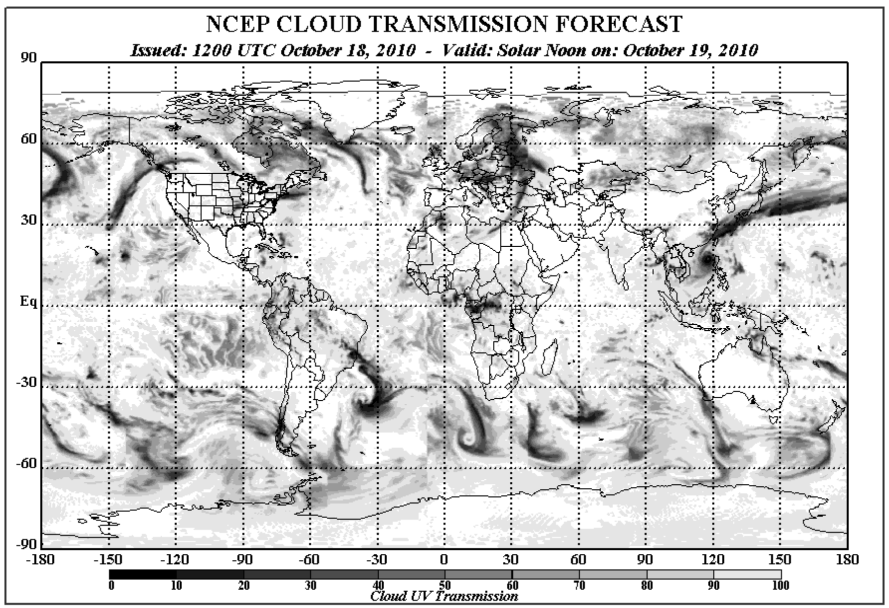
Introduction

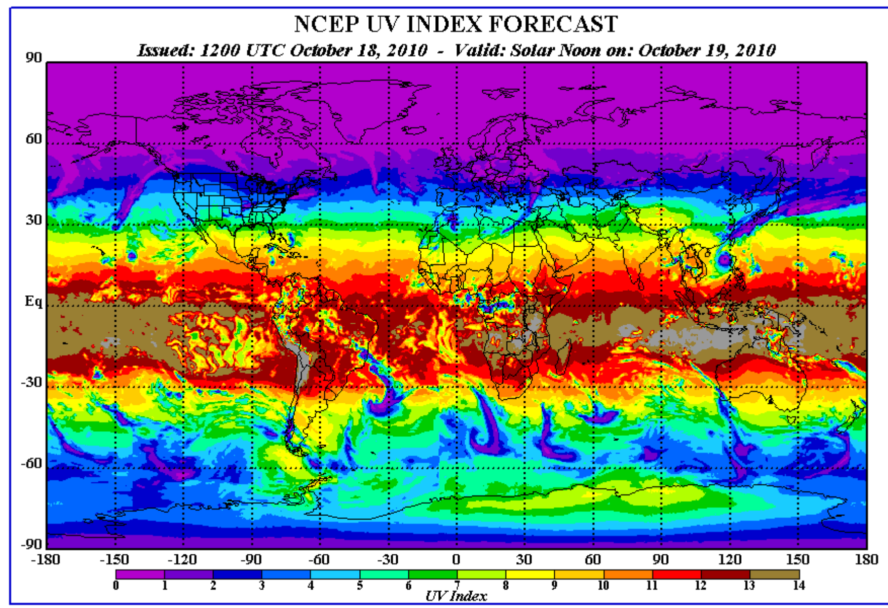
- Past and present research missions demonstrated the wealth of information that can be obtained from observations of atmospheric Nadir and Limb Ozone
- To date, their operational use has been demonstrated for Nadir observations but has been mainly confined to directed scientific studies for Limb
  - Exceptions: Long term monitoring and aerosol trends
- The Ozone Mapping and Profiler Suite (OMPS) improvements are expected to provide operational and research type products that may be exploited for weather and climate operational applications

NADIR Ozone applications example: Global Ozone, forecast clouds and UV index forecast



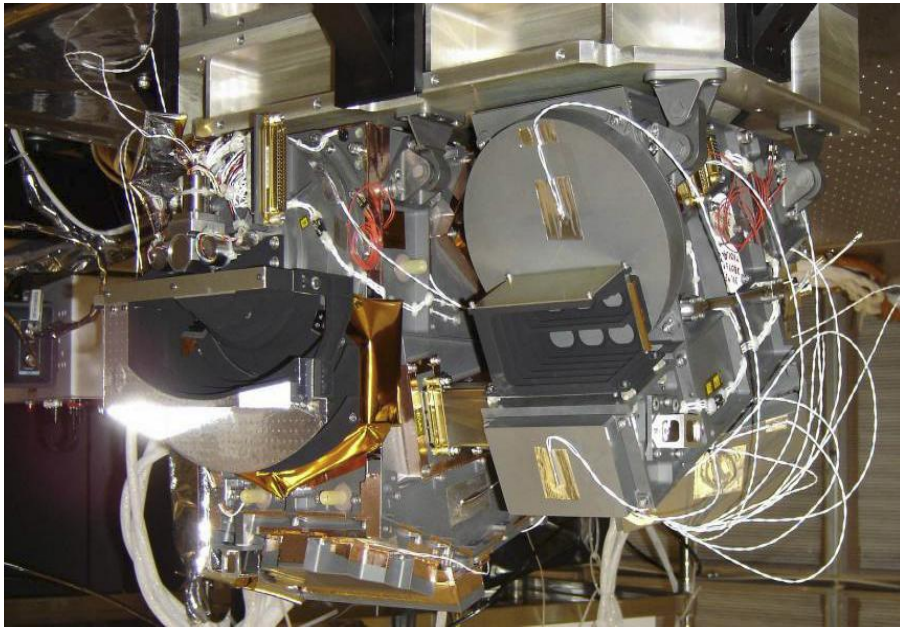


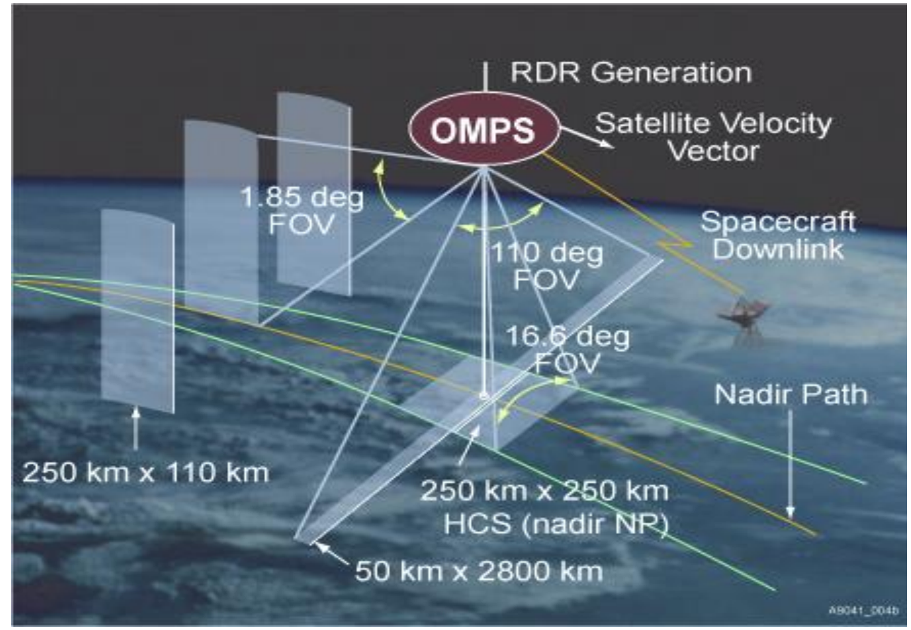




Assimilation of SBUV/2 profile and OMI total ozone data. Note Low ozone and high UV values near Tierra del Fuego

We would like to do better with the Ozone Mapper and Profiler Suite (OMPS)





OMPS Consists of three sensors designed to operate synergistically:

• The Nadir sensors (Nadir profiler, NP, and Total Column ,TC) determine the nadir Ozone profile and the Total Column Ozone

• The Limb profiler (LP) is an experimental limb viewing sensor, measures profiles with a finer vertical resolution.

Figures: courtesy BATC OMPS Team

OMPS Characteristics

Nadir Sensor

- Wavelength range:
  250 nm to 380 nm (TC: 300nm to 380nm – NP: 250nm – 300 + TC)
- Two grating spectrometers w/CCD detectors
- Spectral sampling ~ .41nm, resolution ~ 1 nm
- Spectral channels: TC 196, NP 147
- TC: Push broom 110º FOV telescope 24hs revisit – Day coverage
- NP: Whisk broom 16.6º FOV – Integrated with the TC
- TC: 35 horizontal FOV (50Kmx50Km at nadir).
- NP: 1 horizontal FOV (250Kmx250Km)
- Granule: 37.44sec
- Reflective diffusers for solar calibration

Limb Sensor

- Spectral range :
  290 nm to 1000 nm
- Prism spectrometer w/CCD detector
- Three vertical slits;
  Anti-Ram and ± 250 km cross-track intervals
- Ground revisit time ~ 4 days on average
- Sampling time = 19 seconds
- Afocal telescope with three 1.85º vertical FOVs
- Vertical resolution 2 to 3 km
- Transmissive diffusers for solar calibration
- Vertical coverage : ground to 60 km

OMPS Products and Requirements

Science Data Record (SDR) – Geo-located and calibrated nadir and limb view albedo

Environmental Data Record (EDR) – Total column and profile ozone

Climate Data Record (CDR) – stable long-term time series of EDR products

- Both nadir and limb sensors employ multiple diffusers to correct for long-term drifts
- Total ozone accuracy < **15 DU** precision **< 3 DU +.5% (Total Ozone)**
- Total ozone stability < 1% over 7 years (EDR)
- Profile stability < 2% over 7 years [10 years CDR)]
- Primarily driven by stability of solar diffuser and ability to correct for degradation with periodic reference measurements
  - Diffusers track changes in the instrument throughput over time
- Nadir sensor reflective diffuser will be replaced on F2 with a Quartz Volume Diffuser (QVD) to improve long-term stability

OMPS Nadir Performance Specifications

Spatial Properties`

Cross-track MTF at nadir	>.5 at .01cycles/Km
Cross-track TC macpx. IFOV nadir	<3.44 degrees
Cross-track TC FOV	>110 degrees

Radiometric Accuracy

Pixel-pixel radiometric calibration	<.5%
Non linearity	2% full well
NL knowledge	<.5%
On-orbit wavelength calibration	.01 nm
Stray Light TC OOB + OOF response	<2%
Intra-orbit wavelength stability	.02 nm
Band Pass Shape Knowledge	2%
Bandpass limits TC	50%<1.05 nm 10%<1.9 nm 1%<3.1 nm

Albedo Calibration Accuracy

Wavelength independent	<2%
Wavelength dependent	<.5%
Linear polarization sensitivity	<5%

Radiometric Precision Terms

SNR	1000 for TC 35 for NP
Inter-orbital Thermal Wavelength Shift	.01 nm

Geolocation Error Terms

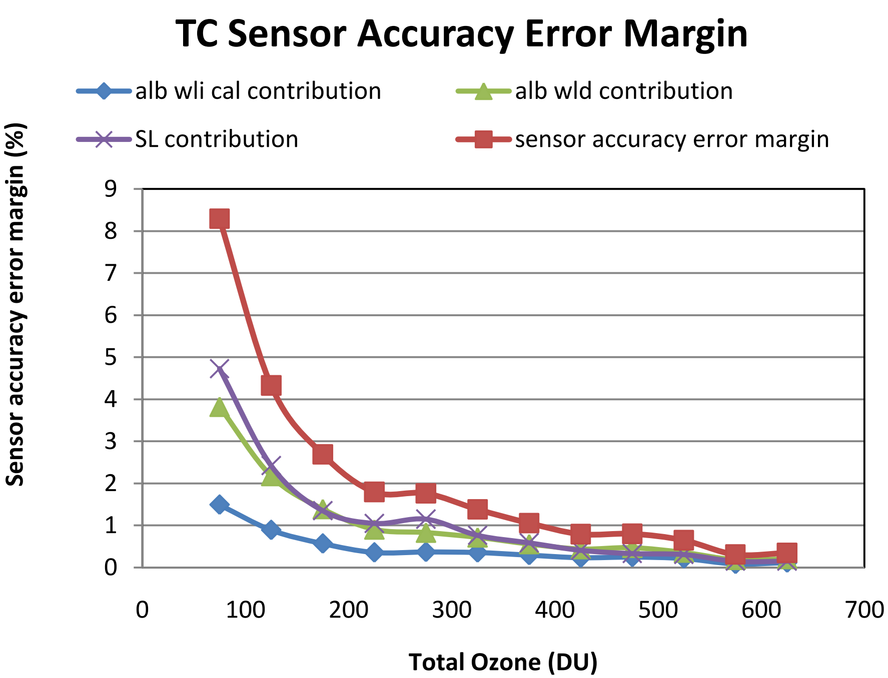
Boresight alignment knowledge uncertainty between nadir instrument interface and nadir alignment reference	<160 arcsec
Total cumulative boresight alignment shift (between final ground calibration and on-orbit operations	<500 arcsec
Database interpolation error	40 arcsec

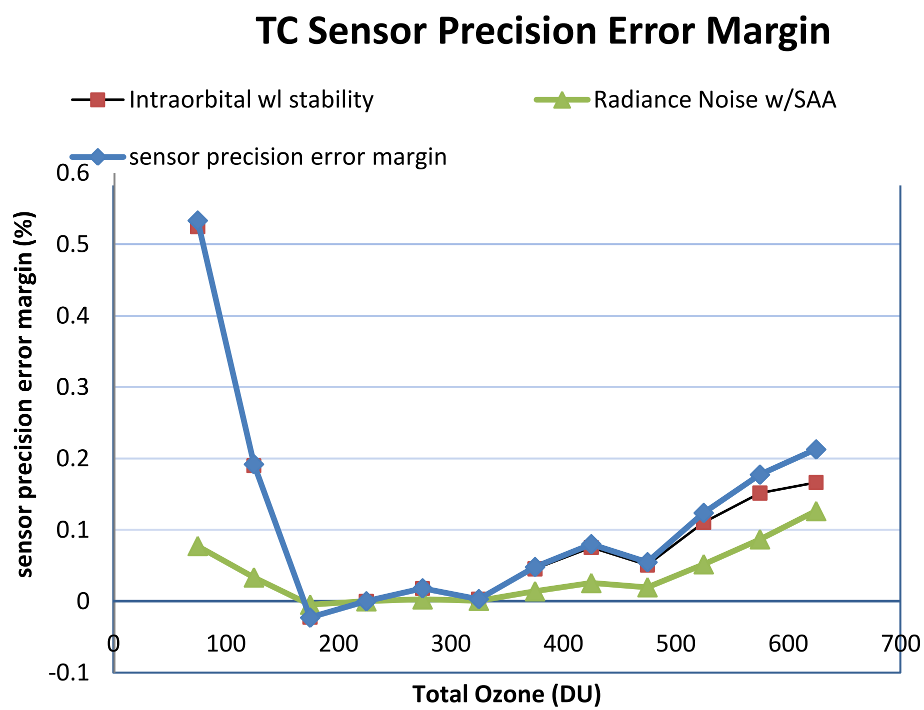
Dominant contribution to EDR accuracy

Dominant contribution to EDR precision

Pre-Launch Calibration

- Extensive ground calibration has been performed to characterize the OMPS sensors and verify the pre-flight performance
- Sensor level performance has positive margin relative to requirements
- Key areas to improve performance associated with sensor calibration:
    - Diffuser goniometric characterization
    - Wavelength scale and bandpass measurements
    - Straylight characterization and modeling





Margin calculated as (Allocated – Predicted) / Total Ozone

Information used to generate these plots courtesy NGAS and BATC OMPS teams

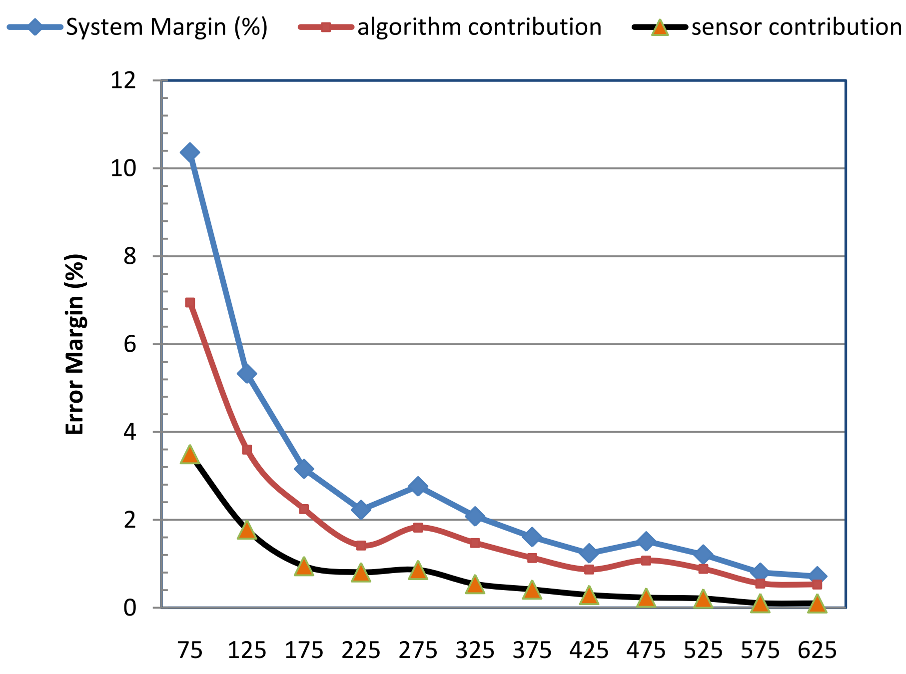
Predicted Error Margin

System level performance has a positive margin relative to the EDR requirements
System precision margin is driven by algorithm contributions

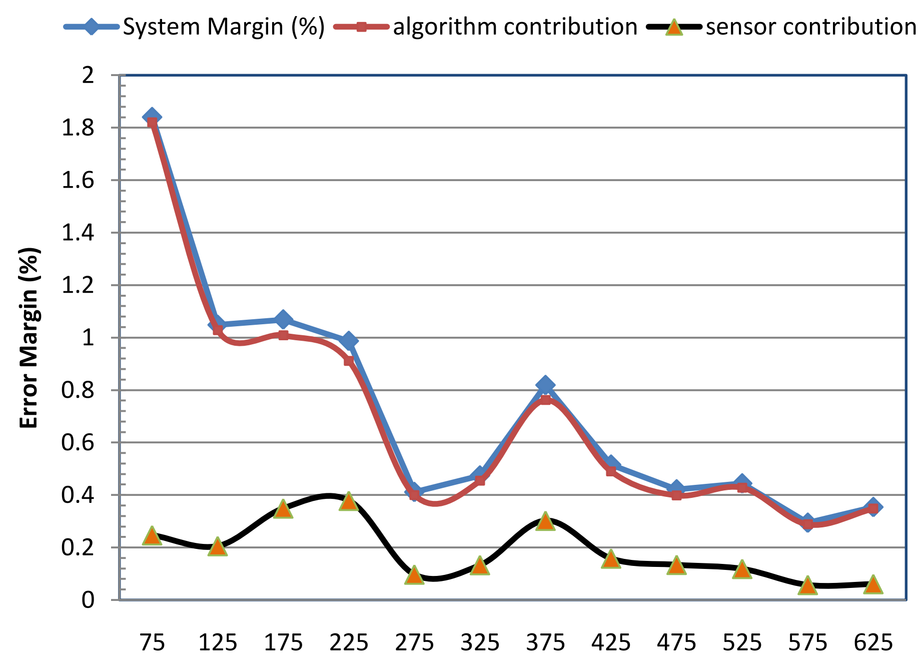
Areas of improvement:

- Ozone retrieval algorithm cloud top pressure information (UV instead of IR)
- The Total column is not expected to be greatly affected by the SAA, but the NP will. Studies with Empirical Ortoghonal Function (EOF) or Nearest Neighbor techniques being considered to remove these errors.

TC System Accuracy Error Margin



TC System Precision Error Margin



Margin = (Requirement*– Predicted)/ Total Ozone

Information used to generate these plots : courtesy NGAS and BATC OMPS teams

Issues and Improvements

Cloud Top Pressure (CTP)

- OMPS CTP obtained from IR measurements by VIIRS. Used for estimating the ozone profile. But UV penetrates deeper into clouds than does IR.
  - Accuracy and precision errors using CTP from VIIRS IR are therefore underestimated.
  - Current analysis indicates that the resulting bias may not drive the system outside its accuracy specifications.
  - The decrease in precision may be worse. Regions with TC = 300DU or 600DU TC may not satisfy requirements
  - Effects as well as mitigation approaches are being investigated:
    - OMI based climatology of UV cloud top pressures can be used to correct accuracy errors
    - Spectral resolution of OMPS may allow UV cloud-top altitudes to be estimated from the filling-in of Fraunhofer lines by rotational Raman scattering (Ref: Vasilkov, A., J. Joiner, R. Spurr, P. K. Bhartia, P. Levelt, and G. Stephens (2008), *J. Geophys. Res.*, 113)

Diffuser interference features

- Spatial non uniformities driven by diffuser surface roughness and optical path of the instrument
- Features on the order of CCD pixel size, affect pre and post launch sensor calibration
- OMPS current mitigation uses a detailed pre launch characterization and analysis – High spatial sampling rate - Non-heritage ground calibration method. (Flight 2 sensor will probably use a QVD)

Stray Light (SL)

- Stray Light corrections may be needed. SL from longer wavelengths affect ozone retrievals that use shorter wavelengths. Without correction there would be little margin at shorter wavelengths.
- Characterization of PSFs permits implementation of corrections in the SDR algorithm. Post-launch SL correction tables are in development.

Ionizing Radiation

- Spurious signals from the CCDs when traversing the South Atlantic Anomaly.
- Exacerbated by on-board binning of data from the two Nadir instruments.
- Might be mitigated for the Ozone Total Column with CrIS Ozone measurements of emissions at 9.6 microns

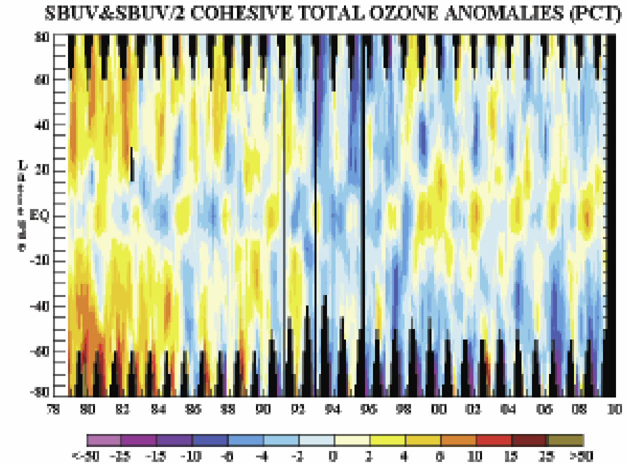
Heritage Sensors
Sensor Evolution and Products

- NADIR

- OMPS Nadir continues 30 year record of ozone monitoring
- Heritage TOMS V7 Total Column EDRs
- Heritage SBUV V6 Nadir Profile Data records
- Improvements will include:
    - ▪IR Total Column data records from Cross-track Infrared Sounder
    - ▪Future TC algorithm will include all measured channels (305nm-380nm)

▪Current OMI algorithms for SO2, aerosols and Cloud Top Pressure may be used to improve algorithms, Opscon.

30-Year SBUV(/2) Atmospheric Ozone
Inter-calibrated 30-year (1979-2008) SBUV(/2) CDR



Monthly average anomaly values (percent) of zonal mean total ozone as a function of latitude (80^0 N to 80^0 S) and time (January 1979 to December 2009). The anomalies are derived relative to each month’s 1979 to 2008 average. Long-term ozone variations may be readily seen. The largest anomalies are found for the polar regions in each hemisphere in winter-spring months, with positive anomalies of more than 10% in the earlier years changing to negative anomalies of greater than -10% for the 1990s and beyond.

Nadir potential improvements over heritage sensors

		OMPS TC		TOMS		OMI
Bands Range		300nm to 380 nm 205 illuminated spectral pixels		308.6, 312.5, 317.5, 322.3 331.2, 360.1 nm		307nm to 383nm 550 spectral pixels
Band pass		1nm		1.1nm		.42 nm
Channel selection		22 channels		4 channels for V8 algorithm		12 channels: 4 Channels to retrieve/adjust total ozone for V8 algorithm ~ 40 spectral pixels with DOAS retrieval
Detectors		CCD		PMT		CCD
IFOV		110 degrees		Scanning = 106 degree scanned FOV		110 degrees
Diffuser		Aluminum – Expect QVD for F2		Aluminum		QVD and Aluminum
Algorithm improvements		•Multiple Triplets •Corrections for T and O3 profile shape, Volcanic SO2 •Corrections for Wavelength scale shift • Colocated VIIRs and CrIS for information on T, reflectivity				•Improved ozone profile, temperature and climatologies. •Improved ozone profile correction •Use of surface UV reflectivity database. •Use of co-located UV Cloud pressure determination using OMI data

Limb sensor Evolution

Instrument	Platform	Launch	Spectral range	Spectral resolution	TH range	Vertical sampling	Vertical resolution
OSIRIS	Odin	Feb 2001	280 – 800 nm	1 nm	7 – 70 km	2.5-3km	≈ 2 km
SAGE III	Meteor-3M	Dec 2001	290 – 1020 nm	1.4 – 2.5 nm	-60 – 165 km	1 km	≈ 1 km
SCIAMACHY	Envisat	Mar 2002	220 – 2380 nm	0.2 – 1.5 nm	0 – 100 km	3.3 km	≈ 2.6-3 km
OMPS	NPP	Fall 2011	290 – 1000 nm	1.5 – 40 nm	10-60 Km	1 km	≈ 2 -3Km

Limb Instruments:

Occultation

SAGE, HALOE, POAM, ACE (FTS, MAESTRO), GOMOS (Stars), GPSRO

Microwave Limb Sounders

MLS, SMILES

Infrared Limb Sounders

LIMS, HIRDLS, MIPAS

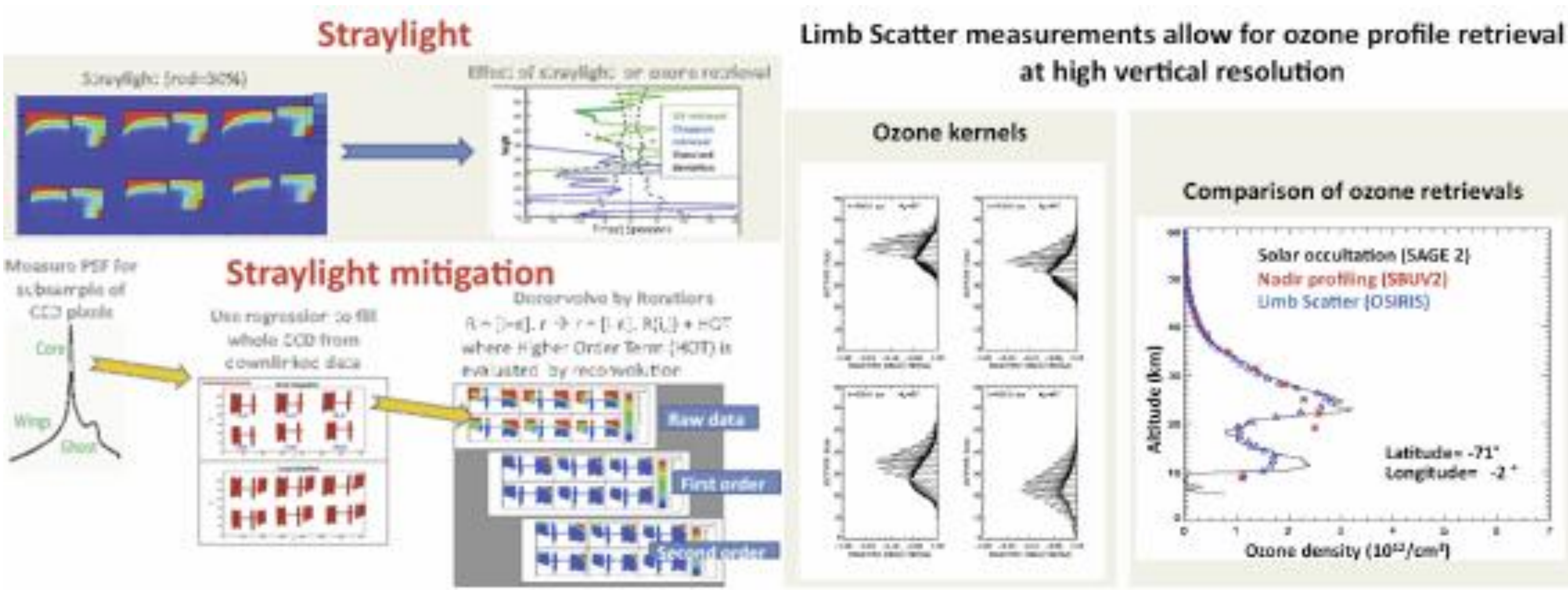
Ultraviolet/Visible Limb Scatter

OSIRIS, SCIAMACHY, SOLSE/LORE, SAGE III

Limb and Climate

The Limb sensor is important for climate change science due to its ability to monitor changes in the lower stratosphere with sufficient vertical resolution to detect possible interactions between climate change and ozone layer recovery, monitoring the ozone hole, effects of volcanoes, smoke, stratospheric clouds on ozone and changes in ozone near the tropopause.

Key product performance is removing stray light artifacts that result from the large dynamic range of the signal present in the limb scene



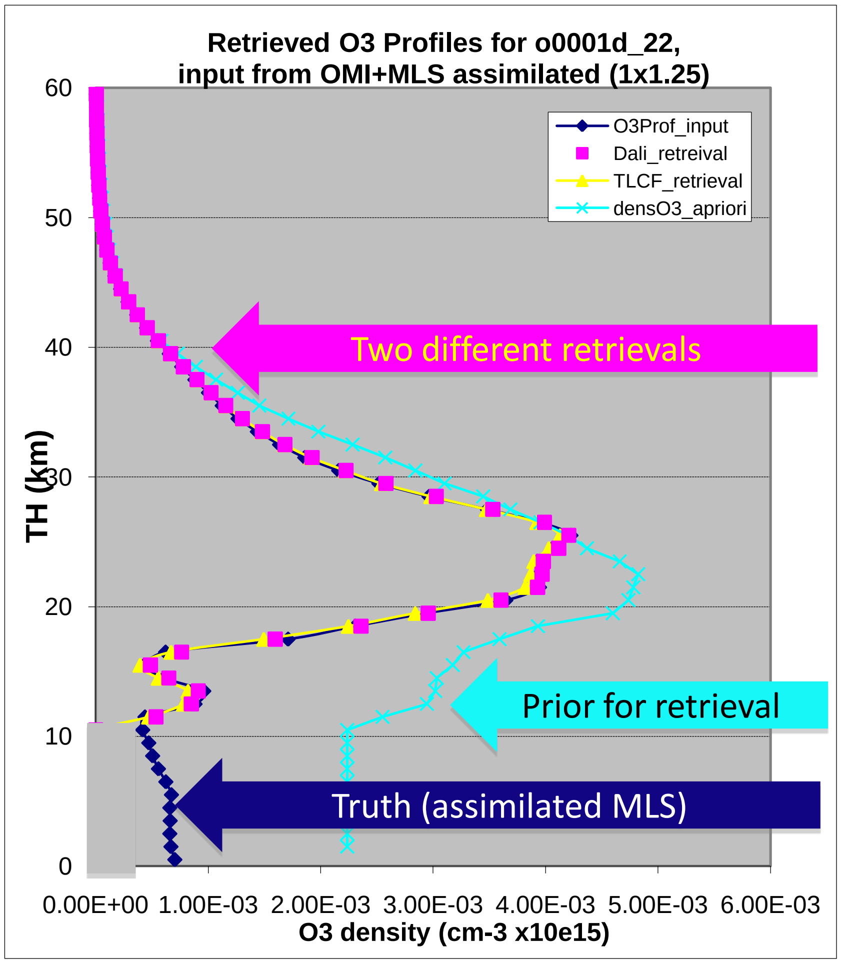
Laboratory measured point spread functions (PSF) are used to reconstruct the instrument function for each pixel and then model the system stray light response and develop correction factors.

Potential areas for limb operational use

- Ozone profiling to study ozone recovery over range of time/spatial scales (SAGEIII, MLS, OMPS Limb)
- Ozone assimilation (MLS, OMPS Limb)
- Tropospheric Residuals (for O3 and NO2)
- Aerosol (upper troposphere and stratosphere, vertical profiles and size)
- Stratospheric intrusions (smoke, volcanic ash)
- Tropospheric, Stratospheric and Mesospheric Cloud height and thickness

Limb Ozone Retrieval Assimilation

Comparison of OMPS retrievals with MLS assimilation, adding noise to radiances



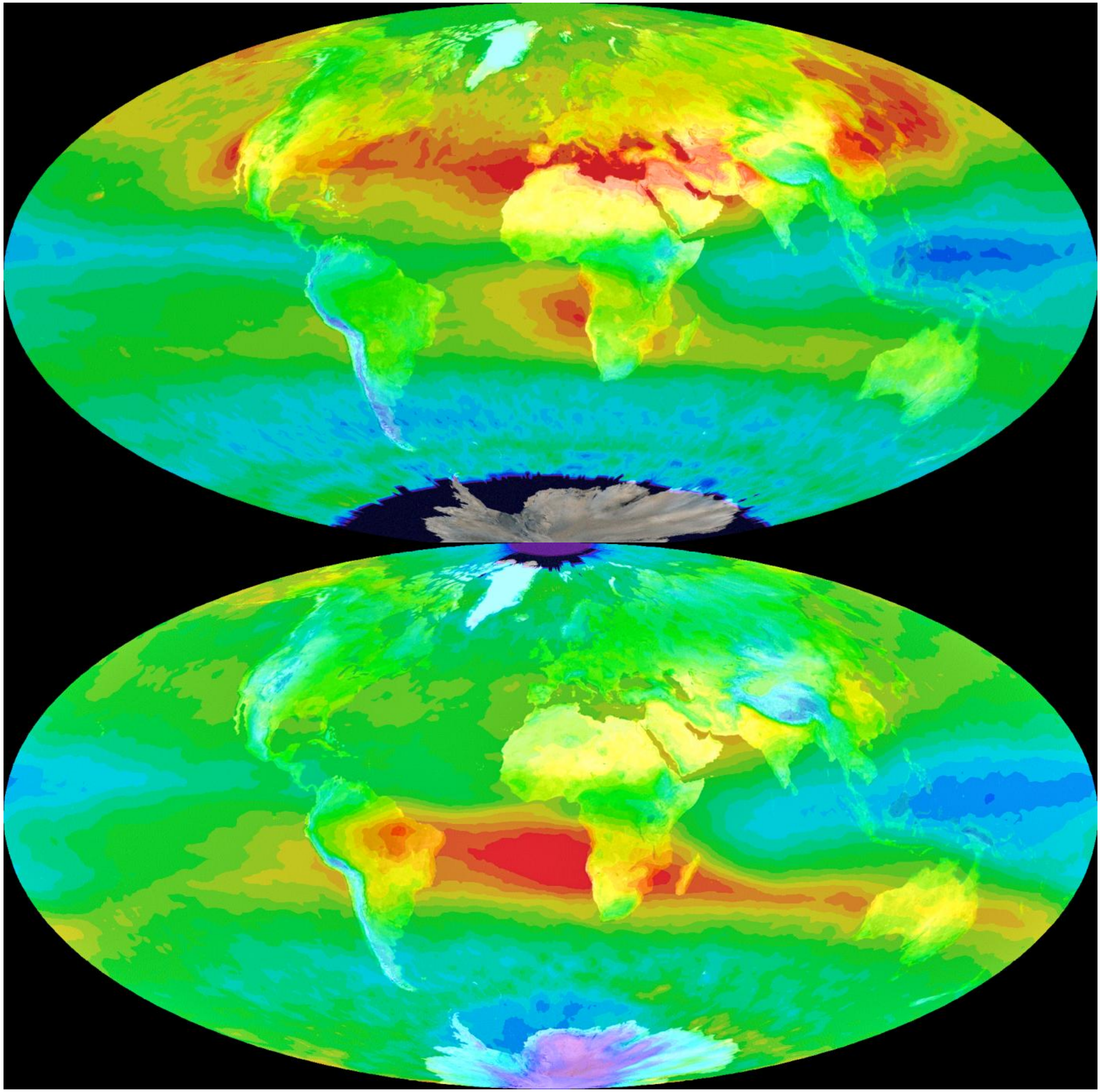
- Quality and high resolution limb O_3 Profiles provide information for
  - UV Index forecasts
  - Ozone Hole monitoring
  - Boundary conditions for Air Quality forecasts.
  - Potential Ocean Color estimation
- They can also be used to obtain improved RTMs, assimilated into NWP:
  - Can reduce Temperature errors, mainly above 30Km

Developments using MLS data are taking place under the JCSDA at NASA and NOAA.

Trop O_3 column from OMI-MLS

Jun-Aug 2008

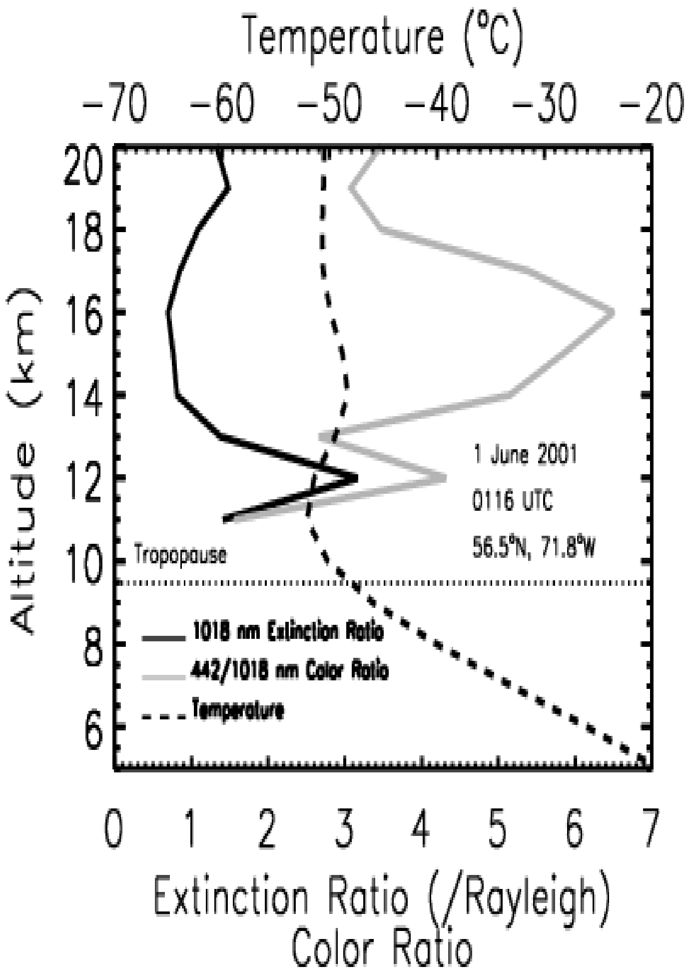
Sep-Nov 2007

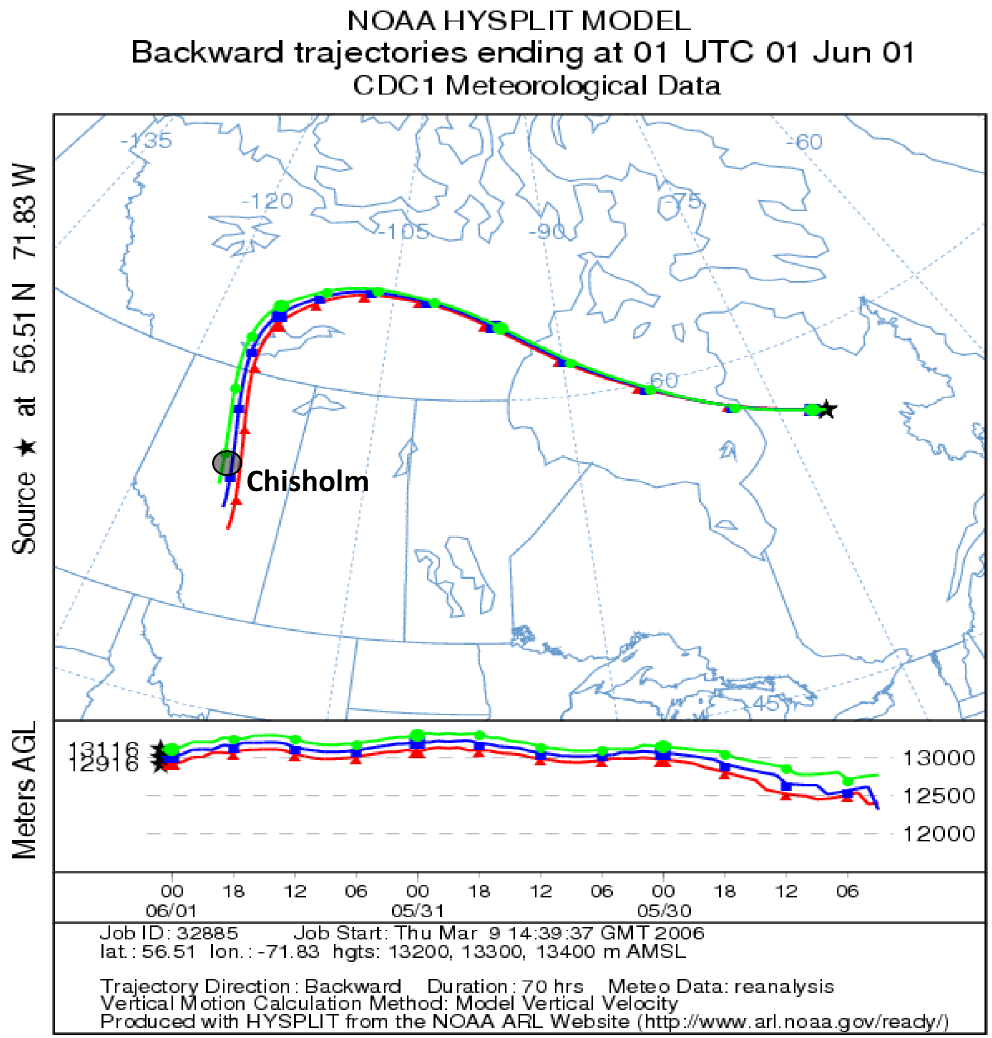


A well-defined stratosphere, together with a column estimate, can be used to generate estimates of the tropospheric residuals. This can be done with constituents other than ozone, e.g., NO_2. (Most tropospheric NO_2 products make an assumption about stratospheric consistency.) Such products provide information for Air Quality applications.

Images courtesy of Mark Schoeberl

Forest Fire Smoke in the Stratosphere – via extinction ratio profiles and back-trajectories: What would OMPS Limb see?





Fromm et al., (2008) JGR, doi:10.1029/2007JD009147

Stratospheric Aerosols

- Air Quality Forecast models are now assimilating large amounts of satellite data.
- The roles and changes in aerosols are a source of major uncertainty in climate change studies
- Key information areas for limb contributions
  - Sources and sinks
  - Vertical distribution
  - Properties

Summary

- OMPS F1 instrument ready to go
- Based on heritage (mainly TOMS, SBUV for NADIR, Sciamachy, Sage lll for LIMB), but including several improvements and a synergistic suite (Nadir/Limb) that may allow exploitation of new operational uses.
- Several improvements over current Nadir operational uses and potential operational uses in the horizon for Limb :
  - Temperature and ozone in the stratosphere
  - Improvement in:
    - UV index forecast
    - Ozone Hole monitoring
    - Boundary conditions for Air Quality forecasts
    - Tropospheric ozone column
    - Tropospheric-stratospheric exchange
    - Ocean Color estimation
    - …

Back up

Sensors coverage and summary of improvements over heritage

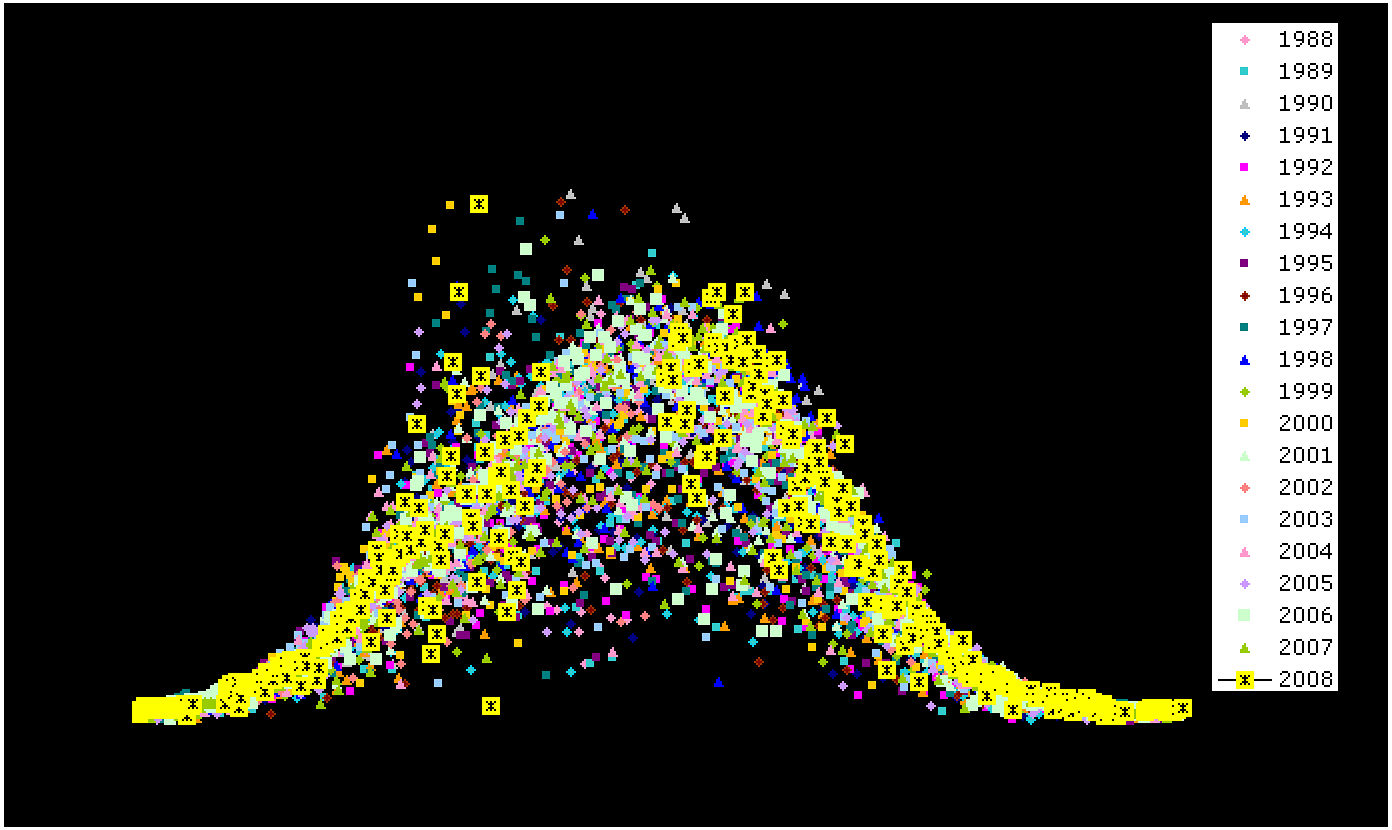
- **Nadir Mapper**: 2800 Km cross-track swath width with the planned JPSS orbital altitudes. Push broom 24hs revisit. 14 orbits/day – Only day coverage, but can use IR (CrIS) to complement for night coverage
  - Based on TOMS system, but also draws from close heritage cousin GOME and OMI.
  - Main improvement comes from co-located external data
  - Additional enhancements are made possible by the CCD detectors that offer continuous coverage from 300nm to 380nm
  - SDR developed to make use of OMPS sensor characteristics and operational design. E.g.: sample tables to correct for bad pixels, pixel to pixel in homogeneities and nonlinearities.
  - The improved design and eventual algorithm enhancements allow for OMPS EDR performance to match or slightly exceed TOMS performance

- **Nadir Profiler**: 250Km cross-track swath width with the planned JPSS orbital altitudes – Whisk broom. With atmospheric motion can get a good sample of the full global ozone profile pattern over 7 days. Coverage is much better at higher latitudes as the orbits converge (also true for the Limb Profiler) but there is never coverage of small areas around each pole
  - Designed to provide continuity for the heritage measurements from BUV, SBUV and SBUV/2.
  - Provides improvements over heritage due to its capability of continuous range of wavelengths in the 250nm to 300nm range
  - The instrument is integrated with the TC to provide expanded wavelength coverage (300nm to 380nm range)
  - Can provide slightly better SNR than heritage
  - Performance expected to match heritage, but algorithm enhancements that make use o the instrument improvements an led to a future better performance

- **Limb Profiler**: three limb curtains positioned at Nadir and 250Km on each side. Approximately a 4-day revisit time. With imperfect or longer repeat cycles there is overlap in the viewing ,but coverage takes longer. With perfect 4-day repeat cycle, at lest ¼ of the Equator would never be viewed.
  - Measurements provide a good representation of ozone profiles in the central 750Km of the orbital track
  - Currently flown as an experimental sensor, but could eventually become operational

UV index values at Ushuaia, Argentina

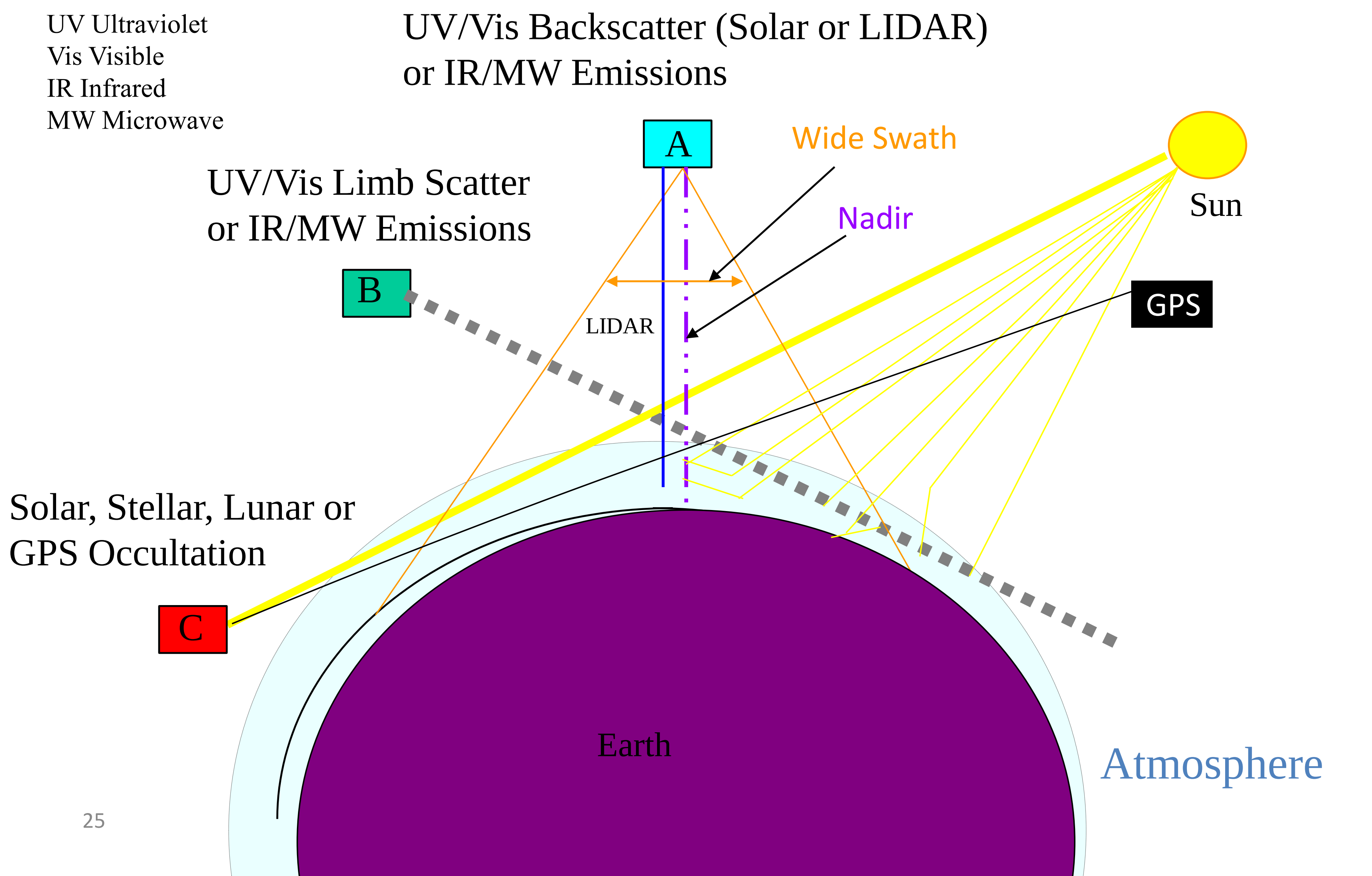
Note occasional high UV Index values occurring between October and December



7 8 9 10 11 12 1 2 3 4 5 6

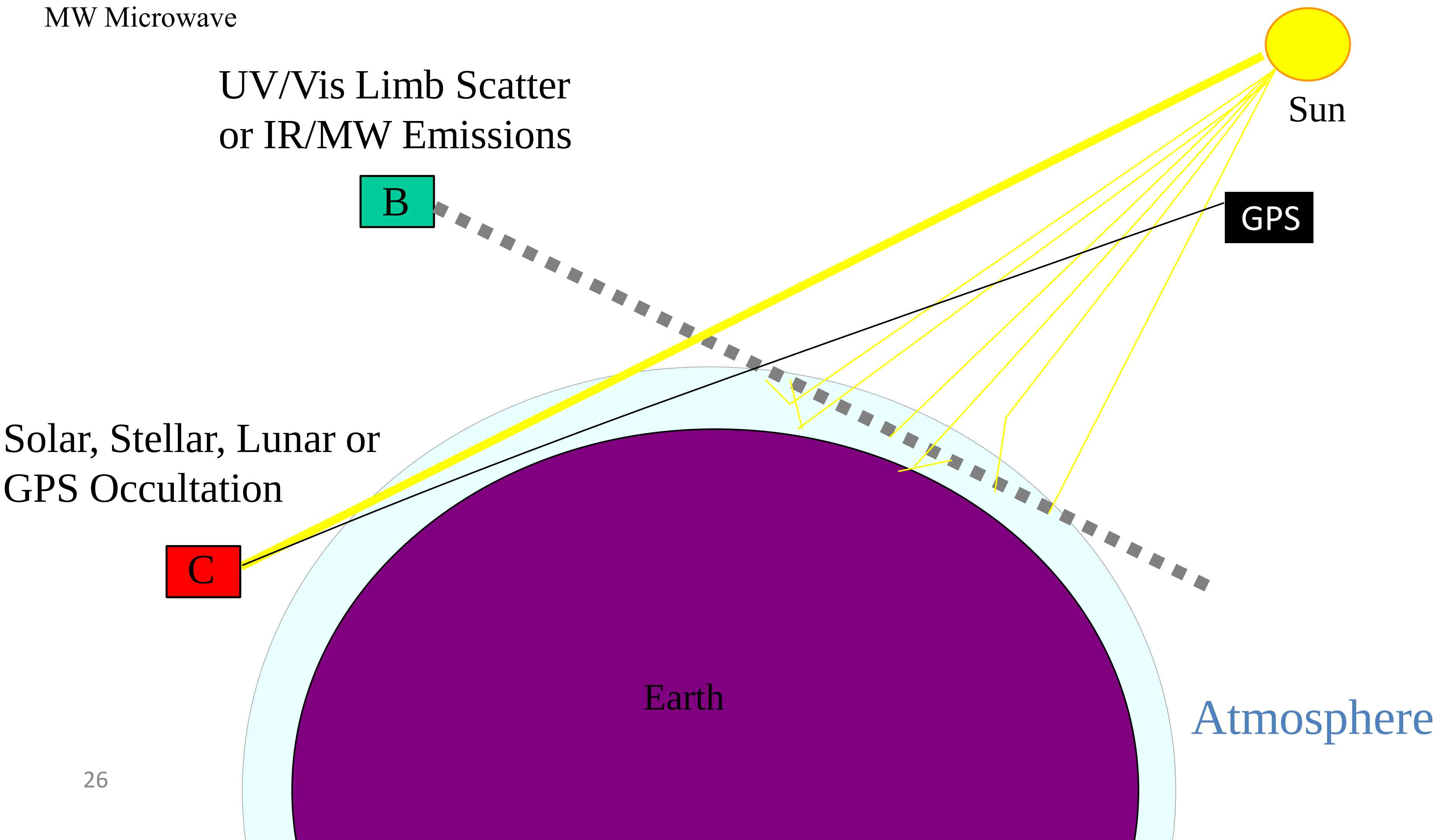
Lines of Sight and Fields of View for Space–Based Remote Sensing for Atmospheric Chemistry Measurements

UV Ultraviolet
Vis Visible
IR Infrared
MW Microwave



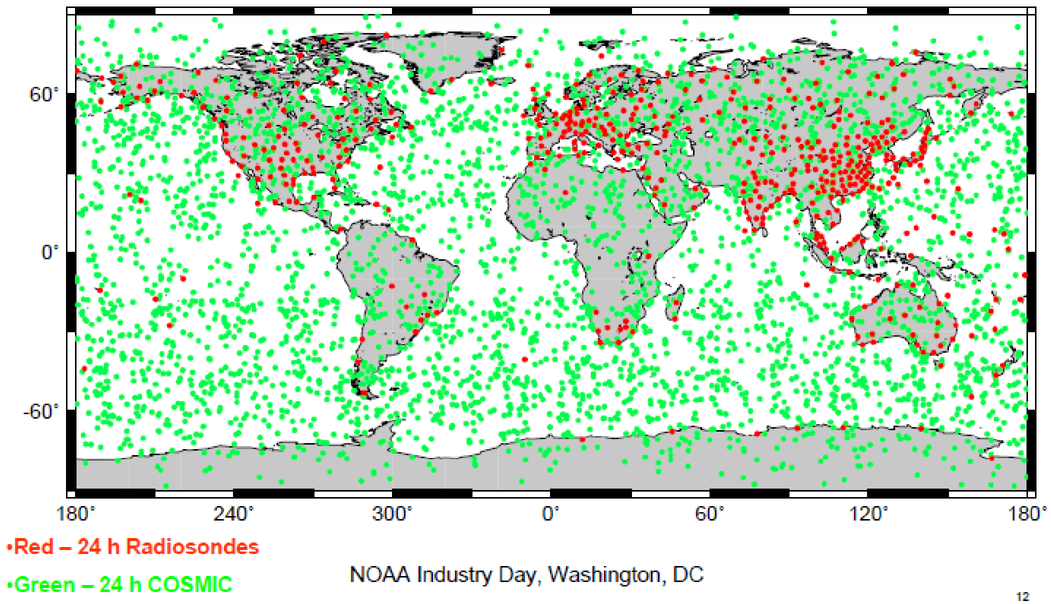
Lines of Sight and Fields of View for Space–Based Remote Sensing for Atmospheric Chemistry Measurements

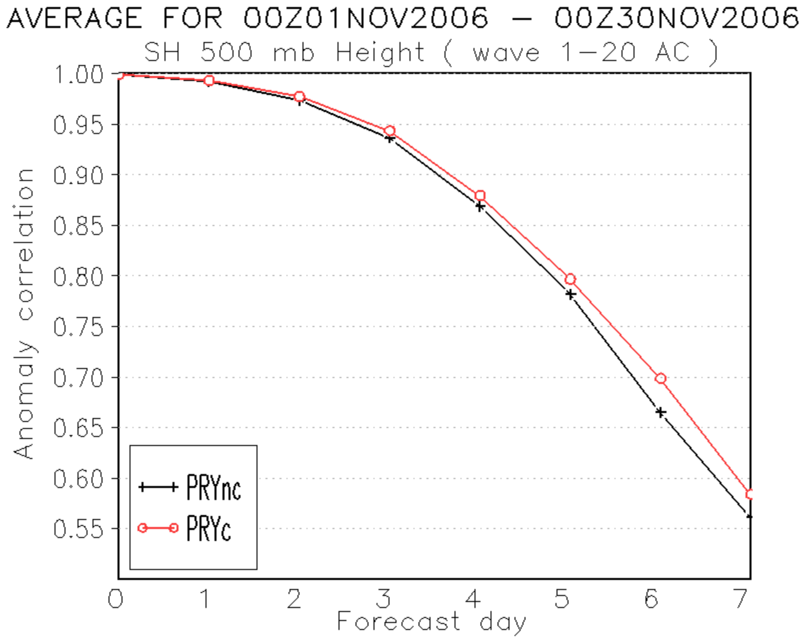
UV Ultraviolet
Vis Visible
IR Infrared
MW Microwave



GPS Radio Occultation

Assimilation of highly accurate temperature profiles from a constellation of satellites are improving forecasts (from a presentation by J. Yoe)

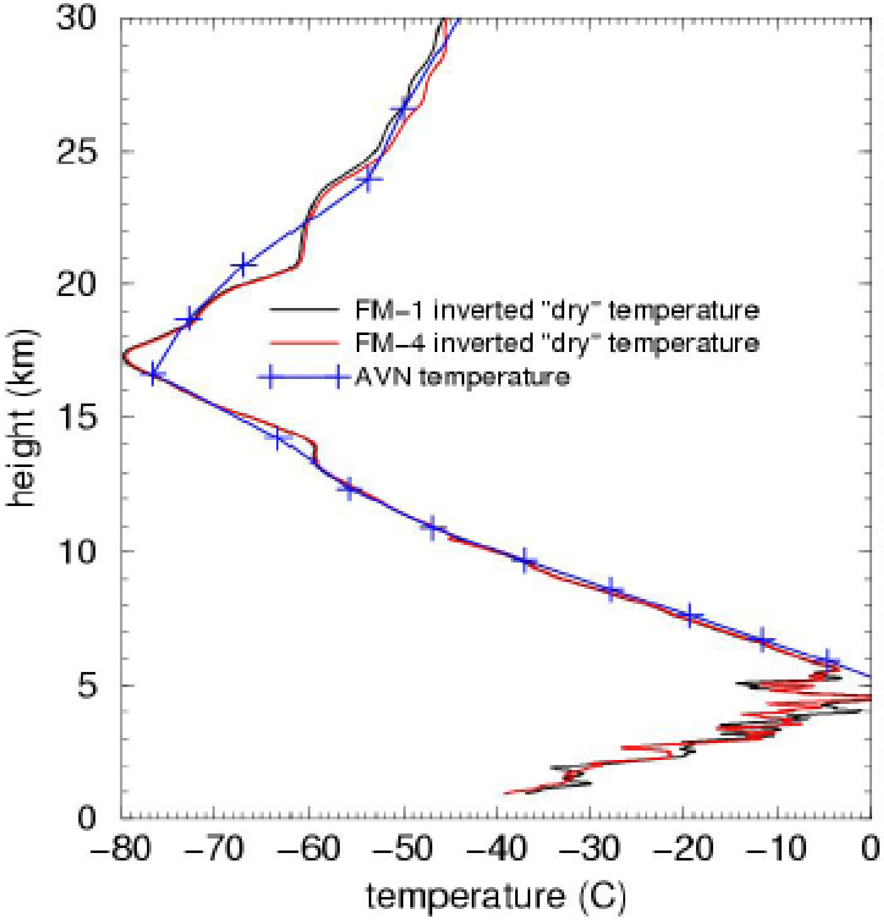




Daily global measurement coverage

Forecast Improvement

GPSRO Contribution to Sounding



- Two nearly coincident COSMIC soundings yield
  - Nearly identical profiles of refractivity to w/in 1 km of surface (precise/stable)
  - Accurate "dry" temperature
    - (Assume zero moisture)
  - Vertical resolution superior to other satellite soundings
  - Vertical coverage to 30 km

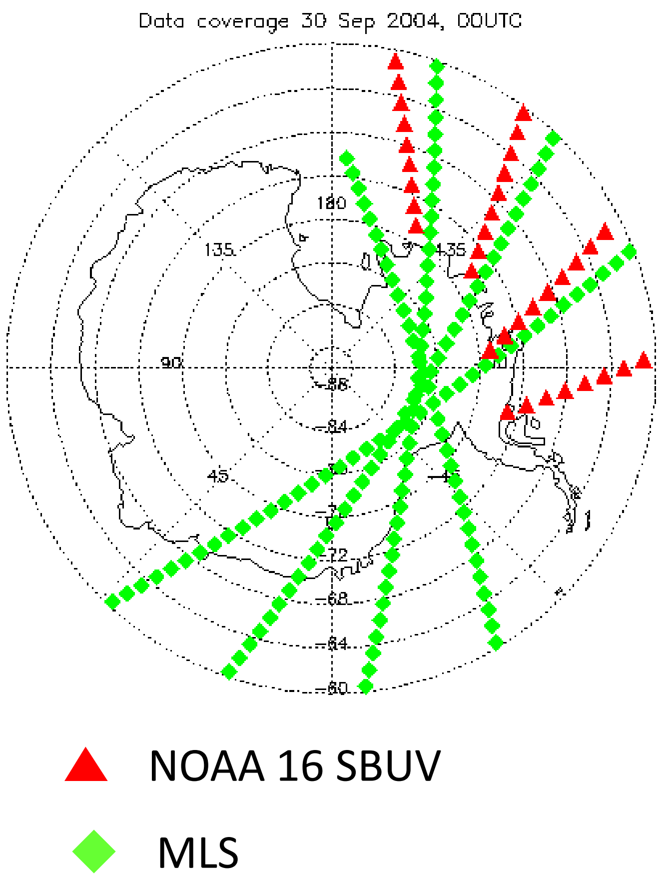
RO useful to calibrate more numerous radiometric soundings – enhance climate data records

Assimilating AURA/MLS ozone

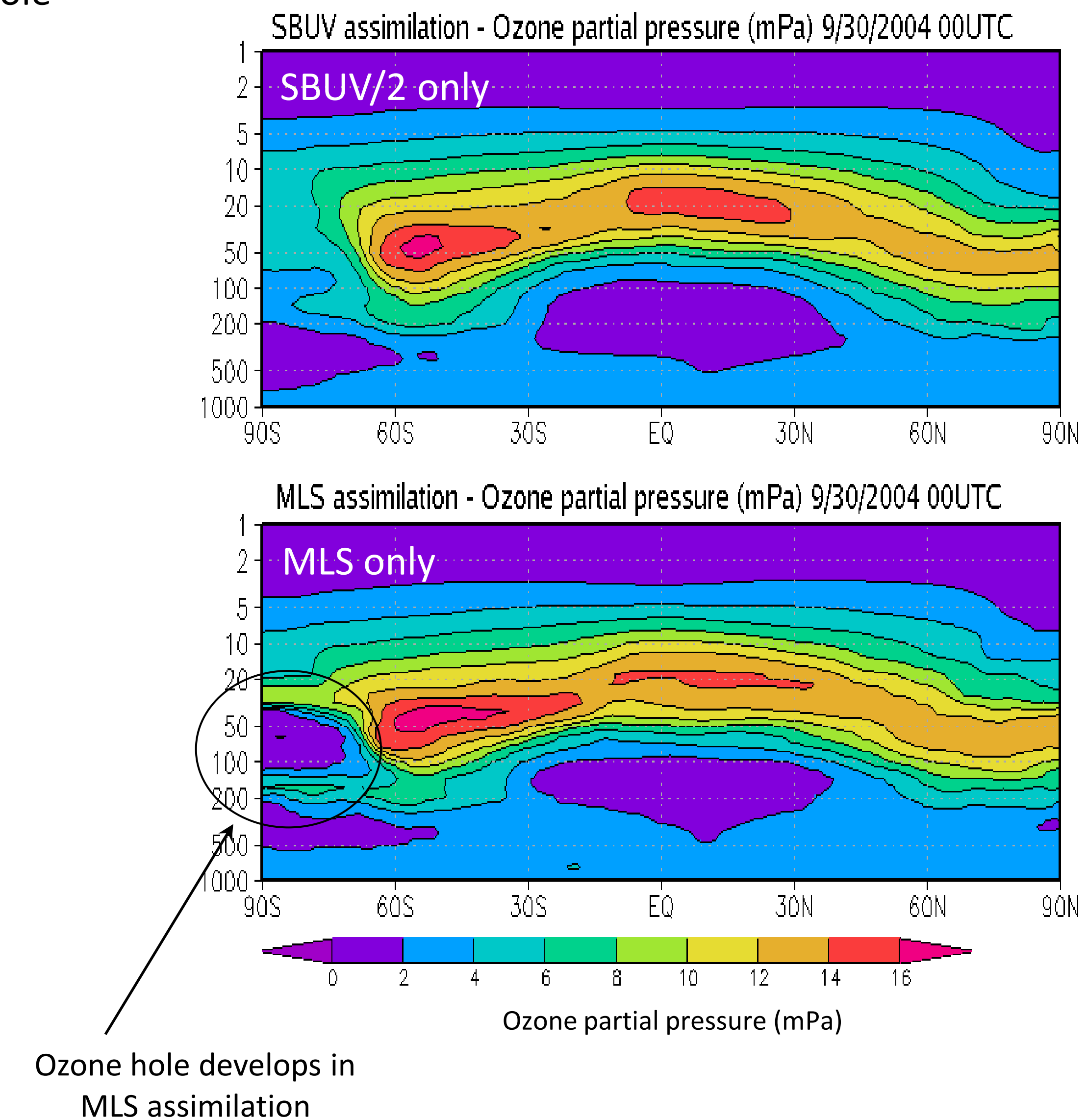
Meta Sienkiewicz (GMAO, with Ivanka Stajner)

SBUV daytime only – no data near South Pole due to high solar zenith angle

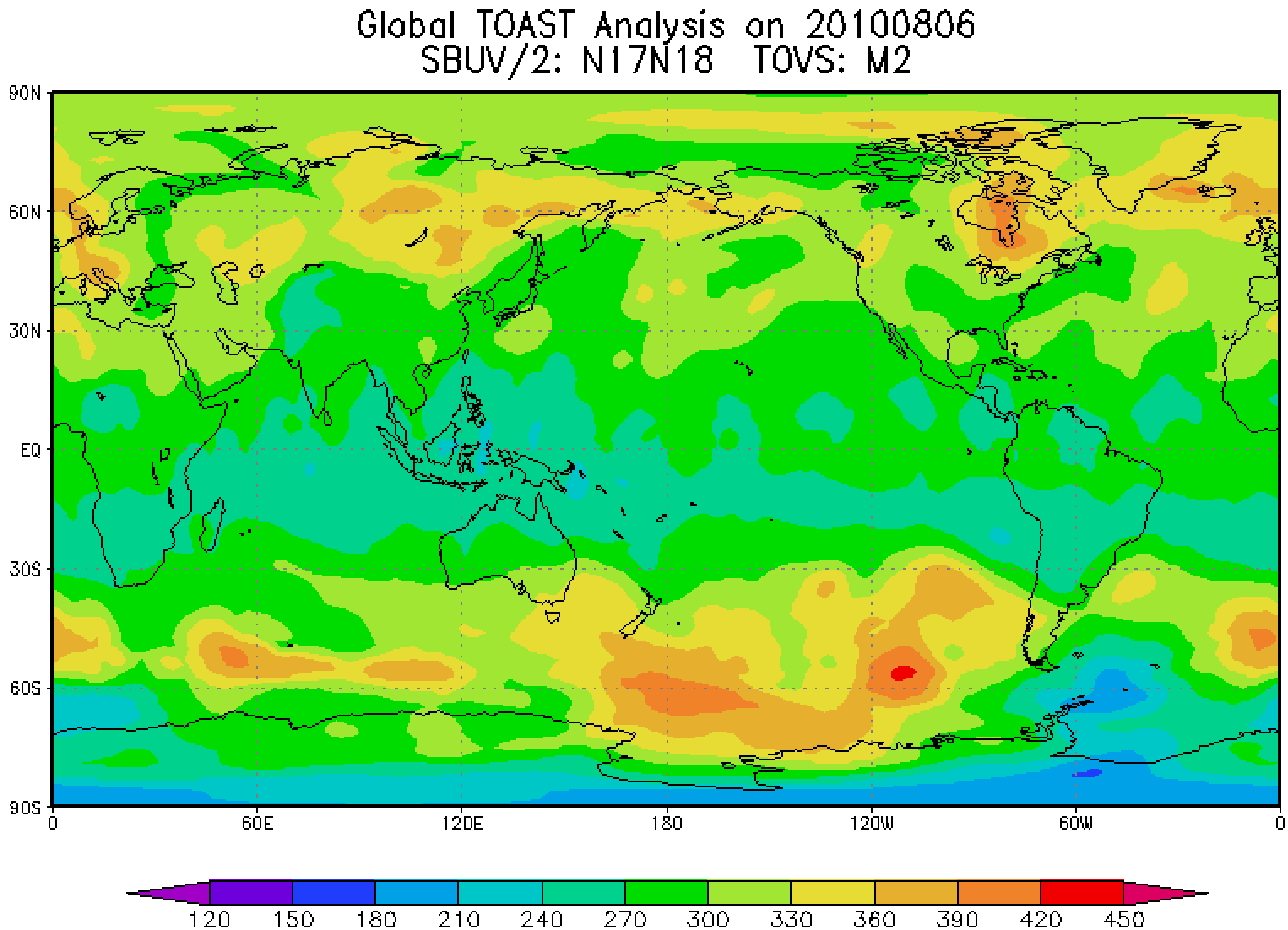
MLS orbital limit ±82º



Zonal mean ozone 9/30/2004 00UTC

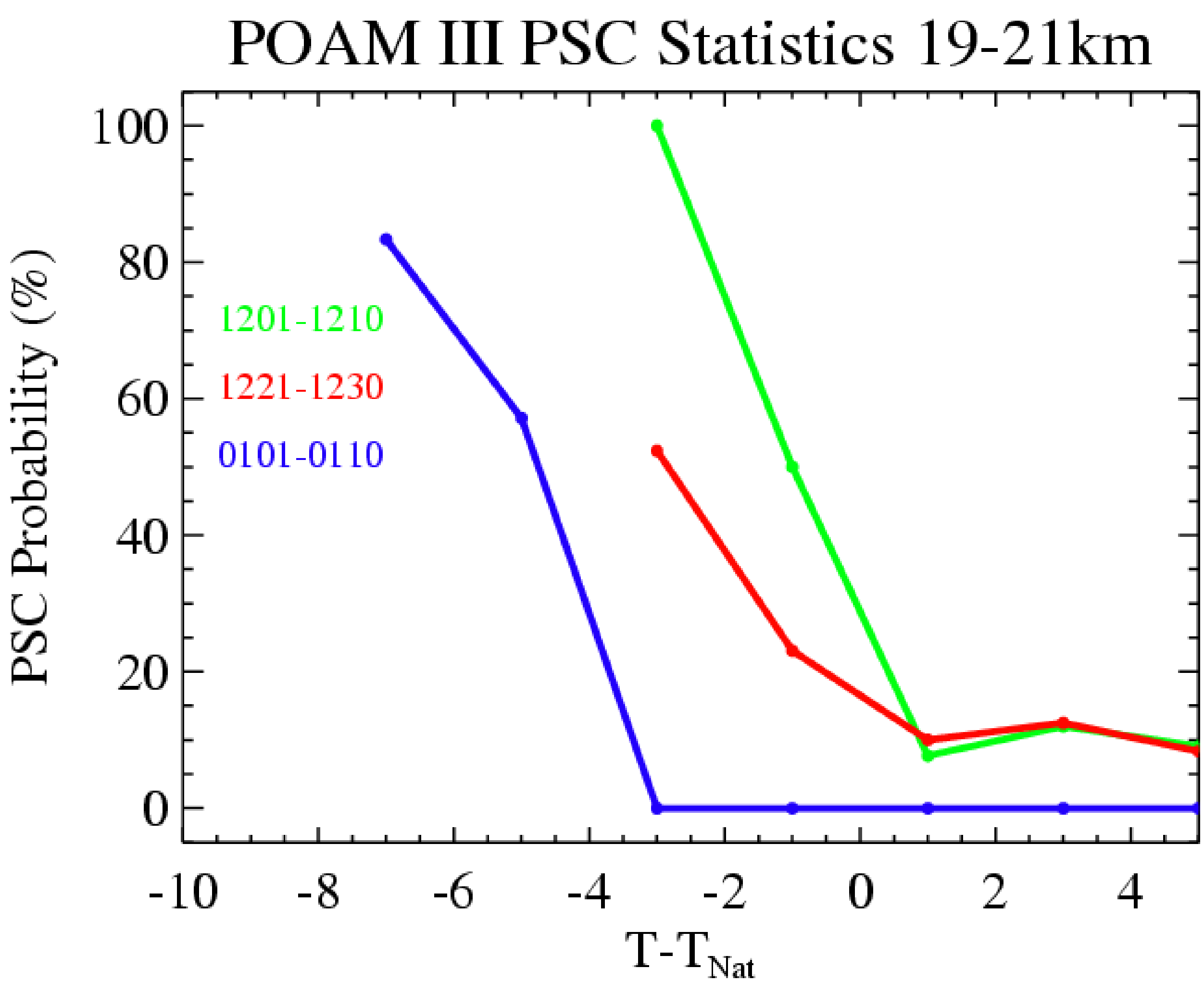


Better LS/UT information can be combined with other retrievals in blended products



Seasonal variation of PSC occurrence in altitude bins

2002/3 NH Winter (SOLVE II)



Polar Stratospheric Clouds (PSCs) are a key element in polar ozone destruction. Their distribution is a limiting factor on Ozone Hole formation and size. There are also questions on changes in their frequency with climate change effects.

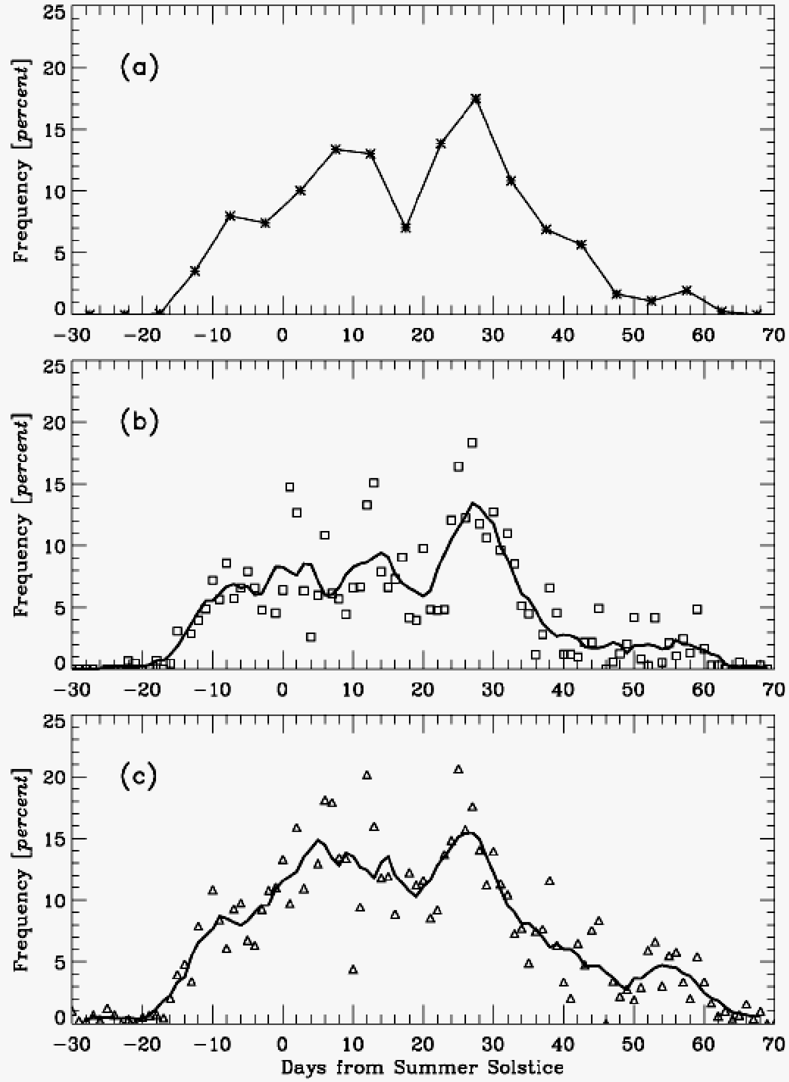


FIGURE 4. PMC frequency values in percent, summed over latitudes between 50°S-82.5°S for the Southern Hemisphere 1985-1986 season. The time coordinate is days from the summer solstice (1985 day 172). (*a*) SME data with LSR > 15, averaged in 5-day bins. (*b*) Nimbus-7 SBUV data. Squares are daily values, and the solid line is a 7-day running average. (*c*) NOAA-9 SBUV/2 data. Triangles are daily values, and the solid line is a 7-day running average.

Polar Mesospheric Clouds (PMCs) can be observed with limb and occultation techniques. Their presence may be increasing in association with climate change. They are active in the Infrared and also contaminate back-scattered Ultraviolet radiances used to determine upper stratospheric ozone.

: DeLand, et al., 2003, JGR, 10.1029/2002JD002398

OMPS instrument status

- OMPS F1 has been shipped and integrated in the NPP spacecraft.
- IMT sequence provided to Mission Operations, CRs submitted and reviewed. Final baseline in progress.
- NPP S/C maneuvers in support of cal & charact. proposed, reviewed, submitted to BATC for evaluation of S/C impacts. Additional observatory-level integration analysis in progress.
- Tool development for pre-launch tasks nearly completed, in progress to execute post-launch tasks.
- OMPS F2 post vibe functional tests have been completed. Changes in boresight due to thermal settling are within expectations.
- F2 measurements of multiple diffuser types (spectralon, opaque quartz, ground aluminum) to decide on best diffuser to reduce spatial features and improve performance is completed. Analysis of results is in progress