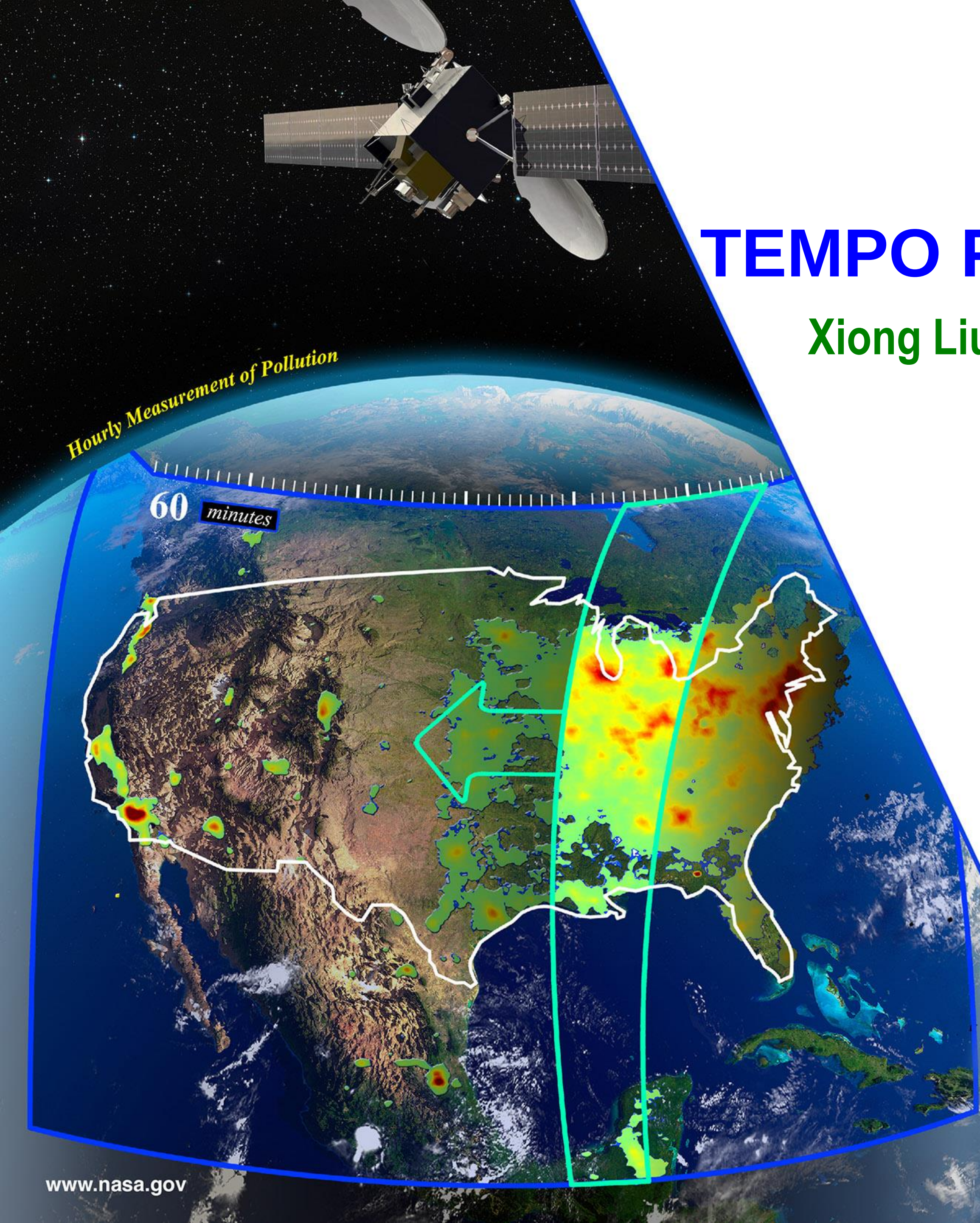

Tropospheric Emissions:
Monitoring of Pollution

TEMPO Products Overview

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Western U.S. TEMPO Early Adopters Workshop

Fort Collins, CO
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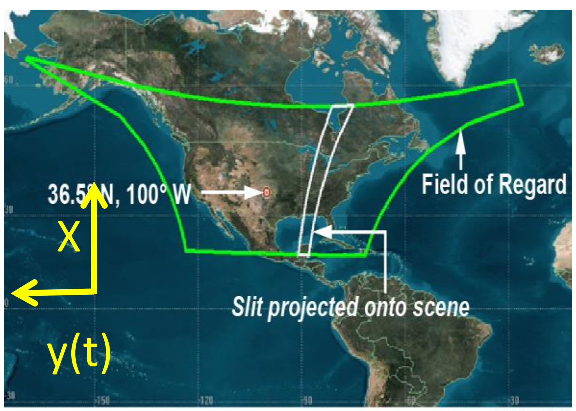
Smithsonian

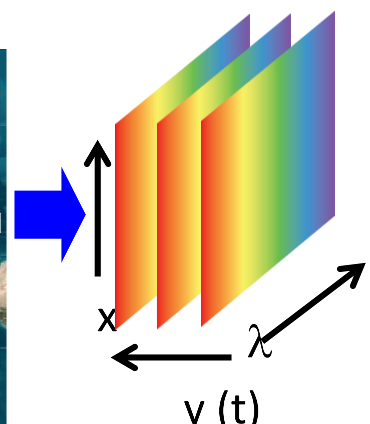
Outline

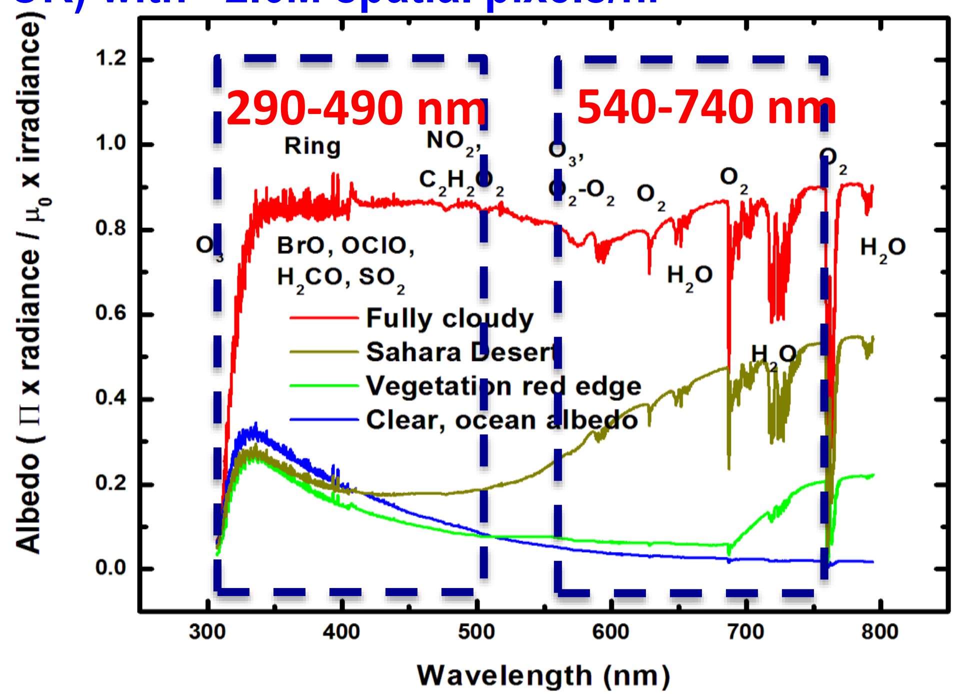
- Introduction
- Baseline products and research products
- Retrieval sensitivity studies, instrument performance and predicted retrieval performance
- Data products definitions (L0-L4) and details (e.g., format, data release, latency, archive, distribution)
- Overview of ground systems and science data processing center (SDPC)
- Science algorithms (L0->L1, L1-L2, L2-L3, L2/3-L4)

TEMPO

- Imaging grating spectrometer measuring solar backscattered Earth radiance
  - 0.6 nm FWHM, 0.2 nm sampling
  - 290-490 + 540-740 nm, 2 channels (1 focal plane but with 2 2-D 2 k x 1k detectors)
- Geostationary, operating on commercial communication satellite as a hosted payload, with acceptable longitude range 115°W-80°W
  - Great North America: Mexico City to Canadian tar sands, Atlantic to Pacific
  - Instrument slit aligned N/S and sweep across the Field of Regard (FOR) in the E/W in 1 hour at ~2.1x4.5 km^2 (center of FOR) with ~2.6M spatial pixels/hr







~20 times of OMI data

Comparable to TROPOMI

TEMPO

Baseline and threshold data products

Smithsonian NASA

Species/Products	Required Precision	Temporal Revisit
0-2 km O_3 (Selected Scenes) Baseline only	10 ppbv	2 hour
Tropospheric O_3	10 ppbv	1 hour
Total O_3	3%	1 hour
Tropospheric NO_2	1.0×10^{15} molecules cm^{-2}	1 hour
Tropospheric H_2CO	1.0×10^{16} molecules cm^{-2}	3 hour
Tropospheric SO_2	1.0×10^{16} molecules cm^{-2}	3 hour
Tropospheric $C_2H_2O_2$	4.0×10^{14} molecules cm^{-2}	3 hour
Aerosol Optical Depth	0.10	1 hour

- Aerosols (AOD, SSA, AAI), SO_2, $C_2H_2O_2$ were removed from baseline products during KDPC
  - Use reserve to bring them back during gap period
- Cloud product (cloud fraction, cloud pressure): used in trace gas retrievals

- Minimal set of products sufficient for constraining air quality
- Across GNA: 18°N to 58°N near 100°W, 67°W to 125°W near 42°N
- Data products at urban-regional spatial scales
  - Baseline ≤ 60 km^2 at center of Field Of Regard (FOR)
  - Threshold ≤ 300 km^2 at center of FOR
- Temporal scales to resolve diurnal changes in pollutant distributions
- Geolocation uncertainty of less than 4 km
- Mission duration, subject to instrument availability
  - Baseline 20 months
  - Threshold 12 months

TEMPO Launch Algorithms for Standard Products

NO_2, H_2CO, SO_2, $C_2H_2O_2$ vertical columns

- Direct fitting to TEMPO radiances (e.g., OMHCHO)
- AMF-corrected reference spectra, Ring effect, etc.
- NO_2 strat/trop separation (STS) adapted from OMI
- Research products could include H_2O, BrO, OClO, IO

O_3 profiles and tropospheric O_3

- SAO OE-based ozone profile method developed for GOME and OMI
- Add visible to improve retrieval sensitivity in the lower troposphere
- May be extended to SO_2, especially volcanic SO_2

TOMS-type total ozone retrieval (OMTO3) included for heritage

Aerosol products based on OMAERUV: AOD, AAOD, Aerosol Index

- Advanced/improved products likely developed @ GSFC, U. Iowa

Cloud Products from OMCLDRR: CF, CTP

- Advanced/improved products likely developed at GSFC

UVB research product based on TOMS/OMI heritage (FMI, GSFC)

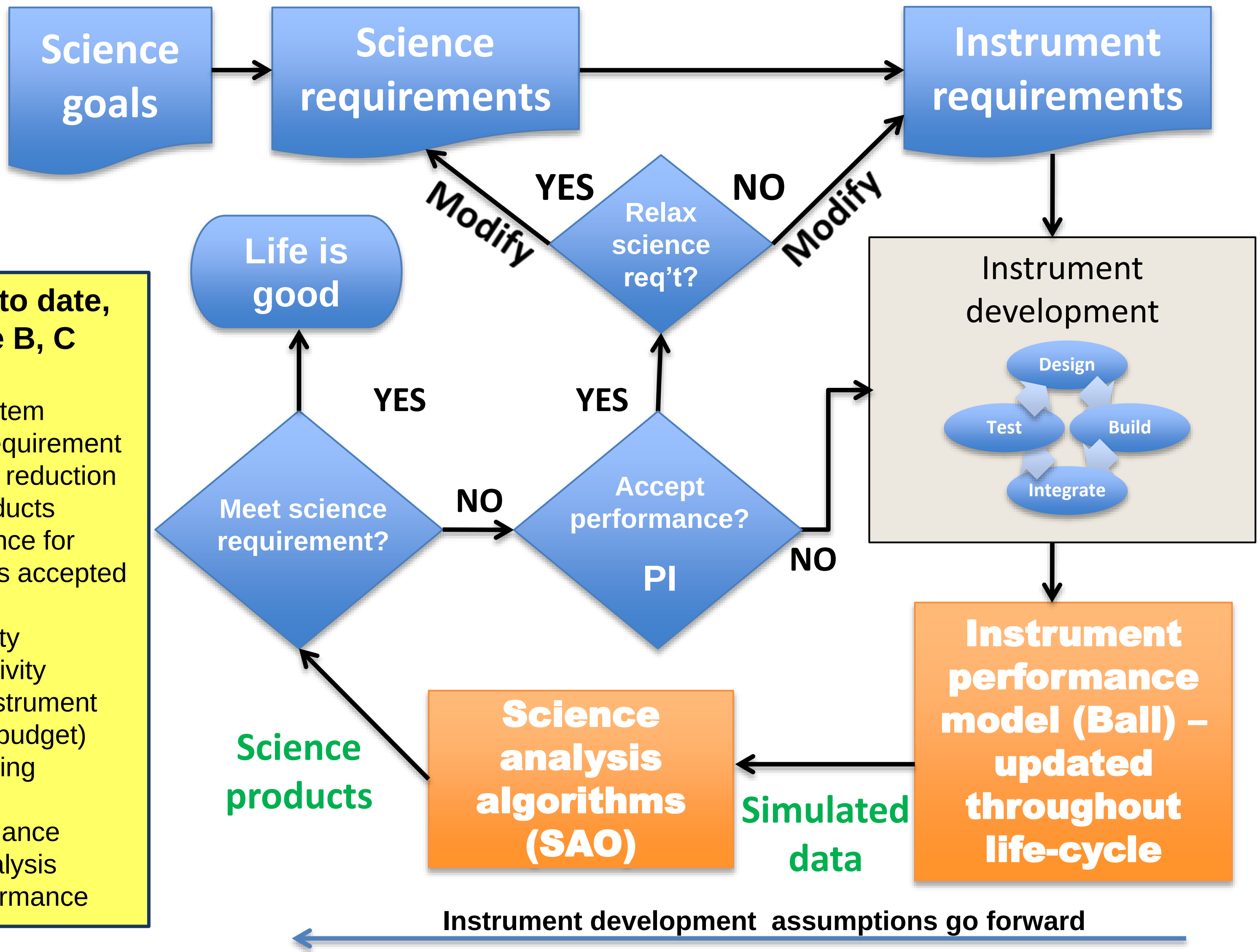
Other Research Products

- **TEMPO research products will greatly extend science and applications**
  - **H_2O, BrO, OClO, IO, volcanic (SO_2 plume height and VCD), and more species (e.g., HONO?)**
  - **Additional/improved cloud with O_2-O_2 bands or O_2-B bands**
  - **Additional aerosol products from hyperspectral spectra, O_2-B and O_2-O_2-bands, and TEMPO + GOES-R synergy at @U Iowa, GSFC, NOAA**
  - **Vegetation products: solar Induced fluorescence (SIF)**
  - **Diurnal out-going shortwave radiation and cloud forcing**
  - **City lights**
  - **Higher-level products: Near-real-time pollution/AQ indices, UVB/UV index**

TEMPO Retrieval Sensitivity Studies

- **Performed RTM simulations of TEMPO radiance spectra and optimal estimation based retrieval sensitivity studies for determining instrument requirements & verifying instrument performance.**
  - **VLIDORT: adapted from previous GEO-CAPE tools, with interfaces for viewing geometry, built-in cross sections, pre- and after- convolution, HITRAN line by line calculations, aerosol profiles and plumes, scattering clouds, IPA, Koelemeijer GOME surface albedo database or input surface reflectance spectra**
  - **Hourly fields of GEOS-Chem model fields over TEMPO field of regard for 12 days (1 day/month) up to SZA 80° → ~90,000 simulations with 10 gases (O_3, NO_2, H_2CO, SO_2, $C_2H_2O_2$, H_2O), BrO, OClO, O_2, O_4, 6 types of aerosols, water/ice clouds**
  - **TEMPO SNR model: account for optical transmission and grating efficiency, including shot, dark current, RTN, readout, quantization, smear, CTE noise terms**
  - **Climatological a priori: climatological for O_3, unconstrained for other trace gas VCDs, consistent with current algorithms**
  - **Optimal estimation to perform retrieval sensitivity and error analysis**

Instrument Design Control Process: Remains key to cost management under FFP



Decisions made to date, Post SRR, Phase B, C

- Reallocate subsystem portions of MTF requirement
- SNR relaxation by reduction of operational products
- Science performance for remaining products accepted after analysis
- Wavelength stability
- Polarization sensitivity
- Field of regard (instrument plus mission jitter budget) resolved by changing acceptable range
- Stray light performance accepted after analysis
- Dark current performance

TEMPO Instrument Performance

Table 1.
Key TEMPO instrument parameters based on the latest design as of February 2016 for a geostationary satellite at 100°W. The signal to noise ratio is the average value over the specific retrieval windows for the nominal radiance spectrum. IFOV is Instantaneous Field of View at 36.5°N, 100°W. MTF is Modulation Transfer Function at Nyquist.

Parameter		Value	Parameter	Value
Mass		148 kg	Spectral range	290–490 nm, 540–740 nm
Volume		1.4 × 1.1 × 1.2 m	Spectral resolution & sampling	0.57 nm, 0.2 nm
Avg. operational power		163 W	Albedo calibration uncertainty	2.0% λ-independent, 0.8% λ-dependent
Average Signal to Noise [hourly @ 8.4 km x 4.4 km]	O_3:Vis (540–650 nm)	1436	Spectral uncertainty	$<$ 0.1 nm
	O_3: UV (300–345 nm)	1610	Polarization factor	$\leq$2% UV, $<$10% Vis
	NO_2: 423–451 nm	1771	Revisit time	1 h
	H_2CO: 327–356 nm	2503	Field of regard: N/ S × E/W	4.82° × 8.38° (greater North America)
	SO_2: 305–345 nm	1797	Geo-location Uncertainty	2.8 km
	$C_2H_2O_2$: 420–480 nm	1679	IFOV: N/S × E/W	2.1 km × 4.4 km
	Aerosol: 354, 388 nm	2313	E/W oversampling	5%
	Clouds: 346–354 nm	2492	MTF of IFOV: N/S × E/W	0.19 × 0.36

Zoogman et al., 2017, JQSRT, TEMPO Overview

*** SNR are for 4 pixels coadded as requirements are derived from coadding 4 pixels at 8.4 x 4.5 km^2!**

TEMPO Retrieval Performance

Table 3.
Statistics (mean and 1σ) of retrieval precisions and errors for various products, and the percentage of scenarios meeting the requirements (MR).

Product[a]	Precision	Total errors	Meets reqs. (%)
UV total O_3	0.32 ± 0.08	0.72 ± 0.08	100
UV trop. O_3	3.05 ± 0.71	6.38 ± 1.98	98.3
UV 0-2 km O_3	2.59 ± 0.70	8.86 ± 1.53	78.2
UV/Vis total O_3	0.30 ± 0.07	0.54 ± 0.13	99.4
UV/Vis trop. O_3	3.04 ± 0.90	5.21 ± 1.72	98.9
UV/Vis 0–2 km O_3	3.29 ± 0.71	7.93 ± 1.41	92.8
NO_2 ($\times 10^{15}$)	0.30 ± 0.08	0.36 ± 0.20	98.4
H_2CO ($\times 10^{16}$)	0.38 ± 0.10	0.42 ± 0.13	100
$C_2H_2O_2$ ($\times 10^{14}$)	4.68 ± 1.56	4.75 ± 1.62	N/A
SO_2 ($\times 10^{16}$)	1.09 ± 0.49	1.86 ± 1.04	N/A

[a] The units are % for total ozone column, ppbv for tropospheric O_3 and 0–2 km O_3, and molecules cm ^{2} for other trace gases.

Zoogman et al., 2017, JQSRT, TEMPO Overview

- Clear-sky conditions
- O_3: fitting precision, vertical smoothing, interferences
- Other trace gases: fitting precision, interference. Uncertainties due to profile shape not considered.

Data Products (L1-L4) Definitions and Details

Data Product	Description	Time beyond on-orbit checkout to deliver initial data	Maximum data latency after first release for ≥ 80% of all products†
Level 0	Reconstructed, Unprocessed Instrument Data	2 months	Within 2 hours of receipt at SAO
Level 1b	Calibrated, Geolocated Radiances	4 months	Within 3 hours of Level 0 and ancillary data receipt at SAO
Level 2	Derived Geophysical Data Products	6 months	Within 24 hours of production of Level 1 at SAO, **mostly within 3 hours except for O_3 profile**
Level 3	Derived Gridded Geophysical Data Products (daily, monthly)	6 months	1 month after completion of data accumulation required for individual geophysical products
Level 4	Derived from multiple Level 2-3 products (e.g., AQ index, UV index)	**Not operational, produced on best effort basis**	

Data products are generated in NetCDF4/HDF5 format with basic ODL-format metadata (can be converted to XML at ASDC)

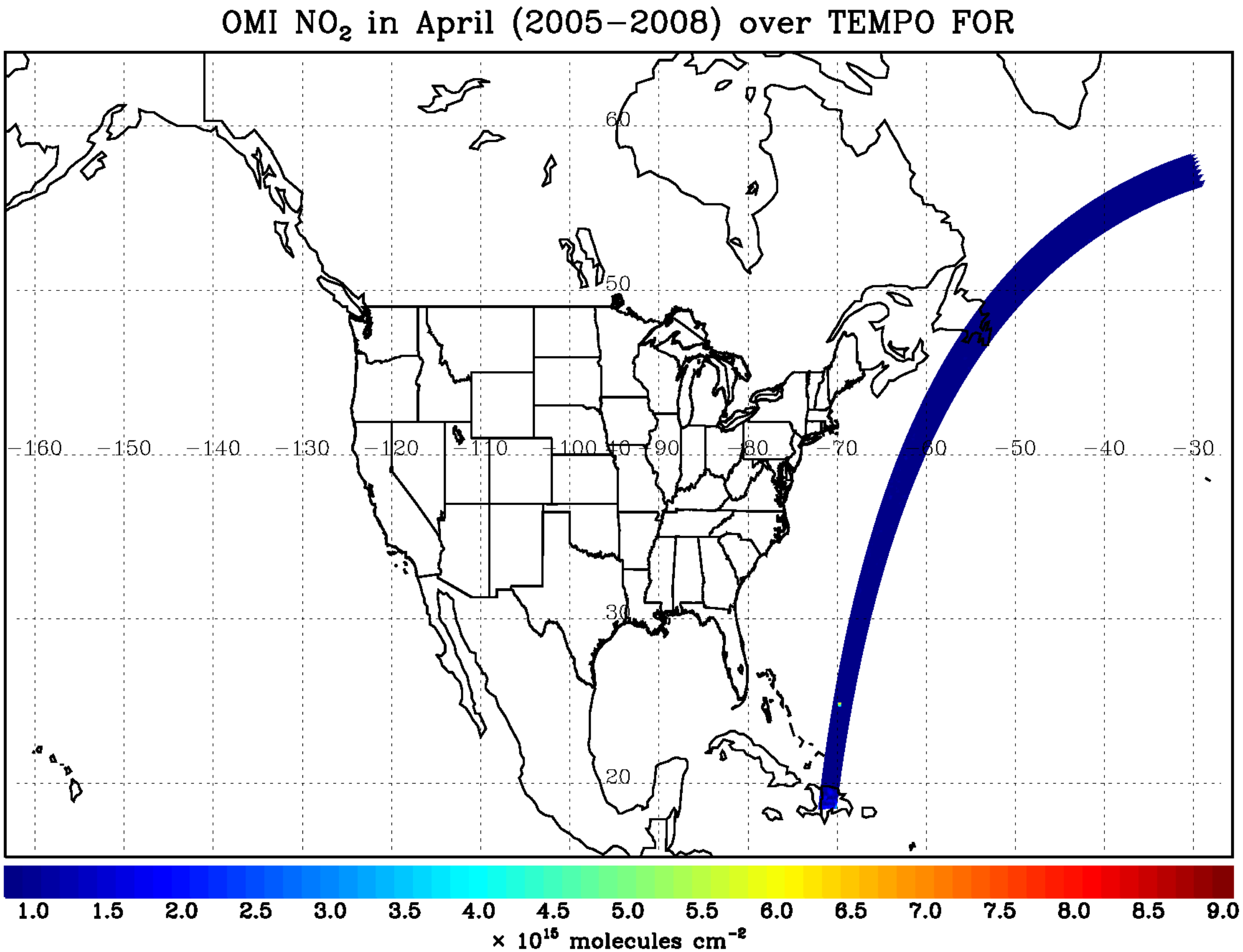
All original observation & standard science data products shall be delivered to NASA LaRc ASDC at within 6 months of completion of the prime mission (plan to archive it as soon as it's generated). ***Data products are publicly distributed during the mission.***

†80% of the products, not 80% of the product types, will be produced within this latency time.

List of Specific Data Products

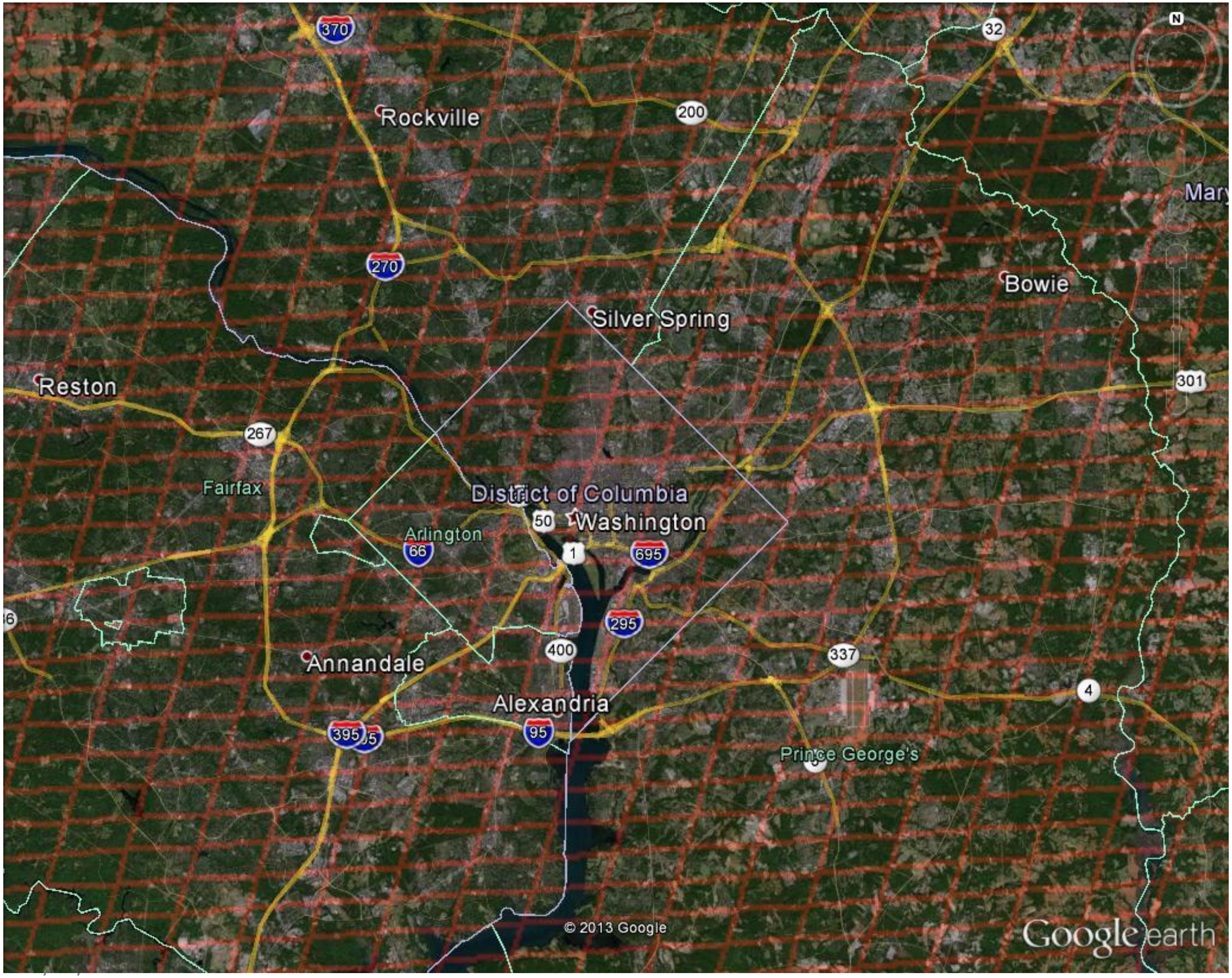
Level	Product	Algorithm	Major Outputs	Spa Res km²	Freq/Size
L1-b	**irradiance**	SAO L0-1	Calibrated & quality flags		daily
	radiance	SAO L0-1	Geolocated,calibrated, viewing,geolocation& quality flags	2.1 x 4.5	Hourly, granule
L2	**Cloud**	OMCLDRR	Cloud fraction, cloud pressure	2.1 x 4.5	Hourly, granule
	O3 profile	SAO O3 profile	O3 profile, total/strat/trop/0-2 km O3 column, errors, a priori, averaging kernels	8.4 x 4.5	Hourly, granule
	Total O3	TOMS V8.5	Total O3, AI, cloud frac	2.1 x 4.5	Hourly, granule
	NO2	SAO trace gas Dalhousie/BU strat/trop sep.	SCD, strat./trop. VCD, error, shape factor, scattering weights	2.1 x 4.5	Hourly, granule
	H2CO	SAO trace gas	SCD, VCD, error, shape factor, scattering weights	2.1 x 4.5	Hourly, granule
	SO2	SAO trace gas		2.1 x 4.5	Hourly, granule
	C2H2O2	SAO trace gas		2.1 x 4.5	Hourly, granule
	H2O,BrO	SAO trace gas		2.1 x 4.5	Hourly, granule
	Aerosol	OMAERUV	AAI, AOD, SSA	8.4 x 4.5	Hourly, granule
L3	**Gridded L2**	SAO L2-3	Same as L2	TBD	Daily/Monthly Hourly, scan
L4	**AQ Index**	Dalhousie, EPA	Air quality index	TBD	Hourly, scan
	UVB	OM UVB	UV irradiance, erythemal irradiance, UV index	TBD	Hourly, scan

TEMPO hourly NO_2 sweep



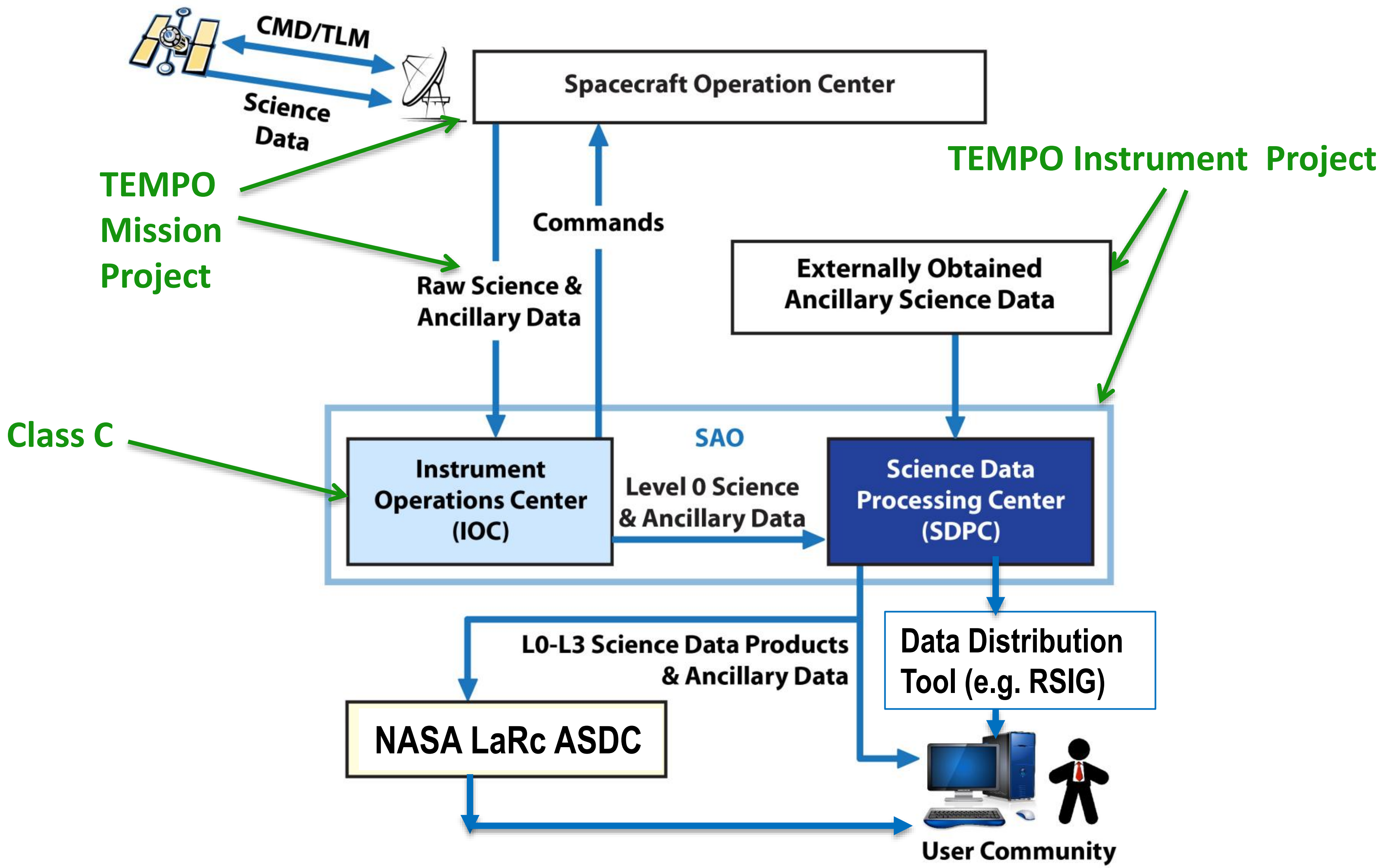
- ~ 1283 steps/hr
- ~ 2.6 M pixels/hr
- ~20 times of OMI data
- L2 files are arranged by products and granules (10 granules, each granule: 6 mins)
- Typical file size for 1 trace gas is ~100-150 MB/granule

Washington, DC coverage

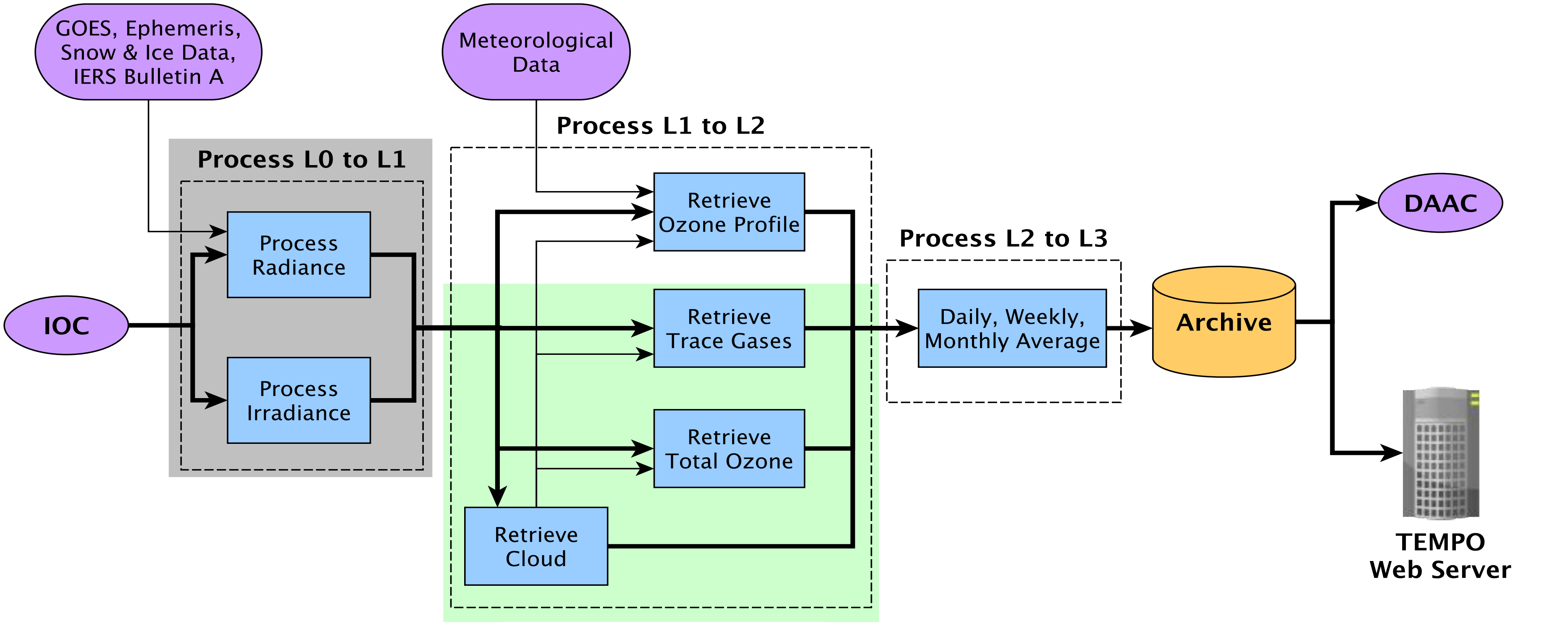


Geolocations will be provided at 4 corners and pixel center

Ground Systems Overview

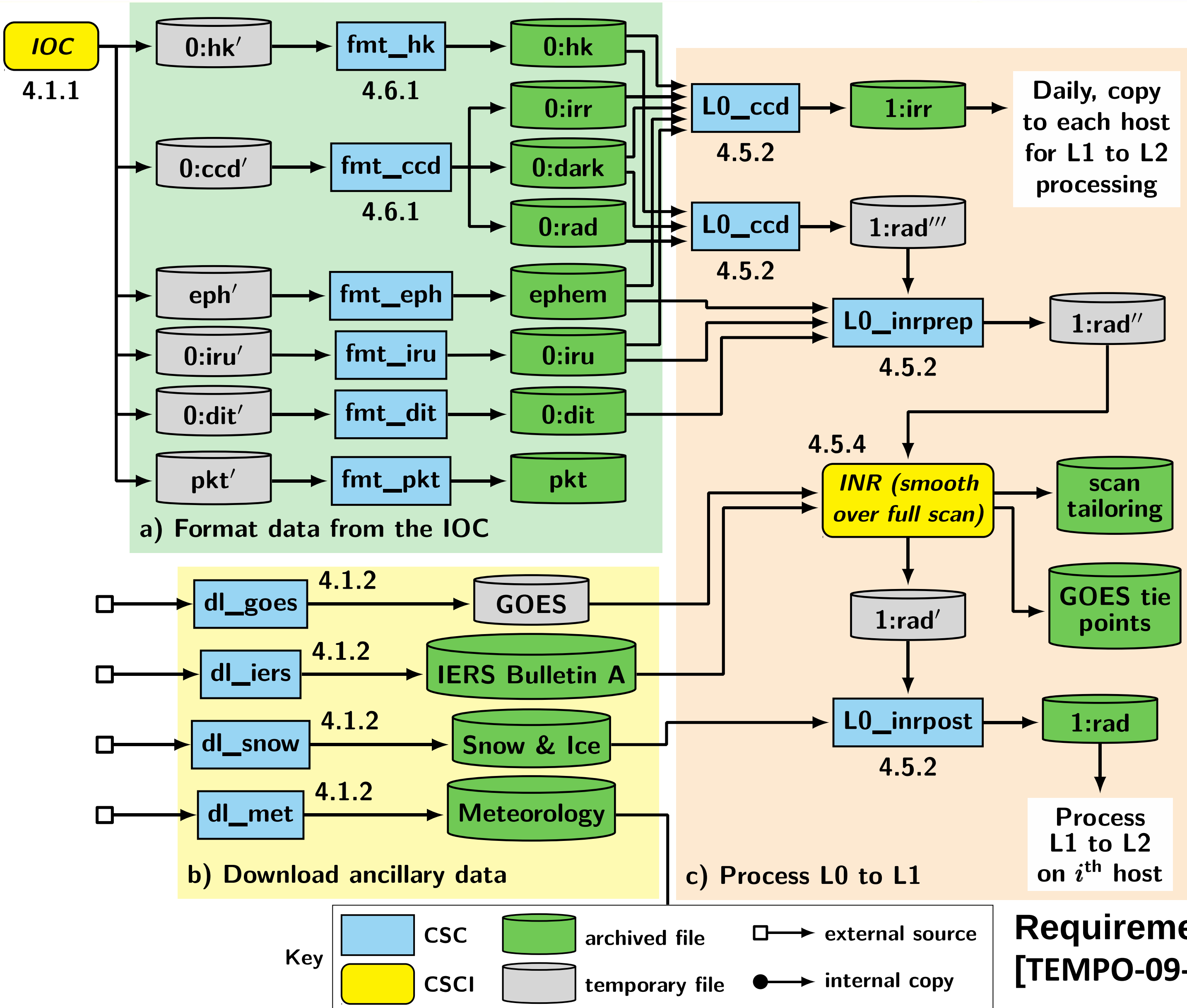


Science Data Processing Center (SDPC) Overview



- L0-L1 algorithm is developed at SAO.
- L1/L2: netCDF4/HDF-5.
- L1->L2: Cloud, total ozone, trace gas code, ozone profile, aerosols.
- L2->L3: re-gridding of L2 products to standard longitude-latitude grid cells hourly at daily/weekly/monthly scales

L0-1 Processor



- **Heritages from: OMI, TROPOMI, OMPS, GOME/GOME-2, GEOTASO**

- **TEMPO specifics**
  - INR (geo-location) by Carr Astronautics
  - T-dependent dark current correction
  - Polarization correction

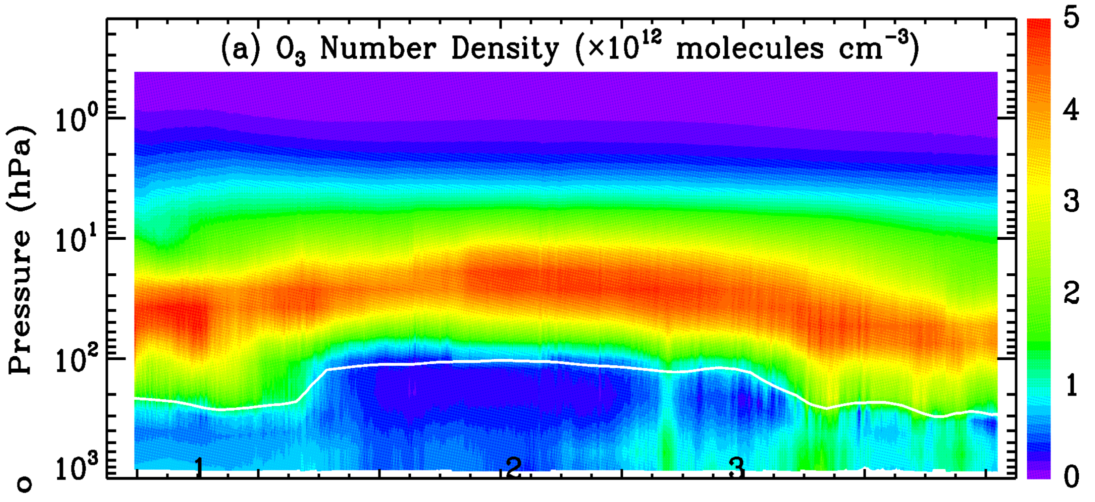
Requirements from SDPCRD [TEMPO-09-0003] labeled as 4.X.X

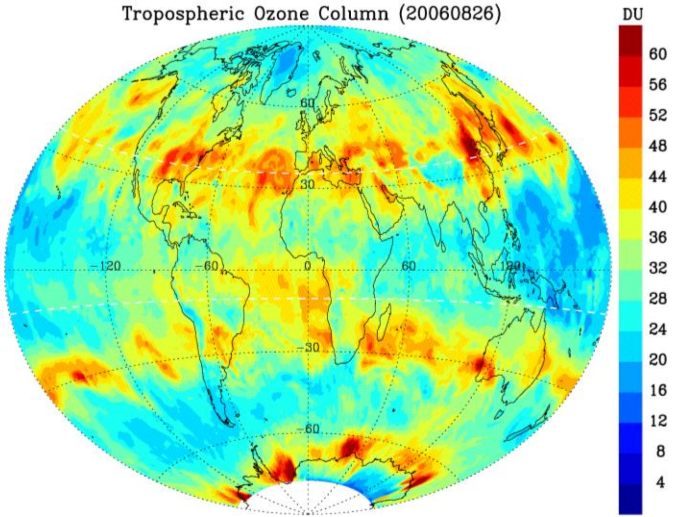
TEMPO Cloud Algorithm

- **Adapted from OMCLDRR to retrieve effective cloud fraction and optical centroid pressure (OCP) from TEMPO normalized radiances in ~346-354 nm**
  - Rotational Raman Scattering (RRS) cloud algorithm developed for OMI titled OMCLDRR by **Joiner et al. at GSFC**
  - RRS by air molecules produces filling and depletion effects in radiance spectrum called the Ring effect, cloud/aerosol reduces RRS
  - Mixed Lambertian Equivalent Model (MLER): cloud/surface is assumed to be opaque Lambertian, an effective cloud fraction is used to weigh the clear and cloudy portion of a pixel
  - Effective cloud fraction is derived from a wavelength not sensitive to RRS and atmospheric RRS
  - RRS is fitted from spectral fitting, and used to derive OCP from a look-up table
- **The RRS cloud retrievals are sensitive to instrumental (e.g., stray light, dark current), geophysical effects (e.g., 3D, shadow)**
  - Backup algorithm is being developed based on absorption O2-O2 at 477 nm at GSFC

TEMPO Ozone Profile and Tropospheric O_3 Algorithm

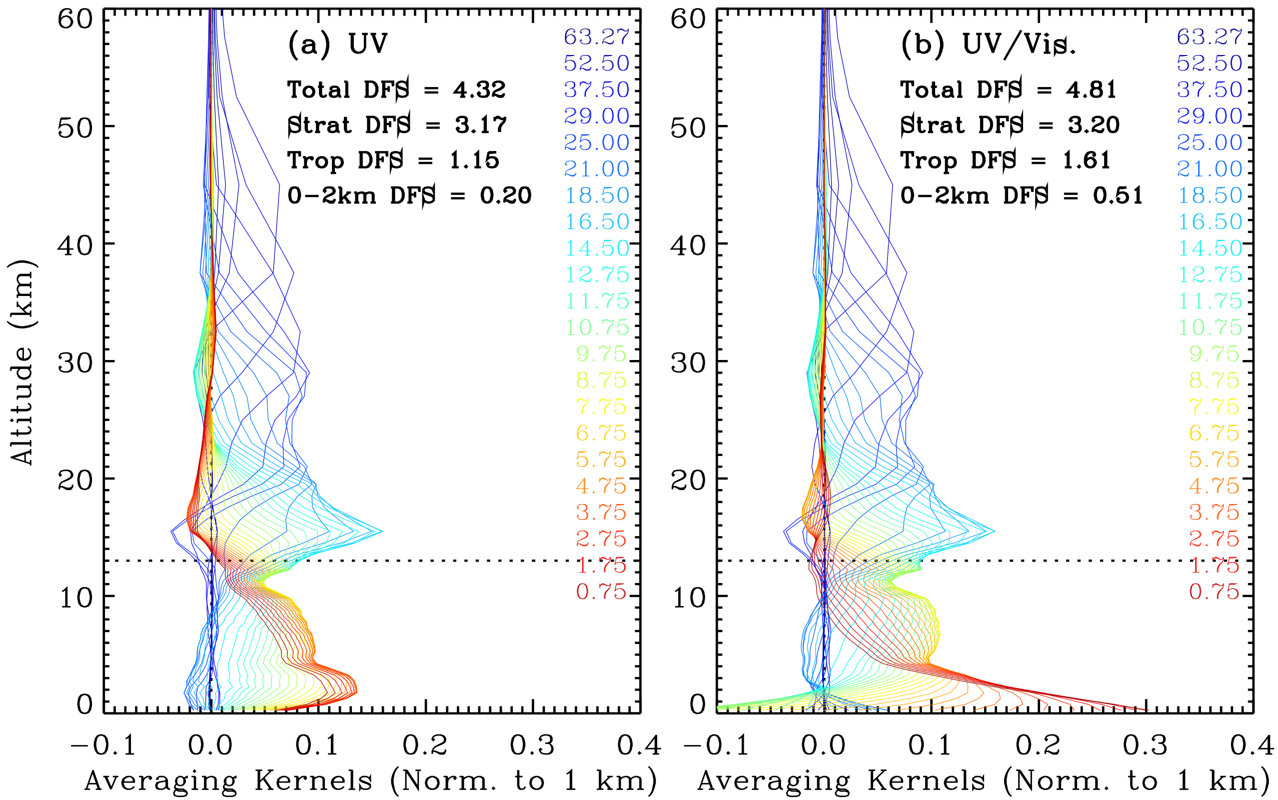
- **Adapted SAO OE-based algorithm developed for GOME and OMI (Liu et al., 2005, 2010) to retrieve <u>partial ozone columns at ~24 layers as well as total, stratospheric, tropospheric, and 0-2 km ozone columns</u> from normalized radiance in the UV (290-345 nm) and visible (540-650 nm)**
  - Climatological a priori: tropopause-based O_3 profile climatology (Bak et al., 2013) or diurnally resolved O_3 climatology based on the GEOS-5 nature run at 12 km x 12 km
  - Include retrieval a priori, retrieval error, retrieval error covariance matrix, retrieval averaging kernels





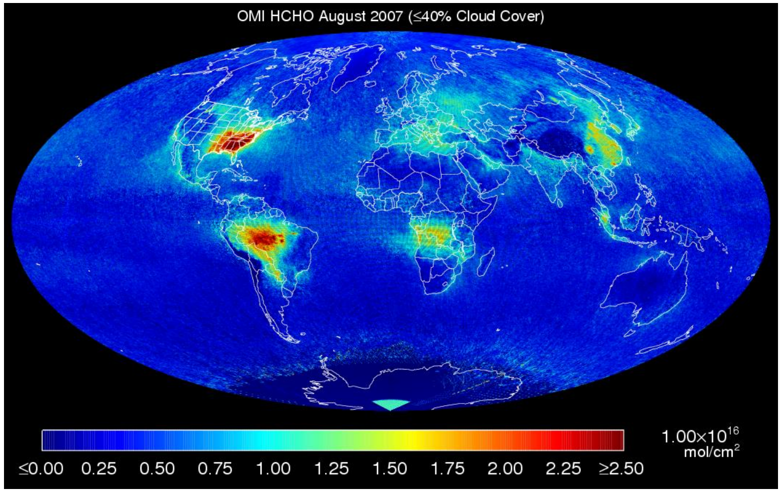
TEMPO Ozone Profile and Tropospheric O_3 Algorithm

- Add visible to improve retrieval sensitivity in the lower troposphere
- Combine MODIS albedo/BRDF database at high spatial resolution with existing spectral albedo libraries to improve the characterization of surface albedo spectra
- Time consuming due to on-line radiative transfer calculations: perform retrievals at 8.4 x 4.5 km^2, data latency within 24 hours

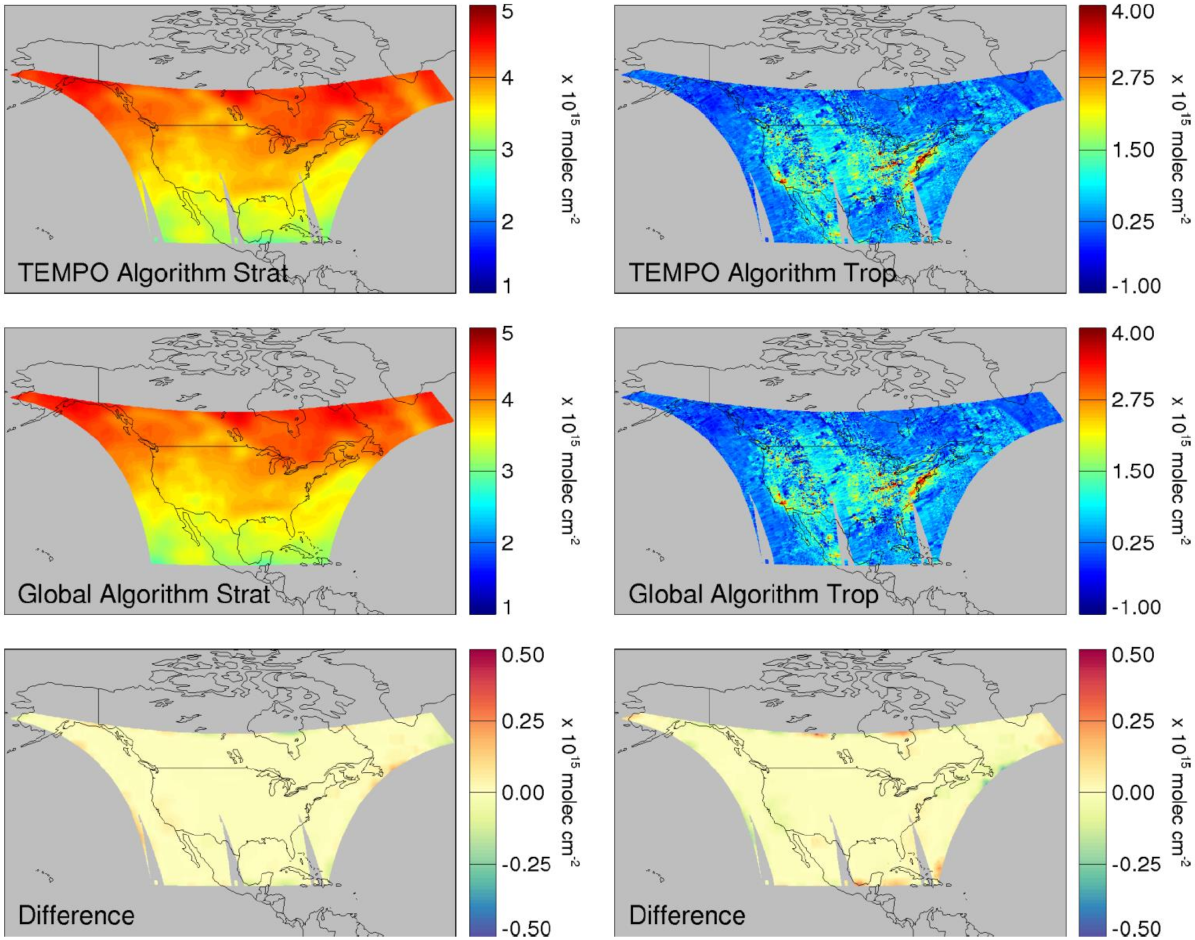


TEMPO Trace Gas Algorithm

- **Adapted from SAO two-step OMI trace gas algorithm and NASA NO_2 stratospheric/tropospheric separation (STS) algorithm to retrieve VCDs of trace gases (e.g., NO_2, H_2CO, SO_2, $C_2H_2O_2$) from normalized radiance in selected spectral windows**
  - Direct fitting to TEMPO radiances (e.g., OMHCHO) to derive SCD
  - Air Mass Factor (AMF) from diurnally resolved trace gas climatology based on the GEOS-5 nature run at 12 km x 12 km, surface albedo climatology, TEMPO cloud products, look-up table of scattering weights
  - Product includes SCD, VCD, retrieval errors, profile shape, scattering weights, AMFs. NO2 product includes separate strat/trop SCDs/VCDs



TEMPO NO2 Strat./Trop. Separation (STS) Algorithm



J. Geddes (BU) and R. Martin (Dalhousie Univ.) adapted NASA OMI NO_2 STS algorithm to TEMPO (limited domain) and found small errors of ~2.0E14 molecules at the edge.

TEMPO Aerosol and Total Ozone Algorithms

- **Will adapt from OMAERUV developed by O. Torres at GSFC to retrieve Absorbing Aerosol Index (AAI), Aerosol Optical Depth (AOD), and Single Scattering Albedo (SSA) from TEMPO normalized radiances at ~354 and 388 nm.**
  - Uses the sensitivity of near-UV observations to particle absorption to retrieve aerosol absorption properties in conjunction with the aerosol extinction optical depth
  - Assume three aerosol types (refractive index & size distribution): carbonaceous, desert dust, and urban/industrial particulate
  - Aerosol height climatology from CALIPO (Cloud-Aerosol Lidar with Orthogonal Polarization) measurements
  - Surface albedo climatology
  - Four pixels might be used for cloud clearing, so the product resolution is at 8.4 x 4.5 km^2.

- **Adapted from OMI TOMS-type V8.5 (OMTO3) to retrieve total ozone, surface reflectivity, AAI, from TEMPO normalized radiances at a few wavelengths (e.g., 317/331 nm, 331/360 nm)**

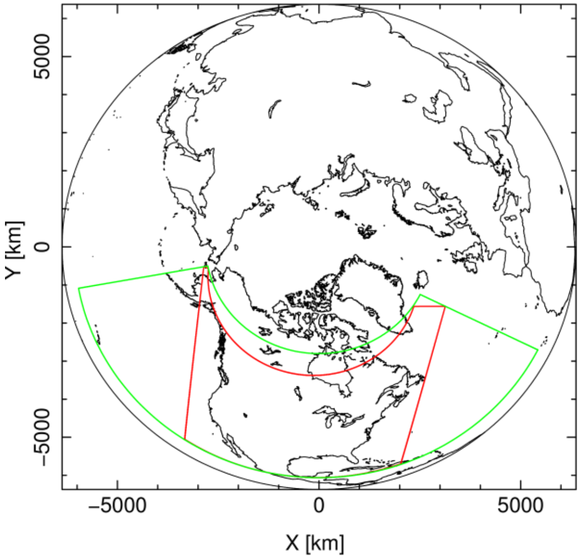
Hourly Level 3 product is a re-gridding of Level 2

- L2 products are trace gas column densities plus related variables
  - derived per-granule, with minimal spatial overlap
  - defined in projection onto a virtual detector plane (individual TEMPO pixels)

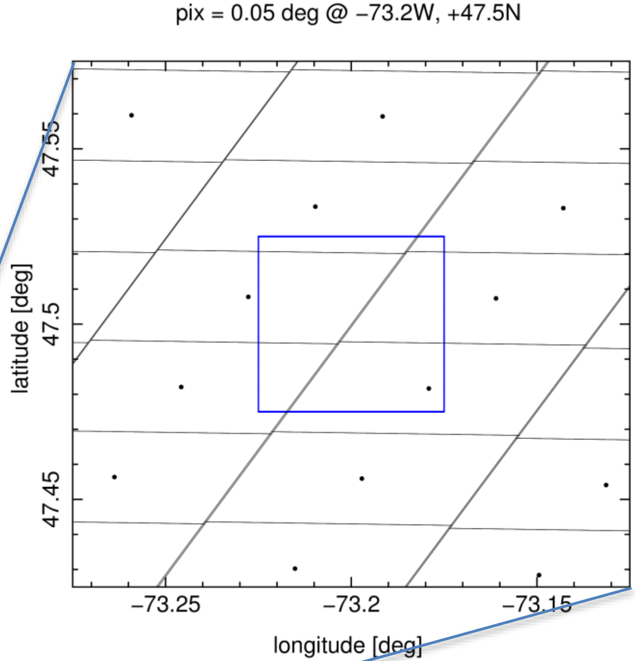
- L3 product involves re-gridding selected L2 product variables onto a longitude-latitude grid with square pixels.
  - Each L3 pixel value is an area-weighted (and also uncertainty-weighted) mean of overlapping L2 pixel values, filtered to exclude bad data.
  - Each L3 product covers a single full east-west scan.

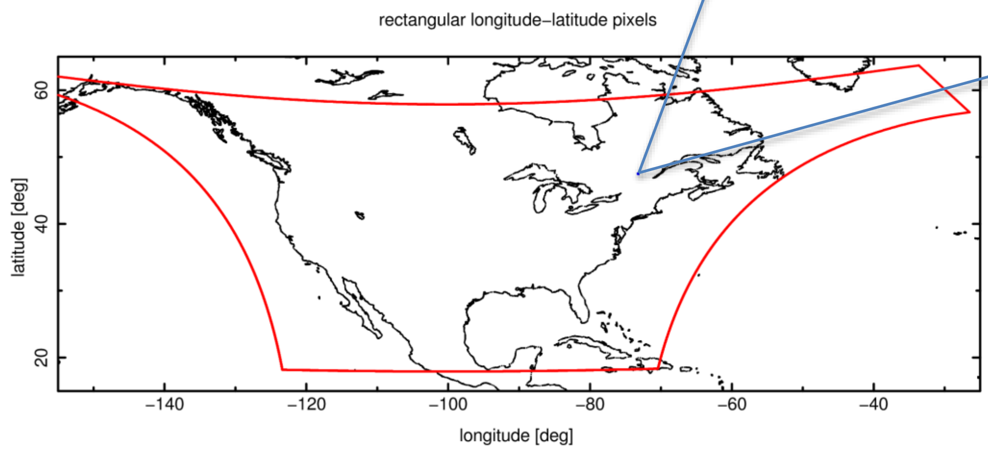
- Relatively inexpensive calculation – geometry & averaging.
  - Geometric projections available from OTS libraries.

Re-gridding of Level 2 data products



North-polar view
red=TEMPO FOR,
green=L3 boundary





L2 pixels, projected
onto the Earth's surface.
L3 pixel = blue square.

TEMPO UVB Algorithm

- **Will adapt from the TOMS and OMI UV algorithm developed at NASA GSFC and FMI to derive <u>downward surface UV irradiance</u>, the <u>erythemally weighted UV irradiance</u>, and <u>UV index</u> from radiative transfer calculations with inputs from multiple TEMPO products**
  - Total ozone, scene reflectance at ~360 nm
  - Cloud product
  - Surface albedo climatology
  - Aerosol product or aerosol climatology

Air Quality and Health

TEMPO's hourly measurements allow better understanding of the complex chemistry and dynamics that drive **air quality on short timescales**. The density of TEMPO data is ideally suited for data assimilation into chemical models for both air quality forecasting and for better constraints on emissions that lead to air quality exceedances. Planning is underway to combine TEMPO with regional air quality models to **improve EPA air quality indices and to directly supply the public with near real time pollution reports and forecasts through website and mobile applications**. As a case study, an OSSE for the Intermountain West was performed to explore the potential of geostationary ozone measurements from TEMPO to improve monitoring of ozone exceedances and the role of background ozone in causing these exceedances (Zoogman *et al*. 2014).

AQ Indices

What is an AQ index?”

“The Canadian Air Quality Health Index is a multipollutant index based on the sum of PM2.5, NO_2, and O_3,weighted by their contribution to mortality in daily time-series study across Canadian cities.” [Cooper et al., 2012]

Cooper et al., for example, propose a satellite-based multipollutant index using the WHO Air Quality Guidelines (AQG):

$$\mathrm{SATMPI} = \frac{\mathrm{PM}_{2.5}}{\mathrm{AQG}_{PM\,2.5}}\left[1 + \frac{\mathrm{NO}_2}{\mathrm{AQG}_{\mathrm{NO}_2}}\right]$$

- Can we define different indices as appropriate to locations, seasons, times?
- Might they be formulated using RSIG?
- Might assimilation be included?

Cooper, M., R.V. Martin, A. van Donkelaar, L. Lamsal, M. Brauer, and J. Brook, A satellite-based multi-pollutant index of global air quality, *Env. Sci. and Tech*., **46**, 8523-8524, 2012.

TEMPO

Summary

- TEMPO will provide hourly atmospheric pollution at high spatial resolution (~10 km^2 at center of FOR) over North America from the GEO orbit.
- TEMPO data products and science algorithms are briefly reviewed.

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Journal of Quantitative Spectroscopy & Radiative Transfer

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Tropospheric emissions: Monitoring of pollution (TEMPO)

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See Zoogman et al. (2017), JQSRT for more detail.

TEMPO

The end!

Thanks to NASA, ESA, Ball Aerospace & Technologies Corp., The Boeing Company

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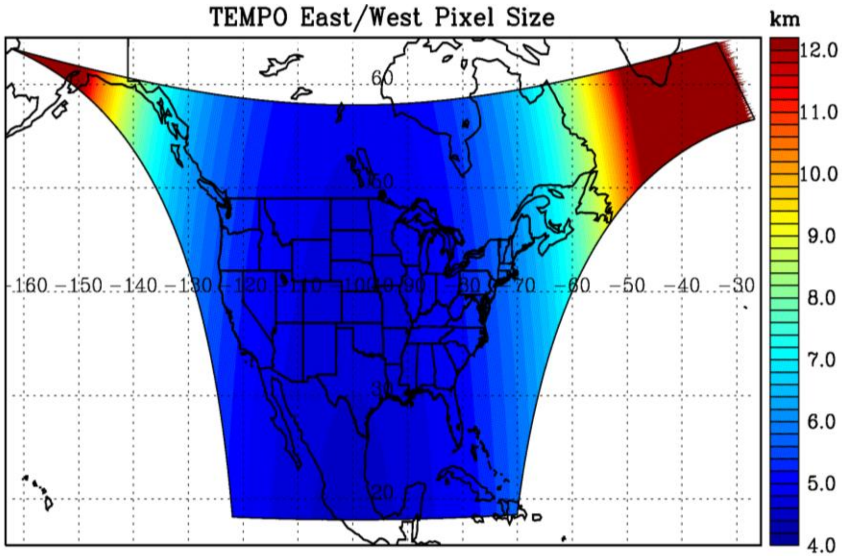
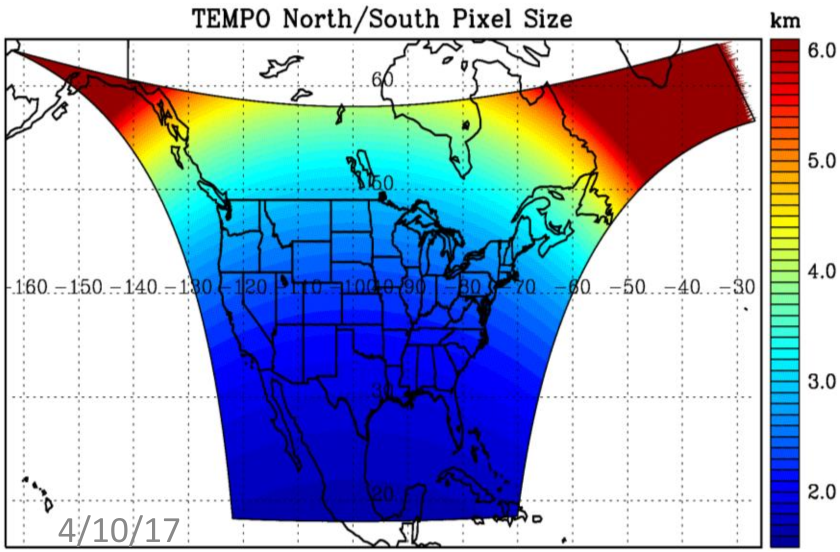
TEMPO footprint (GEO at 100° W)





Location	N/S (km)	E/W (km)	GSA (km^2)
36.5ºN, 100ºW	2.11	4.65	9.8
Washington, DC	2.37	5.36	11.9
Seattle	2.99	5.46	14.9
Los Angeles	2.09	5.04	10.2
Boston	2.71	5.90	14.1
Miami	1.83	5.04	9.0
Mexico City	1.65	4.54	7.5
Canadian oil sands	3.94	5.05	19.2

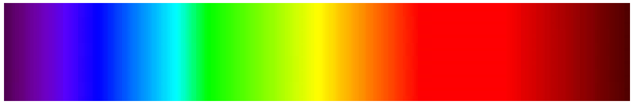
Assumes 2000 N/S pixels

For GEO at 80ºW, pixel size at 36.5ºN, 100ºW is 2.2 km × 5.2 km.

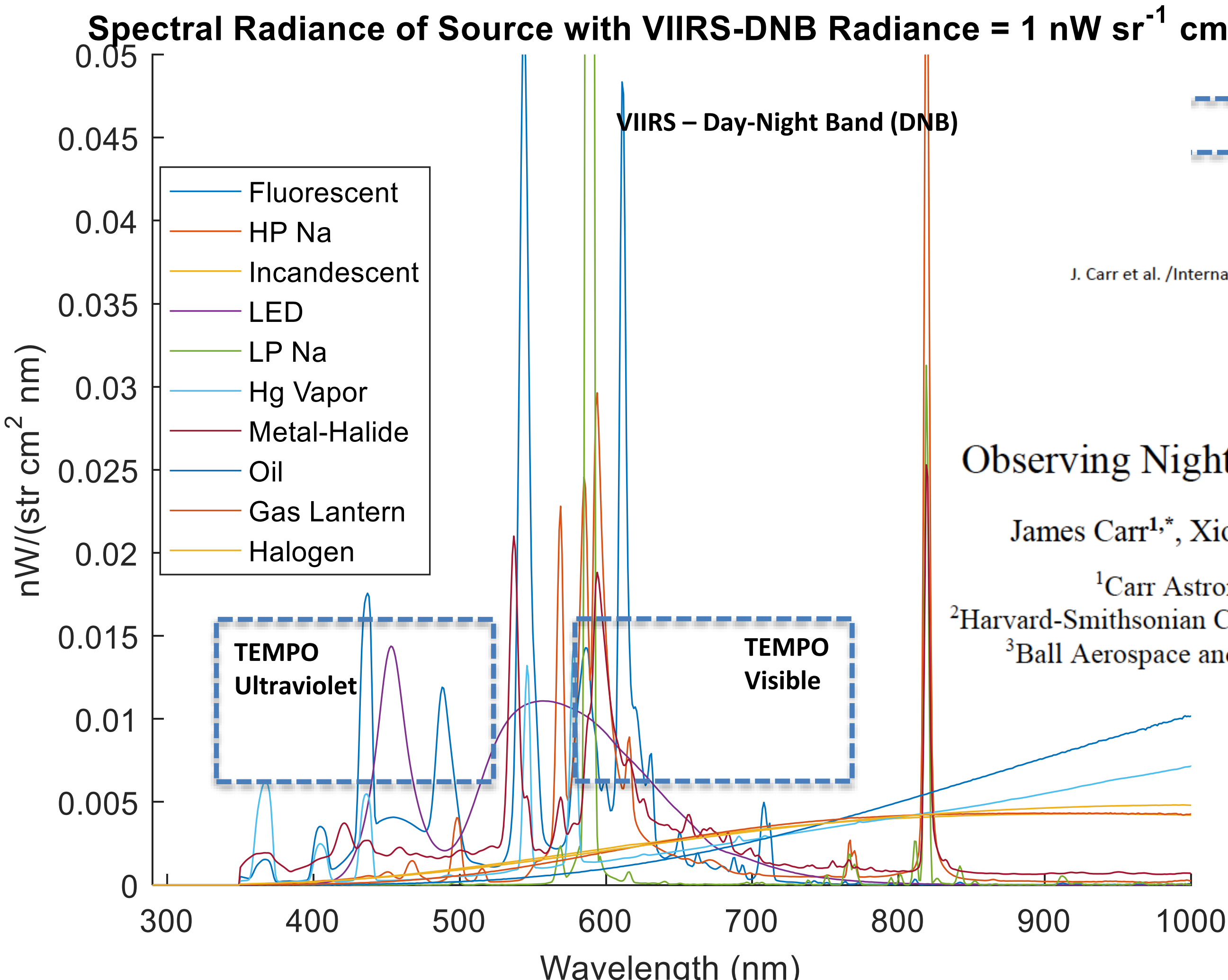
City lights

Nighttime city lights products, which represent anthropogenic activities at the same spatial resolution as air quality products, may be produced twice per day (late evening and early morning) as a research product. Meeting TEMPO measurement requirements for NO_2 (visible) implies the sensitivity for city lights products over the CONUS within a 2-hour period at 2×4.5 km^2 to 1.1×10^{-8} W cm^{-2} sr^{-1} μm^{-1}.

Night Lights Spectroscopic Signatures



Laboratory Spectra of Lighting Types (C. Elvidge):
http://www.ngdc.noaa.gov/eog/night_sat/spectra.html



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Observing Nightlights from Space with TEMPO

James Carr[1,*], Xiong Liu[2], Brian Baker[3], Kelly Chance[2]

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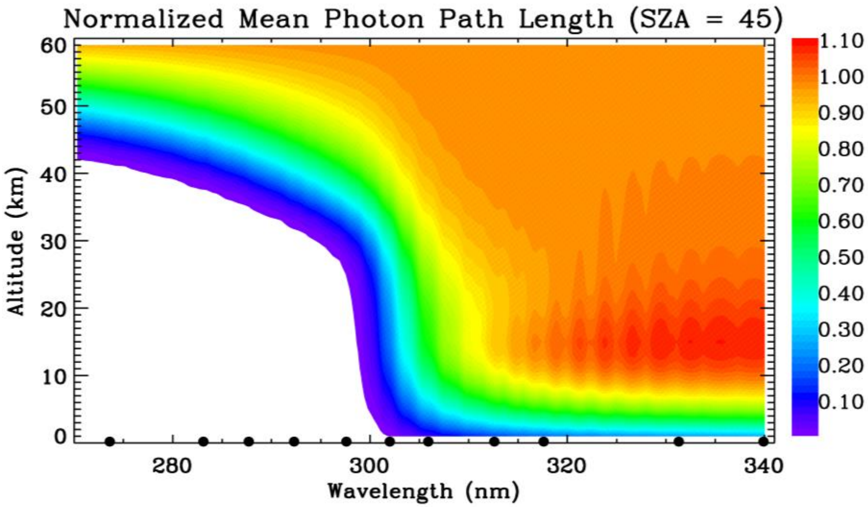
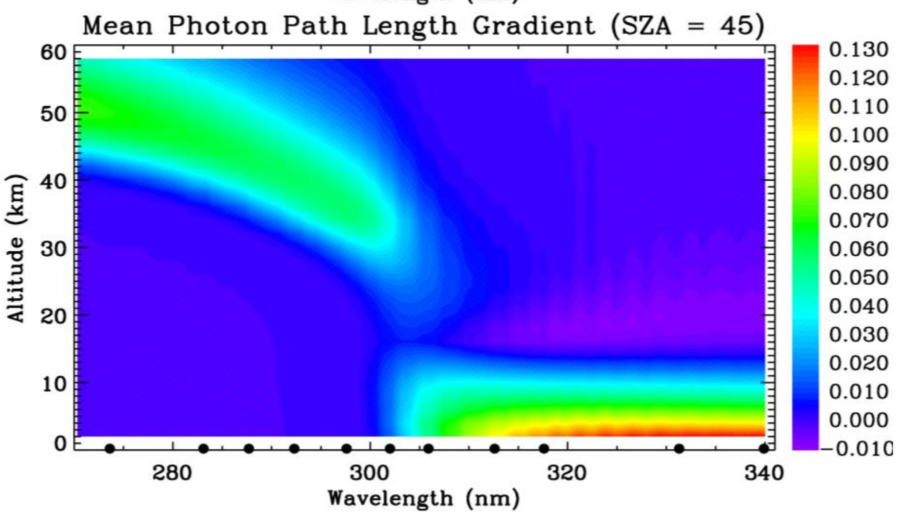
[3]Ball Aerospace and Technologies Corp., Boulder, CO, USA

Physical Principles of BUV Ozone Profile Retrievals

- **Physical principles:** Bhartia (1996), Chance et al. (1997)
- **Normalized photon path length:** 0: no photo penetration, <1 , not all photons penetrate to that level, >1, enhancement due to multiple scattering
- **Path length gradient indicates vertical sensitivity.**





- Vertical discrimination is primarily due to wavelength-dependent photon penetration
- Additional tropospheric O_3 info. from temperature-dependent Huggins bands
- Similar principle applies to plume height retrievals of SO_2 (Yang et al., 2009) and absorbing aerosols
- SBUV provides little vertical tropospheric O_3 information: too few wavelengths and poor signal to noise ratio (~1%) due to spatial aliasing

Physical Principles of BUV Ozone Profile Retrievals

■ Pioneer study by Chance et al. (1996, JQSRT): Possible to extend retrievals to the troposphere from backscattered UV and visible spectra

SATELLITE MEASUREMENTS OF ATMOSPHERIC OZONE PROFILES, INCLUDING TROPOSPHERIC OZONE, FROM ULTRAVIOLET/VISIBLE MEASUREMENTS IN THE NADIR GEOMETRY: A POTENTIAL METHOD TO RETRIEVE TROPOSPHERIC OZONE

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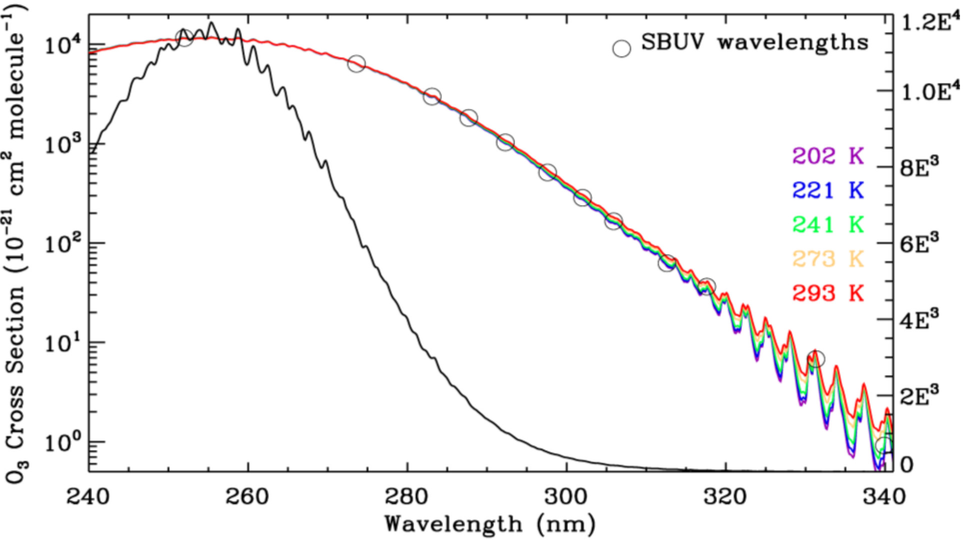
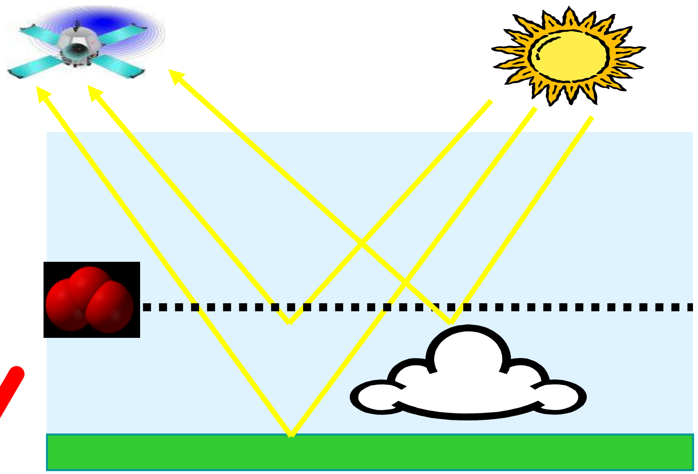
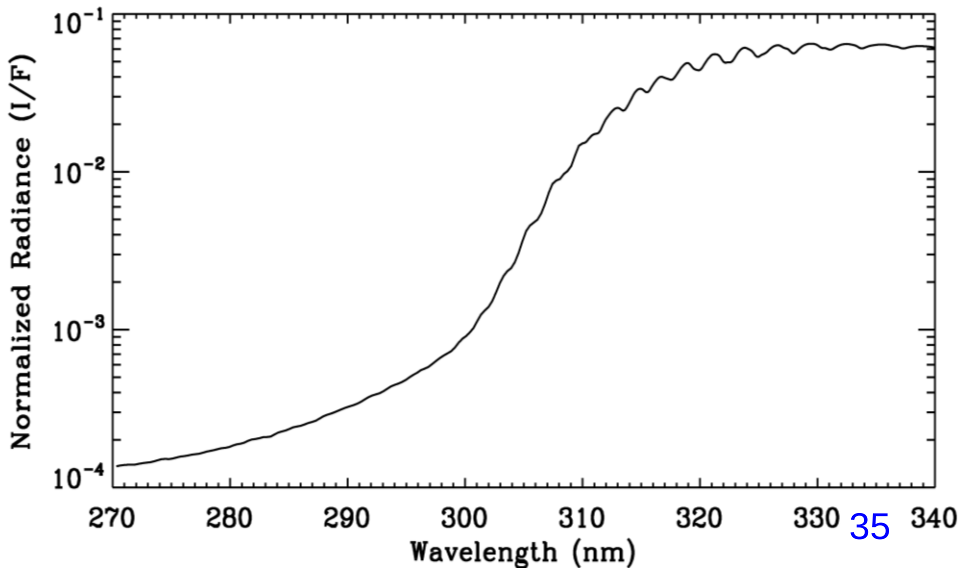


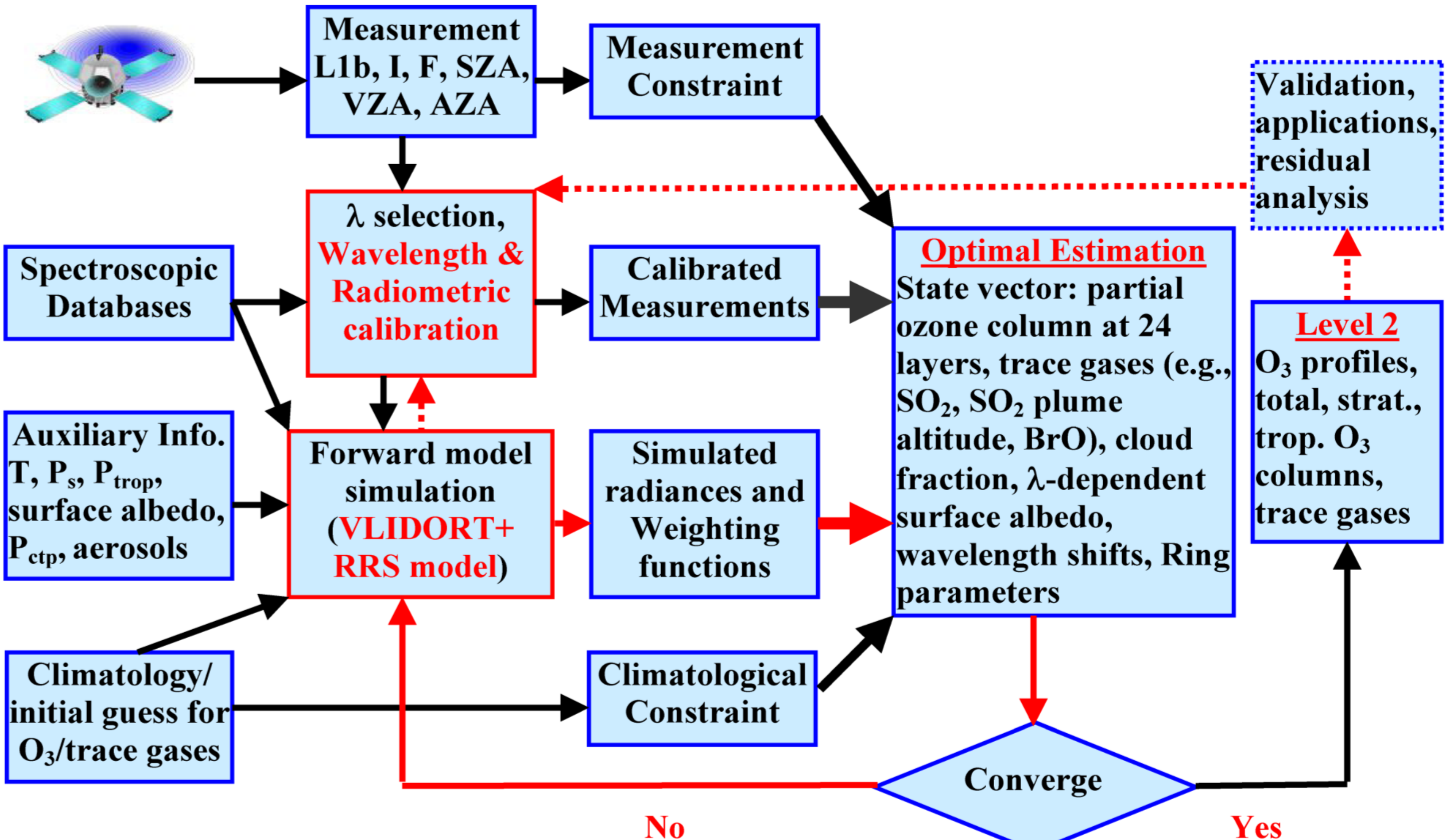




■ Several important implications that makes retrievals challenging:

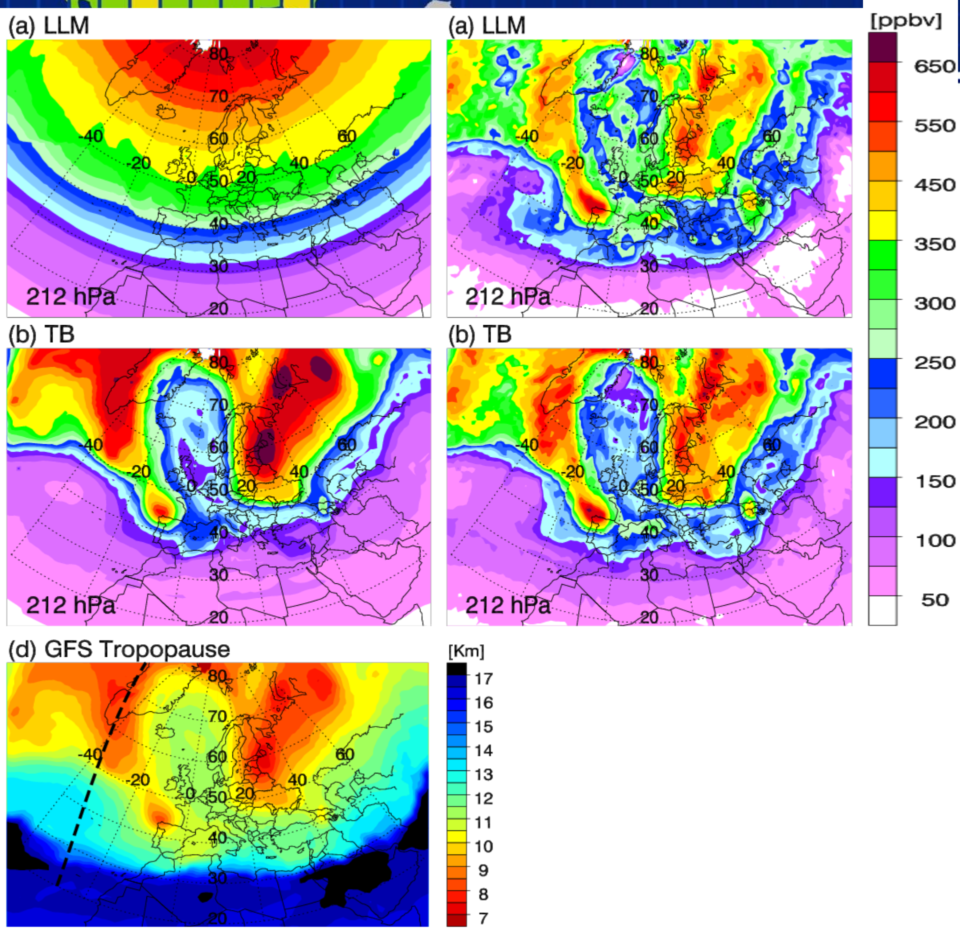
- Radiances are often measured in several channels
- Subject to wavelength and radiometric calibration errors especially at shorter wavelengths, offset between various channels

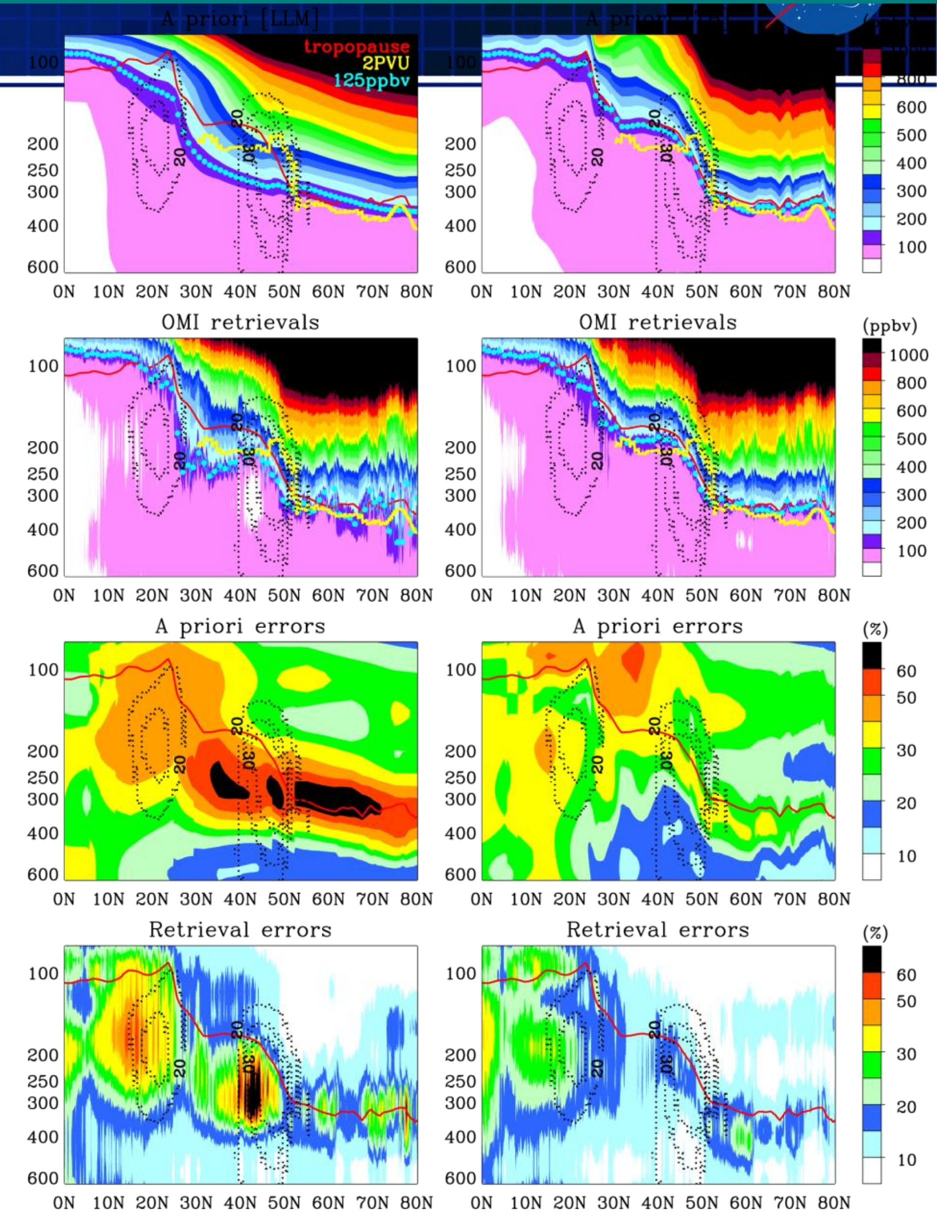
SAO OMI Ozone Profile Retrieval Algorithm



■ **Keys to retrievals:** **accurate calibration and forward model simulations, fit the radiance spectra to ~0.1% in the 310-330 nm**

The Use of Tropospause-based Climatology





- **TB coordinate: preserve gradient & reduce O_3 variability**
- **Capture much better horizontal & vertical gradient over UT/LS**
- **Significantly reduce UTLS retrieval errors**

TEMPO