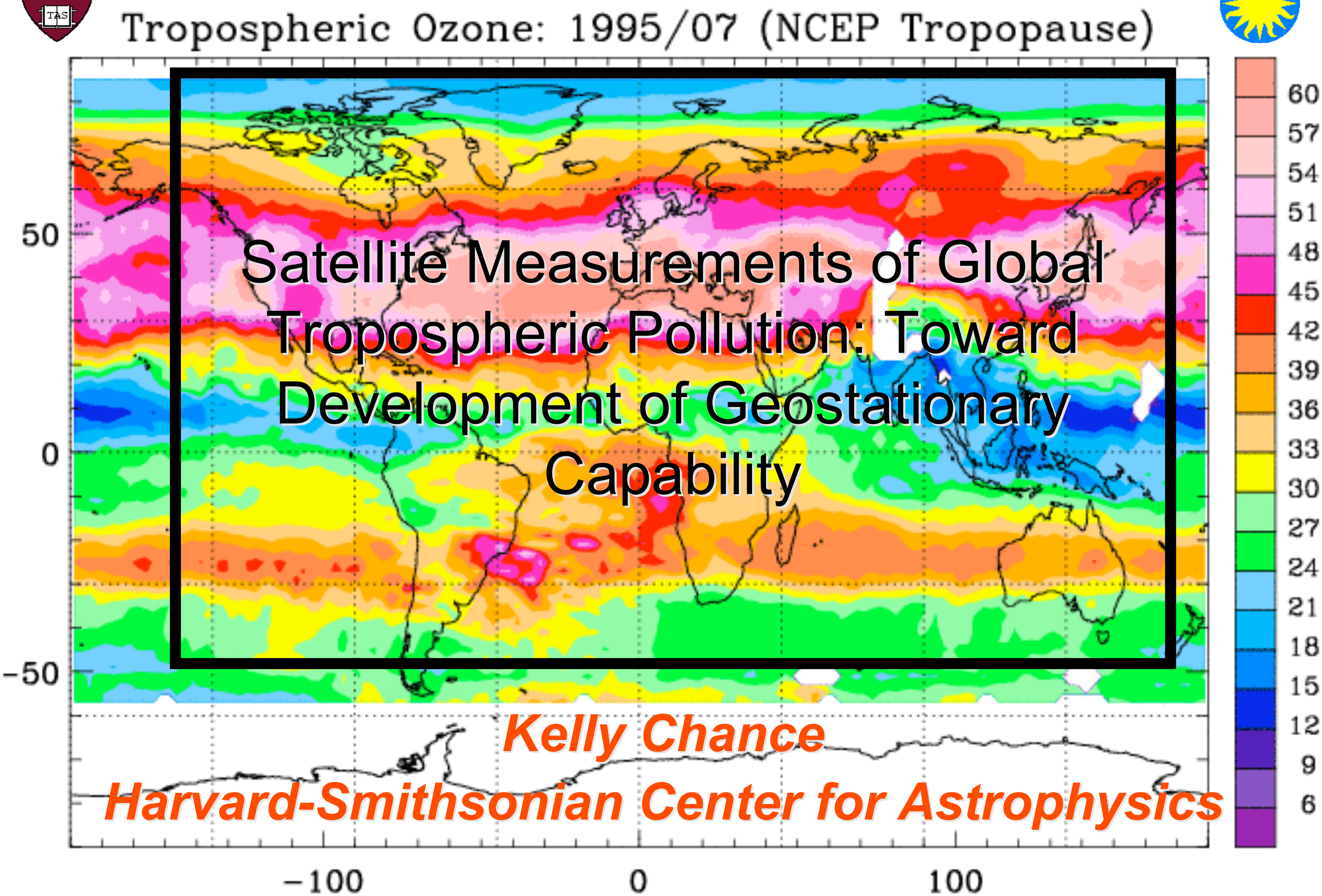

Satellite Measurements of Global Tropospheric Pollution: Toward Development of Geostationary Capability

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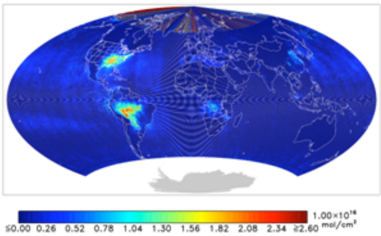
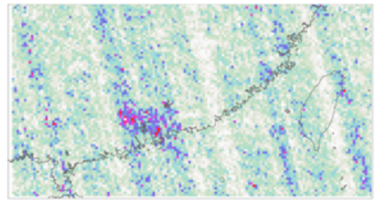
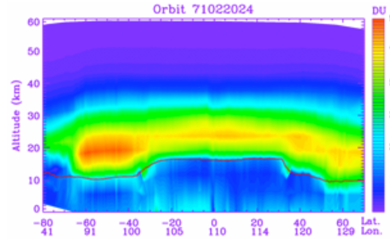
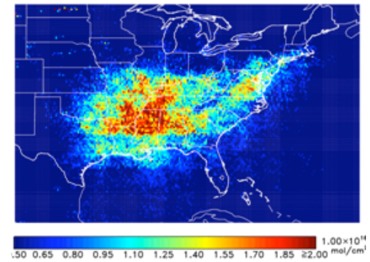






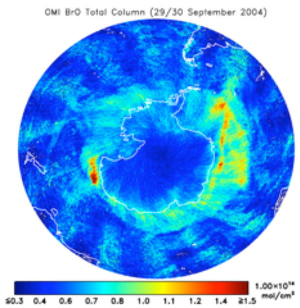


O_3

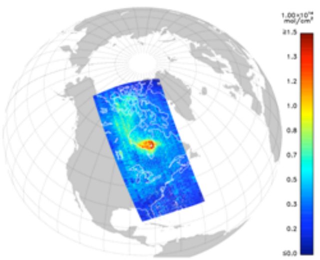
INTRODUCTION

NO_2

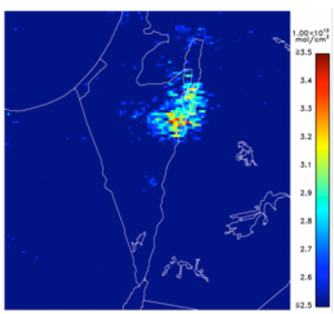
CHOCHO!



GOME, SCIAMACHY, OMI, and OMPS have done much to prepare the way for eventual global and continuous pollution monitoring from space.



This talk uses our 20+ years of experience with GOME, SCIAMACHY, OMI, and OMPS to learn what works and what needs to be improved in order to make operational UV and visible measurements of pollution from geostationary orbit.

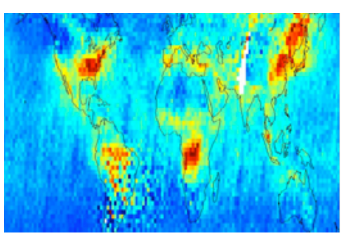


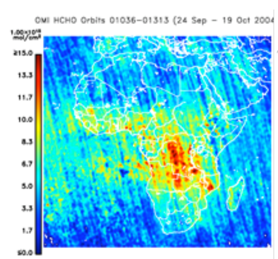
All aspects of the system should be re-considered: Instrument design, detector type, algorithm approaches, reference data, operations. ***Much to do in implementation!***

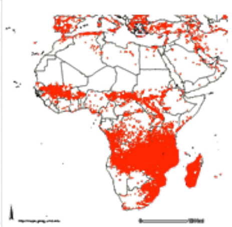
BrO

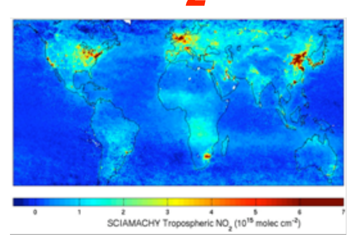
SO_2

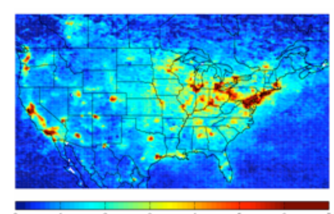
HCHO

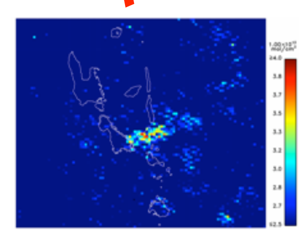












What We Currently Have

Robust algorithms for ozone profiles and tropospheric ozone; tropospheric NO_2, HCHO, and volcanic SO_2; BrO from the ice pack and from volcanoes and salt lakes

Initial measurements for CHOCHO
Algorithm development for H_2O underway
Capability to measure anthropogenic SO_2 needed

CO is measured in the infrared, and is not discussed here

Two detector types/two instrument approaches
- 1-D detectors (Si diode arrays) plus scanners – GOME and SCIAMACHY
- 2-D detectors (CCDs) employing pushbroom scanning - OMI and OMPS
  - 2-D is the choice here given the large number of ground pixel measurements required

Various approaches for
- Instrument characterization
- 0-1 algorithm development and optimization
- 1-2 algorithm development and optimization

Higher level products not discussed here

Assumptions and Implications

Measurements are from geostationary orbit (35,800 km) or, possibly, from inclined 24-hour orbits, which could make measurements to higher latitudes feasible.

At least three instruments are required for global coverage (at least six if inclined orbits are used).

Spatial resolution requirements (depending upon detailed scientific requirement studies) likely be 10×10 km^2 or smaller.

The spatial resolution requirement assumed here is: at least 1000 resolution elements in the East-West and North-South directions (*i.e.*, a grid of 1000×1000 13×13 km^2 pixels for a satellite covering 1/3 of the Earth to latitude limits of ~±60°). Any final selection will likely approximate this (or have slightly smaller pixels).

The major tradeoffs are in orbit selection, detector type (CMOS-Si versus CCD; 2-D detectors assumed here), and in scanning/rastering mode: even instruments using 2-D detectors would need 2-axis scanning to obtain the required spatial coverage.

For mission details and scientific discussion, see NRC Decadal Study White Paper "Earth's first time resolved mapping of air pollution emissions and transport from space," J. Fishman, D. Neil, J. Crawford, R.B. Pierce, D. Edwards, K. Chance. T. Kurosu, W.P. Menzel, G. Foley, and R. Scheffe.

Instrument Types and Issues

GOME and SCIAMACHY employ 1-D detectors and scanners to achieve spatial coverage. Scanners have proved to be very robust, and demonstrated to be suitable for use in long-term space applications. Current flight-qualified ADCs too slow for GEO use.

OMI and OMPS employ 2-D detectors (CCDs) and use the pushbroom technique: One CCD dimension is spectral and the other spatial (across-track; 60 pixels for OMI, 35 for OMPS). The satellite movement then gives the along track variation. In LEO there is a disadvantage of large differences in pixel size and ITF with cross-track position (slightly less for GEO).

A instrument employing 2-D detectors (spatial × spectral), as is used for OMI and OMPS is assumed. Spatial coverage obtained by scanning rather than orbital (pushbroom) motion.

Two-axis scanning will be required for measurements from GEO even with the use of 2-D detectors, *unless* an even more complex approach is developed (such as the use of multiple focal planes), or unless larger formats (≥ 2K × 2K) with sufficient charge capacity become available.

2-Dimensional Detectors

Basic need is for detectors with:

- **Suitably large formats (minimum 1024 × 1024)**
- **> 2×10^6 e^- charge capacity (to meet S/N requirements; note that GOME spectra can be fitted to RMS of < 3×10^{-4} in favorable cases)**
- **High radiation tolerance**
- **Flight qualification**

CCDs exist in suitable formats, and have been flown in space, but

- **They have lower well depths (700,000 e^- is the maximum I have seen)**
- **They are highly subject to degradation due to radiation damage**

CMOS-Si now exists in suitable formats (*e.g.*, Rockwell HyViSI™ TCM 8050 A, 1024 × 1024), with

- **High charge capacity (3×10^6 e^-)**
- **Excellent radiation tolerance**
- **CMOS-HgCdTe versions are also available for infrared applications.**
- **Flight qualification of detectors and fast ADCs probably required**

Recent comparison of CCDs and CMOS detectors: P. Magnan, Detection of visible photons in CCD and CMOS: A comparative view, *Nucl. Instrum. Meth. Phys. Res. A* 504, 199-212 (2003).
http://www.inst.bnl.gov/~poc/LSST/Magnan%20CCD-CMOS%20comparison.pdf

Spectrometer design

Improved optical design is required to:

1. **reduce "smile" on the detector arrays, where the spatial and spectral dimensions are not fully orthogonal (and may alias onto one another if the sampling is insufficient)**
2. **Reduce the variation of instrument line shape across the spatial dimension.**

- ***Many more (at least an order of magnitude) pixels in spatial dimension than for OMI or OMPS.***

Highest instrument development priorities

1. **Evaluate spectrometer designs for spectrum fidelity**
   - Can we get N spectra on an $N \times N$ detector?
2. **Choice of detector type and spectrometer design should proceed together so that the choice is not made prematurely.**
3. **Innovative choices? Multiple focal planes?**

Orbit Considerations

Standard configuration is a constellation of three satellites in geostationary orbits

- **Achieves global coverage up to latitudes limited by viewing angles and physics**
- **Measurements to high latitudes become difficult due to the high viewing zenith angle**
  - **The viewing zenith angle for 60° looking directly N/S is already quite high (68°); It increases to more than 84° for views 60° East or West**
  - **This makes tropospheric measurements, especially in the UV, quite challenging even under high Sun conditions due to the large contribution of Rayleigh scattering to the measured radiances**
  - **Ground pixel size also increases**

Inclined 24-hour orbits could improve this situation, at the cost of more instruments or reduced temporal coverage.

- **A satellite in geostationary orbit at 100°W would effectively cover the U.S. (except for most of Alaska), southern Canada, and South America**
  - **Northern Canada would be problematic (as would much of northern Europe for a European member of the constellation)**
- **Inclining the orbits to 50°, with maximum latitude at solar noon, would permit the Northern Hemisphere to be well-covered during most of the daylit parts of the orbits, but would sacrifice coverage of much of the Southern Hemisphere**
  - **A second set of satellites with opposite phase would recover this**

Algorithm Design and Implementation

Algorithms do not work properly at launch! **Resources for algorithm development and maintenance, and for software engineering should be in place.**

0-1 processing

- **Flexibility and modularity are important**
- **Don't assume that the algorithm structure is fixed at launch and only update of key data parameters is required for improvement**
- **Structural changes in the algorithm should be anticipated, with resources in place**

1-2 processing

- **Fitting assumptions should be tested**
  - **Directly fitting the radiance *R* or one of its derivatives $(R/I_0$, *ln* (R/I_0), *HPF* [*ln* (R/I_0)]**
  - **All choices are in current use; many data products have not benefited from a systematic comparison of choices**
  - **Proper choice can make a factor of 2 in results**

Comprehensive review of reference spectra

- **Rely on best laboratory FTS measurements**
- **O_3 (T) is biggest outstanding need (and has been for a long time)**

Algorithm physics **(Ring effect, wavelength calibration, spectral and spatial undersampling, scattering codes) should be revisited and quantitatively re-tested.**

Instrument characterization

Ample time and resources for

- Instrument transfer function (slit) determination vs. goniometry
- Detector response, nonlinearity
- Etc.
- Basic spectroscopic tests (*e.g.*, room temperature O_3 and NO_2 to test end-to-end instrument performance)
- ***Reserve available resources for quantitative instrument characterization***

Operations

Why operations? Because requirements change after launch

- In orbit calibration (*e.g.*, frequency of dark current measurements)
- Frequency and duration of solar reference measurements
- Injection into operational products

The important issue is built-in flexibility, to avoid the need to delay improvements to data products

Conclusions

Issues of instrument requirements (signal-to-noise ratio and spectral resolution) and algorithm physics have largely been addressed in the development of data products for GOME, SCIAMACHY, OMI, and OMPS. The exact choices for geostationary instruments would need to be made considering the tradeoffs among technical capability, scientific requirements, and cost.

Overall high priorities

1. Instrument design, instrument design, instrument design $ $ $
2. Detector choice, detector and electronics qualification $ $ $

1. Level 0-1 processor design (flexibility!)
2. Operational system design (flexibility!)