Prospects for future spaceborne measurements of interest to the SPARC Data Assimilation community and how to improve those prospects

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Outline of talk

• Background information
  – Review of the main approaches for spaceborne upper troposphere, stratosphere, and mesosphere remote sounding
  – Recent history of such observations and currently confirmed future instruments
  – Some science questions motivating the need for future observations
  – Challenges to be overcome when proposing measurements to address those science questions
  – Approaches to articulating a measurement need
    ▪ The “Science Traceability Matrix”
    ▪ A potential framework for “Continuity” observations

• Instrument concepts currently under development

• What role can the SPARC Data Assimilation community play?
Background information
Atmospheric composition observations from spaceborne limb sounders have formed the basis of many scientific discoveries and advances.

**General properties of limb sounders:**
- Good (~1–5 km) vertical resolution, thanks to observing “edge on”
- Strong signal to noise for tenuous trace gases, thanks to long path
- Poorer horizontal resolution than achievable with nadir sounders

**UV/VIS/NIR sounders:** (e.g., Odin OSIRIS, OMPS-LP, SCIAMACHY)
- Instruments can be very compact and still achieve good vertical resolution
- No cooling is needed
- Requires sunlight, so no nighttime (or polar night) measurements
- Height registration can be dependent on knowledge of spacecraft pointing

**Thermal IR sounders:** (e.g., LIMS, SAMS, CLAES, MIPAS, HIRDLS)
- Can measure with good vertical resolution and excellent signal to noise
- Line width gives pressure information, reducing need for pointing knowledge
- Instruments require cooling for best signal to noise

**Microwave/Submm Sounders:** (e.g., UARS/Aura MLS, Odin SMR, SMILES)
- Can measure in the presence of aerosol and all but the thickest clouds
- As for thermal IR, measuring line width reduces need for pointing knowledge
- Large (~0.7–4 m) antennae needed for best vertical resolution
- They have historically been bulky and power hungry (but far less so now)
Complementary capabilities of occultation sounders

Spaceborne occultation sounders have similarly provided uniquely valuable observations.

**General properties of occultation sounders:**
- Solar occultation instruments have excellent signal to noise.
- Their calibration is generally simpler than limb emission/scattering sounders.
- Their vertical resolution can be slightly better too, in some cases.
  - Spatial/temporal sampling is poorer than for limb emission/scattering.

**Other occultation sounder points/specifics**
- The strong signal to noise, combined with suitably broad spectral sampling (as in ACE-FTS) enables measurement of an unparalleled wealth of species.
- Adding a lunar occultation capability (e.g., SAGE-III) provides some additional spatial and temporal sampling.
- Stellar occultation (e.g., EnviSat GOMOS) allows more measurements, including at other local times, though the signal to noise is weaker.

Five-day coverage of typical limb emission (left) and solar occultation (right) sounders.

Aura MLS example

UARS HALOE example
Other spaceborne observations relevant for SPARC

- **Operational nadir sounders**
  - $O_2$ channels (microwave) and $CO_2$ channels (infrared) provide temperature information that extends to the stratosphere
  - Some microwave instruments (SSMI/S) include channels with weighting functions that peak in the upper stratosphere and mesosphere
  - Previous infrared Stratospheric Sounder Unit (SSU) instruments
  - Water vapor channels in both the infrared and microwave provide humidity information, but typically only up to ~10 km altitude

- **GPS radio occultation**
  - GPS radio occultation instruments make very high resolution vertical profiles of temperature
  - While GPS can also provide information on humidity this doesn’t extend above the lower troposphere

- **Column and coarse profile ozone from UV sounders**
  - Provides information on stratosphere and UT/LS dynamics

- Others?
Current and confirmed future limb/occultation sounders

- In the past decade we had, at peak, twelve instruments operating on eight satellites
- In the coming decade **only one limb scatter sounder** (JPSS-2/3 OMPS-LP) is confirmed for launch, with no occultation sounder planned following the 2017 ISS SAGE-III launch
  - ALTIUS (limb and occultation) is close to confirmation and will clearly help fill the gap for some variables
- We can anticipate OMPS-LP on JPSS-2/3 carrying forward the record of ozone and aerosol profile observations, augmented by SAGE-III (which also measures water vapor and a few other minor species)
Some science questions motivating the need for future observations

1. How will upper tropospheric and stratospheric (UT/S) water vapor and ozone and associated chemical processes evolve in a climate with increased greenhouse gases (GHGs) and changing ozone depleting substances (ODSs)?
2. How will any such changes in UT/S water vapor and ozone feed back on climate?
3. To what degree is the Brewer-Dobson Circulation (BDC) accelerating, and what are the implications of this change?
4. What are the interactions between deep convection, cirrus clouds, and UT/LS water vapor?
5. What are the relative roles of various stratosphere-troposphere exchange (STE) mechanisms (e.g., deep convection, monsoon circulations, intrusion events) in setting stratospheric and tropospheric composition and air quality? How will those roles change in an evolving climate?
6. How are tropospheric and surface ozone changing globally and regionally, what drives that variability on all timescales (emissions, chemical processing, convective lofting, horizontal transport, STE), and what are the implications for climate and human/ecosystem health?
7. What are the impacts of extreme perturbations in stratospheric aerosol, both natural and anthropogenic, on UT/S processes and hence on climate and air quality?
Challenges faced when advocating needed measurements (with quotes)

The comprehensive measurements from previous missions (e.g., Aura, Envisat, Odin, ACE, SAGE, UARS, …)

“These sound just like the Aura science questions!”

“NASA has spent more than three billion dollars over the past thirty years on satellite missions targeting the stratosphere, why have they not answered these questions?”

The relatively high degree of scientific understanding of many of these issues

“My model captures all the [polar ozone loss] processes really well, it agrees so well with MLS and other observations that we really don’t need any more measurements.” [might this apply for other issues too?]

“I can predict stratospheric water vapor simply with temperature profiles from three tropical sonde stations”

These lead to the following assessment of the programmatic environment in which this work takes place

“Any MLS follow-on is basically a continuity mission. You may not like that, but it is true. If you can’t figure out how to sell that, then it’s not going to get sold”

[the above comment probably applies equally to successors for other instruments]

• These (and other) points are potential weaknesses that should be addressed in the narrative of any proposals for new instruments and missions

• Unless the community can speak with a strong unified voice on what observations are essential for the future, our needs will probably be ranked low by Earth-science funding agencies, given the many urgent calls on their limited budgets
Large scale missions recommended by the 2007 Decadal Survey (DS)

- The 2007 Decadal Survey for “Earth Science and Applications from Space” recommended 15 missions for NASA (and NOAA) to implement in the ensuing decade
- So far, one has launched (SMAP), three are under development, some have been partially picked up by the NASA “Earth Venture” program (see below), and some will start development soon
- However, about seven remain to be embarked upon (though NASA technology development programs have matured them). This includes the “Global Atmospheric Composition Mission” (which, on paper, includes a microwave limb sounder)
- Now a new Decadal Survey is underway (more on this later)

The “Earth Venture” (EV) program

- This is a competed program for low cost instruments and missions, targeting focused questions that can be addressed with about two years of observations
- Space missions this has funded thus far include:
  - CYGNSS – LEO constellation GPS reflections for scatterometry/storms (launched 2016)
  - TEMPO – Geostationary UV/Visible imager targeting air quality
  - JEDI – ISS vegetation Lidar
  - MAIA – LEO multiangle polarimeter for aerosol / public health studies
### Focused science paradigm – The “Science Traceability Matrix”

- The “Science Traceability Matrix” is currently central to all NASA proposals for flight projects
- In conjunction with the proposal narrative, it describes how science goals flow down to measurement objectives and instrument/mission requirements

<table>
<thead>
<tr>
<th>Science goal</th>
<th>Science objectives</th>
<th>Measurement requirements (geophysical)</th>
<th>Measurement requirements (observables)</th>
<th>Instrument requirements</th>
<th>Mission requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typically taken from top level NASA science plan</td>
<td>Specific science question to be answered / hypothesis to be tested</td>
<td>Precision, resolution, accuracy, coverage etc. for Level 2 data</td>
<td>Precision, resolution, accuracy etc. for Level 1 data.</td>
<td>Optics, spectrometer, detector, etc. performance requirements</td>
<td>Orbit details, mission life</td>
</tr>
</tbody>
</table>

**Typical content**

Understand and improve predictive capability for changes in the ozone layer, climate forcing, and air quality associated with changes in atmospheric composition

Quantify sources of methane with 1km or better spatial resolution [accuracy, precision requirements]

Daily global observations of methane column with 1km or better spatial resolution [calibration accuracy, radiance noise, etc.]

Daily global measurements of [infrared, presumably] radiances with 1km or better spatial resolution and [spectral resolution, accuracy]

Imaging optics details

FTS / grating characteristics

Detector capability, performance

**Methane mapping example**

- Literature / assessments
- Assimilation studies (OSSEs)
- Retrieval simulations
- Engineering / technology studies

Sun-synchronous polar orbit

Five year mission life
Challenges to adopting this paradigm for SPARC-related measurements

- Most of the variables of interest to the SPARC community that can be observed from space have already been measured by at least one instrument.
- Accordingly, most new SPARC-related mission or instrument concepts are typically seeking to extend (and possibly improve) an existing record.
- Developing a “Science Traceability”-based argument for such measurements can be challenging:
  - “Why can’t you use the multi-year Aura/Envisat/etc. record to address this question?”
- Added to this, advances in data assimilation have helped fill in the “gaps” between our measurements:
  - Not only resolution/coverage gaps, but also missing parameters such as wind.
  - This echoes back to the “My model gets this stuff mostly right” sentiment.
- Even where technology advances enable dramatic improvements in spatio-temporal resolution, it is not clear that the improvements are sufficient for the underlying need:
  - For example, the “Scanning Microwave Limb Sounder” concept (see later), offers 50x50 km horizontal resolution observations every 90 minutes from ~10 km through the mesosphere.
  - However, that spatio-temporal resolution is probably still too coarse to fully resolve key convective transport and STE processes, for which length scales can be as fine as 1–2 km.
  - Some kind of OSSE-like study could help set requirements for new observations and/or quantify the benefits of innovative measurement concepts.
Extra missions and instruments for NASA – climate continuity

• Concurrent with developing the Decadal Survey and Earth Venture missions over the past decade NASA, has also been asked to take on additional work (typically without additional funds)
  – More responsibility for JPSS (formerly NPOESS) and other missions/programs: OMPS-LP, CERES-like measurements, total solar irradiance and a Landsat Data Continuity Mission
  – Other “climate continuity” measurements: A GRACE “Follow On” (following extensive lobbying from the GRACE community) and deploying SAGE-III on the ISS
  – Developing and launching the OCO-2 mission following the failed launch of OCO, and an OCO-3 mission (current status unclear) to continue and augment the OCO-2 record
• All these inevitably reduce funds available for the Decadal Survey and Earth Venture programs
• Accordingly, NASA commissioned a study from the US National Academy of Sciences to suggest a framework for evaluating “continuity” needs and prioritizing such observations in the future
A potential NASA approach for ranking “continuity” needs

**Study finding:** “The starting point for a framework that discriminates among competing continuity-relevant measurements is the identification of Quantified Earth Science Objectives” (QESOs)

A couple of the candidate QESOs used as illustrations in the report:

1. Narrow the IPCC AR5 uncertainty in equilibrium climate sensitivity (ECS) (1.5 to 6°C at 90% confidence) by a factor of 2
2. Detect decadal change in the effective climate radiative forcing (ERF) to better than 0.05 Wm\(^{-2}\) (1σ)

**Suggested scheme for prioritizing missions:**

\[
\text{Value} = f(\text{Importance} \times \text{Utility} \times \text{Quality} \times \text{Success probability, Affordability})
\]

- How important is this quantified objective?
- How well will the mission make those measurements?
- How likely is it that the measurements / mission will succeed?
- How readily can these measurements be afforded?
- How useful are the proposed geophysical measurements for achieving that objective?

The new NASA (and NOAA/USGS) Decadal Survey on “Earth Science and Applications from Space”, currently ongoing, appears, as far as we know, to be embracing this framework, at least in that it solicited white papers that described measurements needs using this terminology.
Some potential high level “QESOs” of relevance to SPARC

- The new Decadal Survey solicited white paper inputs from the community in Fall 2015 and Spring 2016;
- Several groups within the SPARC community provided material for their consideration
- A white paper submitted by members of the MLS team and others articulated the role of the UT/S in addressing the two sample QESOs quoted on the previous slide
- We also suggested some additional, more UT/S-specific, candidate QESOs
  - Detect change in global stratospheric water vapor to better than 0.1 ppmv / decade (~2.5% / decade, the associated radiative impact of which is in line with meeting the radiative forcing QESO described previously)
  - Partition contributions to decadal change in stratospheric ozone profiles at polar, middle and tropical latitudes from GHGs (through changes in temperature and circulation) and ODSs to better than 50% (1σ), where trends in those contributions are discernible against the natural interannual variability. (Important for the impact of solar UV on ecosystems and for ECS.)
  - Partition contributions to decadal change in tropospheric ozone on global, hemispheric, and regional scales from changes in emissions and stratospheric influx to better than 50% (1σ), where trends in those contributions are discernible. (Important for air quality and climate.)
- However, there are many other (perhaps more compelling) candidates, and we welcome discussion
Measurement concepts under development
UV limb aerosol observations – MASTAR (Matt DeLand, USA)

**Concept Name:** Multi-Angle Stratospheric Aerosol Radiometer (MASTAR)

**Team:** Matthew DeLand (SSAI), Peter Colarco (NASA GSFC), Matt Kowalewski (GESTAR), Luis Ramos-Izquierdo (NASA GSFC), Nick Gorkavyi (SSAI)

**Measurements:** Global stratospheric profiles of aerosol parameters using multi-azimuth angle limb imaging

**Approach:**
- Simplified version of OMPS-Limb instrument
- Views eight different azimuth directions simultaneously for improved sensitivity and characterization of size distribution
- 3U Cubesat form factor

**Status:**
- Laboratory prototype developed
- NASA “Instrument Incubator Program” (IIP) funding effort (commencing 2017) to further develop prototype and perform field testing
**Concept Name:** Gas Filter Correlation Radiometer (GCFR) Limb Solar Occultation (GLO). Aka “Solar Occultation Constellation for Retrieving Aerosol and Trace Element Species” (SOCRATES)

**Team:** Richard Bevilacqua (NRL), Scott Bailey (Virginia Tech.) and colleagues

**Measurements:** Gas correlation solar occultation profiles of T, H₂O, O₃, CH₄, N₂O, HCN, CO, HDO, HCl, HF and aerosol extinction (Visible to SWIR)

**Approach:**
- Multi-satellite approach gives much denser coverage than conventional single-spacecraft occultation
- Imaging detectors provide 23 full solar images on 4 separate focal plane assemblies

**Status:**
- Previously proposed to “Earth Venture” call
- New technology being developed under NASA IIP (commenced 2017)
UV/Vis/SWIR limb sounding – CATS (Doug Degenstein, Canada)

**Concept name:** Canadian Atmospheric Tomography System (CATS)

**Team:** Doug Degenstein (U. Sask) and colleagues; Honeywell

**Measurements:** UV/Visible/SWIR limb profiling of ozone, BrO, NO₂, and aerosol

**Approach:**
- Three modules with similar design to Odin OSIRIS
- Measure seven different look directions to enable tomographic reconstruction of fields

**Status:**
- Technology developed under Canadian Space Agency Space Technology Development program
- Work underway to fly blue module in balloon in 2018
- Variations of CATS are under consideration for Canadian micro-satellite development
**Concept name:** Spatial Heterodyne Observations of Water (SHOW)

**Team:** Adam Bourassa (U. Sask) and ABB Inc. Canada

**Measurements:** UTLS water vapor; tomographic limb profiling in the UTLS with high vertical and horizontal resolution (target 300 m vertical; 20 km horizontal)

**Approach:**
- Vertical imaging of spectral limb scattered radiance
- High spectral resolution coverage of 1.36 µm vibrational absorption band of water vapor

**Status:**
- Developed under Canadian Space Agency Space Technology Development program
- Prototype demonstration measurements from stratospheric balloon flight in 2014
- Recent airborne simulator demonstration from NASA ER-2 in July 2017

**SHOW prototype adaptation for ER-2 flight 2017**

**Monolithic optics for spatial heterodyne interferometer**
**Concept name:** Atmospheric Limb Tracker for the Investigation of the Upcoming Stratosphere (ALTIUS)

**Team:** Didier Fussen (Institute d’Aeronomie Spatial, Belgium) and colleagues

**Measurements:**
- 2D limb spectral imaging and solar/stellar occultation
- Limb: O$_3$, NO$_2$, H$_2$O?, CH$_4$?, aerosol (inc. PSC/PMC)
- Solar occultation: As above (with greater confidence on H$_2$O, CH$_4$), plus OCIO, BrO, NO$_3$, Temperature
- Stellar occultation: As solar occultation, but without Temperature, BrO, PMC

**Approach:**
- Continuous 2D limb imaging with acousto-optic and Fabrey-Perot filters
- Additional pointing information from curvature within limb image

**Status:** On track for Preliminary Design review in 2018, with launch in 2020–2021 under ESA Earth Watch
Concept name: Limb Imaging Fourier transform Experiment (LIFE)

Team: Doug Degenstein (U. Sask.), ABB

Measurements:
• Main target – profiles of O₃, H₂O, N₂O, and CH₄

Approach:
• Thermal emission limb Fourier transform spectrometer
• Covers 7–14 µm

Status:
• Being developed through Canadian Space Agency “Flights for the Advancement of Space Technology” (FAST) program
• A version will fly on a stratospheric balloon in the Autumn of 2019
• CSA funding expected to continue through the “Space Technology Development” program (STDP). LIFE will be proposed within future mission concepts
Concept name: AtmoSat
Team: Johannes Orphal (IMK), Martin Riese (FZJ)

Measurements:
- \( T, p, H_2O, HDO, O_3, CH_4, N_2O, CFC-11, CFC-12, HCFC-12, SF_6, HNO_3, N_2O_5, ClONO_2, HO_2NO_2, PAN, C_2H_6, H_2CO, NH_3, \) others, cirrus
- 1 km vertical resolution from upper troposphere through stratosphere (2 km above)

Approach:
- Centered on the “Gimballed Limb Observer for Radiance Imaging of the Atmosphere” (GLORIA) instrument
- 2D-limb imaging/scanning Fourier transform interferometer; 4 – 15 \( \mu \)m
- Includes modes for “Landscape” (dynamics) and “Portrait” (chemistry) observations

Status: Highly recommended by German Research Council; final decision by BMBF in summer 2018
Microwave limb sounding – SMILES-2 (Massato Shiotani, Japan)

**Concept name:** Superconducting Submillimeter-Wave Limb-Emission Sounder 2 (SMILES-2)

**Team:** Massato Shiotani (Kyoto University) and colleagues at JAXA, NICT, and elsewhere

**Measurements:**
- Temperature, Wind, O₂, O₃, N₂O, CO, ClO, BrO, N₂O₃, H₂CO, NO, NO₂, CO, ClO, HCl, H₂O, HOCl, HNO₃
- Vertical range, 15–110 km

**Approach:** Superconducting submillimeter limb sounder with receivers in five spectral regions from 480 to 2060 GHz

**Status:** To be proposed for future launch opportunity (launch no earlier than 2023)
**Concept Name:** Continuity MLS  
**Team:** Nathaniel Livesey, Michelle Santee, Robert Jarnot, Goutam Chattopadhyay, others (JPL)  
**Measurements:** O$_3$, H$_2$O, CO, HNO$_3$, N$_2$O, CI, HOCl, BrO, HO$_2$, CH$_3$CN, HCN, CH$_3$Cl, CH$_3$OH, SO$_2$, T, GPH, IWC, IWP + H$_2$CO and others TBD  
**Approach:**  
- Microwave Limb Sounder with a single receiver in the 340 GHz region  
- Adding a 640 GHz channel would add HCl and improve some other species  
- Technology advances enabled by the communications industry allow far lower cost than previous-generation MLS instruments  
**Status:** Technology development funded under NASA IIP grant, airborne instrument planned for demonstration on the ER-2 in March 2018.
**Concept Name:** Scanning Microwave Limb Sounder (SMLS)

**Team:** Nathaniel Livesey, Michelle Santee, Robert Jarnot, Goutam Chattopadhyay, others (JPL)

**Measurements:** $\text{O}_3$, $\text{H}_2\text{O}$, CO, $\text{HNO}_3$, $\text{N}_2\text{O}$, ClO, HOCl, BrO, HO$_2$, CH$_3$CN, HCN, CH$_3$Cl, CH$_3$OH, SO$_2$, T, GPH, IWC, IWP + $\text{H}_2\text{CO}$ and others TBD

**Approach:**
- As for continuity sounder but adds 2-D scanning capability using much of the same hardware
- 2D scan enabled by cooling the detector to ~20–40 K, providing ~5-fold improvement in signal to noise, thus ~25-fold reduction in needed integration time
- Provides multiple measurements per day over a wide range of latitudes (orbit inclination dependent)

**Status:** Technology development funded under multiple NASA IIP grants, airborne instrument planned for demonstration on the ER-2 in March 2018.
**Concept Name:** Stratospheric Water Inventory – Tomography of Convective Hydration (SWITCH)

**Team:** Nathaniel Livesey, William Read, Goutam Chattopadhyay, Robert Jarnot, Adrian Tang (JPL)

**Measurements:** High resolution (500 m vertical, 10 km along track) tomography of water vapor (other molecules possible with in-flight retuning)

**Approach:**
- Active constellation with multiple 380 GHz transmitters and single receiver viewing all transmitters simultaneously
- Vertical resolution set by spacing of transmitter satellites
- Targeting 6U CubeSat form factor for transmitters and receiver

**Status:** Technology development starting under NASA IIP grant. Plan for balloon-to-balloon test in 2019
What can the SPARC Data Assimilation Working Group do to help?
OSSE-like approaches to advocacy of new measurements

• Building on the extensive use of OSSEs in the NWP community, OSSE-like calculations often underpin the arguments for new observations (not only in Earth science, but increasingly in planetary science also)

• In the case of NWP OSSEs there are generally agreed metrics for quantifying measurement system utility

• When proposing measurements in disciplines beyond NWP, the choice of metric is driven by the science question targeted, and often chosen by the proposer

• However, unless a particular metric or science goal is already widely agreed to be important (e.g., quantification of CO₂ and CH₄ sources/sinks), further explanation (and therefore study) is needed to underscore the importance of the metric and associated science goal (“why do we care”?)

• Quantitatively connecting SPARC-related science questions back to Earth science parameters that are universally recognized as important may well help make the case for future measurements

• Among potential parameters to tie science goals back to, some high profile ones include:
  1. Net radiative forcing and its long term evolution
  2. Equilibrium climate sensitivity
  3. Surface ozone and its evolution on timescales from hourly to decadal
  4. Surface UV insolation and its evolution on timescales from hourly to decadal

• That said, stratospheric contributions to #1–3 are perhaps smaller and more certain compared to contributions from, for example, boundary layer clouds

• #4 is fairly well understood and well described by current and anticipated measurement/model capabilities
Establishing quantified objectives and linking them to measurements

• We do not yet know what stance the new Decadal Survey will take on “continuity observations”
• If they suggest that NASA establish a formal process for entertaining proposals for such observations, it is reasonable to expect that some quantitative framework will be at the core of it
• However, who defines the these objectives, and the metrics or processes to quantify their “Importance”?
• The modeling and assimilation community could clearly play an important role in any such process, whether dictated top down by NASA and/or other agencies, or through bottom up collaborative work with individual proposal teams
• What steps could the SPARC DAWG community take now to lay the ground work for defining relevant objectives and associated measurement needs?
• What are the core quantified objectives for the SPARC (and DAWG) community that we can use as anchor points for an argument for continuity observations?

• We recognize that this is a USA/NASA-focused discussion of the programmatic landscape
• However, the underlying issues are common to all, and the leadership stances are likely shared by other funding agencies
Summary

• In the coming years the number of UT/S species observed near globally from space with good vertical resolution (i.e., 1–5 km) will dramatically decline

• Once Aura MLS, ACE FTS, Odin OSIRIS and SMR observations cease we will have only:
  – Ozone and aerosol from OMPS-LP
  – Ozone, water vapor, aerosol, NO₂, NO₃, and OCIO from SAGE-III ISS

• We will no longer have N₂O, CH₄, HNO₃, ClO, ClONO₂, HCl, BrO, HOCl, CH₃Cl, HO₂, CO, HCN, CH₃CN, HDO, CH₃OH, and many others too numerous to list

• ALTIUS, if confirmed and successfully flown, will be very valuable in helping to redress this gap

• Realistically, it will be at least five years (more likely ten) before any future mission can be ready for launch

• How long a gap can we tolerate? Are we ready for it? What will suffer? What robust and quantitative arguments can we make for re-establishing the measurement capabilities?

• Data assimilation and other tools developed by the SPARC DAWG community could significantly help articulate the case for continued/augmented measurements