An Atmospheric CO_2 Gap Analysis for CEOS

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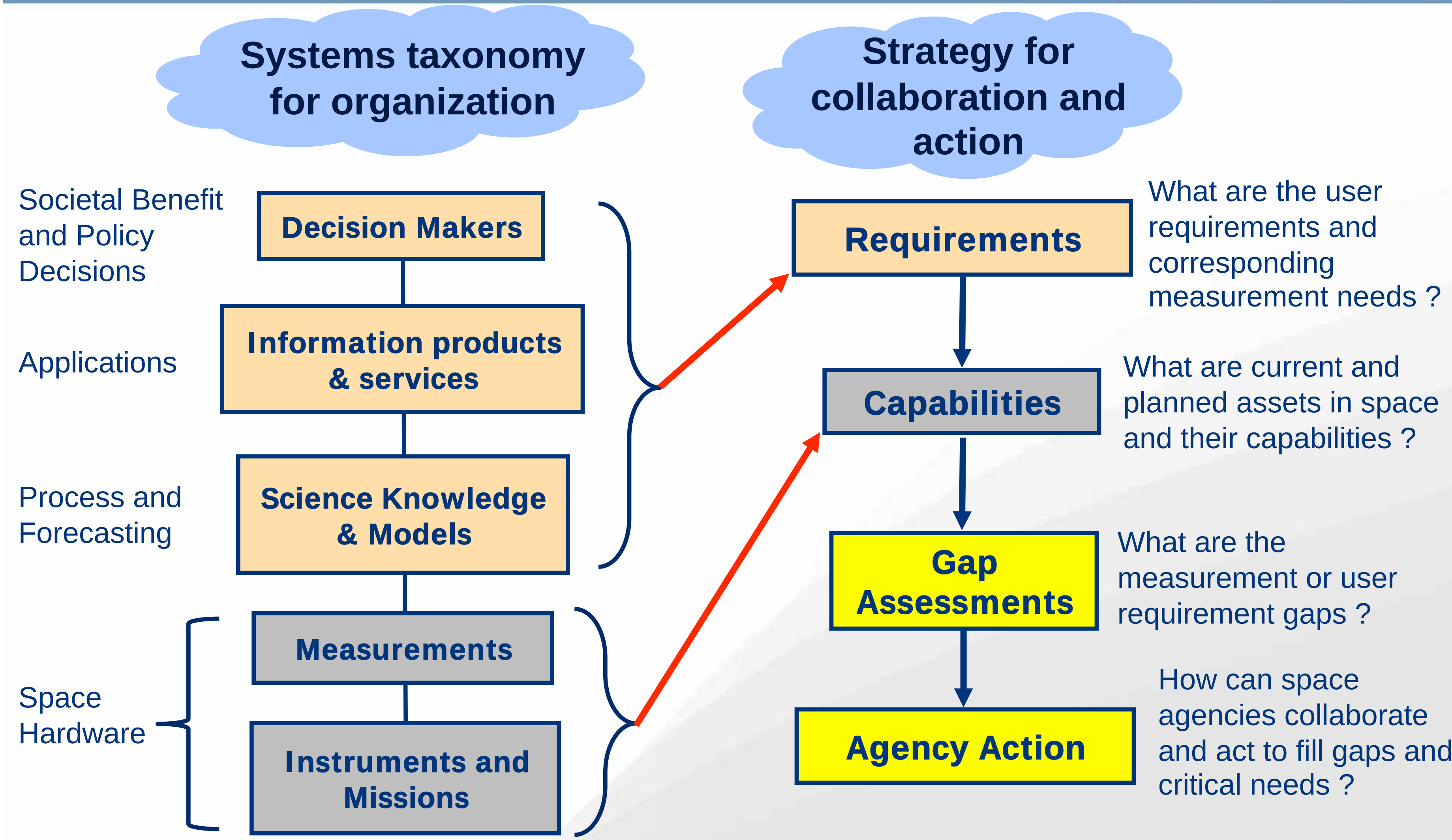
Systems Approach to Climate



Starting Point… the CEOS Databases

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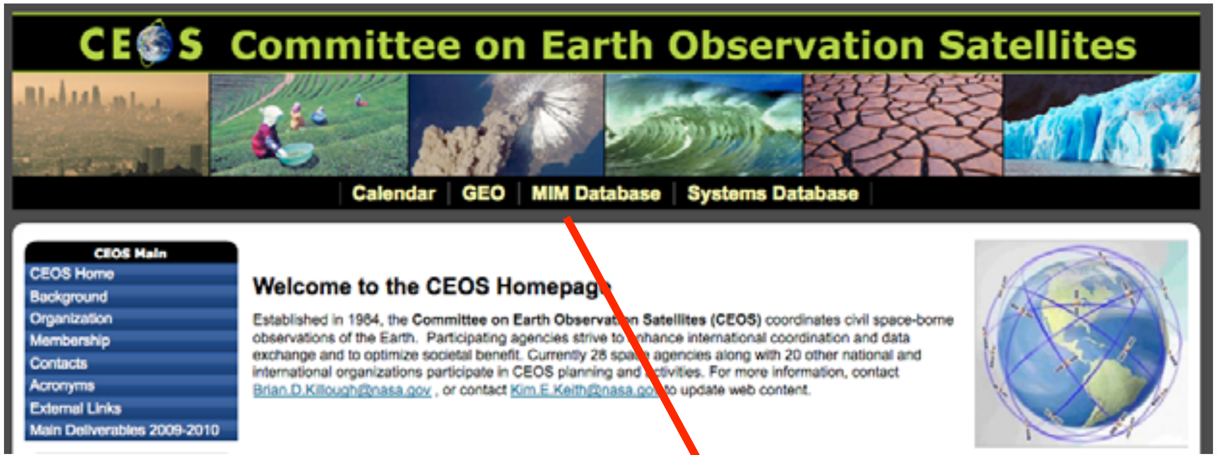
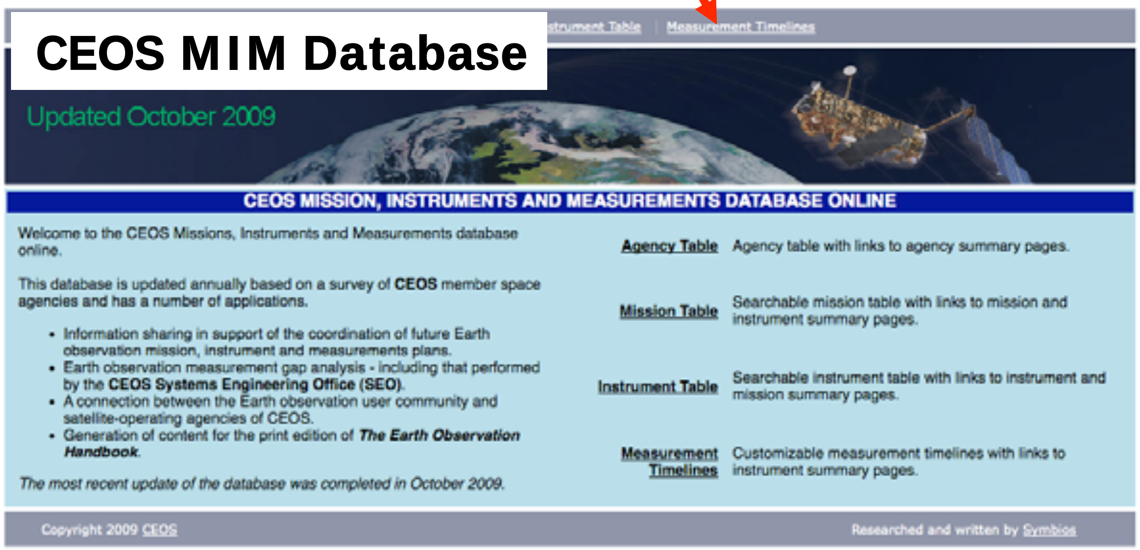
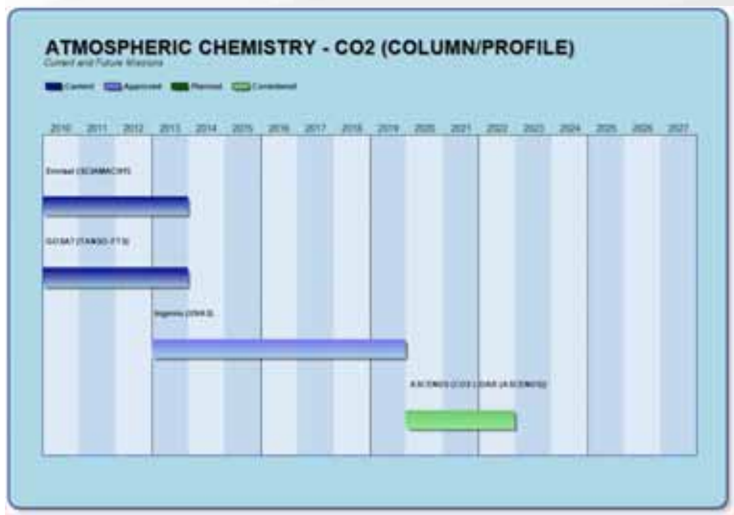


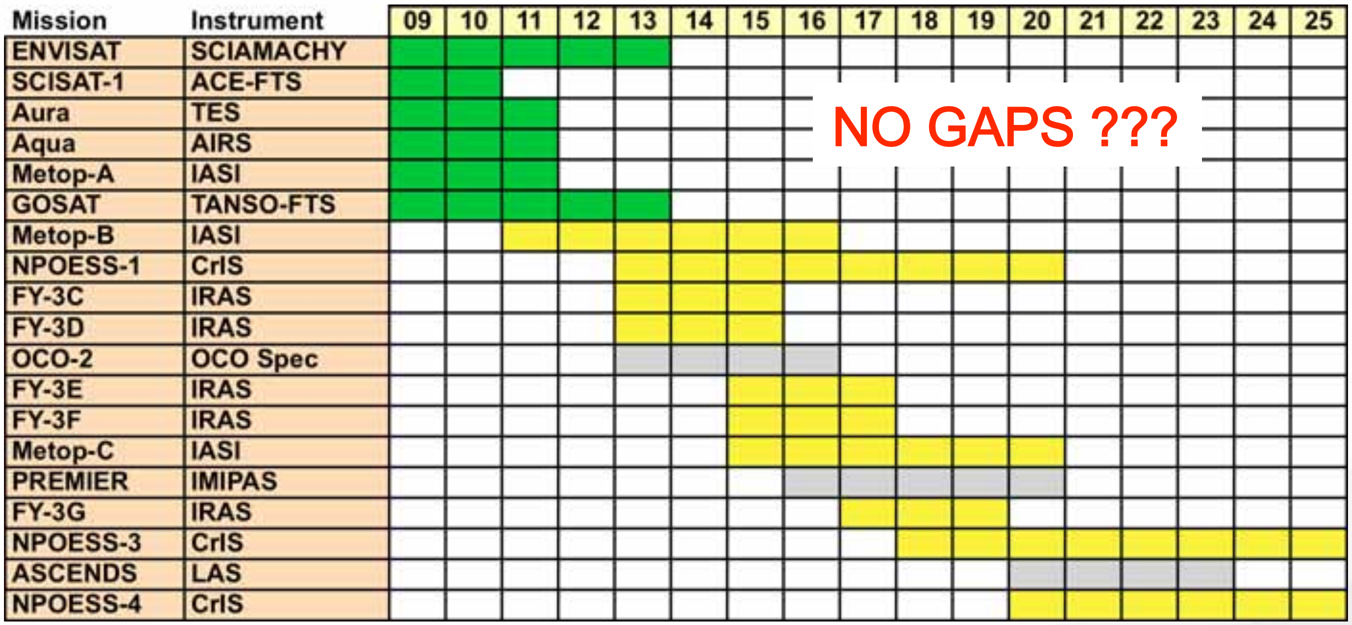
Search for CEOS missions that measure CO_2 … you will find only 4 on the "official" agency MIM list. We know there are many more …

Further web searches found valid CO_2 data products produced by 19 CEOS missions.





General Mission Timeline Results



- Timelines from the expanded mission list (above) **DO NOT** accurately reflect gaps.
- Gap analyses must consider **instrument types** (measurement approach), **atmospheric layers**, and **detailed requirements** (accuracy, spatial resolution, temporal resolution).
- Automation of the detailed gap analysis process using existing CEOS databases is not currently possible … maybe in the future.

Next... Search the Systems Database for Requirements

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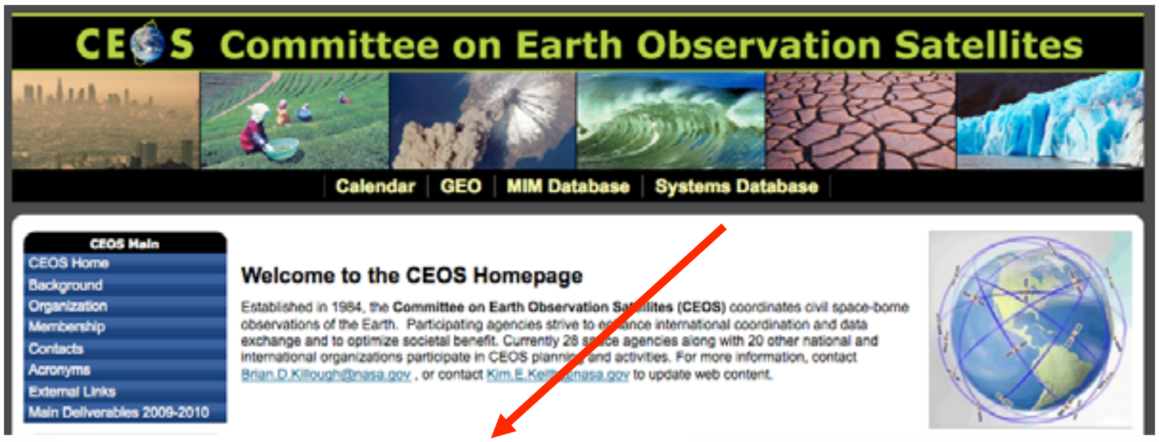


CEOS Systems Database

www.ceos-sysdb.org

Search for CO_2 measurement requirements from GCOS, EUMETSAT, and WMO.

Examples: Spatial resolution, vertical resolution, repeat cycle, accuracy, spectral resolution, atmospheric layers.

Param Type	Application	Source	Accuracy (RMS)		Δx (km)		Δz (km)		Δt (h)		δ (h)	
			thresh	break	thresh	break	thresh	break	thresh	break	thresh	break
Lower Troposphere	Climate	GCOS	2.00000	1.50000	500.00000	70.00000	2.00000	1.00000	12.00000	6.00000	1440.00000	480.00000
Lower Troposphere	Composition and climate	EUM	5.00000	3.00000	250.00000	50.00000	5.00000	2.00000	24.00000	12.00000	6.00000	0.50000
Lower Troposphere	Atmospheric chemistry	WMO	5.00000	3.00000	500.00000	150.00000	4.00000	2.00000	24.00000	12.00000	168.00000	96.00000
Higher Troposphere	Climate	GCOS	2.00000	1.50000	250.00000	100.00000	2.00000	1.50000	6.00000	4.00000	1440.00000	480.00000
Higher Troposphere	Composition and climate	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	6.00000	0.50000
Lower Stratosphere	Climate	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	4380.00000	1680.00000
Lower Stratosphere	Composition and climate	EUM	5.00000	3.00000	250.00000	100.00000	3.00000	2.00000	168.00000	24.00000	6.00000	0.50000
Upper Stratosphere & Mesosphere	Climate	GCOS	2.00000	1.50000	500.00000	350.00000	4.00000	3.00000	6.00000	4.00000	4380.00000	1680.00000
Upper Stratosphere & Mesosphere	Composition and climate	EUM	10.00000	7.00000	500.00000	200.00000	5.00000	2.00000	168.00000	24.00000	6.00000	0.50000
At Cloud Top	Climate	GCOS	2.00000	1.50000	500.00000	100.00000	N/A	N/A	6.00000	4.00000	4380.00000	1680.00000
At Cloud Top	Composition and climate	EUM	1.00000	0.70000	50.00000	25.00000	N/A	N/A	12.00000	6.00000	6.00000	0.50000

Requirements

What are the Detailed Requirements ?

Profile or Column Atmosphere Layer	Application	Source	Accuracy (ppmv)			Δx (km)			Δz (km)			Repeat Cycle (h)		
			thresh	break	obj	thresh	break	obj	thresh	break	obj	thresh	break	obj
CO_2 Profile Lower Troposphere Weighted Columns	Chemistry	WMO	19	12	8	500	150	50	4	2	1	24	12	6
	Climate	GCOS	8	5	4	500	70	10	2	1	0.5	12	6	3
	Composition & Climate	EUMETSAT	19	12	8	250	50	10	5	2	0.5	24	12	6
CO_2 Profile Higher Troposphere Weighted Columns	Climate	GCOS	8	5	4	250	100	50	2	1.5	1	6	4	3
	Composition & Climate	EUMETSAT	19	12	8	250	50	10	5	2	0.5	24	12	6
CO_2 Profile Lower Stratosphere	Climate	GCOS	8	5	4	500	350	250	4	2	1	6	4	3
	Composition & Climate	EUMETSAT	19	12	8	250	100	50	3	2	1	168	24	12

- **GCOS Climate requirements are the most restrictive. For example, objectives of 4-ppm accuracy, 10-km spatial resolution and 3-hour repeat cycle are required in the lower troposphere.**

Source: WMO GOS Dossier Volume-5 compiled for WMO by B. Bizzarri.

What are the Detailed Mission Capabilities ?

Detailed mission capability information is not currently available in the MIM or Systems Databases so this step requires extensive web searches. Hopefully, in the future this level of detail will exist in the databases so this process can be automated.

Mission	Instrument	*Resolutions* Spatial Sample Δx (km)	*Resolutions* Spatial Swath (km)	*Resolutions* Vertical Δz (km)	*Resolutions* Temporal Repeat Cycle Δt (hrs/days)	*Accuracy* Total Troposphere Column
Nadir Absorption, Total Troposphere Columns weighted to the Lower Troposphere						
ENVISAT	SCIAMACHY	30 x 60	960		840 (35 days)	2% (8 ppm)
GOSAT	TANSO-FTS	10.5	790		72 (3 days)	1% (4 ppm)
OCO	OCO Spectrometer	1.3 x 2.25	10		384 (16 days)	0.25% (1 ppm)
ASCENDS	LAS	TBD	TBD		384 (16 days)	0.25% (1 ppm)
Nadir Emission, Total Troposphere Columns weighted to the Mid-Troposphere and Upper-Troposph						
EOS-AQUA	AIRS / AMSU	13	1620		384 (16 days)	0.4% (1.5 ppm)
EOS-AURA	TES	0.5 x 5.0	50		384 (16 days)	0.3% (1.3 ppm)
Metop (A,B,C)	IASI	12	2052		12 hours	0.5% (2 ppm)
METOP and NOAA	HIRS	10	2240		12 hours	1% (4 ppm)
FY-3 (C,D,E,F,G)	IRAS	17	952		12 hours	0.5% (2 ppm)
NPOESS (1,3,4)	CrIS	14	2200		12 hours	0.5% (2 ppm)
Limb Viewing, Stratosphere Profiles						
SCISAT-1	ACE-FTS	500		3	annual	2.5% (10 ppm)
ENVISAT	SCIAMACHY	960		3	840 (35 days)	1% (4 ppm)
SCISAT-2	ACE-FTS	500		3	annual	2.5% (10 ppm)
ENVISAT	MIPAS	300		3	840 (35 days)	0.7% (3 ppm)
PREMIER	IMIPAS	300		3	840 (35 days)	0.7% (3 ppm)

Which Missions Meet the Requirements ?

Mission	Instruments	Requirements Summary: Accuracy	Spatial	Temporal	Vertical
Lower Troposphere					
ENVISAT	SCIAMACHY	Green	Green	Red	Gray
GOSAT	TANSO-FTS	Green	Green	Red	Gray
OCO-2	OCO Spectrometer	Green	Green	Red	Gray
ASCENDS	LAS	Green	Green	Red	Gray
Mid-Troposphere and Upper-Troposphere					
EOS-AQUA	AIRS / AMSU	Green	Green	Red	Gray
EOS-AURA	TES	Green	Green	Red	Gray
Metop (A,B,C)	IASI	Green	Green	Yellow	Gray
METOP and NOAA	HIRS	Green	Green	Yellow	Gray
FY-3 (C,D,E,F,G)	IRAS	Green	Green	Yellow	Gray
NPOESS (1,3,4)	CrIS	Green	Green	Yellow	Gray
Stratosphere					
SCISAT-1	ACE-FTS	Yellow	Yellow	Red	Yellow
ENVISAT	SCIAMACHY	Yellow	Yellow	Red	Yellow
SCISAT-2	ACE-FTS	Yellow	Yellow	Red	Yellow
ENVISAT	MIPAS	Yellow	Yellow	Red	Yellow
PREMIER	IMIPAS	Yellow	Yellow	Red	Yellow

Green: Meets Some or All Objectives (maximum)
Yellow: Meets Some or All Threshold Requirements (minimum)
Red: DOES NOT MEET REQUIREMENTS

Largest issue is temporal sampling (repeat cycle) near the surface ...

Limited LEO missions do not allow adequate sampling to achieve desired threshold requirement of 24-hr (one-day) repeat cycle. GOSAT is best at 3-days due to its wide (790-km) crosstrack scanning capability, but it does not make constant measurements across the swath width.

Detailed Timeline Analysis

Mission	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Lower Troposphere																	
ENVISAT																	
GOSAT																	
OCO-2										GAP							
ASCENDS																	
Mid-Troposphere and Upper-Troposphere																	
EOS-AQUA																	
EOS-AURA																	
Metop (A,B,C)																	
METOP and NOAA	5	5	5	5	4	4	3	3	2								
FY-3 (C,D,E,F,G)						2	2	3	2	3	2	3	2	2			
NPOESS (1,3,4)										2	2	3	2	2	2	2	2
Stratosphere																	
SCISAT-1																	
ENVISAT																	
SCISAT-2																	
PREMIER																	

Detailed timeline analysis takes into consideration the instrument type and atmospheric layer.

Largest issue is the potential time gap beyond OCO-2.

It is unlikely that ENVISAT and GOSAT will last beyond 2015. OCO-2 has fuel for 8-years (till 2020). ASCENDS is uncertain for a 2020 launch and may be later.

OCO-2 may be the only near-surface CO_2 mission in 2015 with limited repeat cycle (16 days) and spatial coverage (swath width 10-km).

Gap Analysis Results

- Atmospheric CO_2 measurements in the lower troposphere (near surface), critical for measuring sources and sinks, have a time gap beyond 2016.
  – see **TIMELINE ANALYSIS**

- Temporal sampling (repeat cycle) requirements are not met for all lower troposphere missions and most mid-troposphere missions. GCOS threshold requirements are 12 hours (lower trop) and 6 hours (middle trop), which requires multiple coordinated LEO satellites with wide swath capabilities.
  – see **REQUIREMENTS ANALYSIS**

- Accuracy requirements (< 4-ppm) are met for all middle-troposphere instruments and most lower-troposphere instruments (exception is SCIAMACHY). Most future low-troposphere instruments expect ~1-ppm accuracy, which will significantly improve our knowledge of sources and sinks.
  - see **REQUIREMENTS ANALYSIS**

Lessons Learned and the Future

Lessons Learned

- Future gap analyses efforts will require detailed assessments of **timelines and requirements** to reach valid conclusions. Online automation of the gap analysis process is not yet possible.

Future Work

- Capabilities need to be updated in MIM database. Agencies need to provide more accurate and complete data for the 2010 MIM data request.
- Plan to review existing requirements and add more space-based measurement requirements for CO_2 and other climate ECVs.
- Consider adding data availability or quality indicators to instrument-measurement combinations.
- Conduct a CH_4 gap analysis. Significant discussion at the recent ACC-5 meeting included several new mission concepts for Methane (CH_4).
- Conduct a coverage analysis for CO_2 to determine the relationship between repeat cycle, swath width and the number of satellites to support solution options for the CO_2 measurement gap.

The full CO_2 Gap Analysis report is available on the CEOS website.

Backup Charts

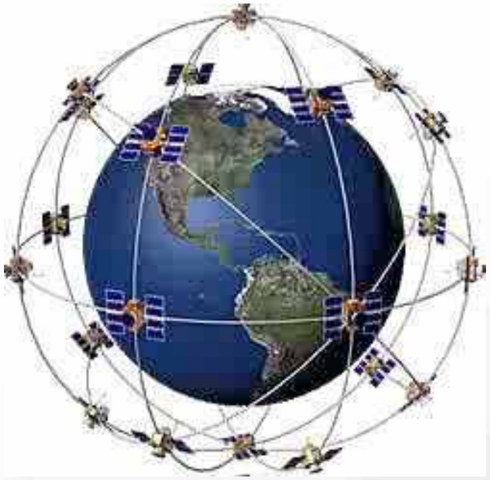
Near-term Potential Solutions

- **Extend existing missions**: Utilize the full mission capacity of ENVISAT and GOSAT to make total column CO_2 measurements in the lower troposphere at least until OCO-2 is launched.
- **Future mission lifetimes**: Consider designing future space missions with more capacity for extended operations. This "research to operations" concept may extend science missions from 3-5 years to beyond 10 years.
- **Adjust new missions**: Optimize time overlap of current and future missions by adjusting launch schedules or adjusting orbits to maximize coverage or sampling.
- **Add new missions**: Consider new missions focused on near-surface (lower troposphere) atmospheric CO_2 measurements with a direct benefit to studies of sources and sinks. This requires absorption spectrometers or lasers focused in the near-IR.

  For example, a JAXA GOSAT follow-on, ESA Earth Explorer CarbonSat 2018 concept, NASA OCO-3 instrument (Mission of Opportunity), Mini-Carb (CNES).

  Are there others ???

Long-term Potential Solution: Constellation Concept



- A constellation of CEOS satellites dedicated to CO_2, requires careful consideration of requirements and must be coordinated with in-situ and ground resources.
- Repeat cycle must be considered along with accuracy (ppm), spatial sampling (single sample) and swath coverage.

  Example:
  GOSAT: 3-day repeat, 4-ppm accuracy, 10.5-km/sample, 790-km swath
  * High repeat cycle achieved with large swath width.
  OCO-2: 16-day repeat, 1-ppm accuracy, 1.3-km/sample, 10-km swath
  * Narrow swath width and sample size to optimize cloud-free scenes.

- Other new mission concepts are being considered internationally, but it is uncertain whether a single satellite, or a constellation of coordinated satellites can meet the full set of space-based requirements.