Optimising Imaging Fourier Transform Spectrometer for GHG from LEO

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The Future…

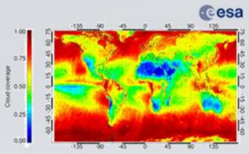
Our generation is facing the inevitable: measurement of GHGs will need to become operational for generations to come to monitor our progress by independent and irrefutable methods. The true niche and economic benefit for operational GHG satellite observations needs to consider the innovation potential in ground sensing solutions (in-situe, drones, aerostats).

Satellites offer unique capabilities:

- Global coverage (ultimate validation of bottom-up inventories)
- Unrestricted access to air space means no one can escape (targeted observations)
- Irrefutable emitters comparison (same sensor/errors for all)
- Follow transport and regional interdependencies.
- Potential to capture unexpected emitters

LEO satellites drawbacks compared ground/air:

- Far from target: poor light collection capacity
- Strongly discontinued view at given ground targets
- Clouds block most of the view
- Emitters are buried under total air column
- High cost



Global annual mean cloud cover derived from three years (2007–09) of Envisat data.

Fully Exploiting the LEO Vantage Point

The ideal spectroscopic sensor in LEO would maximize photon collection for the given observable FOV to boost SNR or allow finer resolution.

Your handles at the SNR problem:

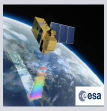
1. Sensor Aperture: bigger is better but rapidly drives cost (> cubic mass dependency…)
2. Orbit height: The closer the better but orbital drag problematic below 600 km.
3. Integration time: Crazy high ground velocity limits useable time to a few seconds (<20s typical)
4. Pixel FOV vs total FOV: users want small pixels, SNR wants big one!
5. Do not discriminate photons based on color: Don't send them back to ground!

(Items 3 and 4: Typically not independent)

Dispersive sensors try to maximize the swath but must sacrifice the along track FOV.

What about maximizing both!

An imaging FTS naturally allows concurrent light integration in the cross & along track direction giving it a strong photon collecting advantage.



Tuning your Imaging FTS for the Job!

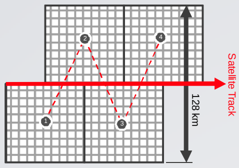
Tracking a fixed square FOV allows to acquire the spectrum in the time domain while maximizing photons collection from the FOV underneath. The Keystone effect sets practical limits to FOV.

	Instantaneous FOV (km) for given array size				
Pixel FOV (m)	128	256	512	1024	2048
50	6	13	26	51	102
100	13	26	51	102	205
250	32	64	128	256	512
500	64	128	256	512	1024
1000	128	256	512	1024	2048
2000	256	512	1024	2048	4096

	Corresponding FOV angle				
Pixel FOV (m)	128	256	512	1024	2048
50	0.6	1.2	2.4	4.9	9.8
100	1.2	2.4	4.9	9.8	19.4
250	3.1	6.1	12.2	24.1	46.2
500	6.1	12.2	24.1	46.2	81.0
1000	12.2	24.1	46.2	81.0	119.3
2000	24.1	46.2	81.0	119.3	147.3

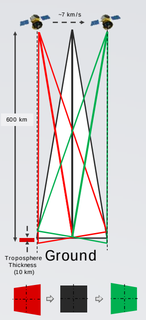
	stare period (s) for contiguous mapping along track				
Pixel FOV (m)	128	256	512	1024	2048
50	0.9	1.7	3.4	6.8	13.7
100	1.7	3.4	6.8	13.7	27.3
250	4.3	8.5	17.1	34.1	68.3
500	8.5	17.1	34.1	68.3	136.5
1000	17.1	34.1	68.3	136.5	273.1
2000	34.1	68.3	136.5	273.1	546.1

We selected here a configuration that maintains a high SNR at the pixel level (> 180) with the least ambitious detector candidate (128 x 128). We compensated the smaller detector FOV by proposing a mosaic interleaved contiguous staring pattern which also minimize Keystone.



Sensor input aperture	8 cm
Detector size	128 x 128 (per band)
Pixel scale	500 m x 500 m
Field of Regard (FOR)	64 km x 64 km
Swath coverage per orbit	128 km (interleave mosaic)
Dwell Time per FOR	4 sec
Pointing mirror scan during dwell	+/- 1.4º
Pointing stability (1/10 pixel criteria)	75 µrad RMS
Spectral bands: Ø O2: B-1 Ø CO2: B-2, B-4 Ø CH4: B-3, B-5 Ø CO: B-5	Band 1: 7880-8000 cm^{-1} Band 2: 6226-6256 cm^{-1} Band 3: 5990-6020 cm^{-1} Band 4: 4980-5010 cm^{-1} Band 5: 4190-4260 cm^{-1}
Spectral grid	0.2 cm^{-1} (MOPD = 2.5cm)
SNR per pixel	> 180

Minimizing the Keystone Effect



An IFTS prefers that interferograms extracted from any given pixel see the same spectral content for the dwell duration. A small image stretch along one edge can quickly lead to more than one pixel offset in the corner of the image depending on array size. Images resampling within the acquired cube can be used to attenuate the Keystone effect within practical limits.

	Keystone Effect pixel shift at corners				
Pixel FOV (m)	128	256	512	1024	2048
50	0.22	0.88	3.57	14.70	62.24
100	0.44	1.79	7.35	31.12	140.42
250	1.12	4.66	20.03	93.54	540.36
500	2.33	10.01	46.77	270.18	N/A
1000	5.01	23.39	135.09	N/A	N/A
2000	11.69	67.54	N/A	N/A	N/A

Pattern of pixel shift on FOV during dwell

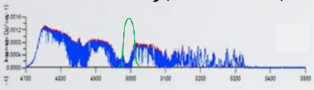
Keystone affects mostly image corners

ABB has demonstrated successfully spectral cube extraction from ortho-rectified image set on SITELLE, an astronomical IFTS using 2k x 2k array detectors.

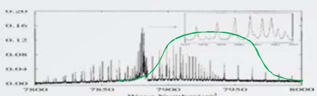
Careful Band Selection

Bands are selected to minimize the distributed photon noise disadvantage of FTS and allow using an interferogram sampling strategy that reduce the detector frame rates within values attained by today's COTS IR array detector. One single interferometer can be used to modulate the whole spectrum but 1 array detector per band must be used.

Band 4 - CO2 strong (4980-5010 cm^{-1})

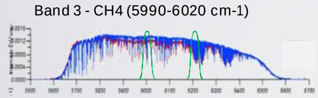


Band 1 - O2 (7880 - 8000 cm^{-1})

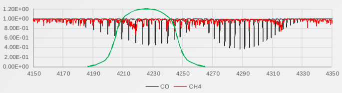


Band 2 - CO2 weak (6226-6256 cm^{-1})

Band 3 - CH4 (5990-6020 cm-1)



Band 5 – CO, CH4 (4190 - 4260 cm^{-1})



Sensors Comparison

Sensor comparison is multifaceted but ultimately trades ground resolution vs instantaneous view vs dwell time. The following table summarizes a high level comparison from literature data .

Satellite	Instrument Type	Orbit Height	Gas Species	Sensor Aperture	Pixel View (km)		Instantaneous Panchromatic View (km)		SNR / Pixel View	nb retreivals per seconds
				cm	km	km^2	km	km^2	albedo = 0.3	
GOSAT-1 (2009-)	FTS	666	CO2, CH4	6.8	10.5 Ø	86.6	10.5 Ø (single pixel)	86.6	300	0.25
GOSAT-2 (2018-)	FTS	615	CO2, CH4, CO	7.7	9.7 Ø	73.9	9.7 Ø (single pixel)	110.3	300	0.25
OCO-2 (2014-)	Grating	690	CO2	11	2.3 x 1.3 (super pixel)	3.0	0.07 x 10.3	0.7	375	24.0
OCO-3 (2018-)	Grating	370	CO2,	11	1.2 x 0.7 (super pixel)	0.84	0.04 x 5.5	0.2	375	24.0
SCIAMACHY (2002-2012)	Grating	800	CO2, CH4, CO		30 x 60	1800	0.6 x 25	15	> 400	0.2
Tropomi (2017-)	Grating	824	CO, CH4	3	7 x 7	49	7 x 2600	18200	100-120	866.7
GHGSAT	F-P	500	CH4 (CO2)	12	0.02 x 0.02	0.001	12 x 12 1-color (circular masking)	113*	N/A	1700**
ABB IFTS	IFTS	600	CO2, CH4, CO	8	0.5 x 0.5	0.25	64 x 64	4096	> 185	3584

* Spectral range reduces with distance to center of swath due to circular fringe pattern. Usefull FOV is thus smaller. Circular FOV also assumed.

** Assumes uninterrupted target acquisition every 20 seconds, 8 x 12 km useable circular FOV & 2x2 binning per retreival (50x50m)

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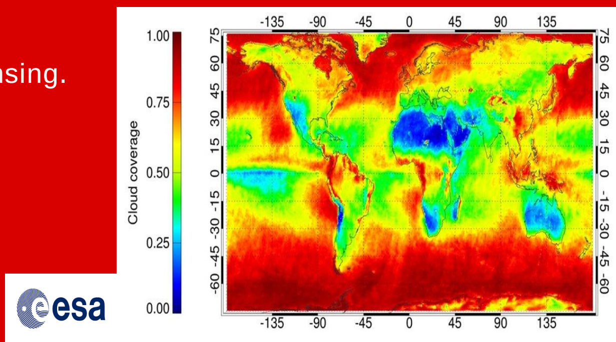
The future…

GHG build up in the atmosphere is well established: sources and sinks need to be determined on a detailed global scale and monitored by independent and irrefutable methods for generations to come. The true niche and economic benefit for satellite sensors needs to be understood in the context of rapid innovations of a broad array of ground sensing solutions (in-situe, drones, Aerostat). Satellites offer the following unique capabilities:

- Unrestricted and global geographic access (not bound by borders)
- Top level emission assessment (validation of bottom-up inventories)
- Irrefutable comparison on global scale (same sensor for all)
- Can follow transport of GHG (regional interdependencies)
- Holds potential to identify poorly known sources and sinks; (ex. remotely located sites or large areas such as oceans)

LEO satellites have some severe drawbacks

  - Compared to other types of ground/air sensing.
- Far from target:
  - Poor and seasonal light collection capacity
- Fast ground speed (~7 Km/s.):
  - Affords only few seconds to observe target.
- Cloud blocks more than 50% of the view
- Emitters are buried under total air column



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Tracking a fixed square FOV allows sufficient time to acquire the spectrum in the time domain without rejecting any photons the duration of the scan. The Keystone effect limits angular tracking.

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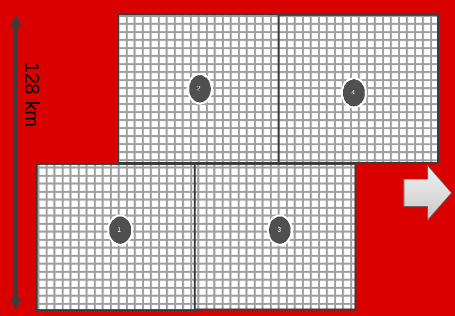
We selected here a configuration that maintains a high SNR at the pixel level (> 185*) with nominal 4s (28 Km displacement). aquistion time and the least ambitious detector candidate (128 x 128). We compensated the smaller detector FOV by proposing a mosaic interleaved contiguous staring pattern.

* albedo=0.3, SZA=30°



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Spectral grid	0.2 cm^{-1} (MOPD = 2.5cm)
SNR per pixel	> 185

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Your handles at the SNR problem:

1. Sensor Aperture: bigger is better but rapidly drives cost (> cubic mass dependency!)
2. Orbit height: The closer the better but orbital drag more problematic below 600 km
3. Integration time: Very high ground velocity of 7 km/s limits useable time to a few seconds
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(Items 3 and 4: Typically not independent)

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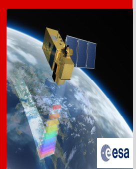
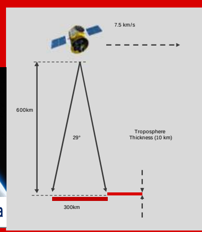
What about maximizing both!

An imaging FTS naturally allows concurrent light integration in the along track direction leading to an important photon collecting advantage.





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Tropomi (2016-) / CarbonSat	Grating	824 / TBD	CO, CH4 / CO2, CH4	7 x 7 / 2 x 3	49 / 2.5	7 x 2600	18200.0		371.4
GHGSAT	F-P	500	CH4 (CO2?)	0.05 x 0.05	0.0025	16 x 16 1-color (circular masking)	256.0	? Likely low	960.0
ABB IFTS	IFTS	600	CO2, CH4, CO	0.5 x 0.5	0.25	64 x 64	4096.0	> 180	3500.0