# *The Orbiting Carbon Observatory-2 (OCO-2) Mission*

*Watching The Earth Breathe…Mapping $CO_2$ From Space.*

## Radiometric Comparison of 0.76, 1.6 and 2.0-μm Bands of OCO-2 with Aqua MODIS over Sahara/Arabian Desert Sites

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Government sponsorship acknowledged

# History of OCO, OCO-2 and OCO-3

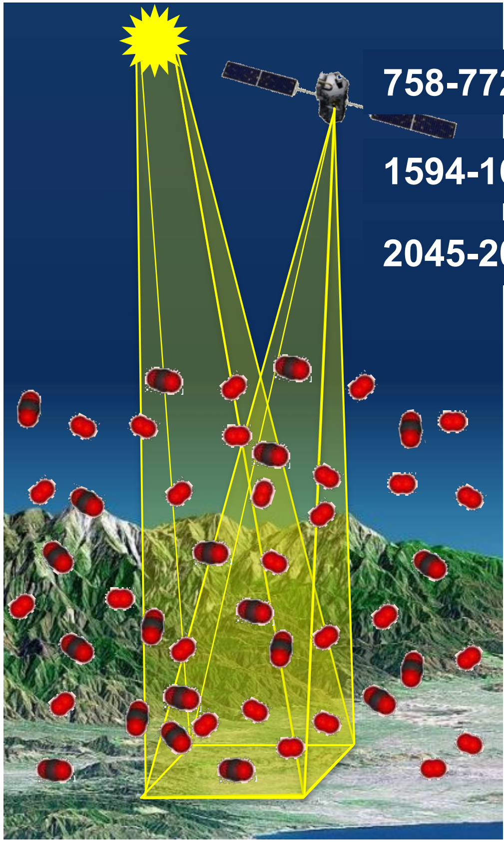
- Orbiting Carbon Observatory approved within the Earth System Science Pathfinder program in July 2002
  - Launched on February 24, 2009 but did not achieve orbit due to launch vehicle failure
- Work on OCO-2 began in March 2010
  - Launched into A-Train successfully from Vandenberg Air Force Base in California on July 2, 2014
  - Exceeded 2-year nominal mission and continues to deliver scientific measurements
- Following the successful OCO-2 launch, work began on converting the spare spectrometer into OCO-3
  - Launched successfully from Cape Canaveral in Florida on May 4, 2019 and docked on ISS on May 6, 2019
  - In-Orbit Checkout through August 2019
  - Planned duration 3 years after In-Orbit Checkout

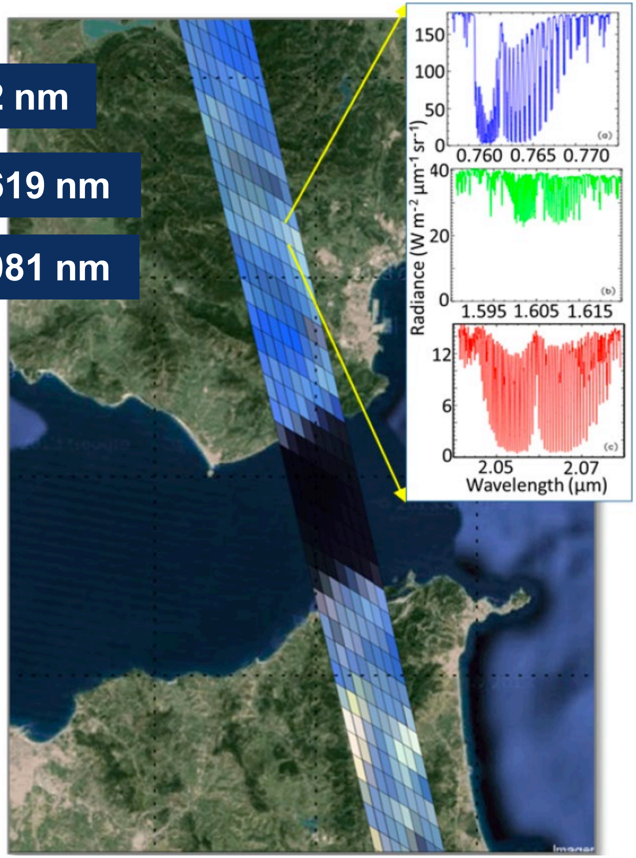
# Instrument and measurement

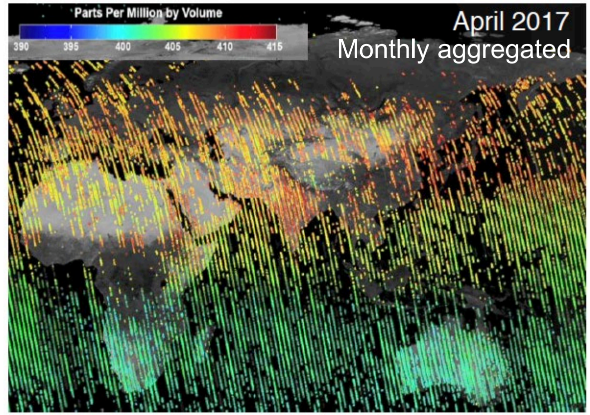
Grating spectrometer looking at Earth's surface in 3 wavelengths

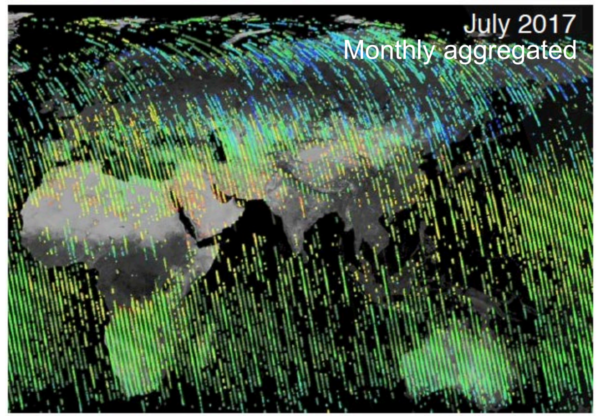
Measure $O_2$ & $CO_2$ spectra
8 cross-track footprints
footprint size=~2.5 km$^2$

Quantify variations in column averaged $CO_2$ dry air mole fraction, $X_{CO2}$

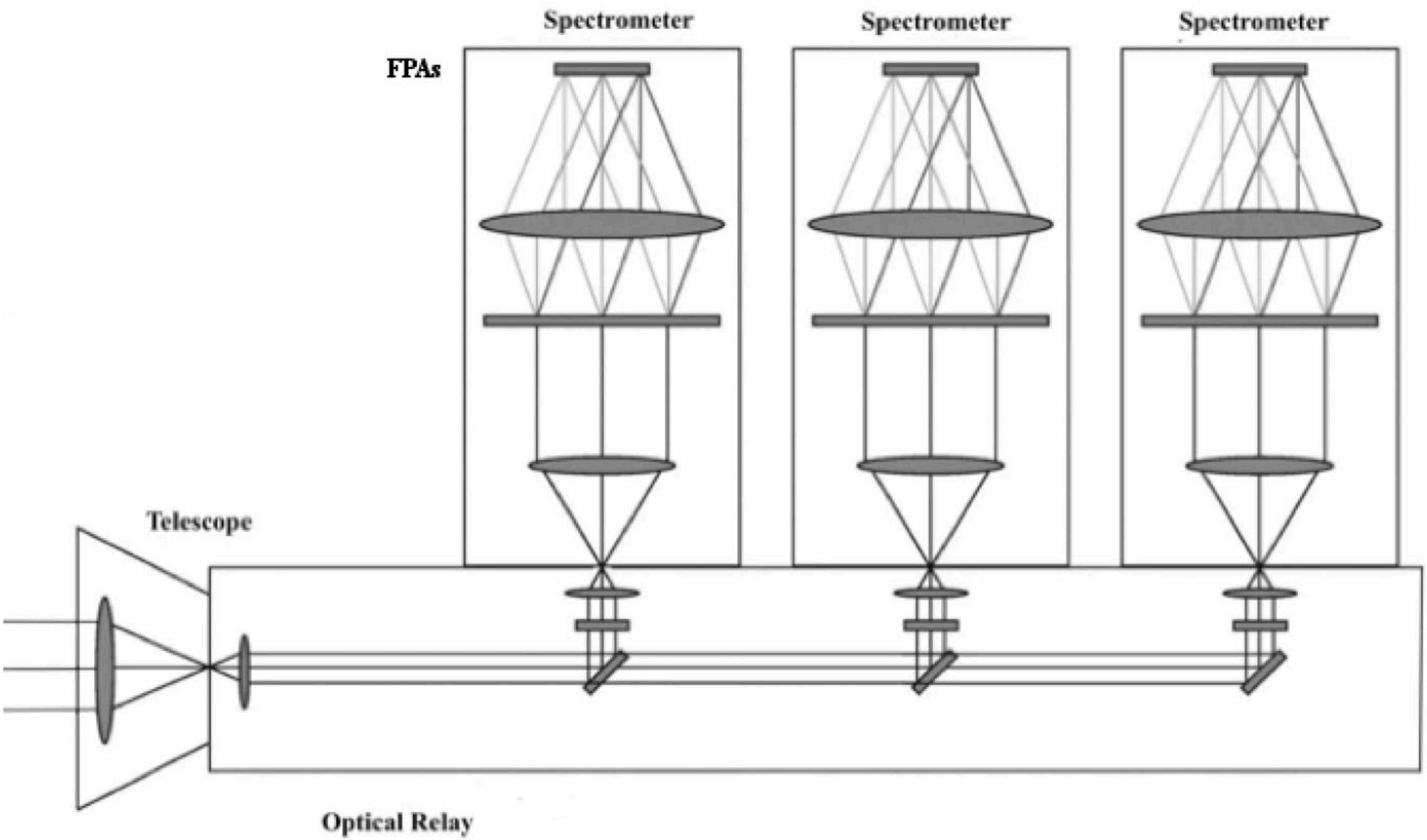


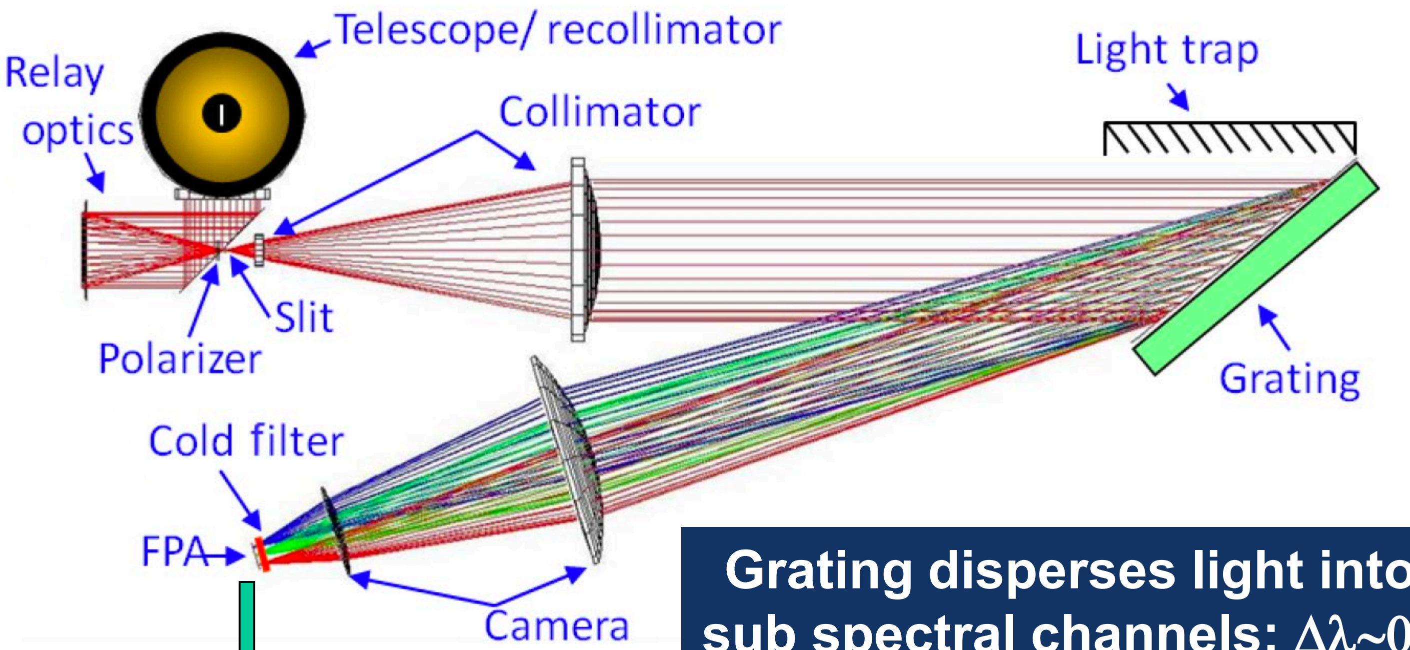



# Schematic of OCO-2's three spectrometers



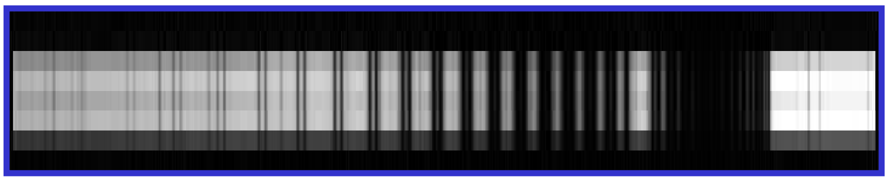
# Major optical components for a single channel




**Grating disperses light into 1024 sub spectral channels: $\Delta\lambda\sim0.05$ nm**

FPA image

Spatial direction (8 footprints)



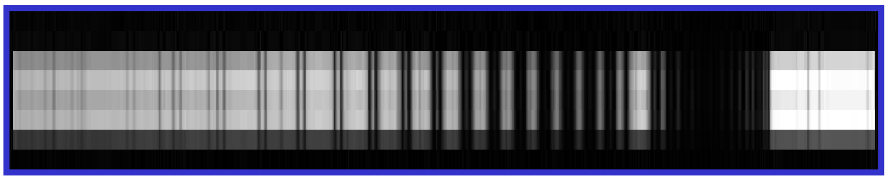
Wavelength direction

# Inflight calibration chain

Uncalibrated Level 1A Signal → Dark Signal (TVAC & updated in flight) → "ZLO" stray light (unilluminated pixels) → Preflight Gain (Sphere in TVAC) → Gain Degradation (change since in orbit checkout) → Calibrated Level 1B Radiance

Unilluminated pixels are at the bottom and the top of PFA image

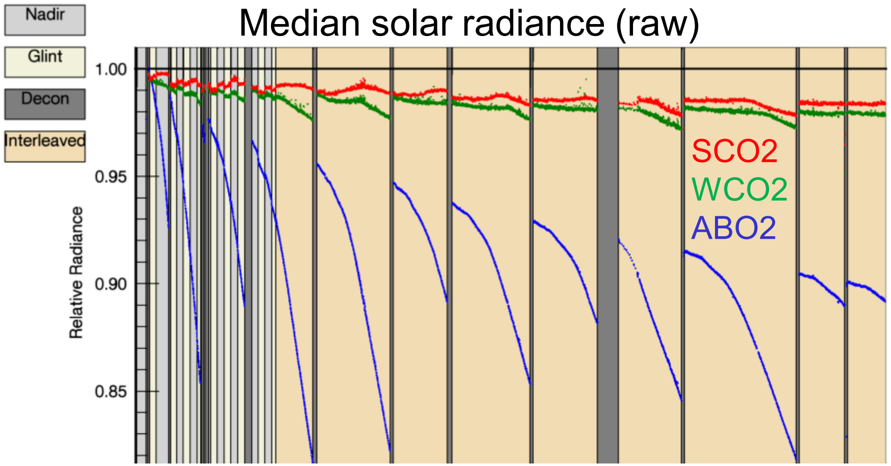
Spatial direction ↓ (8 footprints)



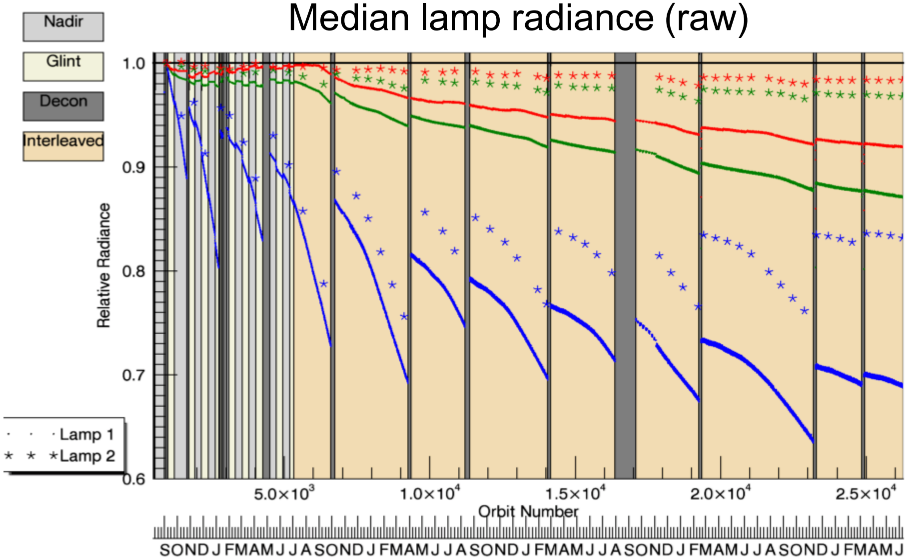
Wavelength direction ⟶

# OCO-2 gain degradation trends

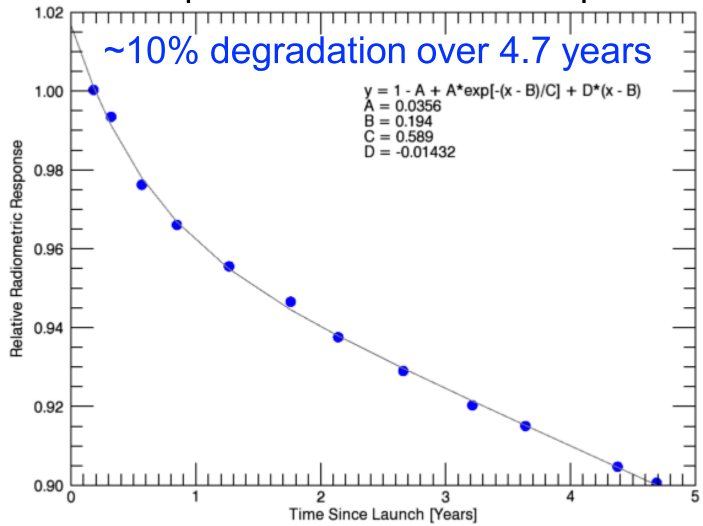
## Median solar radiance (raw)




## Median lamp radiance (raw)




## ABO2 post-decon solar cal response

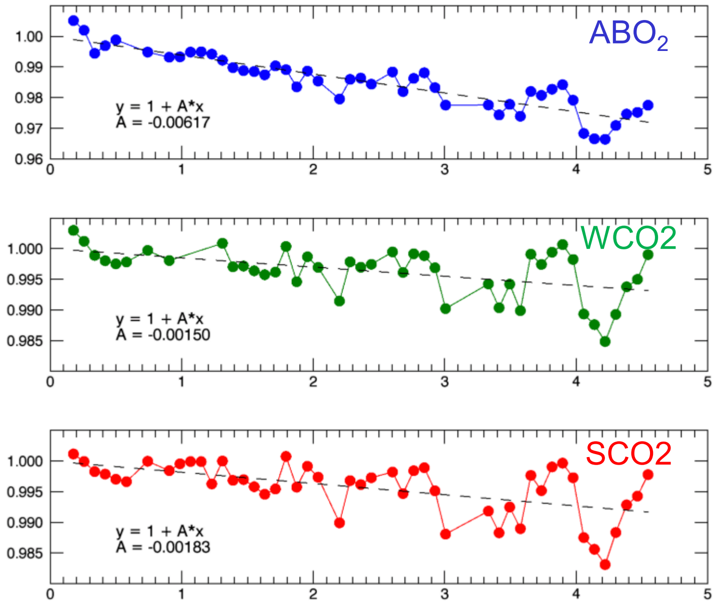



Observations of the sun using the solar diffuser and the lamps using the lamp diffuser show

- **Fast signal losses from water icing that are reversible with decontamination** (ABO2 affected most due to FPA AR coating having an refractive index similar to water ice
- **Irreversible trends** that combine instrument throughput and lamp aging and lamp/solar diffuser degradation

# Lunar calibration tracks science throughput and solar/lamp diffusers degradation

~75% moon irradiance, corrected for undersampling, icing, distance, phase, liberation & polarization




| Irreversible degradation trend (%/yr) | | | |
|---|---|---|---|
| | ABO2 | WCO2 | SCO2 |
| Lunar | -0.6 | -0.2 | -0.2 |
| Solar | -2.1 | -0.3 | -0.3 |
| Lamp | -6.1 | -0.3 | -0.2 |

- Lunar observations track the long term degradation of the throughput of those parts of the optical system used for science observations.
- Comparisons of Solar (with diffuser) and Lamp (with diffuser) to Lunar are used to track the long term degradation
  - the solar calibration diffuser
  - the lamp output and the lamp diffuser

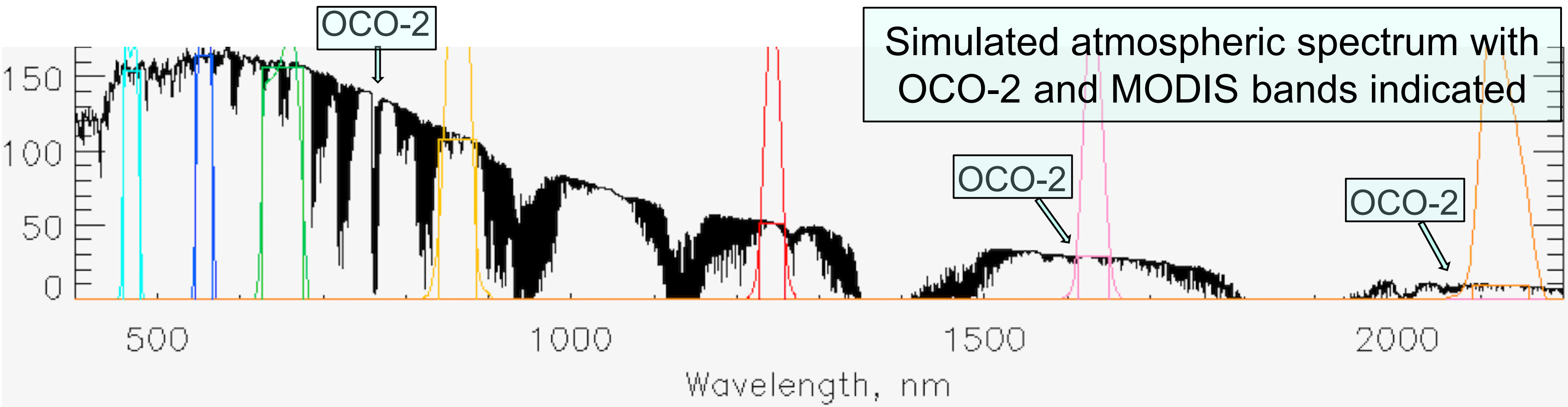
# Absolute radiometric requirement: ≤5% uncertainty

## OCO-2 meets and exceeds its radiometric calibration requirements

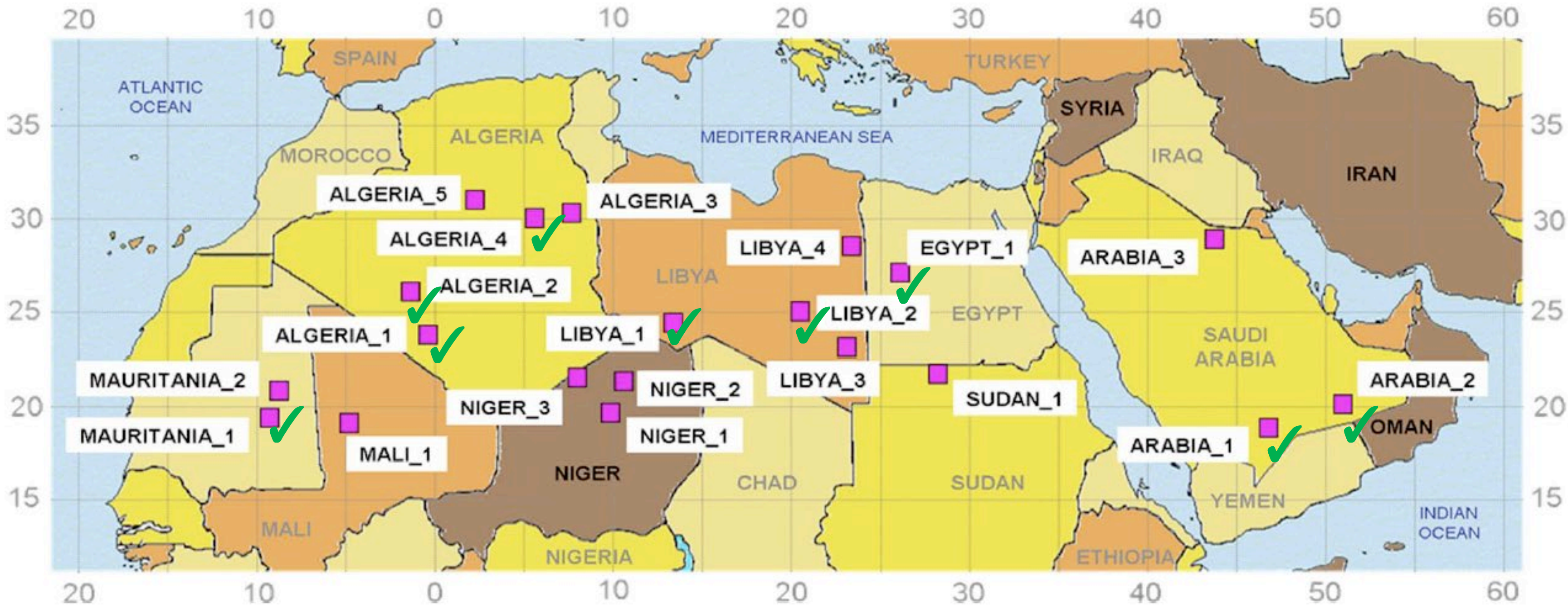
| Calibration Type | OCO-2 Frequency | OCO-3 Frequency | Purpose |
|---|---|---|---|
| Vicarious @ RRV | 3 chances every 16 days<br>~1x per month planned | Varies<br>~5x per 3 months planned | Absolute standard |
| Lunar calibration | Twice per lunar cycle | 4-6x per year (goal) | Pointing & relative radiometric calibration |
| Lamp calibration<br>With a lamp diffuser | ~10x per day | ~15x per day | Short-term stability &<br>Spectrally flat |
| Solar calibration<br>With a solar diffuser | ~10x per day | Not possible | Additional short-term source at different radiance level |
| Dark calibration | ~20x per day | ~30x per day | Dark subtraction / trending |
| Streak Flats<br>(all footprints observe the same Earth scene) | Every Orbit (for free) | Special request<br>(~1x per week) | Relative radiometric calibration among footprints |
| Spacecraft-to-spacecraft cross calibration | 1 chance every 16 days | Varies | Long-term stability |

# Trend OCO-2 B8 radiometric calibration through comparison with MODIS

- Quantify time-dependence in OCO-2/MODIS radiance ratio (specific to one Build)
- Select only clear sky OCO-2 nadir observations over deserts
- Spectral bands: OCO-2 vs. MODIS
  - 0.76 μm vs. (B1+B2)/2 = (0.645+0.859)/2 = 0.75 μm
  - 1.605 μm vs. B6= 1.63 μm
  - 2.06 μm vs. B7= 2.11 μm
- OCO-2 radiances: B8 L2DIA, continuum level from the OCO-2 full physics retrieval
- MODIS radiances: C6.1 MYD02HKM, half-km radiance collocated to the OCO-2 footprints using a 1km circular region around OCO-2 footprint, divided by 2 to account for total intensity vs single linear polarization for OCO-2



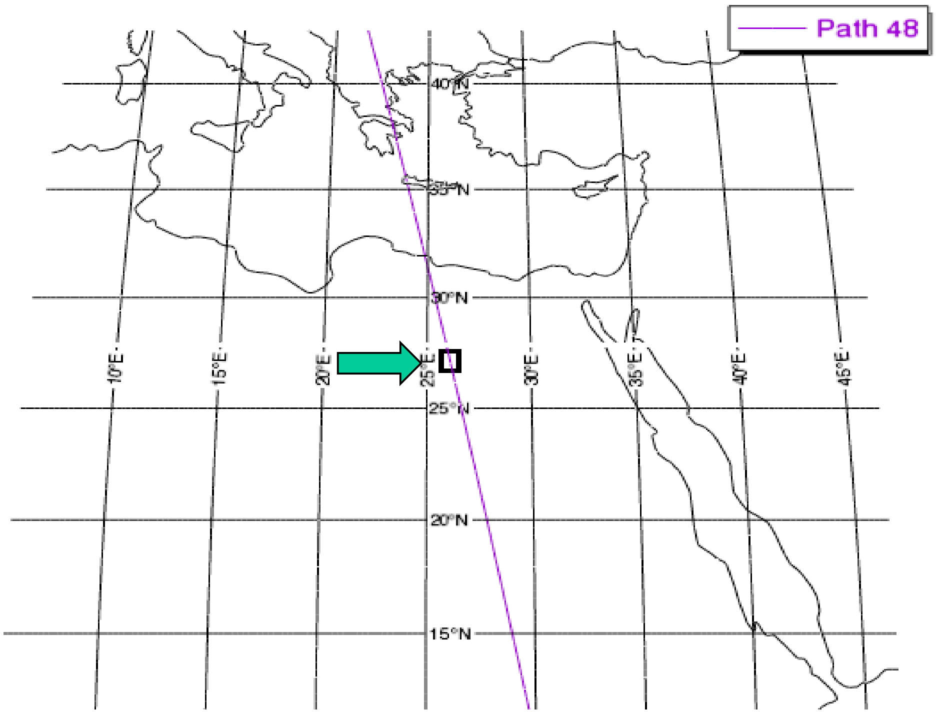
# Used Sahara/Arabian desert sites




- OCO2 has nadir observations over 9 of the 20 sites (green check marks)
- Area of each site is ~100km X 100km

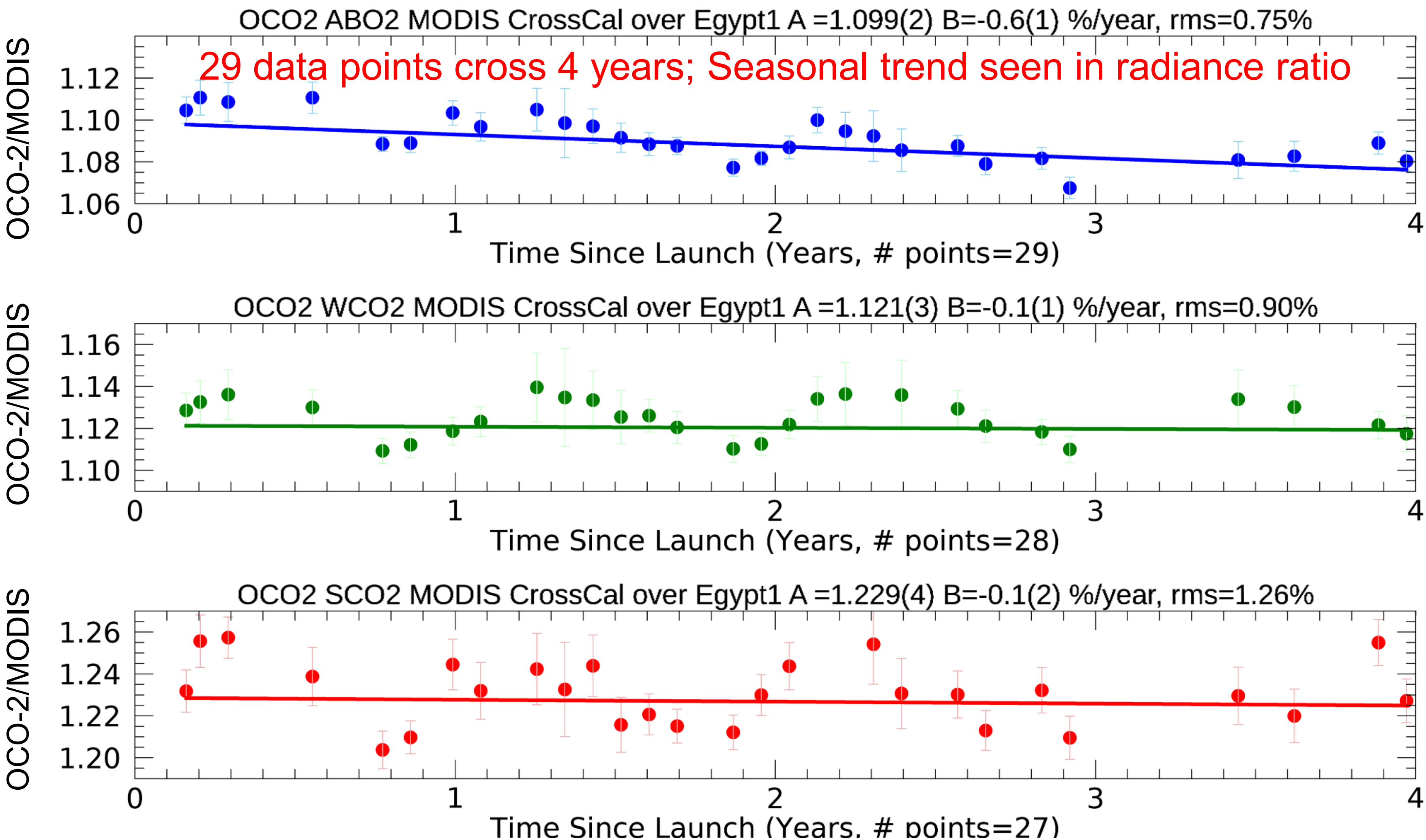
Picture from Lacherade et al 2013

# OCO-2 Path 48 over Egypt1 site

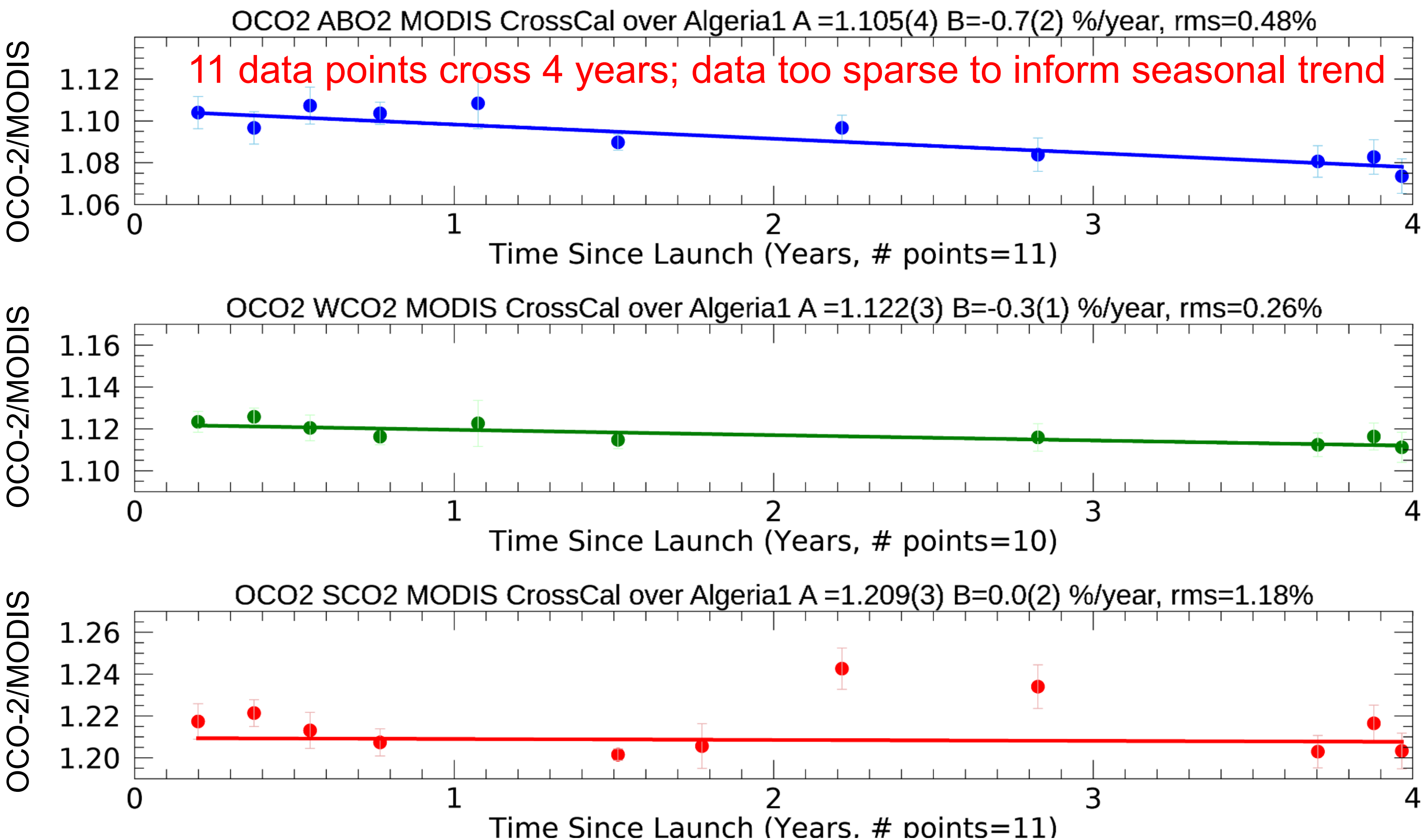



- Find clear sky OCO-2 nadir soundings within the site
- Match MODIS observations (temporal and spatial matches only, viewing geometry match not performedcurrently)
- Calculate OCO-2/MODIS radiance ratio
- Take mean ratio within each orbit
- Perform linear regression of mean ratio vs orbit (time) to determine intercept and slope

# Sample linear regression for single site: Egypt1



# Sample linear regression for single site: Algeria1

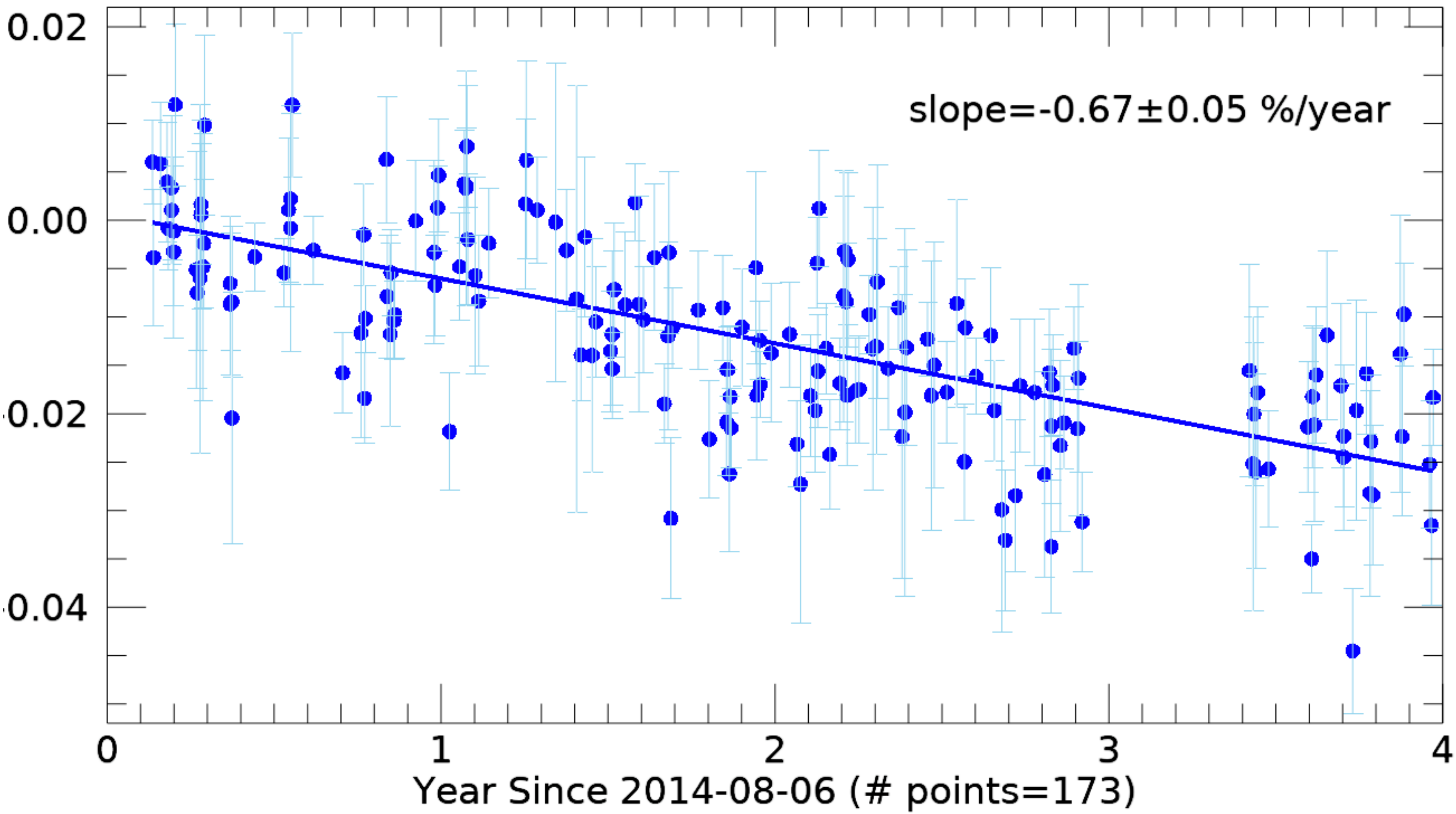


# Summary of OCO-2 B8 CrossCal with MODIS

| Site | Slope (% per year) | | | Intercept | | | # points |
|---|---|---|---|---|---|---|---|
| | ABO2 | WCO2 | SCO2 | ABO2 | WCO2 | SCO2 | in 4 years |
| Algeria1 | -0.7±0.2 | -0.3±0.1 | 0.0±0.2 | 1.106±0.004 | 1.122±0.003 | 1.210±0.004 | 11 |
| Algeria2 | -0.7±0.2 | -0.2±0.2 | -0.8±0.2 | 1.089±0.005 | 1.122±0.006 | 1.225±0.006 | 16 |
| Algeria4 | -0.8±0.2 | 0.1±0.2 | -0.2±0.3 | 1.109±0.006 | 1.112±0.006 | 1.228±0.008 | 17 |
| Arabia1 | -0.7±0.1 | 0.1±0.2 | -0.6±0.2 | 1.091±0.003 | 1.112±0.005 | 1.242±0.005 | 25 |
| Arabia2 | -0.5±0.1 | 0.1±0.1 | -0.2±0.2 | 1.066±0.002 | 1.109±0.002 | 1.222±0.004 | 27 |
| Egypt1 | -0.6±0.1 | -0.1±0.1 | -0.1±0.2 | 1.099±0.002 | 1.121±0.003 | 1.229±0.004 | 29 |
| Libya1 | -0.7±0.2 | 0.4±0.4 | 1.2±0.4 | 1.108±0.004 | 1.118±0.006 | 1.220±0.008 | 12 |
| Libya2 | -0.6±0.1 | -0.1±0.1 | -0.5±0.2 | 1.089±0.003 | 1.125±0.003 | 1.240±0.004 | 23 |
| Mauritania1 | -1.0±0.2 | -0.2±0.2 | -0.5±0.2 | 1.114±0.003 | 1.131±0.003 | 1.251±0.005 | 13 |

- **ABO2 trend: -0.7±0.2 %/yr**
- WCO2 and SCO2 trends: no measurable trend, indicating <0.2%/yr
- Intercept varies from site to site; contributions under investigation
    - Absolute radiance calibration; Spectral band adjustment factor, viewing geometry correction, others?

# ABO2 linear regression for 9 sites with intercept removed

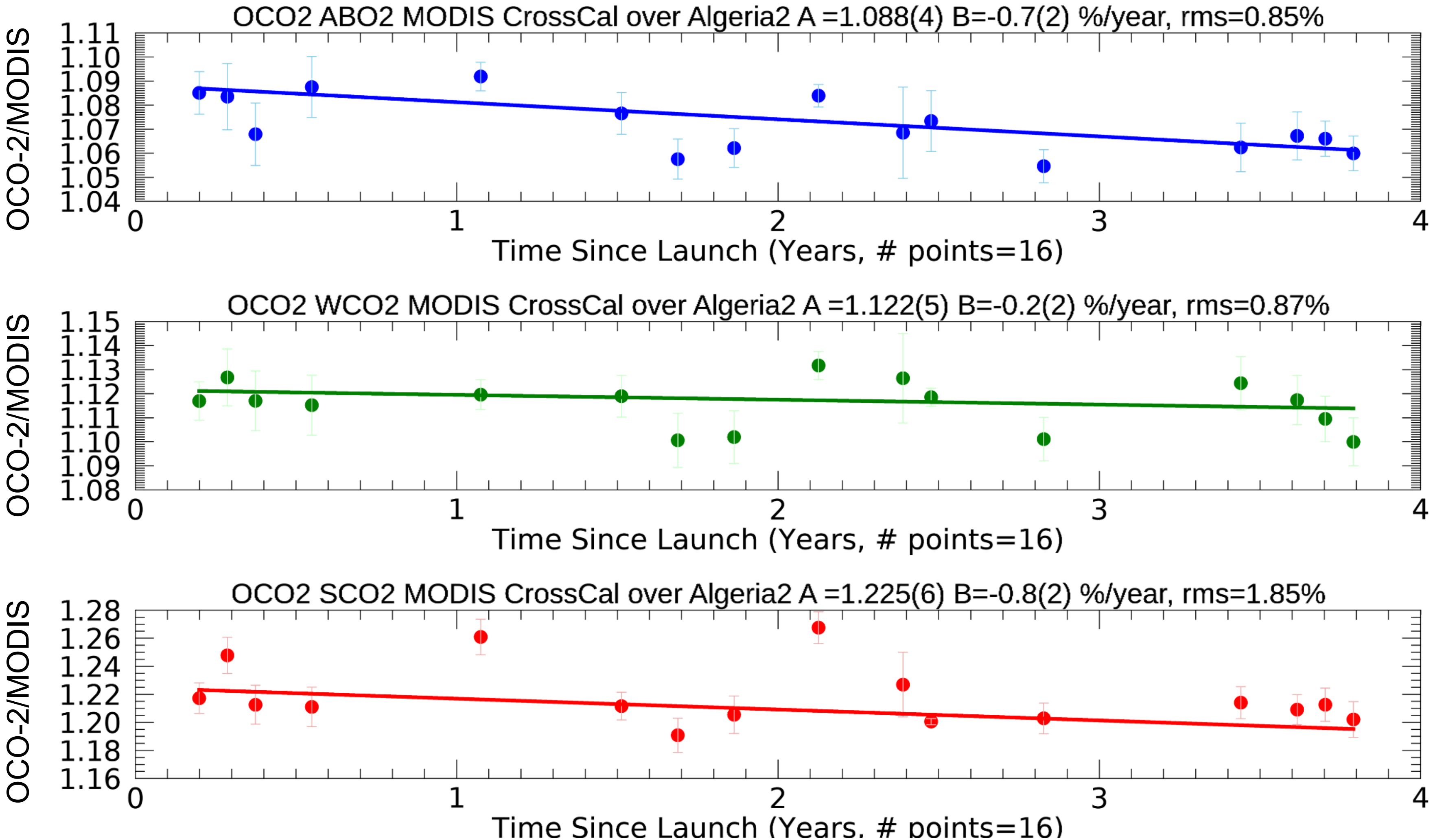


# Conclusions

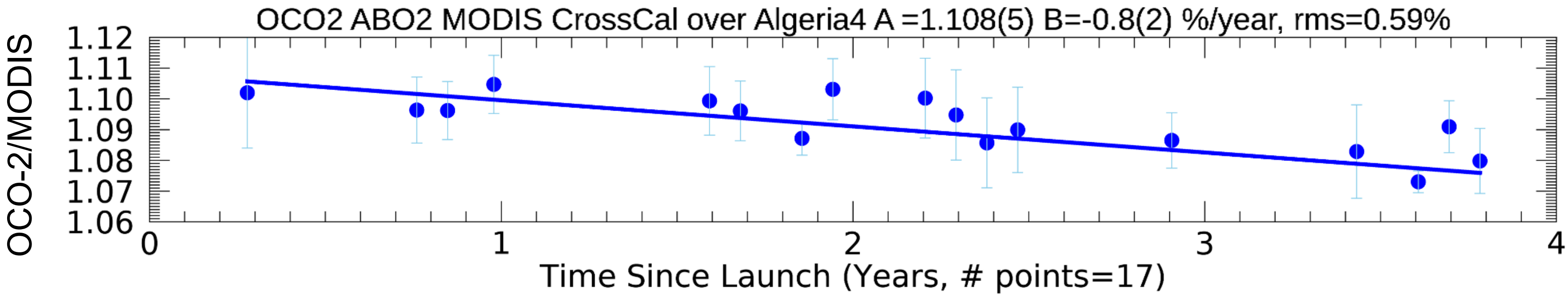
- OCO-2 has demonstrated that its current calibration approach meets and exceeds its radiometric calibration requirements
- The cross calibration approach in this talk represents one of our efforts to find alternative methods for OCO-3, which lacks solar calibration and has limited lunar calibration opportunities
- Planned OCO-3 cross calibration sensors include MODIS, VIIRS, OCO-2, GOSAT-2, TROPOMI
- For additional long-term stability, directly trending reflectance derived from OCO-2 radiance over desert sites is ongoing, currently we are investigating methods to remove observed seasonal trends

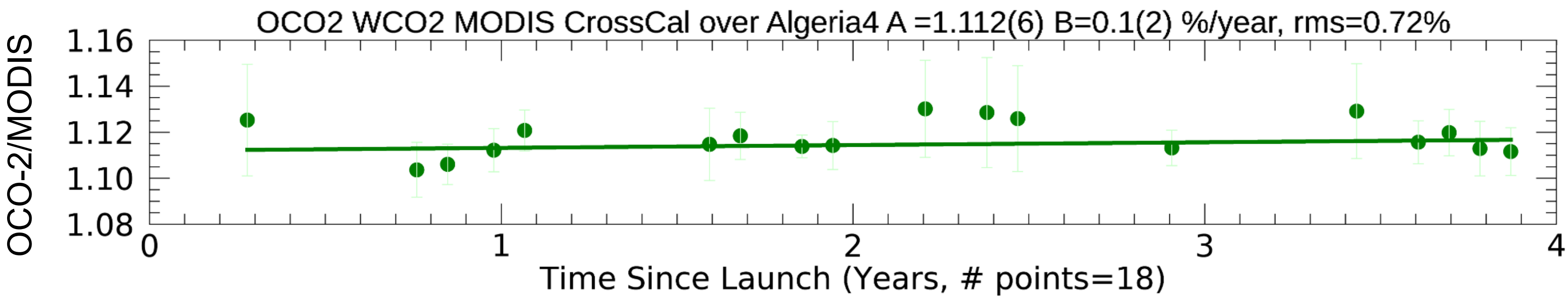
# 7 Backup slides

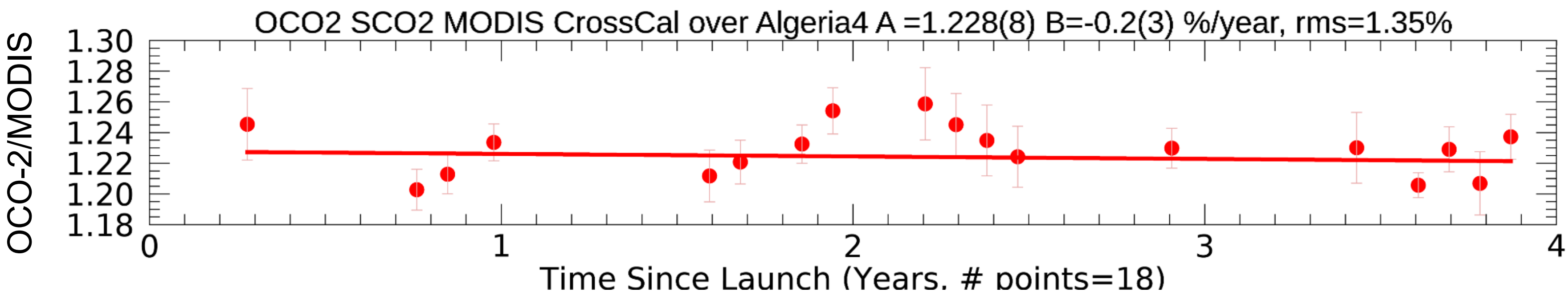
# Linear regression for Algeria2



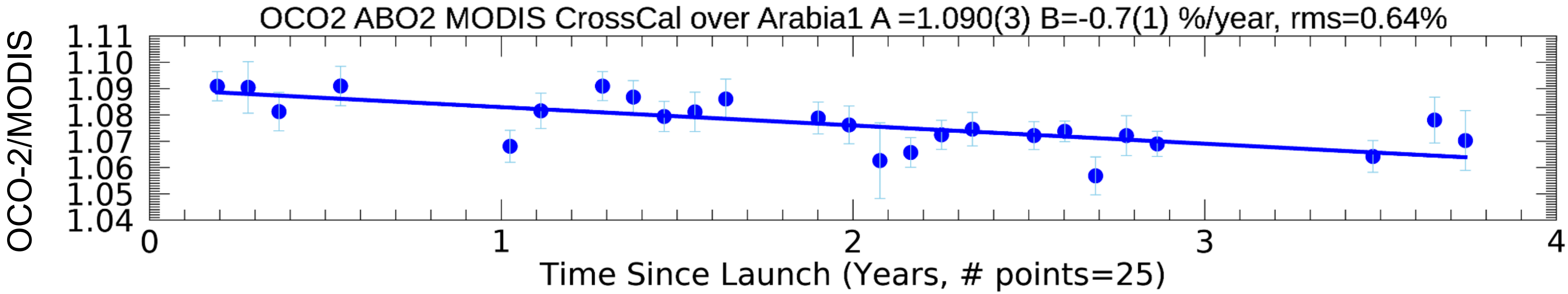
# Linear regression for Algeria4

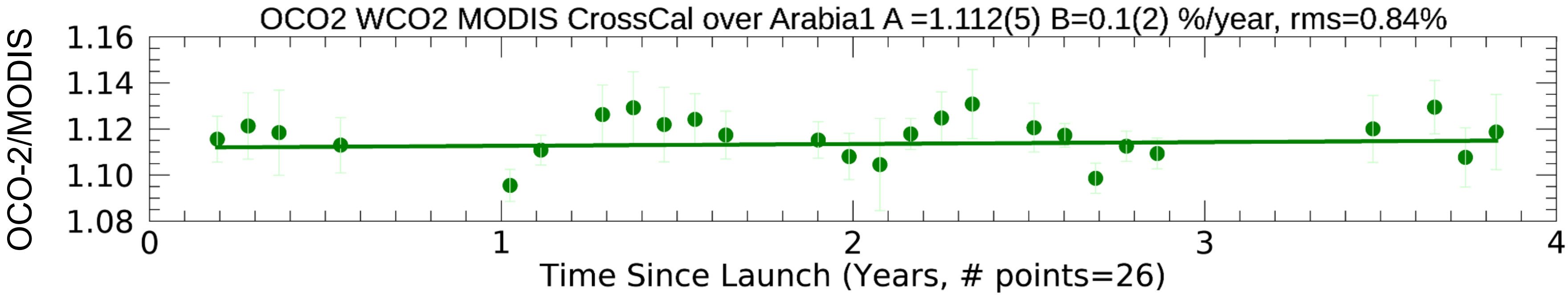


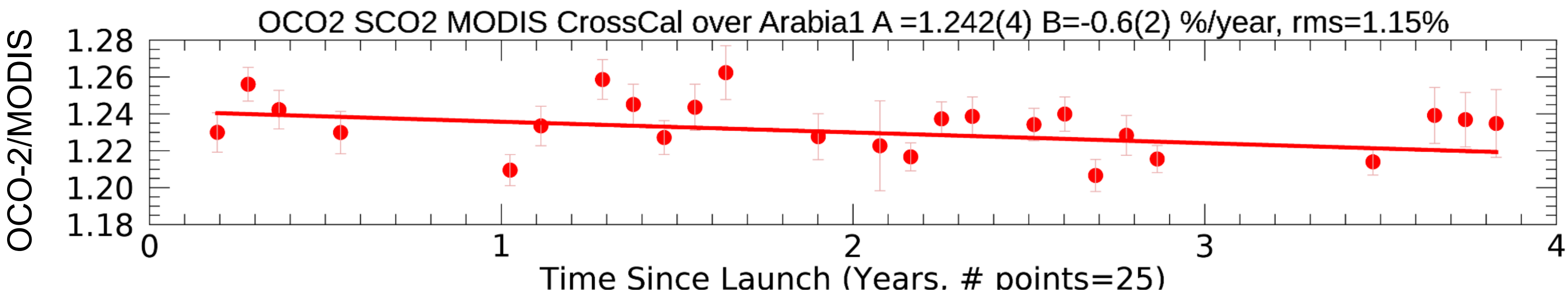



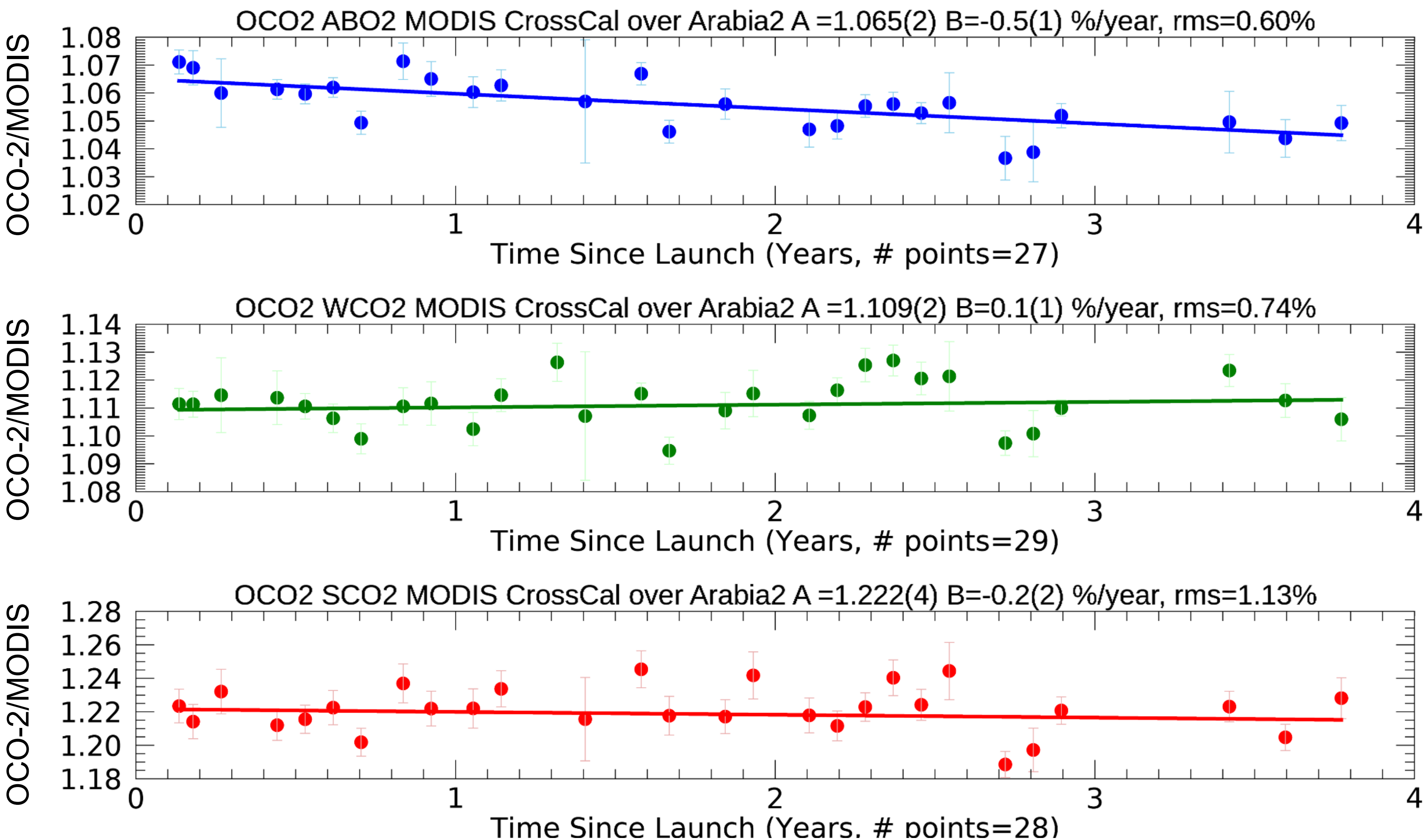
# Linear regression for Arabia1



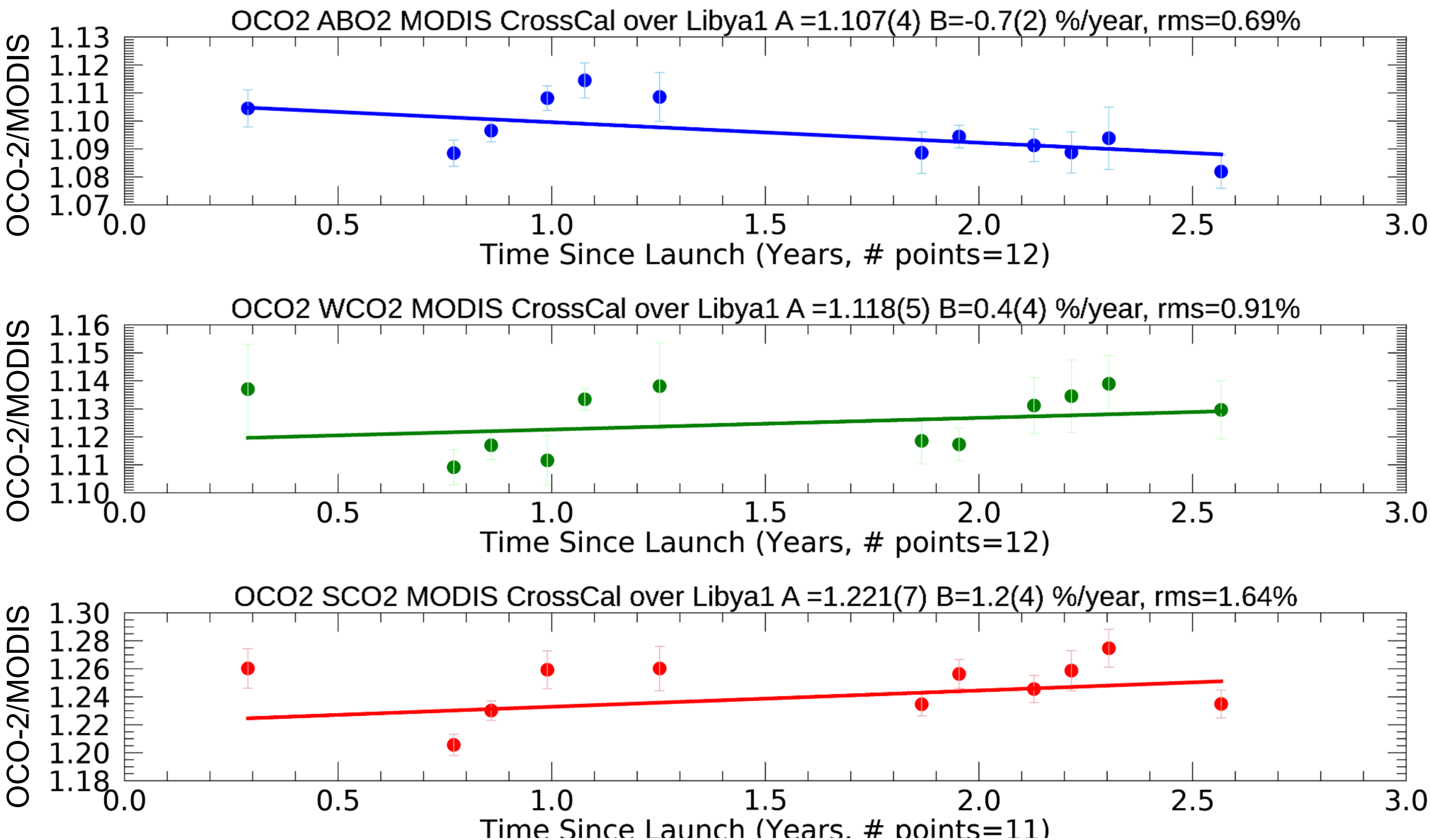



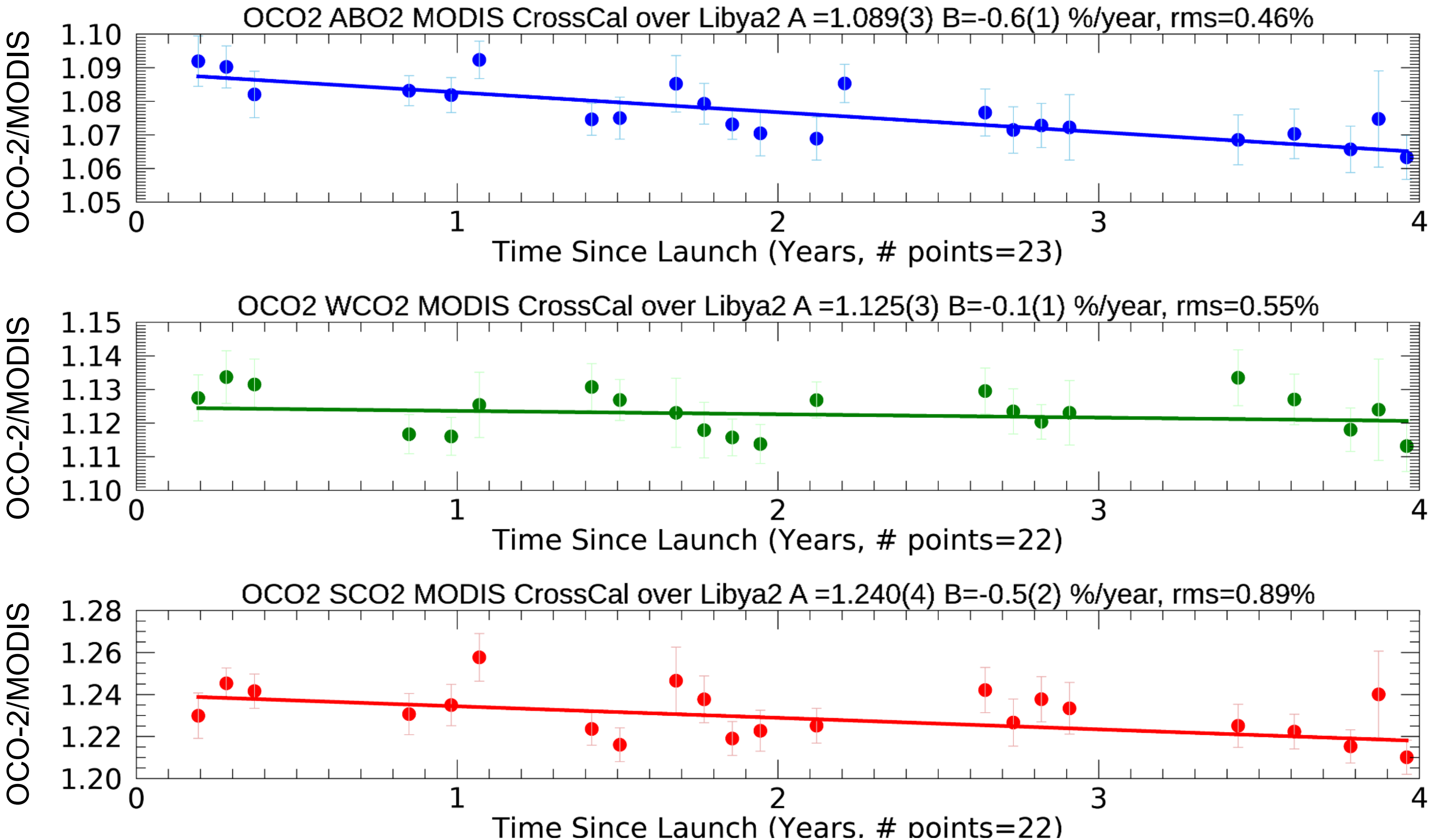
# Linear regression for Arabia2



# Linear regression for Libya1



# Linear regression for Libya2



# Linear regression for Mauritania1