In-Flight Thermal Performance of the OCO-2 (Orbiting Carbon Observatory-2) Instrument

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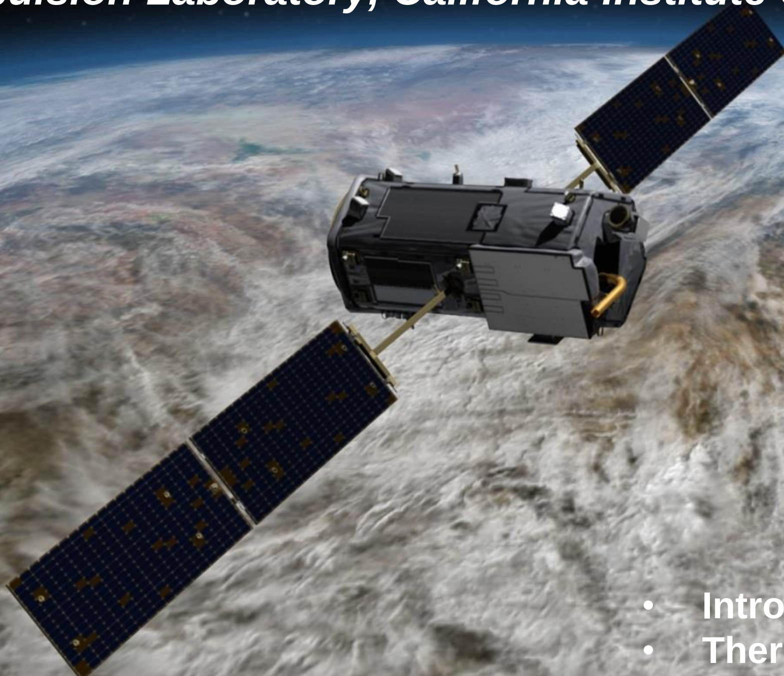
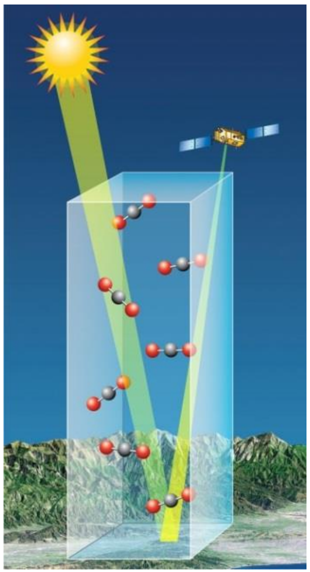


Topics

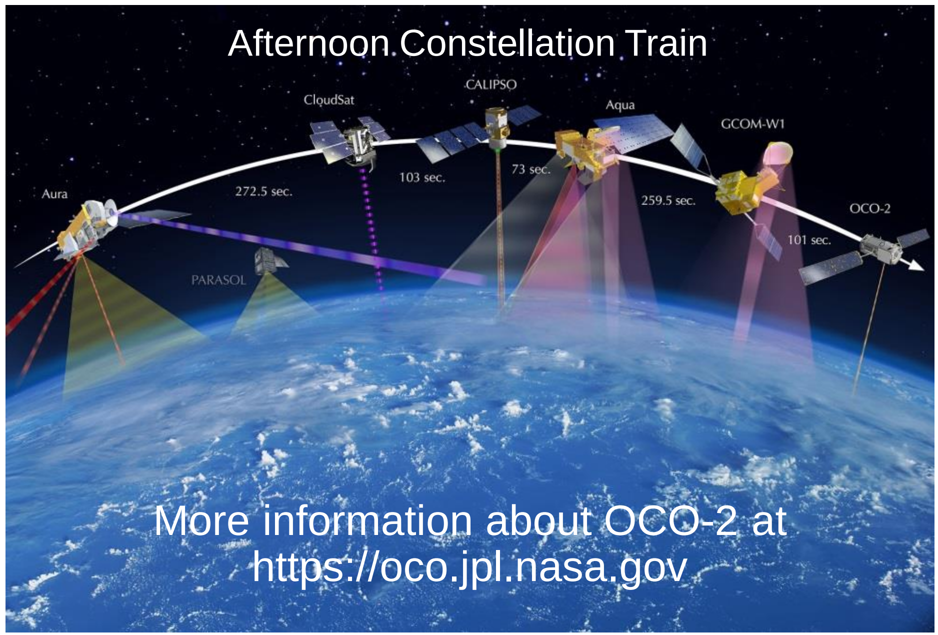
- Introduction to OCO-2
- Thermal Control System Overview
- In-Flight Thermal Performance
- Summary

What is OCO-2?

- The Orbiting Carbon Observatory-2 (OCO-2) retrieves a near-global geographic distribution of carbon dioxide (CO_2) sources and sinks by measuring the intensity of sunlight reflected off the Earth's surface at specific wavelengths
- OCO-2 flies at the head of Earth-observing satellites with related carbon cycle science objectives, known as the A-Train
- OCO-2 launched into orbit on July 2, 2014 and continues to operate nominally



CO_2 column that OCO-2 sees



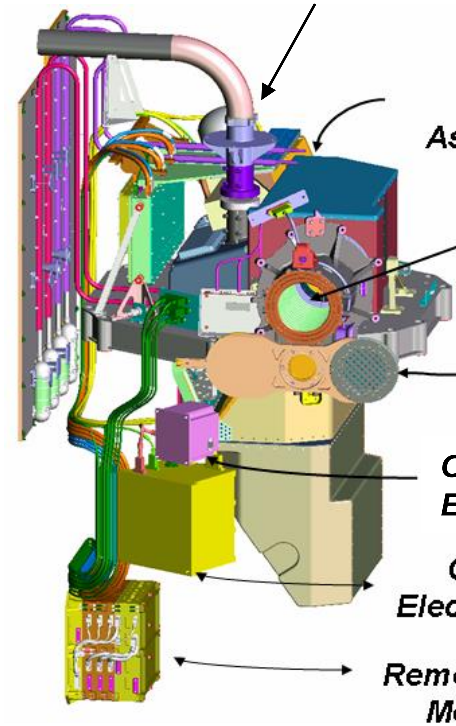
OCO-2 Spacecraft Overview

- LeoStar-2 spacecraft bus provided by Orbital ATK
  - Carries a single instrument
  - Bus made primarily of Al honeycomb panels that form hexagonal structure approximately 1 meter diameter and 2 meters tall
  - Solar array wings each 3 meters in length unfolded
  - Mass of entire observatory is ~ 450 kg
  - Earth-viewing honeycomb bus panels structurally support and remove waste heat from spacecraft components and instrument electronics
  - Momentum wheels onboard the spacecraft point the instrument telescope in three primary observatory operating modes
    - Nadir Mode
      - Directly downwards towards Earth
      - Minimum environmental thermal load
    - Glint Mode
      - Near sun's reflection on the ocean
      - Worst case hot environmental thermal load
    - Target Mode
      - Specific locations on Earth

https://oco.jpl.nasa.gov

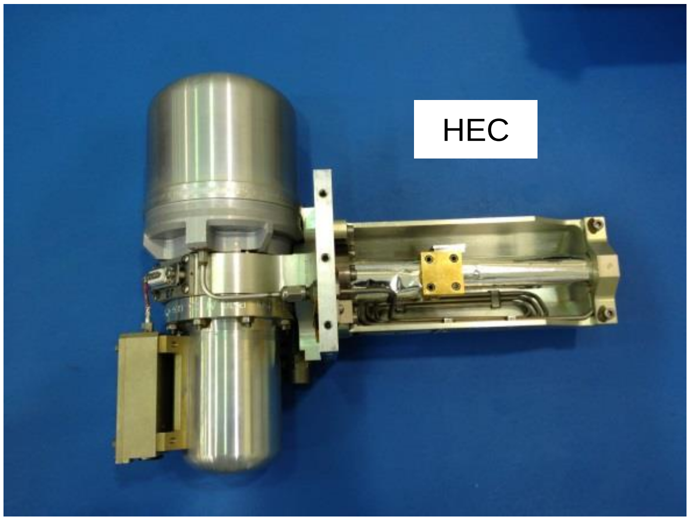
OCO-2 Instrument Overview

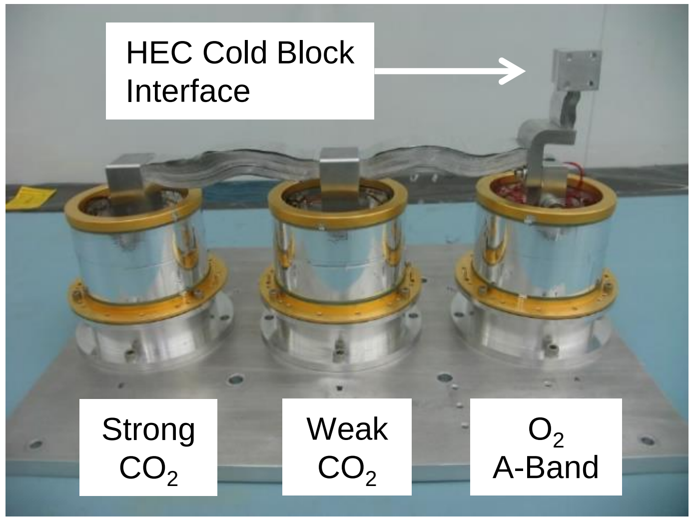
- Instrument provided by JPL
  - Measures gas concentrations at three wavelength bands (1.60 µm Weak CO_2, 2.06 µm Strong CO_2 and 0.76 µm O_2 A-Band), each specific to one of three high-resolution grating spectrometers
  - To reduce thermally induced measurement errors, the three light detectors must remain at a cold and stable temperature, thus a single pulse tube cryocooler is used to keep the temperature of the three FPAs near 120 K
  - REM, CCIE and CCE mounted on spacecraft honeycomb bus panels to remove waste heat



OCO-2 Cryo/Thermal System

- High Efficiency Cryocooler (HEC)
  - Provided by Northrop Grumman Aerospace Systems (NGAS)
  - Single stage linear pulse tube cooler maintains cold head temperature at ~110 K
  - Cryocooler maximum drive limit is set to 50% (~ **48** W compressor power) due to spacecraft power limitations
- Cryogenic Subsystem (CSS)
  - Interface between the three focal plane arrays (FPAs) and the HEC
  - Thermal isolates each FPA from instrument optical bench
  - Flexible aluminum foil thermal link connects each FPA to the HEC
  - With HEC cold block controlled to ~110 K, the CSS maintains the three FPAs at ~120 K





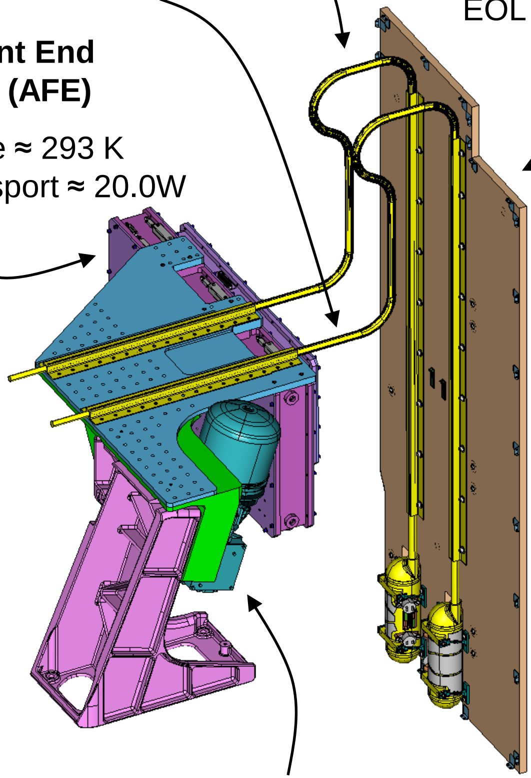
OCO-2 Instrument Heat Rejection System

AFE-Cryocooler Variable Conductance Heat Pipes (VCHP)
Working Fluid = Ammonia

Analog Front End Electronics (AFE)

Temperature ≈ 293 K
VCHP Transport ≈ 20.0W

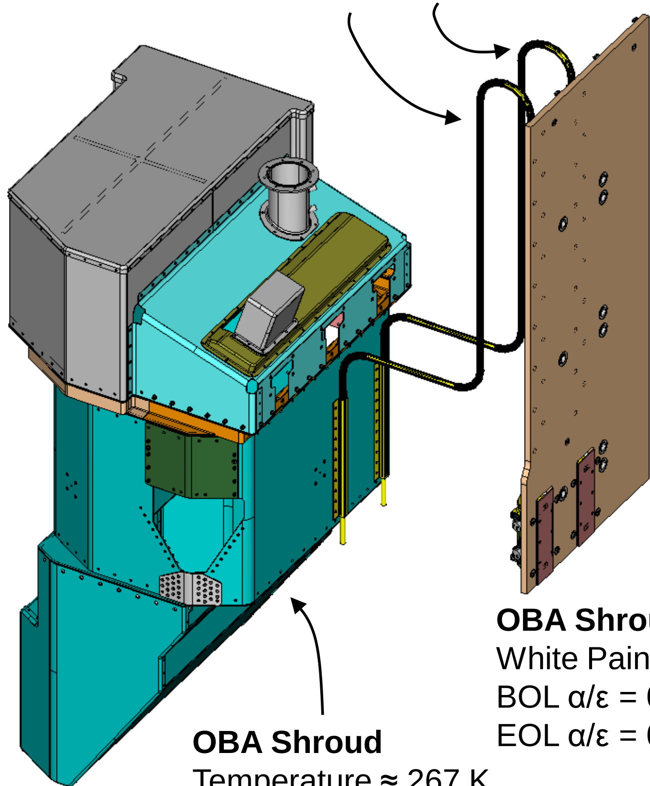
AFE-Cryocooler Radiator
White Paint
BOL α/ε = 0.18 / 0.86
EOL α/ε = 0.3 / 0.86



Cryocooler

Temperature ≈ 300 K
VCHP Transport ≈ 39.6W

OBA Shroud Variable Conductance Heat Pipes (VCHP)
Working Fluid = Ammonia



OBA Shroud Radiator
White Paint
BOL α/ε = 0.18 / 0.86
EOL α/ε = 0.3 / 0.86

OBA Shroud
Temperature ≈ 267 K
VCHP Transport ≈ 7.6W

OBA cooled by radiation heat transfer to shroud

In-Flight History of Events

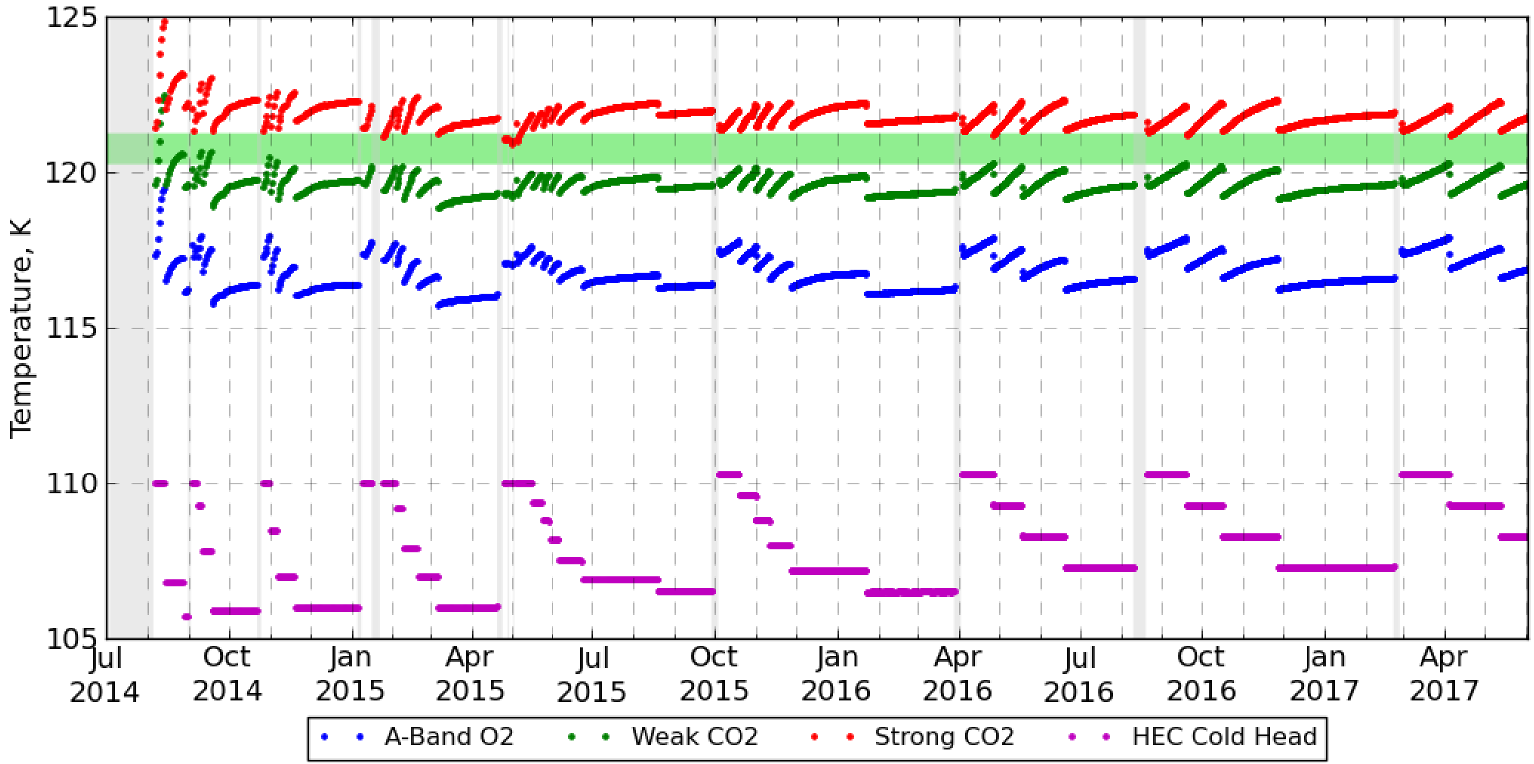
Day	Date	Event
1	7/2/2014	Launch; spacecraft powered ON; survival heaters ON
2	7/3/2014	Instrument powered ON; Decontamination heaters ON to raise FPA detectors and OBA to ~300 K
5	7/6/2014	CCE powered ON; Instrument initial checkout complete
34	8/4/2014	Instrument decontamination heaters OFF after 32 days of outgassing
35	8/5/2014	Cryocooler powered ON to begin cooldown of FPA detectors
36	8/6/2014	Instrument enters operational mode and begins alternating Nadir and Glint modes every 16 days
61-63	8/31/2014 - 9/2/2014	FPA De-Ice Cycle #1 because approaching 50% cryocooler motor drive limit
114-116	10/23/2014 - 10/25/2014	FPA De-Ice Cycle #2 because approaching 50% cryocooler motor drive limit
189-191	1/6/2015 - 1/8/2015	FPA De-Ice Cycle #3 due to gain degradation in the O_2 FPA
200-206	1/17/2015 – 1/23/2015	• Cryocooler OFF due to cryocooler accelerometer overload over-limit, intended to protect the cryocooler against over-stroking • After confirmation of low risk of re-occurence, cryocooler returned to “ON” condition with same fault threshold settings • Opportunity for De-Ice Cycle #4
293-297	4/20/2015 - 4/24/2015	FPA De-Ice Cycle #5 due to gain degradation in the O_2 FPA
301-302	4/28/2015 – 4/29/2015	• Instrument power cycle to fix error in the observatory absolute time sequence used to command OCO-2 autonomously • Opportunity for De-Ice Cycle #6

In-Flight History of Events (cont.)

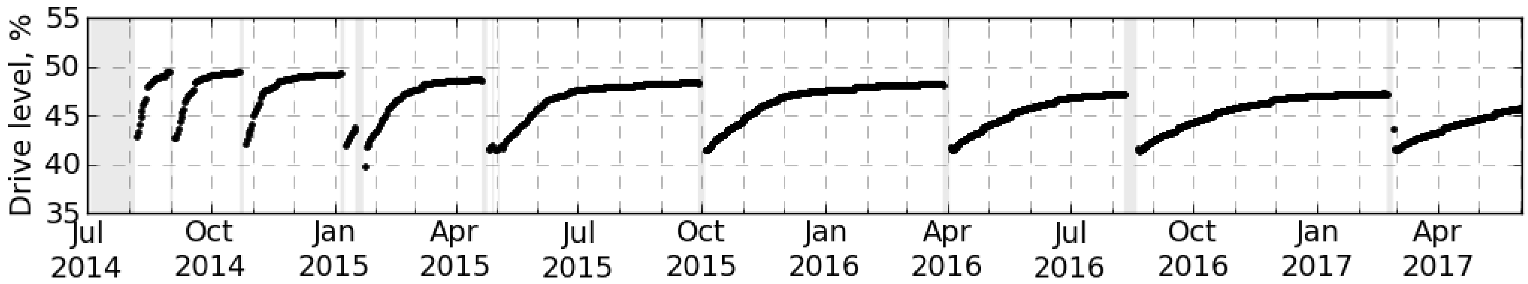
Day	Date	Event
305-306	5/2/2015 – 5/3/2015	• Instrument power cycle to fix error when powering down during the previous instrument power cycle • Root cause of cryocooler accelerometer overload trip could not be identified and appeared to be a false alarm. Disabled the cryocooler accelerometer overload detector during this instrument power cycle to eliminate risk of future false alarms and deemed very low risk due to other layers of cryocooler protection in place, and the cryocooler is operating at a low fraction of its maximum stroke. • Opportunity for De-Ice Cycle #7
367	7/3/2015	Begin alternating Nadir and Glint modes every orbit to acquire valid science data daily (versus every 16 days)
454-462	9/28/2015 – 10/6/2015	FPA De-Ice Cycle #8 due to gain degradation in the O_2 FPA
636-645	3/28/2016 – 4/6/2016	FPA De-Ice Cycle #9 due to gain degradation in the O_2 FPA
771-780	8/10/2016 – 8/19/2016	• Instrument powered OFF by spacecraft fault detection system due to unexpected REM power-on reset over South Atlantic Anomaly. As the REM reboots itself, valid instrument telemetry is delayed. The spacecraft continued to monitor instrument telemetry while the REM was recovering. Due to persistent bad telemetry from the instrument, the spacecraft fault detection shut down the instrument. • Opportunity for De-Ice Cycle #10.
966-974	2/21/2017 – 3/1/2017	De-Ice Cycle #11 due to gain degradation in the O_2 FPA
1066	6/1/2017	Latest operating data prior to publication, no faults of any kind have occurred since day 771, and no de-icing has been required thus far

In-Flight Performance – Cryocooler Cold Head & FPAs

- Ice accumulates on the CSS causing the FPAs to drift up in temperature while cryocooler cold head maintains its setpoint
- Mean of strong and weak CO2 FPAs needs to be maintained at ~120 K, requiring the cryocooler cold head setpoint to be adjusted downwards periodically
- After each de-ice cycle, the frequency to adjust the cryocooler cold head setpoint has decreased



In-Flight Performance – Cryocooler Motor Drive Comparison

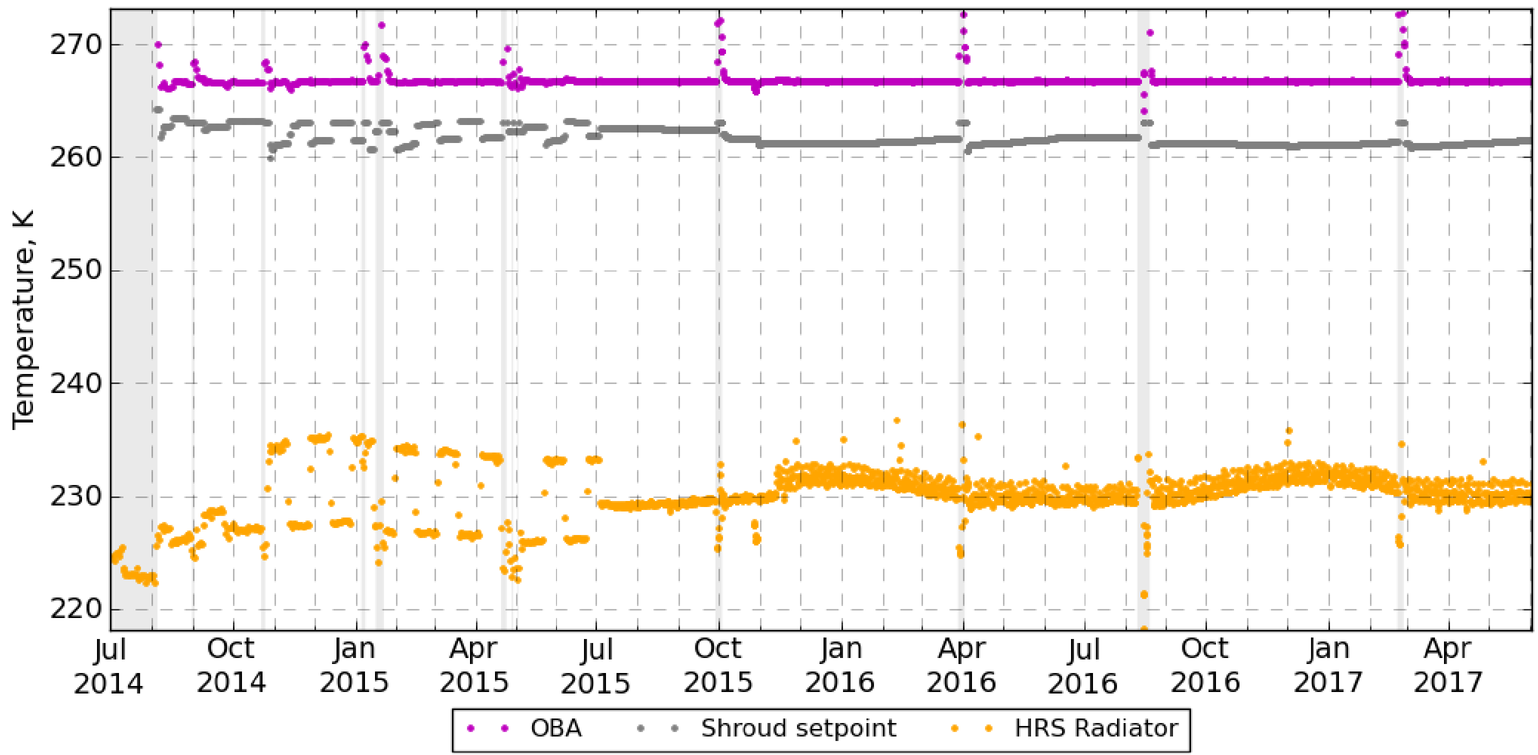


- Initial water ice accumulation on the CSS resulted in the cryocooler drive level increasing at a rate of ~ 0.6% per day
  - Initial 32-day outgassing period not sufficient to remove all water vapor from instrument
  - Water contamination increases the thermal heat load, which leads the cryocooler motor drive level to increase
- To avoid reaching the 50% drive limit (limit due to limitations with the spacecraft power budget), a de-icing cycle is performed
  - Turn off the cryocooler, turn on the FPA decontamination heater to raise the FPAs to 285 K to drive off water contamination, then after ~48 hours turn off the FPA decontamination heater and turn on the cryocooler to return the FPAs to operating temperature
- The level of icing has decreased over time after each de-ice cycle, and the motor drive level now consistently remains well below 50%

- After the second de-ice cycle, the requirement to de-ice is no longer driven by the 50% motor drive limit, but now driven by decreasing responsivity (down to ~95%) in the O_2 FPA
  - O_2 FPA more affected by thin ice layers because it has anti-reflection (AR) coating with refractive index more similar to water ice (1.33) than the other two FPAs which have a better optimized refractive index (~2.0)
  - O_2 FPA performance almost fully restored after each de-ice cycle

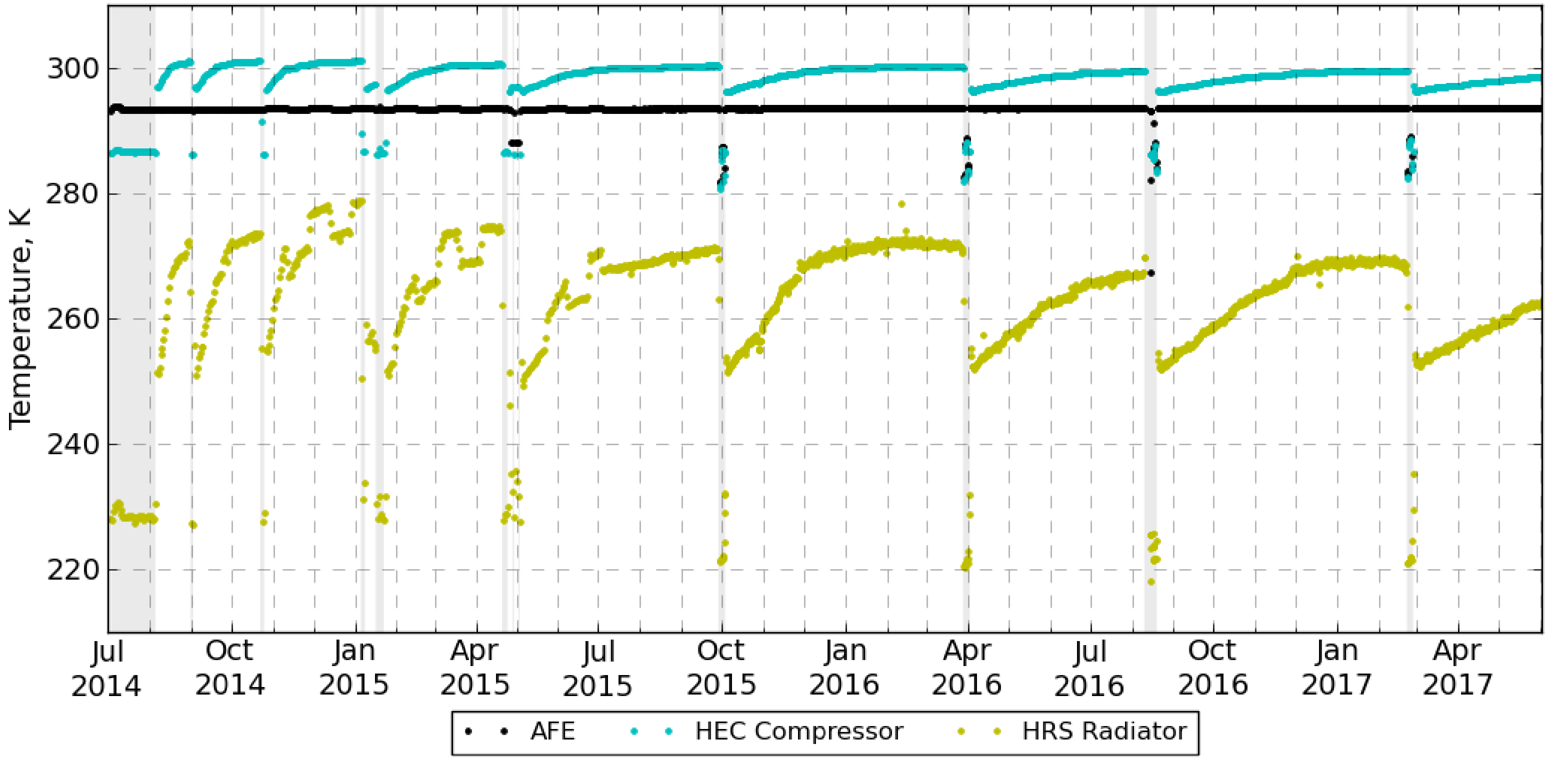
OBA
In-Flight Heat Rejection Performance

- Prior to July 2015, it was difficult to maintain OBA at nominal 267 K due to alternating Nadir/Glint Mode every 16 days
  - Shroud VCHP control setpoint needed a ~ ± 1 K adjustment after each Nadir/Glint mode change
- To acquire science data over land and ocean every day (rather than every 16 days), OCO-2 adopted an alternating Nadir/Glint mode orbit scheme after July 2015
  - Improved OBA temperature control with only ~ ± 0.1 K minor adjustments needed

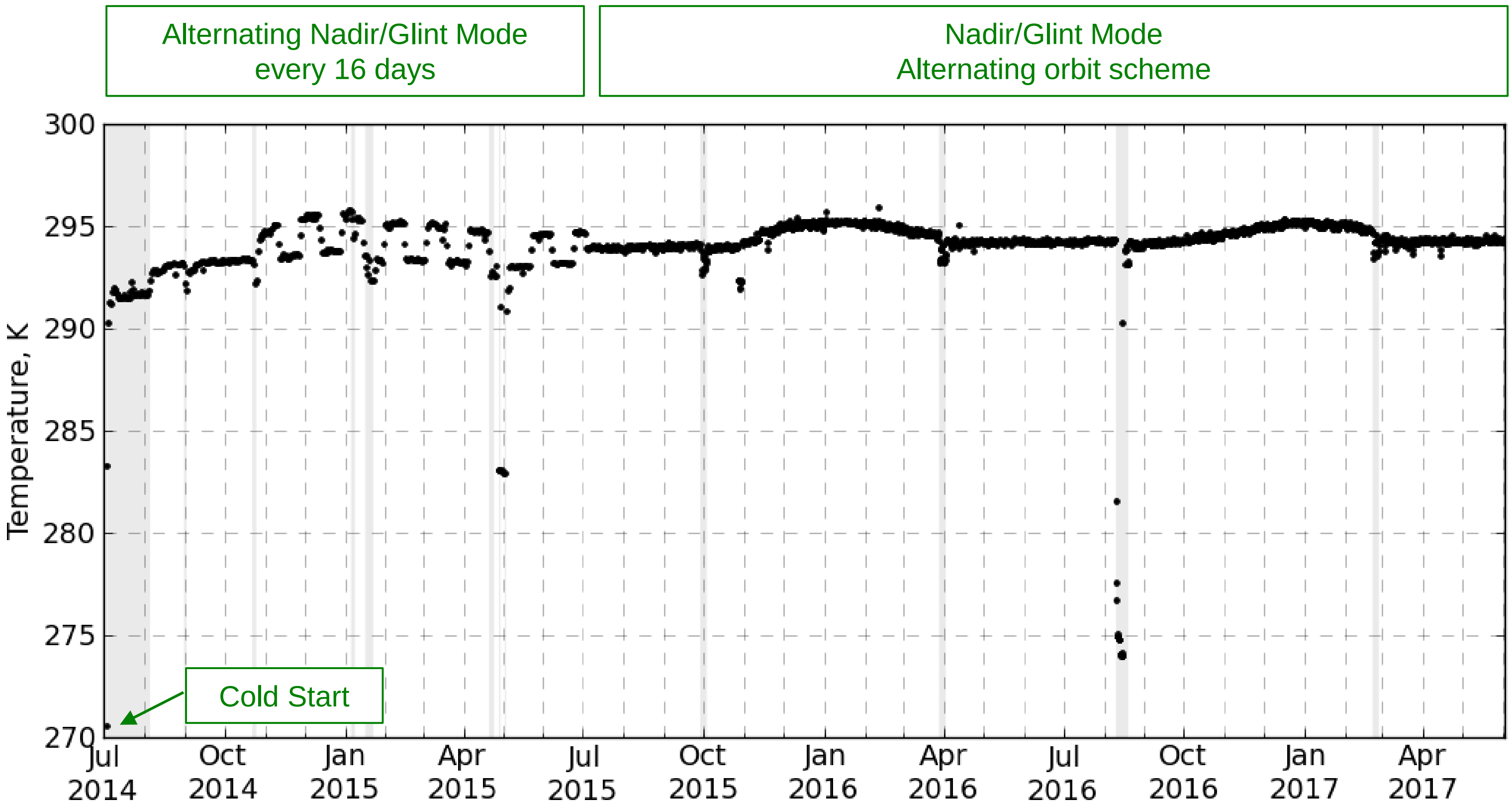


Cryocooler and AFE
In-Flight Heat Rejection Performance

- Cryocooler and AFE maintained between 293-300 K when operating
- Cryocooler and AFE maintained near 283 K when not operating

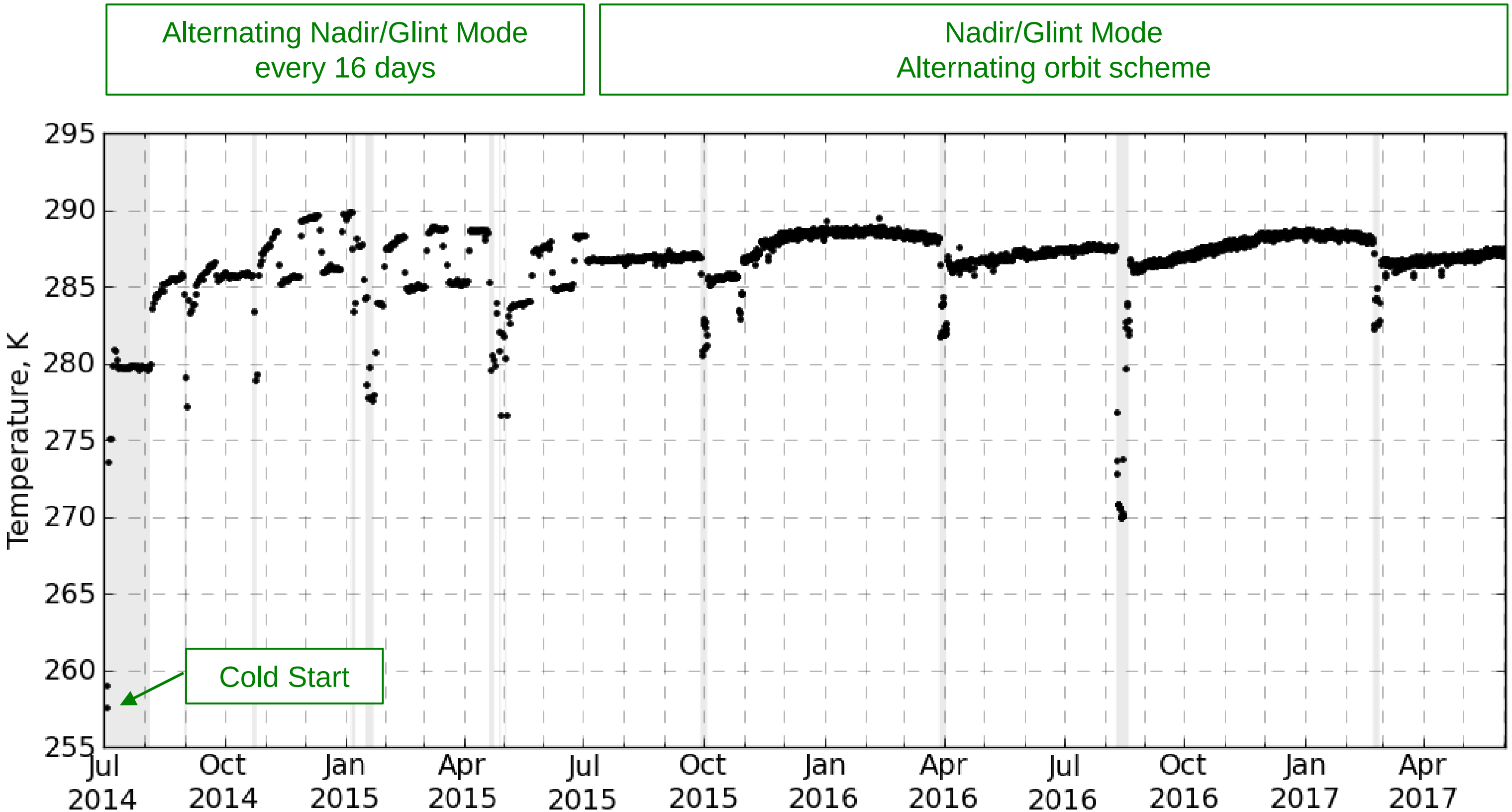


Remote Electronics Module (REM) In-Flight Heat Rejection Performance



- REM is maintained well within allowable flight temperature (AFT) limits

Cryocooler Control Electronics (CCE) In-Flight Heat Rejection Performance



- CCE is maintained well within allowable flight temperature (AFT) limits

Summary

- The heat rejection system for the REM and CCE have performed well, maintaining the REM and CCE near 295 K and 288 K, respectively

- The VCHP heat rejection system for the cryocooler, AFE and OBA have performed exceptionally well, maintaining the cryocooler and AFE within 293-300 K, and the OBA at 267 K

- Ice contamination rate on detectors and cryogenic surfaces has decreased over time such that de-icing cycles are now only performed once every ~ 6 months

- The thermal and cryogenic systems are performing to specification, have enabled OCO-2 to meet its primary mission science objectives, and are expected to continue should there be an extended mission