

Development of the Orbiting Carbon Observatory Instrument Thermal Control System

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ABSTRACT

The Orbiting Carbon Observatory (OCO) will carry a single science instrument scheduled for launch on an Orbital Sciences Corporation LeoStar-2 architecture spacecraft bus in December 2008. The science objective of the OCO instrument is to collect spaced-based measurements of atmospheric CO₂ with the precision, resolution, and coverage needed to identify CO₂ sources and sinks and quantify their seasonal variability. The instrument will permit the collection of spatially resolved, high resolution spectroscopic observations of CO₂ and O₂ absorption in reflected sunlight over both continents and oceans. These measurements will improve our ability to forecast CO₂ induced climate change. The instrument consists of three bore-sighted, high resolution grating spectrometers sharing a common telescope with similar optics and electronics. One spectrometer is used for O₂ observations with a 0.765 μm channel, while the weak and strong CO₂ bands are observed with 1.61 μm and 2.06 μm channels, respectively. The high-resolution spectrometers will measure reflected sunlight to retrieve the column-averaged CO₂ dry air mole fraction, X_{CO_2} . An extensive validation and correlation measurement program was developed for this mission to ensure that X_{CO_2} can be retrieved with precisions of 0.3% (1 ppm) on regional scales ($8^\circ \times 10^\circ$). The nominal mission lifetime for the instrument is 2 years. The OCO spacecraft will be placed in a sun-synchronous near-circular polar orbit with an inclination of 98.2 degrees, mean altitude of 705 km, 98.9 minute orbit period and 1:26 pm ascending node.

The thermal control system consists of passive and active elements to maintain the instrument within allowable flight temperature (AFT) limits. Passive thermal control includes multilayer insulation (MLI) blankets, thermal straps, and surface coatings to manage the transfer of waste energy from sources through structures and ultimately to radiators. Two detectors are cooled to 120 K and the third to 180 K by means of a mechanical pulse tube cryocooler. The optical bench is cooled to -5°C with an outboard radiator. The instrument was fully integrated in December 2007 and has undergone EMI/EMC, vibration and two thermal

vacuum (TV) tests. A general overview of the thermal control system with an emphasis on the two-phase heat rejection system (HRS) as well as the cryogenic subsystem is presented. The paper describes the instrument thermal requirements, thermal control and analysis approach, key design drivers and analysis results.

INTRODUCTION

The OCO instrument developed by the Jet Propulsion Laboratory for NASA, will fly onboard an Orbital Sciences Corporation LEOStar-2 spacecraft scheduled to be launch late in 2008 aboard a Taurus XL (3110) launch vehicle from Vandenberg Air Force Base in California. NASA's Office of Earth Science selected the OCO mission as its fifth mission in its Earth System Science Pathfinder (ESSP) program. OCO was designed and built by Hamilton Sundstrand Space Systems International and JPL with substantial subcontractor support, building critical hardware such as the cryogenic subsystem, HRS, mechanical pulse tube cryocooler, variable conductance heat pipes (VCHPs) and detectors. The OCO project is managed by NASA's ESSP program office out of Goddard Space Flight Center. The OCO instrument, flying aboard a dedicated satellite, will collect a large number of high resolution measurements which will provide the distribution of CO₂ over the entire globe. These measurements combined with data from the ground-based network will provide scientists with the information needed to better understand the processes that regulate atmospheric CO₂ and its role in the carbon cycle. This enhanced understanding will play a key role in improving predictions of future atmospheric CO₂ increases and their impact on the climate. This information will help policy makers and business leaders make better informed decisions to ensure climate stability and, at the same time, retain our quality of life. A detailed description of the OCO mission science is found in Refs. 1-3.

The OCO satellite will fly just ahead of the Earth Observing System afternoon Constellation (A-Train) with the Aqua, CloudSat, CALIPSO, PARASOL, and the other satellites (Ref. 4). The satellite's orbit has a repeat time

of 16 days and allows direct comparison of OCO observations with complementary data taken by Aqua and other A-Train mission instruments. The spacecraft bus will be used to point the OCO instrument for science data collection and instrument calibration operations. The estimated pointing accuracy is ~ 900 arcsec, and pointing knowledge is ~ 200 arcsec. The 16-day orbit repeat cycle allows monitoring of the X_{CO_2} variations on semi-monthly intervals. A detailed description of OCO and its science capabilities is found in Ref. 1. The OCO mission is a component of national and international efforts to better understand the sources and sinks of CO_2 in the Earth's atmosphere.

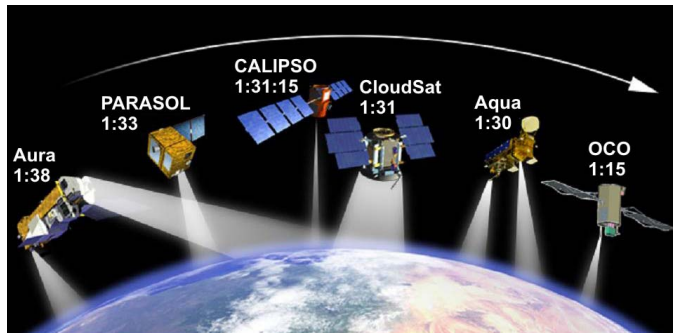


Figure 1. NASA's A-Train Constellation on orbit



Figure 2. An artist concept of the OCO spacecraft on orbit

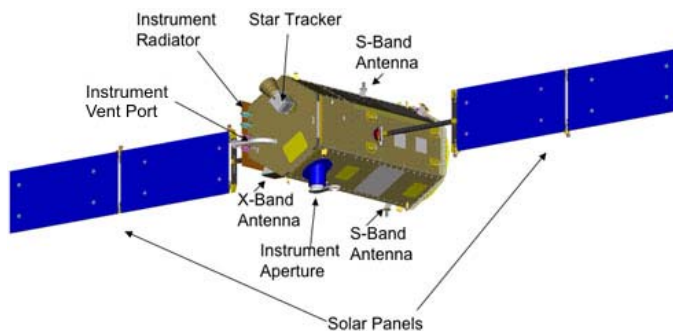


Figure 3. OCO spacecraft without external MLI

An artist's rendition of the OCO spacecraft ahead of the A-Train is shown in Fig. 1. The spacecraft on orbit nadir pointing with all of its external multilayer insulation is shown in Fig. 2. The OCO observatory with the

instrument and major spacecraft components are shown in Fig. 3.

Challenging instrument thermal requirements, tight mass and power budgets, restrictive spacecraft accommodations and widely varying mission environments, posed a challenging opportunity for the OCO instrument thermal control system. Further compounding this challenge was the tight temporal temperature stability requirement for the optical bench operating at $-5^\circ C$.

INSTRUMENT DESCRIPTION

The OCO instrument uses three different science observational modes to collect data on the day-side of the globe. In nadir mode, the satellite points the instrument to the local nadir. Data is collected along the ground track with a swath of 10.5 km just below the spacecraft. This mode will provide the highest spatial resolution on the surface, but may not provide adequate signal to noise over dark ocean surfaces. In glint mode, the instrument tracks the location where sunlight is directly reflected on the Earth's surface. Glint mode enhances the instrument's ability to acquire highly accurate measurements, particularly over the ocean which is a concern in nadir mode. In glint mode, the spacecraft points the instrument toward the bright "glint" spot, where solar radiation is specularly reflected from the surface. Glint measurements should provide much higher signal to noise ratios over the ocean. OCO will switch from nadir to glint modes on alternate 16-day global ground track repeat cycles such that the entire Earth is mapped in each mode on roughly monthly time scales. In target mode, the instrument will be used to track specific surface targets continuously as the satellite passes overhead. Target mode provides the capability to collect a large number of measurements over sites where alternative ground based and airborne instruments also measure atmospheric CO_2 . The OCO science team will compare target mode measurements with those acquired by ground based and airborne instruments to calibrate the OCO instrument and validate the science data.

The heart of the OCO instrument is its three focal plane arrays (FPAs) located in three separate, but thermally coupled, opto-mechanical focal plane assemblies. The CO_2 channels are cooled to 120 K and the O_2 channel to 180 K by means of a mechanical pulse tube cryocooler with an operating coldtip of 110 K. The cryocooler is the Tropospheric Emission Spectrometer (TES) spare flight cooler built by Northrop Grumman Space Technology (NGST), formerly TRW. (See Refs. 5-8). The cryocooler is an integral single-stage pulse tube long-life cooler. Two identical cryocoolers operating at 62 K on the TES instrument in space since July 2004 have successfully accumulated in excess of 31,000 operating hours each.

The spectrometer with its optics housing is maintained at $-5 \pm 0.15^\circ C$ by means of the HRS radiator running at approximately $-25^\circ C$. A second HRS radiator

running at approximately -20°C is used to provide cooling for the cryocooler and the Analog Front End (AFE) electronics.

The spacecraft middeck structure provides support for the entire instrument excluding the HRS. Isometric views from the solid CAD model with the HRS are shown in Fig. 4. The HRS is supported by means of kinematic mounts to the spacecraft bus panel on the +Y side. The instrument envelope is 1.0 m by 1.0 m by 1.2 m without the HRS and fits inside the spacecraft bus. The allocated instrument mass and average operating power is 344 kg and 165 W, respectively.

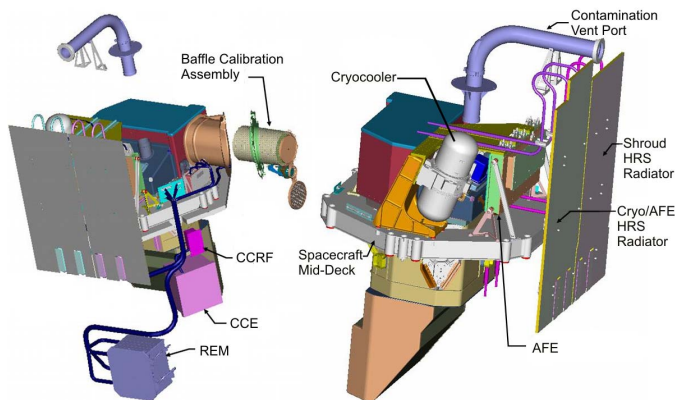


Figure 4. OCO instrument with HRS

The instrument thermal control incorporates both passive and active thermal control elements to reject the instrument waste heat. The cryocooler estimated heat load at 110 K is 1.90 W at BOL and 2.40 W at EOL. The AFE and calibration motor electronic assemblies are mounted to the instrument deck. The remote electronics module, cryocooler electronics and cryocooler ripple filter are mounted on the +Y and +Y-X spacecraft bus panels. The spacecraft coordinates are shown in Fig. 5.

The contamination vent port exits the spacecraft on the +Z axis and makes a 90° bend towards the +Y axis in order to vent away from the HRS radiator panels (see Fig. 5). It provides a 60 mm diameter vent path from the instrument shroud to the outside of the spacecraft bus. This vent port is designed to provide a high free molecular conductance flow path from inside the instrument to the outside vacuum space surrounding the spacecraft. MLI commonly used in cryogenic systems is known to absorb significant amounts of water at ambient conditions. Water absorption occurs fairly quickly within a few hours the MLI is saturated. However, desorption in vacuum takes much longer, with time constants in the order of days to weeks. All the MLI surrounding the cold surfaces from the cryocooler coldtip to the three focal planes will vent via the instrument vent port. The freezing of ice water on cold surfaces increases the emissivity, and consequently, radiation parasitic heat loads increase. This can potentially increase the total heat load on the cooler to high levels such that the cooler can no longer provide sufficient refrigeration to

maintain the required FPA temperature with the cooler power allocation. In addition, if sufficient ice frost is accumulated on the detectors, they can be rendered useless until defrosted. A decontamination heater on the cryocooler thermal strap will allow warm up of all cold surfaces including the three focal planes to defrost and drive away the water vapor.

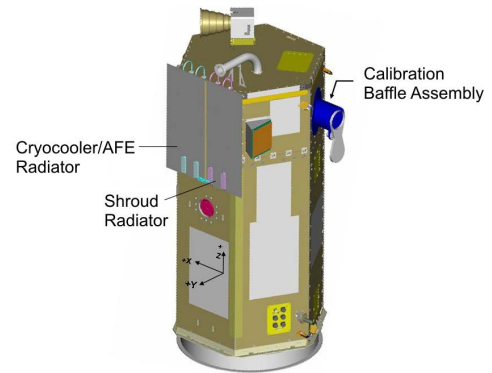


Figure 5. OCO instrument mounted inside the OSC spacecraft bus

SPACECRAFT ENVIRONMENTS

The key drivers for the OCO instrument thermal control system are as follows:

- Orbit parameters: sun-synchronous, 705 km altitude, 1:26 pm ascending node, 98.21 degree orbit inclination
- Spacecraft interface temperatures: $0/+40^{\circ}\text{C}$ for science and $-15/+50^{\circ}\text{C}$ during survival mode
- Heat transfer to spacecraft is limited to less than 10 W, which includes radiation and conduction heat transfer
- Survival heater power allocation is 30 W. This is 18% of the allocated operational average power

The parameters and conditions of each spacecraft state defining the bounding thermal mission environments, including spacecraft attitudes and the solar vector to orbit plane (beta) angle is shown in Table 1. The environmental constants are defined in Table 2.

THERMAL CONTROL REQUIREMENTS

The instrument thermal requirements along with spacecraft mission environments pose a very challenging thermal and cryogenic design problem. Spacecraft requirements dictate that the instrument thermal control be independent of the observatory (Ref. 9). This leads to the use of MLI blankets for the instrument and low conductance structural mounts to provide the required thermal isolation. In addition, outboard radiators are required to reject the instrument power dissipation. The instrument makes use of the HRS radiators on the +Y panel and the spacecraft provided radiators on the +Y and -X+Y panels.

The focal plane and optical bench temperatures are the driving thermal control requirements. The instrument temperature requirements are listed in Table 3 and the power dissipation components are listed in Table 4. The instrument exterior is covered with MLI blankets. The HRS radiators mounted via low thermal conductance mounts on the outside of the spacecraft also make use MLI to minimize radiation heat transfer with the spacecraft +Y panel.

S/C state	Beta angle (degrees)		S/C Attitude
	hot	cold	
Launch	varies	varies	varies
Science	11	28	-X local vertical (nadir pointing)
Safe	11	28	+Y local vertical (sun pointing)
Survival	NA	28	Radiators pointing towards space

Table 1. OCO spacecraft mission environments

Parameter	Cold Case	Hot Case
Solar Flux	1290 W/m ²	1420 W/m ²
Albedo	0.275	0.375
Earth IR	222 W/m ²	243 W/m ²

Table 2. OCO mission environment parameters (Ref. 10)

	Allowable Flight Temperatures (°C)			
	Non-operating	Operating		
	Survival	Orbit Variation	Grad	Design
Primary Instrument Assembly (PIA)	-15/50			0/40
FPA (A-band)	-178/35			-118/-88
FPA (weak/strong CO ₂)	-178/35			-168/-148
Analog Front End Electronics (AFE)	-15/50	5		10/25
Optical Bench Assembly (OBA)	-20/30	0.3	5	-5/0
Remote Electronics Module (REM)	-15/50			0/40
Baffle/Calibration Assy	-15/55			-10/50
Cryocooler/AFE and Shroud HRS	-100/50			-100/35
Cryocooler	-15/50			0/30
Cryocooler Control Electronics (CCE)	-20/50			0/50
Cryocooler Current Ripple Filter(CCRF)	-20/50			0/50

1. Integrated Electronics

2. Pointing and Control Subsystem

Table 3. Allowable flight temperature requirements (Ref. 11)

THERMAL CONTROL SYSTEM

The thermal control system provides four temperature zones required by the instrument, 120 K, 180 K, 268 K, and 290 K zones. It contains three focal plane arrays in three separate housings, two are cooled to 120 K and the third to 180 K by a single pulse tube cryocooler with a 110 K coldtip. A high purity aluminum flexible foil strap

connects all three detectors to the cryocooler coldtip. A variable conductance heat pipe based HRS with space viewing radiators provides cooling for the electronics and cryocooler and maintains the spectrometer at $-5 \pm 0.15^\circ\text{C}$. The AFE electronics require ± 2.5 K temperature control near 293 K.

	Component	Average Power (Watts)
AFE/Cryocooler Radiator	Cryocooler	40.0
	Analog Front End Electronics (AFE)	30.0
	VCHP Reservoir Heaters	6.0
Shroud Radiator	VCHP Reservoir Heaters	6.0
Spacecraft Radiators	Remote Electronics Module (REM)	42.0
	Cryocooler Control Electronics (CCE)	12.0
	Cryocooler Current Ripple Filter (CCRF)	3.5
	Calibration Door Motor	1.0
Total Power Dissipation		125.5

Table 4. Equipment average power dissipation

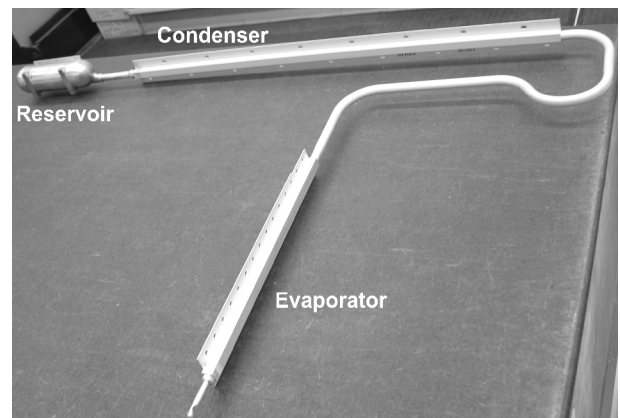


Figure 6. Variable conductance heat pipe for shroud HRS

The VCHPs, with active reservoir closed-loop on/off temperature control, transport waste heat from the instrument located inside the spacecraft to the outboard radiators and provide the required electronics temperature control. Fig.6 shows the VCHP configuration used for the shroud HRS. In survival mode, the instrument is off and the VCHPs are shutdown to minimize survival heater power. Passive thermal control elements include multi-layer insulation blankets, thermal straps, and surface coatings to manage waste heat from sources through structures and to radiators. Active thermal control employs VCHPs, and close-loop heater circuit controllers. Operational heaters are used in science and survival heaters are used in survival and safe modes. Figs. 7-9 show the operational and survival heater circuits.

The 120 K and 180 K zones are contained within each opto-mechanical focal plane assembly (OMFPA). The OMFPA housing interface temperature is maintained at $-5 \pm 0.15^\circ\text{C}$ by means of the optical bench shroud HRS