Design through Integration of On-Board Calibration Device with Imaging Spectroscopy Instruments

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Introduction:

The main purpose of the Airborne Visible and Infrared Imaging Spectroscopy (AVIRIS) project is to "identify, measure, and monitor constituents of the Earth's surface and atmosphere based on molecular absorption and particle scattering signatures." [1] The project designs, builds, and tests various imaging spectroscopy instruments that use On-Board Calibration devices (OBC) to check the accuracy of the data collected by the spectrometers. The imaging instrument records the spectral signatures of light collected during flight. To verify the data is correct, the OBC shines light which is collected by the imaging spectrometer and compared against previous calibration data to track spectral response changes in the instrument. The spectral data has the calibration applied to it based on the readings from the OBC data in order to ensure accuracy.

Once a calibrator is assembled, calibration tests can then be conducted to ensure that it is operating appropriately and is ready to be integrated with the instrument. When all of the components of the instrument are integrated as one unit, the spectrometer goes through an array of preparation and testing in the lab to confirm that it is ready to be delivered to the field to gather data. The final preparations for delivery are checking that there is clear communication with the software, the hardware operates as intended, and the instrument is able to smoothly record test data without errors, comparable to the data collection process of in-flight tests.

When all lab procedures are complete, the instrument and its control racks are installed and integrated into the aircraft. Quick tests are conducted to confirm electronic connections from the racks to the instrument are integrated. When all connectors are attached and the instrument and on-board software are running properly, flight test data is ready to be collected. This phase proves to be critical because recording data while in flight cannot be easily simulated in the lab. The best test datasets for the spectrometer are gathered by recording the light reflecting off of the earth's surface while flying overhead.

In-Lab:

On-Board Calibration:

The On-Board Calibration device enables the spectral and radiometric stabilities of the spectrometer to be monitored by sending its own calibrated and stable light into the vacuum chamber by means of a fiber optic cable. [2] The operator can then use this calibration data to ensure accuracy of the spectrometer. This method is possible because of the careful design of the OBC. Within the calibrator rests a halogen bulb, which has a stable color-balanced spectral signature. At a controlled voltage and temperature, the bulb will shine light in a manner which can be precisely regulated over an extended period of time.

Thermal and Voltage Stability:

The temperature and voltage of the OBC are both variables that must be precisely controlled. The temperature remains stable through the use of heaters and thermocouples that are attached to the housing of the OBC. Regulated by a thermal control unit, the temperature is kept at above ambient to help negate any instability caused by thermal fluctuations. The purpose for constant voltage starts at the bulb source. In order for the desired constant light emission to be produced to give the desired spectral signature, the bulb must operate at a specific voltage. The bulb emits light onto a parabolic mirror, whose focal point meets the end of the fiber optic cable, where 10 fibers from the fiber bundle are redirected away from carrying light to the instrument, as the other 200 fibers do, but reconnect into the OBC box at a feedback detector. The output from this detector is passed to a feedback circuit that adjusts the voltage of the halogen bulb based on the intensity of the incoming light. This feedback mechanism corrects the output level of the light source to emit at an intensity that will output the desired spectral signature. This process continues in order to keep the halogen bulb at the desired voltage during the entirety of its life cycle.

Operation Levels:

The OBC operates at three different levels: an enhanced state, a normal state, and an idle state. The normal state operates at 5 V, allowing for calibration at nominal bulb voltage. This produces the standard operating conditions and gives full-range calibration information. However, the blue levels of the visible spectrum are weak in the normal state, and therefore do not provide an optimal calibration source. To adjust this weak range in the spectral output, the enhanced state runs the bulb at 140% nominal voltage (7 V) to increase the blue levels in the calibration data set. When calibration is not needed, the bulb is put into an idle state, running at 50% nominal voltage (2.5 V) to preserve its lifetime without compromising stability by maintaining a stable halogen cycle during flight. *Figure A* shows the averaged spectra graph for each wavelength, illustrating the enhanced and normal calibration levels. [3]

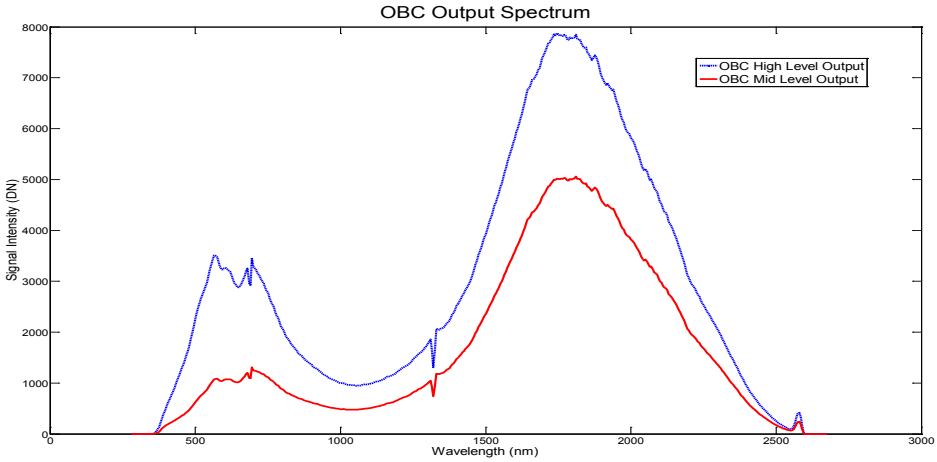


Figure A: OBC output spectrum of averaged spectra for the Enhanced (High) and Normal (Medium) Levels

Design and Drawings:

Previously fabricated calibrators made for an inefficient assembly process because of fasteners breaking due to the restraint of the small hole sizes, only allowing for weaker screws to be used for assembly. Safety was also a factor during assembly based on the sharp sides of the OBC housing, which could damage thermocouple and detector wires pulled around the edges of the calibrator. Many design changes have been made to give aid to these rising issues. Most of the changes were made on SolidWorks, a 3D modeling program used widely by mechanical engineers for designing parts and assemblies. The most recent revision of the OBC altered the parts to allow for larger fasteners to be used, and also implemented rounded edges to ease the safety risk.

The Product Data Management Systems (PDMS) drawings were updated to reflect a higher level of clarity so that manufacturing engineers would better understand the specifications required to fabricate each part. Datums were redefined, new measurements were taken, more thorough instructions were given, and tolerances specified were re-evaluated. *Figure B* is an example of a revised drawing that exemplifies articulateness expected from an official document uploaded on PDMS.

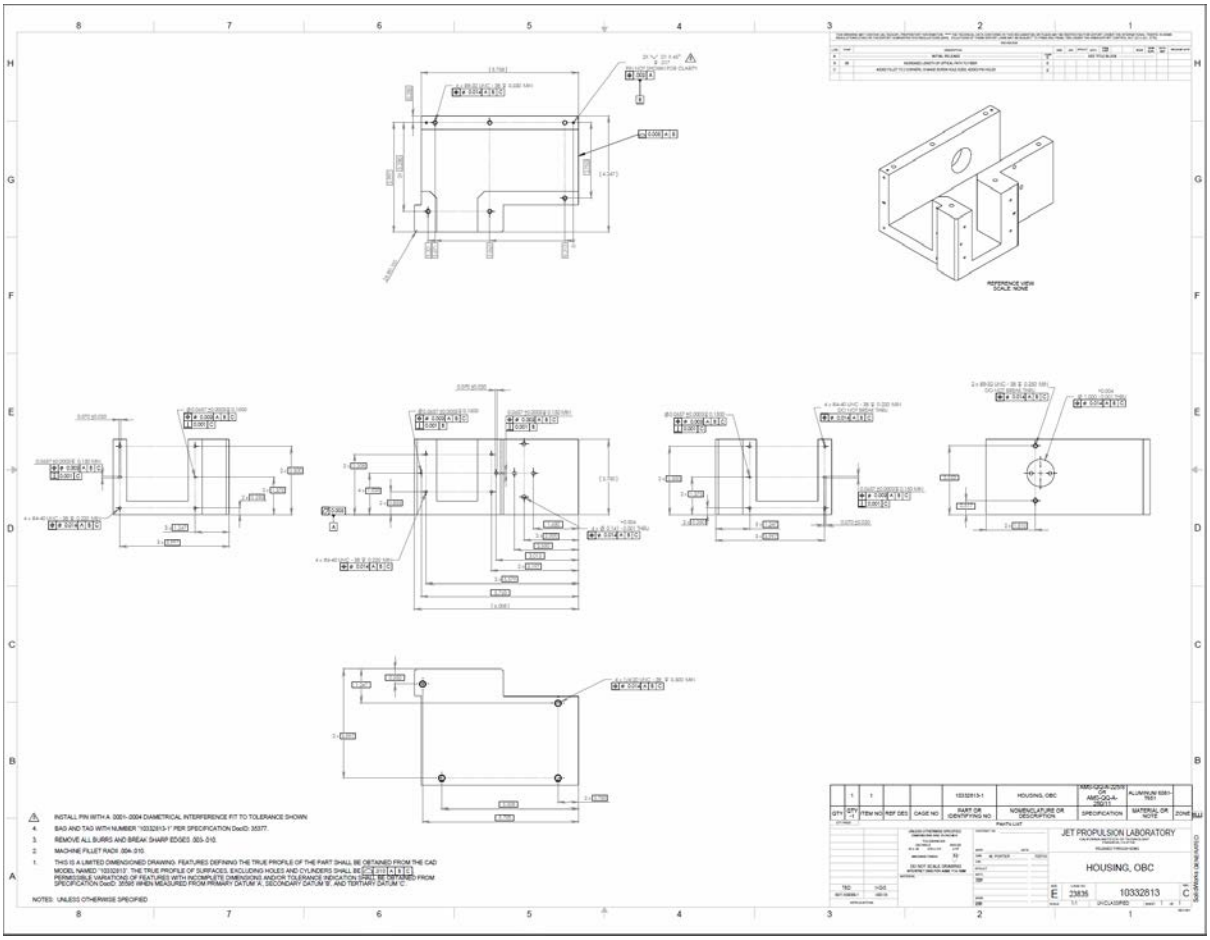


Figure B: PDMS Drawing of Housing, OBC

All new fasteners were also needed for assembly of the OBC. An extensive amount of time is needed to meticulously check each fastener interface. The diameter and depth of each hole needed to be catalogued, along with the appropriate fasteners that could interlock 5 threads. Military Spec. or National Aerospace Services (NAS) certified fasteners were desired due to the trusted testing of the products under these certifications.

Testing:

Upon completing the assembly of the OBC and other devices, the instrument components must undergo a variety of tests checking for full functionality of the hardware and software systems. Communication between the electronic controls and the instrument is crucial for carrying out data collection processes. Incorrect integration of the electronic connections is a primary cause for system failures and should be carefully treated as a vital aspect of preliminary checks before the instrument takes part in any testing.

For calibration tests done in lab, a well-controlled light source is needed to produce accurate results. A black material is needed around the calibration light source environment so no foreign light is reflected into the calibration test to skew data. An additional test is conducted to determine the spectral measurement for true blackness so the most absorbent black material can be used; true black is desired because it absorbs all wavelengths. A Rippey cloth is used to perform the test, which is the closest material to perfect black that can be easily obtained. Rippey cloth contains minimal spectral reading in the Infrared range, but absorbs almost all visible wavelengths, making it a prime candidate for use in calibration test environments.

Testing of the instrument and supporting devices is carried out in three separate but equally important environments: in-lab, in-field, and in-flight. In-lab tests check the functionality of individual components, ensuring that each part can be integrated to the instrument for trusted performance. Upon completion of these in-lab tests, the instrument is ready to be delivered to the field.

In-Field:

Instrument preparation in the field allows for the spectrometer to be tested as a whole unit, confirming that all components are working together, and that data collection runs properly with all devices working concurrently. Once out of the lab, in-field tests are conducted to give quantitative assurance that the instrument is ready for flight.

Ground Truth testing:

For the imaging spectroscopy device to have reliable output data, the spectral readout for any given sample must be accurate to the true spectral signature. Ground truth testing retrieves accurate spectral information that is compared with the spectrometer to confirm valid data collection. The ground truth calibration test is conducted with the Analytical Spectral Device (ASD) Field Spec. portable spectrometer. By collecting spectral signatures on the ground of a sample target and comparing it to the spectral data collected by the instrument in flight, the imaging spectrometer can then be properly calibrated to take scientific data. The first step of this test is to accurately set the spectral reading of the

ASD by measuring the sun's spectral signature, recording data from the reflected light on a spectralon panel. The spectralon panel is manufactured to be 99.9% reflective across all wavelengths of interest so that the spectral signature of the sun can be accurately recorded. A dark measurement is taken after the spectralon panel reading in order to cancel out potential excess noise in the spectralon panel reading. However, to conduct this test there cannot be any trace of clouds that could cause false readings in the data due to extra reflectance. The site used for ground truth testing must be spectrally uniform over a 30m by 30m area to provide minimal variance in the spectral signature. This assures spectra recorded by the ASD will not change based on the location of each sampling within the site. Black tiles separated 1ft, 2ft, and 3ft are used to analyze the precision imaging of the spectrometer, which has the resolution to clearly recognize a one foot by one foot area. *Figure C* depicts the black tiles resting on uniform airport asphalt.

Figure C: Ground truth data being collected at South County Airport of Santa Clara County. Blue tarps mark off the boundary of the 30 meter sample site.

Integration and Installation:

The instrument is installed into a Twin Otter dual propeller aircraft altered specifically for scientific research. The cabin is unpressurized by design, allowing for a cut-out on the underside of the fuselage towards the rear where the instrument is located and can freely collect light from Earth's surface without any material obstruction. The aircraft limits its weight for flight, and must have

proper distribution of that weight for a balanced aircraft. The operating rack and the environmental control rack are strategically placed in the airplane to optimize ease of access as well as create a well-balanced fuselage. This setup can be seen in *Figure D.* The two racks get installed before the instrument because the difficulty of installing in the reverse order would be much greater.

Figure D: Notice the placement of the operating rack (forward) and the environmental control rack (aft). Because they sit on the right side to allow comfortable movement through the center of the cabin, an oxygen bottle (covered in black harness) is purposely put on the left side of the cabin to create proper weight distribution.

Connecting the cables from the racks to the instrument requires much planning as one unconnected interface may result in lost data. With the multitude of devices that require integration to the instrument, the potential for error is high, so much care is needed in this procedure. When all cables from the racks to the instrument have been connected, preliminary operations are conducted to ensure that all programs and devices are functioning properly. An important part of this process involves temperature and pressure. A vacuum is created inside the canister of the imager because lower pressures allow for lower temperatures. The closer the spectrometer is to 0 Kelvin, the less noise will be present in the output data. Once the instrument is pumped down to a nominal level, the cryocoolers are activated which cool down the spectrometer. When this process reaches nominal, and a running, errorless system is in place, the result is an instrument ready for in-flight data collection.

In-Flight:

In-flight data collection from the imaging spectroscopy instrument is the main goal and end result of this project. The final step before the instrument is ready to record scientific data is to carry out the last few in-flight tests, making sure all facets of the system are working properly, and going through the preliminary procedures checklist to ready the equipment and the instrument for flight.

Wiggle Test:

Because the plane tilts during flight due to wind and other factors, the instrument is integrated to the aircraft on a moving mount that keeps the instrument orthogonal to earth's surface. Occasionally the instrument does tilt slightly, changing the preciseness of the data. To adjust for this issue, an orthorectificaiton code and GPS is used to track the movement of the ground below. To check the accuracy of this process the wiggle test is performed, which is a crucial part of the in-lab, in-field, and in-flight phases. However, the most representative of the three tests is the in-flight test because it is not a simulated version. Only one of the three tests is needed, but each is performed in order to discover the most optimal of the set. The wiggle test essentially involves tilting the instrument $\pm$10 degrees as fast as possible, which is done by shifting the instrument position in-lab on the mount, rocking the plane with the integrated instrument in the hangar, or tilting the plane in-flight when the instrument is assembled. The data set taken during this test is used as the input for the orthorectification code, which takes GPS data concurrently and associates a given coordinate and time stamp to each pixel on the spatial grid.

Flight Operator Certification

In order to take data, the aircraft must travel over specifically planned lines that are marked by beginning and ending coordinates. These coordinates are input into a flight GPS that navigates pilots through each line they must fly. Each line has a designated altitude the aircraft must be at in order to collect the appropriate data. Some flights are as low as a few thousand feet above sea level (ASL), and some as high as 20,000ft above sea level. When the lines are going to be at altitudes greater than 12,000ft ASL, proper certification is required by those in the aircraft.

Hypoxia is a condition in which the body is deprived of its needed oxygen supply. Less oxygen is present at high altitudes, resulting in less oxygen in the bloodstream of those who are in these high altitude conditions. To fly at or above 12,000ft, hypoxia training is required due to safety purposes. In history, there have been numerous stories across the world about people who have died and planes that have crashed due to incidences of hypoxia. Gaining authorization for hypoxia training requires a class three medical certificate to prove flight operators are healthy enough to be at such high altitudes. Hypoxia training consists of a one day, traditional class setting where students learn about the symptoms of becoming hypoxic, and recognizing those symptoms when they are experienced. Hypoxia can be present without any signs or knowledge of lack of oxygen, but when blood-oxygen levels are low enough, symptoms will emerge. At the end of the class lesson, participants are then put in a hypoxic state while they control a flight simulator. Those flying the simulator immediately put into practice what was learned about hypoxia and recognize which symptoms appear first. The safety of flights increases dramatically because flight operators will know when they are becoming hypoxic, and can take oxygen before any serious incidences occur.

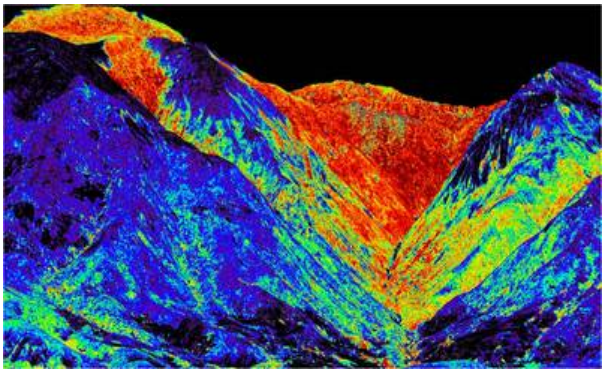
Conclusion:

The progression of an imaging spectroscopy instrument from design to in-flight operation requires a wide range of diverse engineers to bring all the various aspects of the instrument together as one unified complex system that works smoothly between all interfaces. The timeframe for processes involved will exceed expected plans due to the compounded intricacies of the parts and devices used. When each feature of the instrument is syncing and running flawlessly, and the system is performing as planned, even more inspiration and motivation are created for future work.

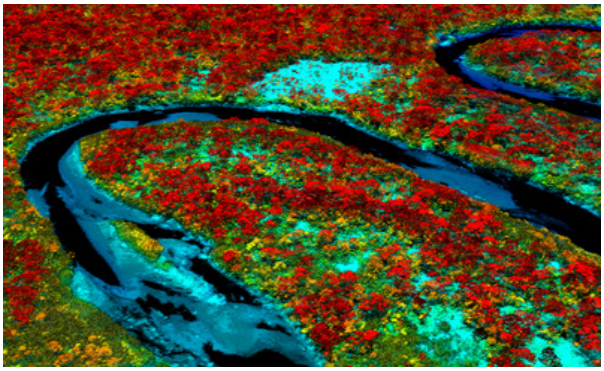
Airborne imaging spectroscopy instruments have facilitated much research, helping scientists learn more about Earth as a result. The Carnegie Airborne Observatory uses imaging spectrometers for investigating the effects forest degradation and deforestation have on carbon emissions in rainforests. [4] Through the use of their spectrometer they can view the spectral signatures of thriving forested areas and compare those findings with the spectral signatures of deforested land. This research could lead to plausible options for reducing emissions in various forests affected by degradation. Another research group, the National Ecological Observatory Network, will be surveying 62 sites across the United States, analyzing the impacts of climate change over a 30 year period. [5] An imaging spectrometer will be used to gather much of this data, cataloging the changes in the ecosystems of America. A third group, the Airborne Snow Observatory, investigates the snow levels of the Sierra Nevada Mountains to determine the amount of snowmelt that will occur during the spring and summer months for the purpose of predicting the water demand in Southern California. Snow and lake levels can be documented through imaging spectroscopy, helping to better understand how the California water cycle is being affected by other natural phenomena. Imaging Spectroscopy instruments provide the tool for multiple facets of scientific research and exploration, proving the need for assuring careful design, assembly, testing, and installation processes of the instrument.

The development of the AVIRIS project's imaging spectrometers constantly expands to new depths as newfound knowledge arises from the findings of new technology. Breakthroughs in results from collected test and calibration data reveal subtle occurrences that, once altered, can improve the accuracy of the instrument. These findings are constantly propelling the engineering of the instrument to discover new ways to create more compact parts, more precise measurements, and more intricate and complex systems that can function with multiple devices.

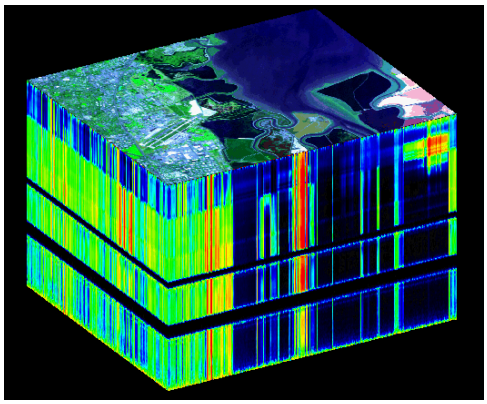
Pictures Documenting Processed Data from Imaging Spectroscopy Instruments



Courtesy of Carnegie Airborne Observatory.
Forest in Madagascar, reds are intact canopy, blues and blacks show deforested areas



Courtesy of Carnegie Airborne Observatory.
Remote Columbian Amazon



Courtesy of AVIRIS.
Image cube, the top face lies in the visible part of the spectrum, and the sides show the 224 spectral channels that accompany each top face pixels.

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[2]
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