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These articles discuss Earth's many dynamic processes and their interactions.

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Formation Flying: The Afternoon "A-Train" Satellite Constellation

Introduction

The changing Earth environment is increasingly a focus of many agricultural, industrial, and societal concerns. Sound policy decisions are needed to address these issues. NASA's Earth Science Enterprise (ESE) provides timely Earth Science data and information to decision makers to help them craft sound and equitable environmental policy. Earth Observing System (EOS) missions, and complementary smaller, more-focused Earth System Science Pathfinder (ESSP) missions, are a primary source of Earth Science information for the ESE. The "A-Train" satellite formation consists of two of the major EOS missions, three ESSP missions, and a French Centre National d'Etudes Spatiales (CNES) mission flying in close proximity (see **Table 1**). This carefully planned formation allows for *synergy*—meaning that more information about the condition of the Earth is obtained from the combined observations than would be possible from the sum of the observations taken independently.

TABLE 1: *Summary of A-Train Missions [See* ***Figure 1*** *for Illustration]*

Spacecraft	Position in A-Train/ Formation Requirements	Summary of Mission	Instruments Carried
Aqua	Lead spacecraft in formation until the launch of OCO.	Synergistic instrument package studies global climate with an emphasis on water in the Earth/atmosphere system, including its solid, liquid and gaseous forms.	AIRS/AMSU-A/HSB AMSR-E CERES MODIS
CloudSat	Lags Aqua by between 30 seconds and 2 minutes. Must maintain extremely precise positioning relative to both Aqua and CALIPSO to permit synergistic measurements with Aqua and CALIPSO.	Cloud Profiling Radar will allow for most detailed study of clouds to date and should better characterize the role clouds play in regulating the Earth's climate.	CPR
CALIPSO	Lags CloudSat by no more than 15 seconds. Must maintain position relative to Aqua to permit synergistic measurements with Aqua.	Observations from spaceborne lidar, combined with passive imagery, will lead to improved understanding of the role aerosols and clouds play in regulating the Earth's climate, in particular, how the two interact with one another.	CALIOP IIR WFC
PARASOL	Lags CALIPSO by about 1 minute.	Polarized light measurements will allow better characterization of clouds and aerosols in the Earth's atmosphere, in particular, distinguishing natural and manmade aerosols.	POLDER
Aura	Lags Aqua by about 15 minutes but crosses equator 8 minutes behind Aqua due to different orbital track to allow for synergy with Aqua.	Synergistic payload will study atmospheric chemistry, focusing on the horizontal and vertical distribution of key atmospheric pollutants and greenhouse gases and how these distributions evolve and change with time.	HIRDLS MLS OMI TES
OCO	Will precede Aqua by 15 minutes when it is launched.	Will make global, space-based observations of the column integrated concentration of CO_2, a critical greenhouse gas.	Three grating spectrometers

Take the “A-Train” to Scientific Discovery

Over the next five years, NASA’s ESE plans to launch four satellite missions that will fly in formation with each other and with the Aqua satellite, which has been in orbit since May 2002. A sixth satellite called Polarization and Anisotropy of Reflectances for Atmospheric Science coupled with Observations from a Lidar (PARASOL), launched by the French Space Agency, will join the four already launched NASA missions in 2005. All six satellites will cross the equator within a few minutes of one another at around 1:30 p.m. local time. Since these missions will all fly in tandem, the set of satellites is referred to as a constellation, or alternatively, as a formation. Furthermore, since this constellation is composed of missions with equator crossings in the early afternoon (and also in the middle of the night, at about 1:30 a.m.), it is referred to as the Afternoon Constellation - to distinguish it from the Morning Constellation consisting of Terra, Landsat-7, SAC-C and the New Millennium Program’s Earth Observing-1 (EO-1), all currently flying. The term “A-Train” comes from an old jazz tune, “Take the A-Train” composed by Billy Strayhorn and made popular by Duke Ellington’s band, and has become a popular nickname for the Afternoon Constellation because Aqua is the lead member of the formation and Aura is in the rear*. The other missions that will eventually make up the A-Train are CloudSat, Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO), and the Orbiting Carbon Observatory (OCO). Each individual mission has its own objectives and will improve our understanding of aspects of the Earth’s climate. The real advantage of formation flying, however, as mentioned in the **Introduction**, is that the data from the various satellites are synergistic.

A Tour of the A-Train

If we think of a railroad train we realize that it is composed of component parts. It has an engine and lead car, and can have as well freight cars, passenger cars, sleeping cars, dining cars, and a caboose. Individual trains may not have all these components, but any train needs a combination of some of these component parts to be most effective. Passengers on board may need to make use of services available from several of the component parts to satisfy their needs. The analogy of a train isn’t perfect for a group of Earth Observing satellites orbiting in space. These satellites do not follow each other in a straight line like the cars of a train along a track. They also aren’t dependent on the lead satellite in any way as a train is dependent on its engine for power. Each satellite is able to function and collect data completely independently of all the others and has an independent mission to fulfill. Nevertheless, the name “A-Train” has stuck, and it can be useful to think of a satellite formation as a train to help understand the concept of formation flying. Let’s take a look in greater detail at each planned component of the A-Train, as we would if we were touring through the individual cars that make up a train, and consider what each individual satellite mission will study. Then we’ll consider how the individual components of the formation can be combined to enhance our understanding of important issues related to climate change.

We begin our tour at the “front” of the satellite formation. Until OCO is launched, ***Aqua*** is the first component (with the earliest equator crossing time) and can thus be thought of as the engine of the A-Train. Aqua was launched on May 4, 2002, and is the second of three major EOS missions, following Terra and preceding Aura. As implied by its name, the Aqua mission focuses on studies of water in the Earth/atmosphere system, although it also deals with additional elements of the climate as well, and with the global biosphere. Aqua carries a synergistic instrument payload that measures water in its gaseous, liquid, and solid forms, plus atmospheric and surface temperatures, land and ocean vegetation, and many other aspects of the global climate system. The Atmospheric Infrared Sounder (AIRS) is a high spectral resolution infrared sounder designed primarily to obtain temperature and humidity profiles from the surface to an altitude of about 40 km. The Advanced Microwave Sounding Unit (AMSU) aids in retrieving atmospheric temperature profiles, especially under cloudy conditions and in the upper atmosphere. The Humidity Sounder for Brazil (HSB) is used to obtain humidity soundings through the atmosphere, for determining cloud liquid water, precipitation, and integrated precipitable water, and was provided by Brazil's National Institute for Space Research. The microwave measurements of the AMSU and HSB are particularly important for enhancing the AIRS measurements in the presence of clouds. Taken together the three sounders (AIRS/AMSU/HSB) make up the most advanced sounding system ever to fly in space. The Advanced Microwave Scanning Radiom-

*** This distinction holds until the launch of the Orbiting Carbon Observatory (OCO)—tentatively planned for 2007—which will cross the equator fifteen minutes ahead of Aqua and thus become the new leader of the formation.**

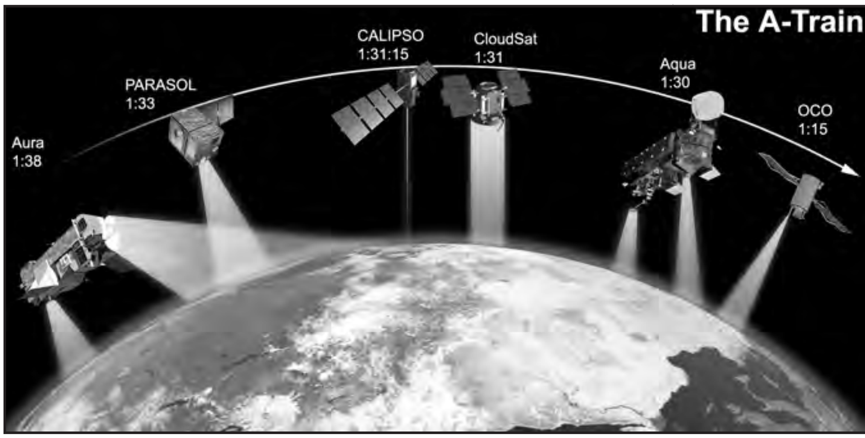

FIGURE 1: *This graphic (not to scale) depicts the satellites that make up the Afternoon Constellation—"The A-Train". Listed under each satellite's name is its equator crossing time. Note that though Aura crosses the equator eight minutes behind Aqua, in terms of local time, because it is along a different orbit track, it actually lags Aqua by fifteen minutes. Note also that CALIPSO trails CloudSat by only 15 seconds to allow for synergy between Aqua, CloudSat, and CALIPSO.* ***Credit****: Alex McClung.*

eter-EOS (AMSR-E) is a passive microwave scanning radiometer designed to measure precipitation, water vapor, sea surface temperature, wind speed, sea ice, snow cover, and soil moisture and was provided by Japan's National Space Development Agency (NASDA). The Clouds and the Earth's Radiant Energy System (CERES) is a broadband scanning radiometer intended to measure major elements of the Earth's radiation balance and aid climate change studies. The Moderate Resolution Imaging Spectroradiometer (MODIS) is a cross-track scanning radiometer with 36 bands spanning the visible and infrared portions of the electromagnetic spectrum. MODIS was constructed to obtain information about a wide variety of biological and physical processes of relevance to Earth system science, most notably for the purposes of the A-Train, cloud and aerosol properties.

The next stop on the tour of the A-Train is ***CloudSat***. CloudSat is an ESSP mission that will launch in 2004 and will study clouds in detail to better characterize the role they play in regulating the Earth's climate. CloudSat is a joint U.S./Canadian mission intended to provide a global survey of cloud properties. Data returned should lead to improved cloud parameterizations in atmospheric models, which should help improve the accuracy of weather forecasts and climate predictions made using these models. CloudSat will carry a powerful Cloud Profiling Radar (CPR) with 500-m vertical resolution. It is not a scanning device like many of the instruments currently flying on other satellites. The radar sends out an active pulse and receives a return signal. Since it transmits in the upper microwave region (94 GHz) where the signal is not significantly attenuated by clouds, the radar should be able to detect 90% of all ice clouds and 80% of all water clouds. Quite a number of data products related to various cloud properties will be derived from the data collected by CloudSat, some of which will depend on data returned from other satellites of the A-Train as well.

Close behind CloudSat is ***CALIPSO***. CALIPSO will be deployed on the same launch vehicle as CloudSat in 2004. CALIPSO is another ESSP mission. It is a joint U.S./French collaboration and will provide unique measurements to improve our understanding of the role of aerosols and clouds in the Earth's climate system. The combined observations from CALIPSO and the other satellites of the A-Train will improve our ability to predict long-term climate change and seasonal-to-interannual climate variability. CALIPSO's main instrument is called CALIOP—short for Cloud Aerosol Lidar with Orthogonal Polarization. This is a two-wavelength polarization-sensitive lidar designed to measure the vertical profiles of aerosols and clouds with 30-m vertical resolution and 333-m horizontal resolution. The lidar profiles provide information on the vertical distributions of aerosols and clouds, cloud ice/water phase, and a qualitative classification of aerosol size. CALIPSO also carries a three-channel Imaging Infrared Radiometer (IIR), developed by CNES, and a single-channel high spatial resolution Wide-Field Camera (WFC) designed to complement the lidar and obtain information on cirrus cloud particle size and radiative characteristics. The WFC also allows highly accurate spatial registration, when required, between CALIOP and instruments on the other A-Train satellites.

Proceeding toward the rear of our train, we find ***PARASOL***—a French mission. It will make measurements of the total and polarized light in several wavelengths and at several different viewing angles. PARASOL will carry an instrument known as Polarization and Directionality of the Earth's Reflectances (POLDER). This instrument cycles through eight narrow wavelength bands and, for certain of these wavelengths, samples three distinct polarizations. All of these data can be combined to give a very thorough assessment of the state of the light reflected by the coupled surface-atmosphere system. Information on polarization in several directions has been shown to be very useful for characterizing clouds (both liquid and ice) and aerosols in the atmosphere. This measurement technique, for example, may help scientists determine exactly how much of the aerosol present in the Earth's atmosphere comes as a by-product of human activities and how much is naturally occurring - an important question in climate change studies.

Finally, we come to the "caboose" of our train—the final component in the formation. ***Aura*** is the third of the major EOS observatories and should launch in 2004. Aura's suite of instruments is designed to study issues related to air quality, stratospheric ozone, and climate change. For example, Aura will allow scientists to trace air pollution events back to local and regional sources and allow for intercontinental tracking of pollution transport. The High Resolution Dynamics Limb Sounder (HIRDLS) will observe global distributions of temperature and several other trace species in the stratosphere and upper troposphere by observing the Earth's *limb*—meaning the instrument scans the horizon as opposed to looking down on the surface. The Microwave Limb Sounder (MLS) will observe the limb to measure concentrations of ozone-destroying chemicals throughout the stratosphere and upper troposphere, as well as water vapor, a greenhouse gas, in the upper troposphere. The Tropospheric Emission Spectrometer (TES) will look downward upon the Earth and will also scan the Earth's limb over a broad range of wavelengths to measure key air-pollution constituents. The Ozone Monitoring Instrument (OMI), provided by the Netherlands' Agency for Aerospace Programs (NIVR) in conjunction with the Finnish Meteorological Institute, is designed to look down through the atmosphere and measure ozone, aerosols and other pollutants in the atmosphere. Taken together, data from the instruments on Aura will provide a rich new source of information on the horizontal and vertical distribution of key atmospheric pollutants and greenhouse gases and how these distributions evolve and change over time. Further, combining Aura data with data from the other A-Train missions will reveal even more information on these and other important issues.

A sixth mission was recently selected that is now expected to be part of the A-Train formation—the ESSP mission called ***OCO***. This satellite will be placed in an orbit ahead of Aqua by 15 minutes when it is launched in 2007 and, at that point, effectively becomes the new lead satellite in our train. OCO will make global, space-based observations of the column integrated concentration of carbon dioxide (CO_2). OCO will be equipped with three grating spectrometers, each covering a separate wavelength range in the near-infrared region of the electromagnetic spectrum. One wavelength is chosen to study the Oxygen-A band. This is a spectral feature used to estimate the total mass of the atmosphere and determine how much of the observed CO_2 variation can be attributed to changes in atmospheric thickness. The other two wavelengths are for measuring CO_2 concentrations. The objective of these measurements is to provide independent approaches to validate the data and ensure high accuracy. OCO will also combine satellite data, meteorological observations, and ground-based CO_2 measurements to characterize CO_2 sources and sinks on regional scales at monthly to interannual time intervals.

The Value of Formation Flying: The Whole Is Greater Than the Sum of Its Parts

Having examined the roles of the individual components of the A-Train, let's consider the value of the entire formation. By combining the components, scientists are able to gain a better understanding of important parameters related to climate change. The A-Train formation will allow for synergistic measurements where data from several different satellites can be used together to obtain comprehensive information about various key atmospheric components or processes. Combining the information from several sources gives a more complete answer to many questions than would be possible from any single satellite taken by itself. Some of the most important questions are listed below followed by information on how the combined resources of the A-Train will help scientists answer these questions.

- ***What are the aerosol types and how do observations match global emission and transport models?*** Aerosol height information obtained by CALIOP will be combined with data on aerosol size distribution and composition obtained by POLDER and MODIS. CALIOP also provides additional information on aerosol shape and a qualitative classification of aerosol size; data from OMI will provide information on the global distribution of absorbing aerosols.

- ***How do aerosols contribute to the Earth Radiation Budget (ERB)/climate forcing?*** Data from CALIOP, POLDER, MODIS and OMI will all help answer this question. In addition, data from CERES is crucial for providing information on ERB. Also, data from AIRS, HSB and AMSR-E will provide information on how aerosol climate forcing changes with atmospheric humidity. Information from these sensors can also be used in conjunction with data from CloudSat's CPR to offer an unprecedented opportunity to understand what role aerosols play in changing cloud properties, and thus changing the ERB.
- ***How does cloud layering affect the Earth Radiation Budget?*** Data obtained by CloudSat's CPR, augmented by data from both CALIOP and MODIS, will provide the first global survey of vertical cloud structure. Scientists plan to use data from CALIOP and MODIS to help enhance the cloud detection capabilities of the CPR. In turn, the CPR will be used to augment the cloud detection capabilities of MODIS. This is another excellent example of the value of synergistic measurements—see **Figure 2** for illustration.
- ***What is the vertical distribution of cloud water/ice in cloud systems?*** Information from the CPR will produce the first vertical profiles of cloud water and cloud ice content, leading to improved estimates of these parameters in weather and climate models. Observations from HSB, AMSR-E, and MLS will be used to further improve the CPR estimates. Adding information from CALIOP and POLDER is expected to shed light on the nature of mixed phase clouds (clouds composed of both water and ice) .
- ***What is the role of Polar Stratospheric Clouds in ozone loss and denitrification of the Arctic vortex?*** Data from CALIOP will provide direct information on polar stratospheric cloud height and, in some instances, on cloud type. Data from HIRDLS will also provide some cloud height

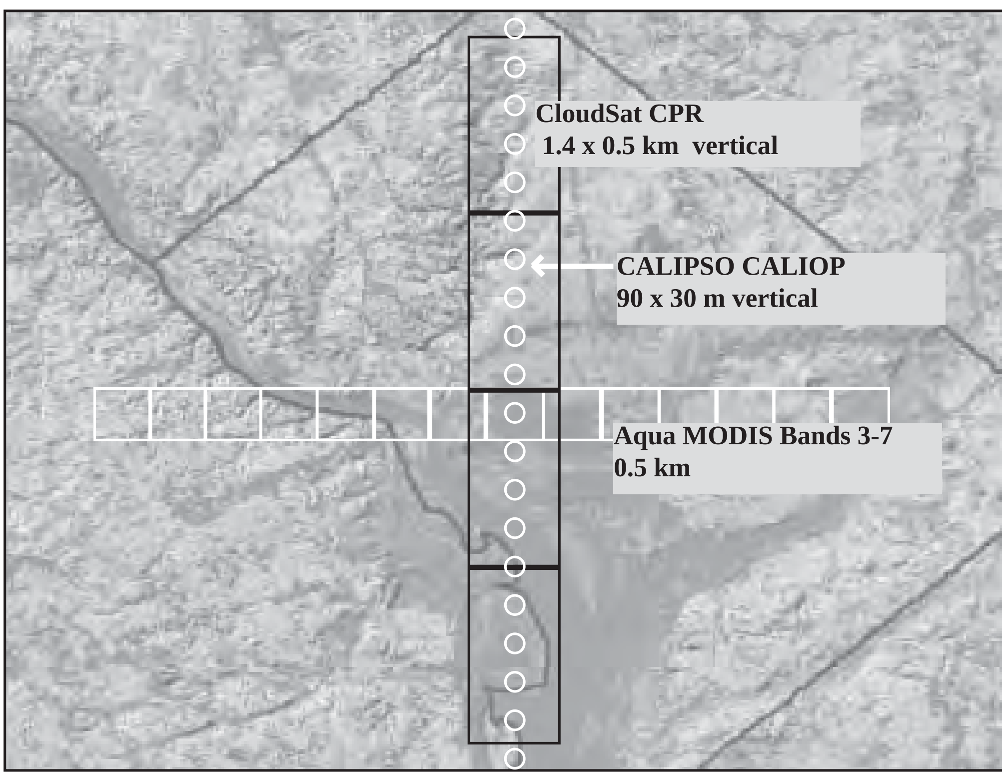

***FIGURE 2**: This figure shows the precise alignment required to successfully obtain a synergistic measurement—in this case cloud layering. To obtain synergy, three different instruments each on a different spacecraft (Aqua MODIS, CloudSat CPR, and CALIPSO CALIOP), and each scanning a different sized region of the Earth, must be precisely aligned to view the same region of the Earth at approximately the same time. This is one of the biggest engineering challenges with formation flying. **Credit**: Modified from original by Mark Schoeberl; underlying map by USGS.*

information. This information will be combined with temperature readings, nitric acid, and chlorine oxide concentrations obtained by MLS and column ozone amounts from OMI to address the role of polar stratospheric clouds in Arctic chemical processes.

The Challenge of Formation Flying

It is not easy to obtain the synergistic measurements described above. One of the biggest challenges in making this formation flying concept a success will be dealing with the wide variety of scales involved. Different instruments in the A-Train have very different resolutions, both vertically and horizontally. Some satellites scan a very large area or swath, while for other instruments the swath is much smaller and only a very small area is viewed. Some instruments have a very large *footprint* (e.g., they have low spatial resolution) while others have smaller footprints and higher spatial resolution. Also, in terms of vertical information, some instruments (or instrument channels) are designed to penetrate only the top portion of the atmosphere while others are designed to focus on the lower portion of the atmosphere. These differences make it a nontrivial matter to "match" measurements from different satellites or even from two different instruments on the same satellite.

In order for the planned synergistic measurements to be successfully obtained, the formation will need to be precisely aligned (described in **Table 1**). This calls for coordinated maneuvering of the various spacecraft to keep them in a tight formation. For example, CALIPSO must not lag Aqua by more than two minutes but may never precede Aqua. In addition, CloudSat has very strict requirements for formation flying. It has to maneuver in tandem with CALIPSO to maintain position relative to Aqua and also maneuvers independently roughly weekly to preserve its position no more than 15 seconds ahead of CALIPSO. No other Earth Science mission to date has attempted formation flying with such stringent requirements. This precise maneuvering will avoid collisions but still allow the measurements from CloudSat CPR, CALIPSO CALIOP, and Aqua MODIS to overlap each other as frequently as possible for synergistic data acquisition. This overlap is depicted in **Figure 2**.

Sometimes, an individual member of the formation may have to give up a bit of its full potential to benefit the formation. For example, if CloudSat were flying alone, it would probably reside at a lower altitude-similar to the one at which the Tropical Rainfall Measuring Mission (TRMM) resides. This would give the cloud profiling radar an even better resolution and improved ability to detect clouds. However, to maximize synergism with the other missions that make up the A-Train, a higher compromise altitude was chosen. The missions of the A-Train have been carefully planned to obtain individual mission objectives yet still allow for intercomparison with data collected from the other missions in the formation.

The Promise of Formation Flying

These substantial challenges not withstanding, the A-Train formation offers unprecedented opportunities to study important questions related to climate change. The information gathered should substantially improve scientists' understanding of the important role that clouds and aerosols play in regulating the Earth's climate. It should also lead to a much better understanding of the chemistry of our atmosphere, how the various atmospheric constituents interact with one another, and what impact changes in the chemical composition of the atmosphere are having on the Earth's climate. Taken together, data from these missions will do much to increase our understanding of the health of our home planet.