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Ronald J. Boain

Jet Propulsion Laboratory
California Institute of Technology

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THE CLOUDSAT MISSION: A VIRTUAL PLATFORM

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CloudSat's Science Team decided from the beginning to capitalize on the synergy between CALIPSO's lidar measurements, Aqua's MODIS measurements, and observations made by CloudSat's Cloud Profiling Radar in making the most comprehensive studies possible of clouds and their impact on climatologically forecasting. The Science Team requested that CloudSat's mission design accommodate requirements on simultaneity and coincidence of measurements to form, in effect, a "virtual platform" of three satellites. This paper describes the mission design for CloudSat that enables and creates this virtual platform. It describes CloudSat's formations with CALIPSO separated by only 15-seconds and its formation with Aqua separated by no more than 90 seconds, and on average by about 61 seconds. It further describes how CloudSat will be controlled to ensure maintenance of the formations per the science requirements.

Introduction

Over the last decade, scientists and other members of society have expressed great interest in understanding whether or not the earth's climate is undergoing out of ordinary change. The prospect of change occurring, hot or cold, is of considerable importance to the state of the world's economy, agricultural output, industrial production, and environment. Answering questions about the recent trend in global warming and whether it is within the norm for variations seen before or is secular are deemed important to the welfare of the world's population. Fortunately, NASA's Earth Science Enterprise has also been thinking about these and other related questions. Moreover, for well over a decade, NASA has been planning, developing, and is now deploying scientific space missions to investigate global climate change.

One set of missions planned by NASA and now in the deployment phase is the Earth Observing System (EOS). Within EOS are missions large and small, but three flagship missions based on large, earth-orbiting platforms are the program's cornerstone: these are Terra, Aqua, and Aura. Collectively these satellites have been designed to make systematic measurements intended to quantify the earth's current climatological state and its rate of change. Terra was launch in December 1999 and has been making measurements for a little more than three years now. Aqua was launch in May of 2002 and is now into its operational activities of collecting calibrated data. The third satellite, Aura, is scheduled for launch in early 2004. As a group, these satellites carry a suite of scientific instruments, e.g., MODIS, AIRS, CERES, MISR, etc., that will enable the measurement of phenomena related to radiation balance, clouds, atmospheric circulation, ocean circulation, atmospheric chemistry, hydrology, aerosols, and more.

In addition to EOS, NASA's Earth Science Enterprise has another set of investigations based on the use of smaller, more focused missions designed to make detailed measurements in specific areas of scientific concern. These investigations are intended to be complementary to the EOS satellites studies. They are being designed and built under the management and direction of NASA's Earth Explorers Program Office, within the Earth System Science Pathfinder (ESSP) Project at NASA's Goddard Space Flight Center. Among the missions currently under development by this Program Office are CloudSat and CALIPSO.

CloudSat is an earth-orbiting mission intended to make active, quantitative measurements of clouds around the globe. Specifically, CloudSat will measure the vertical distribution of ice and liquid water content (crystal and droplet sizes) within clouds, as well as cloud optical depths and cloud-induced radiative heating of the atmosphere. The lack of definitive information about the make-up of clouds and cloud properties is one of the largest uncertainties in the formulation of predictive climate models of today. From these measurements and the parameters derived for characterizing clouds, CloudSat's scientists hope not only to validate, but also to greatly improve the methods used to simulate clouds in climate and weather prediction models (Ref.1).

CloudSat has only one instrument: a Cloud Profiling Radar (CPR). This radar operates at 94 GHz, is nadir-pointed, and accurately measures signals reflected off water and ice within clouds. The radiated power from the radar is greater than 1.5 Kw. As the CloudSat spacecraft moves along its orbit, the radar transmits energy pulses with footprints that cover a spot of ≈1400 meters in diameter. This energy pulse detects and measures the water and ice distribution within clouds to a vertical resolution of 500 meters. Fig. 1 depicts the CloudSat spacecraft in orbit taking measurements with its Cloud Profiling Radar; the figure also lists some of the key spacecraft and radar parameters.

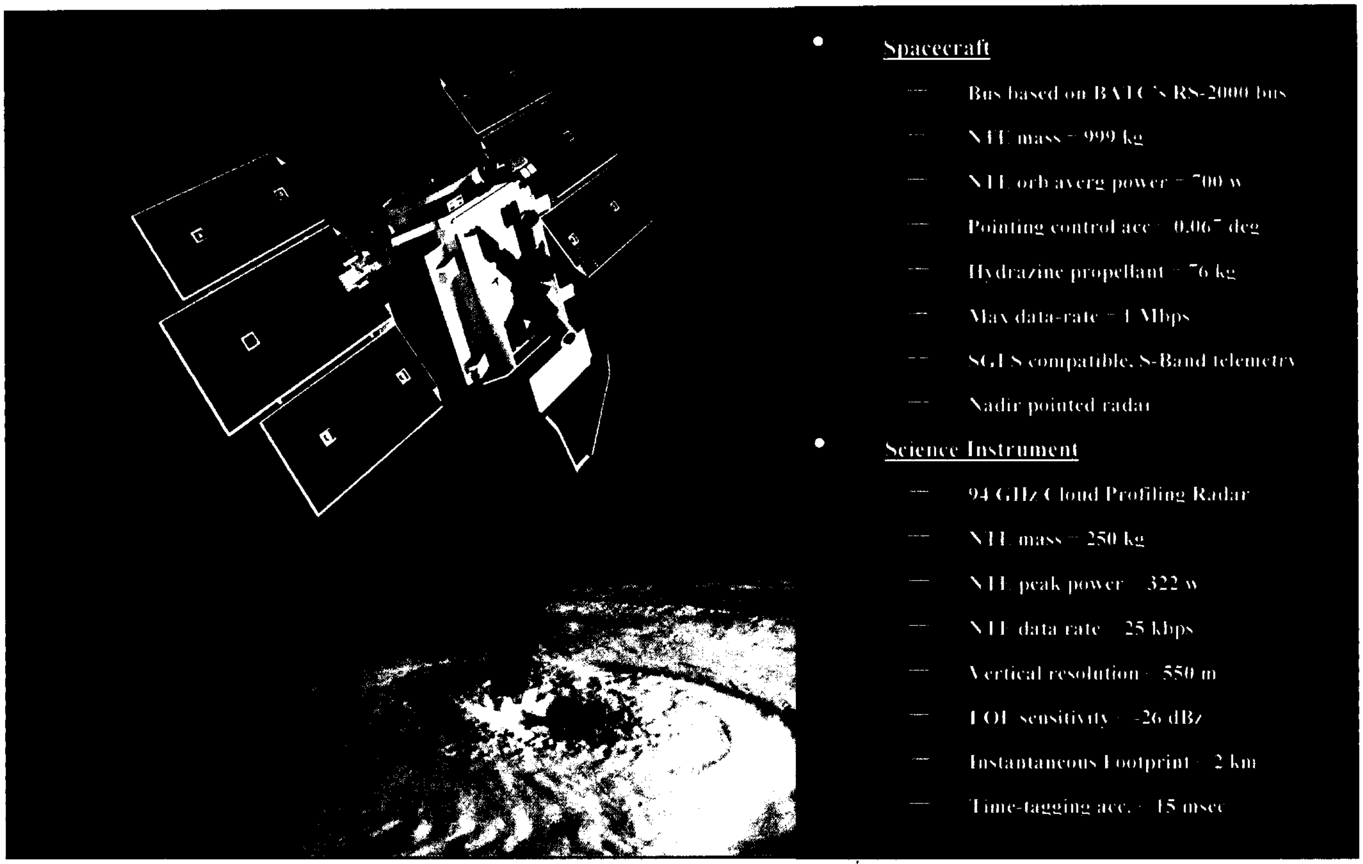

Fig. 1. CloudSat Spacecraft. The CloudSat spacecraft in orbit making measurements with its Cloud Profiling Radar; the figure also lists some of the key spacecraft and radar parameters.

The CloudSat mission is lead by its Principal Investigator, Professor Graeme Stephens, and is a partnership of cooperation between NASA's Jet Propulsion Laboratory, the Canadian Space Agency (CSA), the United States Air Force/Space Test Program, the DOE Atmospheric Radiation Measurement Program, and the European Centre for Medium-Range Weather Forecasting. CloudSat involves scientists and researchers from facilities in the U.S., Canada, Japan, and Europe. The CloudSat spacecraft is being built by the Ball Aerospace & Technologies Corporation; the radar, by JPL and CSA. The PI's home institution is Colorado State University which also serves as the science data processing center.

Originally, the CloudSat spacecraft was designed to carry two instruments: the Cloud Profiling Radar plus a Profiling A-Band Spectrometer/Visible Imager (PABSI). This spectrometer/imager device was for measuring oxygen A-band rotational spectra important in determining cloud optical depth and for the detection of high, thin clouds. It was also useful for acquiring narrow-band images of the cloud fields beneath the spacecraft in order to provide spatial context for the radar's measurements, i.e., pictures of the clouds against the earth background. Unfortunately, the PABSI had to be deleted as a payload for cost reasons at the Project's Mission Confirmation Review held in November 2000. From that time forward, the CloudSat Science Team began examining alternative means for replacing the information to have been provided to the mission by PABSI.

CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations) is another space mission designed to study and quantify the role played by aerosols and clouds on the earth's climate. CALIPSO will carry a suite of three instruments whose measurements will enable 1) observationally-based estimates of direct and indirect aerosol radiative forcing, 2) characterizations of surface longwave radiative fluxes and atmospheric heating rates, and 3) the parameterization of cloud-climate feedback in models. CALIPSO's suite of nadir-pointed instruments includes a lidar, a wide-field camera, and an imaging infrared radiometer. The lidar is a two-wavelength, polarization-sensitive device with a vertical resolution of 30 meters and is capable of producing distribution profiles of aerosols (particulate matter) and clouds (water and ice). The imaging infrared radiometer complements the lidar by obtaining information on particle sizes in cirrus clouds. The high resolution wide-field of view camera provides meteorological context to the lidar's measurements as well as for the imaging infrared radiometer observations.

The CALIPSO mission is also lead by its Principal Investigator, Dr. David Winker, and is a cooperative venture between NASA's Langley Research Center, the French Space Agency (CNES), Hampton University, and the Institut Pierre Simon LaPlace. The CALIPSO spacecraft and one instrument are being provided by CNES. The Ball Aerospace & Technologies Corporation is building the laser instrument. The PI's home institution is NASA's Langley Research Center.

Although both CloudSat and CALIPSO were planned separately and conceived to stand on their own scientific merits, from the beginning, both recognized the scientific value of being able to cross-correlate and cross-calibrate their measurements against measurements from each other and other cloud observing satellites. Of particular interest were the EOS satellites. Thus, CALIPSO based its mission design on the concept of matching orbits and flying in formation with Aqua. Aqua was chosen primarily because of its unique complement of cloud and aerosol measuring instruments, CERES, AIRS, and MODIS, but most especially MODIS. These instruments on the Aqua spacecraft would make complementary measurements synergistic with CALIPSO's lidar and imaging infrared radiometer. (Aqua was also chosen because its development and flight schedule was the most compatible with CALIPSO's planned development schedule.) The CALIPSO/Aqua formation would enable measurements of the same cloud fields with coincident footprints while being taken nearly simultaneously.

CloudSat's Science Team also recognized the strong synergy between CALIPSO's and Aqua's observations and radar observations made by CloudSat. This synergy was considered by some scientists to be strongest between the radar and lidar instruments in that the lidar complemented the radar with an ability to detect and measure profiles of the very thin clouds and aerosols. This was especially true if the radar footprints could be placed directly on top of lidar footprints. These near-simultaneous, coordinated, co-registered radar and lidar measurements would give the most complete picture of a cloud field's water/ice content. On the other hand, Aqua's instrument suite, and especially MODIS, provided spectrometry to assist in determining cloud optical depth. The use of MODIS and other instruments also provided a means for obtaining optical imagery for meteorological context that had been lost with the deletion of the PABSI instrument from CloudSat. CloudSat's Science Team viewed both of these external data sources, CALIPSO and Aqua, as valuable and desirable.

The question then became how could CloudSat position itself on orbit relative to both CALIPSO and Aqua to somehow take advantage of their pre-defined formation? In effect, the Science Team was urging that CloudSat's mission design also use formation flying, but in CloudSat's case, the desire was for a more aggressive formation with a tighter separation between satellites. The scientists wanted observations to be more nearly simultaneous. They wanted CloudSat, CALIPSO, and Aqua to form a "virtual platform".

Subsequently the CloudSat Science Team defined requirements for simultaneity and coincidence of the measurements that, therefore, drove the mission design to make a "virtual platform". More importantly, CloudSat scientists then planned to retrieve and ingest measurement data collected from the MODIS and lidar instruments so that this data could be incorporated into the CloudSat science data products.

With this as background and introduction, the rest of the paper describes how the mission design for CloudSat is derived from these science desires and requirements and how it leads to concurrently flying in formation with both CALIPSO and Aqua. It describes the formation flying relationships that are planned to exist between CALIPSO and Aqua, between CloudSat and CALIPSO, and between CloudSat and Aqua. It will also briefly discuss the basic orbital operations procedures necessary to maintain the formation within what is now being called the "PM Constellation" or the "A-Train". This constellation is envisaged as a grouping of five satellites, Aqua, CloudSat, CALIPSO, Parasol and Aura, all committed to the scientific investigation of the clouds and other earth science pursuits. Fig. 2 shows a schematic of the A-Train with each satellite in its respective position. (Note that CALIPSO is labeled "E-C" in the figure.)

THE CO-MANIFESTED LAUNCH

CloudSat and CALIPSO were originally proposed to the ESSP Project as separate and independent earth science space missions. Each mission was formulated and planned based on its own concept of investigating cloud science. Each mission had its own suite of instruments, different spacecraft, and different operational plans. Each also had its own mission design distinguished by CALIPSO's formation flying with Aqua and CloudSat formation flying with another lidar bearing satellite, ICESat, in an orbit totally different from Aqua and CALIPSO. As a consequence, each mission also required its own launch vehicle to execute these different designs.

Fig. 2. The A-Train. The PM Constellation is comprised of Aqua, as the leading satellite, followed by CloudSat, CALIPSO (labeled as E-C in the figure), Parasol, and Aura.

Written proposals outlining these differences and plans were prepared by each respective mission team and submitted to the ESSP Project in response to the 1998 Announcement of Opportunity for such missions.

During the proposal review and selection process, NASA quickly recognized that these missions had many underlying themes and science objectives in common. Furthermore, NASA observed the potential for scientific synergy between the CloudSat and CALIPSO proposals, in particular, as cloud measuring missions. Equally important, NASA recognized that it could realize considerable cost savings, allowing both CloudSat and CALIPSO to be selected for concurrent implementation, by co-manifesting them and jointly launching them on a single Delta II launch vehicle using a Dual Payload Attach Fitting (DPAF). This technique of launching two payloads at once with a Delta and DPAF was previously utilized for the EO-1/SAC-C and Jason-1/TIMED missions; so the technique was not new.

The DPAF allows this by providing each spacecraft separate structural and electrical interfaces within the standard Delta 10-foot (diameter) fairing. (See Fig. 3.) For the CALIPSO/CloudSat launch, CALIPSO is to be positioned inside of the fairing and on top of the DPAF attached to a structural fitting there. CloudSat at the same time will be carried inside the DPAF on another payload attach fitting within a surrounding canister. After launch and orbit insertion, the CALIPSO spacecraft is first to be separated in orbit. This is followed the separation of the upper part of the DPAF's canister but at a different attitude orientation relative to CALIPSO's separation (hence an orbit different from CALIPSO that moves the DPAF away from and clear of CALIPSO and CloudSat). CloudSat would be the last to be deployed from the Delta second stage and is injected into essentially the same insertion orbit as CALIPSO. Thus, with this "hardwired" separation scenario, CloudSat and CALIPSO from the moment of separation forward have common mission design concerns requiring coordination and cooperation in the conduct of their post-separation on-orbit activities.

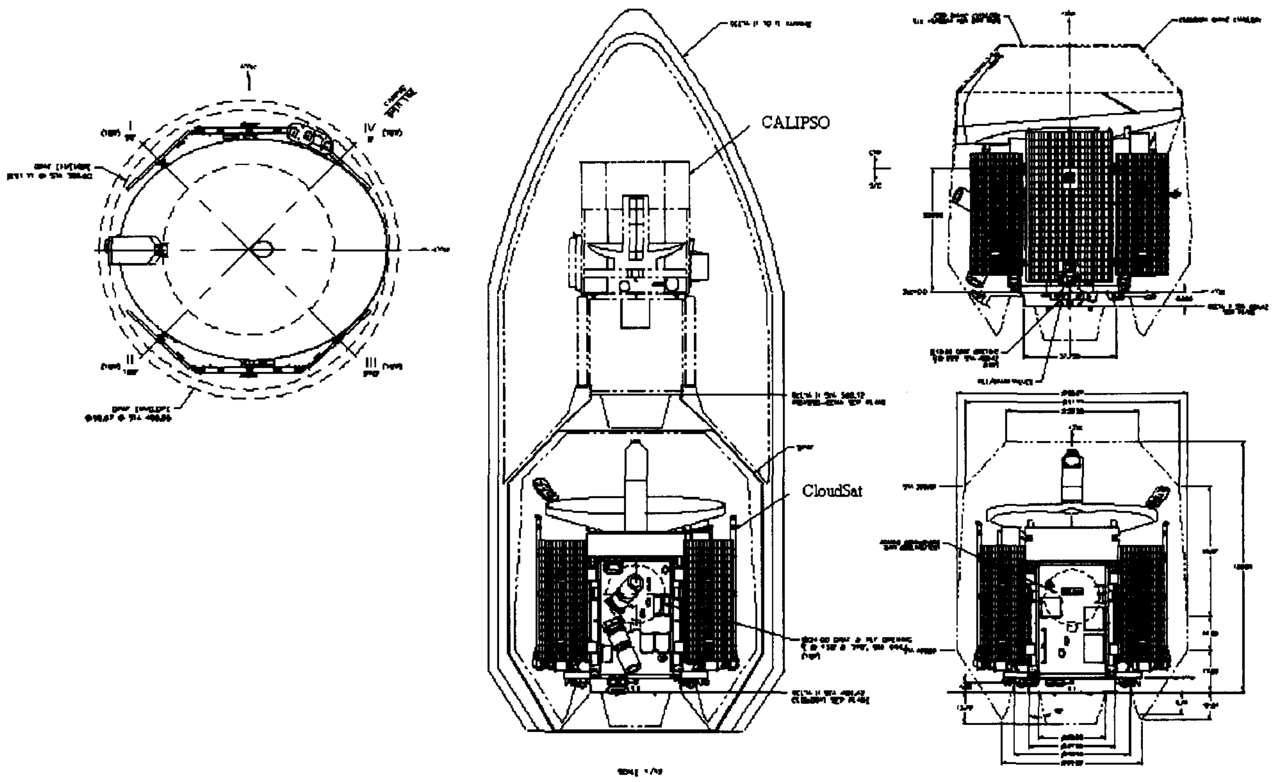

Fig. 3. DPAF Envelope and CloudSat Accommodation. CloudSat's stowed spacecraft configuration was adapted so that it would fit inside the DPAF canister, in the lower berth. CALIPSO sits on top of the DPAF canister.

With the mode of launch now specified by NASA, the joint launch of CloudSat and CALIPSO was scheduled to occur not earlier than October 2004 on the NASA's Launch Manifest.

THE MODIS INSTRUMENT

At this point, it is useful to briefly describe the MODIS instrument and the way in which it operates and collects data. It is also useful to define several terms associated with the measurement geometry, in order to facilitate subsequent discussions about how MODIS and CloudSat's radar interact to make coordinated measurements.

The acronym MODIS stands for "Moderate Resolution Imaging Spectroradiometer". MODIS is an optical instrument which scans in multiple wavebands along a line perpendicular to Aqua's groundtrack with a mirror directing light into collecting optics. These optics have a set of linear detector arrays aligned in parallel rows forming four focal planes. The angular width of the scan in the long dimension is ±55° relative to the nadir point as seen from the Aqua spacecraft; projected on the ground this scan line is called the "line of the MODIS measurement swath" and it runs ±1165 km (±10°) either side of Aqua's groundtrack and is perpendicular to it. With this geometry and the line of the MODIS measurement swath, CloudSat's radar footprints cannot fail to fall on top of a MODIS pixel element within a few seconds after being acquired.

So a mission design with CloudSat flying in tight formation with Aqua (separated along-track by 15-seconds) and over-flying the same groundtrack as Aqua (to within ±1 km) was investigated and shown to be viable as an option for CloudSat. Measurement coordination with CALIPSO would still be desirable, but as a practical matter only as a secondary consideration.

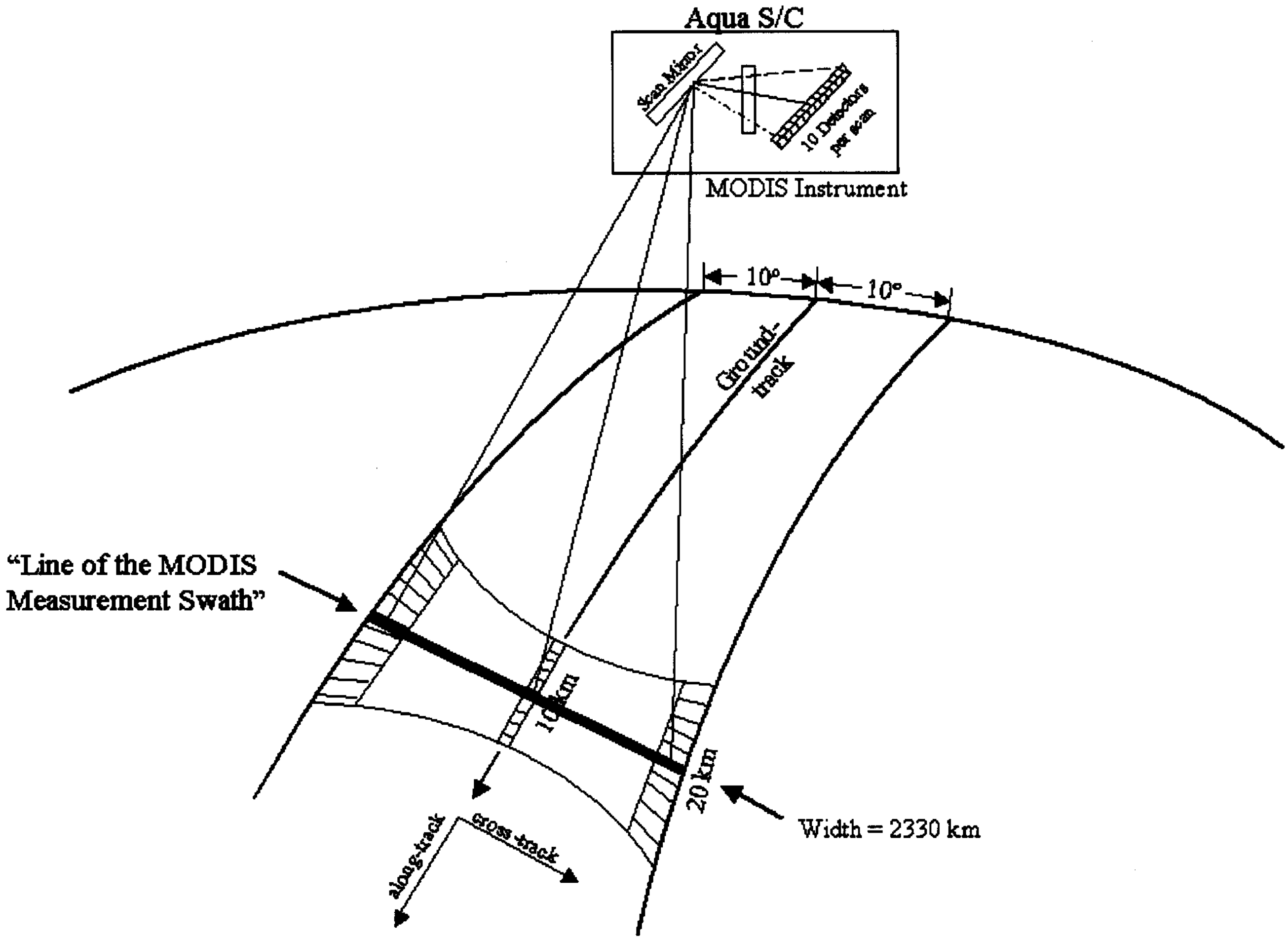

Fig. 4: MODIS Scanning Geometry. As Aqua moves along its orbit, the MODIS instrument scans along the line of the measurement swath which is perpendicular to the groundtrack. This swath is 2330 km in length. The point at which the swath crosses the groundtrack is at Aqua's nadir.

In late June of 2001, however, the ESSP Project at GSFC directed both CloudSat and CALIPSO to continue the development of an operational mission design with CloudSat flying in formation with CALIPSO instead of Aqua. Since CALIPSO would still have its mission design based on formation flying with Aqua, both would have access to Aqua's MODIS data. With this direction, it became necessary for CloudSat, in cooperation with CALIPSO, to re-focus its science acquisition strategy to take the greatest possible advantage of science synergy between the three missions. The direction further implied that CloudSat and CALIPSO should continue coordination for the possible development of a joint science data product involving a mix of radar and lidar measurements. CloudSat had already established a science data-product based on collecting and combining MODIS with radar data.

Again, the principal scientific motivation for flying CloudSat and CALIPSO in close formation together was the possibility of overlaying radar footprints on top of lidar footprints. Lidar measurement footprints are small (only ≈70 meters in diameter) compared to the MODIS swath and factoring in that the CALIPSO spacecraft has pointing control inaccuracies on top of that, it has been estimated that there is only a 75% change of coincidence between the radar and lidar footprints, even under the best of operational conditions (Ref. 2). Nevertheless, even with a probability of occurrence being less than 75% and the fact that knowledge of when these overlaps actually occur being even less, there was still a science desire for and the potential of producing a data-product based on combined radar and lidar data. This emerged as a key science goal driving CloudSat's mission design.

But for CloudSat, there still remained a strong desire by the Science Team to retain a high degree of coordination, co-registry, and simultaneity with Aqua. Therefore, CloudSat evolved its science requirements to include all aspects of the Program Office direction, while retaining an approach to acquiring much of the high value science already planned between the radar and Aqua's MODIS instrument.

AQUA'S MISSION DESIGN

There are certain aspects of Aqua's mission design appropriate for discussion here in order to provide context for the rest of the paper. To first order, the operational orbits for CloudSat and CALIPSO will be essentially the same as Aqua's orbit, i.e., nearly identical orbital elements, except for differences in the nodal positions. (These differences in node are necessary to allow CloudSat and CALIPSO to avoid the sun-glint zone and will be discussed later.) Therefore, an accurate description of the Aqua orbit also serves to describe the orbit to be used by CloudSat and CALIPSO.

In the most basic of terms, Aqua's orbit is nearly circular (with an equatorial altitude of ≈705 km) and is sun-synchronous so that the Mean Local Time (MLT) of the orbit's ascending node remains fixed with respect to the mean solar meridian.

The following is a summary of specific mission characteristics and requirements for Aqua relevant to the discussions within this paper (Ref. 3):

1. Aqua uses a sun-synchronous orbit inclination of ≈ 98.2° on average. Through the mission, the orbital inclination is perturbed, in a predictable way, by luni-solar effects to cause slight variations; spacecraft propulsive maneuvers must then be used to re-set the inclination, holding it near the required average value.

This is important to the CloudSat and CALIPSO missions since they must also make these inclination adjustments along with Aqua in order to preserve the formation relations. The need for these maneuvers is a lien against the ΔV budgets for both missions.

2. Aqua's Mean Local Time of the ascending node is required to lie between 13:15 and 13:45 hours relative to the solar noon meridian. However, due to solar angle constraints, i.e., a solar beta-angle constrained to lie between 16° and 32° in order to accommodate the spacecraft's thermal design, Aqua actually limits its MLT to a smaller range within this band between 13:30 and 13:45 hours. Thus, the angular position of the ascending node ranges between ≈22.5° and 26.25° east of the mean solar meridian.

3. Aqua's eccentricity is non-zero at ≈0.0012 and the argument of periapsis is set to ≈90°. With these values they are locked in a "frozen" relationship, which allows them to vary in a predictable way and still prevent excessive precession of the perigee position. Nonetheless, Aqua's orbit for all practical purposes is circular.

4. Aqua's mean semi-major axis has been selected to yield an orbital period so that the groundtrack repeats every 233 orbital revolutions or equivalently every 16 days. The semi-major axis for Aqua is subject to perturbations, mostly due to atmospheric drag effects on the spacecraft. As a consequence, Aqua must maintain this mean value by periodic propulsive maneuvers, in order to sustain synchronization between the orbital period and the earth's rotational period, i.e., exactly 233 revs in 16 days.

5. Aqua's groundtrack is carefully aligned with the World Reference System (WRS-2) grid and Aqua assumes a specific point on this grid as its "reference point" at the beginning of the mission. This so-called reference point phases it with other satellites on the WRS grid, e.g., Terra and LandSat-7, to avoid resource conflicts in joint operations with these other missions. With the requirements to maintain a 16-day repeat groundtrack and to overfly the WRS-2 grid, Aqua is in effect flying in formation with a virtual, zero-drag satellite with the same orbital parameters and positioned exactly over the grid in phase with the other satellites.

6. Aqua's groundtrack with respect to the WRS-2 grid drifts slowly in time. This cross-track drift is coupled with and is a direct consequence of changes in the orbital semi-major axis, which is being perturbed by drag. So to set bounds on the allowable cross-track deviations, Aqua controls and changes its semi-major axis to limit groundtrack deviations to ±20 km with respect to the WRS-2 at the equator. It is this process of limiting cross-track deviation that defines the degree to which the semi-major axis must be adjusted. Typically the change is semi-major axis is on the order of 100 – 200 meters, depending

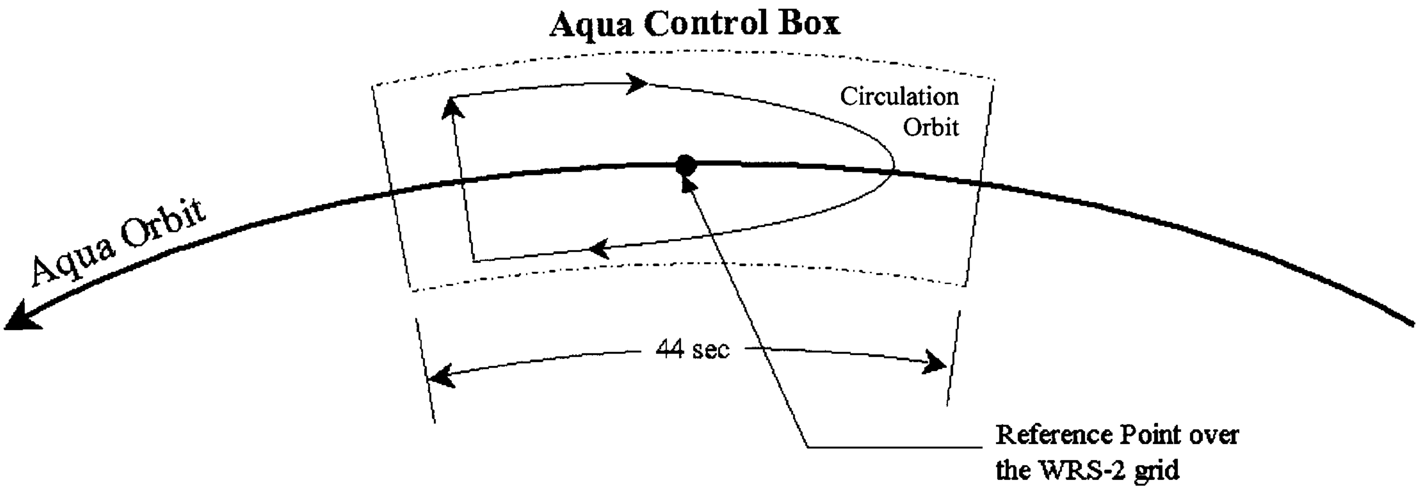

Fig. 5: Aqua Control Box Relative to the WRS-2. Aqua's control box is defined to be ±10 km cross-track with respect to the WRS-2 groundtrack grid and ±22 seconds along-track with respect to the Reference Point. Spacecraft propulsive maneuvers at the ΔV point shown raise the semi-major axis a few tens of meters and re-initialized the motion around the circulation orbit.

on the atmospheric density between propulsive maneuvers. The ΔV for these maneuvers runs about 10 centimeter per second or less.

In fact, there are two parameters dependent on changes in the semi-major axis. The first is the cross-track deviation of the groundtrack relative to the WRS-2 grid as previously described. The second parameter is the along-track position of Aqua relative to its so-called reference point on-orbit. When cross-track errors occur, Aqua also moves forwards or backwards in the along-track direction with respect to its reference point. This motion is either forwards or backwards depending on whether the cross-track deviation is moving either west or east of the WRS. There is a fixed proportionality (related through the orbit parameters and the earth's rotation rate) between the size of the cross-track deviation and the size of the along-track variation. This turns out to be a coupling of a 1 km cross-track error mapping into ≈16.3 km of deviation in the along-track direction. Most often, this along-track deviation is referred to in terms of "seconds" of time ahead of or behind the reference point. So a 16.3 km deviation corresponds to 2.2 seconds of deviation as an equivalent description, i.e., 16.3 km divided by the orbital speed.

Interestingly, the cross-track control requirement specified above in paragraph 6 is not what Aqua plans to implement operationally. In practice, the cross-track deviations with respect to the WRS will be controlled to ±10 km. This implementation more than meets the requirement and provides a desirable goal on which CloudSat and CALIPSO can base their requirements with regard to sizing their formations relative to Aqua. This is good for CloudSat science, as will be discussed.

An important concept derives from Aqua's need to control its cross-track motion to be within tolerances of the nominal value. This is the notion of a so-called "control box" in space along the Aqua orbit. Due to the above requirements, Aqua moves inside a control box east to west by ±10 km and along-track relative to its reference point by ±163 km, or equivalently stated as ±22 seconds. Aqua's control box is illustrated in Fig. 5. Aqua's motion inside of its control box is said to be along its "circulation orbit". Movement along the circulation orbit is a manifestation of the coupling that exists between variations in the semi-major axis, the cross-track position relative to the WRS-2, and the along-track position relative to the reference point. Between semi-major axis adjustment maneuvers, Aqua moves slowly along its circulation orbit, as shown in the Fig. 5. These concepts come up again when describing the formation flying motion of CloudSat and CALIPSO with respect to Aqua and each other.

The importance of the Aqua operations team maintaining the control box as described above lies in its impact on the along-track size of Aqua's control box. If the cross-track deviations were allowed to be ±20 km per the mission requirements, then the along-track dimension of the control box would be ±320 km, or ±44 seconds. For a satellite maintaining formation just outside this box, the total variation in time between over-flights of the same geographical location would be as much as 88 seconds. Since a satellite in formation with Aqua would realistically be positioned at a safe stand-off distance from the boundary of Aqua's control box, the over-flight interval would be much more than 88 seconds between coordinated measurements. This scientifically would be undesirable.

SCIENCE REQUIREMENTS RELATED TO FORMATION FLYING WITH AQUA

For CloudSat scientists, two parameters were initially important to maintaining high correlation between MODIS and radar measurements. These were the simultaneity and the congruency of observations.

The simultaneity of radar and MODIS measurements is quantified by the time interval between one of the MODIS's sweeps across the line of the measurement swath and when the radar's footprint crosses that same line. Clearly, the measurements are more and more simultaneous, for shorter and shorter time intervals between the two spacecraft along their respective orbits. Tight simultaneity ensures that the intrinsic character of the cloud field being measured will not have changed appreciably over the interval between observations.

The Science Team initially specified the simultaneity by stating that CloudSat and Aqua should measure the same cloud field within 180 seconds, or less, of each other. This was estimated to be the longest time interval between sampling of the same cloud that could be tolerated without seriously compromising the quality of data to be compared and combined. But as a goal, the Science Team wanted the formation between CloudSat and Aqua to allow the mean separation time between measurements to average 60 seconds, or less, over the mission duration. (Even this was a compromise from the prior mission study which showed that a 15-second separation between the two spacecraft was feasible.) Suffice it to say that from the Science Team's point of view, the shorter the time interval between measurements the better, and 60-seconds, or less, on average was deemed acceptable. With this requirement for simultaneity, it then became a mission design task to see if it was achievable by positioning the satellites participating in the formation in a way to meet the requirement and to still provide margins of safety and independence in maintenance.

The second science requirement relates to the congruency of measurements and places a limit on how far away in the cross-track direction from Aqua's subsatellite point the CloudSat radar measurement could be made and still have an optical path through the atmosphere sufficiently similar to a MODIS viewing path that displacement and/or attenuation effects could be neglected or compensated for. It was recognized early on that, since CloudSat makes measurements at its nadir, the further CloudSat was from Aqua's groundtrack, the greater would be the slant path of the MODIS measurement of the same geographic position. In other words, ground footprints for MODIS pixels have longer and longer optical paths through space and the atmosphere as the angle between the line of sight and the direction to the nadir increases. (Again see Fig. 4.)

After consideration of this matter by the Science Team, it was decided that if the position at which CloudSat's footprint crosses the line of the MODIS measurement swath was ≤5° from Aqua's nadir position, no algorithmic compensation for excessive slant range would be necessary. This translated into a ground distance of ±62 km from the Aqua groundtrack (Fig. 6.) for the radar footprint to cross the line of the MODIS measurement swath.

However, an issue arose that forced the CloudSat team to abandon this cross-track distance limitation as a mission requirement. In particular, studies by the CALIPSO Science Team indicated that the MODIS instrument did not perform retrievals of aerosols and/or thin clouds when the measurements were made over regions of the earth where significant sun-glint occurred and corrupted the observations. Neither the radar nor the lidar is affected directly by sun-glint, but it compromises the ability to utilize MODIS data in joint data products. Joint analysis of the problem by the CloudSat and CALIPSO teams indicated that the primary sun-glint region could be avoided by shifting the position of the CloudSat/CALIPSO ascending node to be ≈1.9° east of Aqua's nodal position. After a lengthy negotiation and assessment of the feasibility of accommodating this nodal shift, including effects on the system design, the two missions finally agreed to it. The consequences for CloudSat are that MODIS viewing slant angles can be as large as ≈19°, which is much larger than the 5° requirement. This means CloudSat will have to upgrade its MODIS data processing algorithms in order to compensate for different optical paths from MODIS and CloudSat's radar to the same ground spot. Fortunately, for the mission design, this shift in node effects only the time of launch, with the other orbital parameters remaining unchanged.

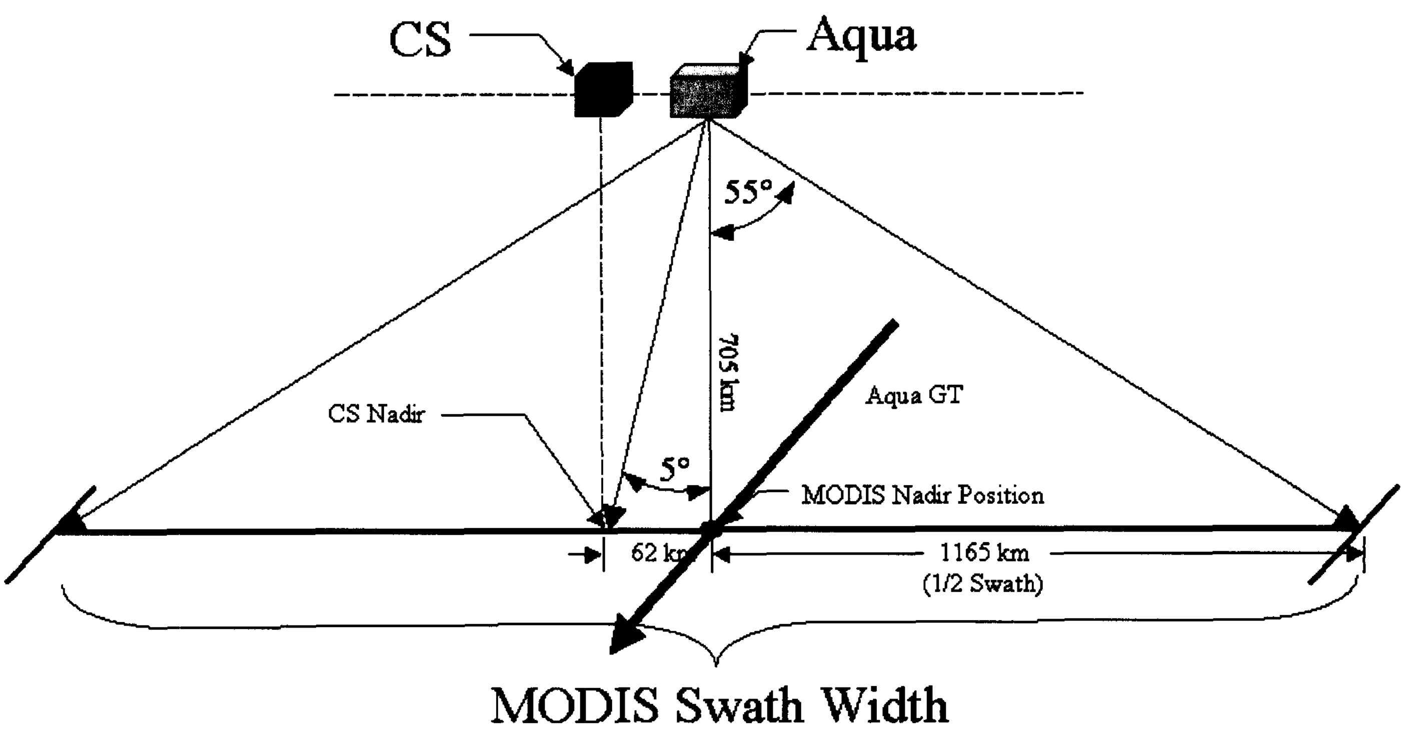

Fig. 6: Cross-Track Measurement Geometry. In the absence of sun-glint, CloudSat would require its radar measurements to be within ±62 km of Aqua's nadir position along its groundtrack. With the requirement, CloudSat would not have to enhance data processing algorithms to account for MODIS slant paths through the atmosphere.

CALIPSO REQUIREMENTS FOR FORMATION FLYING WITH AQUA

Before CloudSat's mission design can be completely described, it is necessary to describe CALIPSO's mission design and formation flying parameters. This design becomes, in effect, the basis and infrastructure on which the CloudSat mission design is built and is inherently dependent. All of what follows has been discussed between CloudSat and CALIPSO and is the basis of the joint mission planning activities currently ongoing by each project.

CALIPSO's science requirement for simultaneity between lidar and MODIS measurements is ≤165 seconds to optimize synergy between observations. Therefore, for CALIPSO flying in formation behind Aqua, it is desired that the back-end of CALIPSO's control box be no more than 165 seconds behind the leading-edge of Aqua's box. As with CloudSat's scientists, CALIPSO scientists desire to make the measurements as closely spaced in time as is possible. With regard to maintaining the center of CALIPSO's control box over or near the WRS, CALIPSO has no explicit requirement. In fact, the CALIPSO team has made clear that, after two years of operations near the WRS formation flying with CloudSat, they plan to change their inclination and initiate a nodal drift that will carry them to the western edge of the MODIS swath over their remaining year of operations. Therefore, in contrast to CloudSat, which would have limited the cross-track variations relative to the WRS grid were it not for sun-glint, CALIPSO is not necessarily concerned with sampling only those MODIS pixels located directly adjacent to Aqua's groundtrack. (It is interesting to note that while CALIPSO is allowing its node to drift toward the western edge of the MODIS swath, it will have to forego its initial requirement to avoid regions of significant sun-glint. During this drift period, the motion of the groundtrack relative to MODIS observations will take it directly through the region most seriously affected by sun-glint.)

As noted before, Aqua maintains a control box on-orbit (again see Fig. 5). Given this and the science requirements, it is CALIPSO's desired to operationally define its formation position and movement with respect to Aqua such that its formation

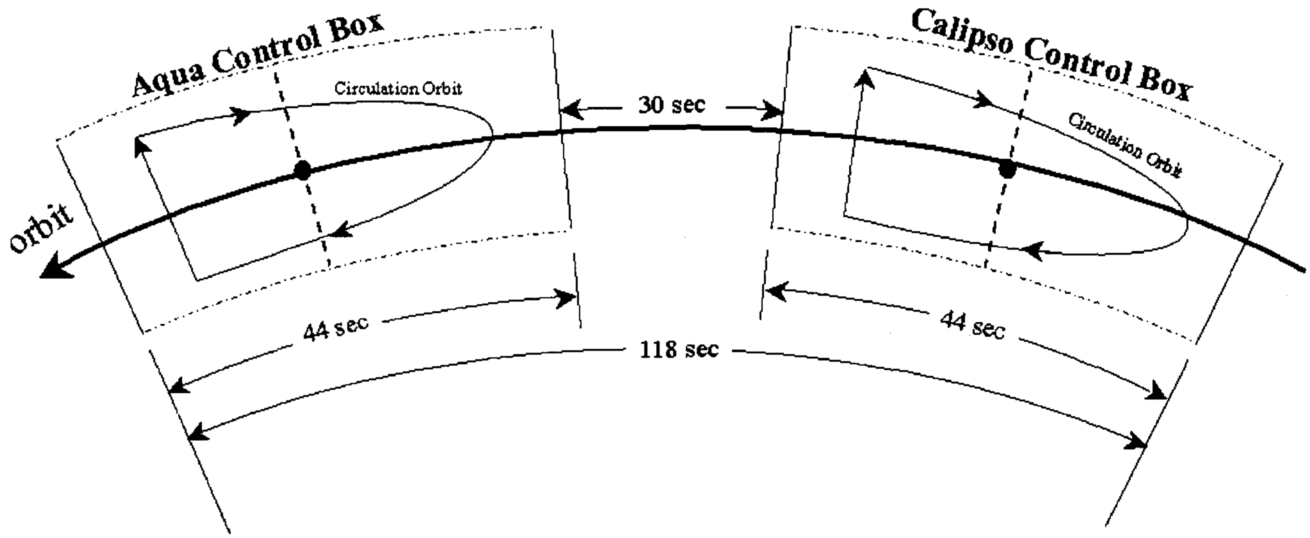

Fig. 7. Aqua and CALIPSO Formulation Flying Control Boxes. This schematic depicts Aqua and CALIPSO flying in formation together, each moving along a circulation orbit constrained in their respective control boxes. With this formation, CALIPSO is never more than 118 seconds behind Aqua.

control activities, e.g., maneuvers times and maneuver magnitudes, are independent of Aqua's control process. CALIPSO purposefully defined its "control box" such that no formal coordination (unless there is a contingency situation) would be necessary between the two missions. Also the box was specified so that there is no overlap between boxes and, in fact, there is a "buffer zone" separating the two boxes by 30 seconds to further ensure adequate separation. Therefore, the front edge of CALIPSO's box will be 30 seconds behind the trailing edge of Aqua's box. This choice of 30 seconds is somewhat arbitrary but gives CALIPSO's operations personnel a comfortable margin of safety relative to the possibility of encroaching on Aqua's control box and significantly reduces the threat of collision owing to the two satellites occupying the same space along the orbit. The down side to this selection is that the larger the size of the buffer zone, the greater is the time interval between lidar/MODIS measurements. With this in mind, CALIPSO has designated the dimensions of its control box to be the same as the dimensions of Aqua's box. Cross-track motion is controlled to ±10 km; this control automatically limits the along-track motion to ±22 seconds relative to a reference point. For a control box with these dimensions and accounting for the buffer zone, the greatest separation between Aqua and CALIPSO would be 118 seconds, with a mean separation of ≈75 seconds. Both Aqua's and CALIPSO's along-track control boxes in relative position to each other are illustrated in Fig. 7.

As an aside, it will be recalled that CALIPSO uses an operational orbit which is essentially the same as Aqua's orbit. CloudSat and CALIPSO are launched and inserted into an injection orbit which is biased 15 km below Aqua's orbit in order to allow the two spacecraft to transfer through a phase angle and catch up with Aqua. CALIPSO and CloudSat have agreed that, after launch and separation, each will perform this catch up and the associated propulsive maneuvers over the next 45 days, or less. The design of this Launch and Early Orbit mission phase and the coordination of events between projects are rather complex and beyond the scope of this paper. The discussion here has been limited to just a description of the formation configuration between CloudSat, CALIPSO, and Aqua. The specific plans for this mission phase are, however, being worked and finalized and are briefly described by Salcedo, et. al., in Ref. 4.

The position of the ascending node for CALIPSO's orbit, i.e., the Mean Local Time (MLT), is driven by the requirement to avoid the sun-glint zone. To a good approximation, it would be 7.7 minutes after Aqua's MLT on the day of launch. Since Aqua's position of the ascending node will drift over the course of their mission, the precise value for CALIPSO's MLT will not be known until the CloudSat/CALIPSO launch date has been firmly established. The position of the ascending node and its MLT with respect to the solar meridian can be seen in Figure 8 where a "to-scale" representation of the orbit and distances between the spacecraft is shown.

SCIENCE REQUIREMENTS FOR FORMATION FLYING WITH CALIPSO

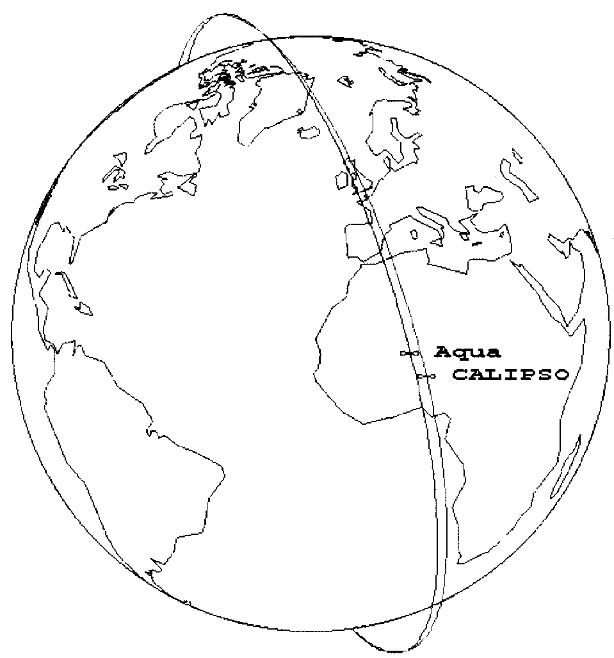

Fig. 8. Aqua's and CALIPSO's Orbits. Shown in the figure is a "to-scale" view of the earth and orbits as seen from the sun for an epoch on 10 July 2005. The figure also depicts the approximate mean separation of 74 seconds along-track between Aqua and CALIPSO. Note the eastward displacement of CALIPSO's node in order to avoid the sun-glint zone.

With CloudSat's and CALIPSO's conditions for formation flying with Aqua now in place, the CloudSat team next set out to develop requirements for formation flying with CALIPSO such that they would be compatible with the above and still meet the science desire for closely coordinated, co-registered radar/lidar measurements. This, of course, would include the science desire to maximize the frequency with which radar and lidar footprints overlapped. Fortunately, this problem had been studied before and resembled CloudSat's original plan to fly in tight formation with ICESat. From this prior analysis, it was clear that achieving congruent radar and lidar footprints depended not only on the mission design, i.e., formation flying parameters, but also on the attitude control and pointing capabilities of each spacecraft. In other words, a requirement could not be written without some implicit dependence on the attitude control capabilities being included. Since both spacecraft were being designed as fairly agile with capable attitude control systems, requirements statements for formation flying could be drafted based on the attitude control requirements. In this way, a mission design for formation flying could be devised with the hope of actual performance bettering the requirement once the true attitude control capability of the spacecraft was known and demonstrated after launch. Since the scientific potential of obtaining highly co-registered radar/lidar data by tight formation flying together was too compelling to be ignored, requirements statements were written with dependency clauses that, at least, enable the mission design to proceed.

Another point to re-iterate in writing these requirements is that, to minimize the impact on the other formation partners, the mission design team would make CloudSat the burdened spacecraft charged with maneuvering to maintain the formation with CALIPSO. These requirements applied only to the development of CloudSat's mission design. Thus, the grand scheme had Aqua and CALIPSO in formation together, essentially independent of each other. CloudSat would be inserted into the picture, but would be tied to CALIPSO in a way that CALIPSO would be, in so far as possible, unaffected by and independent of CloudSat's presence in the formation. And by virtue of CALIPSO's formation with Aqua, CloudSat would also be in formation with Aqua.

For CloudSat science, the key requirements driving the formation arrangement with CALIPSO were related to simultaneity and congruence of footprints. For simultaneity the CloudSat Science Team early on defined a requirement that the time delay between lidar and radar observations of the same cloud field should not exceed 60 seconds. This defined the upper bound on the interval for simultaneity. However, the Science Team later made clear that observations separated by 15-seconds were what was really desired. Thus, 15-seconds between measurements became CloudSat's goal for simultaneity, and with the current mission design, it later became the requirement.

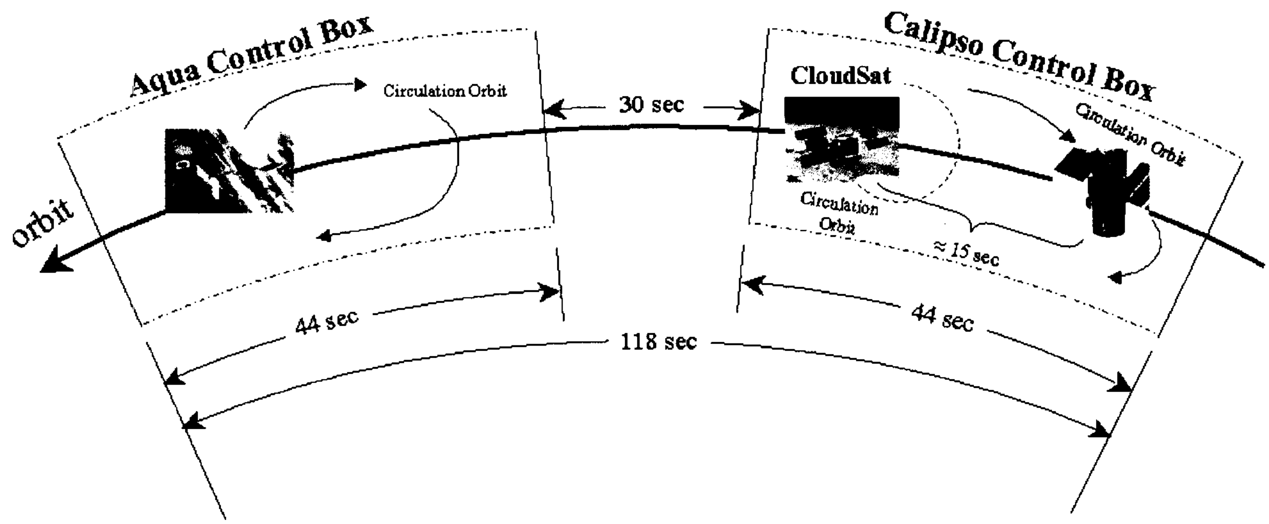

Fig. 9. Configuration of the "Virtual Platform". This schematic represents the Aqua, CloudSat, CALIPSO formation configuration. Aqua leads. CALIPSO follows but maintains its motion within its box independently of Aqua. CloudSat is slaved to CALIPSO.

To be clear on this requirement, CloudSat would define a control box displaced from CALIPSO such that the greatest separation between the two spacecraft would be less than 15-seconds along-track. Like Aqua and CALIPSO, CloudSat would have a control box and fly a circulation orbit within it. But the extreme of the control box would not allow CloudSat to be further than 15-seconds (≈112.5 km) from CALIPSO throughout the mission.

It was then decided that CloudSat would be placed in formation in front of CALIPSO (instead of behind), positioned between Aqua and CALIPSO. This positioning was selected by the CloudSat team in order to better comply with the science desire for CloudSat to also be separated from Aqua by a 60-second interval, on average. Acceptance of this positioning within the formation was also predicated on studies done to show that the risk of collision with either of the other two spacecraft was vanishingly small. So in implementing a mission design to be consistent with this requirement, CloudSat would maintain a position 15-seconds (or less) in front of CALIPSO and would follow CALIPSO around its circulation orbit within its control box. The only exception occurred when CALIPSO moved to the very front of its box, at which time CloudSat's position would be outside of CALIPSO's box in the buffer zone between Aqua and CALIPSO. Even so, CloudSat would still be slaved to CALIPSO, maintaining the formation. Fig. 9 shows a schematic of the formation geometry for all three spacecraft per the formation requirements and the mission design that implements them.

In order for CloudSat to maintain its formation position with respect to CALIPSO, CloudSat will have to also move along its own circulation orbit. This necessitates small propulsive maneuvers of a few centimeters per second (≈2 – 10 cm/sec) done approximately weekly. However, when CALIPSO approaches the front of its control box (closest to Aqua) and needs to make a maneuver to raise its semi-major axis to begin a new circulation orbit, CloudSat must make a like maneuver almost concurrently with CALIPSO. These nearly simultaneous maneuvers are necessary to maintain the formation relation between all three satellites and are the one circumstance where considerable coordination and cooperation between the two operations teams are required.

To define a congruence requirement defining the degree to which the radar and lidar measurements must be coincident, it is first important to recall that the diameter of the radar footprint is nominally 1400 meters while the diameter of the lidar footprint is only 70 meters. Second, it needs to be noted that CloudSat's spacecraft attitude pointing performance, as described in CloudSat's Pointing Error Budget, is capable of directing the radar boresight to be within 0.067 degrees of the satellite's nadir position (2-axes at the 99.7-percentile of occurrence). This is equivalent to being within 824 meters of the nadir. CALIPSO's attitude pointing capability is taken to be 0.08 degrees worst case relative the target, per CALIPSO's requirements for pointing control. This pointing control implies the lidar would be within 984 meters of its intended direction, slightly ahead of nadir but on the groundtrack.

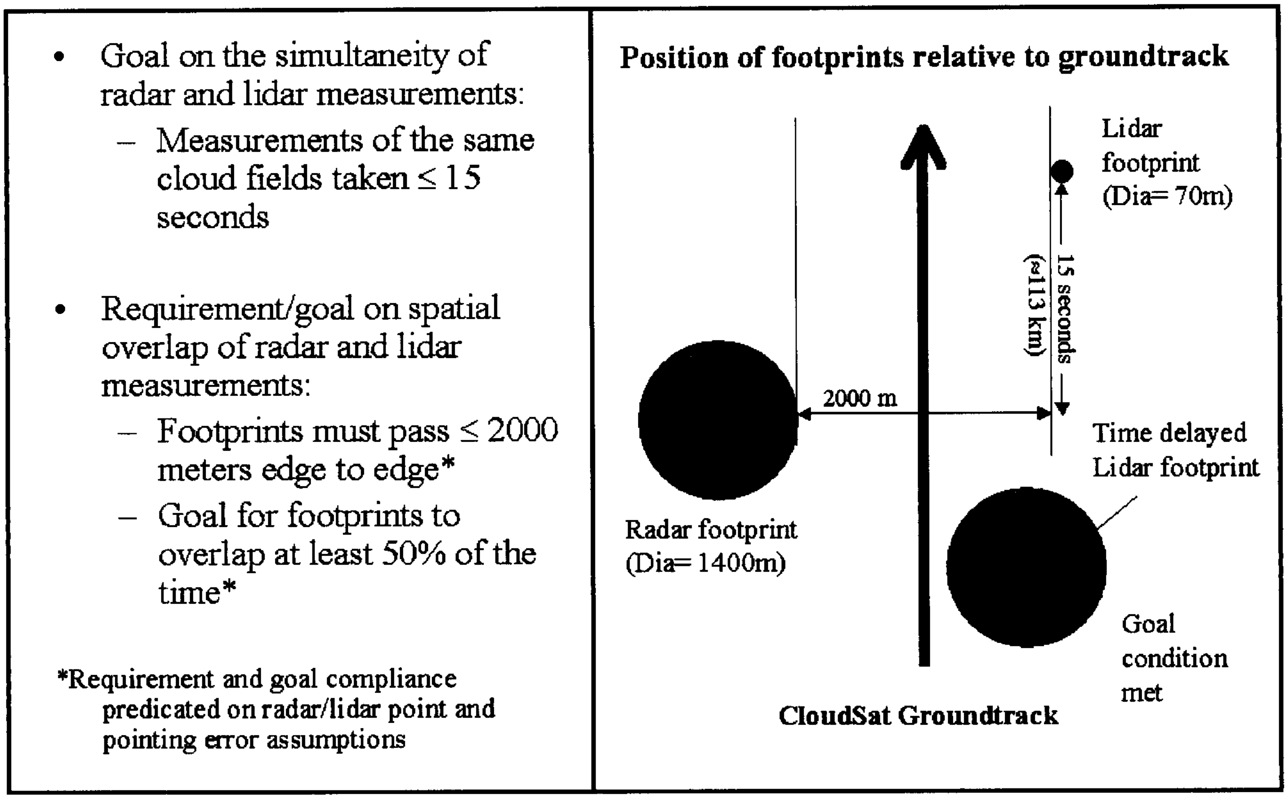

Fig. 10. Science requirements related to formulation flying with CALIPSO.

The requirement for congruence was then defined based on these pointing parameters (with just a little optimism) and strictly on science arguments for proximity of footprints. The requirement for congruence was stated to require the radar footprint to fall within 2000 meters (cross-track) of the lidar footprint, edge to edge. This assumed that CALIPSO's attitude control system would be able to place lidar footprints within ±1500 meters of its groundtrack (well with its attitude requirement). This requirement and others are schematically described in Fig. 13. This in turn dictated that CloudSat must control its groundtrack motion to be within ±1 km of CALIPSO's groundtrack. With the allowable cross-track deviation now specified, the along-track motion about a reference point follows from the previously discussed relation and is ±2.2 seconds.

A goal on the frequency over the mission where the radar and lidar measurement would actually fall on top of each other was also established and stated that footprints must overlap at least 50% of the mission time. As noted before, an analysis of this problem (Ref. 2) suggests that footprint overlap 75% of the time is theoretically achievable.

The mission design for the collective formation is now in place, based on science requirements. CloudSat is tied to CALIPSO, formation flying within 15-seconds from it. CALIPSO is in formation with Aqua, never more than 118 seconds behind and on average just 74 seconds in back. And CloudSat leading CALIPSO but moving around with it, is never more than 88 seconds from Aqua and on average ≈61 seconds behind. The collective formation is now able to operate, collecting synergistic science data as a "virtual platform". Fig. 11 provides a "to-scale" view of this "virtual platform" in orbit over the earth.

FORMATION FLYING BASICS

Now that the essential requirements and conditions for formation flying have been described, it is appropriate to briefly discuss the means by which CloudSat intends to maintain its formation with CALIPSO. The underlying physics for this has been previously developed and described in Refs. 5, 6, and 7. Simply put, formation flying is a problem in managing the semi-major axis of CloudSat's orbit relative to the semi-major axis of CALIPSO's orbit. Once the formation had been properly initialized and in the absence of atmospheric drag, the two spacecraft would require practically no formation maintenance at all. They would remain positioned on the orbit at their initial separation, like two beads glued to a large metal

Fig. 11. Aqua, CloudSat, and CALIPSO in Orbit. Shown in the figure is a "to-scale" view of the earth and orbits as seen from the sun for an epoch on 10 July 2005. The figure also shows the approximate positions of Aqua, CloudSat, and CALIPSO in formation relative to each other for the mean along-track separations as described in the text.

ring spinning around the earth. But in the real world each spacecraft is subject to drag perturbations which slowly reduces semi-major axes causing their orbits to decay.

Further complicating this problem, each spacecraft has a different ballistic coefficient causing drag to act differently and causing their orbits to decay at different rates. It turns out that the CloudSat ballistic coefficient is greater than CALIPSO's coefficient by about a factor of two. Therefore, CALIPSO's orbit decays faster. From the CloudSat perspective, CloudSat's orbit appears to rise with its semi-major axis increasing in time with respect to CALIPSO. So if the two spacecraft were positioned on the same orbit, i.e., identical semi-major axes, with CloudSat in front of CALIPSO, CloudSat's orbit would, in time, rise with its semi-major axis slowly increasing to be greater than CALIPSO's. With CloudSat now being in a higher, larger orbit, the orbital period would be greater than CALIPSO's period, and the net effect would be that CloudSat would revolve around the earth more slowly. CloudSat would move backwards and approach CALIPSO. To be quantitative about this, a difference of just 10 meters in semi-major axis at the nominal altitude maps into a 460-meter change in along-track position relative to CALIPSO per day.

CloudSat, detecting this motion and being the burdened craft, would eventually reach a separation threshold where it would then make a propulsive maneuver to reduce its semi-major axis to be less than CALIPSO's. The total change in semi-major axis required here would be on the order of 50 to 100 meters out of approximately 7084 km, or one part in one-hundred-thousand. The ΔV for such a maneuver would be less than 6 cm/sec. After the maneuver and now with CloudSat having the smaller semi-major axis and the shorter period, its motion relative to CALIPSO would be accelerated away in the forward along-track direction. This forward motion would continue until CALIPSO's orbit had once again decayed and its semi-major axis equaled CloudSat's. At that point, CloudSat's motion with respect to CALIPSO would reverse directions (this time without a maneuver) and CloudSat would begin to close its separation with CALIPSO. This circulation process would repeat so long as CloudSat is able to make propulsive maneuvers to lower its semi-major axis when the separation distance from CALIPSO reaches the threshold defined by formation maintenance requirements. CloudSat would be in its "circulation orbit" relative to CALIPSO, initiated at the point of closest approach between the two spacecraft by the maneuver to lower its semi-major axis.

These characteristics of two spacecraft with essentially the same orbits and perturbed by drag are the principal physical phenomena that enable "tight" formation flying, and they are the basis of CloudSat with CALIPSO formation flying. For sure, other physical factors come into play, e.g., radiation pressure, etc., that also perturb the orbits, but they are so small in comparison to the drag effects that they can be easily eliminated by including small compensating components within the maneuvers to restore the circulation orbit.

The key to making this work is having the ability to observe changes in the semi-major axes. Unfortunately the semi-major axis for an orbit is not directly observable, but has to be inferred from the measurements of some other parameters. It is possible, however, to determine the relative changes in semi-major axes by measuring the in-track separation and relative motions between the two spacecraft. And since both spacecraft have GPS units as navigational data sources to provide precision ephemerides with position knowledge for each spacecraft, CloudSat uses this data to determine and monitor the evolution of the in-track separation.

As a practical matter, all evaluations of the formation are done as CloudSat crosses the equator. This is where the monitoring and controlling the formation automatically satisfies formation maintenance requirement elsewhere on the orbit, owing to the longitudinal compression that occurs as the spacecraft latitude approaches the pole.

Analysis of the dynamics shows that, to a good approximation, the motion of CloudSat's subsatellite point with respect to CALIPSO's groundtrack closely follows a near parabolic path with the motion beginning at or near the western boundary of the control box with a maneuver. After the maneuver, the path moves to cross the CALIPSO's groundtrack an approaches the eastern boundary of the control box. Simultaneously, it also moves forward in the along-track direction approaching the front of its control box. If the maneuver has been carefully sized, the path will turn around within the control box and move again toward the western limit. Thus the fine detail of formation control becomes a matter of selecting the ΔV magnitude and frequency to just keep CloudSat's groundtrack inside of its control box relative to CALIPSO. Considerable analysis and strategy development have been done by CloudSat's mission design team to formulate these algorithms and is document in Ref. 7.

CONCLUSION

Although CloudSat was conceived as a high value, stand-alone mission with sufficient scientific merit on its own accord, the Science Team from the beginning recognized the value of obtaining measurements from other cloud observing spacecraft for the purpose of comparing and potentially combining with CloudSat's radar data. With this prospect in mind, the Science Team went on to define mission requirements for formation flying with other spacecraft. When CloudSat and CALIPSO were co-manifested on the same Delta II launch, this prospect seemed all the more realizable. CloudSat mission design, in cooperation with CALIPSO and Aqua, was then developed to be responsive to these formation flying requirements giving the scientists the opportunity and means to turn the CloudSat mission into a "virtual platform". And the follow-though has been complete, with the realization of a CloudSat data-product that actually combines radar and MODIS data and a plan to formulate another data-product which combines radar and lidar data.

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