THE A-TRAIN:
HOW FORMATION FLYING
IS TRANSFORMING REMOTE SENSING

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INTRODUCTION

This paper was given verbally at the conference. The text of the talk (with minor modifications) follows.

THE A-TRAIN

Good afternoon, ladies and gentleman, and thank you for offering me this opportunity to talk about the A-Train and Formation Flying. First, let me credit my co-authors, Adam Kankiewicz, and Tom Vonder Haar.

Before I start, I would like to state that I speak to you today not as a developer or inventor of the A-Train, but as a user—an appreciative user—of A-Train data.

Figure 1 shows the representation of the A-Train that one usually sees. The A-Train is lead by Aqua, which flies in a sunsynchronous orbit with a 13:30 (afternoon) ascending node that gives the Afternoon Train, or A-Train, its name. Aqua is currently followed by CloudSat, CALIPSO, PARASOL, and Aura. Aqua is an observatory-class satellite with six instruments, which make measurements in the visible through the microwave portion of the spectrum. Aqua produces a prodigious amount of data, and scientific results to match. But there is so much more to do.
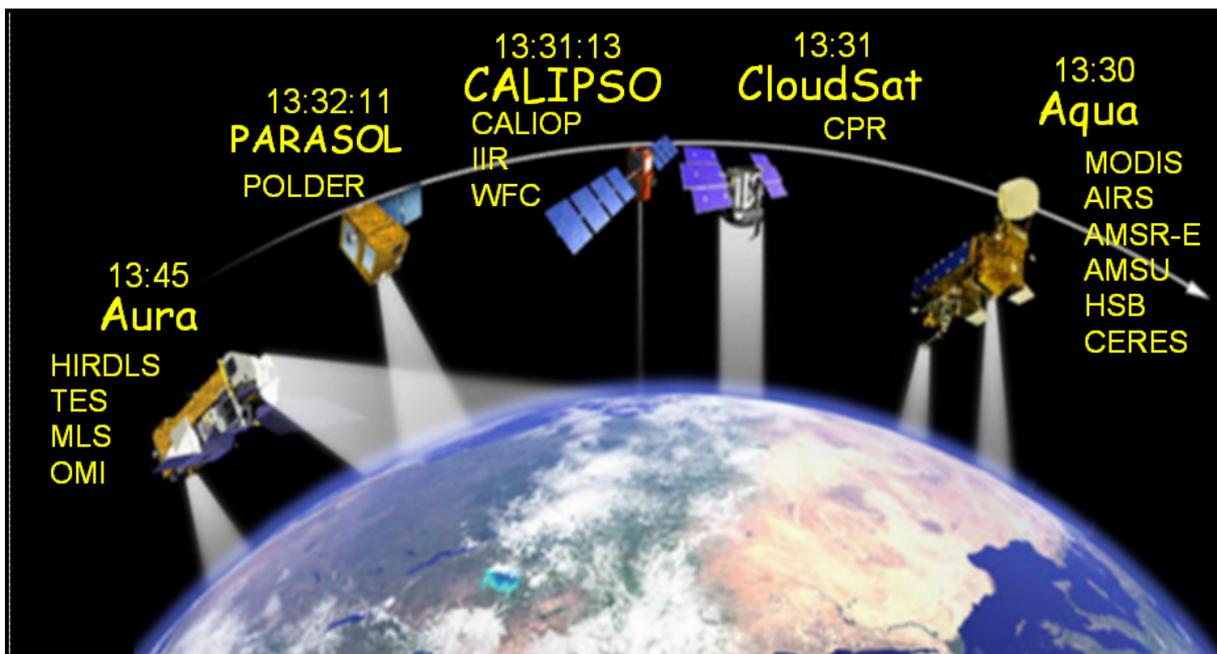

Figure 1: The A-Train

Aqua's instruments are all passive. CloudSat and CALIPSO carry active instruments to sense vertical profiles of clouds and aerosols. CloudSat's 94 GHz, or 3 mm, radar senses larger particles; CALIPSO's 532 and 1064 nm lidars sense smaller particles.

PARASOL carries POLDER, which provides further information—especially polarization information—on the clouds and aerosols observed by Aqua, CloudSat, and CALIPSO. And finally in the A-Train is Aura, the atmospheric chemistry satellite.

The A-Train is more than several satellites following each other in orbit. If one wants multiple instruments to observe the same cloud, those instruments must be sufficiently close together such that they view the cloud within a brief amount of time; else the cloud will have changed. Satellites that carry these instruments must, therefore, fly closely together in a formation, not unlike precision flying teams such as the Blue Angels or even the fighter pilots in the movie Star Wars.

The heart of Formation Flying, as it is called, is control boxes (Fig. 2). The satellites are allowed to drift inside control boxes until they approach the boundaries of the box, then maneuvers are initiated to adjust the orbit. This is crucial both to maintain the observing times and geometries of the instruments, but especially to avoid collisions, which would produce a debris field that would threaten the entire formation.
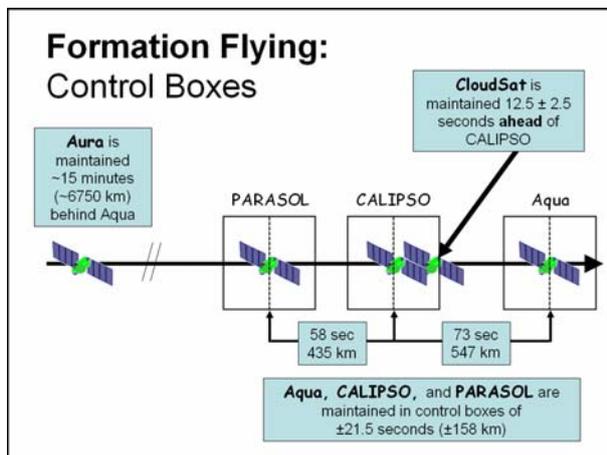

Figure 2: Control boxes.

Aqua is maintained inside a control box of ±21.5 seconds (about ±158 km) so that it makes precisely 233 complete orbits in 16 days and repeats its ground track along the World Reference System (WRS) 2 grid.

CALIPSO is maintained in a ±21.5 second control box averaging 73 seconds, or about 547 km, behind Aqua, which means that CALIPSO is never closer than 30 seconds (or 225 km) to Aqua.

Similarly Parasol flies about 131 seconds behind Aqua, and Aura flies about 900 seconds behind Aqua.

No, I didn't forget CloudSat. CloudSat flies in a mini formation 12.5±2.5 seconds ahead of CALIPSO.

What's remarkable about all this is that the satellites are controlled by different agencies: Aqua and Aura by NASA/Goddard, CloudSat by the US Air Force, PARASOL by CNES, and CALIPSO by NASA/Langley and CNES. Fortunately there is a group coordinating this: the Earth Science Mission Operations Project at NASA/Goddard.

Horizontal separation is another important aspect of Formation Flying (Fig. 3). The first four A-Train satellites fly in tight formation so they can view the same locations from above in a brief time span. Aura is positioned substantially behind the others such that its Microwave Limb Sounder can view horizontally the same portion of the atmosphere that Aqua is viewing from above.
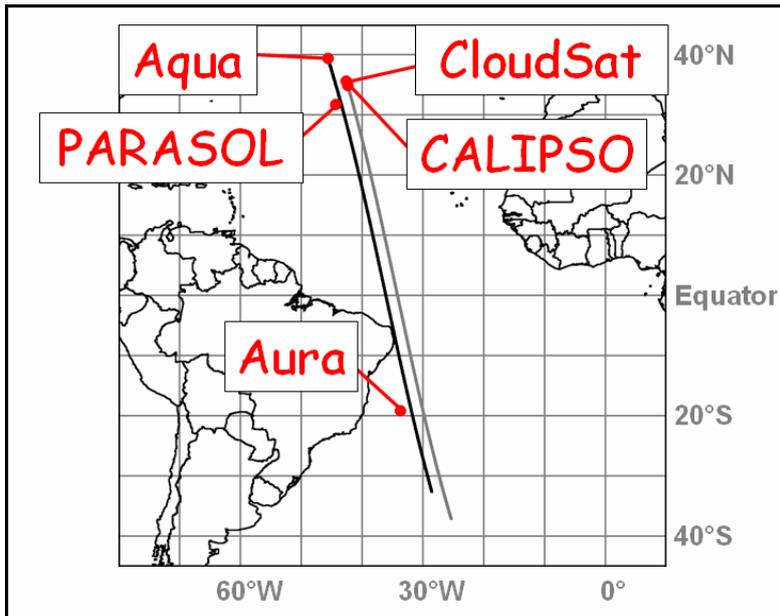
Figure 3: **Formation flying: Horizontal separation.**

CALIPSO is sensitive to sun glint and, therefore, is positioned 215 km to the anti-solar side of the Aqua ground track at the ascending node (Fig. 4). This means, of course, that CloudSat and CALIPSO cross Aqua's path twice each orbit, which emphasizes the need for control boxes. This figure and the previous one illustrate a remarkable advantage of Formation Flying: at the expense of a slight time separation, Formation Flying simulates a satellite that is hundreds of kilometers in size.
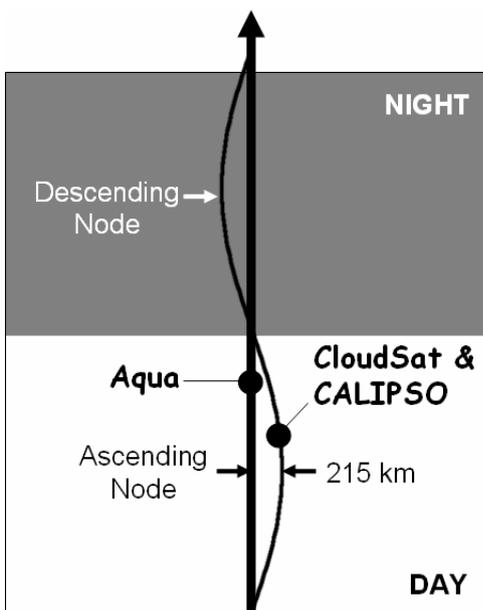

Figure 4: **Orbit offset.**

Finally, it is essential to know how accurately the satellites can be positioned and how accurately the instruments can be pointed (Fig. 5). The pre-launch requirement for alignment of the 1400-m-diameter CloudSat footprints and the 70-m-diameter CALIPSO footprints was that they would would be within 2 km of each other, as sketched on the left. The pre-launch goal was that the footprints would overlap 50% of the time, as shown on the right. In fact, they overlap more than 90% of the time This could be called not just formation flying, but precision formation flying.
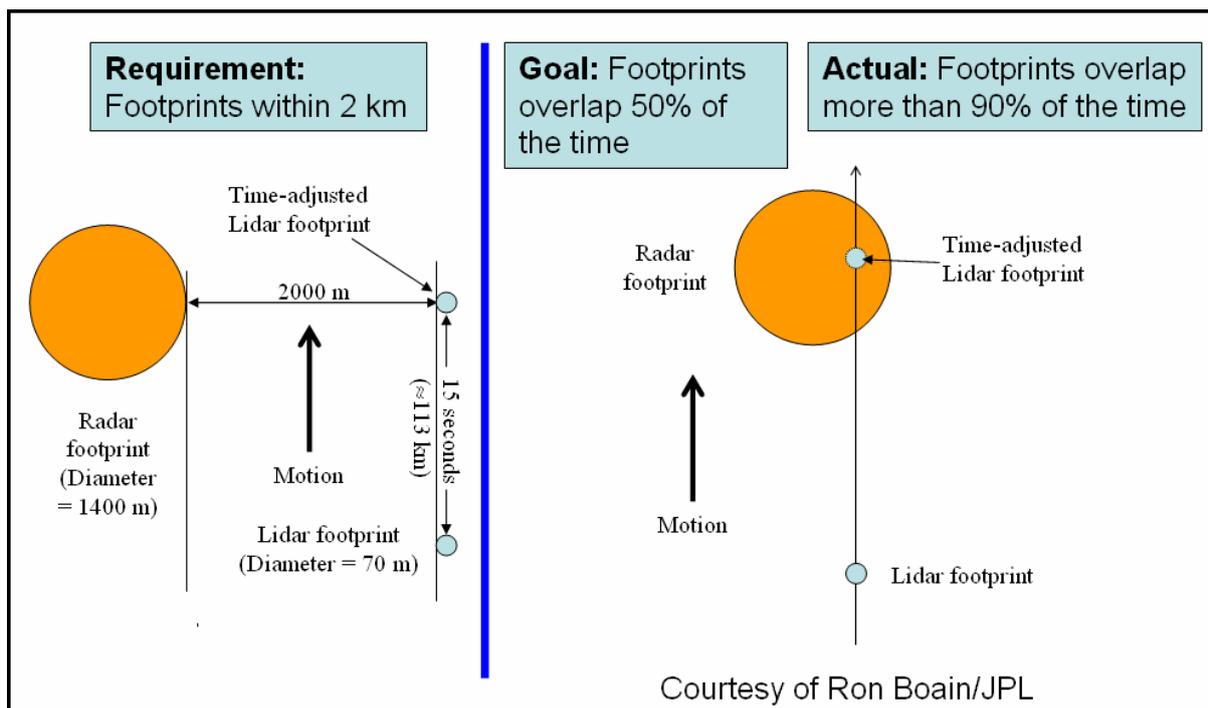
Figure 5: Footprint overlap.

AN APPLICATION OF A-TRAIN DATA

Many, many scientific studies can be conducted with the abundance of high quality A-Train data. I would like to illustrate the power of Formation Flying by discussing just one brief example that we are working on at Colorado State University: mid-level clouds. Figure 6 shows a photo from an airplane of a mid-level cloud under cirrus. Mid-level clouds are important because they are poorly forecast, they obscure visibility, and they present an icing hazard for aircraft.

Figure 6: A mid-level cloud under cirrus.

For many years my coauthors have studied mid-level clouds. Ten field experiments, called Cloud Layer Experiments, or CLEX, have been conducted since 1995 (Fig. 7). Typically these clouds have an unusual structure: they are mixed-phase, with supercooled liquid water above and ice below. Aircraft measurements have revealed this structure. Note, in the illustration at the right, the thin layer of supercooled water (in red) and the much thicker, but less dense ice below (in blue). But field programs allow one to study only a few clouds over restricted areas of Earth. The obvious way to extend this work is with the use of satellite data.
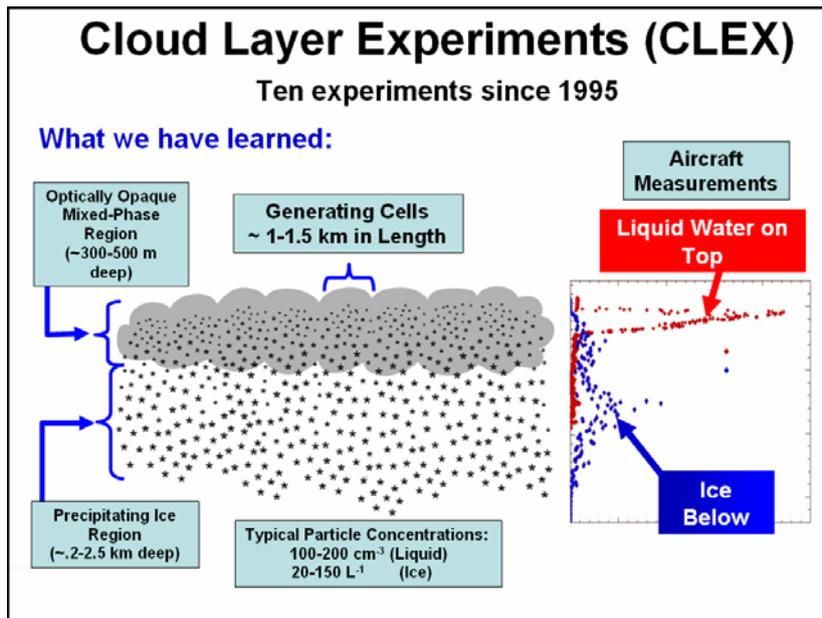
Figure 7: Cloud Layer Experiments.

Since the 1960s we have had satellite imagery similar to the Aqua/MODIS 11 µm image of a cloud band in the remote South Pacific Ocean shown in Fig. 8. The brightness temperature range of 0°C to greater than −40°C is the right range for mixed-phase clouds, but one can tell little else from this one wavelength. Fortunately help is on the way: CloudSat and CALIPSO traveled the path from A to B within 75 seconds after Aqua made this image. For future reference, please note the convective element to which the arrow points and how difficult it is to distinguish this element from the rest of the cloud band.
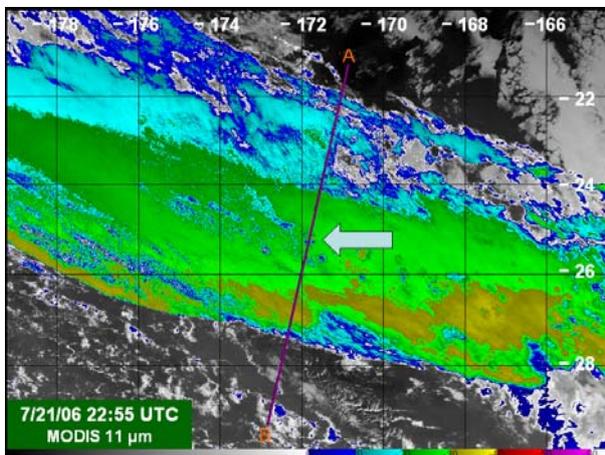

Figure 8: An 11 µm image of a mid-level cloud band.

MODIS, of course, is a 36-channel instrument, and those channels can be used to analyze the cloud. I applied the VIIRS Cloud Phase Algorithm (Fig. 9), which is based on the work of Pavolonis and Heidinger (2004) and Pavolonis et al. (2005). (VIIRS is the MODIS-like instrument which is to fly on the NPOESS satellites.) At first glance, the algorithm looks pretty good. Yellow symbolizes "mixed-phase clouds," which one would expect to be present in this cloud band. The cyan clouds are "cloud overlap," which is defined as a layer of ice cloud over a layer of water cloud. Again, it's not improbable. Gray (that is, "clear") and red (that is, "warm liquid water clouds") look good. Blue, symbolizing "thick cirrus" is a little more problematic; it seems to detect cloud edges more than thick ice clouds. So, how do we determine if this analysis is correct? By examining other data, of course, CloudSat and CALIPSO data, in this case. Remember that CloudSat and CALIPSO flew along the line from A to B.
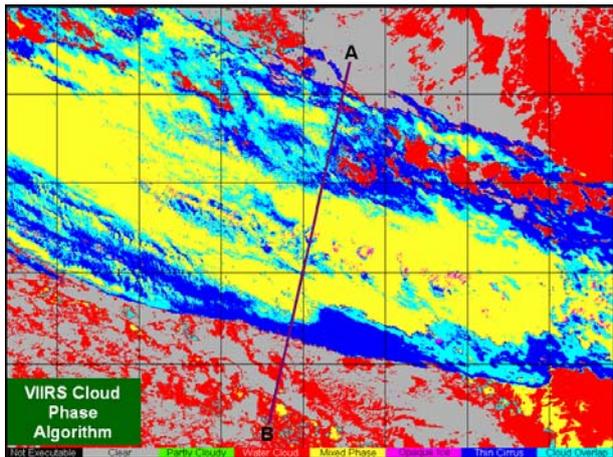
Figure 9: VIIRS Cloud-Phase Algorithm.

Shown in the top panel of Fig. 10 is the CloudSat radar reflectivity; in the bottom panel, the CALIPSO 532 nm backscatter. These images are a vertical slice through the clouds from A, on the left, to B, on the right. The scale on the left is 0−10 km altitude. CALIPSO shows a thin layer of high backscatter particles which completely attenuates the signal; there is no return from below the layer. In all likelihood this is a layer of supercooled liquid water, given the ECMWF temperatures, which are shown with the dashed lines. The low depolarization ratios (not shown) corroborate this assertion. CloudSat shows several things: first the convective element with high reflectivities below (arrow). CloudSat, it turns out, is quite good at sensing drizzle, which is missed by previous rainfall-detecting instruments. In the southern (right) portion of the cloud band is a thick layer of what I interpret as ice particles below the liquid water layer, as seen in other mid-level clouds. In the northern (left) part of the cloud band are very few ice particles, perhaps caused by a lack of ice nuclei. The interesting thing is that there is little evidence of this ice/no ice boundary in either the CALIPSO data or MODIS 11 µm data.
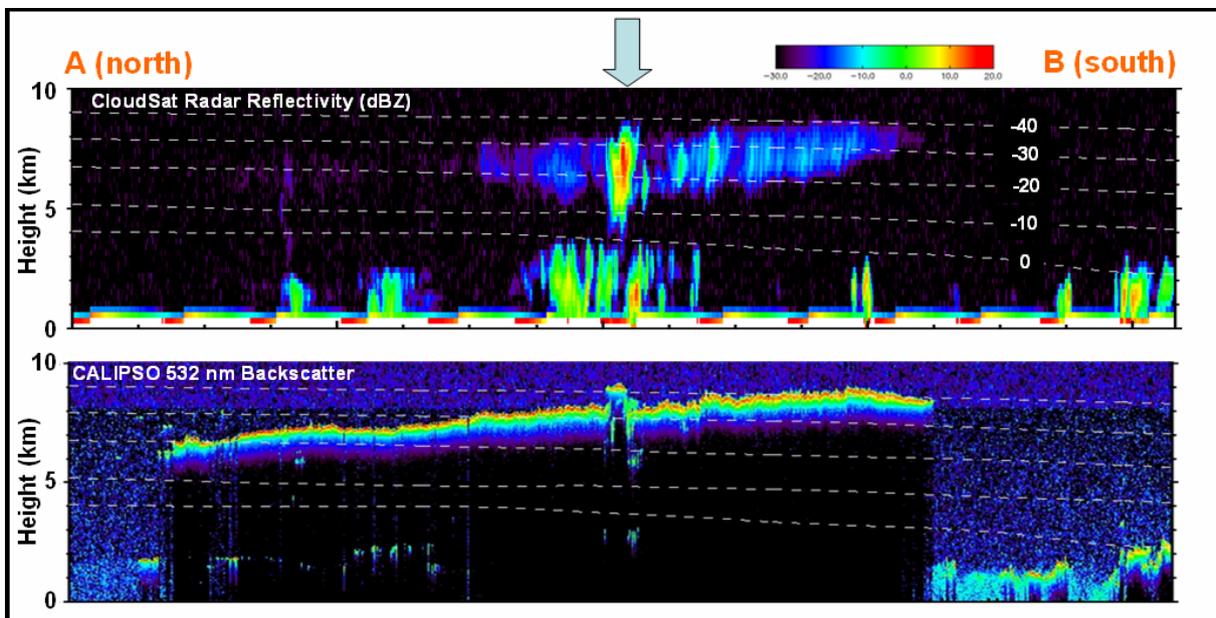

Figure 10: CloudSat and CALIPSO data through the cloud band shown in Figs. 8 and 9.

Jay Mace, of the University of Utah, has put together a combined CALIPSO/CloudSat product which attempts to use the strengths of each instrument to detect clouds (Fig. 11). This product is available at the CloudSat Data Processing Center (http://www.cloudsat.cira.colostate.edu). Up to five layers of clouds are determined. The height of the top and bottom of each layer and the instrument which detected the top and bottom are recorded in Jay's algorithm.
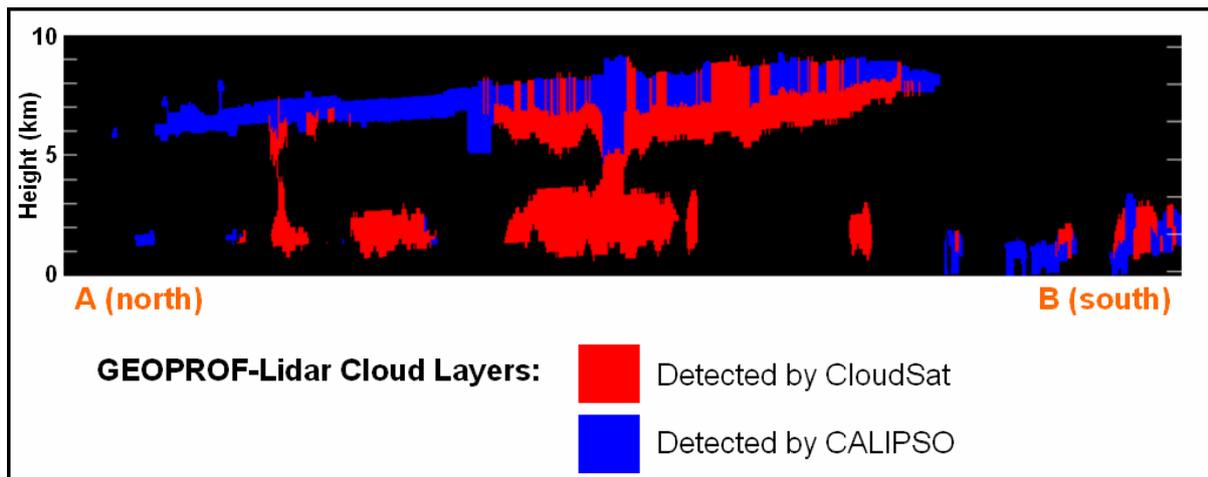
Figure 11: **CloudSat and CALIPSO cloud layers.**

Because the location accuracy of the satellites and the pointing accuracy of the instruments in the A-Train is so high, we can pick out the precise pixel in the MODIS data which was sampled approximately one minute later by CloudSat and CALIPSO (Fig. 12). The MODIS 11 µm brightness temperature is shown in white. Please note the temperature scale at the right, from warm at the bottom to cold at the top. The VIIRS cloud phase can also be calculated. In the thicker right portion of the cloud, the brightness temperature is smooth, and the cloud phase indications look reasonable: mostly mixed phase or cloud overlap, although the overlap would be water over ice, and not ice over water. In the thinner left half of the cloud the brightness temperature is much more irregular, indicating "holes" in the cloud, and the cloud phase is problematic. The algorithm indicates quite a bit of thin cirrus (blue), when in fact it is likely to be thin liquid water. A good deal of cloud overlap is also indicated, although this time it would appear to be liquid water over liquid water, not ice over water.
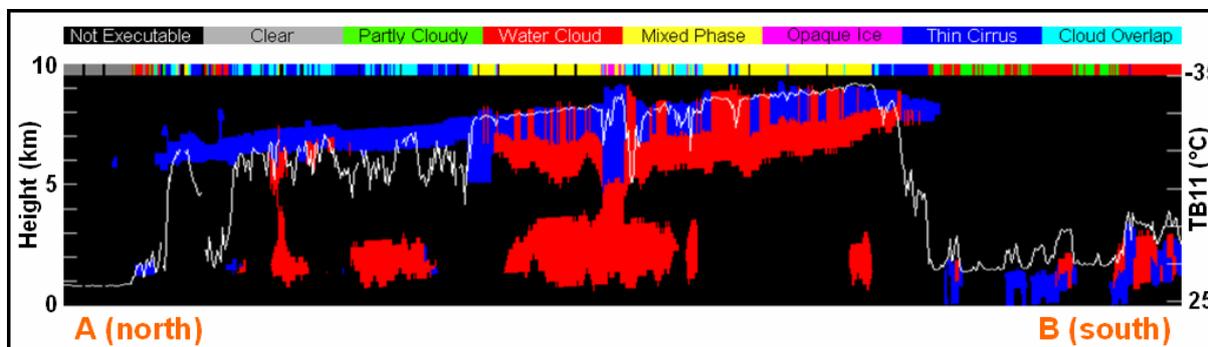

Figure 12: **CloudSat/CALIPSO Cloud Layers overlaid with the MODIS 11 µm brightness temperature (white line) and with the VIIRS Cloud Phase (colored band at the top of the image).**

But my purpose here is not to criticize algorithms. Rather I wish to point out that formation flying has transformed remote sensing. A single sensor is no longer sufficient. The way to understand the workings of nature is to observe phenomena with multiple sensors. Formation flying allows us to do this for many atmospheric phenomena for the first time.

THE FUTURE

So what does the future of formation flying look like? In the short term, it means more satellites in the A-Train. The Orbiting Carbon Observatory (OCO) and GLORY (to measure solar irradiance and aerosols) are scheduled to join the A-Train in 2008 or 2009 (Fig. 13).

Figure 13: **Joining the A-Train in 2008 or 2009 are GLORY and OCO.**

We expect that in the future there will be more trains. Actually the A-Train was not the first train. Landsat 7, EO-1, SAC-C, and Terra flew (and some still fly) in a morning train (Fig. 14). We fully expect that nearly all future earth-sensing satellites will be part of a train.
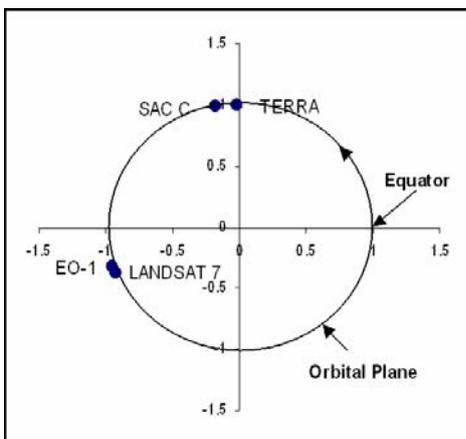

Figure 14: **The A-Train was not the first Train: EO-1 flew 1 min behind Landsat 7;SAC-C flew 27 min behind EO-1; and Terra flew 2.5 min behind SAC-C.**

And finally, we note that there are many possibilities for using formation flying to calibrate satellite instruments in other orbits, if they share the same orbital plane. Satellites like NPP, for example, which will fly in an 824 km orbit, could be (and, perhaps, will be) placed in nearly the same orbital plane as the A-Train flying in a 705 km orbit (Fig. 15). While NPP would orbit the Earth at a different speed, it would observe the same spot on Earth within 15 minutes about 30% of the time. This would leverage the considerable effort to calibrate the A-Train satellites.
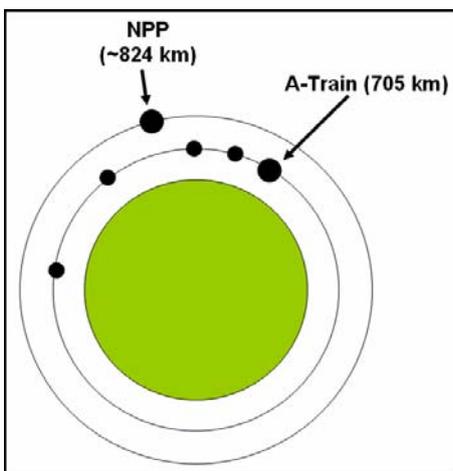

Figure 15: **Satellites in the same orbital plane, but at different altitudes would leverage the extensive cal/val efforts of the A-Train satellites (or satellites in other trains).**

In conclusion, let me say that in our opinion

- The A-Train has definitively proven the concept of Formation Flying,

- The synergy of nearly coincident observations from multiple instruments has transformed remote sensing of the atmosphere, and

- There aren't enough letters in the alphabet to name all of the "trains" which will soon be flying.

Thank you.

REFERENCES

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Pavolonis, M. J., Heidinger, A. K., and Uttal, T., (2005) Daytime Global Cloud Typing from AVHRR and VIIRS: Algorithm Description, Validation, and Comparisons. *Journal of Applied Meteorology*, **44**, 804−826.