HOW TO ENTER, FLY IN, AND EXIT THE A-TRAIN CONSTELLATION

Mark A. Vincent*

The collaborative science obtained from the satellites in the A-Train is an unparalleled success. The constellation framework that has evolved is well-formulated and documented by its international members. Communication between teams is enhanced by a web-based Constellation Coordination System. Safety and correlated observations are ensured by defining independent control boxes with buffers in between. Each mission stays within its control box by regular drag make-up maneuvers. Annual inclination adjustments are coordinated by all missions to maintain their absolute and relative Mean Local Time of Ascending Node (MLTAN). Since the satellites are in different orbit planes their separation involves a three-dimensional triad made up of the alongtrack separations, reference groundtracks and MLTAN's. For further safety, a Constellation Envelope has been defined to determine safe entry and exit orbits.

INTRODUCTION

When NASA's Terra satellite was launched in late 1999 it joined Landsat 5 and 7 in a similar orbit that repeated in 16 days/233 revolutions and had a descending node near 10:30 AM. All three satellites maintained their groundtracks to be close to the World Reference System II (WRS-2). However the satellites were far enough apart alongtrack that strict definitions for constellation flying were not really necessary (though see the later discussion when Landsat 5 decided to change the local time of its descending node). Aqua was later launched into a similar orbit in 2002 but having an ascending node near 1:30 PM. It was followed by Aura and Parasol two years later with similar afternoon orbits but again there were large alongtrack separations. However when it was decided to launch CALIPSO and CloudSat into the space between Aqua and Parasol the need to formalize the concepts of constellation flying became apparent. This was concurrent but somewhat independent of the process of enacting the formation flying between CALIPSO and CloudSat themselves. The satellites in the afternoon orbits became the Afternoon Constellation otherwise known as the A-Train. The satellites in the morning orbits are called the Morning Constellation even though they still fly in the looser, widely separated manner.

Comparisons of different types of constellation and formation flying were presented in an earlier paper[1] and expanded upon in a subsequent paper.[2] Repeated briefly here, Constellation Flying implies satellites flying independently in their own control boxes which are separated by buffers,

* Senior Principal System Engineer, Intelligence, Information & Services, Raytheon, 299 N. Euclid Ave. Suite 500, Pasadena CA 91101.

with the control boxes and buffers being defined with respect to either their (clock) time of crossing the equator (the common practice) or to the points the two relevant orbit planes cross near the poles (more appropriate for safety reasons). Formation Flying implies a master satellite which has one or more satellites doing maneuvers to remain in a dead-band range alongtrack with respect to the master. A new third definition has been added due to the modifications in the manner CloudSat flies with CALIPSO. It has been named *Coordinated Flying* and can be thought of as a hybrid of Constellation and Formation Flying. Specifically CloudSat now has its own control box to fly in the A-Train but also does formation flying with CALIPSO, albeit in a looser manner than they were doing originally, so the two satellite's groundtracks remain close to each other. Note the constellation requirements overrule the formation flying ones, which can be thought of as safety trumping improved science measurements.

As the title suggests this paper will be composed of three topics, however entering, flying in and exiting the A-Train (or any other constellation) are all intertwined. So much so that the concepts of flying in the Constellation will be presented first, followed by the methods of targeting the launch vehicle into an injection orbit and then ascending into the appropriate position in the Constellation. Finally the process of exiting the Constellation will be shown to be similar to the entry process in reverse.

CONSTELLATION FLYING

Once the control boxes have been defined, Constellation Flying can be thought of as the combination of individual satellites staying within their boxes and maintaining the control box/buffer configuration. To aid in describing these concepts *virtual satellites* (the red dot in Figure 1) were defined. The simplest definition of a virtual satellite is one flying such that its groundtrack is the Reference Ground Track (RGT) of the particular mission in an atmospheric drag-free environment. The RGT can have evenly spaced nodal crossing corresponding to a zonal-only gravity field[1] or in the case where the RGT must be closer to reality it includes the effect of the sectorial gravity terms.[3] The A-Train uses the evenly-spaced model, though note the ascending nodes are not evenly spaced between the descending nodes (which are defined in the WRS-2) because the ellipticity of the reference frozen orbit is taken into account. That is, the reference orbit takes longer to go from descending node to ascending node than ascending to descending.

The Circulation Orbit

The Alongtrack Control Box, otherwise known as the Phasing Control box is in the orbit plane with the corresponding virtual satellite in its center. Its alongtrack dimension corresponds to the amount of motion permitted with respect to an anchor satellite (which is Aqua for the A-Train). For this discussion consider the orbit plane fixed and the only perturbation of importance is the atmospheric drag. The Circulation Orbit can be thought of as the satellite starting above the reference semi-major axis (sma) near the front of its box. As in seen in Figure 1, the larger semi-major axis makes the satellite drift back in its box but the sma is decreasing because of the drag. At the point when the sma equals the reference value the backwards motion reverses so the satellite heads towards near the front of its box. When it again gets near the front of its box a Drag Make Up (DMU) maneuver is performed. The size of the DMU is chosen with a prediction of the atmospheric conditions that will occur during the next circulation orbit.

While the satellite is traversing its circulation orbit there is a corresponding motion of the groundtrack within a Groundtrack Control Box. Basically the satellite being near the front of its Phasing Control Box corresponds to it being near the eastern edge of its Groundtrack Control Box. Then the parabolic motion is towards the western edge and back, at which point the DMU is performed. The position in the Groundtrack Control Box is generally of interest to the scientists while the position in the Phasing Control Box (or outside of it) is important for maintaining safety in the Constellation. And the importance of the distinction between the two types of control boxes is explained in the next section.

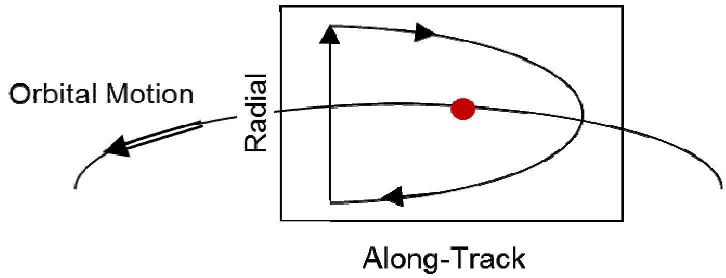

Figure 1. The Circulation Orbit.

MLTAN and the Triad

The Mean Local Time of Ascending Node (MLTAN) is the angle between the Mean Sun and the ascending node of the satellite of interest. The fact that is usually measured in HH:MM:SS has led to confusion in the past, in particular with the equator crossing time used in the Phasing Control Box definition. For a perfect sun-synchronous orbit the orbit inclination is such that the even zonal terms of the Earth's gravity field cause a precession at the rate of the Mean Sun. However as seen by taking the singly-averaged luni-solar third-body potential[4] and using Lagrange's equations, the dominant term in the inclination rate for satellites with small eccentricities is proportional to the MLTAN in the following manner[4]:

$$di/dt \;\alpha\; \sin\left[2 * (\Omega - M')\right] \qquad (1)$$

where the difference in the right ascension of the satellite node and the Mean anomaly of the Sun ($\Omega - M'$) is equivalent to the MLTAN. Note the that this implies that for afternoon satellites in the A-Train, the inclination will be increased with a maximum perturbation at 3:00 PM MLTAN while for the Morning Constellation the inclination will be decreased.

The dominant effect of the change of inclination will be the precession due to the J_2 gravity term will be increased for the A-Train and decreased for the Morning Constellation. In other words the satellites in the A-Train naturally drift to later MLTAN values. In order to maintain MLTAN near their nominal values, each Spring the A-Train does a coordinated set of Inclination Adjustment Maneuvers (IAM), reducing their inclinations to a value below the sun-synchronous value. This causes a drift to earlier MLTAN until the luni-solar effect increases the inclination enough to reverse the drift so the MLTAN becomes later until the next round of IAM. Note that for annual IAM the total range from earliest to latest MLTAN for the A-Train is about 45 seconds. The parabolic motion in MLTAN is analogous to, and as the next paragraph explains, coupled to, but should not be confused with the Circulation Orbit. Also note that satellites with a 6 AM or 6 PM ascending node will be at a stable null point for MLTAN change while noon or midnight orbits are at an unstable null.

The Triad was introduced[1] to explain the relationship between the three quantities; Alongtrack Phasing, MLTAN and the Groundtrack. This relationship is integral to the previously mentioned process of keeping the proper buffers between the Phasing Control Boxes. The important take-away message is that only two of them are independent. The easiest way to explain this is to give some examples and examining Figure 2. If two satellites have the same RGT (for example GCOM-W1 and Aqua in the figure) then the difference in their MLTAN is also equal to their alongtrack phasing (shown as difference in equator crossing time in the figure). However, with different RGT, the MLTAN and Phasing are different. This is important when considering the phasing at the polar crossing points.[5] Or another example is that if a satellite maintains its groundtrack but allows it MLTAN to vary then its Phasing will vary accordingly. The most infamous case for the A-Train was when Landsat-5 did this and passed Aqua, CloudSat and CALIPSO before reversing its MLTAN motion and passing them again, albeit in a controlled manner the second time around.[6]

The experience with Landsat-5 also emphasized the interdependence of the Morning Constellation and the A-Train. The term "705-km Fleet" was proposed but never caught on in popularity. Nevertheless all the satellites in 705-km orbit can be thought of as flying in control boxes with buffers and the control boxes can overlap if the MLTAN are allowed to vary too much. Also note that the two constellations are further intertwined if one considers the crossing points of all the orbits near the poles. The time sequence of satellites arriving at these points is Landsat-7, Terra, the whole A-Train and finally Landsat-8 (noting Landsat-5 exited the Morning Constellation in 2013).

ENTERING THE A-TRAIN

There are different methods to launch and enter a constellation and this paper will explain the method used for the CALIPSO/CloudSat combination[7,8] and OCO-2[9], although all the 705-km members used a similar method. The cited references go into the details and a brief summary will be given here. An Injection Orbit is chosen to be safely below the satellites in 705-km orbits (see the Envelope section below). The difference in sma allows the new satellite to catch up to its alongtrack slot in the A-Train though of course, fuel on the new satellite must then be used to raise its orbit to that of the A-Train. For the three satellites considered here an Injection sma 15 km below the A-Train was a good compromise. As explained in the references for each day in a 16-day cycle the phasing angle to catch up (not to be confused with the Phasing angle discussed above) to the desired slot increases 202.5 degrees (modulus 360). Thus the time available (which is also a function of the dispersion in sma from the launch vehicle) is a function of the launch day. Plus, since there is a commissioning time before any orbit raises can happen on some launch days an extra 360 degrees must be added to this phasing; this is called a "Once Around."

The other facet of launch/ascent/insertion is that due to the Triad and requirement of a RGT there is also a required MLTAN (for the chosen final Phasing, i.e. the "slot"). So the method used for these three satellites and other members is to launch to the Operation Orbit inclination but move the launch time earlier which compensates for the faster precession rate of the Injection Orbit. This faster rate is due to the lower sma of the Injection rate but the total drift in MLTAN is proportional to the catch-up phasing angle[7], at least to order J_2. Thus the proper final MLTAN is achieved independent upon both launch vehicle error in sma (though errors in inclination have to be corrected as soon as possible) and the choice of the number and timing of the orbit raises. The major caveat being that choice of whether to go Once Around or not must be picked pre-launch for each launch day (though typically of the 16 days the choice is obvious for all but one or two days). Also note that if for some reason the number of Once Around's has to be altered, for example by a spacecraft anomaly, there are methods to maneuver the orbit back to the desired MLTAN.

The final insertion into the A-Train is usually done with a pair of burns which maintains the near-frozen orbit eccentricity and argument of perigee that has been established, or nearly established in previous maneuvers. Another consideration is the exact final target point. The center of the control box (virtual satellite) would be the choice if there were concerns with the maneuver execution errors. However, in most cases these errors are small enough that a more convenient choice is made such as choosing the central alongtrack point but slightly higher than the reference sma. Thus a small parabolic motion will postpone the need to do the first DMU.

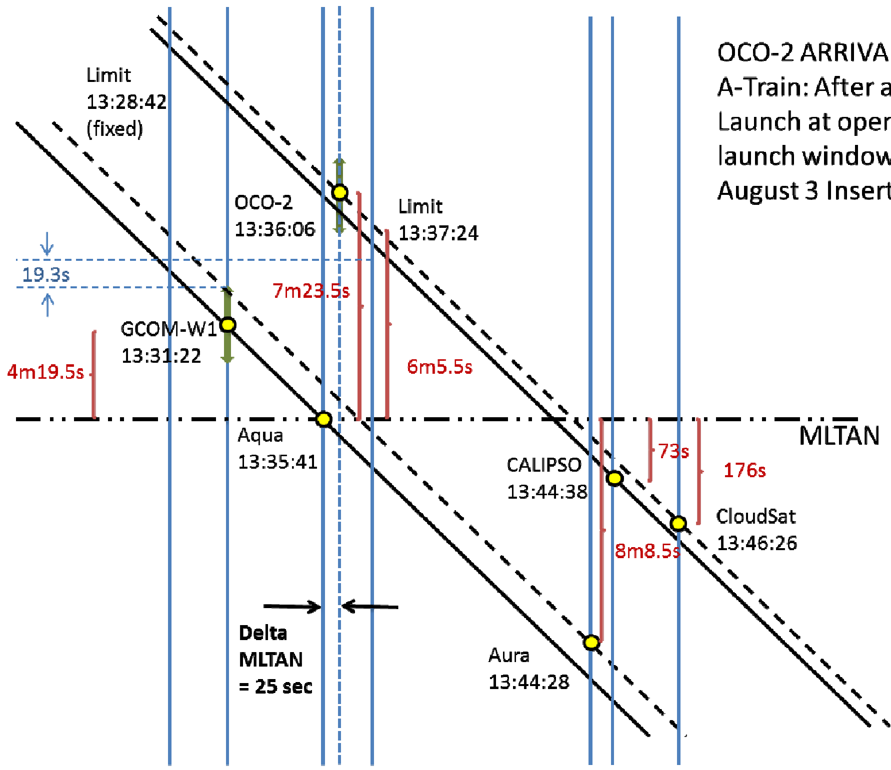

Figure 2. Snapshot of the A-Train at OCO-2's Arrival.

Explanation of Figure 2

There is a wealth of information in Figure 2 that deserves some explanation, although earlier references had similar figures and explanation.[2,9] The term "Snapshot" was chosen since the figure represents the juxtaposition of two reference frames at a single epoch. Specifically, the vertical lines represent MLTAN values in a Sun-orientated frame, though it is simpler for the purpose here to consider the satellites orbit planes fixed so these lines represent an inertial frame. The diagonal lines represent RGT's fixed to the Earth, though their linearity and angle with respect to the Equator (the dash-dot-dot line) is chosen for clarity rather than geometrical accuracy. The yellow dots represent the virtual satellites for each mission. The horizontal dimension is MLTAN and the vertical dimension is relative equatorial crossing time (i.e. a good graphical depiction of the difference between the two "times"). Thus for a fixed MLTAN vertical motion represents the alongtrack motion of the Circulation Orbit, examples are given by green arrows for GCOM-W1 and OCO-2.

Earlier versions of this plot showed the range of values that OCO-2 was allowed to be inserted. Specifically an early MLTAN limit so that a 15-seond buffer at the poles was ensured with respect to Terra (not shown in the figure) and a late MLTAN limit so that a 19.3 seconds buffer was ensured with respect to GCOM-W1. The 19.3 seconds was chosen because it corresponded to a 15 second buffer at the poles where the OCO-2 and GCOM-W1 orbits crossed. OCO-2 actually hit the targeted MLTAN within a second, that is the target was the latest value (i.e. closest to the A-Train) to allow for all the factors that could have made it even later.[9] Also note on the figure that GCOM-W1 and Aqua are on the same RGT, the WRS-2, with Aura on a separate though close-by RGT. Before launch it was decided to move the CALIPSO RGT 215 km to the east of the WRS-2 so the data its mission used from the MODIS instrument on Aqua was not affected by the solar glint spot.[10] But later on it was decided to point the lidar instrument on CALIPSO 0.3 degrees forward so the groundtrack of the lidar footprint is actually 217.3 km east of the WRS-2 (dashed line of the figure). Therefore the RGT for both CloudSat and OCO-2 was chosen to correspond to the 217.3 km offset so that when their instruments were pointed in the nadir direction there was better overlap with CALIPSO's lidar.

EXITING THE A-TRAIN

The process of exiting the A-Train is similar to entering the A-Train but with a different emphasis on certain aspects of the process. One of the more subjective factors is the assumption that satellite will be operating better during the insertion that the exit. Nevertheless if the insertion is done in two burns, the occurrence of the first burn but not the second, should be considered. But for this discussion, first consider an instantaneous retrograde burn from the A-Train reference orbit. The initial point of tangency will rotate at the apsidal period but the important point is that the exiting spacecraft continues to have a point of possible conjunction with the A-Train satellites even if they remained in the reference orbit. Analysis had shown that a finite burn does provide some separation between the orbit and further analysis has shown that this separation is maintained[11] with the following caveats. As explained in the Circulation Orbit section, some of the time the semi-major axis is less than the reference values, plus as mentioned in the next section the A-Train satellites are not maintained to be perfectly frozen themselves, that is they are in near- frozen orbit themselves. Also the osculating effect of the Earth's gravity has a small effect on the differential effect between two nearby orbits. In summary, the separation has to be large enough to account for all these small effects and thus tends to require two burns rather than a single finite one. But again, once these two burns create a new orbit below the original one then (central body) gravity will not cause them to intersect in the future.[11] This concept of an adequate separation led to the creation of the Constellation Envelope described in the next section. That is, once a satellite performs at least two burns so its orbit is entirely below the Envelope then it has safely exited.

Recently there has been an inadvertent consequence of the defining the new Constellation Envelope. The current NASA (and other agency) requirement is for satellites to re-enter in 25 years (or be above the LEO region). However some satellites are grandfathered from needing to satisfy this requirement. This has led to the discussion of the issue that if the Envelope can be used to describe a safe exit orbit, what is a safe disposal orbit? This has led to on-going analyses of the risk that a satellite poses when it is at various orbits below the Envelope. Again, it poses no risk of re-contact with the A-Train while it is an intact satellite, but if it gets hits by another object, the resulting debris would increase the risk to the A-Train, albeit to a degree that is still being studied. There is a further issue that the intact satellite could be in a region used for other satellites to enter or exit the 705-km constellations, but again it has to be determined if this is a substantial risk above that from the already existing secondary objects in that region.

THE ENVELOPE

The new Constellation Envelope was published and discussed earlier.[2] The definitions will be repeated here in the following: Satellite A with Mean semi-major axis sma_A and a maximum Mean eccentricity e_{AMAX} is said to be completely *within* the Envelope if and only if:

$$|sma_R - sma_A| + |sma_R * e_R - sma_A * e_{AMAX}| < M + F \tag{2}$$

Satellite B with Mean semi-major axis sma_B and a maximum Mean eccentricity e_{BMAX} is said to be completely *outside* the Envelope (that is, *completely below* or *completely above*) if and only if:

$$|sma_R - sma_B| - |sma_R * e_R - sma_B * e_{BMAX}| > M + F \tag{3}$$

Where:

- sma_R = Mean semi-major axis of the 705-km Reference Orbit
- e_R = Mean eccentricity of the 705-km Reference Orbit
- M = *Margin* = 2.5 km
- F = *Frozen Orbit Tolerance* based on a maximum eccentricity deviation of 0.0002 (this is equivalent to approximately 1.5 km)

Any satellite that satisfies neither of the conditions of Satellites A or B is said to be *traversing* the Envelope.

Some additional comments and updates are warranted. The e_{MAX} terms can be derived by integrating the Mean elements over an apsidal period (116 days for the A-Train) however an easier method is to consider the eccentricity vector in e*sin(ω) vs. e*cos(ω) "space" where e and ω are the Mean eccentricity and Mean argument of perigee respectively. First calculate Δe, the magnitude of the deviation of the eccentricity vector from the frozen vector via law of cosines using the current values of e and ω:

$$\Delta e^2 = e_R^2 + e^2 - 2*e_R*e*\cos(90 - \omega) \tag{4}$$

Then simply $e_{MAX} = e_R + \Delta e$. This definition of the envelope has been adopted by the A-Train in its Constellation Coordination document and has already led to some new applications. As explained previously[2] there are three benefits of using the envelope. Knowing whether conjunctions with other objects can occur can be analyzed by accounting for the secondary objects being within, outside or traversing the envelope. This technique has been used to look at active satellites from all countries "near" the A-Train. The second benefit of being able to define safe launch vehicle injection orbits has been discussed for future missions. And finally the use of the envelope (both as a benefit and a provoker of new debate) for defining exit strategies was discussed in the previous section.

COORDINATION AND COOPERATION

Even though the control boxes permit independent flying, as explained above, the maintenance of the control boxes with respect to each other requires coordination between the missions. The prime example is the Spring IAM campaign when Aqua as the anchor satellite announces the schedule of inclination decreases and the other members arrange their maneuvers so the delta MLTAN over the next year is maintained to a certain degree. Currently the suggestion is to limit this variation to +/- 2 seconds. Though it is important to note that the Phasing Control Box is the only real requirement and thus such a variation in delta-MLTAN really corresponds to moving the Groundtrack the same number of seconds with the end result that more DMU maneuvers have to be performed to maintain it (while maintaining the Phasing Control Box). Coordination and cooperation between the A-Train members is facilitated in several ways. Semi-annual Mission Operations Working Group (MOWG) meetings provide a face-to-face venue for discussions. Agreements are documented in a Constellation Coordination document and a separate document for the Spring IAM Campaign each year. Day-to-day ephemeris transfers are performed using a web-based tool named the Constellation Coordination System (CCS). The CCS also has a set of tools to allow the analysis of past, current and future data. And finally, all members use the Conjunction Assessment Risk Analysis (CARA) service and share ideas of how to handle the growing risk of conjunctions with secondary objects.

CONCLUSION

The concepts and definitions developed for the A-Train have been groundbreaking and prove that separate platforms can be safely flown together so that congruent (both temporally and spatially) scientific measurements can be taken. In particular the construct of control boxes provides both independence and a framework for cooperation. Safe entry and exit from the constellation is simplified by the definition of a Constellation Envelope. Coordination of any constellation is greatly enhanced by a combination of regular meetings and a web-based tool to transfer data products. The A-Train has been so successful that new constellations are being considered.[2]

ACKNOWLEDGMENTS

The analysis presented here was supported by Raytheon contracts with both NASA's Goddard Space Flight Center and the Jet Propulsion Laboratory which is managed by the California Institute of Technology. The author would like to thank David Tracewell, Warren Case and Ted Sweetser for their editorial reviews.

REFERENCES

[1] M.A. Vincent, "Lessons Learned from the 705-km Fleet." Proc. SPIE 8516, Remote Sensing System Engineering IV, 851608, October 2012; doi:10.1117/12.940771

[2] M.A. Vincent, "Similarities and Differences between the A-Train and the Proposed J-Train." Proc. of the 1st International Earth Observation Convoy and Constellation Concepts Workshop, Noordwijk, The Netherlands, October 9-11, 2013.

[3] T.H. Sweetser, M.A. Vincent & S.J Hatch, "Shootin' the Pipe around the World: Orbit Design and Maintenance for L-Band SAR Radar Interferometry." Proc. of the AIAA/AAS Astrodynamics Specialist Conference, San Diego, CA, August 4-7, 2014.

[4] W.M Kaula, "Development of the Lunar and Solar Disturbing Functions for a Close Satellite." Vol. 67, No. 5, 2005, pp. 300–303: Astronomical Journal, June, 1962.

[5] M.A. Vincent, "Two Geometric Aspects of the Orbiting Carbon Observatory 2 Mission." Proc. 22nd AAS/AIAA Space Flight Mechanics Meeting, Charleston South Carolina, January 29 – February 2, 2012.

[6] J.A. Levi and E. Palmer, "Strategy for Mitigating Collisions Between Landsat 5 and the Afternoon Constellation." Proc. Of AAS/AIAA Astrodynamics Specialist Conference, Girdwood, Alaska July 31-August 4, 2011.

[7] M.A. Vincent and C. Salcedo, "The Insertion of CloudSat and CALIPSO into the A-Train Constellation." Proc. Of AAS/AIAA Astrodynamics Specialist Conference, Big Sky, Montana August 3-7, 2003.

[8] M.A. Vincent "The "Playbook" for Inserting CloudSat into the A-Train Constellation." Proc. Of AAS/AIAA Astrodynamics Specialist Conference, Lake Tahoe, CA, August 7-11, 2005.

[9] M.A. Vincent & M.D. Garcia, "The Plans for Getting OCO-2 into Orbit." Proc. of AAS/AIAA Astrodynamics Specialist Conference, Girdwood, Alaska July 31-August 4, 2011.

[10] L.M. Mailhe, C. Schiff & J.H. Stadler, "CALIPSO Mission Design: Sun-Glint Avoidance Strategies." Proc. of AAS/AIAA Space Flight Mechanics Conference, Maui, Hawaii February 8-12, 2004.

[11] T.H. Sweetser & M.A. Vincent, "The Eccentric Behavior of Nearly Frozen Orbits." Proc. of AAS/AIAA Astrodynamics Specialist Conference, Hilton Head, South Carolina, August 11-15, 2013.