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THE PLANS FOR GETTING OCO-2 INTO ORBIT

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The method and terms used to design the target parameters that will be used to insert the Orbiting Carbon Observatory 2 (OCO-2) into the A-train are defined. Comparisons are made to the plan that would have been used had OCO-1 successfully achieved its Injection Orbit. Major differences arise from the fact that OCO-1 was launched on a Taurus XL with a target 65 km below the A-Train while OCO-2 will be launched on a Delta II with a target only 15 km below the A-Train. The new plan is similar to the one used for the CloudSat/CALIPSO missions, but reformulated into a one-step iteration process that is easier to understand.

INTRODUCTION

The Orbiting Carbon Observatory 2 (OCO-2) mission will make global measurements of column CO_2 concentration using a three-channel spectrometer. In "OCO-2" the suffix 2 refers to the fact that the previous attempt to fly an identical instrument on a similar satellite failed to reach orbit due to a launch vehicle malfunction. The Operational Orbit for each OCO mission corresponds to flying at the front of the A-Train Constellation, a series of satellites in sun-synchronous orbits with an equatorial altitude of 705 km and groundtracks that repeat in 16 days and 233 revolutions. One significant change to the Constellation in the time period between the OCO-1 launch and OCO-2 was the insertion of the Japanese (JAXA) satellite named GCOM-W1 in front of the previous lead satellite, NASA's Aqua, so now OCO-2 will fly directly in front of GCOM-W1 rather than Aqua.

The biggest change between the two versions of OCO will be the launch vehicle used to place the observatory (combination of satellite and instrument) into its Injection Orbit. For OCO-1 a Taurus XL was used, for OCO-2 a Delta II will be used. The Taurus used a solid last stage while the Delta uses a liquid one, thus permitting the Delta to be much more accurate in achieving its targeted injection parameters. The enhanced accuracy modifies the appropriate ascent plan to be used, as described below.

There are two main reasons an Injection Orbit is used rather than targeting directly to the Operation Orbit, namely Safety and Phasing. Safety can be thought of as not interfering with the satellites in the A-Train (or its sister constellation called the AM Constellation; the combination of the two constellations is called the "705-km Fleet"). For satellites with eccentricity vectors either librating around their frozen values or circulating around the Earth, there is a maximum eccen-

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tricity (e_{MAX}) when the argument of perigee is 90 degrees. To always maintain, for example, a 2 km buffer with respect to the nominal Fleet orbit, the injection orbit can be restricted to have a difference in semi-major axis Δsma with respect to the Fleet and an e_{MAX} such that:

$$\Delta sma - sma_F*(e_{MAX} - e_F) > 2 \text{ km}$$

where sma_F and e_F are the semi-major axis and eccentricity of the nominal, frozen Fleet orbit.

For the Taurus launch vehicle this restriction (plus some margin) dictated a semi-major axis (sma) equivalent to a 640-km equatorial altitude and being 65 km below the 705-km Fleet (i.e. Δsma = 65 km). However the Delta can target a near-frozen orbit with smaller semi-major axis dispersions, which allows a much higher target sma. The current design corresponds to a 690 km injection equatorial altitude, equivalent to 15 km below the 705-km Fleet.

Phasing refers to the amount of relative along-track motion required for the observatory to travel from its point of injection to the target assigned to it in the A-Train. Previous analysis (*Vincent & Salcedo*) explains why this target moves 202.5 degrees alongtrack per each daily launch opportunity, thus the amount of phasing required is launch-date dependent. For a launch to 640 km this phasing difference was not as important because the much shorter synodic period associated with a 65 km semi-major axis difference implied that OCO-1 would have passed many times under its target before doing the final insertion. However, as was the case for the CloudSat/CALIPSO ascent done in 2006 (*ibid*), from only 15 km below, the synodic period is such that either zero or one underpass must occur assuming a nominal time to do the initial check-out of the spacecraft and perform the orbit ascent maneuvers.

The two methods to do the injection and ascent that are relevant are discussed below. The first was used for the OCO-1 launch vehicle targeting and would have been used for its ascent. The other was used for CloudSat and CALIPSO (and the JAXA mission GCOM-W1). However when doing a comparison it is worth noting that the "end game" of the OCO-1 method is very similar to the method used by CloudSat/CALIPSO. Also there is more flexibility in the final location of OCO-2 than there was for CloudSat/CALIPSO. This leads to options for the timing of the launch for OCO-2. Timing of the maneuvers during the ascent and effect of launch vehicle dispersions for the nominal July 1 launch date will also be discussed.

DEFINITIONS

Virtual Satellites: In general, the purpose of defining virtual satellites is to be able to define the motion that a real satellite would experience if the effects of atmospheric drag were not present. Since the satellites in the 705-km Fleet are "constellation flying," these drag effects are compensated by Drag Make-Up (DMU) maneuvers so the motion of the virtual satellites can be thought of as averaging out the decrease in semi-major axis due to drag and the DMU maneuvers. However as the next four subsections indicate there are some nuances in defining different types of virtual satellites.

Reference (Groundtrack) Virtual Satellites: This was the origin of the idea of virtual satellites and is described in detail by the "Triad" in *Vincent 2012b*. Briefly, of the three quantities:

- Mean Local Time of Ascending Node (MLTAN) of a virtual satellites (which is the same as the MLTAN of the corresponding real satellite)
- The Reference Ground Track (RGT) used, and
- The alongtrack position of a virtual satellite in its orbit

only two of them are independent. One aspect of this concept is that the time difference between the real and virtual satellites crossing the equator is directly proportional to the groundtrack de-

viation from the RGT measured along the equator, sometimes called the Ground Track Error (GTE), which is typically limited due to science measurement requirements.

Phasing Virtual Satellites: One aspect of the above definition is that as the MLTAN changes, the motion of the Reference virtual satellite is altered. Satellites flying in constellations usually have a small range of MLTAN that they are allowed to fly in. Because of this, Inclination Adjustment Maneuvers (IAM) are required to counteract the luni-solar precession that perturbs pure sun-synchronous flying (see *Vincent 2008*). Satellites in the A-Train coordinate their IAM to occur near the Vernal equinox. Even with perfectly executed IAM, there are differential effects which cause the difference in MLTAN between the reference Aqua and other satellites in the A-Train to drift small amounts. But the control boxes used to define the acceptable alongtrack motion of the satellites are referenced to Reference Virtual Aqua. Specifically the Phasing Virtual Satellite corresponding to the center of these control boxes is defined both by its RGT and an agreed-upon fixed MLTAN difference with respect to Aqua, not the actual difference. The agreed-upon value often comes from the predefined amount of buffer required between adjacent satellites. Thus all Reference virtual satellites (except for Aqua) can be slightly ahead or behind their corresponding Phasing virtual satellites. Although this difference is usually limited to a few seconds, there are nevertheless a couple of operational implications: a) when the two types of virtual satellites drift apart, the DMU is designed taking into account that the alongtrack control box has shrunk the same number of seconds and b) often the metric used during operations is the GTE, however this effect implies that the MLTAN should also be monitored and if necessary an inclination tweak be done to drift back closer to the nominal MLTAN difference.

Mean (aka Circular) Virtual Satellites: The "Mean" here refers to using the Mean Anomaly to describe the virtual satellite's alongtrack position which is equivalent to a satellite in a circular orbit. Quite often this is a good enough approximation, however as described in the next paragraph, its applicability actually is a function of the definition of the RGT.

True (aka Elliptical) Virtual Satellites: In this case "True" refers to using the True Anomaly to describe the virtual satellite's alongtrack position. The World Reference System 2 (WRS-2) used by the 705-km Fleet is defined at the descending nodes, though they are evenly spaced implying that the tesseral effect of the gravity field (which would move the nodes east or west a few hundred meters) have not been included. The A-Train members decided to define the ascending nodes as if a satellite was in a two-body orbit with frozen eccentricity and argument of perigee. Since the latter is 90 degrees, the time to go from descending to ascending nodes is about 4 seconds (2968.75 vs. 2964.30) longer than going from ascending to descending. In terms of longitude this means the defined ascending nodes are 1.86 km (equivalent to 4 seconds of Earth's rotation) to the west of the mid-point of the descending nodes. True virtual satellites follow the RGT corresponding to these definitions of descending and ascending nodes (i.e. the tesseral effects are still ignored, at least for the 705-km Fleet application).

PREDICTING THE STATE OF THE AQUA REFERENCE

Virtual Aqua is the anchor of the A-Train and in essence the anchor for the AM Constellation (the latter agreement is in the process of being ratified). Thus, the first step in determining where OCO-2 will be flying and subsequently where to target the launch vehicle, is predicting where Aqua will be on the launch date of interest. The discussion in the previous sections suggests that the sma, eccentricity, inclination and argument of perigee of all the virtual satellites are predetermined. Actually the sma is adjusted slightly because of the motion of the MLTAN (see *Vincent 2008*) but the only time this small difference needs to be considered is during the final insertion

into the Operational Orbit and even then it may be small compared to the execution error of that maneuver.

The choice of injection target inclination warrants more explanation. As mentioned earlier, the inclination of the A-Train is decreased by the luni-solar gravitational perturbation (for the AM Constellation the opposite is true see *Vincent 2012b* for an explanation) which is compensated for by IAM in the Spring. Predicting the inclination of Aqua is therefore just choosing the value from the corresponding saw-tooth pattern. After some relatively large adjustments by Aqua, this pattern has settled down to being close to being repetitive, with the small variation in the size of the IAM being announced years in advance by the Aqua Team. Finally, since the A-Train members attempt to synchronize their inclinations, the value used for the OCO-2 target is the same as the predicted value for Aqua. As a side note, the fact that the inclination and thus the groundtrack anywhere but the equator is allowed to vary in the described manner is because the WRS groundtrack is only defined at the nodes (though the associated WRS cells used for scientific cataloguing do assume the nominal sun-synchronous inclination value).

The prediction of the Aqua MLTAN is similarly tied to the predicted annual IAM and the subsequent parabolic motions caused by the luni-solar perturbation. Of interest is the fact that the Solid Earth Tides have a significant effect on the propagation of the MLTAN values (see *McKinley 2005*). The MLTAN of the OCO-2 Operational Orbit has a relationship to the Aqua MLTAN but is, in general, not the same. This relationship and how it corresponds to a launch target MLTAN will be discussed later.

The combination of Virtual Aqua flying the WRS nodes and the prediction of its MLTAN determine its alongtrack position. In other words, when Virtual Aqua is on the equator it is at the longitude of one of the WRS nodes. This actually implies that there are 16 places it could be for a given MLTAN (*Vincent 2003*) but of course knowing where the real Aqua is determines which of these 16 possibilities that Virtual Aqua is actually on. To change to a different position it would have to "jump to a different WRS path." This is not impossible, the Aura mission did this orbit modification, but there are no plans for Aqua to ever do this. The alongtrack position of Virtual Aqua therefore being known allows the relative alongtrack position of OCO-2 to be designed.

DEFINING THE OCO-2 OPERATIONAL ORBIT LIMITS

One of the first choices of where to fly OCO-2 is which reference groundtrack to use. This is driven by scientific reasons: in particular, how the OCO-2 measurements would benefit from overlap with measurements taken by other satellites (but note there are no formal requirements stating that OCO-2 needs these data) or *vice versa*. The three viable possibilities are: 1) the WRS-2 (matching the RGT of Aqua and GCOM-W1); 2) the RGT of the CALIPSO groundtrack (the current OCO-2 requirement) which is 215 km east of the WRS-2 at the equator or 3) the RGT of the CALIPSO lidar and CloudSat, another 2.3 km to the east of the RGT of the CALIPSO satellite (the proposed new requirement). Figure 1 is called a "snapshot" because the diagonal RGT's move to the right as the Earth rotates, while the satellites move vertically up the page. Figure 1 has updated the fourth figure of *Vincent 2012b* to include the CloudSat RGT (the rightmost dashed line). The decision had been made not to fly the WRS-2 (as OCO-1 would have done) so the rest of the analysis presented here will just include the latter two options.

Once the RGT has been chosen then choosing the alongtrack position is the same as choosing the MLTAN (via the Triad). OCO-1 was scheduled to fly in front of Aqua and after its failure, GCOM-W1 was placed about 3 minutes in front of Aqua. This still left room for OCO-2 to fly in front of GCOM-W1 without interfering with the tail of the AM Constellation (which is Terra, now that Landsat-5 has exited the Fleet).

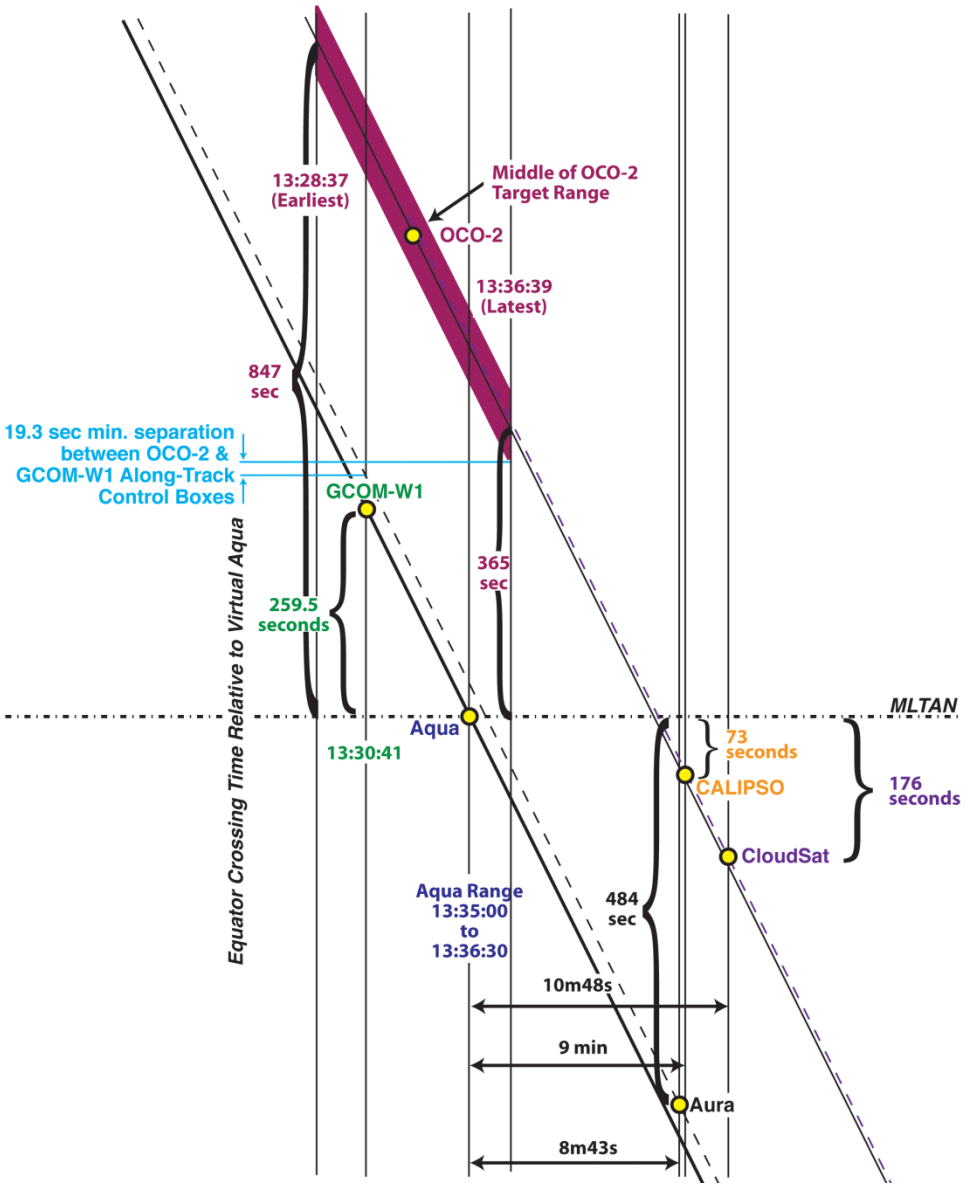

Figure 1. A "Snapshot" of the Relative Positions of the A-Train Members

The first half of *Vincent 2012a* explains the geometry involved in the crossing points of the orbits of any two members of the 705-km fleet. These two north and south crossing points represent the two places that the satellites can possibly collide (only when satellites have co-planar orbits can they collide at any point in their orbits). A spreadsheet was created that determines the MLTAN range that OCO-2 can be in to maintain a 15-second buffer both between OCO-2 and Terra and between OCO-2 and GCOM-W1 at these crossing points (equivalent to 19 seconds at the equator).

Since Terra is not synchronized with the A-Train, the worst-case (latest) MLTDN of Terra was used to produce fixed no-earlier-than OCO-2 MLTAN limits for both the CALIPSO and CloudSat RGT's. But GCOM-W1 will be synchronized along with the rest of the A-Train so the

no-later-than limits for OCO-2 were derived as the GCOM-W1 MLTAN plus a fixed offset, again for both the CALIPSO and CloudSat RGT's.

ASCENT METHODS

As mentioned in the Introduction there are two methods to do the injection and ascent. For OCO-1, the Mean Local Time of Ascending Node (MLTAN) of the Operational Orbit and the sun-synchronous inclination for the 640 km nominal launch altitude were chosen as launch targets. Thus the nominal ascent had to change both the semi-major axis and inclination during the initial phase of the ascent, either as closely linked pairs of burns or a combined maneuver (to maintain the sun-synchronicity and the desired MLTAN). That is, the so-called "combo maneuvers" would occur near the equator and have both an alongtrack and out-of-plane component. Then the "end game" consisted of first matching the inclination of the rest of the A-Train and then doing a pair of maneuvers to achieve the final semi-major axis and to shape the orbit eccentricity and argument of perigee to their frozen values, though some orbit-shaping could be done with the previous orbit raises by choosing where in the orbit they would occur (though to a limited amount if combo maneuvers near the equator were used).

For OCO-2 the plan will be similar to both the above end game and the method used to place CloudSat and CALIPSO into their A-Train slots. In this case the Operational Orbit inclination is targeted by the launch vehicle, as was the case for CloudSat/CALIPSO. Then the launch time can be moved earlier to account for the predetermined MLTAN drift during the ascent and thus place the satellite at the correct MLTAN upon arrival at the Operational Orbit. As explained in *Vincent 2003*, the amount of MLTAN drift is, to first order, directly proportional to the phasing between OCO-2 at separation from the launch vehicle and its final chosen spot in the A-Train (i.e. the center of its control box). In particular it is independent on the altitudes used for injection and during the ascent, with the important caveat that the phasing must account for the total in-plane angle traversed, including "Once Arounds" (OA) where OCO-2 passes underneath its target and has to travel another 360 degrees to be in the position to be inserted.

Before considering the off-nominal launches it is useful to compare the two ascent methods for perfect injections. The major advantage of the OCO-1 method (though noting that this method may never be used) is that if a satellite anomaly happens before or during the ascent, the MLTAN will stay close to the final target (luni-solar perturbations only causing a slow drift) since it will be at the sun-synchronous inclination value for the particular semi-major axis it happens to be at. Another advantage is that, down at a 620 km altitude orbit, the synodic period with respect to the target is relatively short (about 5 days) so predicting and accounting for the number of Once Arounds for different sma dispersions (discussed more below) would be complicated. The biggest disadvantage of this method is that for each ascent step it takes about the same amount of fuel to do an independent inclination change as it does to raise the sma. With combo maneuvers the efficiency is improves, but still results in sqrt(2) times the amount of fuel being used compared to if only sma raises were done, as is the case for the other ascent method. In addition, the pointing commands for combo burns are more complicated and, as mentioned previously have to be done near the equatorial nodes.

If the OCO-2 ascent method had been used following a Taurus launch vehicle injection, then the points made in the previous paragraph could be reversed. It uses less fuel and the maneuvers are easy to execute but there is an ambiguity in the number of Once Arounds and, to hit the same Operational Orbit MLTAN a different launch time has to be calculated for each day. It is important to emphasize that this comparison is somewhat moot for the Delta launch vehicle since the end of the OCO-1 ascent method is similar to the OCO-2 method.

For off-nominal launches, first consider the dispersions in sma, inclination and MLTAN. A low sma implies that the target will be reached in a shorter time, and for a high injection a longer time. This can mean on some launch days that a high or low injection can change the number of OA. But for the OCO-1 ascent method, a non-nominal sma implies that the injection orbit is not sun-synchronous (unless there happens to be a compensating inclination error of just the right size and direction). As studied extensively for the OCO-1 mission, the plan following an off-nominal launch was to maneuver back to the sun-synchronous line in sma/inclination space. Specifically, if the injected inclination was high, for the achieved sma to do sma-only increases and conversely if the inclination was low, with inclination-only maneuvers. During the time period while not on the sun-synchronous line, MLTAN drift error would be accumulating. So, in summary, for the Taurus launch, the OCO-2 method had complexities with Once Arounds while the OCO-1 method had to allow for additional accumulated MLTAN error and extra fuel being used.

Inclination errors affect both ascent methods in similar manners. Before the dispersion can be corrected back to the targeted value there will be MLTAN drift. In particular, this drift will occur during the check-out phase (that includes propulsion system calibrations) before the first large maneuver could be performed. In general, for the OCO-2 ascent plan there might be some launch days when there is a trade between doing the inclination correction as the first maneuver at the cost of missing the first opportunity to do an orbit raise and forcing a Once Around or accepting a little more possible MLTAN drift by doing the inclination correction after the first or second orbit raise. The last option brings up the question of pointing errors during a large inclination correction while inside the control box. That is, if the alongtrack error component of the inclination maneuver is much larger than, say a DMU, then the newly-arrived satellite might quickly exit its control box.

The MLTAN error imparted by the launch vehicle affects both ascent methods in the same manner and must be accounted for in a linear manner in the budget for the final MLTAN error incurred once in the Operational Orbit. Another factor that will not be discussed here is the introduction of a launch window. Suffice to say that the total extent of possible Injection Orbit MLTAN is a combination of the Right Ascension of Ascending Node error due to the launch vehicle and the range of launch times that might exist if a launch window is used.

Discussion about the dispersions in eccentricity and argument of perigee will be limited to a few qualitative observations. The Taurus launch vehicle did have large dispersions in these elements, however even with the combo burns limited to near the equator, the analysis showed that the orbit could be made to be roughly frozen on the way up and then frozen within operational limits with the final insertion maneuvers. The only exception might have been for an orbit which was both very high and very unfrozen, though in that case the fuel saved by having to do less orbit-raising which could be used for orbit shaping including an apogee lowering if necessary. The Delta launch vehicle is capable to launching to a near-frozen orbit, so no issues exist.

OBSERVATIONS AND THEORY LEADING TO RESULTS

Manipulating Aqua Data

Predicted Aqua data was supplied by the Aqua Team at the Goddard Space Flight Center. For this preliminary analysis it was obtained for July 1, 2014, the first possible launch date, in 5-minute intervals. The Aqua data came as Osculating elements in the EME2000 coordinate system, along with the Brouwer-Lydanne J2 (BLJ2) elements utilized by GSFC. The Osculating elements were converted to True of Date coordinates and then to the Mean elements corresponding to the full gravity field, in both cases with JPL software. Comparisons were made along the way

and were the subject of a separate analysis. Two of these results will be briefly described here since they are relevant to the OCO-2 targeting:

- MLTAN: Using Osculating elements at random points around the orbit gives a scatter of up to 2.5 seconds so is not very useful. BLJ2 removes some of the scatter but the full gravity field conversion is needed to see the MLTAN drift of about 0.5 seconds over a day corresponding to July 1 in the yearly MLTAN parabola. However, at the equatorial nodes the Osculating and Mean values are close to being the same. Note that Mean elements are used in Table 1 to define MLTAN.
- Inclination: Considering the (full-gravity) Mean elements in the True of Date coordinate system a comparison was made between removing and not removing the medium period terms (m times per day, the "m-daily terms" corresponding to the m order in an ℓ by m gravity field). There was a large signal at twice per day corresponding to the C_{22} and S_{22} gravity terms which needs to be removed to see the slow linear drift in inclination due to the luni-solar perturbation.

A simple parabolic model was used to extrapolate the Aqua MLTAN for the rest of July. For example, by the end of the month the change of MLTAN was reduced to closer to 0.3 seconds per day. This modeling will be checked against future deliveries from GSFC right up to the point of delivering the final OCO-2 targets so the best predictions will have been incorporated. This process is also used to update the inclination target.

As explained in the previous sections, the OCO-2 ascent method matches the inclination of Aqua and the rest of the A-train, both for injection and operations. And the nominal Mean semi-major axis, frozen eccentricity and argument of perigee for the 705-km are known. For the OCO-2 launch vehicle target, a Mean semi-major axis that is 15 km below this nominal value is used. And the frozen values of the Operational Orbit are used, even though at the injection orbit sma they are slightly different. The MLTAN targets were determined in a manner similar to Vincent and Salcedo but in one-step iteration rather than a closed formula. These five elements form the basis of the injection orbit design with the other two parameters (alongtrack position and time) left free for the design of the launch vehicle ascent. However since launch service providers prefer to deal with Osculating elements, a reference point of the ascending node closest to the separation of observatory and launch vehicle is used and the Mean target elements (which now include an implied Mean Anomaly) are converted to Osculating.

Relationship between MLTDN, East Longitude and UTC

With the east longitude of the WRS-2 node (λ_E) and the MLTAN of Aqua's orbit known, the Mean Local Time of the Prime Meridian (PM) is also known which is equivalent to UTC (ignoring things like UT1/UTC differences). So the time of the Descending Node (DN) is known. Adding 2968.75 seconds (corresponding to the southerly portion of a frozen orbit, ignoring the negligible amount of MLTAN drift) gives the time of the subsequent Ascending Node (AN) which will be used to calculate the phasing for this ascent analysis.

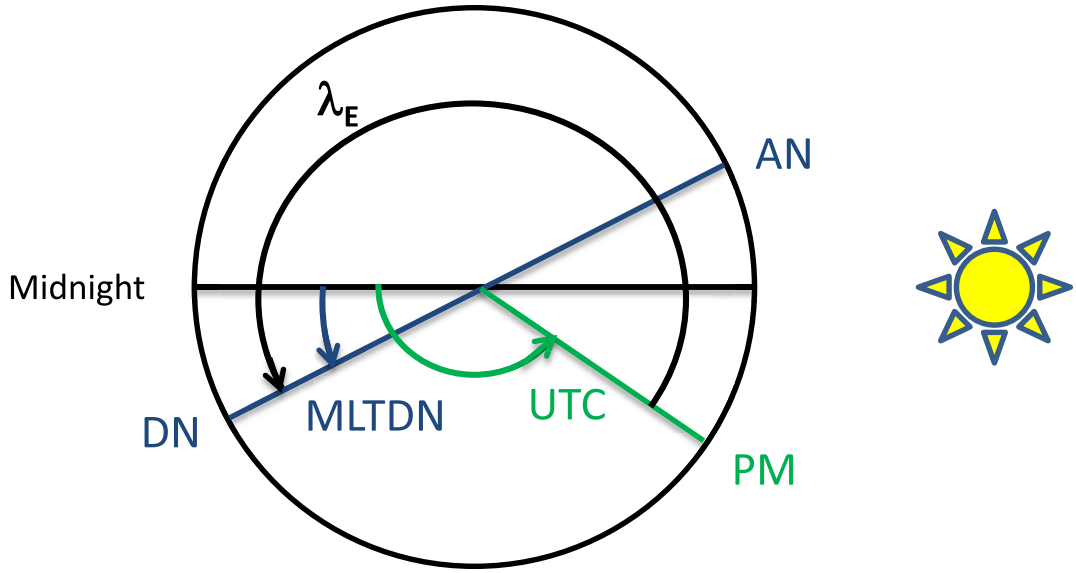

Figure 2. Relationship between MLTDN, DN East Longitude and UTC

Factors causing MLTAN Drift

If MLTANMAX is the maximum value for OCO-2, a number of additional quantities have to be subtracted; they will be represented by the formula below and described in the following text:

$$MLTAN_{TARGET} = MLTAN_{MAX} - XTRABUF - LVDISP - MLTDRIFT$$

XTRABUF is the extra buffer between OCO-2 and GCOM-W1 beyond the agreed upon 15 seconds. Since the science preference is to fly closer to the A-Train, this value is usually zero however as explained later, it can serve different purposes.

LVDISP is the combination of the pertinent dispersions caused by the launch vehicle. The direct one is the Right Ascension of Ascending Node dispersion at injection, which has an immediate effect on the MLTAN. The launch vehicle analysis results indicate that allocating 30 seconds for this direct effect is appropriate, including some margin. The indirect effect is that inclination errors imparted by the launch vehicle create a MLTAN drift (note this is different than the MLTDRIFT shown above) until an inclination correction maneuver is performed. Since the earliest this maneuver can be performed (due to spacecraft check-out including propulsion system calibration) is launch plus 10 days then the drift for 10 days must be included. Since the nodal precession (Ω') due to the dominating J_2 gravity term is proportional to cos(i) where i is the inclination, then the proportional change of precession rate due to an error in inclination is given by:

$$\Delta\Omega'/\Omega' = - \tan(i)\, \Delta i$$

and substituting: the nominal sun synchronous rate of 0.9856263 deg/day for Ω' and the nominal inclination of 98.2 deg. If the dispersion Δi is 0.05 deg, the current requirement defined for the launch vehicle Trajectory Feasibility Analysis (TFA), then the ΔΩ is 0.060 deg in 10 days, which is equivalent to 14.3 seconds in MLTAN. This quantity can be included in the LVDISP (though note the later discussion that if on certain launch dates there is a possibility that the inclination correction might be delayed beyond 10 days, extra buffer can be added). Again there is the contribution of having a launch window which is still a topic being discussed for OCO-2, so it won't be elaborated on here except to say that if the window opens earlier than the nominal value from

all other factors then it just adds extra buffer (and historically it is the most likely time to launch) but the end of the window must correspond to this nominal value (or conversely extra buffer must be added).

Finally what is depicted by MLTDRIFT is the aforementioned drift in MLTAN caused by the sma of the Injection Orbit being less than the Operational Orbit and is directly proportional to the phasing angle. From *Vincent and Salcedo* this value is 37.45 seconds for 360 degrees of phasing and can be scaled accordingly. An interesting observation that occurred during this OCO-2 analysis resulted from the fact that in the CloudSat/CALIPSO case there was no flexibility in the final value of MLTAN (at least within a second). Thus in the formula used in that analysis it was not evident that the amount of drift for a given launch date is independent of the chosen location of the target with respect to the Aqua target. Putting this in different words, if OCO-2 wants to fly closer to Aqua/GCOM-W1 by x seconds, say, then we launch x seconds later which means Virtual Aqua has moved x seconds alongtrack, but our Operational Orbit target has moved x seconds back alongtrack so the (Injection to Operational Orbit) phasing remains the same.

RESULTS

Explanation of the Table

A useful way to present the results is to describe the process in terms of block of rows in Table 1. Rows 1-5 start with the predetermined MLTAN of Aqua and determine the properties of the Descending Node (DN) of interest. This leads to Rows 6-8 depicting the PM and UTC times involved. Row 9 then switches to GCOM-W1 (GCW) and Rows 10-13 for the MLT of the final OCO-2 target in the Operational Orbit, first for the latest (max) value (assuming the CALIPSO RGT) and then for the adjusted value as described earlier (noting that for this row a fixed MLTDRIFT of 60 seconds was used). Using the known longitude of the DN (Row 14) the nodal times (Row 15 & 16) for this Ops target are calculated. From the TFA the relationship between the time of this node and the Injection target MLTAN is known and results in the value in Row 18. Rows 19-23 then depict the phasing between the injection point and the Ops target, first for no Once Arounds (OA) and then including an OA if appropriate. Whether an OA is appropriate can be discerned from Row 24, the number of days to reach the target, specifically considering that the case where it is 30 days would have been 8 days if an OA had not occurred. Row 25 gives the MLTAN drift during this period due to the sma difference which then results in the final MLTAN (ignoring the luni-solar effects that both orbits incur). Row 27 then gives the launch times if the analysis stopped here (that can be seen to slowly change at the 0.5 sec/day rate that the Aqua MLTAN is changing).

However the values in Row 25 can now be used instead of the fixed MLTDRIFT value and the whole process is iterated (It) as shown in Rows 28-38. As can be gathered (and is graphically shown in Figure 3), now the situation for Rows 37 & 38 is reversed from that of Rows 26 & 27. That is, now the final MLTAN varies slowly as Aqua's MLTAN changes while the launch times jump back and forth to account for the MLTAN drift during ascent due to the sma difference.

Table 1: RESULTS

Row	Date	1-July	2-July	3-July	4-July	17-July
1	Aqua MLTDN	01:35:26.0	01:35:25.5	01:35:25.0	01:35:24.5	01:35:18.7
2	Aqua DN Deg	23.85833	23.85626	23.85421	23.85219	23.82793
3	Path Diff		-9	7	-9	7
4	WRS Path	46	37	44	35	46
5	DN Long	225.87210	239.77768	228.96223	242.867806	225.87210
6	PM Angle @ DN	157.98624	144.07858	154.89199	140.984380	157.95583
7	UTC of DN	10:31:56.7	09:36:18.9	10:19:34.1	09:23:56.3	10:31:49.1
8	UTC of AN	11:21:25.4	10:25:47.6	11:09:02.8	10:13:25.0	11:21:18.1
9	GCW MLTAN	13:31:06.5	13:31:06.0	13:31:05.5	13:31:05.0	13:30:59.2
10	OC MLTAN Max	13:37:04.5	13:37:04.0	13:37:03.5	13:37:03.0	13:36:57.2
11	OC MLTAN Adj	13:35:04.5	13:35:04.0	13:35:03.5	13:35:03.0	13:34:57.2
12	OC MLTDN Adj	01:35:04.5	01:35:04.0	01:35:03.5	01:35:03.0	01:34:57.2
13	OCO DN Deg	23.76875	23.76668	23.76463	23.76260	23.73835
14	RGT DN Long	227.80348	241.70906	230.89361	244.79919	227.80348
15	OC PM DN	155.96527	142.05761	152.87102	138.96341	155.93486
16	UTC of DN	10:23:51.7	09:28:13.8	10:11:29.0	09:15:51.2	10:23:44.4
17	UTC of AN	11:13:20.4	10:17:42.6	11:00:57.8	10:05:20.0	11:13:13.1
18	Inj AN UTC	10:56:05.4	10:56:04.9	10:56:04.4	10:56:03.9	10:55:58.1
19	Phase sec	4898.0	2302.3	5639.7	3044.0	4898.0
20	Phase deg	297.2	139.7	342.2	184.7	297.2
21	No of OA	0	1	0	0	0
22	Adj Phase	4898.0	8235.4	5639.7	3044.0	4898.0
23	Adj deg	297.2	499.7	342.2	184.7	297.2
24	Days	17.8	30.0	20.5	11.1	17.8
25	Drift sec	30.9	52.0	35.6	19.2	30.9
26	Result MLTAN	13:35:35.4	13:35:56.0	13:35:39.1	13:35:22.2	13:35:28.1
27	Launch UTC	09:55:48.2	09:55:47.7	09:55:47.3	09:55:46.8	09:55:40.9
28	It AN Adj	13:35:33.6	13:35:12.0	13:35:27.9	13:35:43.8	13:35:26.3
29	It DN Deg	23.88993	23.80008	23.86630	23.93255	23.85953
30	It Pr Mer DN	156.08645	142.09102	152.97269	139.13335	156.05604
31	It UTC of AN	11:13:49.5	10:17:50.6	11:01:22.2	10:06:00.8	11:13:42.2
32	It inj AN UTC	10:56:34.5	10:56:12.9	10:56:28.8	10:56:44.7	10:56:27.2
33	It Adj Pha	4898.0	8235.4	5639.7	3044.0	4898.0
34	It Adj deg	297.2	499.7	342.2	184.7	297.2
35	It Days	17.8	30.0	20.5	11.1	17.8
36	It Drift sec	30.9	52.0	35.6	19.2	30.9
37	It Result MLTAN	13:36:04.5	13:36:04.0	13:36:03.5	13:36:03.0	13:35:57.2
38	It Launch UTC	09:56:17.3	09:55:55.8	09:56:11.7	09:56:27.6	09:56:10.0

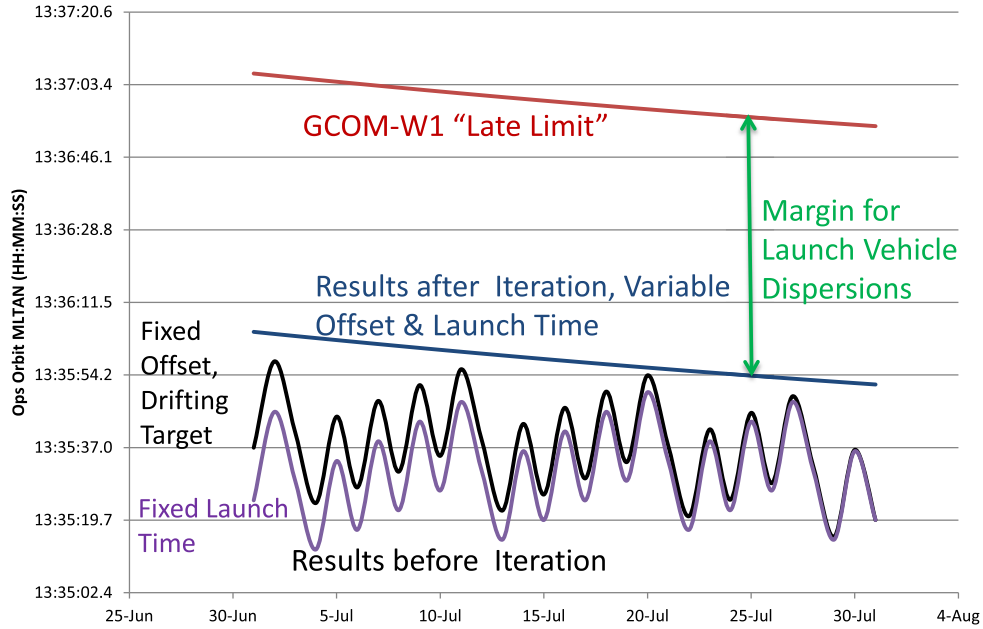

Figure 3. Choices for Final Operational Orbit MLTAN

The "Fixed Launch Time" curve reflects choosing the launch time for July 31 for all launch dates which results in extra separation from the limit for all the previous launch dates. In summary, the coordinated colors in Figure 3 and 4 indicate constant launch times imply variable MLTAN values and *vice versa*.

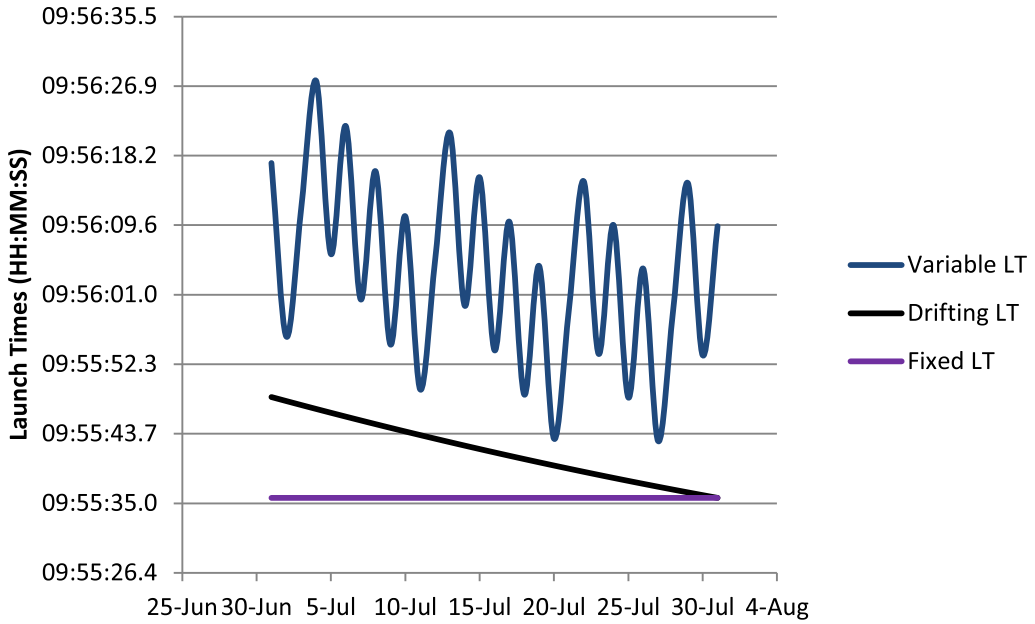

Figure 4. Launch Times for Different Strategies

EFFECTS OF LAUNCH VEHICLE DISPERSIONS

As was done in *Vincent 2005*, tables will be created in the future to represent the results of studying how the dispersion in semi-major axis (and to a lesser degree, inclination) imparted by the launch vehicle affect the timing and general overall design of the ascent. In this paper only the results for the nominal launch date of July 1 will be presented as an example. Specifically we will consider 3-sigma high and low dispersions in semi-major axis with and without a needed correction to an inclination dispersion.

For the 3-sigma sma dispersion, the TFA limits of +/-5 km will be used. For a 3-sigma high value the procedure is straightforward. Since the time to achieve the target is close to being linearly related in the inverse difference in values in sma between the injection and operational orbits, the value of 17.8 days shown in Table 1 for the nominal difference of 15 km can be scaled by 15/10 to get the longer time of 26.7 days. This cause no problems with Operations (except perhaps, for waiting!) and any inclination errors can be corrected as soon as possible, nominally 10 days from launch.

The 3-sigma low injection is more interesting. In this case the time to the target is 15/20 * 17.8 = 13.4 days. This makes a full, but still viable schedule. Here is an example schedule: on the day that starts at L+ 10, any inclination dispersion is corrected. Then if 5 km below the A-Train is chosen as an intermediate orbit (this was the value used for CloudSat, though OCO-2 will have some flexibility in this choice) then doing the first orbit raise on L+ 12.9 slows the approach to the target by a factor of 4 (i.e. from the ratio 5/20). Thus the second orbit raise will occur at L+ 14.9, thus preserving the operational rule of having two days between maneuvers. Note that these two orbit raises will probably consist of two burns each separated by an orbit and a half with the location in the orbit (and thus exact timing) of all 4 burns used to shape the orbit. There is software at both the Orbital Sciences Corporation (where operations occur) and the Jet Propulsion Lab (for verification purposes) to perform the optimization of the size and timing of these burns.

On other launch dates (see *Vincent 2005*) there is the possibility that a low insertion would necessitate adding an OA, or for a more marginal case, doing the inclination correction between or even after the orbit raises. In the CloudSat/CALIPSO case these were called "non-preferred launch dates," however both of these projects agreed to launch on them if needed (the actual launch was not on one of these days). The conservative approach in these cases is to assume the OA and accept the longer time for operations to start. However, it is a judgment call; for example, say the 3-sigma low sma case is the one that would entail the OA, then the launch inclination and MLTAN errors would also have to contribute in the "later MLTAN" direction, otherwise the final MLTAN would still be in the expected range. For OCO-2 adding extra buffer and making the MLTAN target/launch time earlier would further allow for the extra 37.45 seconds from going OA with the cost just being slightly further ahead of GCOM-W1 for the nominal (no OA) case.

CONCLUSIONS

Although all the final orbit choices have not been made for OCO-2, this paper provides a framework on how to make those decisions. In particular, the distance in front of GCOM-W1 and the rest of the A-Train could be minimized while still allowing for all launch vehicle dispersions. Alternatively, the launch times for each launch date could vary in a slow manner as the Aqua reference MLTAN drifts or the launch times could be made the same for the entire July launch period. The previously-used method of calculating the MLTAN drift during the ascent and adjusting the launch time accordingly was replaced by an easier-to-understand single iteration in a spreadsheet. This led to the realization that the amount of MLTAN drift was independent of the distance chosen for OCO-2 to fly ahead of GCOM-W1.

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