ASCENT PLAN FOR AQUA (EOS-PM1) INCLUDING PHASING WITH TERRA (EOS-AM1)

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ABSTRACT – *Aqua is the lead satellite in NASA's Earth Observing System's PM constellation. Since Aqua will be launched into an orbit 25-km lower than its operational orbit, it will be necessary to perform a series of ascent burns to raise its orbit. The ascent burns must be performed so that the orbit meets a number of mission and operational constraints. Mission constraints include altitude and frozen orbit constraints, ground track error constraints, and phasing constraints. Operational constraints include performing burns within TDRSS contacts and having adequate planning time between maneuvers. An automated process has been developed to calculate these ascent burns using a combination of optimization routines in a bootstrapping fashion. Nominal ascent plans have been developed, for each of 16 launch dates, consisting of 6 burns over a 38-day period.*

KEYWORDS: Aqua, Terra, EOS, Optimization, Phasing, Ascent, SQP, Simplex Method

INTRODUCTION

Aqua is the second spacecraft in NASA's Earth Observing System (EOS) and the lead satellite in the PM constellation. The primary science objectives of the Aqua mission are to gather data pertaining to atmospheric radiation, cloud formation, atmospheric temperatures and humidities, precipitation, radiative balance, terrestrial snow, sea ice, sea-surface temperatures and ocean productivity. The PM constellation, made up of Aqua, Aura, CloudSat, and ESSP-3 will compliment the AM constellation made up of Terra, Landsat-7, EO-1, and SAC-C. Aqua will carry six science gathering instruments into orbit. These instruments consist of the Advanced Microwave Scanning Radiometer-EOS (AMSR-E), the Atmospheric Infrared Sounder (AIRS), the Advanced Microwave Sounding Unit (AMSU-A), the Moderate Resolution Imaging Spectroradiometer (MODIS), the Clouds and Earth Radiate Energy System (CERES), and the Humidity Sounder for Brazil (HSB). Aqua's nominal mission duration is currently 6 years.

Equatorial Altitude	705 km
Semi-Major Axis	7077.8 km
Inclination	98.2°
Mean Local Time	$13:30 \pm 00:15$ (Ascending Node)
Eccentricity	0.0012 ± 0.0004
Argument of Perigee	90 ± 20
Ground Track Error	± 20 km
Orbit Repeat Cycle	16 days (WRS-2)
Beta Angle	$24 \pm 8°$, (limits MLT to 13:30-13:45)

Table 1: Aqua Nominal Orbit

MISSION REQUIREMENTS

Aqua's will maintain a nominal 705-km altitude Sun-synchronous orbit with an inclination of 98.2° and a mean local time (MLT) at the ascending node of 13:30. Aqua's ground track will follow the WRS-2 grid and will repeat every 16 days. Details of Aqua's nominal mission orbit are listed in Table 1.

Aqua will maintain its ground track relative to the WRS-2 grid to within ±20-km with regular drag make-up burns and maintain its mean local time range with periodic inclination adjustments. Aqua's propulsion system consists of a standard mono-propellant hydrazine blowdown arrangement feeding four redundant pairs of 1.0 lbf thrusters aligned generally in the -X direction. These are used for both velocity change and attitude control as required. See Figure 1 for a diagram of the spacecraft.

Aqua will be launched on a Boeing Delta II 7920-10 from Vandenberg AFB, California into an orbit which will initially have an altitude of 680-km at the equator. This initially low altitude will necessitate a gradual ascent to mission orbit. It is this ascent period to mission orbit which will allow Aqua to meet its requirement to phase with Terra and the AM constellation in addition to reaching its mission orbit. This phasing requirement is what drove the ascent planning work that is described below.

PHASING REQUIREMENTS

The Aqua mission orbit requirements are very straight forward and could easily be accomplished by a simple ascent to achieve the proper semi-major axis, ground track, and frozen orbit conditions. However, in addition to the orbit requirements discussed so far, Aqua also has a requirement to 'phase' with several spacecraft currently flying in very similar orbits. Phasing is used to describe the precise placement of Aqua with respect to several other polar orbiting spacecraft, all in similar repeating ground track, Sun-synchronous orbits. Phasing is necessary to avoid ground station conflicts between members of the AM and PM constellations.

The Earth Science Mission Operations (ESMO) Project at Goddard Space Flight Center currently oversees the operations of several of the Earth Observing spacecraft, all operating in what is essentially the same polar, Sun-synchronous orbit, though in different orbit planes.

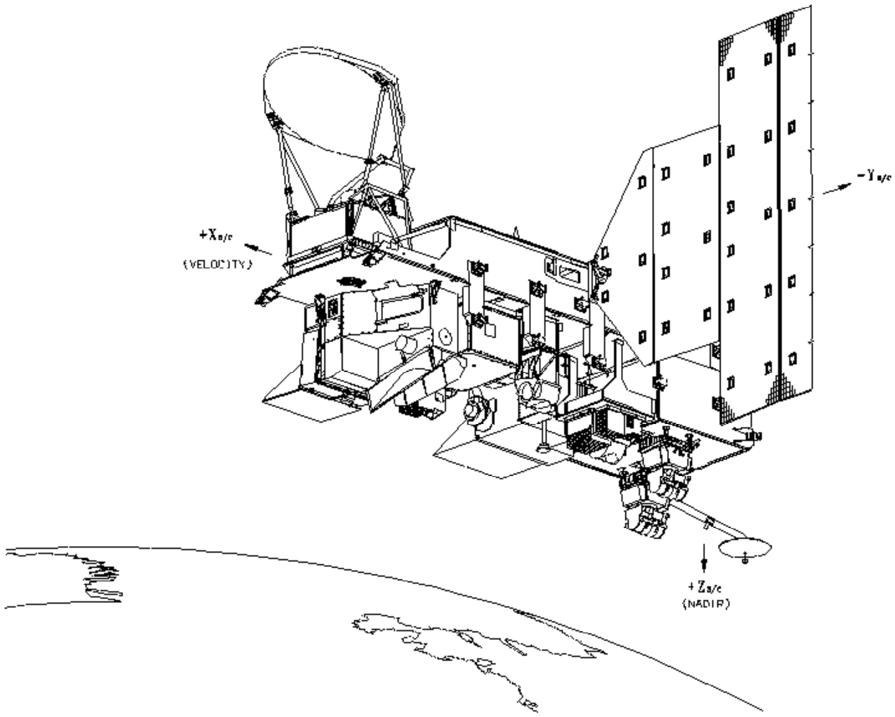

Figure 1: EOS-AM1 Aqua Spacecraft

The Landsat-7, Terra, and EO-1 missions are flying in formation, imaging the same scenes, in the mean local time (MLT) range of 10:00 a.m. to 10:40 a.m., measured at the descending node. This group of spacecraft is known as the AM Constellation, due to their morning mean local time crossing. Two ground stations located in the northern latitudes support these polar orbiting spacecraft and at least one station provides visibility of each spacecraft on every orbit pass. These ground stations, located in Svalbard, Norway, and Fairbanks, Alaska, and their support networks are known as the Polar Ground Network (PGN), and were developed specifically to support the polar orbiting Earth observing spacecraft. SAC-C, the Argentine sponsored member of the AM Constellation, does not use the resources of the PGN.

In planning for the arrival, on orbit, of the Aqua spacecraft, ESMO personnel recognized the possibility of conflicts at the tracking stations due to overlapping contacts between the Aqua spacecraft and the AM Constellation spacecraft. The Aqua spacecraft is to be the first spacecraft in what is known as the PM Constellation. The PM refers to the fact that Aqua will image the Earth from a Sun-synchronous orbit with an ascending node mean local time of 1:30 p.m. There are also plans for least four additional spacecraft, including Aura, CloudSat, and ESSP-3, to fly in formation with Aqua. Figure 2 illustrates the nature of the relationship between the AM and PM Constellation orbits at the poles. The red area shows the region of visibility from Svalbard, Norway.

In this illustration, the two spacecraft pass over the North Pole at separate times, however, unless Aqua is purposely placed in this manner, this will most likely not be the case. For any given Aqua launch date, the relative position between Aqua and the orbiting AM Constellation spacecraft varies. Before the phasing approach was implemented, three-

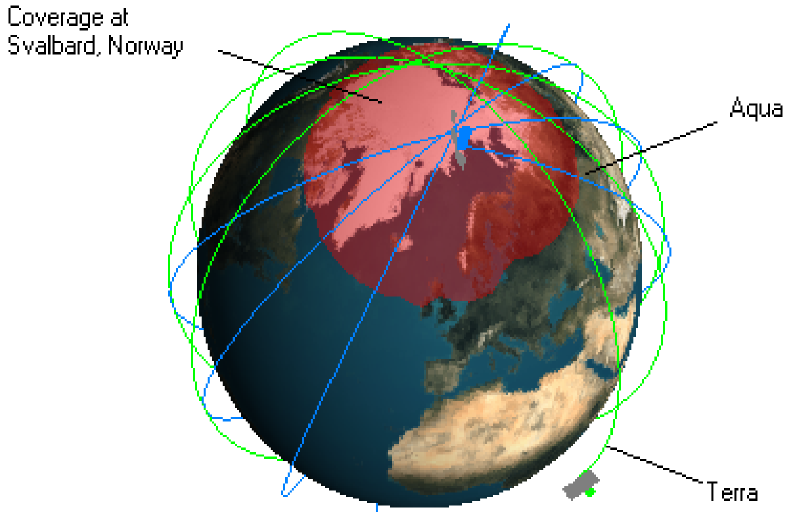

Figure 2: AM and PM Orbits over Svalbard, Norway

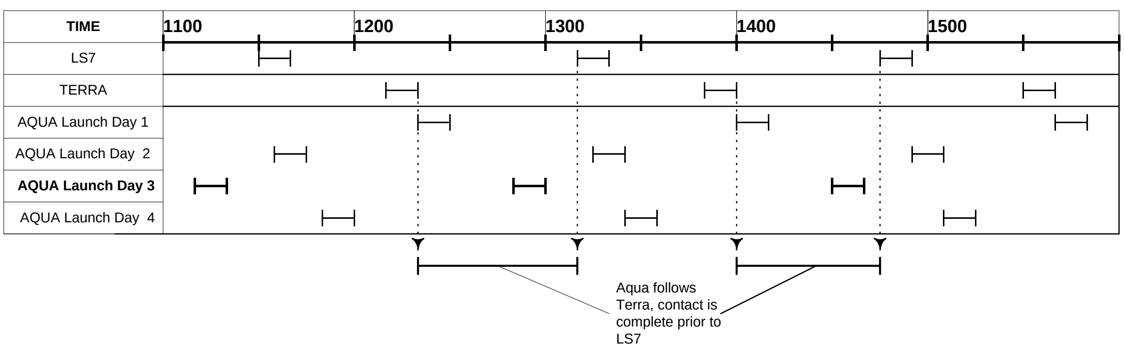

Figure 3: Variations in the Contact Times between Aqua and Terra without Phasing

fourths of the post-launch mission orbits for (12 out of a possible 16, because of the 16-day repeat cycle of the orbits) resulted in either overlapping contacts or contacts with very close spacing. Figure 3 shows the station contact times for Landsat-7, Terra, and Aqua at Svalbard for four Aqua launch dates. Of these four, only one, Day 3 in the figure, produced a desirable spacing. It was clear that the only way to ensure that are no conflicts at the ground stations is to purposely place Aqua in orbit such that these overlaps were avoided, or phase Aqua with respect to the AM Constellation.

It is important that Aqua have available to it every possible ground station pass. Aqua requires one pass per orbit to down load a high volume of science data. The Aqua science data latency requirement is just 3 hours, and even just one missed pass requires approximately 5 orbits to recover, limited by the duration of the passes and the solid state recorder capacity. This violates the 3-hour requirement. Phasing Aqua also has the added benefit of reducing radio frequency interference (RFI) between the PGN users, and eliminating close approaches between the spacecraft over the poles, as their orbit planes intersect.

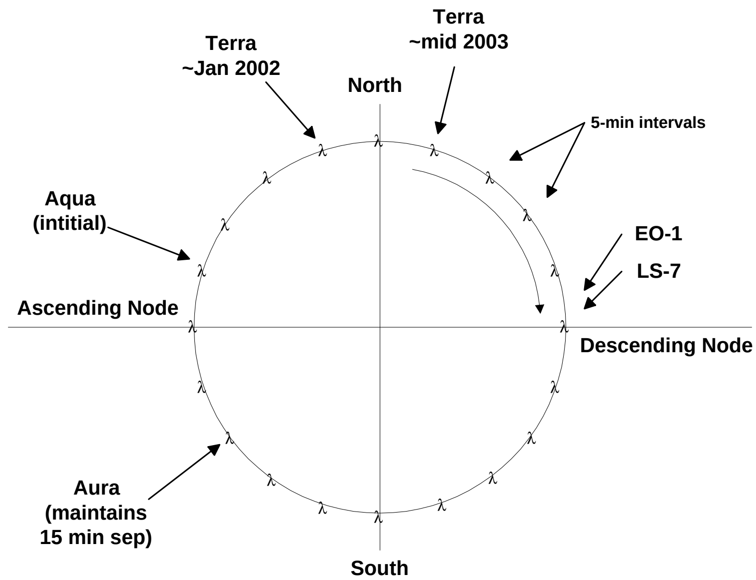

Figure 4: Relative Spacing Options

Once it was decided that phasing was required for Aqua, the question remained, where was the optimal location to place Aqua with respect to the AM Constellation spacecraft, taking into account where the spacecraft are currently located, where they will be located during the Aqua mission lifetime, and where the later members of the PM Constellation are to be located. Figure 4 illustrates the relative spacing options in the two orbit planes between the spacecraft in both the AM and PM Constellations using a simple 2-dimensional sketch.

The circle represents the approximately 100-minute orbital period, with the tick marks representing 5-minute intervals. Using Landsat-7 and EO-1 (EO-1 trails Landsat-7 by just one minute) as the starting points as they cross their descending nodes, it can be seen that Terra will trail these two by around 30 minutes in January 2002. The gap between Terra and Landsat-7 is currently closing, as Terra drifts towards an earlier mean local time (the time between the spacecraft is directly proportional to the mean local time difference because both spacecraft are on identical ground tracks). The planned mean local time operating range for Terra is not certain at this time. Options are being considered for maintaining Terra near 10:30 a.m., or near 10:15 a.m. Once decided, the Terra mean local time will be maintained in the chosen range with inclination adjust maneuvers. Landsat-7 will continue to operate in the 10:00 a.m. to 10:05 a.m. range.

The current planned target phasing time for Aqua is 18 minutes. This is based on a December, 2001, Aqua launch and the current and predicted Terra and Landsat-7 mean local time profiles (assumes Terra is maintained between 10:15 a.m. to 10:20 a.m.). The 18-minute time difference allows for sufficient spacing between the spacecraft for non-interfering ground contacts. This location satisfies both the immediate requirement and the long-term requirement, as the Aqua and Terra mean local times drift in their relative directions. This location also allows the maximum amount of space behind Aqua, for the other members of the PM Constellation. The final choice for the initial phasing time will depend on the chosen Terra mean local time maintenance plan.

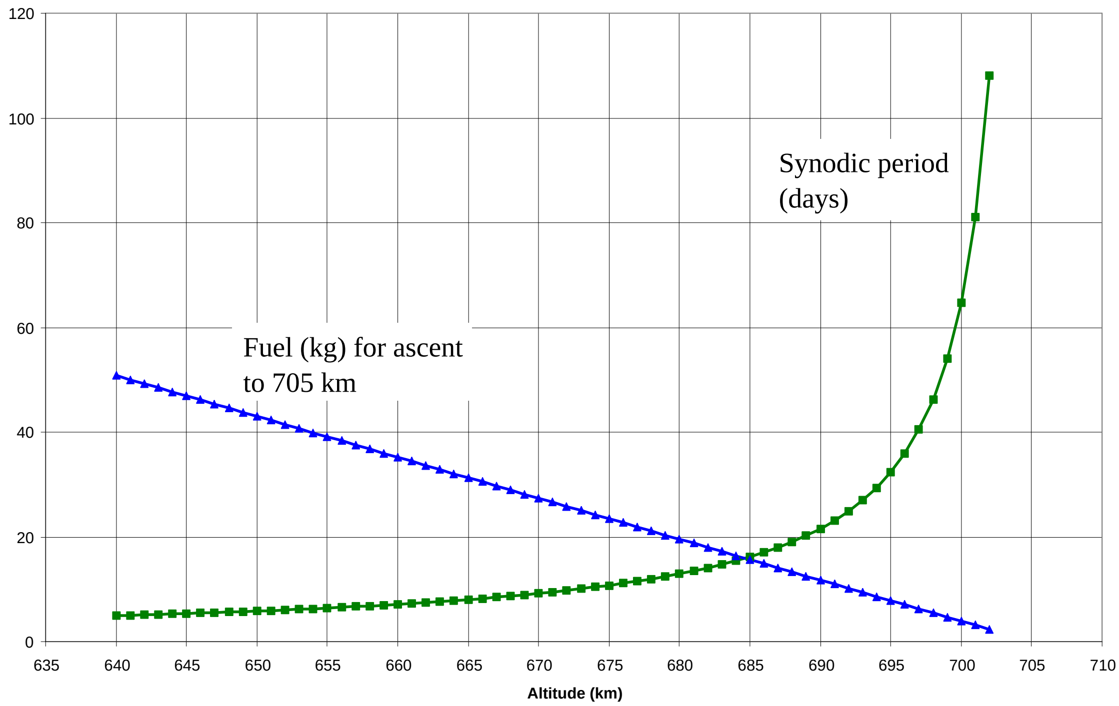

Figure 5: Synodic Period and Fuel Requirements for Phasing

Updates to Aqua Injection Orbit for Phasing

When the phasing requirement was levied on the mission, several mission design factors had to be examined. The pre-phasing injection orbit was just 10-km below the nominal, at 695-km, allowing for only a large enough margin to account for launch dispersions so that retro-grade maneuvers were avoided. With the prospect of phasing, this had to be re-examined.

In order for Aqua to achieve a desired phasing with respect to Terra, Aqua needs to achieve a specific phase angle with respect to Terra. The synodic period is the time required for any phase angle to repeat itself, and is a function of the altitude difference between the two spacecraft. The greater the difference in altitude, the shorter the synodic period. A shorter period means that there are more frequent opportunities to achieve the desired formation. Of course there is a trade-off in the fuel required for the additional altitude increase required. The plot in Figure 5 shows the synodic period and fuel required as a function of the altitude. On the x-axis is the altitude, in km, and on the y are both the fuel required, in kg, for the ascent to 705-km and the synodic period, in days between the two orbits.

Without altering the injection state, the only way to attain the proper phase angle with respect to Terra would be to either limit the launch date, or launch any date, but assume a more lengthy time period until mission orbit is reached. From the plot it can be seen that from the original 695-km Aqua injection orbit, the synodic period is approximately 32 days. This translates to an opportunity for phasing the two spacecraft every 32 days. This time period, combined a fixed 7-day time period prior to an ascent start and the time required to complete to 4 burns (approximately 7 days), pushed the maximum time to achieve mission orbit to 46 days. If the altitude were lowered, then this period can be shortened, however, the fuel costs then go up. The Aqua Project personnel sought a solution that would allow Aqua to launch any date, and permit a shorter time to achieve mission orbit. The fuel increase was not a large consideration for Aqua, as the mission is very fuel rich. The possible options were examined, and the decision was made to inject Aqua into a 680-km orbit with a synodic period of 13 days that would use an additional 16-kg of fuel.

One additional adjustment was made to the Aqua injection orbit. Aqua has a 10-minute launch window, timed to achieve an initial mean local time at the ascending node of 1:35 p.m. to 1:45 p.m. This range was chosen, along with the initial inclination, to maximize usage of the entire mean local time range with minimal inclination adjustments. However, both the inclination and semi-major axis affect the mean local time drift. The new, lower, 680-km injection orbit caused the mean local time to drift in the later direction. For a launch at the end of the window, this would result in a violation of the mean local time range almost immediately after launch. To mitigate this, the launch window was shifted by one minute, to produce a 1:34 p.m. to 1:44 p.m. initial mean local time.

ASCENT OVERVIEW

With the mission orbit and phasing requirements now defined, and the maneuver constraints well understood, the Aqua ascent plan could be designed and developed. A baseline ascent sequence was computed for each of 16 consecutive launch dates using the nominal prelaunch injection orbit, based on a launch at the beginning of the launch window. Because of the 16-day / 233 orbit repeat cycle of these orbits, there are 16 different initial phasing relationships, and 16 different solutions for the ascent. All solutions must satisfy the orbit, phasing, and spacecraft requirements and constraints. To recap, here are the orbit, phasing, and spacecraft requirements:

Orbit

- Equatorial altitude of 705-km
- Frozen orbit mean argument of perigee of $90 \pm 20°$
- Frozen mean eccentricity of 0.0012 ± 0.0004
- WRS grid at the descending node, within ±20-km

Phasing

- Follow Terra by 15-20 minutes, measured at the descending node crossing

Spacecraft

- Thruster duty cycle of 0.91 used for all thrusters
- Propulsion system modeled in full blowdown mode for determining thrust and Isp levels

In addition to the mission orbit, phasing, and spacecraft requirements, the Aqua ascent plan has to satisfy these additional operational requirements:

Operational

- Execute a short 30-second engineering burn on mission day 5
- Begin ascent burns no earlier than mission day 7
- Use a minimum of 1 day between burns for ease of operations, however, 2 days are used where possible
- Schedule burns in the prime shift (1300 - 2200 GMT), if possible
- Assume zenith omni half-angle of 86° when calculating TDRSS contacts (maximum pass duration of 40 minutes)
- Begin the burns no earlier that 15 minutes following acquisition of signal (AOS)
- End the burn within 2 minutes of the loss of signal (LOS)

With the addition of these operational requirements, especially the contact time requirement, planning the Aqua ascent becomes much more complicated. To compute a set of maneuvers that simultaneously satisfies this large set of requirements is tedious, to say the least. So an automated targeting scheme was developed, using FreeFlyer and MatLab, to compute the ascent sequences.

ASCENT TARGETING

The goal of the Aqua ascent targeting is to find a sequence of maneuvers that raises the orbit from the injection altitude (680-km) to the operational altitude (705-km). This raising must be done in such a way so that both the mission constraints and operational constraints are met. The mission constraints include the frozen orbit conditions, the WRS-2 grid requirement and the requirement of phasing with Terra. Operational constraints include performing the burns within TDRSS contacts, performing the burns at least 2 days apart, and limiting the burns to no more than 15 minutes duration. Limiting the burns to under 15 minutes duration requires performing 6 burns to raise the orbit from 680-km to 705-km altitude. In order to facilitate the calculation of a six burn ascent for each of 16 possible launch days, it was desired to automate the process as much as possible. This automation was made possible by using the optimization routines available in MatLab in conjunction with the dynamic modeling and scripting capabilities of FreeFlyer.

The use of FreeFlyer and its unique scripting capabilities simplifies the calculation of the ascent plan by allowing much of the orbital dynamics to be separated from the optimization. This allows the ascent to phrased as a parameter optimization problem where the parameters to be optimized are the time interval between burns. The FreeFlyer scripts used are set up so that Aqua achieves its nominal mission altitude after performing maneuvers at the desired intervals. The other parameters of interest, phasing, ground track error, eccentricity vector, and location of burns relative to TDRSS contacts, are seen by the optimizer simply as functions of the maneuver intervals.

The amount of ΔV required for the ascent depends primarily on the amount Aqua orbit must be raised rather than the location of the burns. So instead of trying to minimize the amount of fuel used, the purpose of the optimization performed was to find a maneuver sequence that satisfies all the constraints. There is however, some difficulty in defining an

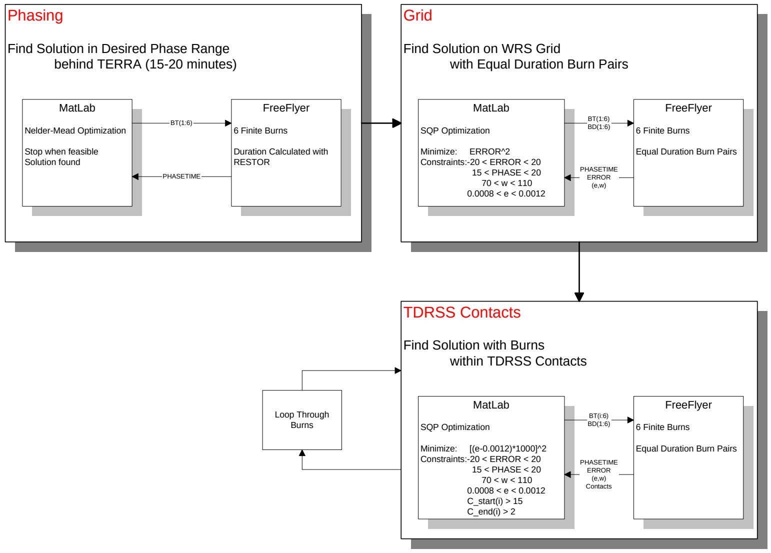

Figure 6: Three Stage Ascent Targetting

optimization problem that will converge to the desired solution in the presence of a large number of non-linear constraints. To over come this problem, the Aqua ascent targeting was broken down into several sub-problems. The solution to each sub-problem could then be used to move the solution of the next sub-problem closer to the solution of the overall problem.

This bootstrapping approach consists of three stages, outlined in Figure 6. The first stage finds the burn duration and burn interval necessary to meet the phasing requirement. The second stage adjusts the spacing of the burns so that the ground track requirement is satisfied at the completion of the ascent. The third stage further refines the maneuver interval so that the each of the burns occur within TDRSS contacts.

Stage One: Phasing

The purpose of the first stage of the ascent targeting was to find a sequence of maneuvers that would meet the phasing requirement of being 15-20 minutes behind Terra. To do this, an optimization method that could explore a wide region of the search space without becoming bogged down in the regions of local minima was required. The direct search method of Nelder and Mead[1](known as the Downhill Simplex or Amoeba Method) was chosen for this stage of the optimization. The advantages of this method include not requiring the calculation of derivatives of the performance index and the ability to handle discontinuous functions and the constraints expressed as exact penalty functions[2].

The FreeFlyer script used in this stage propagated the Aqua spacecraft with a full dynamic model including, 21x21 gravity field, atmospheric drag, solar radiation pressure, and third-body gravity from the Sun and the Moon. The maneuvers were modeled as finite burns in full blow down mode. The magnitude of the maneuvers was calculated using the procedure presented by Nickerson, Herder, Glass and Cooley[3](referred to hereafter as RESTOR) which also achieves the desired values for eccentricity and argument of perigee. Since the

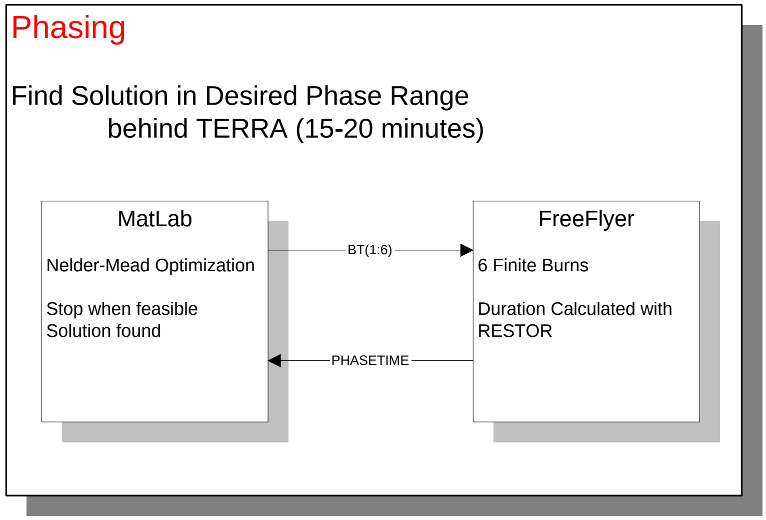

Figure 7: Stage One: Phasing

time of the maneuver is input, the actual maneuver occurs on the next orbit at the argument of latitude specified by the RESTOR calculation.

The performance index minimized using the Nelder-Mead method was:

$$J(X[1:6]) = 1.0 + max(0, Phase - 15) + max(0, 20 - Phase) \quad (1)$$

where X[1:6] are the maneuver intervals and Phase is the time between Terra and Aqua's descending node crossings. This cost function has a value of 1.0 when the phase constraint is satisfied and is greater than 1.0 when the constraint is violated. Since the goal of this stage is just to find a solution that satisfies this constraint, the optimization is stopped once any such solution is found. This was done to greatly speed up the calculation of what is just the starting point of this process. The relative flow of information between MatLab and FreeFlyer in this first stage is shown in Figure 7

Stage Two: Ground Track Error

The completion of the first stage of the targeting results in 6 time intervals between burns and 6 burn durations. The burn durations resulting from the RESTOR calculation typically are a short burn followed by a long burn. There is, however, a desire operationally to have the burns be more equal in magnitude, so for the next stage of the targeting the 6 burn durations are averaged in pairs (1 with 2, 3 with 4, and 5 with 6) to remove much of the variation between consecutive burns. In this stage the duration of the burns is no longer calculated by FreeFlyer but are now a fixed input.

The optimization performed in this stage uses MatLab's sequential quadratic programming routine (SQP), fmincon[4]. The goal of this optimization is to minimize the ground track error relative to the WRS-2 grid while maintaining the frozen orbit and phasing constraints.

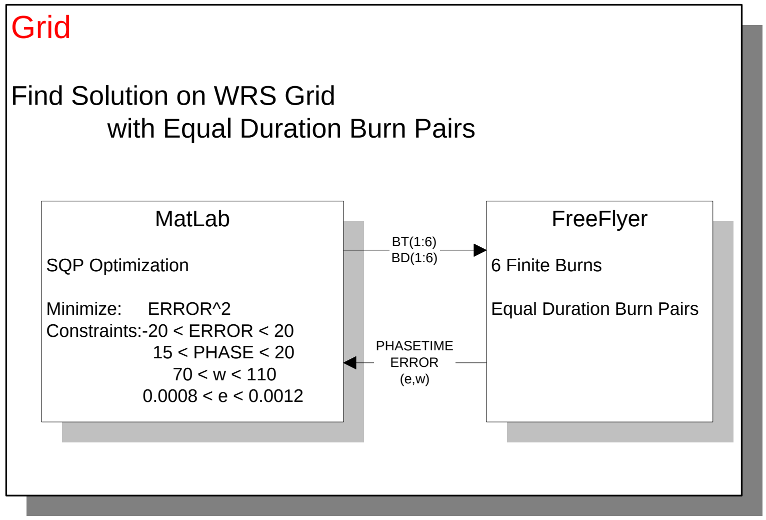

Figure 8: Stage Two: Ground Track Error

This problem can be expressed as:

$$
\begin{aligned}
minimize \quad J\left(X[1:6]\right) &= Error^2 \\
subject\ to: & \\
Phase &> 15 \\
Phase &< 20 \\
Error &> -20 \\
Error &< 20 \\
e &> 0.0008 \\
e &< 0.0016 \\
\omega &> 70 \\
\omega &< 110
\end{aligned}
\tag{2}
$$

where Error is the ground track error relative to the WRS-2 grid, e is the eccentricity, and ω is the argument of perigee. The required derivatives are calculated numerically with a minimum perturbation of 0.07 days, which corresponds to approximately one orbit. This allows the search routines to reestablish the frozen orbit conditions. The relative flow of information between MatLab and FreeFlyer is shown in Figure 8. The completion of this targeting stage results in a sequence of maneuver intervals that places AQUA in its operational orbit with the desired phasing and on the WRS-2 grid.

Stage Three: TDRSS Contacts

At this point an ascent plan has been developed that meets the mission constraints for the the AQUA orbit. It is at the desired altitude, frozen, phased with TERRA, and on the WRS-2 grid. There is however, no guarantee that the burns occur within TDRSS contacts. That is the purpose of the third stage of the targeting.

This stage is divided into 6 sub-stages. Each sub-stage establishes one burn within a TDRSS

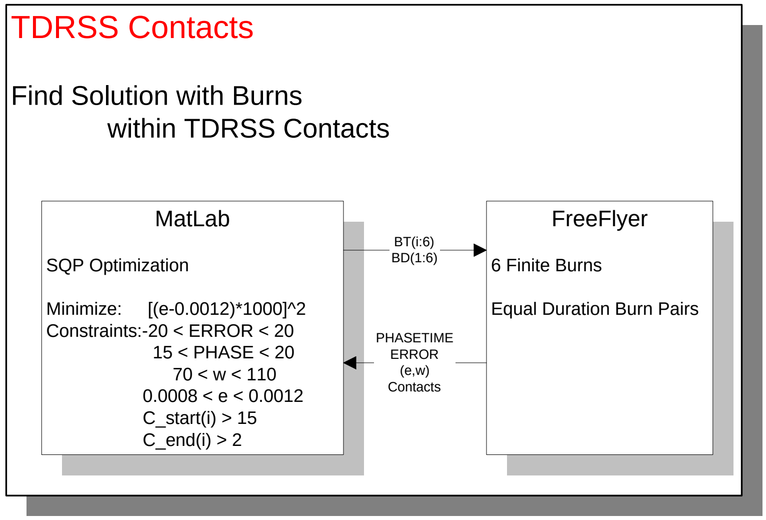

Figure 9: Stage Three: TDRSS Contacts

contact. Once the sub-stage is complete, the interval between that burn and the previous burn is fixed. So initially there are 6 free parameters that can be adjusted to get the first burn into a TDRSS contact. Then there are 5 for the second, 4 for the third, and so on. The cost function used was chosen to ensure that the frozen orbit conditions are maintained. This problem can be expressed as:

$$\begin{aligned} minimize \quad J(X[i:6]) &= ((0.0012 - e) * 1000)^2 \qquad (3) \\ subject\ to: & \\ Phase &> 15 \\ Phase &< 20 \\ Error &> -20 \\ Error &< 20 \\ e &> 0.0008 \\ e &< 0.0016 \\ \omega &> 70 \\ \omega &< 110 \\ C^i_{Start} &> 15 \\ C^i_{End} &> 2 \end{aligned}$$

where i is the burn being placed in a contact, $X[i:6]$ are the free maneuver intervals, C^i_{Start} is the time between AOS and the burn start, and C^i_{End} is the time between the burn end and LOS. If at any sub-stage the optimizer returns a solution that does not meet all the constraints the optimizer is re-run after adding 0.001 days to the first free maneuver interval.The exchange of information between MatLab and FreeFlyer is shown in Figure 9.

Stage 1	
Initial Interval	[3.0000 3.0000 3.0000 3.0000 3.0000 3.0000]
Final Interval	[7.8094 3.3753 3.0407 3.2258 3.2135 3.3302]
Burn Durations	[211.989 674.355 346.895 732.275 349.991 790.884]
Phase	19.98
Error	-43.63
Stage 2	
Burn Durations	[443.172 443.172 539.585 539.585 570.438 570.438]
Initial Interval	[7.8094 3.3753 3.0407 3.2258 3.2135 3.3302]
Final Interval	[3.0311 3.1432 5.3157 5.9918 12.000 3.4123]
Phase	18.55
Error	0.024
(ω, e)	(77.17, 0.001110)

Table 2: Nominal Ascent Plan, Stage One and Two

RESULTS

The nominal ascent plan for the December 20, 2001 launch date is shown in Tables 2, 3, and 4 along with the intermediate solutions to each stage of the optimization. The first stage determines the total burn duration necessary to achieve the operational orbit. Averaging the burn durations prior to the second stage causes the frozen orbit and phasing constraints to be violated. By using a large perturbation in the second stage, these constraints are restored and the ground track error is placed very near the center of the control box. In the third stage, the spacing of the burns is adjusted until all the burns occur within TDRSS contacts.

Ascent plans for other launch dates are shown in Tables 5, 6, 7, and 8. Note that the total duration of the ascent varies between 33 and 54 days. This is primarily driven by the first burn which establishes the phasing with Terra. Once the ascent has begun, it takes between 23 and 30 days to complete. The ascent for most dates begin within one synodic period of the first possible opportunity. Three ascents begin in the second synodic period and two in the third period. Further analysis may show that the ascent on these days can begin earlier.

Each of the ascent plans presented were calculated autonomously, requiring very little user intervention. This allowed a large number of scenarios to be examined to find ascent sequences that meet all the mission and operational constraints. The success of this procedure is due largely to the ability to separate the orbital dynamics from the optimization process using FreeFlyer.

Stage 3	
Burn Durations	[443.172 443.172 539.585 539.585 570.438 570.438]
Burn 1	
Initial Interval	[3.0311 3.1432 5.3157 5.9918 12.000 3.4123]
Final Interval	[3.7791 3.6367 7.9022 2.1689 5.9969 9.7559]
Phase	18.89
Error	-9.35
(ω, e)	(102.53, 0.001236)
C_{Start}	[30 2 2 16 23 -6]
C_{End}	[2 14 30 14 6 37]
Burn 2	
Initial Interval	[3.7791 3.6367 7.9022 2.1689 5.9969 9.7559]
Final Interval	[3.7791 3.6591 7.6752 2.8046 6.4497 8.3143]
Phase	18.39
Error	4.29
(ω, e)	(89.18, 0.002629)
C_{Start}	[30 25 3 0 11 31]
C_{End}	[2 2 29 13 21 0]
Burn 3	
Initial Interval	[3.7791 3.6591 7.6752 2.8046 6.4497 8.3143]
Final Interval	[3.7791 3.6591 7.7197 2.4295 7.4526 7.6443]
Phase	17.84
Error	19.98
(ω, e)	(75.37, 0.001579)
C_{Start}	[30 25 15 11 26 34]
C_{End}	[2 2 16 18 -8 -2]

Table 3: Nominal Ascent Plan, Stage 3

Stage 3	
Burn Durations	[443.172 443.172 539.585 539.585 570.438 570.438]
Burn 4	
Initial Interval	[3.7791 3.6591 7.7197 2.4295 7.4526 7.6443]
Final Interval	[3.7791 3.6591 7.7197 2.4407 7.3104 7.6412]
Phase	18.19
Error	9.93
(ω, e)	(86.19, 0.000995)
C_{Start}	[30 25 15 27 1 27]
C_{End}	[2 2 16 2 15 -6]
Burn 5	
Initial Interval	[3.7791 3.6591 7.7197 2.4407 7.3104 7.6412]
Final Interval	[3.7791 3.6591 7.7197 2.4407 7.3283 7.6486]
Phase	18.09
Error	12.73
(ω, e)	(86.86, 0.001242)
C_{Start}	[30 25 15 27 18 27]
C_{End}	[2 2 16 2 6 4]
Burn 6	
Initial Interval	[3.7791 3.6591 7.7197 2.4407 7.3283 7.6486]
Final Interval	[3.7791 3.6591 7.7197 2.4407 7.3283 7.6475]
Phase	18.09
Error	12.63
(ω, e)	(84.57, 0.001183)
C_{Start}	[30 25 15 27 18 25]
C_{End}	[2 2 16 2 6 6]

Table 4: Nominal Ascent Plan, Stage 3 continued

Launch Date	Dec 20 2001
Maneuver Interval	[3.7791 3.6591 7.7197 2.4407 7.3283 7.6475]
Maneuver Duration	[443.172 443.172 539.585 539.585 570.438 570.438]
Phase	18.10
Error	12.63
(ω, e)	(84.57, 0.001183)
C_{Start}	[30 25 15 27 18 25]
C_{End}	[2 2 16 2 6 6]
Launch Date	Dec 21 2001
Maneuver Interval	[6.9236 9.6697 4.5500 8.1807 4.8251 3.8035]
Maneuver Duration	[458.456 458.456 539.576 539.576 590.844 590.844]
Phase	19.26
Error	-4.74
(ω, e)	(75.11, 0.001568)
C_{Start}	[23 29 30 29 20 15]
C_{End}	[2 5 2 2 11 16]
Launch Date	Dec 22 2001
Maneuver Interval	[35.3012 4.7112 2.0181 6.7103 6.5808 2.9164]
Maneuver Duration	[531.157 531.157 580.310 580.310 526.313 526.313]
Phase	15.00
Error	-2.67
(ω, e)	(70.53, 0.001002)
C_{Start}	[29 21 18 16 15 16]
C_{End}	[2 7 13 15 18 16]
Launch Date	Dec 23 2001
Maneuver Interval	[14.1958 2.5891 5.7804 11.9166 2.0242 2.0248]
Maneuver Duration	[533.381 533.381 555.119 555.119 500.608 500.608]
Phase	19.52
Error	-6.24
(ω, e)	(75.17, 0.001135)
C_{Start}	[29 15 15 15 15 19]
C_{End}	[3 16 2 14 17 7]

Table 5: Ascent Plans, December 20-23

Launch Date	Dec 24 2001
Maneuver Interval	[13.7130 6.8766 11.9647 3.3190 10.2184 11.6261]
Maneuver Duration	[512.745 512.745 580.753 580.753 522.362 522.362]
Phase	19.85
Error	18.12
(ω, e)	(102.40, 0.000630)
C_{Start}	[15 25 19 15 15 16]
C_{End}	[10 2 2 16 13 17]
Launch Date	Dec 25 2001
Maneuver Interval	[4.7027 10.0148 9.8508 9.7851 7.3015 2.1192]
Maneuver Duration	[458.442 458.442 538.058 538.058 601.878 601.878]
Phase	19.01
Error	19.24
(ω, e)	(79.62, 0.001516)
C_{Start}	[21 32 23 23 28 15]
C_{End}	[2 2 2 9 2 14]
Launch Date	Dec 26 2001
Maneuver Interval	[11.3158 4.7226 2.9749 2.4308 8.0473 5.9677]
Maneuver Duration	[450.269 450.269 543.303 543.303 586.130 586.130]
Phase	18.95
Error	5.52
(ω, e)	(109.72, 0.001072)
C_{Start}	[15 24 19 16 16 15]
C_{End}	[16 2 11 11 13 15]
Launch Date	Dec 27 2001
Maneuver Interval	[14.1930 4.4058 2.0164 11.6790 11.5141 10.1251]
Maneuver Duration	[526.468 526.468 562.604 562.604 515.238 515.238]
Phase	19.65
Error	19.65
(ω, e)	(84.58, 0.001340)
C_{Start}	[25 15 18 18 17 24]
C_{End}	[7 14 13 12 14 8]

Table 6: Ascent Plans, December 24-27

Launch Date	Dec 28 2001
Maneuver Interval	[16.6792 3.5648 3.9344 2.0177 2.0593 4.1399]
Maneuver Duration	[514.448 514.448 556.688 556.688 522.410 522.410]
Phase	18.56
Error	18.35
(ω, e)	(108.24, 0.001574)
C_{Start}	[15 25 29 15 27 15]
C_{End}	[17 3 2 5 2 8]
Launch Date	Dec 29 2001
Maneuver Interval	[21.2574 2.3310 6.5363 2.5991 8.8738 2.1347]
Maneuver Duration	[530.078 530.078 570.129 570.129 507.413 507.413]
Phase	19.50
Error	16.69
(ω, e)	(89.49, 0.001538)
C_{Start}	[15 21 27 18 15 31]
C_{End}	[14 6 2 7 14 2]
Launch Date	Dec 30 2001
Maneuver Interval	[30.0000 3.6556 4.6529 4.1484 4.4916 2.1558]
Maneuver Duration	[532.276 532.276 579.951 579.951 506.312 506.312]
Phase	15.00
Error	-8.99
(ω, e)	(72.47, 0.000932)
C_{Start}	[15 15 15 22 24 15]
C_{End}	[16 16 15 8 8 18]
Launch Date	Dec 31 2001
Maneuver Interval	[10.5036 2.0144 2.4614 7.2907 7.3059 4.4228]
Maneuver Duration	[509.947 509.947 564.997 564.997 496.353 496.353]
Phase	18.54
Error	18.71
(ω, e)	(74.89, 0.001560)
C_{Start}	[22 23 15 15 15 20]
C_{End}	[9 4 14 16 12 9]

Table 7: Ascent Plans, December 28-31

Launch Date	Jan 01 2002
Maneuver Interval	[19.7921 5.7723 2.0582 2.0222 2.0259 2.0862]
Maneuver Duration	[530.878 530.878 559.021 559.021 511.385 511.385]
Phase	18.98
Error	17.45
(ω, e)	(70.88, 0.001425)
C_{Start}	[22 16 21 27 30 19]
C_{End}	[9 2 8 4 2 10]
Launch Date	Jan 02 2002
Maneuver Interval	[8.9355 2.2851 9.1643 4.6645 6.6804 5.2562]
Maneuver Duration	[526.059 526.059 559.862 559.862 493.849 493.849]
Phase	18.88
Error	18.30
(ω, e)	(95.79, 0.001587)
C_{Start}	[30 15 15 24 15 29]
C_{End}	[2 11 16 7 12 2]
Launch Date	Jan 03 2002
Maneuver Interval	[2.0254 2.0191 9.3770 10.5759 2.0240 2.8459]
Maneuver Duration	[509.932 509.932 547.994 547.994 500.425 500.425]
Phase	18.61
Error	10.51
(ω, e)	(86.69, 0.001521)
C_{Start}	[15 15 22 15 15 15]
C_{End}	[11 17 9 13 17 17]
Launch Date	Jan 04 2002
Maneuver Interval	[11.3842 10.1198 2.9450 2.0156 2.1321 2.3973]
Maneuver Duration	[517.922 517.922 561.673 561.673 495.127 495.127]
Phase	18.77
Error	19.74
(ω, e)	(95.62, 0.000656)
C_{Start}	[15 15 16 15 19 15]
C_{End}	[10 17 12 15 10 16]

Table 8: Ascent Plans, January 1-4

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