

Heuristic Modeling for TRMM Lifetime Predictions*

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Abstract

Analysis time for computing the expected mission lifetimes of proposed frequently maneuvering, tightly altitude-constrained, Earth-orbiting spacecraft has been significantly reduced by means of a heuristic modeling method implemented in a commercial-off-the-shelf spreadsheet product (QuattroPro) running on a personal computer (PC). The method uses a look-up table to estimate the maneuver frequency per month as a function of the spacecraft ballistic coefficient and the solar flux index, then computes the associated fuel use by a simple engine model. Maneuver frequency data points are produced by means of a single 1-month run of traditional mission analysis software for each of the 12 to 25 data points required for the table. As the data point computations are required only at mission design start-up and on the occasion of significant mission redesigns, the dependence on time-consuming traditional modeling methods is dramatically reduced. Results to date have agreed with traditional methods to within 1 to 1.5 percent.

The spreadsheet approach is applicable to a wide variety of Earth-orbiting spacecraft with tight altitude constraints. It will be particularly useful to such missions as the Tropical Rainfall Measurement Mission (TRMM), scheduled for launch in 1997, whose mission lifetime calculations are heavily dependent on frequently revised solar flux predictions.

1.0 Introduction

In the past, TRMM lifetime predictions have been performed using the Goddard Mission Analysis System (GMAS) average variation-of-parameters (VOP) propagator—including detailed modeling of atmospheric drag, solar radiation pressure, and the effects of the nonspherical Earth—followed by an elaborate data processing effort involving several PC and mainframe routines and a spreadsheet. In addition, because TRMM's tight altitude constraints require frequent maneuvering (Reference 1), the calculated lifetime is heavily dependent on solar flux predictions (produced by Dr. Kenneth Schatten, References 2 and 3) and must be recomputed following each of the approximately quarterly updates of those predictions. The spreadsheet-based lifetime estimation tool, using a heuristic modeling method that is based on 25 years of mission design experience, has been developed to provide lifetime analysis of the scope required for such projects at acceptable cost. Results to date have agreed with traditional analysis methods to within 1 to 1.5 percent, with a time reduction of as much as 95 percent for a full study incorporating six of Dr. Schatten's nine predicted flux-level cases.

2.0 The Spreadsheet Concept

The underlying assumption of the spreadsheet approach to mission lifetime estimation is that, within a given set of mission altitude constraints, maneuver frequency is ultimately dependent on two parameters: the prevailing solar flux level and the ballistic coefficient of the spacecraft. To implement this assumption, time-independent maneuver-frequency data points, indexed by ballistic coefficient and predicted solar flux level, are computed as described in Section 3 and provided in a look-up table that the spreadsheet draws on for its computations. Using as indices the ballistic coefficient and solar flux level predicted for a given month, the spreadsheet interpolates

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between the data points in the table to predict the number of maneuvers for that month, then uses a simple engine model to compute the fuel use associated with that maneuver activity for the current propulsion system state. The available fuel is then decremented, the propulsion system state is updated, and computation continues for the succeeding month, iterating until all available fuel has been used. At the conclusion of the computation, all input and computed values are available in the spreadsheet for continuing analysis and/or convenient graphical output.

Traditional propagation methods, based on the spacecraft design and altitude constraints for the given mission, are used to design any maneuvers needed to achieve the initial target orbit and to compute the time-independent maneuver frequency data points for the look-up table. These computations are required only at mission design start-up and on the occasion of significant mission redesigns. It is further recommended that a single traditional lifetime study be performed at mission design start-up for purposes of spreadsheet verification and estimation of the Semi-Annual Effect (Section 3.3). Detailed descriptions of key concepts, models, and algorithms implemented in the spreadsheet, and a discussion of supporting functions, are provided in Sections 3 and 4. Full user-oriented documentation is provided in the spreadsheet.

3.0 The Heuristic Model Rule Base—Producing the Look-Up Table

The methods and assumptions involved in producing the time-independent maneuver-frequency data points for the look-up table are described below.

3.1 Determining the Solar Flux and Ballistic Coefficient Index Values

Maximum and minimum solar flux and ballistic coefficient index values for the maneuver frequency table are selected to provide comfortable margins above and below the ranges of those values expected during the mission lifetime. Intermediate index values are computed by the spreadsheet based on the desired matrix dimensions. The ballistic coefficient computation is given below.

3.2 Computing the Data Points

The maneuver frequency look-up table comprises as many as 25 data points (depending on mission needs—TRMM uses 12) in units of maneuvers per month. Each of the data points is computed in an “average” 1-month propagation run using the GMAS VOP propagator or another appropriate propagation tool with full modeling capabilities. Inputs for the run include the ballistic coefficient and Schatten flux values defined as the indices (see above) for the data point being computed, the maximum and minimum altitudes defined as the mission stationkeeping constraints, and parameters reflecting the modeling assumptions listed below. The resulting data points can be used for all subsequent lifetime predictions for the mission in question, unless the altitude requirements are redefined or the spacecraft itself is redesigned so dramatically that the original range of ballistic coefficients is no longer sufficient. In such cases, the data points must be recomputed and/or additional points must be provided.

3.2.1 Atmospheric Drag Assumptions

For computation of the data points, the TRMM mission uses the Jacchia-Roberts (J-R) atmospheric drag model, with a specially prepared “flat” (or constant-flux) J-R data file reflecting the Schatten flux value defined as the index for the data point being computed. (Preparation of the special J-R data files is described in the spreadsheet documentation page.)

Because a single ballistic coefficient value, defined as

$$\text{Ballistic Coefficient} = \text{Spacecraft Mass} / (\text{Spacecraft Cross-Section} * \text{Drag Coefficient})$$

cannot be input directly into the GMAS propagation software, the value specified as the ballistic coefficient index for the data point being computed is obtained by judicious selection of the component factors, which are input separately. The components are chosen as follows: the spacecraft cross-sectional area and the drag coefficient are held constant at the mission-specified values. The spacecraft mass is computed from these values and the desired ballistic coefficient value by the following reformulation of the ballistic coefficient equation:

$$\text{Spacecraft Mass} = \text{Ballistic Coefficient} * \text{Spacecraft Cross-Section} * \text{Drag Coefficient}$$

Design changes in either the spacecraft mass or spacecraft cross-section will not require additional data-point computation unless the range of ballistic coefficients resulting from the redesign exceeds that provided for in the look-up table index.

3.2.2 The Average Month

The propagations used to compute the data points for the look-up table are run for one average month, which (for missions using the Jacchia-Roberts atmospheric drag model, see Section 3.3) is defined to be September of a convenient mid-mission year. The duration of the average month is chosen as described below.

As Section 3.2.1. explains, the maneuver frequencies computed for the average month are based on a drag model that uses a flat solar flux data file, which is necessary to preserve the time-independent nature of the look-up table. It results, however, in a maneuver frequency data point that is based on a series of maneuvers performed at fixed intervals across the month. In a “natural” month, by contrast, solar flux index values will either increase or decrease as time advances. In periods approaching solar maximum, the solar flux levels increase across the month, producing increasing drag and a proportional shortening of the intervals between maneuvers. In periods approaching solar minimum, decreasing solar flux leads to decreasing drag and a proportional lengthening of the intervals between maneuvers. A natural month could, therefore, require more or fewer maneuvers than the estimate provided by the average month, depending on the phase of the solar cycle.

It was observed that the maneuver frequency estimate could be improved, without jeopardizing the time-independent nature of the look-up table, by choosing the average month to be longer (by 1 day) for missions prior to solar maximum and shorter (by 1 day) for missions prior to solar minimum. Thus, a maneuver in the *last day* of the average month will be *omitted* from the maneuver frequency data point when maneuver intervals are increasing (after solar maximum). Conversely, a maneuver in the *first day after* the average month will be *included* in the maneuver frequency data point when maneuver intervals are decreasing (prior to solar maximum).

The rule of thumb for the duration of the average month is as follows:

- 31 days for a mission primarily on the increasing leg of the solar cycle
- 29 days for a mission primarily on the decreasing leg of the solar cycle
- 30 days for a mission that evenly bridges either the maximum or the minimum

3.2.3 Computing the Data Point Value

The data point resulting from each 1-month propagation is the number of whole and fractional maneuver intervals ($N.nn$) occurring in the average month for the ballistic coefficient and flux level being modeled. Fractional maneuver intervals are used instead of integer maneuvers to ensure that the decay time remaining after the final maneuver in each 1-month computation is fully accounted for in the lifetime estimation. The $N.nn$ value is determined as follows:

$$N = \text{the number of impulsive maneuvers actually modeled within the average month, and}$$

$$.nn = (B - A) / (C - A)$$

where

- A = the date of the final maneuver in the average month
- B = the date of the end of the average month (see above)
- C = the date of the first maneuver following the end of the average month

3.3 Dealing With the Semi-Annual Effect

The semi-annual effect (SAE) is an empirically determined seasonal variation in maneuver frequency that is applied in the Jacchia-Roberts drag model as a variation in atmospheric density both by season and by altitude (Reference 4). Because the TRMM mission design uses the Jacchia-Roberts model, the SAE is clearly an issue for

this mission. However, some other drag models (such as the Harris-Priester model) do not apply this variation, so its use may not be appropriate to all missions. For this reason, an approximation of the SAE, as described below, is provided as a user option in the spreadsheet. Maneuver frequency studies for the TRMM spacecraft using the same Schatten solar flux prediction set, but with the SAE turned on in one and off in the other, are shown in Figures 1 and 2, respectively.

The SAE has raised two important questions in development of the spreadsheet. First, given that the maneuver frequency look-up table must provide a clean, time- and season-independent representation of maneuver frequency as a function of ballistic coefficient and flux level *alone*, and given that data points for the table are computed using the Jacchia-Roberts drag model, how can the SAE be removed from the table? Second, once the SAE is removed to provide time-independent data points for the table, how can it be reapplied to the resulting time-dependent maneuver-frequency profile once the mission lifetime computation is complete?

The answer to the first question is illustrated in Figure 3. As shown there, the maneuver frequency curve from a recent traditional TRMM lifetime study was smoothed using a standard curve-fitting routine, then plotted against the original unsmoothed curve. The seasonal variation that characterizes the SAE is clearly evident in the original curve, in which the first month of each season has been marked. The smoothed curve is completely free of seasonal effects. (It is interesting to note that its linear profile suggests that of the Schatten index curve for the period, only flatter, as if modified by the influence of the ballistic coefficient curve from the same lifetime study.) Note that the September frequency point from the original curve lies on or near the September frequency point from the smoothed curve in all mission years. For this reason, the month of September is assumed to be the month in which the pure maneuver frequency (computed from ballistic coefficient and solar flux level alone) is least affected by the SAE as applied by the Jacchia-Roberts atmospheric model. September was, therefore, selected as the average month for computation of the data points for the maneuver frequency look-up table.

Question two, regarding the SAE adjustment to be applied at user option to the maneuver frequencies computed from the look-up table, is addressed by analysis of the differences between the original curve from Figure 3 (“GMAS: + JR SAE” in Figure 4) and the maneuver frequency profile for the same period as computed in the spreadsheet (“Sheet: no SAE” in Figure 4). The data points from these two curves were differenced for each of the 44 months of the traditional mission lifetime study and an adjustment factor was produced in each case by the following formula:

$$\text{Adjustment factor} = (\text{GMAS mnvr freq} - \text{spreadsheet mnvr freq}) / \text{spreadsheet mnvr freq}$$

A monthly SAE adjustment factor was computed for each calendar month as the average of the individual adjustment factors produced for the three or four occurrences of that calendar month in the lifetime study. (For example, the adjustment factor to be applied each January from 1998 through 2001 was computed as the average of the individual adjustment factors produced for January 1998, January 1999, January 2000, and January 2001). The adjustment factors produced in this manner for each of the 12 calendar months were input into the spreadsheet together with the corresponding Schatten solar flux predictions (the January adjustment factor with each January flux level, and so on) and the spreadsheet lifetime study was repeated. The resulting maneuver frequency curve is shown as “Sheet: + SAE Adj” in Figure 4. Figures 1 and 2 further illustrate the effect of this adjustment. For new missions, the SAE adjustment factors can be prepared in the same way, using the traditional lifetime study performed to verify the spreadsheet results. (See the spreadsheet documentation page for details.) A flag, provided on the spreadsheet’s data input page, allows the adjustment to be selected or deselected with ease.

4.0 Performing Lifetime Analysis

This section discusses the set up, computation sequence, and key mathematical models involved in lifetime computation via the spreadsheet. The complete spreadsheet functional outline is given in Reference 5.

4.1 Setting Up the Spreadsheet for Mission Design

In addition to computation of data points for the look-up table, spreadsheet initialization for mission design includes the operations and data inputs outlined below.

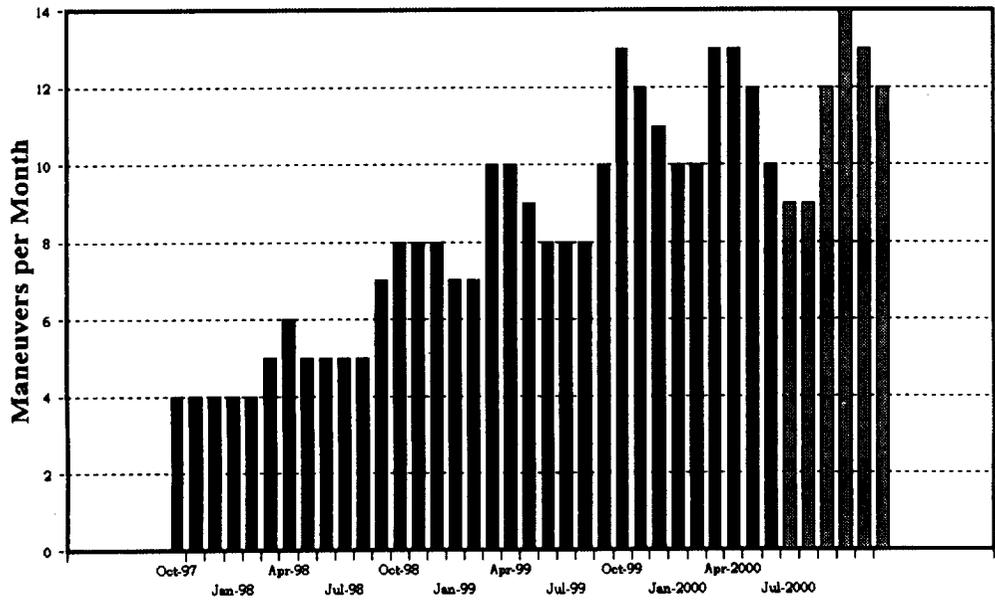


Figure 1. Representative TRMM Lifetime With Semi-Annual Effect

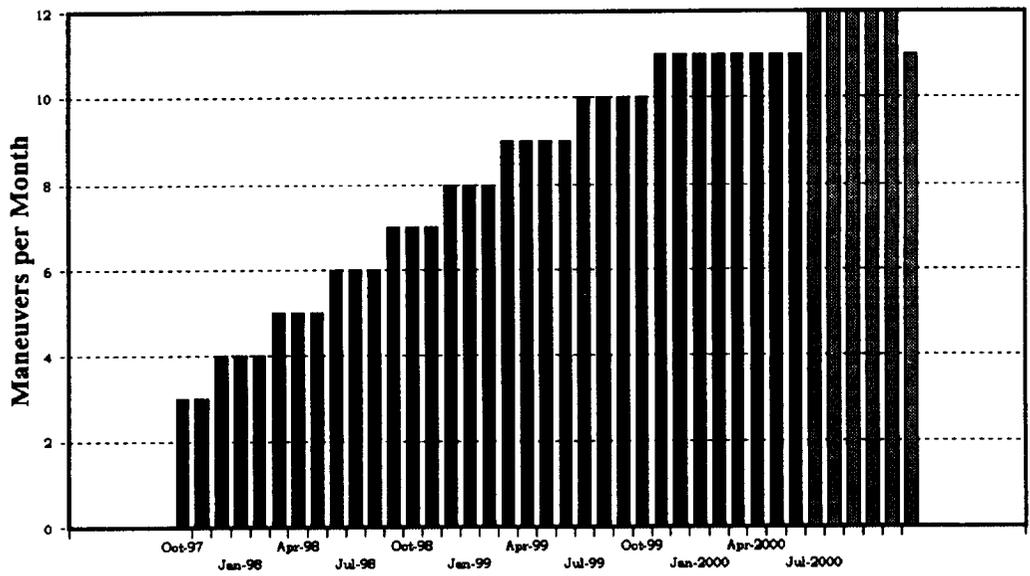


Figure 2. Representative TRMM Lifetime Without Semi-Annual Effect

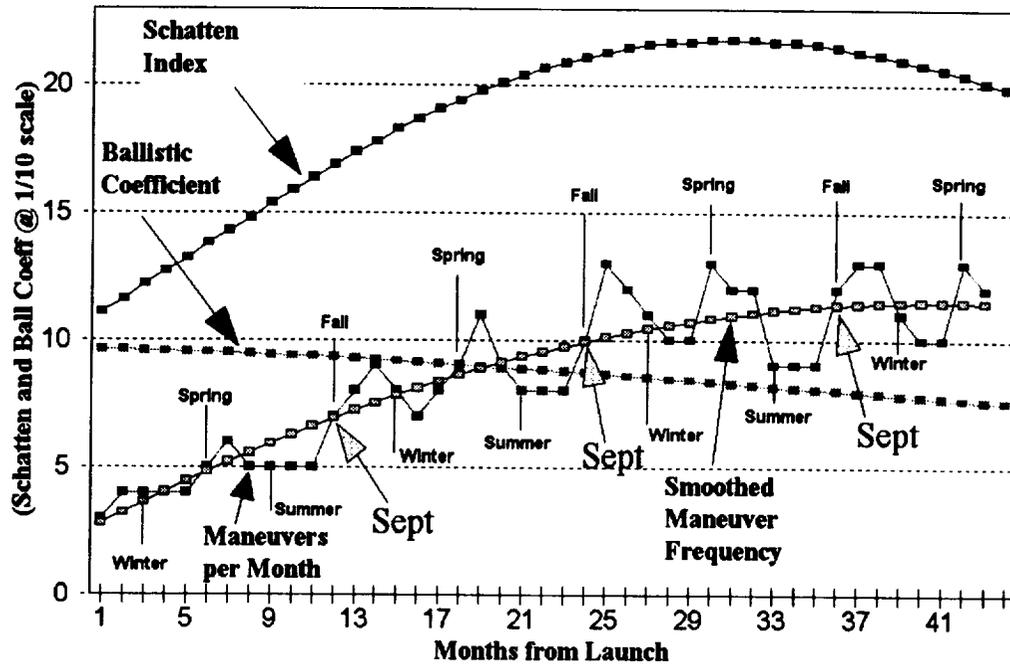


Figure 3. Removing the Semi-Annual Effect From Tabular Data

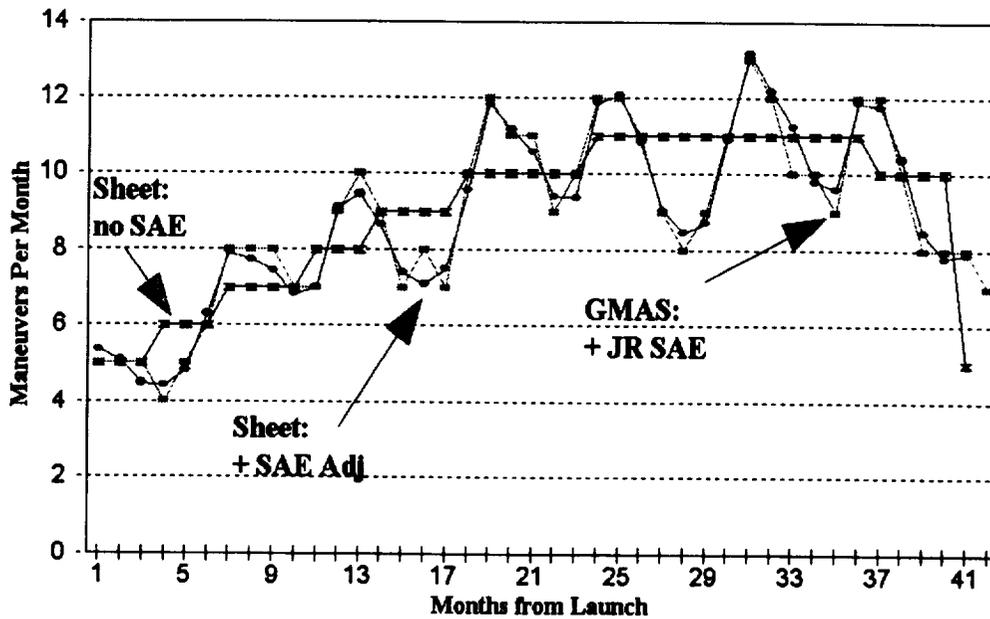


Figure 4. Adjusting for the Semi-Annual Effect in the Spreadsheet

4.1.1 The Early Mission Profile

Determination of the early mission profile requires GMAS or another propagation method to plan an initial ascent or descent to bring the spacecraft from its post-launch altitude to the nominal top-of-the-box altitude on the date when the operational mission and stationkeeping activities are scheduled to begin. The ignition and burnout semimajor axis values computed by this method are used in the spreadsheet to estimate the fuel-use for the initial maneuver and deduct it from the loaded fuel mass prior to normal stationkeeping computations. This option allows evaluation of the changing costs of these early-mission maneuvers as launch dates change, so the semimajor axis values need not be recomputed unless the launch date, the altitude constraints, or the spacecraft design changes significantly. The early mission step can be avoided by inputting a post-launch altitude identical to the nominal top-of-the-box altitude and reducing the loaded fuel mass value by the amount required for the ascent or descent.

4.1.2 Standard and Mission-Specific Parametric Values

The spreadsheet accepts user inputs for such values as gravitational constants, spacecraft dry and fuel masses, the spacecraft cross-sectional area and drag coefficient, mission altitude constraints, propulsion system parameters, and a variety of similar data types.

4.1.3 Schatten Solar Flux Data and SAE Adjustment Factors

Schatten solar flux predictions are input into the spreadsheet in columns, in the form of sequential solar flux levels time-tagged by month and year. The timespan is selected to begin with the first month of the nominal mission lifetime and to continue well beyond its anticipated end. A third column is provided for the corresponding SAE adjustment factors, which are described in Section 3.3.

4.2 The Computation Sequence

As described in Section 2, the spreadsheet uses the ballistic coefficient and predicted solar flux level for a given month as indices to estimate the corresponding maneuver frequency from a look-up table. The ballistic coefficient index is shown in the third column from the left and the flux index in the second row from the bottom of the look-up table, as illustrated in Table 1. The spreadsheet then computes the fuel-use associated with the maneuver frequency taken from the table, decrements the available fuel, and updates the propulsion system state for the subsequent month's computations, iterating these operations until all available fuel is used. The interpolation method, engine model, and propulsion system model used for these computations are described below.

Table 1. Maneuver Intervals per Month as a Function of Ballistic Coefficient and Schatten Flux Index

Ballistic Coefficient	S/C Cross-Sectional Area (m ²)	Drag Coefficient	S/C Mass (kg)	S/C Mass (kg)	S/C Mass (kg)
150					
100					
100	0.86	2.8	5.5	9.3	
80	1.04	3.4	7.25	11.5	
70	1.35	4.5	9.3	15	
Row	50	125	175	275	300

Notes:

- The Ballistic Coefficient column (3rd from left) and Flux Index row (2nd from bottom) show the index values used in computing the maneuvers-per-month data points given in the table.
- The 'row' (2nd column from left) and 'col' (bottom row) numbers are those used in QuattroPro's internal tabulation function.
- The S/C Mass column (farthest left) reports the spacecraft mass required to achieve the associated Ballistic Coefficient index value for the spacecraft cross-sectional area and drag values specified.

4.2.1 The Interpolation Method

The maneuver frequency prediction for a specific month is computed from the tabulated (i.e., from the look-up table) and current index values by a bilinear interpolation scheme that was obtained from Reference 6 and is implemented in the spreadsheet.

For a 4-point grid square identified by Points 1, 2, 3, and 4 as shown in Figure 5, the Point $y(x_1, x_2)$ is obtained by the following:

$$y(x_1, x_2) = (1 - t)(1 - u)y_1 + t(1 - u)y_2 + tuy_3 + (1 - t)uy_4$$

where

$$t \equiv (x_1 - x_1[j]) / (x_1[j+1] - x_1[j])$$

$$u \equiv (x_2 - x_2[k]) / (x_2[k+1] - x_2[k])$$

where

$$x_1 \equiv \text{current solar flux}$$

$$x_2 \equiv \text{current ballistic coefficient}$$

$$x_1[j] \leq x_1 \leq x_1[j+1] \quad \{x_1 \text{ with bounding flux indices}\}$$

$$x_2[k] \leq x_2 \leq x_2[k+1] \quad \{x_2 \text{ with bounding bal. coeff. indices}\}$$

and

$$y_1 \equiv y[j][k] \quad \{\text{pt.1 in Figure 5}\}$$

$$y_2 \equiv y[j+1][k] \quad \{\text{pt.2 in Figure 5}\}$$

$$y_3 \equiv y[j+1][k+1] \quad \{\text{pt.3 in Figure 5}\}$$

$$y_4 \equiv y[j][k+1] \quad \{\text{pt.4 in Figure 5}\}$$

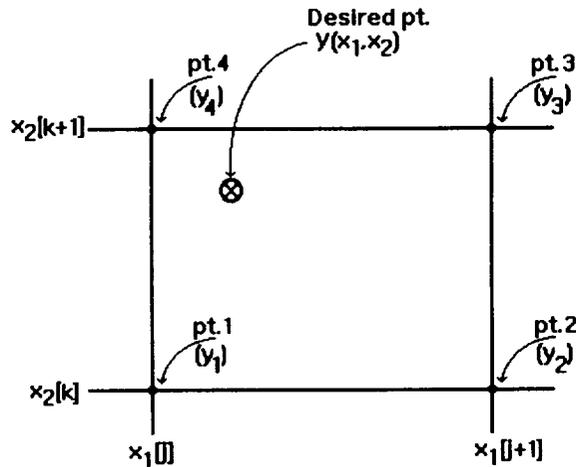


Figure 5. The Bilinear Interpolation Scheme

4.2.2 The Engine Model

Both the post-launch adjustment and operational orbit maintenance maneuvers are modeled impulsively as Hohmann transfers for computation of delta-V. Fuel use and other propulsion system parameters are computed from the impulsive delta-V using the rocket equation in the formulation given below:

$$W_f = W_i / e^{(dV/(G \cdot I_{sp}))}$$

where

- W_f ≡ final (end of the month) spacecraft weight
- W_i ≡ initial (beginning of the month) spacecraft weight
- dV ≡ computed delta-V for the month
- G ≡ the gravitational coefficient
- I_{sp} ≡ current specific impulse

4.2.3 The Propulsion System Model

The propulsion system model includes a user-specified number of tanks (all of the same user-specified volume) and input options allowing specification of a pressure-regulated mode, a blowdown mode, or a combination of the two with transition from one to the other based on a fuel-remaining threshold. The tank pressure and the specific impulse (I_{sp}) for both modes are computed by the equations given below. The spreadsheet accepts user inputs for coefficients and scale factors for both modes.

$$P = P_i / ((1 + F) / (P_i * V_p))$$

where

- P = current pressure
- P_i = initial pressure
- F = fuel used to date
- V_p = pressurant volume

$$I_{sp} = (C_1 + C_2 * P + C_3 * P^2 + C_4 * P^3) * SF$$

where

- I_{sp} = specific impulse
- C_n = coefficient n
- P = pressure
- SF = scale factor

4.3 Dealing With the Final Month

Because of the units (maneuvers-per-month) used for the points in the look-up table, the mission lifetime is initially computed to the end of the month in which the fuel was exhausted. To obtain the final mission day and to account for the fuel mass required for deorbiting maneuvers, the spreadsheet reduces the number of maneuvers computed for the final month by a percentage derived from the fuel use computed for the month versus the amount of fuel actually available for use. The final month's delta-V and fuel use are then reduced by the same percentage, and the mission lifetime is determined to end on the final maneuver date plus the number of days required to decay to the minimum mission altitude. These adjustments are fully reflected in the output summary and final tabulated results.

5.0 Spreadsheet Evaluation: Agreement With Traditional Methods

While all mission lifetime computation methods provide, at best, an approximation of a mission's life expectancy, the GMAS method—which uses the average variation of parameters propagator and models stationkeeping maneuvers impulsively—has come to be used most consistently for FDF mission design, including previous TRMM lifetime computations. As such, it was the logical choice for a yardstick against which the reasonableness

of the spreadsheet results could be evaluated. The same approach should be taken for verification purposes (Section 2.0) when the spreadsheet is being set up for a new or significantly redesigned mission. The verification run can also provide data for the SAE adjustment factors (Section 3.3) as well as the early-mission semimajor axis values required for the post-launch maneuver fuel-use computation (Section 4.1.1).

5.1 The Comparison

As Table 2 shows, spreadsheet and GMAS results were compared for five TRMM cases, comprising various permutations of two spacecraft load masses, two launch dates (October 1997 and April 1998), two sets of I_{sp} scale factors, and two Schatten prediction sets (December 1994 and May 1995 predictions for the +2 sigma, nominal timing case). For each of the five cases, the table compares the GMAS and spreadsheet results in total maneuvers performed and total days in the mission lifetime, both with and without the Semi-Annual Effect. In each comparison, the percentage of disagreement between GMAS results and spreadsheet results was by:

$$[(GMAS\ value - spreadsheet\ value) / GMAS\ value] * 100\%$$

5.2 The Results

As Table 2 shows, the greatest differences between GMAS and spreadsheet results *without* the Semi-Annual Effect were 1.6 percent (Cases 3 and 5) for the total number of maneuvers and 2.4 percent (Case 4) for total duration. When the Semi-Annual Effect was turned on, the greatest differences were 1.4 percent (Case 3) for the total number of maneuvers and 1.5 percent (Case 2) for total duration. This is reasonable, considering that the spreadsheet results were being compared with GMAS results, which always use the SAE. The higher-than-usual 2.4 percent disagreement between GMAS and the spreadsheet (without the SAE) in Case 4 occurred for two reasons. First, the mission duration in that case was not evenly divisible into 6-month intervals, so the effect of the semi-annual variation in the GMAS run did not average out over the mission lifetime as well as in other cases. Second, the mission ended in the August-to-September timeframe, following the three lowest maneuver months of the SAE scheme. That meant that the GMAS run, benefiting from significantly fewer maneuvers than the spreadsheet run (without the SAE) in the final months, had the fuel available to continue almost a month longer than the spreadsheet computation.

Table 2. Comparison of Lifetime Results From GMAS and the Spreadsheet With and Without the Semi-Annual Effect

Test Cases Examined					% Difference Between GMAS and the Spreadsheet*			
Case	Schatten Prediction	Launch Date	Fuel Mass**	Isp Scale Factor (%)	Without SAE		With SAE ***	
					Mnvrs	Dur	Mnvrs	Dur
1	Dec-94	Oct-97	890 kg	4.5	0.5	0.4		
2	May-95	Oct-97	890 kg	4.5			1.1	1.5
3	May-95	Oct-97	890 kg	5.5 / 7.5	1.6	1.0		
4	May-95	Apr-98	890 kg	5.5 / 7.5	1.1	2.4		
5	May-95	Apr-98	790 kg	5.5 / 7.5	1.6	1.2		

Notes:

- * The spreadsheet agrees with GMAS to within the percentage of disagreement shown.
- ** Total spacecraft mass is 3620 kg in all cases.
- *** The method of approximating the Semi-Annual Effect is described in the text.

Shaded blocks indicate the smallest difference between GMAS and the spreadsheet in each case. Dual scale factors are applied as follows: 5.5% inefficiency for the pressure regulated mode and 7.5% inefficiency for the blowdown mode.

6.0 Spreadsheet Maintenance

As mentioned above, updates of spreadsheet parameters computed by the traditional propagation method may need to be performed if the mission is significantly redesigned. Other changes, such as the arrival of new Schatten predictions, will require less time-consuming updates. The information in Table 3 is provided to clarify when updates are necessary, which specific inputs need to be changed, and how.

Table 3. Spreadsheet Maintenance Requirements

Condition	Flux data: Update	Flux data: Adj Timespan	Data pts: Rerun	Data pts: Add Points	Early Mission: Rerun	SAE Factors: Recompute
New Schatten Predictions	√					
Launch Date Change (mos)		√				
Launch Date Change (yrs)		√			√	√
New Altitude Constraints			√		√	√
Ballistic Coef Exceeds Range				√		
Schatten Index Exceeds Range				√		

7.0 Summary and Applications

The spreadsheet approach allows lifetime analysis using all nine Schatten flux-level cases to be performed in a matter of minutes. It is designed for flexibility in terms of spacecraft and mission design and is well-documented internally for the convenience of users. Its results agree well enough with traditional lifetime computation methods (to within 1 to 1.5 percent) to be useful for normal lifetime recomputations such as those following solar flux level updates or moderate spacecraft reconfigurations. This makes it useful to a wide variety of altitude-constrained Earth-orbiting spacecraft whose mission lifetimes depend heavily on frequently updated solar flux predictions.

8.0 References

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