A project present to
The Faculty of the Department of Aerospace Engineering
San Jose State University

in partial fulfillment of the requirements for the degree

The Designated asters 'roject)ommittee Approves the Thesis Titled

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A''.*6ED F*. T3E AE.*S'A)E E-0+-EE.+-0 '.*0.A

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ay !"#$

Dr& 'eri(lis 'apadopoulos	Aerospace Engineering
Dr& Sean S5ei	-ASA Ames .esearch)enter
ary Johnson	-ASA Ames .esearch)enter

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A	Unpertur%ed geostationary semimajor a;is C <!#=<&! (m
a	*r%it semimajor a;is
D	Drift rate
e	*r%it eccentricity
E)F	Earth)entered Fi;ed
E)+	Earth)entered +nertial
0AST	0reen5ich Apparent Sidereal Time
0 ST	0reen5ich ean Sidereal Time
i	inclination
p	SemiDlatus rectum
	'osition vector of the satellite
r	agnitude of the position vector of the satellite
ŕ	Acceleration vector
raan	. ight ascension of the ascending node
)	6elocity vector
6	agnitude of velocity vector
E	Argument of perigee
ν	True anomaly
;	; component of position vector
y	y component of position vector
8	8 component of position vector

* +

*r%ital maneuvers have %een studied for a long time& 3ohmann solved the pro%lem of transfers %et5een t5o coplanar circular or%its 5ith a minimum velocity applied to the space vehicle I3ohmann9 #@!AJ& The pro%lem of t5o impulse or%it maneuvers has %een studied over the years 5ith minor t5ea(s in order to apply solutions to real spacecraft& Je8e5s(i and ittleman I#@?!J 5rote a%out an analytical approach to t5o fi;ed impulse transfers9 5hile Jin and elton I#@@#J concluded that using t5o impulsive maneuvers of fi;ed magnitudes is only possi%le for certain thrust directions&

+n the current age of afforda%ility in the Aerospace industry9 optimi8ation pro%lems are %ecoming increasingly important& As a satellite nears completion of or%it transfer9 plans must %e made in order to place the satellite into its final or%it& 0eostationary satellites are equipped 5ith thrusters that allo5 the satellite to %e commanded to maneuver the spacecraft into the desired or%it& These %urns are usually tangential to the or%it plane or orthogonal to the or%it plane& Tangential %urns are also (no5n as alongDtrac(%urns9 and changes the longitude of the satellite& This affects the semimajor a;is9 the longitude drift rate and the eccentricity vector& *rthogonal %urns change the orientation of the or%it plane& This includes the inclination and the ascending node& ISoop9 !"#"J&

This paper deals only 5ith tangential %urns in line 5ith the or%it plane& +n order to KstopL at the final station location in geosynchronous or%it9 the satellite needs to have a semimajor a;is of <!#=<&! (m9 a drift rate of 8ero9 and an eccentricity vector very close to 8ero&

+t is usually optimal to command or%it maneuvers during the apsides of the or%it ISgu%ini9 M Teofilatto9 !""!J9 %ut 5ith afforda%ility %eing a main driver9 for the sa(e of time9 or%it maneuvers are sometimes scheduled at nonDoptimal times& The time of the maneuver can %e varied to change the eccentricity vector direction9 ho5ever9 5ith this %eing set %y limitations of time9 having multiple %urns ena%les some varia%ility in the final eccentricity of the or%it& This paper 5ill deal 5ith t5o %urns separated %y #! hours& This first o%jective of this 5or(is to identify the si8es of these t5o %urns for a specific or%it that 5ill give the result of a final eccentricity as close as possi%le to the target eccentricity& The second o%jective is to find any general conclusions %et5een the %urn si8es and eccentricity that can %e used on general or%its&

, % &

The investigation 5as done %y varying the ratio of the t5o %urns and propagating through an ephemeris at a specified %urn time9 using atla% as the computing tool& The or%it 5as modeled using the t5o %ody model equations 5ith no pertur%ations& The input sheet includes the ephemeris in classical or%it parameters9 5hich are then rotated into Earth)entered +nertial IE)+J coordinates for propagation using the equations #D< I 1ert8 M 4arson9 #@@@J&

Equation 1

$$p = a\ (1 - e^2)$$

Equation 2

$$r = \frac{p}{(1 + e\ \ \cos\ \ )}$$

Equation 4

ω+¿

ω+¿

(¿¿+e cos ω)

cos ¿

¿

ω+¿

ω+¿

(¿¿+e cos ω)

cos ¿

¿

ω+¿

cos(¿¿+e cos ω)

i (¿]

(¿¿+e sin ω) − cos raan cos i ¿

sin ¿

sin raan ¿

(¿¿+e sin ω) + sin raan cos i ¿

sin ¿

cos raan ¿

¿

$$-\sqrt{\frac{\mu}{p}}\ ¿$$

$$V=\begin{bmatrix}\delta x\\ \delta y\\ \delta z\end{bmatrix}=¿$$

The vector can %e propagated for5ard in time %y multiplying a time step 5ith the velocity and acceleration found from equation A I6allado9 !"">J&

Equation 5

$$\acute{r}+\frac{\mu}{a^3}r=0$$

The initial drift rate of the or%it9 or ho5 quic(ly the or%it is rotating 5ith respect to the rotation of the earth9 is given %y equation = ISoop9 !"#"J& To find the thrust needed to reduce the drift rate to 8ero9 Soop I!"#"J provides equation >&

Equation 6

$$D=\frac{-1.5\ \delta a}{A}$$

Equation 7

$$\Delta D = \frac{-3\Delta V}{V}$$

Using the F69 an array is created %y splitting the value %et5een the t5o %urns %y a percentage& +n this simulation9 one percent 5as the step change %et5een each case& A custom .unge Nutta algorithm 5as 5ritten in order to propagate the ephemeris 5hile controlling the time steps& +n the simulation a time step of =" seconds 5as used& The .unge Nutta algorithm also chec(ed to see if the %urn time 5as passed during the calculation step9 and if it 5as9 inserted an instantaneous thrust or d6 at that time&

+n order to see if the space vehicle ends up at the correct station9 longitude also needed to %e calculated& Although the ephemeris is already calculated in E)+9 this needs to %e converted to an Earth)entered Fi;ed IE)FJ coordinate system& Since longitude is only %ased on the position9 5e only need to convert the position vector from E)+ to E)F9 given %y Eagle In&d&J in equation ? and @&

Equation 8

$$r_{ecf} = [T]\, r_{eci}$$

Equation 9

$$[T] = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

5here 0 is equal to the 0reen5ich sidereal time at the moment& This can %e calculated from the current day and time %y first calculating the Julian Date using Equation #" I6allado9 !"">J9 then %y finding 0reen5ich ean Sidereal Time I0 STJ %y using equation ## and #! I6allado9 !"">J&

Equation 10

$$JD = 367 \quad year - \int \left\{ \frac{7\left\{ year + \int \left(\frac{month + 9}{12} \right) \right\}}{4} \right\} + \int \left(\frac{275\, month}{9} \right) + day + 1721013.5 + \left(\frac{second}{60} + minute \right)$$

The equations for nutation in longitude and nutation in o%liquity using the trigonometric arguments are listed %elo5 in arc seconds IEagle9 n&d&J&

Equation 18

$$\Delta \# = -17.20 \sin \ ' - 1.32 \sin 2 \ \% - .23 \sin 2 \ \%' + 0.21 \sin 2 \ '$$

Equation 19

$$(" = 9.20 \cos \ ' + 0.57 \cos 2 \ \% + 0.10 \cos 2 \ \%\& - 0.09 \cos 2 \ '$$

After converting the results from equations #? and #@ into degrees and putting them along 5ith the result from equation #< into equation #$ the 0reen5ich Apparent Sidereal Time in degrees is o%tained& This can %e put %ac(into equation @ 5hich 5ill create the matri; to convert the position E)+ vector into the position E)F vector&

1ert8 and 4arson I#@@@J provide the equation to calculate longitude from the E)F vector&

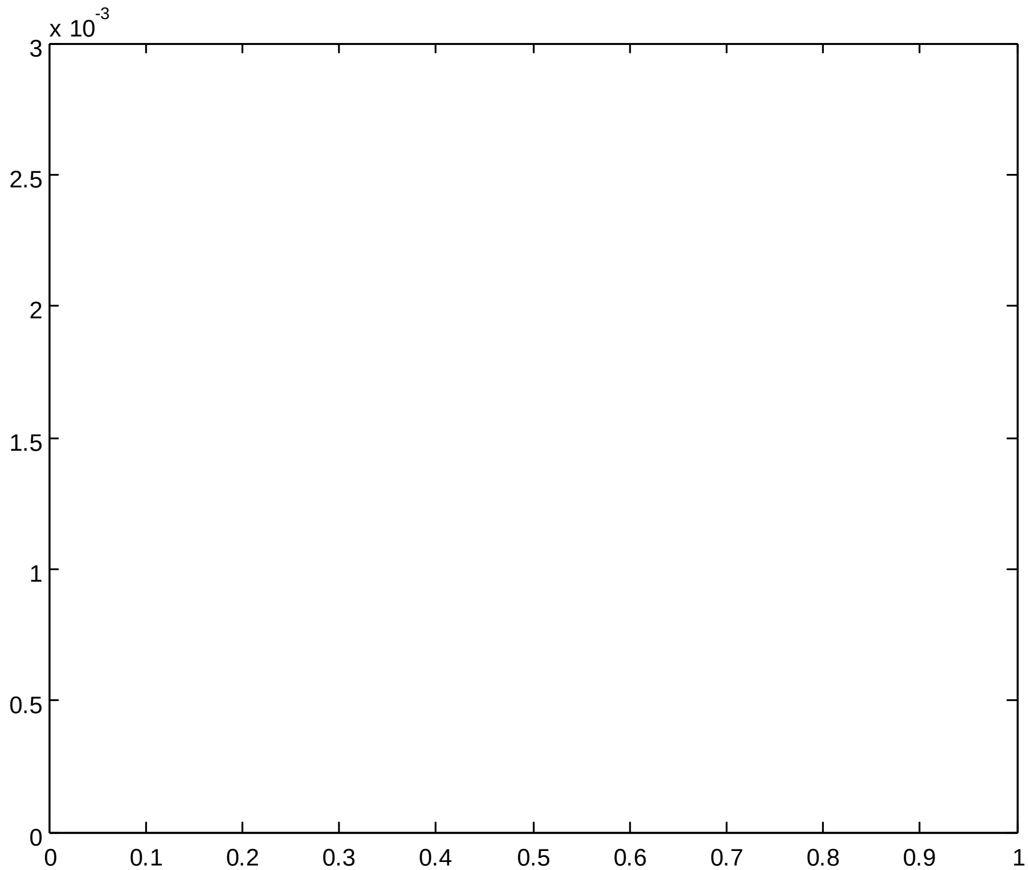
Equation 20

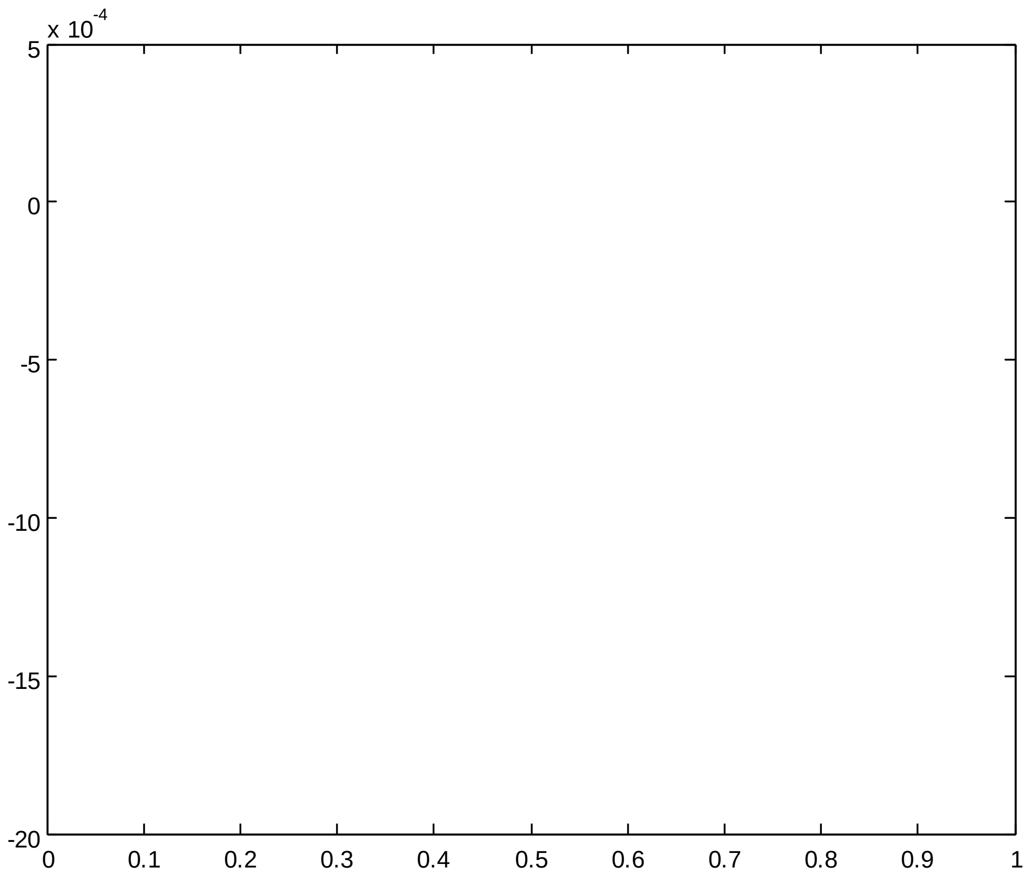
$$) = \tan^{-1} \frac{y}{x}$$

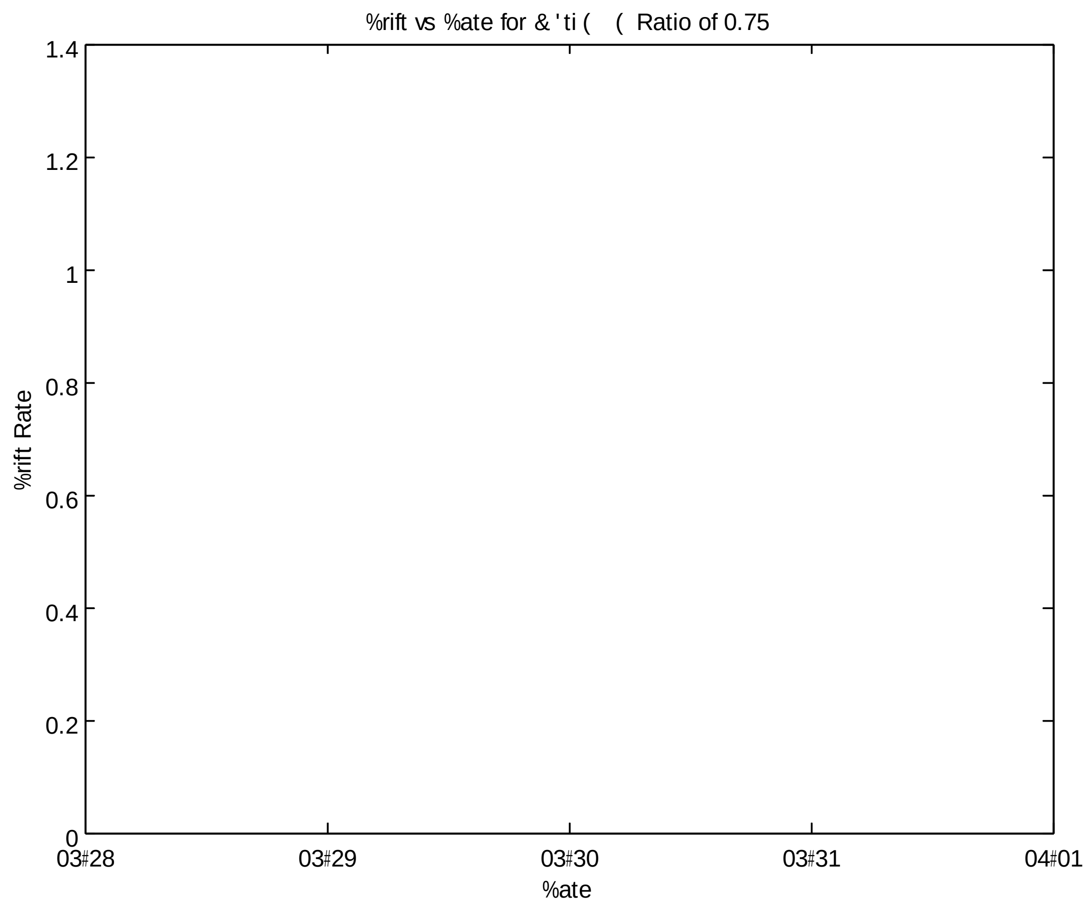
The longitude value is calculated at every step of the .unge Nutta and at the end of the script the %urn parameters 5ith the longitude closest to the desired longitude is selected&

- &

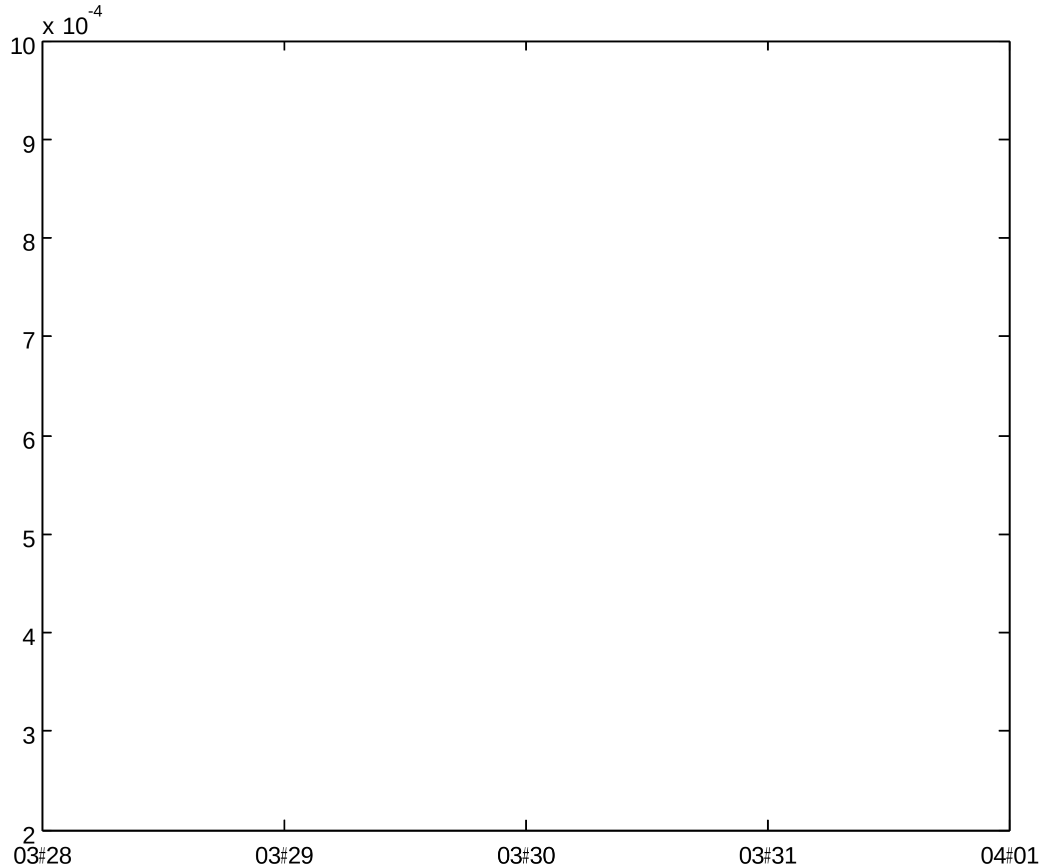
For this simulation9 an or%it and a %urn time 5ere randomly selected& A starting drift rate of # deg:day Ieast5ardJ 5as selected as this seems to %e reasona%le for current satellites& The input file can %e seen in Appendi; A& These results do not target a specific longitude&



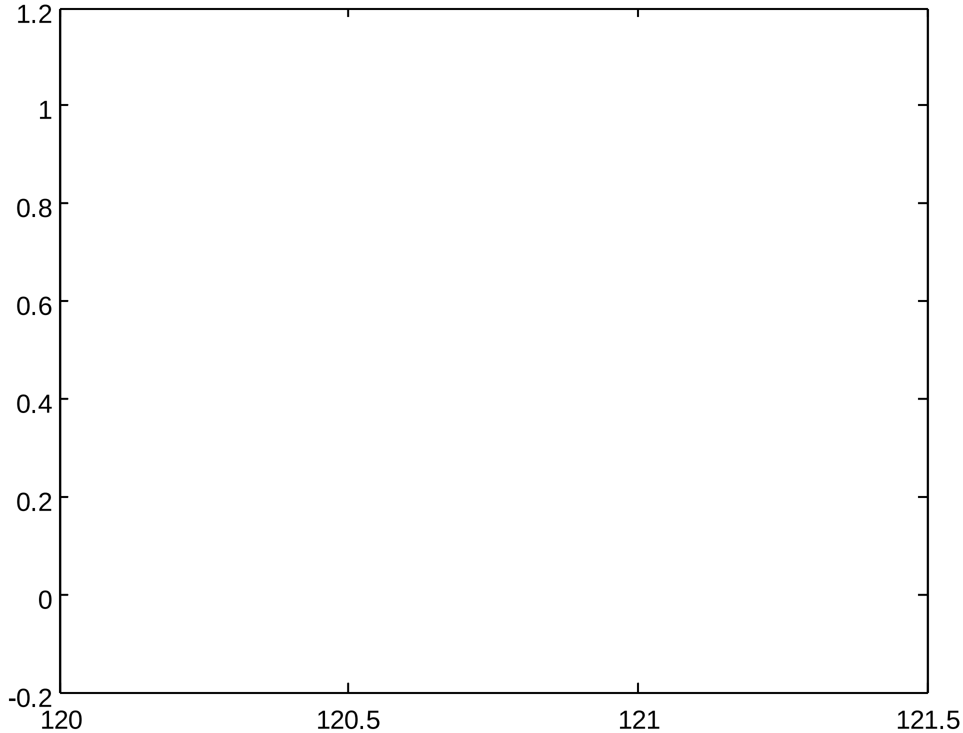

x 10^-4
5
0
-5
-10
-15
-20
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1



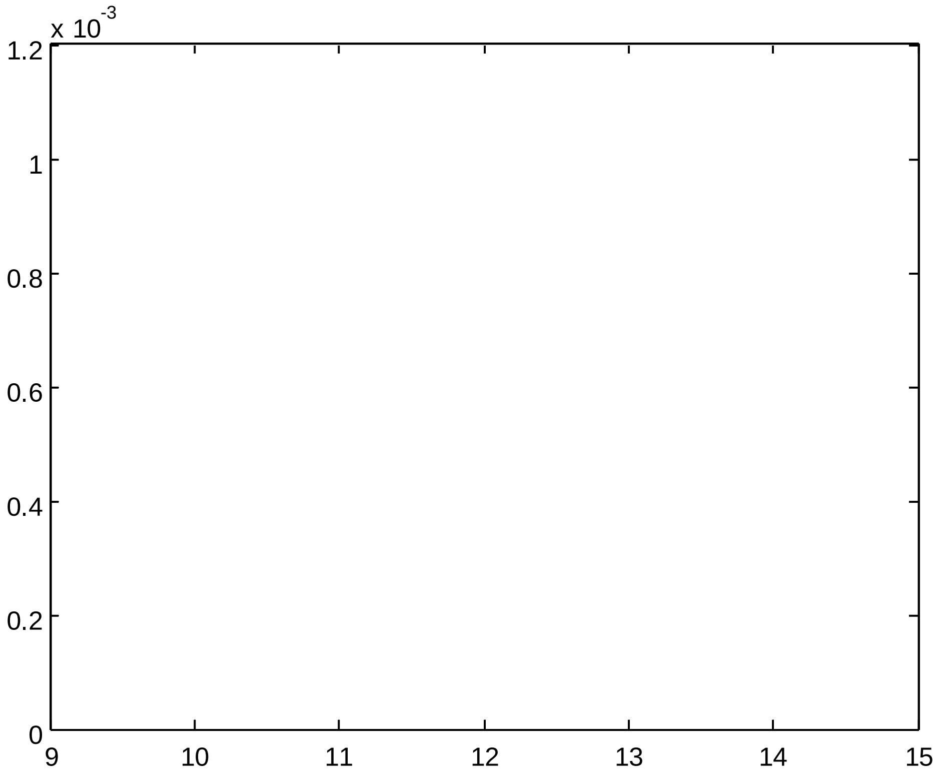
'igu e 3(, E7l3abPu u4)[illegible]7at9$n1t5[illegible]7u9u 5%#2 qfa[illegible]

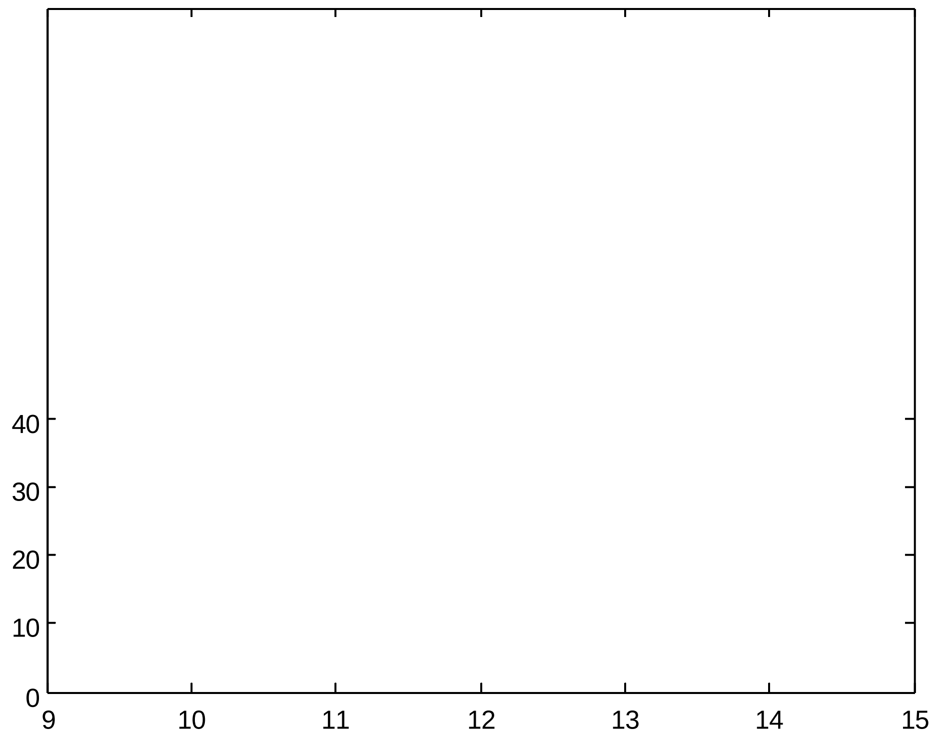

x 10^-4
10
9
8
7
6
5
4
3
2
03#28
03#29
03#30
03#31
04#01

+n comparison to Figure $9 Figure A sho5s an optimal ratio of !A& This is very different from the ratio of >A for Figure $9 ho5ever %oth still result in a drift rate close to 8ero&

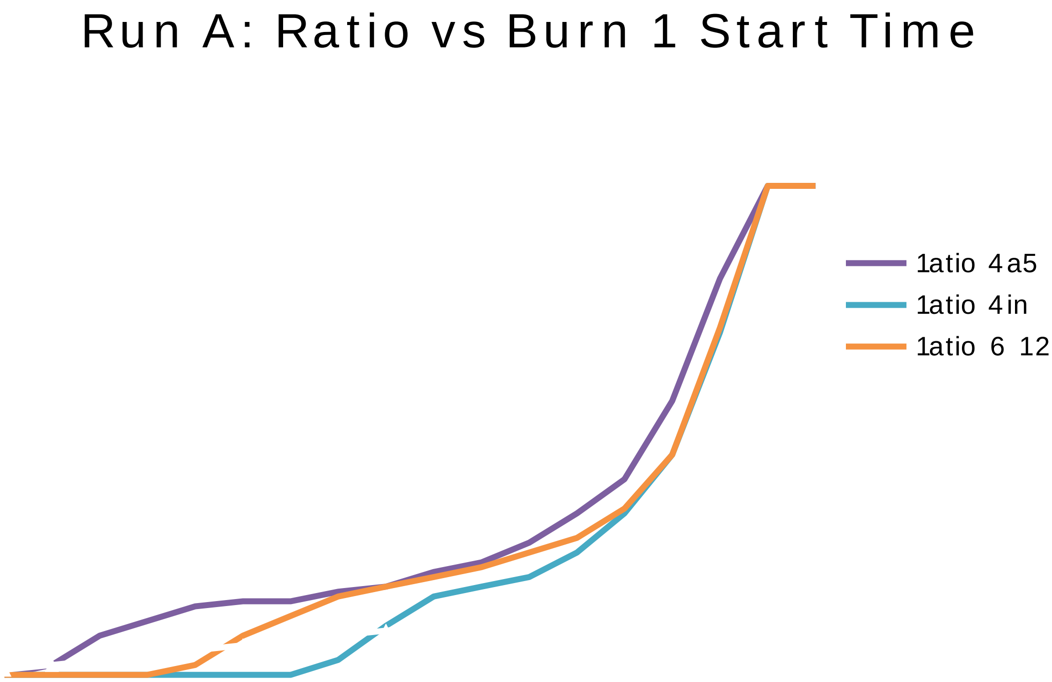

1.2
1
0.8
0.6
0.4
0.2
0
-0.2
120
120.5
121
121.5

second %urn and its result for %urn ratio and eccentricity&


x 10^-3
1.2
1
0.8
0.6
0.4
0.2
0
9
10
11
12
13
14
15



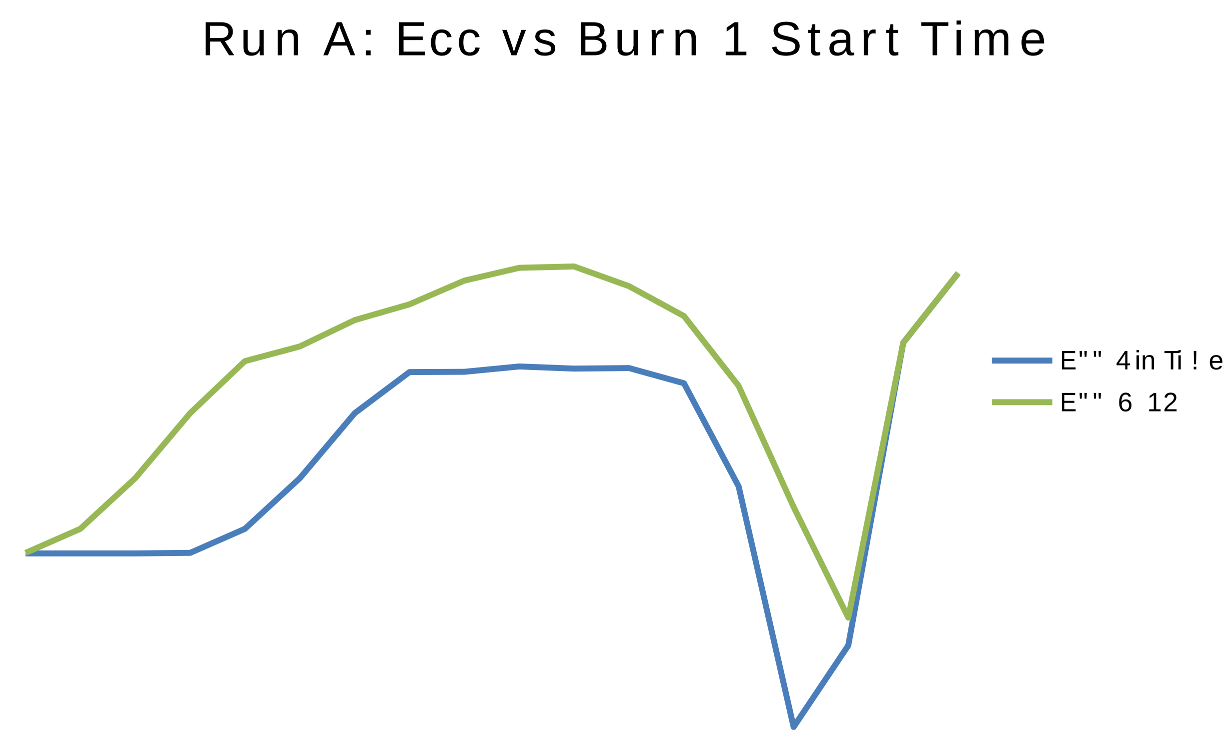
40
30
20
10
0
9
10
11
12
13
14
15



'igu e 11(1un 2(*u n 1atio)a ying 3ta t Ti ! es

. atio S #! plots the optimal ratio for the first %urn sho5n %y the hori8ontal a;is and the second %urn #! hours later& . atio in and a; sho5 the minimum and ma;imum optimal ratios 5hen varying the start time of the second %urn %y three hours&

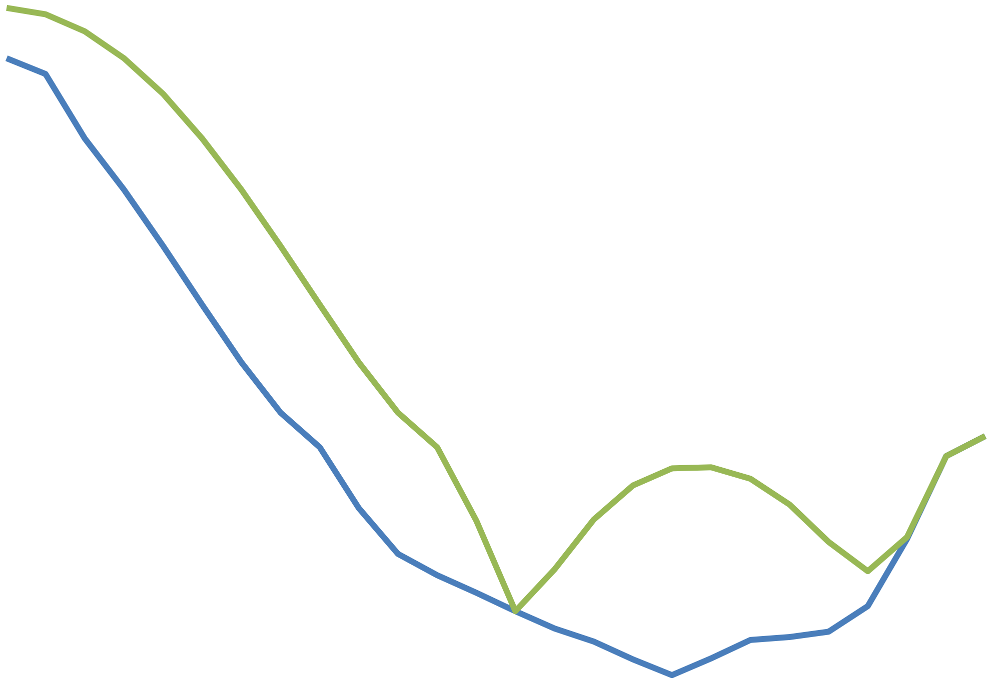
There is a limit on %oth e;tremes& The values all go to 8ero 5hen the %urns start too early& Since the simulation calculates an optimal d6 %ased on one impulse9 if the %urn starts 5hen the initial longitude is too far a5ay there is no 5ay that the d6 5ill %e a%le to achieve the desired longitude 5ith any %urn ratio& 4i(e5ise if the first %urn starts too late9 there is no time for a second %urn and the %urn ratio is al5ays #"" R&



'igu e 12(1un 2('inal E""ent i"ity)a ying 3ta t Ti ! es

Similar to the Burn .atio plot sho5n in Figure @9 Ecc S #! plots the final eccentricity for the first %urn sho5n %y the hori8ontal a;is and the second %urn #! hours later& Ecc in Time sho5s the minimum final eccentricity 5hen varying the start time of the second %urn %y three hours&

Ecc S #! is consistently larger than the minimum eccentricity e;cept near the end of the data& Ta%le # sho5s the %rea(do5n of the time of the minimum eccentricity&



	75		
4728713 11(00	0%0006267	11%25	0%0006334
4728713 12(00	0%000958	12	0%000958
4728713 13(00	0%001038	12	0%001038

4i(e in .un A9 the eccentricity is at a minimum near 5hen the %urn ratio is "R and the time %et5een the %urns is high& The optimum time %et5een %urns also decreases as the %urn ratio gets higher&

- &

0iven an initial or%it and %urn time9 this simulation successfully ans5ers the question of 5hat si8e t5o %urns #! hours apart should %e in order to get a minimum eccentricity value 5hile targeting a specific longitude& +n addition9 the simulation can vary the separation time %et5een the t5o %urns in order to further minimi8e the eccentricity value&

1hile this simulation does ans5er the specific question of the optimal %urn percentage split for a particular or%it9 it is very specific to each case& A general conclusion that can %e made is that if the d6 needed to get 8ero degrees drift rate is too small9 no amount of varying the %urns satellite to point in the correct direction& Also9 as satellites reach their final geosynchronous or%it9 they start to (eep trac(of time in terms of the satelliteTs position and the sunTs position& This allo5s spacecraft operators to (eep trac(of 5hen the satellite 5ill %e su%ject to thermal constraints& Adding this time system to the simulation 5ill ma(e it easier for users to calculate %urn times&

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. un A input file

+nitial Semi ajor A;is B<!"?=
+nitial eccentricity B&"""@$#<<<$A?
+nitial inclination B&##!A<@=@!
+nitial raan B D&=@#!?<=A>
+nitial arg of perigee B $&#$?A>##"#
+nitial true anomaly B D"&#?!<<!>A>
Solar . adiation I) pJ B #&!A
+nitial epoch year B !"#!
+nitial epoch month B "$
+nitial epoch day B !?
+nitial Epoch hour B #!
+nitial Epoch minutes B #$
+nitial epoch seconds B $#
Burn epoch year B !"#!
Burn epoch month B "$
Burn epoch day B !@
Burn Epoch hour B ""
Burn Epoch minutes B ""
Burn epoch seconds B ""

0

. un A input file

+nitial Semi ajor A;is I(mJ B<!"?=
+nitial eccentricity B&"""@