AD-A158 112 INSTANTANEOUS ORBIT PARAMETER CHANGES PRODUCED BY 1/1
IMPULSIVE THRUSTING WIT..(U) NAVAL SURFACE WEAPONS
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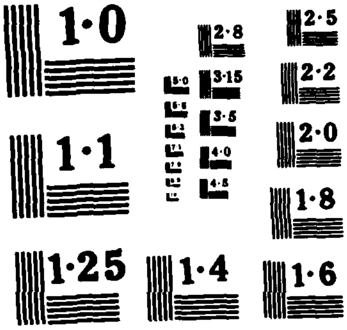

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20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)* An impulsive thrust profile is applied to the Lagrange planetary equations to obtain analytic expressions for thrust-induced changes in orbital parameters. Approximations are introduced for small eccentricity orbits and are used to generate a set of graphical orbit adjust design aids. The orbit adjust design program ORBADJ is discussed, and a program listing and sample output are presented.		

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FOREWORD

This document has been prepared to provide a set of graphical tools that may aid the orbit analyst in the selection of thrust parameters to be used during the planning phase of an orbit adjust design for satellites operating in small eccentricity orbits. It is also intended to serve as the formulation document for the NSWC orbit adjust design software program ORBADJ. This is a general software program that may be used to generate thrust parameters for the initial planning phase of an orbit adjust design. This report has been reviewed and approved by Dr. R. J. Anderle.

Released by:

O. F. BRAXTON, Head
Stategic Systems Department

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ILLUSTRATIONS

INTRODUCTION

The existence of mission-related constraints and flight profiles requires that periodic orbital maintenance thrusting be performed on most artificial earth satellites. This is especially true for low-altitude satellites, since they are continuously perturbed by their interaction with the atmosphere. Operational orbit adjust designs for earth satellites are normally performed in an iterative fashion using coarse satellite ephemerides for early planning and updated precise ephemerides for the final design. Although the desired orbital modifications are known from a comparison of mission requirements with current mission performance, the analyst must still select the most expedient thrust parameters for the design. Initial estimates for these parameters are often made by using the results obtained from orbit perturbation equations and are improved during the iterative design procedure mentioned above.

The following sections of this report are concerned with the development of formulations and data that can be used to provide thrust parameter estimates. Such information can be used as tools for the applied theorist as well as the operational analyst. Considered first are derivations of analytic expressions that relate changes in certain orbital parameters produced by an applied impulsive thrust. These relationships are then used to provide some approximate results that are useful for satellites in small eccentricity orbits. A general discussion of the NSWC orbit adjust design computer program ORBADJ is provided in the final section.

FORMULATIONS

The changes in orbital parameters caused by instantaneous velocity impulses can be determined from results obtained from the Lagrange planetary equations.[1] These equations, expressed in their Gaussian component form, are given by

$$\dot{a} = 2a^2 \left(\frac{v}{\mu} \right) F_1 \tag{1}$$

---

[1] P. M. Fitzpatrick, *Principles of Celestial Mechanics*, Academic Press, Inc., New York, New York, 1970.

$$\dot{e} = \left(\frac{r \sin \theta}{av}\right) F_R + 2\left(\frac{\cos \theta + e}{v}\right) F_I \tag{2}$$

$$(i) = \left(\frac{r \cos u}{h}\right) F_C \tag{3}$$

$$\dot{\omega} = - \frac{(1+e^2) \cos \theta + 2e}{e (1 + e \cos \theta) v} F_R + 2\left(\frac{\sin \theta}{ev}\right) F_I - \frac{r \sin u}{h} \left(\frac{\cos i}{\sin i}\right) F_C \tag{4}$$

$$\dot{\Omega} = \frac{r \sin u}{h} \left(\frac{1}{\sin i}\right) F_C \tag{5}$$

and

$$\dot{u} = - \frac{r \sin u}{h} \left(\frac{\cos i}{\sin i}\right) F_C \tag{6}$$

where a, e, i, ω, and Ω are the usual Keplerian elements; μ is the earth's gravitational constant; θ is the true anomaly; and u is the true argument of latitude defined as

$$u = \theta + \omega \tag{7}$$

The quantities r, v, and h are the satellite radial distance, speed, and angular momentum, respectively. These are defined as follows:

$$r = \frac{a (1 - e^2)}{1 + e \cos \theta} \tag{8}$$

$$v = \sqrt{\mu \left(\frac{2}{r} - \frac{1}{a}\right)} \tag{9}$$

and

$$h = \sqrt{\mu a (1 - e^2)} \tag{10}$$

The acceleration components F_i (i = R, I, C) appearing in the planetary equations are defined by the vector equation

$$\vec{F} = F_R \hat{R} + F_I \hat{I} + F_C \hat{C} \tag{11}$$

where

$$\hat{C} = \frac{\vec{r} \times \dot{\vec{r}}}{|\vec{r} \times \dot{\vec{r}}|} \tag{12}$$

$$\hat{I} = \frac{\dot{\vec{r}}}{|\dot{\vec{r}}|} \tag{13}$$

and

$$\hat{R} = \hat{I} \times \hat{C} \tag{14}$$

Here $\vec{r}$ and $\dot{\vec{r}}$ are the satellite position and velocity vectors.

Verification that the thrust parameters associated with an orbit adjust design produce the desired orbital parameter changes requires that the thrust profile be integrated over the finite thrust interval. A very analytically tractable approach, which yields quite useful estimates, uses an impulsive thrust model in which the Dirac delta function describes the thrust profile. Specifically, if the thrust components defined by

$$F_i = \Delta V_i \ \delta(t - t_{OA}), \ (i = R, I, C) \tag{15}$$

where δ is the Dirac delta function and t_{OA} is time at which the thrust impulse is applied, are substituted into Equations 1 through 6 and the equations are integrated over a small time interval centered about t_{OA}, the following relations are obtained:

$$\Delta a = 2a^2 \left(\frac{v}{\mu}\right) \Delta V_I \tag{16}$$

$$\Delta e = \left(\frac{r \sin \theta}{av}\right) \Delta V_R + 2\left(\frac{\cos \theta + e}{v}\right) \Delta V_I \tag{17}$$

$$\Delta i = \left(\frac{r \cos u}{h}\right) \Delta V_C \tag{18}$$

$$\Delta \omega = - \frac{(1 + e^2) \cos \theta + 2e}{e(1 + e \cos \theta) v} \Delta V_R + 2\left(\frac{\sin \theta}{ev}\right) \Delta V_I - \frac{r \sin u}{h}\left(\frac{\cos i}{\sin i}\right) \Delta V_C \tag{19}$$

$$\Delta\Omega = \frac{r \sin u}{h}\left(\frac{1}{\sin i}\right)\Delta V_C \qquad (20)$$

$$\Delta u = -\frac{r \sin u}{h}\left(\frac{\cos i}{\sin i}\right)\Delta V_C \qquad (21)$$

ere all quantities are preadjust values at t_{OA}.

These results can be applied to those obtained from two-body analytics to obtain results other parameters of interest. The changes in apogee distance, perigee distance, orbital iod, and true anomaly are given by

$$\Delta r_A = \left(\frac{r \sin \theta}{v}\right)\Delta V_R + 2\frac{a}{v}\left(\frac{1 + e}{1 - e}\right)(1 + \cos\theta)\,\Delta V_I \qquad (22)$$

$$\Delta r_P = -\left(\frac{r \sin \theta}{v}\right)\Delta V_R + 2\frac{a}{v}\left(\frac{1 - e}{1 + e}\right)(1 - \cos\theta)\,\Delta V_I \qquad (23)$$

$$\Delta P = 3Pa\left(\frac{v}{\mu}\right)\Delta V_I \qquad (24)$$

l

$$\Delta\theta = \frac{(1 + e^2)\cos\theta + 2e}{e(1 + e\cos\theta)}\,\Delta V_R - 2\,\frac{\sin\theta}{ev}\,\Delta V_I \qquad (25)$$

pectively, where P is the Keplerian period

$$P = 2\pi\left(\frac{a^3}{\mu}\right)^{1/2} \qquad (26)$$

A SUMMARY OF APPROXIMATIONS VALID FOR SATELLITES IN SMALL ECCENTRICITY ORBITS

For sufficiently small eccentricities, the following approximations may be made:

$$r \approx a \tag{27}$$

$$v \approx \sqrt{\frac{\mu}{a}} \tag{28}$$

and

$$h \approx \sqrt{\mu a} \tag{29}$$

By applying these approximations to Equations 16 through 24, one can form the following approximate ratios between thrust components and induced orbital parameter changes:

$$\frac{\Delta a}{\Delta V_I} \approx \frac{P}{\pi} \tag{30}$$

$$\frac{\Delta e}{\Delta V_R} \approx \left(\frac{a}{\mu}\right)^{1/2} \sin \theta \tag{31}$$

$$\frac{\Delta e}{\Delta V_I} \approx 2 \left(\frac{a}{\mu}\right)^{1/2} \cos \theta \tag{32}$$

$$\frac{\Delta i}{\Delta V_C} \approx \left(\frac{a}{\mu}\right)^{1/2} \cos u \tag{33}$$

$$\frac{\Delta \Omega}{\Delta V_C} \sin i \approx \left(\frac{a}{\mu}\right)^{1/2} \sin u \tag{34}$$

$$\frac{\Delta u}{\Delta V_C} \tan i \approx -\left(\frac{a}{\mu}\right)^{1/2} \sin u \tag{35}$$

$$\frac{\Delta r_A}{\Delta V_R} \approx \frac{P}{2\pi} \sin \theta \tag{36}$$

$$\frac{\Delta r_A}{\Delta V_I} \approx \frac{P}{\pi} (1 + \cos \theta) \tag{37}$$

$$\frac{\Delta r_P}{\Delta V_R} \approx - \frac{P}{2\pi} \sin \theta \tag{38}$$

$$\frac{\Delta r_P}{\Delta V_I} \approx \frac{P}{\pi} (1 - \cos \theta) \tag{39}$$

$$\frac{\Delta P}{\Delta V_I} \approx 6\pi \left(\frac{a^2}{\mu}\right) \tag{40}$$

ere P is the period given by Equation 26. Ratios for $\Delta\omega$ and $\Delta\theta$ are not given because the small divisor problem associated with the small eccentricity assumption. These ratios plotted for the reader's convenience in Figures 1 through 9 for several orbital periods ween 5200 and 7000 sec.

Based on the results given above, the following generalizations may be made:

- Only in-track thrusting can produce changes in a and P.
- Only cross-track thrusting can produce changes in i, Ω, and u.
- Radial thrusting produces equal and opposite changes in r_A and r_P.
- In-track thrusting at apogee (perigee) produces no change in apogee (perigee) distance, but produces maximum change in perigee (apogee) distance.

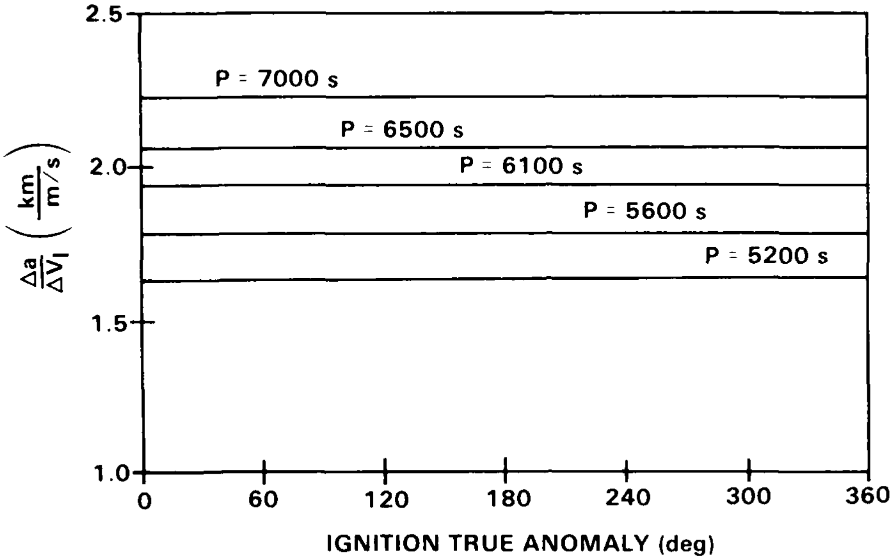

FIGURE 1. CHANGE IN SEMIMAJOR AXIS PER UNIT IN-TRACK VELOCITY IMPULSE

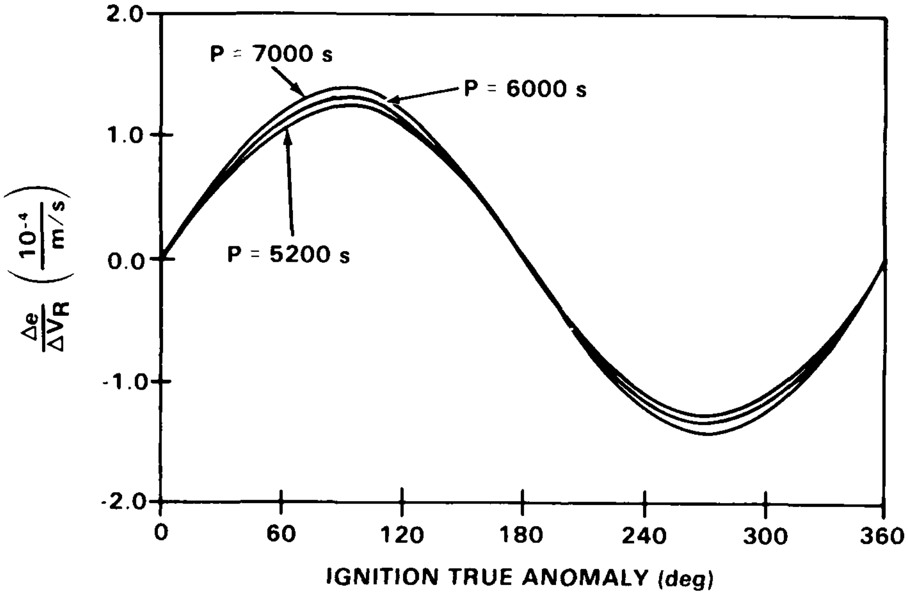

FIGURE 2. CHANGE IN ECCENTRICITY PER UNIT RADIAL VELOCITY IMPULSE

```
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 PRINT 21,DPCH,DAPC,DVIK,BA
 FORMAT(/  ,5X,*TO PRODUCE A *,F6.2,* SEC PERIOD CHANGE*,/5X,*AND A
1 *,F7.2,* DEG PERIGEE ROTATION REQUIRES AN INTRACK VELOCITY IMPULS
2E OF *,F7.2,* METERS PER SEC*,/5X,* AT A TRUE ANOMALY OF *,F7.2,
3* DEG*)
 PRINT 22, J
 FORMAT(/,5X,*CONVERGENCE OCCURRED IN *,I5,* ITERATIONS*)
 RETURN

 PRINT 31, J
 FORMAT(///,5X,*CONVERGENCE DID NOT OCCUR IN *,I5,* ITERATIONS*)
 STOP
 END
 SUBROUTINE POSVEL (A,CE,CI,CL,G,H,BO,R1,R2,R3,V1,V2,V3,R,VEL)
 CALL NWTRPH (CL,CE,E,SINEP,COSEP)
 HSIN=SIN(H)
 HCOS=COS(H)
 GSIN=SIN(G)
 GCOS=COS(G)
 CISIN=SIN(CI)
 CICOS=COS(CI)
 A11=HCOS*GCOS-HSIN*CICOS*GSIN
 A12=-HCOS*GSIN-HSIN*CICOS*GCOS
 A21=HSIN*GCOS+HCOS*CICOS*GSIN
 A22=HCOS*CICOS*GCOS-HSIN*GSIN
 A31=CISIN*GSIN
 A32=CISIN*GCOS
 FUN=SQRT(1.-CE*CE)
 R1=A*(A11*(COSEP-CE)+A12*(FUN*SINEP))
 R2=A*(A21*(COSEP-CE)+A22*(FUN*SINEP))
 R3=A*(A31*(COSEP-CE)+A32*(FUN*SINEP))
 R=A*(1.-CE*COSEP)
 FUN1=(SQRT(BO*A))/R
 V1=FUN1*(A11*(-SINEP)+A12*FUN*COSEP)
 V2=FUN1*(A21*(-SINEP)+A22*FUN*COSEP)
 V3=FUN1*(A31*(-SINEP)+A32*FUN*COSEP)
 VEL=FUN1*SQRT(1.-(CE*COSEP)**2)
 RETURN
 END
 SUBROUTINE NWTRPH (QL,B,E2,SE,CE)
 NEWTON RAPHSON SOLUTION TO KEPLERS EQUATION SUBROUTINE
 E1=QL+(B*SIN(QL))/(1.-B*COS(QL))
 SE=SIN(E1)
 CE=COS(E1)
 E2=E1+(QL+B*SE-E1)/(1.-B*CE)
 IF(ABS(E2-E1)- 1.E-8 )4,4,3
 E1=E2
 GO TO 2
 SE=SIN(E2)
 CE=COS(E2)
 RETURN
 END
/9
```

```
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   PRINT 10
10 FORMAT(///,1X,*DVI(M/S)*,1X,*DVC(M/S)*,1X,*DVR(M/S)*,1X,*DA(KM)*,3
  1X,*DE *   ,3X,*DI(DEG)*,1X,*DW(DEG)*,1X,*DOM(DEG)*,1X,*DU(DEG)*,1X,
  2*DTA(DEG)*,1X,*DRA(KM)*,1X,*DRP(KM )*,1X,*DP(SEC)*,1X,*TAI(DEG)*)

   PRINT 11,DDVI,DDVC,DDVR,DA,DE,DDI,DDW,DDO,DDU,DDTA,DRA,DRP,DP,TTA
11 FORMAT(/,3(1X,F8.3),1X,F6.2,1X,F7.4,1X,F7.4,1X,F7.2,1X,F8.3,1X,
  1       F7.2,1X,F8.3,1X,F6.2,1X,F8.2,1X,F7.2,1X,F8.2)

   RETURN


20 PRINT 21,DA,DE,DDI,DDW,DDO,DDU,DDTA,DRA,DRP,DP,TTA
21 FORMAT(/,28X,F6.2,1X,F7.4,1X,F7.4,1X,F7.2,1X,F8.3,1X,F7.2,1X,F8.3,
  1       1X,F6.2,1X,F8.2,1X,F7.2,1X,F8.2)

   RETURN
   END
   SUBROUTINE REQCH(DPCH,DAPC)

***THIS ROUTINE COMPUTES AN INTRACK VELOCITY IMPULSE REQUIRED TO
***PRODUCE A DESIRED PERIOD CHANGE AND PERIGEE ROTATION.

   COMMON/ELEM/A,E,I,W,O
   COMMON/BURN/TAI,DVI,DVC,DVR

   REAL I,MU

   DATA MU/398600.8/,PI/3.14159265359/
   J=1
   DPC=DAPC*PI/180.
   DVC=0.0
   DVR=0.0
   TAI = 0.00
   P = 2.*PI*(((A*A*A)/MU)**0.5)
10 TAIO = TAI
   R=(A*(1.-E*E))/(1.+E*COS(TAI))

   V2= MU*((2./R)-(1./A))
   V = SQRT(V2)

   DVI = ( DPCH * MU ) / ( 3. * P * A * V )
   SA =0.5*((DPC*E*V)/DVI)
   TAI=ASIN(SA)
   IF(TAI.LT.0.0) TAI=TAI+2.*PI
   TST=ABS(TAI-TAIO)
   IF(TST.LT.0.01) GO TO 20
   J=J+1
   IF(J.GT.500) GO TO 30
   GO TO 10


20 DVIK=1000.*DVI
   BA=TAI*180./PI
```

```
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      V=SQRT(V2)
      U=TAI+W
      VP2=(MU/A)*((1.+E)/(1.-E))
      VP=SQRT(VP2)
      RP=A*(1.-E)
      H=VP*RP
      IF(U.GT.PI2)U=AMOD(U,PI2)
      DRA=((R*SIN(TAI))/V)*DVR+2.*(A/V)*((1.+E)/(1.-E))*(1.+COS(TAI))*
     1    DVI

      DRP=-((R*SIN(TAI))/V)*DVR+2.*(A/V)*((1.-E)/(1.+E))*(1.-COS(TAI))*
     1    DVI

      DP=3.*P*A*(V/MU)*DVI

      DA=2.*A*A*(V/MU)*DVI

      DE=((R*SIN(TAI))/(A*V))*DVR+2.*((COS(TAI)+E)/V)*DVI

      DI=((R*COS(U))/H)*DVC

      DW=-((((1.+E*E)*COS(TAI)+2.*E)/(E*(1.+E*COS(TAI))*V))*DVR+2.*(SIN(T
     1   AI)/(E*V))*DVI-((R*SIN(U)*COS(I))/(H*SIN(I))))*DVC

      DOM=((R*SIN(U))/(H*SIN(I)))*DVC

      DU=-((R*SIN(U)*COS(I))/(H*SIN(I)))*DVC

      DTA=DU-DW

      RETURN
      END
      SUBROUTINE OUTD(J)

****THIS PROGRAM OUTPUTS THE THRUST INDUCED CHANGES TO THE ORBITAL
****PARAMETERS.

      COMMON/BURN/TAI,DVI,DVC,DVR
      COMMON/DELTA/DRA,DRP,DP,DA,DE,DI,DW,DOM,DU,DTA
      DATA PI/3.14159265359/

      DDVI=1000.*DVI
      DDVC=1000.*DVC
      DDVR=1000.*DVR
      DDI =DI*180./PI
      DDW=DW*180./PI
      DDO=DOM*180./PI
      DDU=DU*180./PI
      DDTA=DTA*180./PI
      TTA=TAI*180./PI

      IF(J.NE.1) GO TO 20
      PRINT 9
    9 FORMAT(////,5X,*THRUST PARAMETERS AND INDUCED CHANGES IN ORBITAL P
     1ARAMETERS*)
```

```
    3               *ARGUMENT OF PERIGEE                  =*,G16.10,*DEG*/5X,
    4               *RIGHT ASCENSION OF ASCENDING NODE=*,G16.10,*DEG*/5X,
    5               *TRUE ANOMALY                         =*,G16.10,*DEG*)
C
C
      RETURN
      END
      SUBROUTINE MNAN(TAI,E,AM)
C
C*****THIS ROUTINE COMPUTES AN APPROXIMATE VALUE FOR THE MEAN
C*****ANOMALY ASSOCIATED WITH A GIVEN TRUE ANOMALY TO THIRD
C*****ORDER IN ECCENTRICITY.
C
      AM=TAI-2.*E*SIN(TAI)+0.75*E*E*SIN(2.*TAI)-0.33333*E*E*E*SIN(3.*
     1   TAI)
C
C
      RETURN
      END
      SUBROUTINE OUTC(X,Y,Z,XD,YD,ZD,R,V)
C
C*****THIS ROUTINE OUTPUTS CARTESIAN POSITION AND VELOCITY COMPONENTS,
C*****AS WELL AS THE ASSOCIATED RADIUS AND SPEED.
C
      PRINT 10,X,Y,Z,XD,YD,ZD,R,V
   10 FORMAT(/,10X,*X      =*,G16.10,*KM*/10X,
     1              *Y      =*,G16.10,*KM*/10X,
     1              *Z      =*,G16.10,*KM*/10X,
     1              *XDOT   =*,G16.10,*KM PER SEC*/10X,
     1              *YDOT   =*,G16.10,*KM PER SEC*/10X,
     1              *ZDOT   =*,G16.10,*KM PER SEC*/10X,
     1              *RADIUS=*,G16.10,*KM*/10X,
     1              *SPEED =*,G16.10,*KM PER SEC*)
C
C
      RETURN
      END
      SUBROUTINE ADJUST
C
C*****THIS COMPUTES CHANGES TO ORBITAL PARAMETERS DUE TO IMPULSIVE
C*****VELOCITY CHANGES.
C
      COMMON/ELEM/A,E,I,W,O
      COMMON/BURN/TAI,DVI,DVC,DVR
      COMMON/DELTA/DPA,DPP,DP,DA,DE,DI,DW,DOM,DU,DTA
C
      REAL I,MU
C
      DATA MU/398600.8/,PI/3.14159265359/
C
      R=A*(1.-E*E)/(1.+E*COS(TAI))
C
      P=2.*PI*(((A*A*A)/MU)**.5)
      PI2=2.*PI
      V2=MU*((2./R)-(1./A))
```

```
         V=VBR+(J-1)*VGR
         IF(IDC.EQ.0)GO TO 121
         IF(IDC.EQ.1)GO TO 122
         DVR=V
         DVI=0.0
         DVC=0.0
         GO TO 123
 121     DVI=V
         DVR=0.0
         DVC=0.0
         GO TO 123
 122     DVC=V
         DVR=0.0
         DVI=0.0
 123    CONTINUE
C
C
        DO 130  K=1,IJA
          TAI=AB+(K-1)*AG
C
          CALL ADJUST
C
          CALL OUTD(K)
C
 130    CONTINUE
 120     CONTINUE
C
C
      STOP
C
C
C*****ENTER MODE=2 PROCESSING
C
C
 200  PRINT 10
      PRINT 210
 210  FORMAT(/  ,1X,*MODE=2 ORBIT ADJUST DESIGN*)
C
C
      READ *,DPCH,DAPC
C
      CALL REQCH(DPCH,DAPC)
C
      GO TO 220
C
      END
      SUBROUTINE OUTK(A,E,INC,PER,RA,ANOM)
      REAL INC
C
C*****THIS ROUTINE OUTPUTS KEPLERIAN ELEMENTS
C
      PRINT 10,A,E,INC,PER,RA,ANOM
   10 FORMAT (/,5X,*SEMIMAJOR AXIS                  =*,G16.10,*KM*/5X,
     1            *ECCENTRICITY                     =*,G16.10/5X,
     2            *INCLINATION                      =*,G16.10,*DEG*/5X,
```

```
      CALL ADJUST
C
      CALL OUTD(1)
C
      PRINT 14
   14 FORMAT(///,5X,*POST-ADJUST KEPLERIAN ELEMENTS AND CARTESIAN VECTOR
     1S*)
C
      A=A+DA
      E=E+DE
      INC=INC+DI*180./PI
      I=I+DI
      PER=PER+DW*180./PI
      W=W+DW
      RA=RA+DOM*180./PI
      O=O+DOM
      ANOM=ANOM+DTA*180./PI
      TAI=TAI+DTA
C
      CALL OUTK(A,E,INC,PER,RA,ANOM)
C
      CALL MNAN(TAI,E,AM)
C
      CALL POSVEL(A,E,I,AM,W,O,MU,X,Y,Z,XD,YD,ZD,R,V)
C
      CALL OUTC(X,Y,Z,XD,YD,ZD,R,V)
C
      STOP
C
C
C*****BEGIN MODE=1 PROCESSING
C
C
  100 READ *,ANB,ANE,ANG,IDC,VB,VE,VG
C
C*****CONVERT TO RADIAN MEASURE AND KM. PER SEC.
C
      AB=ANB*PI/180.
      AE=ANE*PI/180.
      AG=ANG*PI/180.
C
      VBR=VB/1000.
      VER=VE/1000.
      VGR=VG/1000.
C
C
      PRINT 10
      PRINT 110
  110 FORMAT(///,1X,*MODE=1 ORBIT PARAMETER CHANGE ENVELOPES*)
      PRINT 10
C
      IJA=((AE-AB)/AG)+2
      IJV=((VER-VBR)/VGR)+2
C
      DO 120  J=1,IJV
```

```
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C     *******************************************************************
C
C
      COMMON/ELEM/A,E,I,W,O
      COMMON/BURN/TAI,DVI,DVC,DVR
      COMMON/DELTA/DRA,DRP,DP,DA,DE,DI,DW,DOM,DU,DTA
C
      REAL INC,I,MU
C
      DATA PI/3.14159265359/,MU/398600.8/
C
C
C
      READ *, MODE
      READ *, A,E,INC
      READ *, PER,RA
C
C*****CONVERT DEGREES TO RADIANS
C
      I=INC*PI/180.
      W=PER*PI/180.
      O=RA*PI/180.
C
C*****SELECT PROPER MODE LOGIC
C
      IF(MODE.EQ.1) GO TO 100
      IF(MODE.EQ.2) GO TO 200
C
C*****ENTER THE MODE=0 PROCESSING
C
      READ *,ANOM,DELI,DELC,DELR
C
      TAI=ANOM*PI/180.
      DVI=DELI/1000.
      DVC=DELC/1000.
      DVR=DELR/1000.
C
      PRINT 10
   10 FORMAT(1H1)
      PRINT 11
   11 FORMAT(///,1X,*MODE=0 ORBIT ADJUST DESIGN*)
C
  220 PRINT 12
   12 FORMAT(///,5X,*PREADJUST KEPLERIAN ELEMENTS AND CARTESIAN VECTORS*
     1)
      CALL OUTK(A,E,INC,PER,RA,ANOM)
C
      CALL MNAN(TAI,E,AM)
C
      CALL POSVEL(A,E,I,AM,W,O,MU,X,Y,Z,XD,YD,ZD,R,V)
C
      CALL OUTC(X,Y,Z,XD,YD,ZD,R,V)
C
C*****COMPUTE THRUST INDUCED CHANGES TO ORBITAL PARAMETERS
C
```

```
                                                          08.39.13 03/11/83

      PROGRAM ORBADJ (INPUT,OUTPUT,TAPE6=OUTPUT)
C
C     ******************************************************************
C     *                                                                *
C     * THIS PROGRAM COMPUTES THE CHANGES PRODUCED IN KEPLERIAN        *
C     * ELEMENTS AND OTHER RELATED ORBITAL PARAMETERS DUE TO IMPULSIVE *
C     * THRUSTING. THREE COMPUTATIONAL MODES ARE AVAILABLE AND ARE     *
C     * DELINEATED IN THE INPUT CARD STRUCTURE BELOW:                  *
C     *                                                                *
C     *                                                                *
C     * CARD 1: COMPUTATIONAL MODE FLAG (MODE). FOR                    *
C     *        MODE=0    ORBITAL PARAMETER CHANGES AND PRE- AND POST-  *
C     *                  ORBIT ADJUST KEPLERIAN ELEMENTS AND THE       *
C     *                  ASSOCIATED CARTESIAN POSITION AND VELOCITY    *
C     *                  COMPONENTS ARE COMPUTED BASED UPON A USERS    *
C     *                  DESIGN.                                       *
C     *        MODE=1    ORBITAL PARAMETER CHANGES ARE COMPUTED FOR A  *
C     *                  USER SPECIFIED DELTA-VELOCITY RANGE AND       *
C     *                  GRANULARITY AND IGNITION TRUE ANOMALY RANGE   *
C     *                  AND GRANULARITY.                              *
C     *        MODE=2    AN INTRACK DELTA-VELOCITY AND IGNITION TRUE   *
C     *                  ANOMALY ARE COMPUTED FOR A USER SPECIFIED     *
C     *                  PERIOD AND ARGUMENT OF PERIGEE CHANGE. ALSO   *
C     *                  COMPUTED ARE THE ASSOCIATED CHANGES IN THE    *
C     *                  ORBITAL PARAMETERS.                           *
C     *                                                                *
C     * CARD 2: FIRST KEPLERIAN ELEMENT CARD CONTAINING IN FREE FORMAT *
C     *         THE SEMI-MAJOR AXIS IN KILOMETERS, THE ECCENTRICITY,   *
C     *         AND THE INCLINATION IN DEGREES.                        *
C     *                                                                *
C     * CARD 3: SECOND KEPLERIAN ELEMENT CARD CONTAINING IN FREE FORMAT*
C     *         THE ARGUMENT OF PERIGEE AND RIGHT ASCENSION OF THE     *
C     *         ASCENDING NODE BOTH EXPRESSED IN DEGREES.              *
C     *                                                                *
C     * FOR MODE=0 ONLY :                                              *
C     *                                                                *
C     * CARD 4: IGNITION TRUE ANOMALY IN DEGREES, IN-TRACK VELOCITY    *
C     *         IMPULSE IN METERS PER SECOND, CROSS-TRACK VELOCITY     *
C     *         IMPULSE IN METERS PER SECOND, AND RADIAL VELOCITY      *
C     *         IMPULSE IN METERS PER SECOND .                         *
C     *                                                                *
C     * FOR MODE=1 ONLY :                                              *
C     *                                                                *
C     * CARD 4: STARTING IGNITION TRUE ANOMALY, STOPPING IGNITION TRUE *
C     *         ANOMALY, IGNITION TRUE ANOMALY GRANULARITY ALL IN      *
C     *         DEGREES; IMPULSE DIRECTION CODE (=0 FOR IN-TRACK,=1    *
C     *         FOR CROSS-TRACK,=2 FOR RADIAL); ASSOCIATED STARTING    *
C     *         IMPULSE, STOPPING IMPULSE, AND IMPULSE GRANULARITY     *
C     *         (ALL IN METERS PER SECOND).                            *
C     *                                                                *
C     * FOR MODE=2 ONLY :                                              *
C     *                                                                *
C     * CARD 4: THE DESIRED PERIOD CHANGE IN SECONDS; THE DESIRED      *
C     *         CHANGE IN ARGUMENT OF PERIGEE IN DEGREES.              *
C     *                                                                *
```

APPENDIX A

LISTING OF PROGRAM ORBADJ

impulse range and granularity and ignition true anomaly range and granularity. The last mode computes the in-track velocity impulse and ignition true anomaly required to produce a user-supplied period change and argument of perigee rotation. Changes in the orbital parameters are also computed, as well as the associated preadjust and postadjust Keplerian elements and Cartesian position and velocity components. A listing of this program is provided in Appendix A. Samples of ORBADJ output are presented in Appendix B.

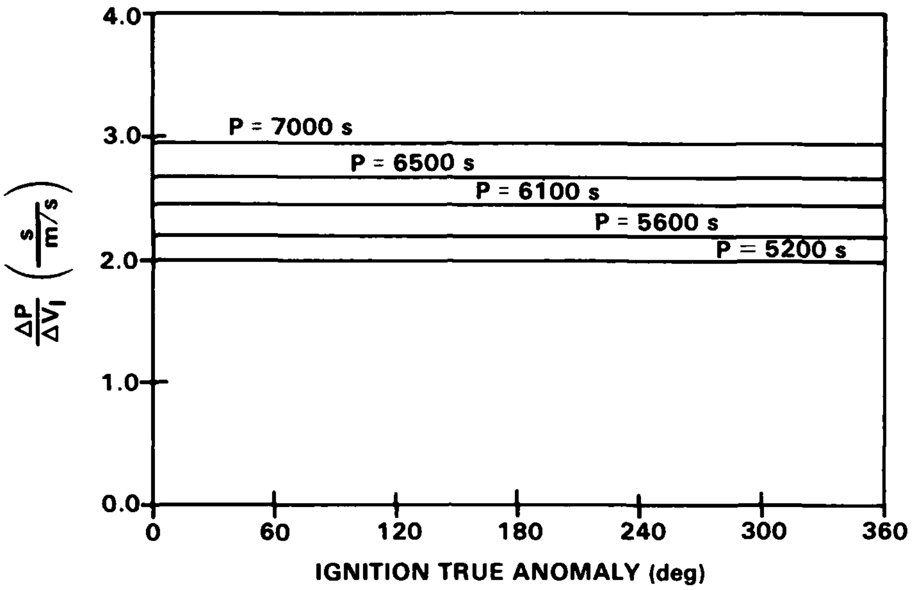

FIGURE 9. CHANGE IN ORBITAL PERIOD PER UNIT IN-TRACK VELOCITY IMPULSE

To illustrate the utility of Figures 1 through 9, consider the simple example where an orbit adjust must be designed for a low-altitude satellite operating in a 5200-s orbit. It is required that this adjust increase the period by 40 s with no corresponding change in perigee distance. From Figure 9 it is seen that an in-track velocity impulse of approximately 20 m/s applied at any true anomaly will increase the period by 40 s. Since no change in perigee distance is wanted, the thrust must be applied at perigee (i.e., a true anomaly of 0°). However, as can be seen from Figures 3 and 7, the eccentricity and apogee distance will be increased by about 5.1×10^{-3} and 66 km, respectively. Since cross-track thrusting is not applied, the inclination, right ascension of the ascending node, and true argument of latitude will not be changed.

REMARKS CONCERNING PROGRAM ORBADJ

The exact impulsive thrust equations of the Formulations section have been implemented into an NSWC computer program called ORBADJ. This program can be used to provide initial orbit adjust designs and can operate in one of three different user selectable modes. The first mode computes orbital parameter changes, pre- and post-orbit adjust Keplerian elements, and the associated Cartesian position and velocity components based on a user-supplied design. The second mode computes orbital parameter changes based on a user-supplied velocity

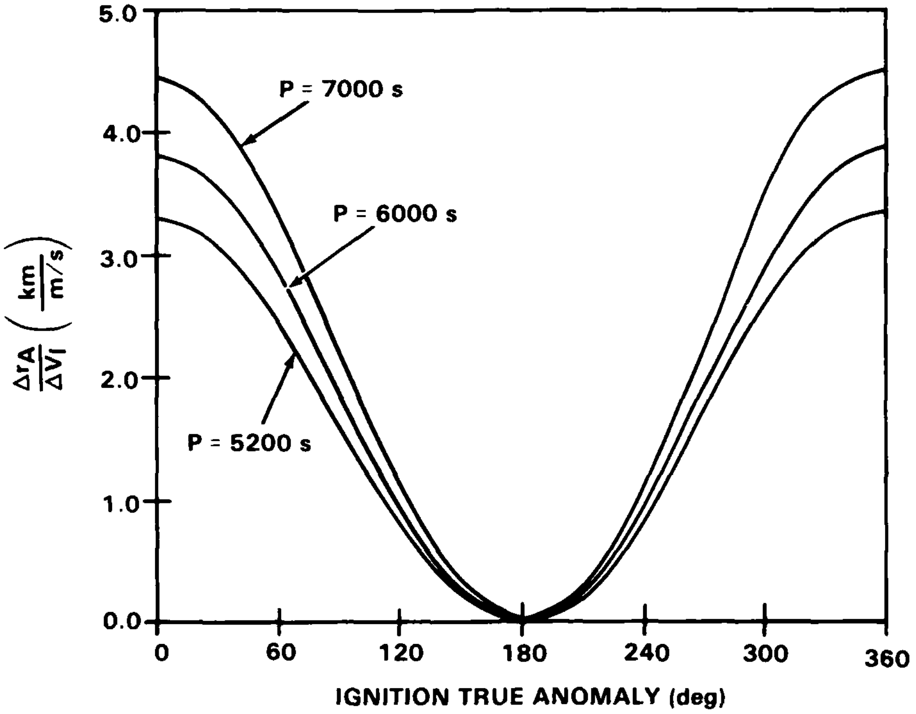

FIGURE 7. CHANGE IN APOGEE RADIAL DISTANCE PER UNIT IN-TRACK VELOCITY IMPULSE

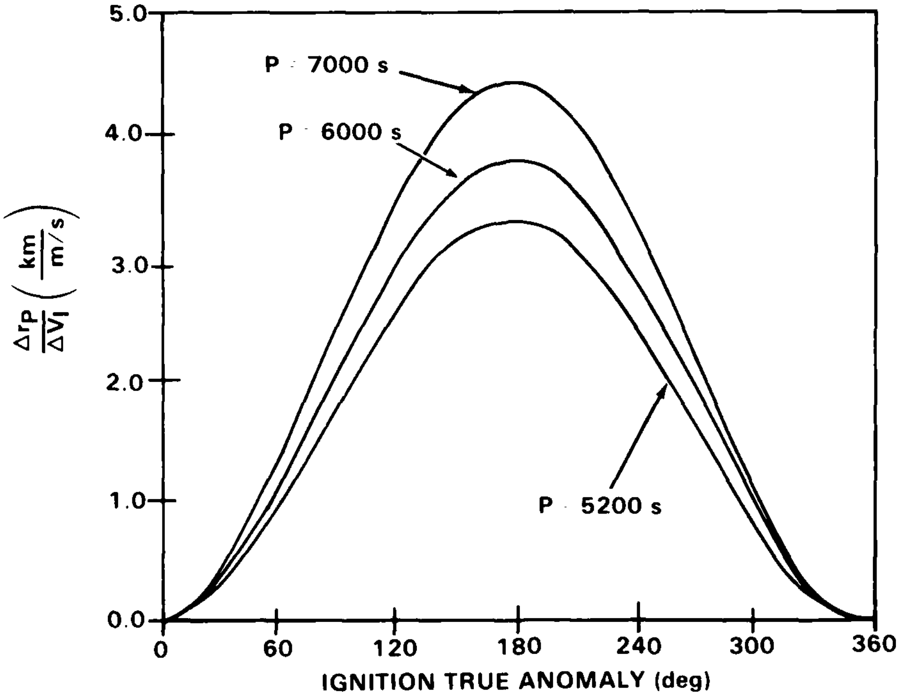

FIGURE 8. CHANGE IN PERIGEE RADIAL DISTANCE PER UNIT IN-TRACK VELOCITY IMPULSE

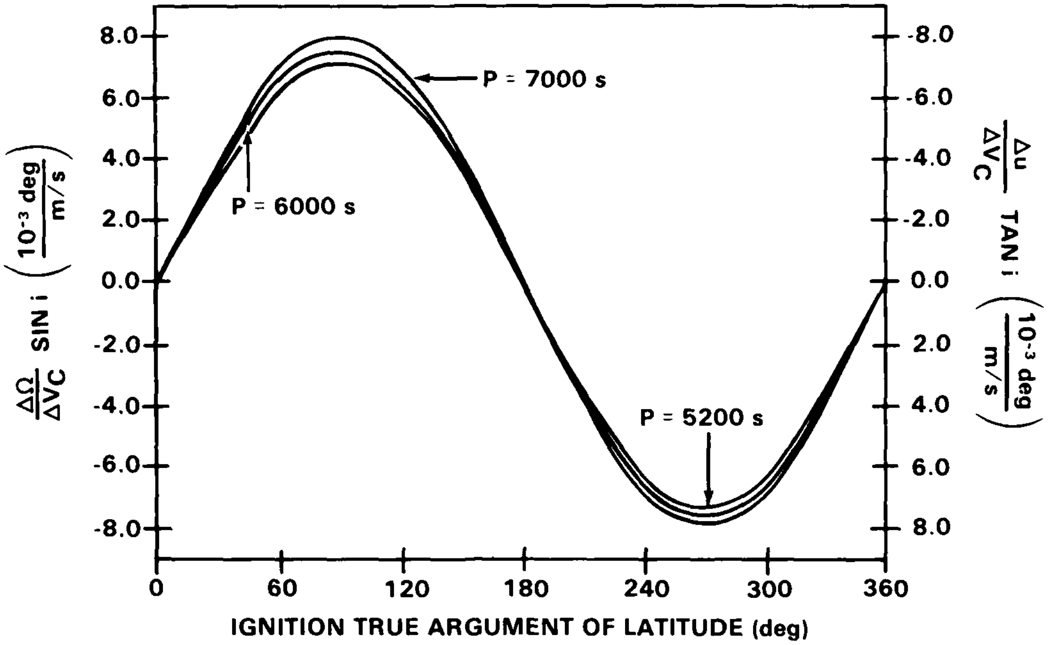

FIGURE 5. CHANGES IN RIGHT ASCENSION OF ASCENDING NODE AND TRUE ARGUMENT OF LATITUDE PER UNIT CROSS-TRACK VELOCITY IMPULSE

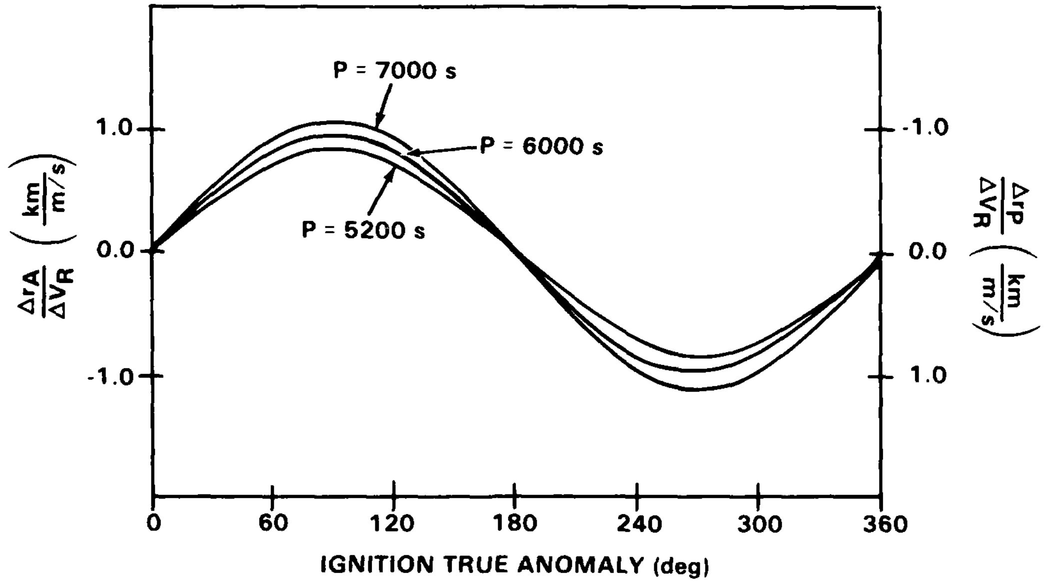

FIGURE 6. CHANGES IN APOGEE AND PERIGEE RADIAL DISTANCE PER UNIT RADIAL VELOCITY IMPULSE

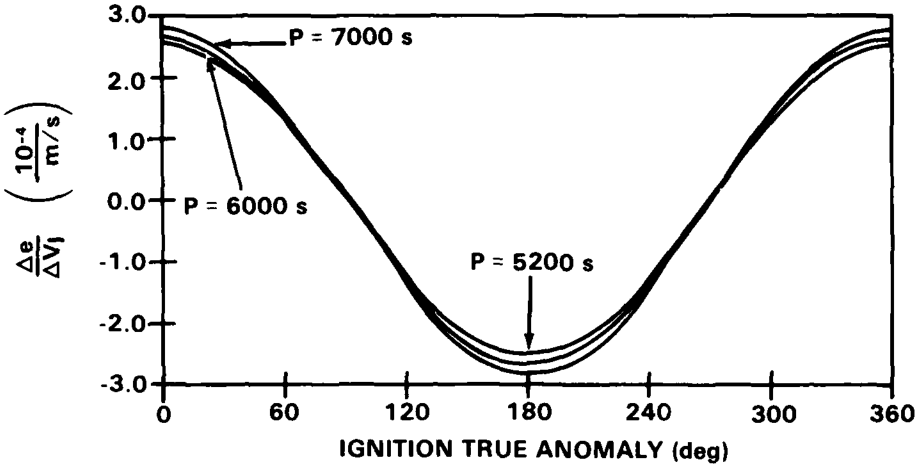

FIGURE 3. CHANGE IN ECCENTRICITY PER UNIT IN-TRACK VELOCITY IMPULSE

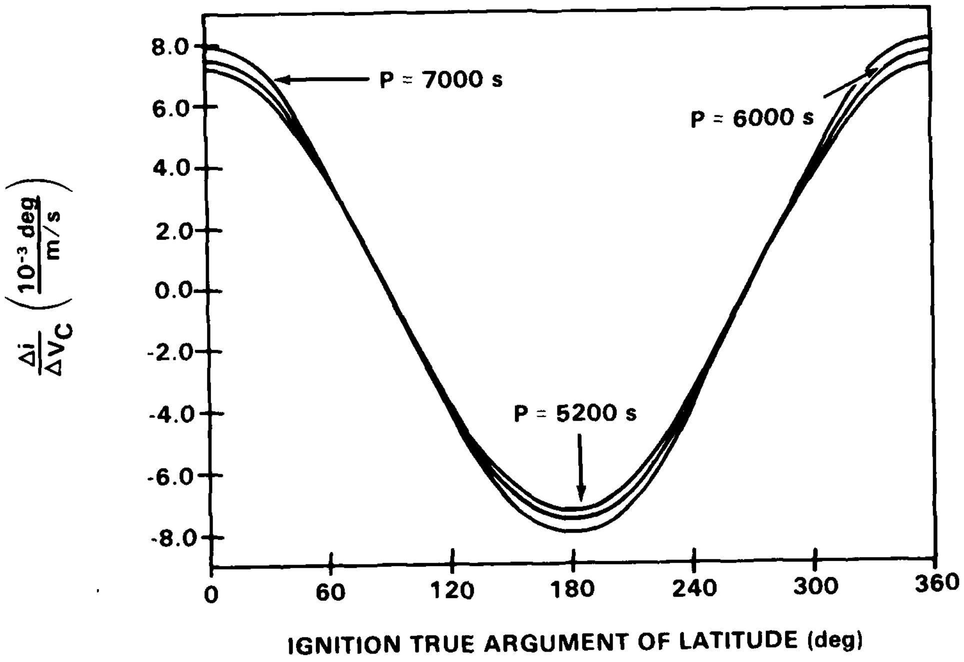

FIGURE 4. CHANGE IN INCLINATION PER UNIT CROSS-TRACK VELOCITY IMPULSE

APPENDIX B

SAMPLE ORBADJ OUTPUT

```
MODE=0 ORBIT ADJUST DESIGN


    PREADJUST KEPLERIAN ELEMENTS AND CARTESIAN VECTORS

    SEMIMAJOR AXIS                    = 6756.776000     KM
    ECCENTRICITY                      = .1810700000E-01
    INCLINATION                       = 96.97440000     DEG
    ARGUMENT OF PERIGEE               = 178.3081000     DEG
    RIGHT ASCENSION OF ASCENDING NODE= 336.0182000     DEG
    TRUE ANOMALY                      = 0.              DEG

         X      =-6068.735922    KM
         Y      = 2673.633495    KM
         Z      = 194.4317197    KM
         XDOT   = .1748423179    KM PER SEC
         YDOT   = .9011706505    KM PER SEC
         ZDOT   =-7.759773932    KM PER SEC
         RADIUS= 6634.431057     KM
         SPEED = 7.821030005     KM PER SEC



    THRUST PARAMETERS AND INDUCED CHANGES IN ORBITAL PARAMETERS


DVI(M/S) DVC(M/S) DVR(M/S) DA(KM)    DE     DI(DEG) DW(DEG) DOM(DEG) DU(DEG) DTA(DEG) DRA(KM) DRP(KM ) DP(SEC) TAI(DEG)

   5.000    0.000    0.000   8.96   .0013  0.0000    0.00    0.000     0.00    0.000  17.92     0.00   10.99     0.00


    POST-ADJUST KEPLERIAN ELEMENTS AND CARTESIAN VECTORS

    SEMIMAJOR AXIS                    = 6765.733872     KM
    ECCENTRICITY                      = .1940875565E-01
    INCLINATION                       = 96.97440000     DEG
    ARGUMENT OF PERIGEE               = 178.3081000     DEG
    RIGHT ASCENSION OF ASCENDING NODE= 336.0182000     DEG
    TRUE ANOMALY                      = 0.              DEG

         X      =-6068.725255    KM
         Y      = 2673.628796    KM
         Z      = 194.4313780    KM
         XDOT   = .1749542130    KM PER SEC
         YDOT   = .9617857777    KM PER SEC
         ZDOT   =-7.764740010    KM PER SEC
         RADIUS= 6634.419396     KM
         SPEED = 7.826635285     KM PER SEC
```

THRUST PARAMETERS AND INDUCED CHANGES IN ORBITAL PARAMETERS

```
DVI(M/S) DVC(M/S) DVR(M/S) DA(KM)   DE    DI(DEG) DW(DEG) DOM(DEG) DU(DEG) DTA(DEG) DRA(KM) DRP(KM ) DP(SEC) TAI(DEG)

  2.000    0.000    0.000   3.58  .0005  0.0000   0.00    0.000    0.00    0.000    7.17     0.00    4.40     0.00
                            3.58  .0005  0.0000    .42    0.000    0.00    -.419    7.05      .11    4.39    15.00
                            3.57  .0005  0.0000    .81    0.000    0.00    -.811    6.70      .45    4.39    30.00
                            3.56  .0004  0.0000   1.15    0.000    0.00   -1.150    6.15      .98    4.37    45.00
                            3.55  .0003  0.0000   1.41    0.000    0.00   -1.414    5.42     1.68    4.36    60.00
                            3.54  .0001  0.0000   1.58    0.000    0.00   -1.584    4.57     2.50    4.34    75.00
                            3.52  .0000  0.0000   1.65    0.000    0.00   -1.647    3.65     3.39    4.32    90.00
                            3.50 -.0001  0.0000   1.60    0.000    0.00   -1.599    2.72     4.29    4.30   105.00
                            3.49 -.0003  0.0000   1.44    0.000    0.00   -1.440    1.84     5.14    4.28   120.00
                            3.47 -.0004  0.0000   1.18    0.000    0.00   -1.180    1.08     5.87    4.26   135.00
                            3.46 -.0004  0.0000    .84    0.000    0.00    -.837     .50     6.43    4.25   150.00
                            3.46 -.0005  0.0000    .43    0.000    0.00    -.434     .13     6.79    4.24   165.00
                            3.46 -.0005  0.0000   -.00    0.000    0.00     .000    0.00     6.91    4.24   180.00
                            3.46 -.0005  0.0000   -.43    0.000    0.00     .434     .13     6.79    4.24   195.00
                            3.46 -.0004  0.0000   -.84    0.000    0.00     .837     .50     6.43    4.25   210.00
                            3.47 -.0004  0.0000  -1.18    0.000    0.00    1.180    1.08     5.87    4.26   225.00
                            3.49 -.0003  0.0000  -1.44    0.000    0.00    1.440    1.84     5.14    4.28   240.00
                            3.50 -.0001  0.0000  -1.60    0.000    0.00    1.599    2.72     4.29    4.30   255.00
                            3.52  .0000  0.0000  -1.65    0.000    0.00    1.647    3.65     3.39    4.32   270.00
                            3.54  .0001  0.0000  -1.58    0.000    0.00    1.584    4.57     2.50    4.34   285.00
                            3.55  .0003  0.0000  -1.41    0.000    0.00    1.414    5.42     1.68    4.36   300.00
                            3.56  .0004  0.0000  -1.15    0.000    0.00    1.150    6.15      .98    4.37   315.00
                            3.57  .0005  0.0000   -.81    0.000    0.00     .811    6.70      .45    4.39   330.00
                            3.58  .0005  0.0000   -.42    0.000    0.00     .419    7.05      .11    4.39   345.00
                            3.58  .0005  0.0000    .00    0.000    0.00    -.000    7.17     0.00    4.40   360.00
                            3.58  .0005  0.0000    .42    0.000    0.00    -.419    7.05      .11    4.39   375.00
```

```
MODE=2 ORBIT ADJUST DESIGN

    TO PRODUCE A  13.00 SEC PERIOD CHANGE
    AND A   -4.30 DEG PERIGEE ROTATION REQUIRES AN INTRACK VELOCITY IMPULSE OF     5.97 METERS PER SEC
     AT A TRUE ANOMALY OF  298.10 DEG

    CONVERGENCE OCCURRED IN     3 ITERATIONS


    PREADJUST KEPLERIAN ELEMENTS AND CARTESIAN VECTORS

    SEMIMAJOR AXIS                      = 6756.776000    KM
    ECCENTRICITY                        = .1810700000E-01
    INCLINATION                         = 96.97440000    DEG
    ARGUMENT OF PERIGEE                 = 178.3081000    DEG
    RIGHT ASCENSION OF ASCENDING NODE=  336.0182000    DEG
    TRUE ANOMALY                        = 0.             DEG

         X      =-3017.923892    KM
         Y      = 545.3392087    KM
         Z      = 5954.022666    KM
         XDOT   =-6.114472035    KM PER SEC
         YDOT   = 3.192597566    KM PER SEC
         ZDOT   =-3.529684383    KM PER SEC
         RADIUS= 6697.435732    KM
         SPEED = 7.748426893    KM PER SEC


    THRUST PARAMETERS AND INDUCED CHANGES IN ORBITAL PARAMETERS


DVI(M/S) DVC(M/S) DVR(M/S) DA(KM)   DE    DI(DEG) DW(DEG) DOM(DEG) DU(DEG) DTA(DEG) DRA(KM) DRP(KM ) DP(SEC) TAI(DEG)

   5.969    0.000     0.000  10.59  .0008  0.0000   -4.30    0.000     0.00    4.300  15.88     5.31   13.00   298.10


    POST-ADJUST KEPLERIAN ELEMENTS AND CARTESIAN VECTORS

    SEMIMAJOR AXIS                      = 6767.369902    KM
    ECCENTRICITY                        = .1886059852E-01
    INCLINATION                         = 96.97440000    DEG
    ARGUMENT OF PERIGEE                 = 174.0079456    DEG
    RIGHT ASCENSION OF ASCENDING NODE=  336.0182000    DEG
    TRUE ANOMALY                        = 4.300154355    DEG

         X      =-3017.851231    KM
         Y      = 545.3260852    KM
         Z      = 5953.879268    KM
         XDOT   =-6.119578949    KM PER SEC
         YDOT   = 3.195177603    KM PER SEC
         ZDOT   =-3.531986561    KM PER SEC
         RADIUS= 6697.274440    KM
         SPEED = 7.754568685    KM PER SEC
```

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