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STUDY ON THE STATION KEEPING MAINTENANCE FOR THE TPF MISSION

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The main goal of this paper is to extend the results of [2], related to the execution of the formation manoeuvres of the TPF constellation, including the controls for the station keeping and allowing a greater flexibility in the basic manoeuvres to be done by the formation.

INTRODUCTION

In 1995, Mayor and Queloz [5] detected for the first time a planet orbiting a nearby star (15.4 parsecs). Since then, the interest in the detection of extra-solar planets, in order to learn about the origin, evolution and composition of planetary systems, has been grown and at this moment more than 150 extra-solar planets have been found. Almost all of them have been discovered using indirect methods, mainly with the Doppler effect, with which it is possible to measure very small periodic changes in the velocity of the star, due to the orbiting planet gravitational force. However, direct imaging together with the spectroscopic analysis of the light coming from the planet, is the only way to obtain information about its nature and, eventually, to detect features which could indicate that the planet supported or could support life (this planets are referred in the literature as terrestrial or Earth-like planets).

Leaving aside the high resolution required for the detection of an Earth-like planet at a distance of 15 parsecs, the main problem for direct imaging is that planets are associated with a much brighter source of light. The contrast ratio between a Jupiter-like planet and its parent star can be of the order of 10^9, depending on the wavelength. One possible procedure to reduce this ratio, as well as the star diffraction pattern, is the use of nulling interferometry. Some experiments, such as the one conducted by Hinz *et al.* [4] to detect light from nearby sources as close as 0.2 arcsec around Betelgeuse after cancelling the light coming from the star, have already shown the viability and power of this procedure for the purpose under consideration.

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In order to increase the resolution of such an interferometer using telescopes with relatively small apertures, as well as to be able to detect the mid-infrared wavelengths of light that the atmosphere blocks and to low down the temperature of the telescopes –in order to reduce the infrared signal radiating from the telescopes themselves– it is convenient to place the interferometer outside the Earth atmosphere and far from the Earth–Moon enviroment. The orbits around the L_2 libration point of the Sun–Earth system provide an excellent site for such an observatory for different reasons:

1. They are easy and inexpensive to reach from Earth.
2. They provide a constant geometry for observation with more than half of the entire celestial sphere available at all times, since the Earth and the Sun are always alligned with the spacecraft and both at the same side of the line joining the three bodies.
3. The communications system design is simple and cheap, since the libration orbits around L_2 of the Sun–Earth system always remain close to the Earth at a distance of roughly 1.5 million km with a near-constant communications geometry.
4. Since the Sun is always behind the Earth, as seen from this location, orbits around L_2 are thermally very stable.

At this moment, two space interferometric missions, with the above mentioned purposes, have been foreseen: the ESA mission "Darwin" and the NASA mission "Terrestrial Planet Finder" (TPF). Although the geometry of the formation of spaceraft defining the interferometer is not completely fixed, their configurations are very similar: the spacecraft that act as collectors are always aligned (with the line joining them spiraling along a reference libration point orbit) and an additional spacecraft, not aligned with the collectors, completes the rigid body formation as a combiner of the light captured by them.

Leaving aside all the technological problems (such as the ones related to the devices providing very accurate metrology measurements, or the engines delivering an extremly low thrust) there are several questions that must be solved in connection with the analysis of such a complex mission. They are related to items such as:

- The extremely precise control required for the nulling interferometer.
- The control strategy required for keeping the formation of spacecraft moving along the reference libration point orbit selected.
- The deployment of the constellations as a function of the transfer procedure selected and the nominal orbit used. The spacecraft can be launched in different stages and the formation adquisition can take place at the end of the transfer to the libration point orbit with a similar fuel consumption for all of them.
- The execution of the basic manoeuvers, rotations and homotetic transformations, required for the reorientation of the constellation.

In a previous paper [2] we studied the control manoeuvers required for the pattern maintenance of the formation and its reconfiguration. Here we will show how the same kind of control manoeuvers used for the formation maintenance can be used for the station keeping along a certain libration point orbit around the L_2 point. We will mainly concentrate in the TPF formation, for other geometries the results can be easily extended.

THE GEOMETRY OF THE TPF FORMATION

The TPF formation is formed by five spacecrafts, four of them (the collectors) are aligned and evenly spaced and the fifth one (the combiner) forms an equilateral triangle with two of the aligned spacecrafts, as is shown in Figure 1.

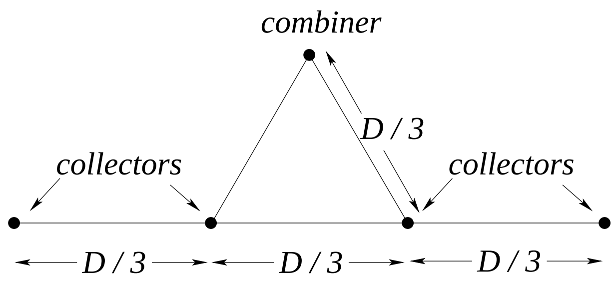

Figure 1: The geometry of the TPF formation.

The formation is required to rotate, as a rigid body, around the central point of the segment containing the four aligned spacecrafts. At the same time, this central point must follow a given nominal orbit, namely, a halo orbit around the L_2 libration point. In the sequel the central point will be referred as *the leader*.

For this purpose it is convenient to require the spacecrafts to move along the edges of suitable N-gons. In particular, we introduce 3 of them, all with the same number of edges and diameters equal to: D for the outermost one, $D/3$ for the innermost one and $D/\sqrt{3}$ for the one that will be followed by the combiner spacecraft, as is displayed in Figure 2.

In addition to the above data (number of edges and diameter), the inertial plane containing the formation must also be specified. This is done, due to the symmetry of the formation, with only two angles: the argument of the ascending node (Ω) and the inclination (i).

Due to the small size of the formation when compared with the halo orbit, it is convenient to use local coordinates with respect to the leader in the computations related to the satellites of the formation.

COST ESTIMATIONS IN FREE SPACE

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IMPLEMENTATION OF THE SIMULATOR

In the present paper computations have been done in the Earth-Sun restricted three

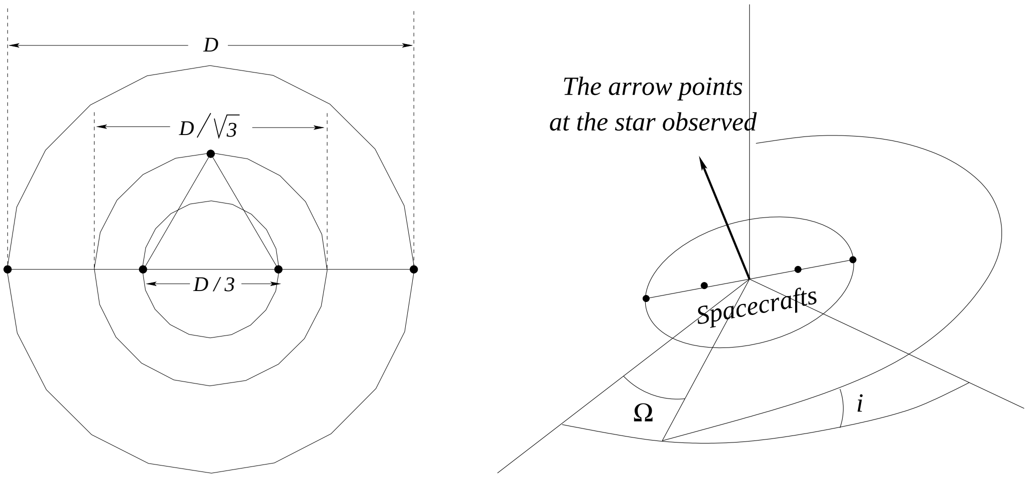

Figure 2: The N-gons used for the TPF formation and definition of the angles i and Ω.

body problem, although any other vectorfield may be used for the same purpose.

A halo or Lissajous orbit (see [3]) in the L_2 neighbourhood has been taken as a nominal path for the leader of the formation. Since the size of the formation is very small when compared to the one of the nominal orbit, the equations of motion corresponding to relative distances between satellites have been linearized about the non-linear nominal orbit.

Let us denote by $\dot{X} = F(X)$ the equations of motion of the RTBP. Here X is the state (position and velocity) of the satellite and F stands for the vectorfield. Given a nominal trajectory, $Z(t)$, solution of the former equations of motion, the linear model we consider are obtained by means of the variational equations,

$$(\Delta X)^{\cdot} = A(t)\Delta X, \tag{1}$$

where $A(t) = DF(Z(t))$ and ΔX mesure deviations in positions and velocities with respect to $Z(t)$. In the simulations the trajectory of each satellite is represented by a $\Delta X_i(t)$, $i = 1, \ldots, 5$.

Another point to account for because the huge difference between scales in the computations (nominal orbit with respect to the formation) is that RTBP units are not well suited to describe relative distances of few meters. To keep accuracy, specially during numerical integration or when relative distances between satellites have to be mesured and so differences between $\Delta X_i(t)$ must be computed, the model (1) has been implemented in any "local" units. This is, independent units for distances and time can be chosen, and from this units other magnitudes like velocity and acceleration follow. In our simulations distance has usually been taken in meters and time in minutes.

During the simulations it is also common the need of a nominal position and velocity when the satellite is in a vertex of a N-gon. For this purpose a small database containing the main characteristics of different N-gon of the simulation has to be filled. We consider that we switch from an N-gon to another when the pointing, size, number of edges or spin rotation is changed. So an N-gon is characterized by a radius, number of vertex, spin rate of rotation, and two angles (Ω and i as shown in Fig. 2) determining its pointing direction in inertial space.

Nominal position of a vertex is computed in a reference N-gon of the given size, shape and spin and then translated into inertial coordinates using the two pointing direction angles. Local units are used to express these inertial coordinates. Finally these coordinates are appropiately rotated and cast into the ones of (1).

THE CONTROL FOR THE FORMATION MAINTENANCE

The control procedure for the formation maintenance solves the following basic problem: consider a nominal path, defined by a certain initial state

$$(t_0, x_0, v_0),$$

and a true state of the spacecraft at $t = t_0$ (see Figure 3), given by

$$(t_0, x_0 + \Delta x, v_0 + \Delta v) = (t_0, x_t, v_t).$$

The goal is to recover the nominal path at a certain epoch $t_N > t_0$, this is, we want to reach the state

$$\phi_{t_N - t_0}(x_0, v_0),$$

where ϕ is the flow associated to the problem. The solution to this basic question can be easily adapted in the case that the final state of the spacecraft, at $t = t_N$, is not $\phi_{t_N-t_0}(x_0, v_0)$ but some well defined state: $\phi_{t_N-t_0}(x_0, v_0) + (\Delta x_N, \Delta v_N)$.

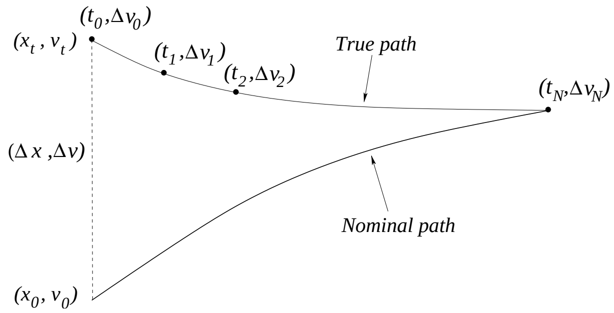

Figure 3: Illustration of the formation maintenance procedure.

This control problem has been solved as follows: we introduce a sequence of manoeuvres

$$\Delta v_0, \Delta v_1, ..., \Delta v_N,$$

to be done at some chosen epochs

$$t_0, t_1, ..., t_N.$$

The manoeuvres should then verify the following constraint

$$\phi_{t_N - t_{N-1}} (\dots \phi_{t_2-t_1} (\phi_{t_1-t_0}(x_t, v_t + \Delta v_0) + \Delta v_1) + \dots + \Delta v_{N-1}) + \Delta v_N = \phi_{t_N-t_0}(x_0, v_0).$$

Of course, there are infinitely many different values of $\Delta v_0, \Delta v_1, ..., \Delta v_N$ verifying the above equation. The ones selected minimise

$$\sum_{j=0}^{N} q_j \|\Delta v_j\|^2,$$

where q_0,...,q_N are weights which must be fixed in advance. For the simulations we have used

$$q_j = 2^{-j},$$

so the magnitude of two consecutive manoeuvres decays approximately by a factor of 2. For the solution of this problem, the flow ϕ can be replaced by its linear approximation, given by the variational equations, provided we are not far from the nominal path.

Contents of the input data files

Table 1: Coding for the distance and time units. The RTBP distance unit is the distance between the two primaries and 2π RTBP time units correspond to the time required by one primary to give a revolution around the other.

Code	Time unit	Code	Distance unit
0	RTBP	0	RTBP
1	days	1	km
2	hours	2	m
3	minutes	3	cm
4	seconds		

Using the convention defined by the coding given in Table 1, the simulation program starts reading the following data from the input file:

```
3               ! Time unit for the local vector-field
2               ! Distance unit for the local vector-field
3 4             ! Distance and time units defining the velocity unit
0.D0            ! Adimensional RTBP time associated to the initial integration epoch
```

Next, the characteristics of the basic nominal libration point orbit, a flag for the generation of data files, suitable for graphical representations, and the number of points written for the transfer and reconfiguration are defined.

```
15              ! Order of the Lindstedt Poincare expansion of the Lissajous obit
0.01  0.01      ! Alpha and beta amplitudes of the Lissajous obit
0.0  0.0        ! Phases (in radians) of the Lissajous obit
0 5 5           ! Output data flag, # points transfer, # points reconfiguration
```

The description of the geometry and the spin rate of the constellation are also defined in the input data file of the simulation program. In its actual version, each run of the program simulates the behaviour of one spacecraft of the formation so, for the full simulation of the formation, 5 runs are required. Each one with the following parameters for the different N-gons used:

```
#---------------------------- NGON Number 1 -----------------------------
20           ! Number of edges
90.0         ! Radius (meters)
45.0 60.0    ! Argument of the ascending node and inclination (degrees)
3            ! Spin rate (revolutions/day)

#---------------------------- NGON Number 2 -----------------------------
20           ! Number of edges
90.0         ! Radius (meters)
45.0 60.0    ! Argument of the ascending node and inclination (degrees)
3            ! Spin rate (revolutions/day)

#---------------------------- NGON Number 3 -----------------------------
20           ! Number of edges
51.96        ! Radius (meters)
45.0 60.0    ! Argument of the ascending node and inclination (degrees)
3            ! Spin rate (revolutions/day)

#---------------------------- NGON Number 4 -----------------------------
20           ! Number of edges
30.0         ! Radius (meters)
45.0 60.0    ! Argument of the ascending node and inclination (degrees)
3            ! Spin rate (revolutions/day)

#---------------------------- NGON Number 5 -----------------------------
20           ! Number of edges
30.0         ! Radius (meters)
45.0 60.0    ! Argument of the ascending node and inclination (degrees)
3            ! Spin rate (revolutions/day)
```

In the deployment of the constellation each spacecraft must reach the suitable edge of its associated N-gon. Once the deployment manoeuvres have finished the formation must start spining around the leader which, as we said, it moves along a nominal trajectory. To define the deployment and how each spacecraft evolve along the edges of the N-gon some additional data is required. For the different satellites of the formation, the following data is required:

```
#---------------------------- NGON Number 1 -----------------------------
0   0.0       ! Target vertex of the n-gon and phase of the vertex (degrees)
5.0 2         ! Time required for the transfer: value and unit time code
40  1         ! Number of jump manoeuvres along the N-gon and step (signed)
0.0 0         ! Time required for the reconfiguration: value and time code

#---------------------------- NGON Number 2 -----------------------------
0   180.0     ! Target vertex of the n-gon and phase of the vertex (degrees)
5.0 2         ! Time required for the transfer: value and unit time code
40  1         ! Number of jump manoeuvres along the N-gon and step (signed)
0.0 0         ! Time required for the reconfiguration: value and time code

#---------------------------- NGON Number 3 -----------------------------
0   90.0      ! Target vertex of the n-gon and phase of the vertex (degrees)
5.0 2         ! Time required for the transfer: value and unit time code
40  1         ! Number of jump manoeuvres along the N-gon and signed step
0.0 0         ! Time required for the reconfiguration: value and time code

#---------------------------- NGON Number 4 -----------------------------
0   0.0       ! Target vertex of the n-gon and phase of the vertex (degrees)
5.0 2         ! Time required for the transfer: value and unit time code
40  1         ! Number of jump manoeuvres along the N-gon and signed step
0.0 0         ! Time required for the reconfiguration: value and time code

#---------------------------- NGON Number 5 -----------------------------
0   180.0     ! Target vertex of the n-gon and phase of the vertex (degrees)
5.0 2         ! Time required for the transfer: value and unit time code
40  1         ! Number of jump manoeuvres along the N-gon and signed step
0.0 0         ! Time required for the reconfiguration: value and time code
```

Using any of the above different sets of data, the corresponding spacecraft will go from its state before the deployment to the suitable vertex of the N-gon in 5 hours. Once the vertex is reached, the spin motion (at 3 revolutions per day) starts. Since we ask for 40 jump manoeuvres with a step of one edges per manoeuver and the N-gon has 20 edges, each spacecraft will do 2 revolutions in the 20-gon in the positive sense (counterclockwise). As another example, a pair 40 -2 is defining 40 jumps with step 2 in clockwise sense. The satellite will do 4 revolutions following ten of the vertices. The last parameters of the input data set (reconfiguration time) are not used in the simulations.

As final input data, some characteristics on the control must be given. These are,

1. 1-sigma relative errors in the three components when performing the local precise formation maneuvers.

2. The time span (and units) allowed to cancel a certain error in the local maneuvers.
3. Number of controls to cancel local errors in the manoeuvre and values of the weights ($q_j = N^{-j}$) used used in the determination of these controls. If the value of the parameter N defining the weight is set equal to 1, then all the $q_j = 1$.
4. 1-sigma errors in position (km) and in velocity (cm/s) in the components of the leader position after Orbit Determination from ground.
5. 1-sigma relative errors in the performance of the station keeping maneuvers of the formation.
6. Rule of choice for the station keeping maneuvers. They can be performed at regular time spans or when the leader deviates more than a given distance from the nominal orbit.
7. Time span to be used in the controller related to the station keeping maneuvers. (The station keeping controller for the formation is the same one as the one to cancel local errors but other choices can be easily implemented).
8. Number of controls and weights to be used by the afore mentioned controller in order to compute the station keeping manoeuver.
9. 1-sigma errors in position (km) and in velocity (cm/s) to set the initial position of the leader with respect to the nominal orbit.
10. An initial seed for the random number generator.

An example of this set of data is the following (vcontrl.dti):

```
#************** CONTROL CHARACTERISTICS FOR sitnghc ********************
# -- Local maneuvers to keep the precise formation
0.05 0.05 0.05  ! xyz 1-sigma relative errors in the maneuvers
1.0 3           ! Time to cancel local errors: value and unit time code
5  2.           ! Number of controls and weights for local maneuvers
# -- Station Keeping Maneuvers to keep the formation at Li
10 10 10 .1 .1 .1 ! 1-sig err in pos (m) and vel (cm/s) after OD.
0.05 0.05 0.05  ! xyz 1-sigma rel errors in Li maintenance maneuvers
20.0 1          ! DT (days IND=1) or Dist to nominal (km IND=2) for STK man
50.0            ! DT horizon for the STK controller (days)
5  2.           ! Number of controls and weights for STK maneuvers
# -- Other things needed
1. 1. 1. 1. 1. 1. ! 1-sig errs in pos (km) & vel (cm/s) for ini leader wrt nom
-1              ! Seed for the random number generator (integer <0)
```

THE CONTROL PROCEDURE FOR THE STATION KEEPING

Since the reference libration orbit is highly unstable and the maneuvers for the formation maintenance are done locally, i.e. without a measurement of the drift of the leader with respect to the nominal orbit, some additional station keeping maneuvers are required in order to keep the leader in a vicinity of the nominal orbit.

There are many different strategies for the determination of the station keeping maneuvers: Floquet mode approach, target mode approach, minimisation of a suitable weighted cost function,... In practice, the results obtained with any of the above procedures do not give substantially different results. For the present report we have used a very simple one which also gives good results. The procedure performs a station keeping manoeuver using a similar algorithm that for the local ones as it is explained later. The user can simulate these maneuvers at a fixed time intervals or when the leader deviates a certain distance from the nominal orbit. In order to not interfere with the period of observations, for the execution of these type of maneuvers we select an epoch just before the formation starts a revolution around the N-gon.

As we previously stated, the station keeping manoeuver is computed using the same strategy as for the formation maintenance maneuvers. Recall that one formation maintenance manoeuver is composed of several control maneuvers of decreasing magnitude ($q_j = N^{-j}$). For the station keeping maintenance, we just use the first one ($j = 1$) of this sequence. This is a manoeuver which should done for all the spacecraft simultaneously.

To get an idea of the magnitude of the $\|\Delta v_j\|$ in a sequence of four weighted by $q_j = 2^{-j}$, $j = 1, ..., 4$, the following table gives their average values of a run of the simulation program. controls is:

j	$\|\Delta v_j\|$
1	$0.2135170848E-01$
2	$0.5083740113E-02$
3	$0.2541870057E-03$
4	$0.1525122034E-02$

When these maneuvers are used for station keeping purposes, only the first one (which is at least one order of magnitude larger that the others) is done.

SOME NUMERICAL EXAMPLES

As it has been previously mentioned, the input parameters that control the programs are configured in two files: `sitnghc.dti` for the characteristics of the mission to be simulated and `vcontrl.dti` for the parameters and variables related to the control both local and at the vicinity of L_2.

When executing the program `sitnghc1.exe`, it reads these files and produces an output showing the progress in the simulation. The output contains information about the "jump" that it is visiting the first vertex of the N-gon as well as the time since the last station keeping manoeuver and the distance of the leader from the nominal orbit. The line ends with a 0 in case that no station keeping manoeuver is advised for the current time or with a

1 in case that a station keeping manoeuver is advised. In this latter case, the following line contains the time and the magnitude of the applied manoeuver to each one of the spacecraft.

```
STK-MAN TEST:     1 vtx,    0.21 days,     0.396 km, 0
STK-MAN TEST:    21 vtx,    0.54 days,     0.394 km, 0
STK-MAN TEST:    41 vtx,    0.88 days,     0.385 km, 0
STK-MAN TEST:    61 vtx,    1.21 days,     0.384 km, 0
STK-MAN TEST:    81 vtx,    1.54 days,     0.380 km, 0
......       .........
STK-MAN TEST:  1181 vtx,   19.87 days,     0.401 km, 0
STK-MAN TEST:  1201 vtx,   20.21 days,     0.413 km, 1
STK MAN. T (days) & DV (cm/s):   20.2083333  0.0299118486
STK-MAN TEST:  1221 vtx,    0.33 days,     0.390 km, 0
STK-MAN TEST:  1241 vtx,    0.67 days,     0.388 km, 0
STK-MAN TEST:  1261 vtx,    1.00 days,     0.375 km, 0
....         .........
```

When the simulation ends, the program produces an output containing final statistics both for local and station keeping maneuvers. For the local maneuvers we can find the number of reconfigurations done, these are the number of sets of local maneuvers that have been performed and some magnitudes that are given in the units according to the codes stated in the beginning of the `sitnghc.dti` input file. The information for the station keeping maneuvers is given in days and in cm/s.

```
....         .........
STK-MAN TEST:  4981 vtx,    2.33 days,     0.421 km, 0
 ---------- FINAL STATISTICS LOCAL MAN -----------
 TOTAL SIMULATED TIME (days):  83.5416667
 NUMBER OF LOCAL RECONFIG. MANEUVERS DONE:  5000
 AVERAGE COST TO CANCEL REC ERR:   0.0248505171
 MIN AND MAX OF ABOVE:  0.000326525895  0.0907993193
 AVERAGE COST RECONF MANOEUVER:   0.510075581
 MIN AND MAX OF ABOVE:  0.509825443  1.7439637
 AVERAGE RELATIVE COST:   0.000640466065
 CONTROLS USED IN EACH LOCAL RECONF:  5
 AVERAGE, MIN and MAX SEQUENCES OF THE CONTROLS:
  1  0.1782170007E-01  0.2341700390E-03  0.6511728614E-01
  2  0.4916331054E-02  0.6459863143E-04  0.1796338928E-01
  3  0.4609060363E-03  0.6056121688E-05  0.1684067745E-02
  4  0.7681767271E-03  0.1009353617E-04  0.2806779575E-02
  5  0.8834032362E-03  0.1160756659E-04  0.3227796511E-02
 ---------- FINAL STATISTICS STK MAN -----------
 NUMBER OF STK MAN:  4
 MIN and MAX (cm/s):  0.0179611622  0.048713981
 AVERAGE MANOEUVER (cm/s):  0.0292219778
```

```
 MIN and MAX T (days):  20.  20.3333333
 AVERAGE TIME BETWEEN MAN (days):  20.21875
```

Program `sitnghc2.exe` does the same simulation but it in the output it includes information about each one of the local reconfiguration maneuvers. Units of the magnitudes are according to the codes selected in the input file `sitnghc.dti`. An example for the first two reconfiguration maneuvers is the following one,

```
STK-MAN TEST:     1 vtx,    0.21 days,     0.396 km, 0
----------------------------------
 TIME, CNTRL COST, ERRP, ERRV_before, ERRV_after:
  1  0.3000000000E+03   0.0586761   0.0000000   0.0709425   0.0122663
  2  0.3002500000E+03   0.0161865   0.0018400   0.0122663   0.0039202
  3  0.3005000000E+03   0.0015175   0.0012519   0.0039202   0.0054377
  4  0.3007500000E+03   0.0025291   0.0004363   0.0054377   0.0029085
  5  0.3010000000E+03   0.0029085   0.0000000   0.0029085   0.0000000
 TOTAL COST OF REFORMATION:   0.0818177796
 COST OF INITIAL MANOEUVER:   1.7439637
 ----------------------------------
 TIME, CNTRL COST, ERRP, ERRV_before, ERRV_after:
  1  0.3240000000E+03   0.0188729   0.0000000   0.0228183   0.0039454
  2  0.3242500000E+03   0.0052063   0.0005918   0.0039454   0.0012609
  3  0.3245000000E+03   0.0004881   0.0004027   0.0012609   0.0017490
  4  0.3247500000E+03   0.0008135   0.0001403   0.0017490   0.0009355
  5  0.3250000000E+03   0.0009355   0.0000000   0.0009355   0.0000000
 TOTAL COST OF REFORMATION:   0.0263163209
 COST OF INITIAL MANOEUVER:   0.509830093
 ----------------------------------
 ..........  .........
```

CONCLUSIONS

ACKNOWLEDGEMENTS

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