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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 [1], 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 [2] 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 grown tremendously and at the present more than 150 extra-solar planets have been detected. 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's 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 (these planets are referred to 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.* [3] 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 lower 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's 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 many 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 Sun, Earth, and Moon are always behind the spacecraft in halo orbit around L_2.
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, Earth, and Moon are always behind the spacecraft in halo orbit around L_2, this provides a very stable thermal environment.

Currently, two space interferometric missions, with the above mentioned purposes, have been planned: the ESA "Darwin" mission and the NASA "Terrestrial Planet Finder" mission (TPF, see Beichman *et al.* [4]). Although the geometry of the formations of spaceraft defining the interferometer are not yet 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 the collector spacecraft.

Leaving aside all the technological problems (such as those related to the devices providing highly 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 homothetic (scale) transformations, required for the reorientation of the constellation.

In a previous paper [1] 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 on the TPF formation, for other geometries the results can be easily extended.

THE GEOMETRY OF THE TPF FORMATION

The TPF constellation is formed by 5 spacecraft: 4 of them (the collectors) are aligned and evenly spaced and the fifth (the combiner) forms an equilateral triangle with two of the aligned spacecraft, as is shown in Figure 1.

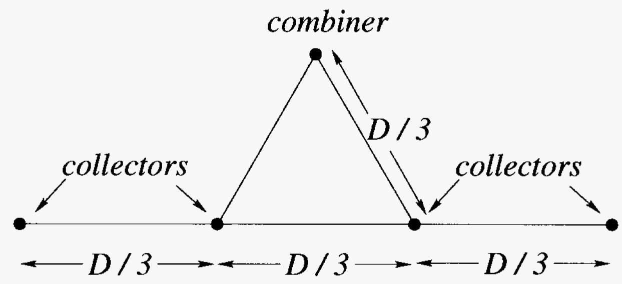

Figure 1: The geometry of the TPF formation.

The formation is required to rotate, as a rigid body, around the central point of the segment containing the 4 aligned spacecraft. 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 spacecraft 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 parameters (number of edges and diameter), the inertial plane containing the formation must also be specified. This can be specified, 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 spacecraft of the formation.

COST ESTIMATIONS IN FREE SPACE

We present the cost estimation for a formation in free space first to gain some insight on the performance cost. Let us assume that the N-gon has radius R, then the longitude of each edge of the N-gon is $2R\sin\frac{\pi}{N}$ and the total length of the N-gon is $L = 2RN\sin\frac{\pi}{N}$.

Let us assume that the N-gon spins at a rate of α revolutions per unit of time. Then

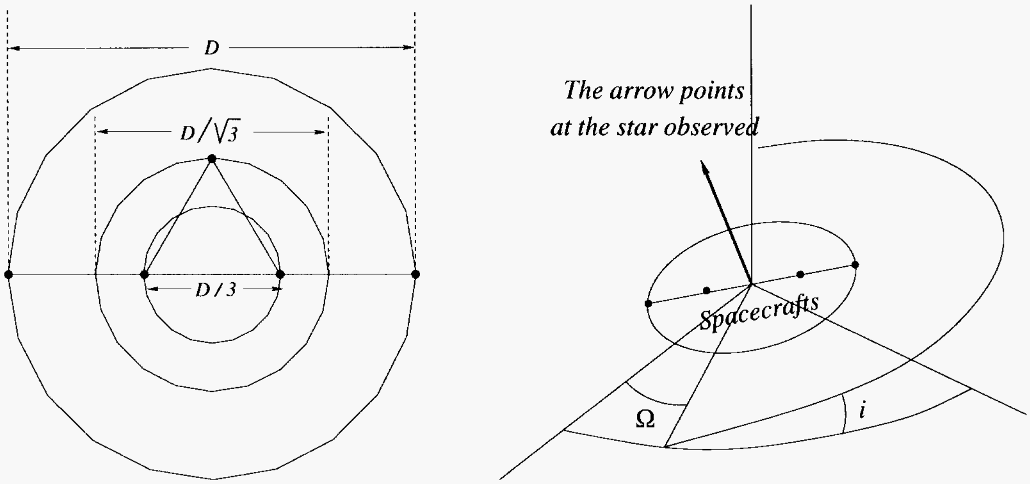

Figure 2: The N-gons used for the TPF formation and definition of the angles i and Ω.

the velocity of the spacecraft, assumed with constant modulus all the way, is $V = L\alpha = 2RN\alpha\sin\frac{\pi}{N}$. The ΔV that we must apply at each vertex to change its direction by an angle $\theta = 2\pi/N$ is,

$$\Delta V = 2V\sin\frac{\theta}{2} = 4RN\alpha\sin^2\frac{\pi}{N},$$

and the total ΔV expended at each revolution,

$$\Delta V_T = N\Delta V = 4RN^2\alpha\sin^2\frac{\pi}{N}.$$

This is similar to an inclination change which is bet performed when the spacecraft is in the line of intersection of the two orbit planes.

We note that as the numbers of vertices tend to infinity and the control becomes a continuous low thrust control to keep the formation spinning in a circle of radius R, the modulus of the needed acceleration tends to the well known value $4R\pi^2\alpha^2 = R\omega^2$, where $\omega = 2\pi\alpha$ denotes the angular velocity in radians per unit of time. In the same way ΔV_T tends to $4R\pi^2\alpha = 2\pi R\omega$. As an example in this limiting case, to keep a spacecraft of 100 kg spinning at 3 revolutions per day in a circle of radius 100 m needs a continuous thrust of 4.76×10^{-4} N pointing towards the center of rotation.

IMPLEMENTATION OF THE SIMULATOR

In the present paper computations have been performed in the Sun-Earth restricted three body problem, although any other vectorfield (force field) may be used for the same purpose.

A halo or Lissajous orbit (see [5]) in the L_2 neighbourhood has been taken as the nominal path for the leader of the formation. Since the size of the formation is very small when compared to the size of the nominal orbit, the equations of motion corresponding to relative distances between spacecraft 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 spacecraft 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,

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

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

Another point to account for, due to 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 a few meters. To maintain accuracy, especially during numerical integration or when relative distances between spacecraft have to be measured and so the differences between $\Delta X_i(t)$ must be computed, the model (1) has been implemented in "local" units. That is, independent units for distances and time can be chosen, and from these 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 to need the nominal position and velocity when the spacecraft is at a vertex of the N-gon. For this purpose a small database containing the main characteristics of different N-gons for the simulation has to be created. We consider that we switch from one 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 vertices, 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 $t_N > t_0$, that 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: $\phi_{t_N - t_0}(x_0, v_0) + (\Delta x_N, \Delta v_N)$.

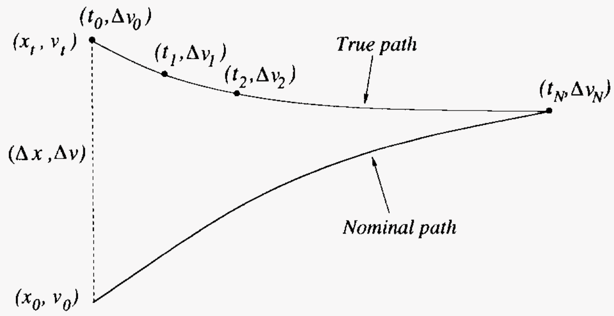

Figure 3: Illustration of the formation maintenance procedure.

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

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

to be performed at some chosen epochs

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

The manoeuvres should then satisfy 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 $\Delta v_0, \Delta v_1, ..., \Delta v_N$ satisfying the above equation. The ones selected should minimise

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

where q_0,...,q_N are weights which must be determined 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. A similar strategy was proposed by Howell and Pernicka [6] in 1993.

Contents of the input data files

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
```

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 make one 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		

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 stated earlier, moves along a nominal trajectory. To define the deployment and how each spacecraft evolves along the edges of the N-gon, some additional data are required. For the different spacecraft of the formation, the following data are 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 spacecraft 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 in the determination of these controls. If the value of the parameter N defining the weight is set 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, minimization 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 paper 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 which will be explained later. One 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 observation period, 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 be done for all the spacecraft simultaneously.

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

j	$\|\Delta v_j\|$ (cm/s)
1	0.02135170848
2	0.005083740113
3	0.0002541870057
4	0.001525122034

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 performed. If a typical station keeping maneuver is about 0.02 cm/s ms indicated by the table above, it may be too small to be performed by available thrusters. One can easily defer such maneuvers until larger errors have built up. For example, this was done for the Genesis mission.

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 of 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 where no station keeping manoeuver is advised for the current time or with a 1 in case where 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 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

Our simulations on a 20-sided polygon formation with 100 m diameter and 3 rotations per day required station keeping maneuvers of 0.03 cm/s every 20 days. Over 10 years (5 years nominal mission plus 5 years extended mission), this amounts to just 0.055 m/s of total Δv per spacecraft. Of course, this requires roughly 18 station keeping maneuvers per year. But seeing how small the Δv requirement is, one can easily wait several months to perform the station keeping maneuvers. In a subsequent paper, we will examine this issue more closely with parametric studies and more realistic force models including JPL ephemerides and solar radiation pressure. From experience with libration orbits, we do not expect the more accurate force models would require any significant increase in the propulsion requirements.

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References

[1] G. Gómez, M.W. Lo, J.J. Masdemont, and K. Museth. "Simulation of Formation Flight near L2 for the TPF Mission," *In ASS/AIAA Space Flight Mechanics Conference*. Paper AAS 01-305, 2001.

[2] M. Mayor and D. Queloz. "A Jupiter-Mass Companion to a Solar-Type Star," *Nature*, 378, 355-359, 1995.

[3] P.M. Hinz, R.P. Angel, W.F. Hoffmann, D.W. McCarthy, P.C. McGuire, M. Cheselka, J.L. Horan, and N.J. Woolf. "Imaging Circumstellar Environments with a Nulling Interferometer," *Nature*, 395, 251–253, 1998.

[4] C.A. Beichman, N.J. Woolf, and C.A. Lindensmith (editors). "The Terrestrial Planet Finder (TPF): A NASA Origins Program to Search for Habitable Planets," *JPL Publication* 99-003, (http://tpf.jpl.nasa.gov/), 1999.

[5] G. Gómez, M.W. Lo, and J.J. Masdemont (Eds.) "Libration Point Orbits and Applications" *World Scientific*, 2003.

[6] K. Howell, H. Pernicka. "Station Keeping Method for Libration Point Trajectories," *Journal of Guidance, Control, and Dynamics*, Vol. 16 No. 1, 151-159, Jan.-Feb. 1993.

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