POINTING DYNAMICS OF TETHER-CONTROLLED FORMATION FLYING FOR SPACE INTERFEROMETRY

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ABSTRACT

The pointing dynamics of a tethered interferometer composed of one central combiner and two radial collectors orbiting in an Earth trailing, heliocentric orbit is analyzed. This is one of the configurations envisioned for future space interferometry applications. The tether provides the control of the spacecraft formation by keeping the two light collectors and the central combiner aligned while spinning about the boresight of the interferometer. The range of allowable spin velocities is computed based on the light collection requirements and the mechanical characteristics of the tether. Analytical and numerical experiments described in the paper show that the environmental perturbations are sufficiently weak so that the pointing errors of a well-designed tethered interferometer are within the required limits. A multi-line tether is also proposed with the capability of surviving 5 years with a probability of survival to micrometeoroid impact higher than 99%.

INTRODUCTION

Formation flying has recently been proven ([10], [11], [12], and [13]) to be an extremely powerful and revolutionary approach for space based scientific exploration, and many efforts are being made to bring this technology to the forefront as quickly as possible.

The use of kilometer-size tethers is a possible and versatile solution for precision control of spacecraft formations with baselines from tens of meters up to a few kilometers. This concept seems to be very suitable for space interferometry purposes, particularly for space based imaging interferometry. In fact the motion of the required collectors during the coverage of the sampled data space in frequency domain (u-v plane) would be prohibitive in terms of fuel consumption if free flying separated spacecraft were employed for a mission of equal duration [1,2].

In a spinning tether configuration the image synthesis is performed by simply reeling in and out the collectors, and making them follow a spiral movement that leads to a rather complete coverage of the u-v Fourier plane. The energy needed by the tether reels for the reconfiguration (retrieval phase) can be simply provided by solar panels, and the only fuel expenditure required is the one necessary for spacecraft retargeting after an observation has been completed. In this way, a tethered system can offer a much faster and more economic observation scheme with respect to a free flying configuration.

The fundamental question is whether an appropriately controlled tethered system is able to achieve a relative position and bearing accuracy between vehicles and a target pointing stability at the level of the separated formation flying configurations. Those limits are particularly stringent in the case of space interferometry applications with high resolution goals. In interferometry, the Optical Path Delay for the source being observed needs to be as stable and as small as possible to improve fringe tracking efficiency during the observations. Consequently the two tether
branches (see Figure 1) are required to maintain their lengths at the cm level and the deviation of the rotational plane direction from the line of sight has to be less than one arcminute [4]. Furthermore it is very advantageous for the optical metrology and control system to be able to predict small changes of both spacecraft pointing and tether length variations.

Based on the aforementioned requirements and on the material and mechanical properties of the tether wire, we propose a three-spacecraft-on-a-line configuration (a central combiner and two end collectors) with constant angular momentum during observations (see Figure 1). The mechanical constraints that drive the choice of the constant value of the angular momentum magnitude during observation are analyzed in the following.

The orbit chosen for the analysis is a heliocentric Earth-trailing orbit whereby the interferometer follows the Earth at a suitable distance in its orbit around the Sun. The Earth-trailing orbit is particularly suited for optical interferometry as it offers continuous viewing of most of the sky, constant illumination for power generation, a relatively benign orbital environment, and good communication link with the Earth.

The influence of the environmental perturbations, i.e. solar radiation pressure, gravity gradient and thermal variations, is also investigated in this paper.

![Figure 1 Tethered Interferometer Movement during Source Observation](image)

**SYSTEM REQUIREMENTS**

There are several potential drivers and constraints that affect a tethered interferometer system design [2,4]:

- **pointing stability:** The pointing direction of the interferometer is required to be held within one arcminute (at 1 km baseline) with respect to the line of sight throughout the period of an observation.
- **distance collectors-combiner:** The distances collector1-combiner and collector2-combiner must never differ more than 10 cm from each other.
- **minimum tether tension:** For a tether to be controlled at the cm level a minimum tension of about 100mN is required so that inner residual tensions and hysteresis phenomena can be limited. Moreover a higher tension is an asset for the stability of the interferometer subjected to solar pressure.
- **maximum tether tension:** Depending on the diameter of the tether the tension should be at least one order of magnitude less than the material yield tension, based on current structural margins used in design.
- **maximum tangential velocity:** The minimum number of photons of the observed source to be collected at a certain baseline length and orientation provides a limit for the maximum tangential velocity of the end mirrors. This velocity should be of the order of 1-5 m/s, provided that sufficiently large mirrors and advanced photon detection systems are employed.
• Boresight with respect to the Sun: The angle between the anti-Sun direction and the boresight axis must be kept under 20-30 degrees to prevent the solar radiation noise from degrading the measurement.

• \(u,v\) plane coverage: The Fourier plane would need to be fully sampled from ideally zero to 1000m baseline and as rapidly as possible (i.e. not longer than 3 days). The high-resolution area (from 100 to 1000 m baseline) is scientifically the most important.

• fuel consumption: The thrusting maneuvers should be reduced as much as possible. The ideal solution would be to keep the magnitude of the angular momentum constant throughout the entire observing mission and be able to fulfill all the requirements.

• survivability: The tether has to be able to survive in a micrometeoroid environment with high probability (more than 95%) after a 4-5 years mission.

CONSTANT ANGULAR MOMENTUM CONFIGURATION

If the angular momentum vector is kept constant in magnitude, the tangential velocity, angular rate and tension vary as:

\[
V \propto \frac{1}{R}; \quad \omega \propto \frac{1}{R^2}; \quad T \propto \frac{1}{R^3} \tag{1a,b,c}
\]

Considering a baseline range from 100 m to 1 km, the tangential velocity increases 10 times from the maximum to the minimum baseline, the angular rate 100 times, and the tension 1000 times.

Figure 3 shows constant angular momentum curves for a system with two end masses of 350 kg each. It is clear that the limit on the tangential velocity is much more stringent than the one on the maximum tension. The value of the end masses is very important for the dynamics. The heavier the end masses the lower we can go in terms of angular rate with equal tension so that the interferometry requirements (low tangential rate) are better satisfied. This is true to the extent that the pointing and thermal stability (directly connected to the angular rate: see next paragraphs) does not decrease significantly. Moreover, too low an angular rate slows down the \(u,v\) plane sampling with a loss of observation efficiency.

Figure 2 Interferometer Parametric Curves: constant angular momentum (dots), Maximum and minimum tension (dash-dots), 4 m/s tangential velocity limit(solid line). Platform mass = 350 kg each
TARGET POINTING WITH GRAVITY GRADIENT PERTURBATION

With a three-body-on-a-line model for a spinning interferometer, it is not possible to univocally define a pointing direction by relying only on the geometrical properties of the spacecraft. In fact the system can be regarded as a very slender gyro (the axial moment of inertia is negligible when compared to the one with respect to a line orthogonal to the baseline) with indeterminate axial rotation. For this reason the pointing vector is here dynamically defined as the angular momentum $\mathbf{L}$ vector of the system.

The influence of the gravity gradient on the pointing stability is analytically investigated for a dumbbell model with two point end masses connected by a rigid massless tether of small length $l$.

Referring to the scheme of Figure 3, we write the equations of angular momentum for a spinning tethered interferometer in solar orbit for the general case of initial in-plane and out-of-plane different from zero. The equations are written with respect to a floating frame parallel to an inertial frame and with the origin moving along a solar circular orbit.

![Figure 3: Geometry of a Dumbbell Model for a Tethered Interferometer](image)

The expression of the gravitational potential with respect to the Sun center for a generic point $(x, y, z)$ in a frame parallel to the inertial frame and centered at the spacecraft center of mass ('floating frame') is:

$$V = -\mu_S \cdot [((x + R \cos(\Omega t))^2 + (y + R \sin(\Omega t))^2 + z^2]^{-1/2}$$  \hspace{1cm} (2)

where $\mu_S$ is the Sun gravitational constant and $R$ is the distance of the floating frame from the planet center. We also assume that the X-axis of the floating frame lies on the same line as the one of the inertial frame for $t=0$.

After performing a second-order approximation of $V$ and carrying out the derivatives, we obtain the gravitational force per unit mass as follows:
\[ f_G = \frac{\Omega^2}{2} \left( \begin{array}{c} x(1 + 3\cos(2\Omega t)) + 3y\sin(2\Omega t) - 2R\cos(\Omega t) \\ y(1 - 3\cos(2\Omega t)) + 3x\sin(2\Omega t) - 2R\sin(\Omega t) \\ -2z \end{array} \right) \]  

(3)

After noting that the rotation of the floating frame is null, we can write the equations of motion with respect to the floating frame considering that the expression of the acceleration is

\[ \ddot{r} = f_G = \ddot{\mathbf{R}} + \dot{\mathbf{R}} = R\Omega^2 \left( \begin{array}{c} -\cos(\Omega t) \\ -\sin(\Omega t) \\ 0 \end{array} \right) + \left( \begin{array}{c} \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{array} \right) \]  

(4)

Consequently, the accelerations with respect to the floating reference frame are

\[ \ddot{\mathbf{R}} = f_G - \ddot{\mathbf{R}} \]  

(5)

and the equations of motion with respect to the floating frame become

\[ \left( \begin{array}{c} \ddot{x} \\ \ddot{y} \\ \ddot{z} \end{array} \right) = \frac{\Omega^2}{2} \left( \begin{array}{c} x(1 + 3\cos(2\Omega t)) + 3y\sin(2\Omega t) \\ y(1 - 3\cos(2\Omega t)) + 3x\sin(2\Omega t) \\ -2z \end{array} \right) \]  

(6)

The variation of the angular momentum with respect to the floating frame can be computed as follows:

\[ \Delta L_x = \int_0^t M_x \, dt \; ; \; \Delta L_y = \int_0^t M_y \, dt \; ; \; \Delta L_z = \int_0^t M_z \, dt \]  

(7)

The vector \( \mathbf{p} = \mathbf{OP}_1 = (x, y, z)^T \) (in which reference frame?) is given by:

\[ \mathbf{p} = \frac{l}{2} \left( \begin{array}{c} -\cos(\omega t) \sin(\theta) - \sin(\omega t) \cos(\theta) \sin(\phi) \\ \cos(\omega t) \cos(\theta) - \sin(\omega t) \sin(\theta) \sin(\phi) \\ \sin(\omega t) \cos(\phi) \end{array} \right) \]  

(8)

where \( \theta \) and \( \phi \) are the pointing angles that identify the angular momentum vector with respect to the floating frame (see Figure 2) and \( l \) is the tether length.

After substituting Eq. (8) in Eq. (6), we obtain the force per unit mass acting on \( P_1 \), and the torque per unit mass acting on \( P_1 \) is:

\[ \mathbf{M} = \mathbf{r} \times \mathbf{F} \]  

(9)

which leads to:

\[ M_x = \frac{3}{16} \left( \sin(\theta)\sin(2\Omega t) + 2\cos(\theta) \cos(2\Omega t) - \cos(\theta) \sin(2\Omega t) + \cos(\phi) \cos(2\Omega t) + \sin(\theta) \sin(\phi) \cos(2\Omega t) + 2\sin(\theta) \sin(\phi) \cos(2\Omega t) + \cos(\theta) \sin(\phi) \sin(2\Omega t) \right) \]  

(10)
M_y = \frac{3}{16}\left\{ [-\sin(\theta)-2\sin(\theta)\cos(2\Omega t)+\cos(\theta)\sin(2\Omega t)]\cos(\phi)\sin(2\omega t)+ [2\cos(\theta)\sin(\phi)+2\sin(\theta)\sin(2\Omega t)+4\cos(\theta)\sin(2\Omega t)\cos(\phi)\cos(2\omega t)+ +[-\sin(\theta)\sin(2\Omega t)\cos(\theta)\sin(\phi)-2\cos(\theta)\sin(\phi)\cos(2\Omega t)]\cos(\phi)\right\} l^2 \Omega^2 \tag{11}

M_z = \frac{3}{8}\left\{ [\sin(2\theta)\sin(\phi)\sin(2\Omega t)+4\sin(\theta)\cos(2\theta)\cos(2\Omega t)]\sin(2\omega t)+ +[-(-2\sin(2\theta)\cos(2\Omega t)+2\sin(2\Omega t)\cos(2\theta)\cos^2(\phi)+4\sin(2\theta)\cos(2\Omega t)+ -4\sin(2\Omega t)\cos(2\theta)]\cos(2\omega t)+[\sin(2\theta)\cos(2\Omega t)-\sin(2\Omega t)\cos(2\theta)]\cos^2(\phi)\right\} l^2 \Omega^2 \tag{12}

By integrating each component with respect to time we obtain the variation of the angular momentum component:

\[ dL_x = f_x(\Omega, \omega, \theta, \phi, l, t) \tag{13} \]
\[ dL_y = f_y(\Omega, \omega, \theta, \phi, l, t) \tag{14} \]
\[ dL_z = f_z(\Omega, \omega, \theta, \phi, l, t) \tag{15} \]

The long trigonometric expressions obtained by the integration are skipped for the sake of brevity.

The total angular momentum can be obtained by adding the initial value of the angular momentum \( L_0 \) to the variation of the angular momentum computed above:

\[ L_x = \frac{l^2}{4} \omega \cos(\theta) \cos(\phi) + dL_x \tag{16} \]
\[ L_y = \frac{l^2}{4} \omega \sin(\theta) \cos(\phi) + dL_y \tag{17} \]
\[ L_z = \frac{l^2}{4} \omega \sin(\phi) + dL_z \tag{18} \]

The in-plane and out-of-plane displacement angles can be finally calculated as:

\[ \Delta\theta = \tan^{-1}\left(\frac{L_y}{L_x}\right) - \theta \tag{19} \]
\[ \Delta\phi = \sin^{-1}\left(\frac{L_z}{L}\right) - \phi \tag{20} \]

After some trigonometric simplifications and neglecting terms containing \( \Omega^3 \) and \( \Omega^4 \) the two displacement angles can be expressed as:

\[ \Delta\theta \equiv \tan^{-1}\left(\frac{8 \sin \theta + a \cdot \zeta + b \cdot \zeta^2}{8 \cos \theta + c \cdot \zeta + d \cdot \zeta^2}\right) - \theta \tag{21} \]
\[ \Delta\phi \equiv \sin^{-1}\left(\frac{8 \sin \phi + h \cdot \zeta + k \cdot \zeta^2}{8 \cdot (1 - \zeta^2)}\right) - \phi \tag{22} \]

Where:
ζ = Ω/ω  

a = 3\sin φ \cdot [\sin(\theta - 2Ωt) - 2Ωt \cdot \cos \theta - \sin \theta]  

b = 3\sin(2ωt) \cdot \sin φ \cdot [\cos \theta + \cos(\theta - 2Ωt)] + 
  + 3\cos(2ωt) \cdot [\sin \theta + \sin(\theta - 2Ωt)] - 14 \sin \theta  

c = 3\sin φ \cdot [2Ωt \cdot \sin \theta - \cos(2Ωt - 2\theta) + \cos \theta]  

d = -3\cos(2ωt) \cdot \cos(\theta - 2Ωt) + 3\sin(2ωt) \cdot \sin(φ) \cdot \sin(\theta - 2Ωt) + 
  -3\cos(θ - 2Ωt) - 8 \cos(θ)  

h = 3\cos(φ)^2[\cos(2Ωt - 2θ) - \cos(2θ)]  

k = 3\sin(2ωt) \cdot [\sin(2Ωt - 2θ) \cdot \cos^2 φ - 2 \sin(2Ωt - 2θ)] + 
  -6\cos(2ωt) \cdot \sin(φ) \cdot \cos(2Ωt - 2θ) + 2 \sin(φ) \cdot [3 \cos(2θ) - 4]  

This mathematical derivation is valid within the approximation because the gravity gradient force was computed with the assumption that the in-plane and out-of plane angles were constant. Consequently, the equations are valid so long as the pointing displacement angles are small, which is definitely the case for the tethered interferometer in solar orbit.

It is clear from Eqs (21-29) that the pointing displacement angles do not depend on the length of the baseline but they do depend on the interferometer’s spinning rate and on the orbital rate Ω. The resulting effect is a very low frequency (Ω/2π) motion to which a higher frequency (ω/2π) oscillation is superimposed, as clearly appears from Figure 4 and from Eq (24-29). As one can easily conclude from intuition, the higher the rotational rate the more stable the interferometer will be and the smaller the angular displacements. On the other hand the baseline length and the spinning rate are mutually dependent because of the conservation of angular momentum. In conclusion we can say that the interferometer has a better pointing stability at shorter baseline lengths thanks to the faster spin than at longer baseline lengths.

![Figure 4a Out of plane displacement angle of a tethered interferometer in solar orbit with ω=7.56e-4 rad/s (T=138.5 min) and for the following (θ,φ) initial orientations: (0°, 30°) dash; (30°, 30°) dot; (30°, 0°) solid line.](image-url)
If the orbital rate becomes too high, as in LEO or even in GEO orbit (see Figure 5), the displacement angles largely surpass the arcminute margin, and continuous undesirable thrusting would be required to satisfy the desired pointing requirements.
SOLAR PRESSURE EFFECT ON POINTING STABILITY

Solar radiation pressure acts on the three heavy modules (collectors+combiner) and on the tether in a non-negligible way. In order to limit the thermal noise coming from the solar radiation and affecting the interferometry measurements both the combiner and the collectors should have thermal shields mounted on the side facing the Sun. This makes the surface/mass ratio of the heavy module higher and, in turn, the acceleration induced by the solar pressure. We consider a 12 m diameter shield for every module. From that assumption and considering a tether of 2.5 mm diameter, the action of the solar pressure in the case of maximum baseline and both pointing angles $\theta$ and $\phi$ equal to zero is described in Table 1:

<table>
<thead>
<tr>
<th></th>
<th>Mass(kg)</th>
<th>Surface(m$^2$)</th>
<th>Force(N)</th>
<th>Accel.(m/s$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tether (500m*)</td>
<td>2.5</td>
<td>3.92</td>
<td>7.45×10$^{-6}$</td>
<td>3.20×10$^{-6}$</td>
</tr>
<tr>
<td>Combiner</td>
<td>350</td>
<td>113</td>
<td>9.96×10$^{-4}$</td>
<td>2.84×10$^{-6}$</td>
</tr>
<tr>
<td>Collector</td>
<td>350</td>
<td>113</td>
<td>9.96×10$^{-4}$</td>
<td>2.84×10$^{-6}$</td>
</tr>
</tbody>
</table>

*kevlar tether with a spectra jacket

Table 1 Solar pressure action on a tethered interferometer with $(0^\circ, 0^\circ)$ pointing direction

Under ideal conditions the resultant of the solar pressure force on the whole spacecraft is applied at the system’s center of mass and does not influence the pointing dynamics of the interferometer. However, a non-negligible torque is experienced in the case of a difference in optical properties, view factors, or masses in the two branches of the interferometer. Such phenomenon may be due to manufacturing defects, material inhomogeneities in the spacecraft components or differential degradation after a long period of time in orbit as well as unwanted tilt motion of the collector’s sunshields.

The case of a 1% to 5% reflectivity loss for one sunshield with the other completely reflective has been simulated. As showed in Figures 6 and 7 such an asymmetry results in a ‘wobbling’ motion of the interferometer. We must stress that because of the gyroscopic stability this deviation is by far smaller than the one experienced by a non-rotating spacecraft exposed to solar pressure. Moreover it is a periodical deviation (as long as optical properties, spacecraft mass or solar activity do not considerably change throughout an observation) that decreases in amplitude as the spinning rate grows (Figure 7).

Figure 6 In plane pointing displacement angle of a tethered interferometer with different reflectivity ratios for the two end sunshields. Baseline= 1km; $\omega= 7.56e-4$ rad/s
Figure 7 In plane pointing displacement angle of a 1 km tethered interferometer with 5% reflectivity ratios for the two end sunshields and several spinning rates

SOLAR PRESSURE INDUCED OSCILLATIONS

Differences in surface/mass ratio, view factor and reflectivity between collectors and combiner or between heavy modules and tethers cause the structure to oscillate laterally with respect to the baseline. The three modules can be subjected to different accelerations if their surface/mass ratios are different. A difference in acceleration between the central combiner and the collectors brings about a lateral oscillation of the central combiner with respect to the baseline connecting the two end collectors. A similar behavior is induced by a difference of acceleration between tether and heavy modules. When the interferometer has pointing angles different from zero in-plane oscillations couples with the out of plane ones as showed in Figure 10.

The computer code, based on a lumped-mass visco-elastic tether, accounts for the direct effect of the solar pressure upon the two collectors, the central combiner and the two tether segments. The output parameters considered herein are the displacements of the lump masses orthogonal to the rotational plane of the system (ε_{out}) and the ones orthogonal to the baseline but in the rotational plane (ε_{in}).

Figure 10 a,b In ona Out of plane oscillations of the combiner with respect to the baseline for a 1 km tethered interferometer with (30°, 30°) pointing direction and 5% difference in reflectivity between combiner and collectors
THERMAL ANALYSIS

The non-linear thermal equation of the tether can be easily written as:

$$\frac{dT}{dt} = \frac{2aS_0 \sin \beta - 2\pi \sigma \varepsilon T^4}{\pi \mu cR}$$

(30)

Where:

$\mu$ = tether material density (kg/m$^3$)
$\sigma$ = Stefan-Boltzmann constant ($5.67 \times 10^{-8}$ W/m$^2$K$^4$)
$a, \varepsilon$ = tether surface absorptivity and emissivity
$S_0$ = solar energy flux at 1AU ($\sim 1370$ W/m$^2$)
$c$ = specific heat (J/kgK)

and $\beta$ is the illumination angle between the solar radiation and the tether axis

$$\sin(\beta) = f(\theta, \phi, t) = \sqrt{1 - A^2 \cos^2(\omega \cdot t - \psi)}$$

(31)

with:

$$A = \sqrt{\sin^2(\theta) + \cos^2(\theta) \sin^2(\phi)} ; \quad \psi = \tan^{-1}\left(\frac{\cos(\theta) \sin(\phi)}{\sin(\theta)}\right)$$

(32)

When the pointing direction does not coincide with the anti-Sun direction the view factor (Eq (31)) becomes time varying and the tether experiences a cyclic temperature variation with increasing frequency as the interferometer angular rate grows.

If the term $\mu cR$ in Eq. (30) was zero the tether would constantly be at the equilibrium temperature:

$$T_{eq} = \frac{4aS_0 \sin(\beta)}{\pi \sigma \varepsilon}$$

(33)

And the maximum temperature variation would be:

$$\Delta(T_{eq})_{max} \propto \frac{4aS_0}{\varepsilon}$$

(34)

which suggests the use of tether jacketing materials with low $a/\varepsilon$ ratio.

From Eq (31-33) it can be seen that the maximum thermal variation, given a limit of 30 deg inclination with respect to the anti-Sun direction, occurs when the pointing angles are both 30 deg. In reality the quantity ‘$\mu cR$’ is not zero and this limits the thermal variation as appears in Figure 11.

In order to reduce the temperature fluctuations and the consequent thermal expansion-dilation of the wire it is advantageous:

- To increase the angular rate of the interferometer
- To increase the diameter of the wire
- To have higher $\mu$ and $c$ for the core of the tether
Finally the tether length variation (see Figure 12) is directly connected to the temperature variation via the thermal expansion coefficient of the core of the tether. In this regard the synthetic fiber Kevlar is an appropriate choice thanks to its low thermal expansion coefficient ($\alpha = -2.0 \times 10^{-6} \text{ K}^{-1}$). All things considered a good compromise for high thermal stability is as follows: 2 - 2.5 mm diameter tether with a low expansion material core jacketed with a low $\alpha/\varepsilon$ ratio material.

Figure 11 Temperature cycles of spectra-coated tether branches for different diameters. Pointing direction = (30°, 30°); Baseline = 1km; $\omega = 7.56 \times 10^{-4} \text{ rad/s}$

Figure 12 Baseline length variation for different diameters (same parameters as Figure 11)
TETHER SURVIVABILITY

A two-line tether design (see the scheme of Figure 13) is proposed to achieve a very high survival probability to micrometeoroids impact after 5 years mission.

Figure 13 Schematic of a two-line tether (n=2) with m=5 cells

The combined probability of survival for an n-line tether with m cells can be computed from [14] and considering the combined probability of a series of m cells with each cell consisting of n segments in parallel:

\[
P = \left[ 1 - \left( 1 - e^{-\frac{\alpha}{m}} \right)^n \right]^m
\]

(35)

where \( \alpha = \) is the critical-impactor impact rate for the single-line tether which depends on the size of the tether, the environmental micrometeoroids flux and the mission duration.

Figure 14 shows the survival probability of a 2-line tether (caduceus\(^4\)) interconnected at intervals L/m with m =1000, L = 1 km and a mission duration of 5 years.

A two-line caduceus of diameter \( d = 1.25 \) mm (per line) and lines interconnected every meter (i.e., \( m = 1000 \)) increases the survival probability to 99.8% from the 90% of a single-tether with the same overall cross section.

Figure 14 Survival probability of a 1-km, 2-line caduceus with 1000 cells

\(^4\) The caduceus tether design was first proposed by J.A. Carroll of Tether Applications Inc.
CONCLUSIONS

The potential advantages of using a tethered system for space based imaging interferometry may be substantial. By choosing a low gravity gradient and thermally stable orbit like the Earth trailing heliocentric orbit and with a careful design of the spacecraft the pointing requirements for the interferometric system can be met.

Solar radiation pressure and thermal variations are the dominant perturbations. The former affects the pointing stability of the interferometer and can give rise to lateral oscillations of the system, the latter causes cyclic variations of the tether length when the interferometer is pointed off of the anti-Sun direction. Regarding the pointing stability the configuration with larger baseline length and lower angular rate is the most critical one.

Particular attention must be given towards designing a system that is optically symmetric from the viewpoint of the solar radiation pressure.

The choice of a low expansion material (e.g. kevlar) with a low absorptivity/emissivity ratio surface (e.g. using a spectra jacket) is the key to meeting the requirements on the tether length variations.

Finally a 99.8% survival probability can be met by making use of a two line-tether design. Future work will examine the retargeting dynamics of the interferometer, as well as methods to decouple the attitude dynamics of the combiner and the collectors from the dynamics of the tether during observations.

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