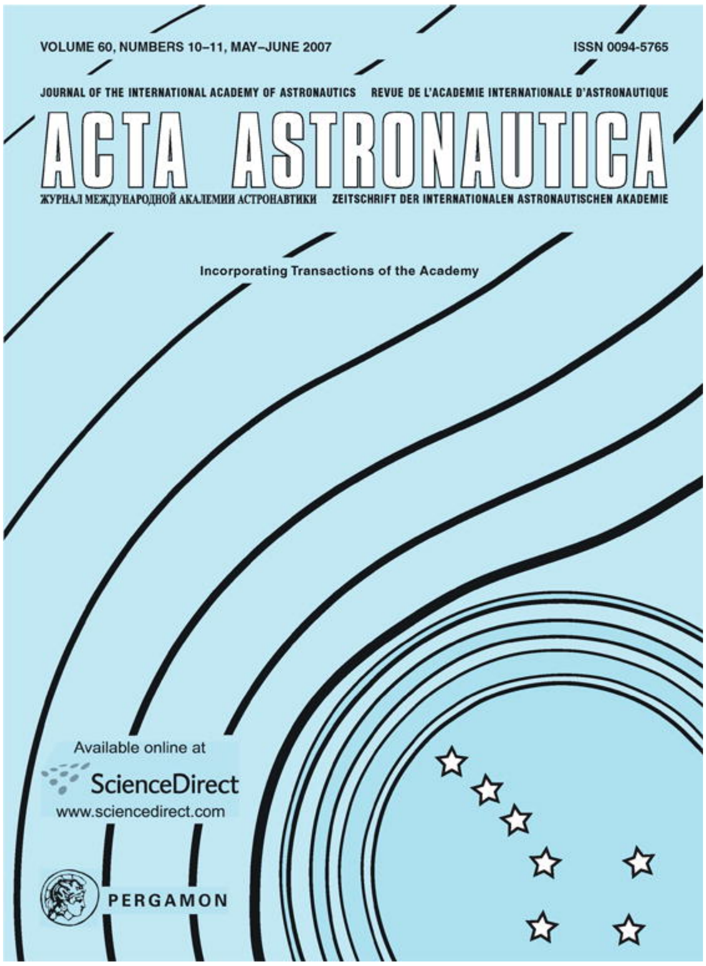
VOLUME 60, NUMBERS 10–11, MAY–JUNE 2007
ISSN 0094-5765
JOURNAL OF THE INTERNATIONAL ACADEMY OF ASTRONAUTICS
REVUE DE L'ACADEMIE INTERNATIONALE D'ASTRONAUTIQUE
ACTA ASTRONAUTICA
ЖУРНАЛ МЕЖДУНАРОДНОЙ АКАДЕМИИ АСТРОНАВТИКИ
ZEITSCHRIFT DER INTERNATIONALEN ASTRONAUTISCHEN AKADEMIE
Incorporating Transactions of the Academy
Available online at
ScienceDirect
www.sciencedirect.com
PERGAMON

PERGAMON

Available online at www.sciencedirect.com

ScienceDirect

Acta Astronautica 60 (2007) 828 – 833

ACTA ASTRONAUTICA

www.elsevier.com/locate/actaastro

Self-stabilising attitude control for spinning tethered formations

Carlo Menon*, Claudio Bombardelli

Advanced Concepts Team, ESTEC, ESA, The Netherlands

Received 2 February 2006; accepted 13 November 2006
Available online 16 January 2007

Abstract

The paper analyses the dynamics of a spinning tethered formation where the tethered units are modelled as extended rigid bodies. The system, composed by two platforms linked by a flexible tether a few hundreds of meters long, constitutes the building block of more complex tethered architectures utilised in proposed space interferometry missions. The issue investigated herein is the transfer of a collimated beam from one platform to another in the presence of environmental perturbations and structural vibrations affecting the position and attitude of the two tethered units. We propose to damp residual oscillations and limit the effect of environmental torques with the aid of two passive dampers placed at the tether attachment point. When the damping system is properly tuned, this approach has the considerable advantage of rapidly bringing the system to a minimum energy configuration (zero residual vibrations) without any external control force. Numerical results show the effectiveness of the proposed control strategy and provide an important element towards the implementation of future space-based observatories and formation-flying demonstration mission based on tether-connected architectures.

Keywords: Tether; Formation; Attitude; Spinning; Interferometer

1. Introduction

International space agencies envision future space missions involving formation flying of multiple separated spacecraft acting collaboratively as a single unit for a specific task. Often, not only the relative positions of the individual spacecraft need to be accurately controlled but also their attitude, as in the case of space interferometry applications where the individual platforms need to be accurately pointed towards the same inertial target while keeping a precise relative attitude for optical beam transmission purposes.

Space interferometers can have inter-spacecraft separation of several hundred meters to kilometres in order to reach a desired spatial resolution for a given wavelength of operation [1–5].

While the separation distance increases the need to accurately relay an optical beam from one spacecraft to another makes the relative position and attitude requirements more and more stringent. For example a cm-level beam centering accuracy over 500 m separation requires a maximum inter-spacecraft bearing angle not exceeding 4 arc s. In addition, this tight control requirement may be complicated by the fact that for many interferometry missions the spacecraft is constantly moving along a non-keplerian path (e.g. the whole formation may be required to rigidly rotate around the direction of the observed target) while keeping their relative positions and attitudes accurately controlled at all times.

* Corresponding author.
E-mail addresses: menoncarlo@stargatenet.it, carlo.menon@esa.int (C. Menon), claudio.bombardelli@esa.int (C. Bombardelli).

0094-5765/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.actaastro.2006.11.013

In this scenario, the continuous action of control actuators (reaction-wheel and/or thrusters) may give rise to broadband structural vibrations which are detrimental for the beam transmission and optical path delay stabilisation and can compromise the performance of the interferometric subsystem (delay lines and fringe tracker) [6,7].

Recent studies [9–13] have shown that long baseline space interferometric formations can be implemented linking the different platforms with long tethers having small diameter and light mass as proposed for the NASA-funded SPECS interferometry mission [13]. Spinning tethered formations have the advantage of a significantly reduced fuel consumption and a simplified control scheme for the position of the individual units based on passive stabilisation.

The attitude dynamics and control of a tethered rigid body has received considerable attention in the literature. Lemke et al. [14] first explored the possibility of controlling the attitude of a tethered satellite by exploiting the torque provided by the tether tension. The paper proposed to generate the required control torque by the planar motion of the tether attachment point (offset control) and with the addition of a reaction wheel to achieve complete controllability. Bergamaschi [15] investigated the coupling between tether lateral vibrations and planar attitude motion of a tethered subsatellite. Pradhan et al. [16] developed a more complex model to account for a variable length visco-elastic tether system composed by an extended platform linked to a point-mass subsatellite and proposed an offset control algorithm based on feedback linearisation and LQG/LTR approach. Modi et al. [17] studied the attitude dynamics and control of a rigid body platform tethered to a subsatellite also modelled as a rigid body. This latter reference takes into account three-dimensional motion of both tethered bodies and of the massive visco-elastic tether and proposes a very efficient offset control algorithm based on the Liapunov second method where the chosen Liapunov function is related to the generalised potential and kinetic energy of the controlled coordinates. More recently Williams et al. [18] have shown that an offset control scheme at the tether attachment point added to a current-based control algorithm can be used to damp the librations of a flexible electromagnetic tether.

All these studies considered a gravity-gradient Earth-orbiting tether (also known as hanging tether) while the attitude control of tethered platforms in spinning tether formations has not yet been addressed.

In the framework of dynamics and control of spinning tethered interferometers, previous work [9–12] has been focused on the issue of controlling the position of the individual platform modelled as point masses, while the problem of attitude stabilisation of the tethered units has not yet been addressed.

This paper investigates and demonstrates the possibility of exploiting the presence of a tether link to stabilise the attitude of the individual platforms modelled as rigid bodies and explores the possibility of utilising a passive control scheme in which the system's oscillatory energy is suppressed by a system of two gimbals with rotational dampers at the tether attachment point. The stabilisation technique exploits the presence of the damping interface to make the system converge towards a minimum energy configuration where the tether residual vibrations are damped out and each platform is kept pointed towards an inertial target while spinning around its axis of maximum moment of inertia. In this way, each individual spacecraft can maintain a stable inertial pointing where high-precision actuators (e.g. fast-steering mirror, μN-level thrusters) are only used in the last stage of the attitude control process.

This very simple control scheme, which basically bypasses the coarse level metrology and control phase typical of formation flying architectures, has the merit of reducing the complexity of the system, increasing its reliability and minimising the resources employed.

With reference to proposed space interferometry projects under study, we analyse the case of two rigid bodies linked by a 500 m tether, where the whole system is spinning around its centre of mass and following a halo orbit around the L2 Lagrangian point as proposed for the DARWIN-TPF and SPECS missions. The tether is connected to both rigid bodies through a system of two gimbals about the in- and out-of-plane directions.

The system dynamics are analysed for two scenarios. In the first scenario the system is perturbed with a constant solar radiation torque on each tethered unit caused by a shift between centre of pressure and centre of mass of the rigid body. The stabilisation effect of the tether link against the external torque is studied numerically. In the second scenario the system is given a transient excitation with the tethered unit oscillating by a few degrees. Subsequently the dampers are activated and their effectiveness in stabilising the structure and suppressing residual vibrations is evaluated numerically.

2. Model description

The system (Fig. 1) is composed of two tethered rigid bodies with inertial characteristics listed in Table 1.

The formation spins around its centre of mass at a rate of about 1 round every 28 min. The tether has diameter 2.5 mm and linear density 8×10^{-3} kg/m, and

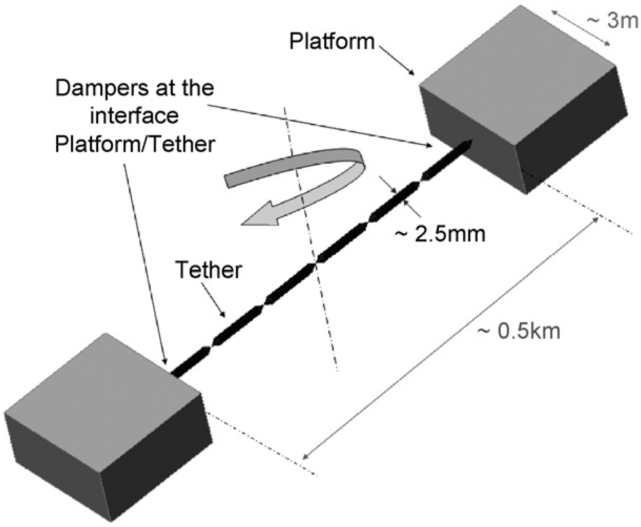

Fig. 1. Schematic of spinning tethered system.

Table 1
Inertia characteristic of each platform

Mass	IXX	IYY	IZZ
kg	kg m^2	kg m^2	kg m^2
500	470	470	750

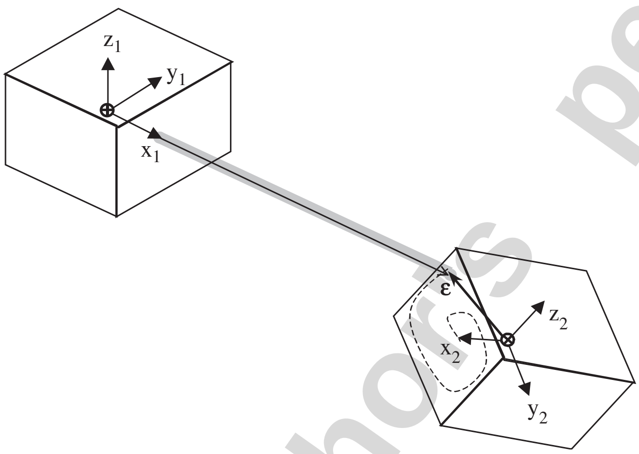

Fig. 2. Schematic of beam offset (ε).

is modelled as a series of six massive hinged rods to account for its lateral dynamics.

The tether is attached to each unit through a gimbal system allowing two relative rotations, the first around each platform Z body axis the second around the Y body axis. The gimbals are characterised by a constant damping coefficient to dissipate the structure residual vibration energy. The centre of mass of the individual rigid bodies is located at a distance $d = 1.5$ m along the X-principal axis from the tether attachment point.

The performance metric of interest in the present analysis is the *offset of the incoming beam* with respect to the receiver, and is defined as the point of intersection ε between the X body axis of platform 1 (i.e. the beam incoming axis) and the plane parallel to the Y–Z body plane of platform 2 and passing through the receiver (Fig. 2).

3. System frequencies

Conceptually it is useful to divide the oscillation modes of the system in two classes.

The first class contains oscillation modes which are mainly determined by the inertial characteristic of the end bodies and the formation spin rate. For the present design these modes are mostly independent of the inertial characteristic of the tether and we will refer to them as *pendular modes*. The lowest frequency pendular mode is an oscillation of each platform around its own X body axis (Fig. 2). The oscillation period can be computed with good approximation based on free rigid body dynamics theory for tri-inertial systems [19] as follows:

$$T_{\text{roll}} = \frac{2\pi}{\omega}\sqrt{\frac{I_X}{I_Z - I_Y}}, \tag{1}$$

where ω is the formation angular velocity and I_X, I_Y, I_Z are the principal moment of inertia of each rigid body.

The other two pendular modes are rotations of the platform around the Y and Z axes. Again, the periods of oscillation around the Y and Z axes, respectively, can be derived from simple dynamics as

$$T_{\text{pitch}} = \frac{2\pi}{\omega}\sqrt{\frac{I_Y}{md(\ell/2 + d)}}, \tag{2}$$

$$T_{\text{yaw}} = \frac{2\pi}{\omega}\sqrt{\frac{I_Z}{md(\ell/2 + d)}}, \tag{3}$$

where d is the distance from the tether attachment to the centre of mass of each platform, ℓ is the tether length and m the mass of each platform.

The second class of oscillations are mostly determined by the tether tension and linear density. We will refer to them as *string modes*. The period of oscillations of the string modes are given by the well-known formula [20]:

$$T_{\text{str}} = \frac{2\ell}{k}\sqrt{\frac{\rho}{N_0}}, \quad k = 1, 2, \ldots \infty, \tag{4}$$

where N_0 is the tether tension and ρ its linear density.

Table 2
System oscillation periods

T_{roll}	T_{pitch}	T_{yaw}	T_{str1}	T_{str2}
2216 s	82 s	103 s	72 s	36 s

With the inertial, geometric and dynamical characteristics described above and setting $d = 1.5$ m we obtain the oscillations period listed in Table 2. All of the frequencies match very well the results from numerical simulations. We must stress that these oscillations have very low frequencies and are hence easier to be measured and compensated.

4. Response to external torques

As suggested by recent studies [8] a tethered interferometer spinning at a sufficiently high rate relatively to the orbital rate is able to counteract environmental perturbations thanks to its natural spin stabilisation, and to provide a cm-level relative position accuracy between tethered units.

We will here focus on the effect of external torques on the attitude of the individual platforms and, in turn, on the beam offset ε_B described earlier.

The space interferometry missions DARWIN/TPF and SPECS, both flying around the L2 Lagrangian point are characterised by the presence of large sunshields (7–12 m in diameter) mounted on the Sun side of all platforms. This makes the solar radiation pressure the dominant perturbation.

With reference to these space interferometery missions we assume a 100 m^2 cross-section for each of the two tethered bodies and a 10 cm offset between centre of pressure and centre of mass of each platform. The resulting torque $\tau = 4.6 \times 10^{-5}$ Nm is applied around the X and Y body axes of each platform. We must point out that the torque was applied as a step function, which represent a worse-case scenario in terms of structural modes excitation. Note also that, for the orbit and system considered here, this torque exceeds the value of the gravity gradient torque by orders of magnitude, so the latter can be neglected.

Fig. 3 plots the z component of the beam offset when the torque is applied along the X and Y axes. In both cases the offset is kept below the centimetre level which corresponds to a bearing angle precision of better than 4 arc s. This fact is due to the stabilising effect of the tether tension.

Fig. 3 highlights also the role of the damping system in abating the transient excitation given by the solar torque discontinuity. The y component of the beam offset has seen to be stable to less than 1 mm and is not plotted here.

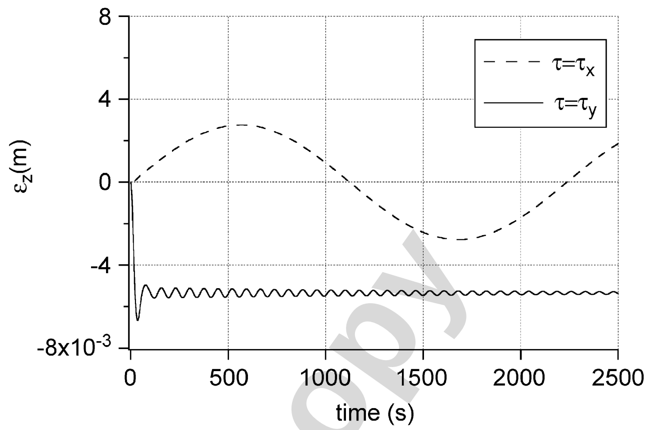

Fig. 3. Effect of solar radiation torques on the Z-component of the beam offset. The torque is applied along the Z and Y body axes.

5. Response to transient excitation

A fundamental feature of every space system is the ability to react to off-nominal events and component failures through a pre-planned fault protection strategy.

Space interferometers based on free-flying distributed modules require redundant metrology and control schemes in order to prevent collisions between different spacecraft and loss of modules due to excessive drift.

In general, the formation should have the ability to autonomously recover from a chaotic state with the aid of coarse metrology and control for the initial phase, and progressively acquire a more precise relative positioning and attitude between its members by switching to more accurate sensors and actuators [21].

The case of spinning tethered formations is quite different. The first peculiarity of these systems is the existence of a minimum energy equilibrium position which opens the possibility for the system to recover itself from a chaotic state by simply dissipating the excessive energy. The second is the presence of tether links which provide a good initial estimation of the relative position of the different modules. In this way, higher accuracy sensors (e.g. lasers and star trackers) may be employed from the beginning of the measurement process.

In the following we investigate the behaviour of the tethered formation previously described after an initial excitation of a few degrees of the satellite attitudes obtained by imparting off-nominal initial conditions to the tether. The damping system, which is tuned in such a way to optimise the dissipation of pendular modes, is

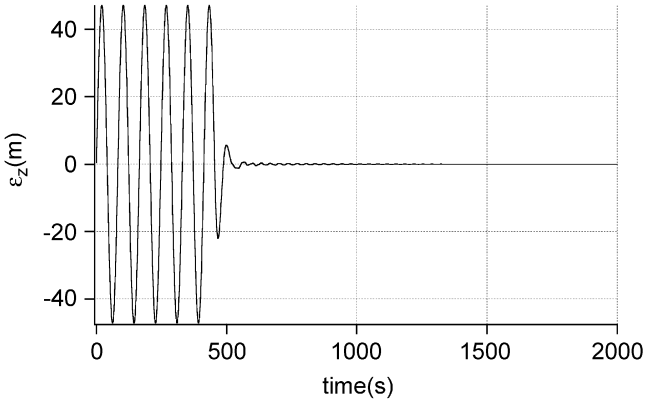

Fig. 4. Beam offset stabilisation (z-component) after activating the dampling system (from $t = 400$ s).

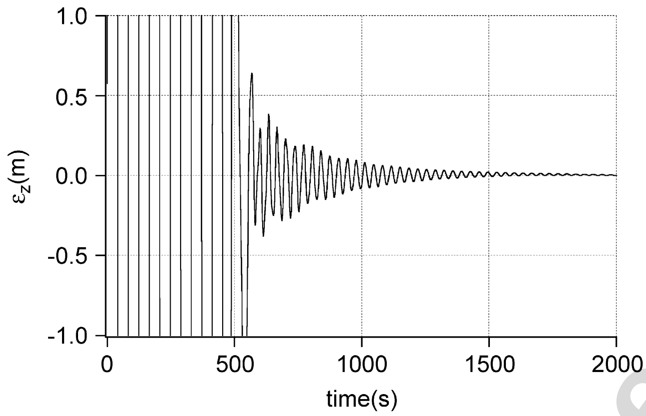

Fig. 5. Close-up of Fig. 4.

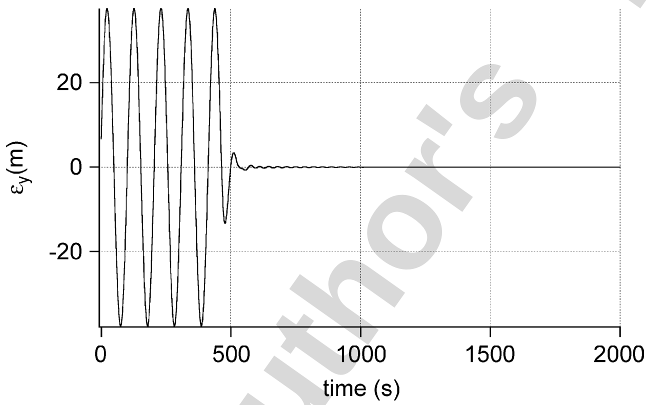

Fig. 6. Beam offset stabilisation (y-component) after activating the dampling system (from $t = 400$ s).

activated after about 400 s from the beginning of the simulation.

Figs. 4–9 highlights the excellent performance of the damper, which allows to quickly stabilise the beam offset at the cm-level. The damper is also effective in abating string-like modes.

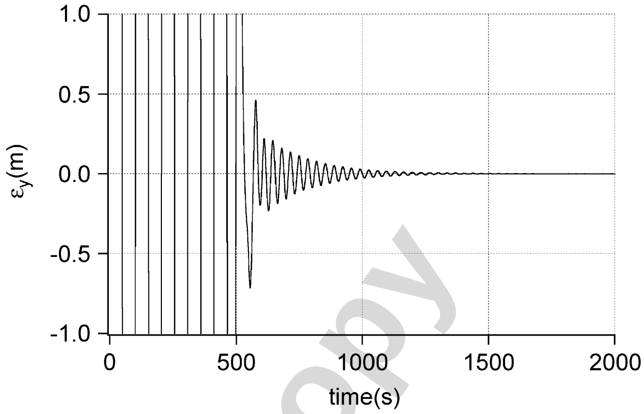

Fig. 7. Close-up of Fig. 6.

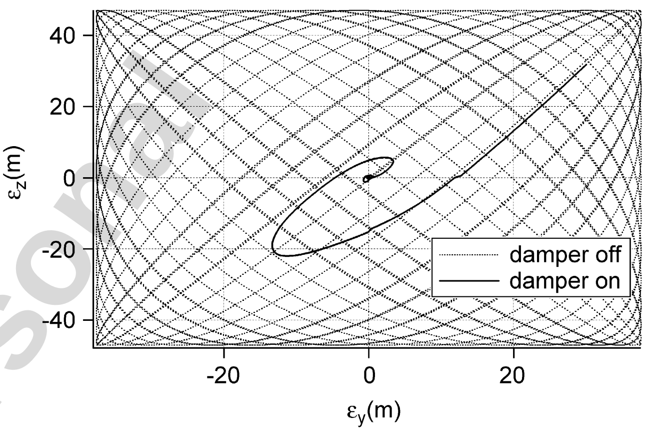

Fig. 8. Beam offset path along the X–Z plane before and after the activation of the damper.

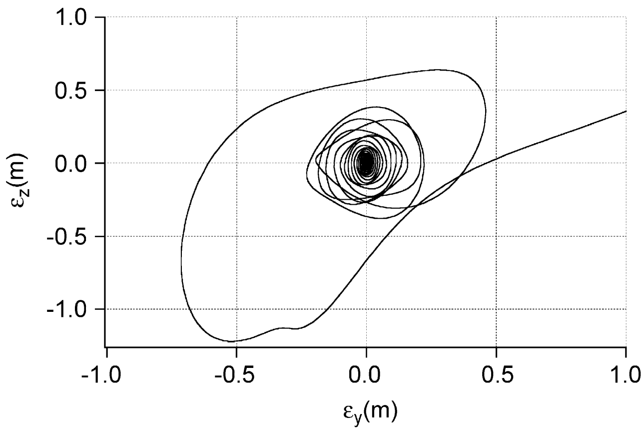

Fig. 9. Close-up of Fig. 8.

6. Conclusions

We have analysed the dynamics and control of the attitude of individual platforms in a spinning tethered formation based on space interferometry requirements. The results suggest the feasibility of passively controlling the attitude of the platforms and damping residual tether oscillations by placing a two-dimensional damper at the tether attachment point. When the dampers are properly tuned transient attitude and tethered oscillations can be abated in a few minutes while the tethered formation naturally converges towards its minimum energy configuration. In addition, the passive control scheme can absorb a significant part of attitude disturbances due to unbalanced solar radiation pressure torques. This allows transmitting a collimated beam from platforms separated by a few hundred meters within a few millimetres offset without the need of constantly controlling the attitude of sending and receiving platforms.

This result is very relevant for space interferometry applications, as it dramatically reduces the complexity of both metrology and control systems of the interferometric formation.

Future studies will be focused on the optimisation of the damping strategy presented based on more sophisticated analytical models and on the analysis of the inertial pointing stability of the individual tethered platforms.

References

[1] European Space Agency, DARWIN the infrared space interferometer: concept and feasibility study report, Technical Report ESA-SCI (2000) July 12, 2000.

[2] C.A. Beichman, N.J. Woolf, C.A. Lindensmith (Eds.), Planet Finder, JPL Publication 99-3, Jet Propulsion Laboratory, Pasadena, CA, 1999.

[3] D. Leisawitz, et al., Scientific motivation and technology requirements for the SPIRIT and SPECS far-infrared/submillimeter space interferometers, Proceedings SPIE, 4013, 2000, p. 36.

[4] K. Carpenter, et al., The stellar imager (SI) mission concept, Proceedings SPIE 4854, 2002, p. 293.

[5] K.C. Gendreau, et al., The MAXIM pathfinder X-ray interferometry mission, Proceedings SPIE 4851, 2002, p. 353.

[6] L.D. Peterson, J.D. Hinkle, Implications of structural design requirements for selection of future space telescope architectures, in: H.A. MacEwen (Ed.), UV/Optical/IR Space Telescopes: Innovative Technologies and Concepts, Proceedings of the SPIE, vol. 5166, 2004, pp. 27–38.

[7] L. Elias, et al., A methodology for modeling the mechanical interaction between a reaction wheel and a flexible structure, Proceedings of SPIE Astronomical Telescopes and Instrumentation Conference, Waikoloa, Hawaii, August 2002.

[8] S.G. Tragesser, A. Tuncay, Orbital design of earth-oriented tethered satellite formations, The Journal of the Astronautical Sciences 53 (1) (2005).

[9] C. Bombardelli, E.C. Lorenzini, M.B. Quadrelli, Formation pointing dynamics of tether-connected architecture for space interferometry, The Journal of the Astronautical Sciences 52 (4) (2004).

[10] C. Bombardelli, E.C. Lorenzini, M.B. Quadrelli, Retargeting dynamics of a linear tethered interferometer, Journal of Guidance, Control and Dynamics 27 (6) (2004).

[11] E.C. Lorenzini, C. Bombardelli, M.B. Quadrelli, Analysis and damping of lateral vibrations in a linear tethered interferometer, 13th AAS/AIAA Spaceflight Mechanics Meeting, Ponce, Puerto Rico, February 2003.

[12] M.L. Cosmo, E.C. Lorenzini, C. Bombardelli, Space tethers as testbeds for spacecraft formation-flying, AAS Publications Paper AAS 04-171 14th AAS/AIAA Space Flight Mechanics Conference, Maui, Hawaii, February 8–12, 2004.

[13] Leisawitz, et al., A SPECS update: engineering and technology requirements for a space-based far-IR imaging interferometer (Invited Paper), Astronomical Telescopes and Instrumentation 21–25 June, Glasgow, Scotland, UK.

[14] L.G. Lemke, J.D. Powell, X. He, Attitude control of tethered spacecraft, The Journal of the Astronautical Sciences 35 (1) (1987).

[15] S. Bergamaschi, F. Bonon, Coupling of tether lateral vibration and subsatellite attitude motion, Journal of Guidance, Control and Dynamics 15 (5) (1991).

[16] S. Pradhan, V.J. Modi, A.K. Misra, Tether-platform coupled control, Acta Astronautica 44 (1999) 243–256.

[17] V.J. Modi, G. Gilardi, A.K. Misra, Attitude control of space platform based tethered satellite system, Journal of Aerospace Engineering 11 (2) (1998).

[18] P. Williams, et al., Libretion control of flexible tethers using electromagnetic forces and movable attachment, Journal of Guidance, Control and Dynamics 27 (5) (2004).

[19] P.C. Hughes, Spacecraft Attitude Dynamics, Wiley, New York, 1986, pp. 104–107.

[20] L. Meirovitch, Elements of Vibration Analysis, vol. 83, McGraw-Hill, New York, 1986, p. 214.

[21] J.Y. Tien, et al., Relative sensor with 4π coverage for formation flying missions, Second International Symposium on Formation Flying Missions & Technologies, September 14–16, Washington, DC, 2004.