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# Acquisition, Tracking and Pointing control of the Bifocal Relay Mirror Spacecraft

Marcello Romano\* and Brij N. Agrawal†

*Spacecraft Research and Design Center  
Naval Postgraduate School, Monterey, CA 93943*

This paper presents the results of both numerical and experimental studies on the guidance, dynamics and control of the Bifocal Relay Mirror spacecraft. This proposed spacecraft consists of two large gimbaled telescopes, that are optically coupled and used to redirect a laser beam from a ground-based source to a distant point. The attitude control system consists of reaction wheels, star trackers and gyros. The optical control system consists of fast steering mirrors and optical tracker sensors. The very tight pointing and jitter requirements, together with the multi-body nature of the spacecraft, make the control of the system very challenging. Numerical simulations have been performed on a complete analytical model of the system dynamics, in order to compare two different control approaches proposed for the attitude and tracking/pointing. Moreover experiments were carried out on a spacecraft simulator test-bed, modelling the transmitter portion of the Bifocal Relay Mirror spacecraft. The main tasks of the presented experiments were: first, to validate the attitude stabilization control together with the target acquisition-tracking-pointing and laser jitter rejection; second, to prove the effectiveness of the test-bed itself as an important tool to be used in the following researches.

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## I Introduction

MANY of the current and near future space missions requires high accuracy pointing and tracking. Applications include optical communications relay link satellites<sup>1</sup> and laser sensors for formation flying fleets of space probes.<sup>2</sup> Optical frequencies provide extremely high antenna gain for relatively small antenna size, thereby allowing cross links to be closed with relatively low transmitter power and small terminals.<sup>3</sup> However, the extremely narrow beam-width poses severe pointing, acquisition and tracking requirements.<sup>4</sup>

The Spacecraft Research and Design Center of Naval Postgraduate School participated in the Bifocal Relay Mirror (BRM) project, aiming to the preliminary study of a laser relay spacecraft for non-weapon military applications of laser links. The Bifocal Relay Mirror spacecraft is composed of two optically coupled telescopes and is used to redirect the laser light from ground-based, airborne or spacecraft based laser sources to distant target points on the earth or in space. The receiver telescope cap-

tures the incoming energy from the laser source, while a separate transmitter telescope, movable with respect to the first telescope, directs the laser beam at the desired target.

A Relay Mirror space application is an application of increased difficulty with respect to the typical spacebased telescopes application. In fact beyond a high line of sight stabilization capability it requires also the capability of line of site rate tracking. Moreover the foreseen Multibody Bifocal Relay Mirror Spacecraft application is even more challenging than the single body Relay Mirror Experiment.<sup>5</sup>

Agrawal and Senencko<sup>6</sup> presents the analytical model of the dynamics of the Bifocal Relay Mirror Spacecraft and reports results of simulations on the attitude determination and control. Romano and Agrawal<sup>7</sup> take in account the dynamics and control of the two fast steering mirrors, constituting the tertiary mirrors of the transmitter and receiver telescopes, and present the results of simulations on the acquisition, tracking and pointing aspects. Spencer et al.<sup>8,9</sup> describes a previous version of the Three Axis Simulator test-bed and reports the results of preliminary experiments.

\*Ph.D., US National Research Council Associate Fellow. AIAA member.

†Professor and Director. AIAA Associate Fellow.

# Report Documentation Page

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The present paper focuses on several new recent developments in the researches regarding the Bifocal Relay Mirror spacecraft. In particular the following points are treated:

- Analytical development of a more complete model for the optical subsystem and pointing error.
- Analytical development for the computation of the reference system motion, based on the relay mission geometry.
- Report of new simulation results.
- Description of the upgraded experimental test-bed and report of new experimental results.

Section two of this paper introduces the analytical development and reports the results of numerical simulations. Section three describes the Bifocal Relay Mirror Spacecraft Simulator test-bed and reports the results of experiments, carried out with that system.

## II Analytical Development and Numerical Simulations

### A Dynamics of the Bifocal Relay Mirror system

#### A.1 Model of the spacecraft

The Bifocal Relay Mirror Spacecraft consists of two main bodies: transmitter telescope and receiver telescope. The receiver telescope rotates with respect to the transmitter around an axis, which contains, as a design hypothesis, the center of mass of the receiver telescope itself: then the center of mass of the overall system does not change during the relative rotation of the two telescopes. Looking at figure 1 the relative rotation axis is  $x_R$ , while the center of mass of the receiver and of the overall system are respectively  $O_R$ , on the rotation axis, and  $O_S$ .

The other bodies considered in the dynamic model are:

- four reaction wheels mounted in tetrahedral configuration on the transmitter telescope section of the system and used as actuators for the spacecraft attitude control;
- two fast steering mirrors, mounted as tertiary mirrors of the two telescopes. Each fast steering mirror is actuated in such a way it can rotate about two radial axes crossing its center of mass.

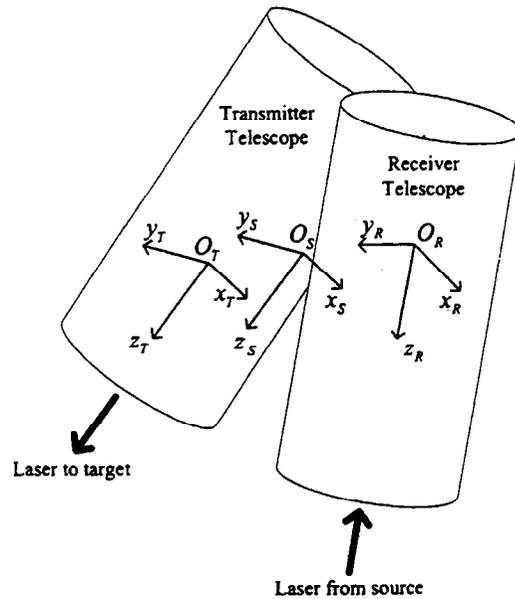


Fig. 1 High level model of the Bifocal Relay Mirror Spacecraft

In summary, the Bifocal Relay Mirror spacecraft, as described in our model, has a total of 11 significant degrees of freedom: three d.o.f. for the position of the center of mass of the system; three d.o.f. for the attitude position of the transmitter; one d.o.f. for the position of the receiver with respect to the transmitter; two d.o.f. each for the position of the fast steering mirrors with respect to their base.

A complete analytical model for the dynamics of the Bifocal Relay Mirror, has been previously developed and presented.<sup>6,7</sup> Hence, the equations of motions are not reported here.

A brief description of the methods used in expressing the equations of motions follows. The motion of the center of mass is obtained by propagation of the analytical solution for the circular orbit. The attitude dynamics equations of the system, assumed to be composed of rigid bodies, can be written first in vectorial form (see, for instance, ref.<sup>10</sup> for the underlying theory) and then in scalar form, expressing the vectors and dyadics in the same reference frame (we used the frame  $x_S, y_S, z_S$  in figure 1) and choosing a set of attitude parameters (we used the Euler parameters). The motion of the receiver telescope with respect to the transmitter is considered to follow the pre-computed reference angular motion, designed in order to maintain the optical link between source and target during an orbital passage, as described in section D. As regards the dynamics

of the fast steering mirrors, they are modelled as rigid bodies connected to the spacecraft by a series of two hinges, located at the center of mass of the mirrors and each possessing torsional stiffness and torsional damping. With the hypothesis of considering small relative rotation angles, each fast steering mirror is then modelled as a set of two decoupled linear torsional oscillators.

As external disturbance torques, the gravity gradient and magnetic disturbance are considered in the simulations.

### B Model of the Inertial Reference Unit sensors

Rate gyros to determine spacecraft angular rates and star trackers to determine spacecraft attitude are considered in the model. The rate gyros's bias errors and star trackers' measurement gaps have been simulated. During the measurement gap for the star trackers, rate gyros are used to determine angular rates and angular position. When the star trackers measurements are taken, using a simulated Kalman Filter, the angular position is corrected and rate gyro biases are updated.

### C Model of the optical subsystem

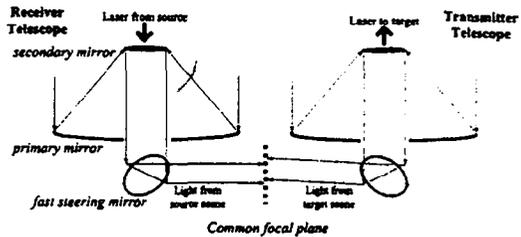
Aiming to a preliminary study of the dynamics of the overall optical relay spacecraft, and in particular on the attitude dynamics, we considered a simple functional model for the optical subsystem. In particular we limited our analysis to geometric optics, without discussing the aspects of wave surface deformation, that will require the use of an adaptive optics system. However we think that our model gives an original and useful approximation.

For the study presented in this article, we focused on the pointing control of the transmitter portion of the optical subsystem, considering the receiver portion always working nominally. In other words, we assumed valid the following hypothesis:

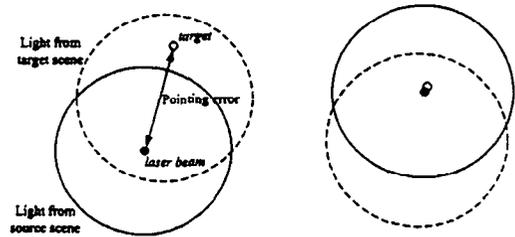
**Hypothesis 1.** *The laser beam coming from the receiver telescope is maintained in the center of the common focal plane by the receiver control system.*

This simplifying hypothesis is based on the fact that the tracking and pointing of the source is intrinsically less demanding than the tracking and pointing of the target, because of the assumed source's cooperativeness. Then, for a preliminary characterization of the possible system performance, we concentrated our effort in simulating more realistically the tracking and pointing of the target, being that the most demanding task.

This is the working concept, considered for the optical subsystem: the fast steering mirrors of the



a) High level scheme of the optical subsystem



b) Images on the common focal plane: pointing error

c) Compensated pointing error

**Fig. 2** Basic concepts of the optical subsystem of the Bifocal Relay Mirror Spacecraft

transmitter and receiver telescopes, with Cassegrain configuration, convey the light respectively from the target scene and the source scene toward a common focal plane. The light is considered collimated on the fast steering mirrors by the telescopes secondary mirrors.

Figure 2 gives a high-level description of the optical subsystem of the Bifocal Relay Mirror spacecraft, as it has been considered for the present study.

Figure 2(b) shows a typical situation at the beginning of the pointing process, looking on the common focal plane. While the laser beam is approximately in the center of the image coming from the source scene, which is the nominal situation, there is a pointing error between laser beam and target. By suitably moving the transmitter fast steering mirror, the image of the target moves on the common focal plane with respect to the image of the source and the error between the laser beam and the target is reduced, as figure 2(c) shows. Then, the target fast steering mirror corrects the residual target boresight error.

Moreover the fast steering mirrors have also to reject the Line of Sight jitter. Details on how to insure the alignment of the two focal planes (receiver and transmitter) are not discussed.

C.1 Model of the target pointing error

The target pointing error is considered, in our simulations, as the set of the two angles of which the laser beam has to be moved, around two cartesian axes orthogonal with respect to the optical axis of the transmitter telescope (i.e. axes  $x_T$  and  $y_T$  in figure 1), in order to reach the target point. In other words, the target pointing error is considered as the set of two coordinates (azimuth and elevation) under which an observer, fixed with the spacecraft and looking along the current transmitter telescope optical axis, sees the target point.

The following simplifying hypotheses, have been applied:

**Hypothesis 2** *The target error is zero when the error between the current and the reference attitude is zero, and the transmitter fast steering mirror is in its neutral position;*

I.e. the target is considered to be in the position where the optical axis of the transmitter mirror intersects the target, when the current attitude corresponds to the reference one.

**Hypothesis 3** *The attitude error is considered small.*

Moreover, the correction of the laser pointing ahead, which is due to the combination of the effects of the finite propagation time of the light across the link and the relative motion of the spacecraft with respect to source and target, has not been considered.

The target pointing error can then be defined by the following column matrix :

$$e = \{ e_x \ e_y \}^T \cong 2 \{ q_{e1} \ q_{e2} \}^T \quad (1)$$

where  $q_e$  are the quaternion giving the reference attitude with respect to the current attitude.

C.2 Model of the optical tracker sensors

Two optical tracker sensors, supposed fixed with respect to the common focal plane, process the images from the two telescopes, and their outputs are available to the controllers of the fast steering mirrors. In particular, the target optical tracker senses the motion of the target relative to the focal plane and commands the fast steering mirror of the transmitter telescope in order to reduce the pointing error. In our simulations we have modeled the target tracker sensor of the transmitter telescope, with the simplifying hypothesis that it has continuous output and no noise.

The mathematical expression considered for the tracker sensor output is:

$$e_{meas} = \eta e - e_c \quad (2)$$

where  $\eta$  is the angular magnification factor of the transmitter telescope,  $e$  is the target angular pointing error, defined in eq. 1, and  $e_c = f(\beta_{x_m}, \beta_{y_m})$  is the angular pointing correction due to the motion of the transmitter fast steering mirror.

In order to obtain the explicit form of the mentioned function  $f$ , it is useful to write the optics law of specular reflection in the following vectorial way (see, for example, ref.<sup>11</sup>):

$$\underline{r}_r = 2(\underline{r}_i \cdot \underline{n}_m)\underline{n}_m - \underline{r}_i \quad (3)$$

where  $\underline{r}_r$  is the versor parallel to the reflected ray,  $\underline{r}_i$  is the versor parallel to the incident ray and  $\underline{n}_m$  is the versor normal to the surface of the mirror.

Following the hypothesis 1, the versor  $\underline{r}_i$ , giving the direction of the laser ray coming from the receiver side and incident into the common focal plane and the transmitter fast steering mirror, is in our case lying on the axis  $x_R \equiv x_T'$ . Where the frame  $T'$  is defined as being parallel to the frame  $T$  and located at the center of the transmitter fast steering mirror. The rotation axis  $x_T'$ , coincides with the rotation axis between the two telescopes and the optical axis of the common focal plane.

The normal to the transmitter fast steering surface is nominally directed as the bisectrix of the angle  $\widehat{x_T', z_T'}$ , when the mirror is in its neutral position.

Projecting the equation 3 on the axes  $x_T'$  and  $y_T'$ , processing the resulting mathematics under the hypothesis of small deflection angles and considering that the column vector of the components of  $\underline{r}_r$  on  $x_T'$  and  $y_T'$ , can be written as:

$$\underline{r}_r \cong \{ e_{cy} \ -e_{cx} \}^T \quad (4)$$

the following relation between the angular pointing correction and the tilting angles of the target fast steering mirror is finally obtained:

$$e_c \cong \{ \sqrt{2}\beta_{x_m} \ 2\beta_{y_m} \}^T \quad (5)$$

C.3 Model of the target Line of Sight jitter

An artificial Line of Sight jitter has been added in the simulations as a pseudo-random disturbance input to the transmitter fast steering mirror. The assumption is that the jitter act as a random, zero mean process, which can be represented as colored (filtered) white noise, such that the power spectral density of the experimentally measured noise

is reproduced. In absence of experimental measurements, hypothetical values are used for the sake of carrying out preliminary simulations.

The aim of this artificial jitter is to represent several effects, that has not been modelled in the derivation of the dynamics of the system: in particular, the structural flexibility of the spacecraft, the noise introduced by the reaction wheels and cryocoolers (which are likely needed for the tracker sensors), the uncertainties in the determination of the reference motion and the effect of the atmosphere on the laser beam propagation.

**D Geometry of the laser relay mission**

This section focuses on the analytical design of the mission geometry of the laser relay spacecraft, during a nominal(\*) engagement (or relay) phase: that is the portion of an orbital passage during which the laser connection between source and target is established.

In particular, the analysis of the mission geometry aims to the determination of the reference attitude motion for the guidance of the relay spacecraft during the laser link operation. The reference attitude motion can then be used both to determine the feed-forward torques portion of the control, as a function of the time, and to compute the feedback error, on an instant by instant base. In the ideal case of no disturbances, the application to the spacecraft of the feed-forward torques alone would guarantee the laser link connectivity between source and target location.

The following hypotheses have been assumed for the sake of the computation of the reference motion:

**Hypothesis 4** Both target and source are considered fixed on the Earth's surface.

**Hypothesis 5** The Earth is considered spherical and with a flat surface.

**Hypothesis 6**  $O_R \equiv O_T \equiv O_S$

The following three conditions have to be satisfied at each instant, during a nominal engagement:

1. The optical axis  $z_T$  of the transmitter telescope crosses the target and the optical axis  $z_R$  of the receiver telescope crosses the source, that is in mathematical notation:

$$k_T \doteq \frac{L_{tg} - O_S}{|L_{tg} - O_S|} \quad k_R = \frac{L_{sr} - O_S}{|L_{sr} - O_S|} \quad (6)$$

where  $k_T$  and  $k_R$  are the versors of  $z_T$  and  $z_R$  respectively,  $L_{tg}$  is the location of the target and  $L_{sr}$  is the location of the source;

\*Nominal here means with fast steering mirrors fixed in the idle position and no disturbances

2. The value of the relative angle between the two telescopes ( $\alpha$ ) equals the angular separation between target and source as seen at the spacecraft location, that is:

$$\alpha = \arccos(k_R \cdot k_T) \quad (7)$$

where  $\alpha$  is the relative rotation between the two telescopes;

3. The rotation axis  $x_R$  between the two telescopes is perpendicular to the plane defined by the locations of the spacecraft, the target point and the source point. That is:

$$i_R = \frac{k_T \wedge k_R}{|k_T \wedge k_R|} \quad (8)$$

where  $i_R$  is the versor of the axis  $x_R$ .

The following algorithmic steps are carried out in order to obtain the reference attitude at a particular instant of the engagement: calculation of the position of source and target in the Earth Celestial Frame (ECF), starting from their known positions in the Earth Geographic Frame (EGEOF); deduction of the current position of the spacecraft and the sub satellite point (SSP) in the ECF, starting from the orbital parameters; imposition of the three conditions above. The attitude of the transmitter body fixed frame with respect to the Spacecraft Celestial Frame (SCF) is finally obtained, for example using quaternions. Useful mathematical relations for the implementation of this algorithm have been found in ref.12

Repeating the above described algorithm, at regular time-steps along the duration of the engagement, a sequence of quaternions, giving the evolution of the reference attitude, is finally obtained. The calculation of the reference attitude can be carried out off-line and the sequence of quaternions recorded for the successive utilization during the simulations of the dynamics and control of the Optical Relay Spacecraft. A similar procedure could be carried out for the operation of the real satellite.

The reference attitude trajectory results in a quasi-periodic trend of the norm of the angular momentum accumulated in the reaction wheels during a relay operation, making the use of reaction wheels particularly suitable for that maneuver.

**E Control approaches**

The Two control approaches, described in the following subsections, have been considered in the simulations:

**E.1 Independent control of fast steering mirrors and spacecraft attitude**

Using this approach, the spacecraft attitude is controlled independently with respect to the fast steering mirrors motion.

The spacecraft attitude is controlled by the following feed-forward plus PD-feedback control law:

$$T_c = T_{ff} + K q_{ve} + C \omega_e \tag{9}$$

where  $T_{ff}$  represent the feed-forward components of the torque, computed by using the expression of the equation of motions and the reference attitude trajectory;  $q_{ve}$  is the vectorial component of the quaternion error, giving the relative angular position of the body frame in the reference attitude with respect to the body frame in the current attitude;  $\omega_e$  is the difference between the reference and the current angular velocity;  $K$  and  $C$  are positive diagonal matrices of gains. The current attitude is considered sensed by an Inertial Reference Unit (IRU), composed by star trackers and rate gyros.

The transmitter and receiver fast steering mirrors are controlled by a PID control, sensing the target and source errors with the optical sensors.

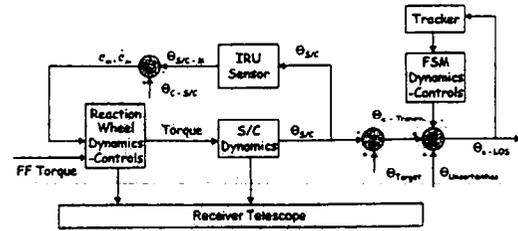
This control approach is described by the block diagram in figure 3(a).

The significance of symbols in figure 3(a) are listed here below:

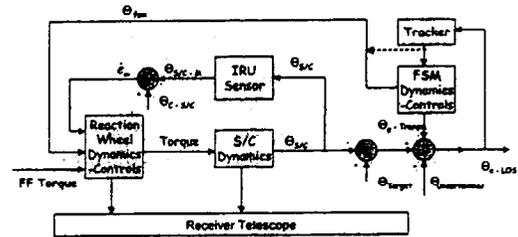
- $\Theta_{SC}$  = true attitude of the spacecraft. In the reality this quantity is not known. In the simulations it is given by the integration of the equations of motion.
- $\Theta_{S/C-M}$  = measured attitude of the spacecraft.
- $\Theta_{C-SC}$  = reference attitude of the spacecraft.
- $\Theta_{Target}$  = attitude of the spacecraft at which the transmitter telescope axis hits the target. In the presented simulations this quantity is considered equal to  $\Theta_{C-SC}$ .
- $\Theta_{e-transm}$  =  $\Theta_{Target} - \Theta_{SC}$  = true pointing error.
- $\Theta_{LOS\ uncertainties}$  = line of sight uncertainties. It can derive from different causes, as explained in section II C.3.

**E.2 Integrated control of transmitter fast steering mirror and spacecraft attitude**

Using this control approach, the transmitter fast steering mirror position relative to the structure is



a) Independent spacecraft-fast steering mirrors control



b) Integrated spacecraft-fast steering mirrors control

**Fig. 3** The two control approaches considered.

measured and used to control the spacecraft attitude. Indeed, the mirror position is proportional to the not corrected target pointing error. The angular position around the yaw axes and the angular rate data, for the attitude control, still comes from the IRU sensors. The concept of this control approach is described by the block diagram in figure 3(b). The dashed line on the output of the target tracker indicates that, in the simulation with fixed fast steering mirror, we considered directly the output of the target as a feedback signal.

**F Implementation of the simulation program**

A new Matlab-Simulink program, called SELTZ (Spacecraft Engineering Library of Tools), custom developed, has been used both for the computation of the reference motion and as a framework for the execution of the program simulating the system dynamics and control laws.

**G Simulation results**

Simulations are carried out during a relay phase. The integration is started at the instant when both target and source become visible to the spacecraft. As sample case for the simulations, we considered the target located in Albuquerque, New Mexico, [ at  $-106^\circ - 37'$  long.,  $35^\circ 3'$  lat.], and source located in Monterey, California, [ at  $-121^\circ - 54'$  long.,  $36^\circ 36'$  lat.]. In particular, we considered the relay phase, during an orbit passing over the target: indeed; this case requires the maximum pitch rate. The space-

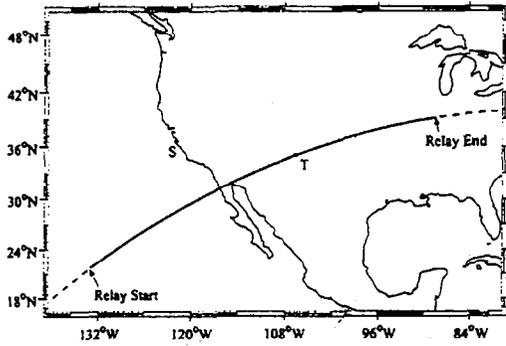


Fig. 4 Ground track of the orbit considered in the simulations: the full line portion indicates the phase of relay between the source (S) and the target (T).

craft orbit is considered circular, with altitude of 715 km and with an inclination of 40 degrees.

As reference frame for the simulations, we considered a spacecraft centered frame, that is inertially oriented parallel to the Pitch-Roll-Yaw frame at the beginning of the simulation.

Figure 4 reports the ground track of the considered orbit on the world map, with highlighted the relay portion of the orbit.

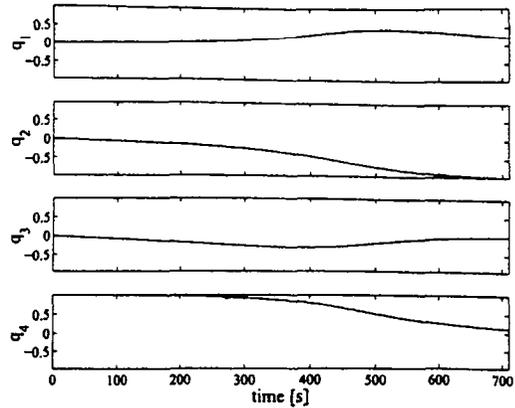
Figures 5 reports the reference motion for the attitude and the joint angle  $\alpha$  between the two telescopes.

The simulation time period is 710 seconds. The simulation solver method is ode5 (Dormand-Prince), and the solver fixed step size is 0.005 seconds.

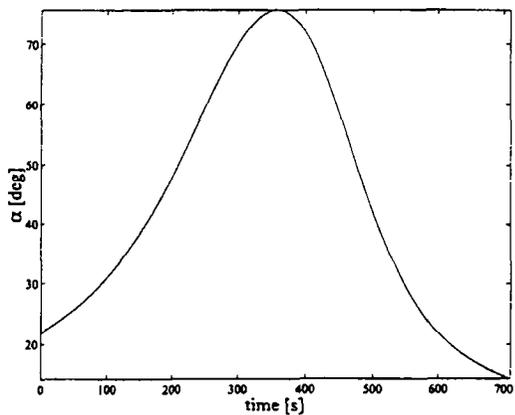
The spacecraft mass is 3240 kg at launch. Mass of the transmitter telescope:  $m_1 = 2267 \text{ Kg}$ , mass of the receiver telescope:  $m_2 = 973 \text{ Kg}$ . Both receiver and transmitter telescopes have 1.64 meter diameter. Transmitter telescope inertia:  $I_{xTxT} = 2997 \text{ Kg m}^2$ ,  $I_{yTyT} = 3164 \text{ Kg m}^2$ , and  $I_{zTzT} = 882 \text{ Kg m}^2$ ; receiver telescope inertia:  $I_{xRxR} = 1721 \text{ Kg m}^2$ ,  $I_{yRyR} = 1560 \text{ Kg m}^2$ , and  $I_{zRzR} = 183 \text{ Kg m}^2$ . For both the transmitter and receiver fast steering mirrors:  $j_{x_m} = j_{y_m} = 0.01 \text{ Kg m}^2$ . Natural frequency around both  $x$  and  $y$  axes:  $\omega_{n_{x_m}} = \omega_{n_{y_m}} = 10 \text{ Hz}$ . Damping ratio around both  $x$  and  $y$  axes  $\xi_{x_m} = \xi_{y_m} = 0.01$ .

Magnification factor of both telescopes: 8.2. Field of view for both telescopes:  $5 \times 10^{-4} \text{ rad}$ . This field of view corresponds to a circular footprint area with radius of 375 m on the earth surface, when the telescope axis is perpendicular to the surface.

The final mission requirements are for a beam width of 3 m, when telescope axis is perpendicular to the surface and maximum Line of Sight jitter re-



a) Reference attitude motion

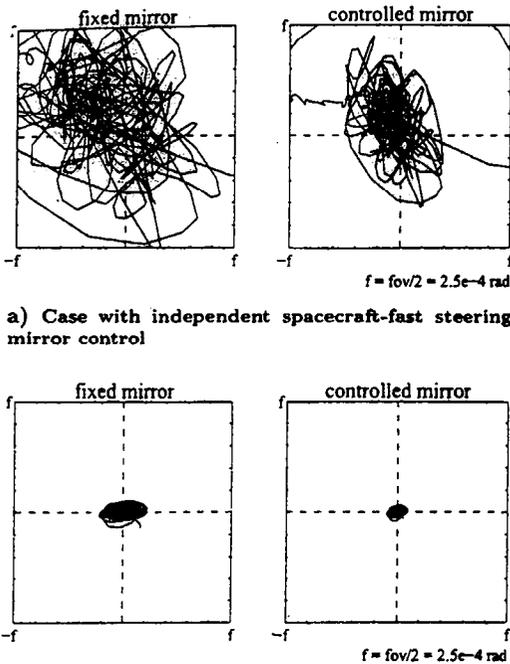


b) Reference motion of the joint angle

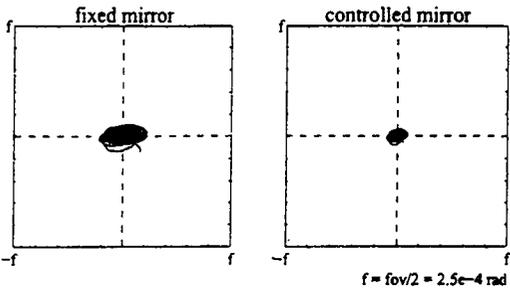
Fig. 5 Reference motion of the Bifocal Relay Mirror spacecraft, computed for the relay phase in fig. 4.

quirements of  $1.18 \times 10^{-6} \text{ rad}$ , at the transmitter fast steering mirror.<sup>6</sup> Nevertheless, in this study we have focused on the preliminary comparison of two different control method without evaluating the strict respect of the final requirements.

The secular torques magnitude is  $1 \times 10^{-4} \text{ Nm}$ . The control law delay for initial determination errors is 30 seconds. A star tracker measurement gap is considered in the period between 100 and 300 seconds. The rate gyros static rate biases are  $1 \times 10^{-4} [-1, 1.5, 1] \text{ rad/sec}$ . The initial errors are set: for quaternion  $[0.001, 0.001, -0.001]$  and for angular rate  $[-0.0001, 0.0001, 0.0001] \text{ rad/sec}$ . Control gains for the PD control of the spacecraft,  $k = [1500, 3500, 2250]$  and  $k_d = [1000, 2000, 1000]$ . For the reaction wheels, the maximum allowable torque is 1 Nm and the maximum angular momentum is



a) Case with independent spacecraft-fast steering mirror control



b) Case with integrated spacecraft-fast steering mirror control

Fig. 6 Simulated view of the track on the target sensor.

$40 \text{ Nm/sec}$ . Gains for the PID control of the transmitter fast steering mirrors:  $k_p = [160, 160]$ ,  $k_d = [10, 10]$ ,  $k_i = [15, 15]$ .

An artificial line of sight jitter is added in the simulation model, upstream with respect to the fast steering mirror. The artificial jitter is in the form of white noise having standard deviation equal to two times the max LOS jitter requirements and low pass filtered at  $15 \text{ Hz}$ .

Figures 6 give the results of two simulation runs, representing the view of the target track as captured by the target tracker sensor. The laser beam spot corresponds to the center of the square area in the figures and each side of the square corresponds to the field of view of the telescope.

Figures 6(a) represent the results of the simulations in the case of system with independent spacecraft fast steering mirror control. The case of uncontrolled target error (i.e. mirror fixed) is compared to the case of target error controlled by tilting the fast steering mirror.

Figures 6(b) represent the results in the case of integrated spacecraft-fast steering mirrors control. The reduction of pointing errors with respect to the independent control is evident.

### III Experiments on a Spacecraft Simulator test-bed

#### A The experimental test bed

The experimental test-bed, that has been redesigned and updated for the presented research, consists of several subsystems, that act together to simulate the transmitter portion of the Bifocal Relay Mirror spacecraft.

The three main functional parts of the test-bed are:

1. a three axes stabilized spacecraft simulator, carrying an optical payload and floating on a spherical air bearing.
2. a laser source ( $\text{He} - \text{Ne}$ ,  $.8 \text{ mWatt}$ ), fixed on the ground and located at a distance of  $\sim 3 \text{ m}$  from the spacecraft simulator
3. a target area (a geographical map of the world), hanged on a wall at a distance of  $\sim 7 \text{ m}$  from the spacecraft simulator

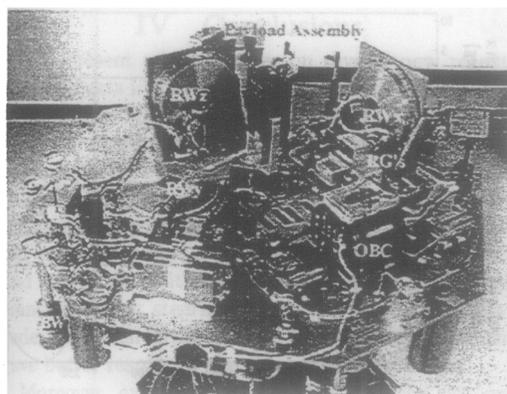
Two desktop computers (Athlon 1.4 GHz), located on the ground, are also part of the test bed: the first PC is used for transferring the commands and telemetry data to/from the spacecraft on board computer, while the second one is used for the independent control of the optical payload.

#### A.1 The Three Axes Spacecraft Simulator

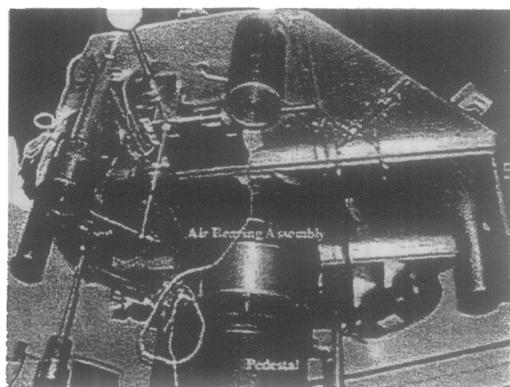
The Three Axes Spacecraft Simulator (TASS) of the NPS-AFRL Joint Laboratory at the Spacecraft Research and Design Center allows the simulation of the zero-g attitude motion of a spacecraft, by free floating a hardware spacecraft model through a spherical air bearing. Indeed, a virtually torque-free environment is achieved if the center of mass of the spacecraft model coincides with the center of rotation of the air bearing.

The core of the TASS spacecraft model consists of a  $1.3 \text{ m}$  wide octagonal metallic structure, which is mounted on top of a  $1.4 \text{ m}$  high pedestal, through an hemispherical air bearing interface. The main bus elements of the TASS, used for the presented research, are listed here below and shown in figures 7:

- three orthogonally mounted reaction wheels, with max angular momentum of  $20.3 \text{ Nm s}$  @  $2500 \text{ rpm}$  and max torque of  $0.16 \text{ Nm}$ , manufactured by Ball Aerospace (RW in figure 7(a)).
- three orthogonally mounted mechanical rate gyroscopes, by Humprey (RG in figure 7(a)).



a) Top view

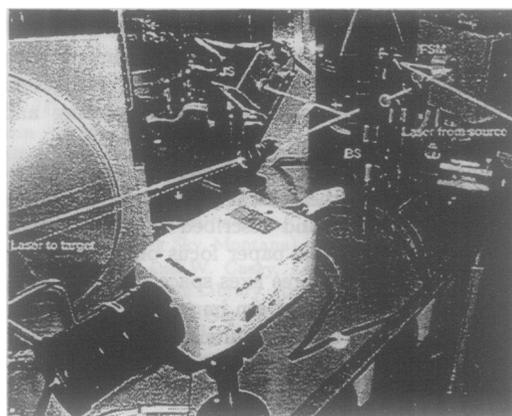


b) Bottom view

**Fig. 7** The Three Axes Spacecraft Simulator at the NPS-AFRL Optical Relay Spacecraft Laboratory of the Spacecraft Research and Design Center.

- two analog inclinometers, by Seilka, used as attitude sensors around the pitch ( $x$ ) and roll ( $z$ ) axes.
- one infrared sensor used for the attitude around the yaw axis ( $y$ ).
- one on board embedded computer and input/output cards (OBC in figure 7(a)). Commands are sent from and telemetry data are retrieved to a desktop computer via wireless Ethernet connection.
- balancing and ballast weights for the precise positioning of the center of mass (BW in figure 7(a)).

The TASS overall floating mass is  $\sim 200\text{ kg}$ , and the moments of inertia are  $I_{xx} \cong 29\text{ kg m}^2$ ,  $I_{yy} \cong$



**Fig. 8** Detail of the optical payload developed by the Air Force Research Laboratory.

$29\text{ kg m}^2$ ,  $I_{zz} \cong 45\text{ kg m}^2$ . The air bearing allow an angular motion range of  $-30 - +30\text{ deg}$  around pitch and roll axes and unlimited motion around yaw axis.

#### A.2 The optical payload

The optical payload, developed by the U.S. Air Force Research Laboratory and mounted on the Three Axes Spacecraft Simulator, consists of a two axis fast steering mirror,<sup>13</sup> an optical train, a beam jitter sensor and a digital camera pointed toward the target area and acting as target sensor. The goal of the optical payload is to represent the transmitter telescope section of the bifocal relay mirror optical section.

Figure 8 shows the optical payload. The laser beam, coming from the source on the ground, after having passed through a primary mirror, is reflected by the fast steering mirror (FSM in figure 8) and focused on a beam splitter (BS in figure 8). A portion of the light is sent to a quad-cell jitter sensor (JS in figure 8), while the main beam is directed to a beam spreader and then to the target. The fast steering mirror is controlled by two feedback loops: the first loop, having a bandwidth of  $\sim 500\text{ Hz}$  is closed with the quad-cell sensor and an analogue PID control circuit and aims at the beam jitter reduction. The second control loop, having a bandwidth of  $\sim 10\text{ Hz}$  is closed with the digital camera and one personal computer on the ground, running a custom image processing software. This second loop aims at the pointing and tracking of the laser beam.

The beam jitter is mainly due to the structural vibrations of the spacecraft bus.

## B Experimental results

The main tasks of the presented experiments were to validate the attitude stabilization control together with the target acquisition-tracking-pointing and laser jitter rejection.

Since the laser jitter rejection and target tracking capability of the optical payload have already been demonstrated and described in ref.<sup>9</sup>, the results presented in this paper focus on the attitude stabilization of the three axes spacecraft simulator, whose performance has been improved considerably with respect to previous results<sup>8</sup>.

Three independent PID control laws are used for the attitude stabilization control. The gain of the controllers were chosen as  $k = 13$ ,  $k_d = 1.3$ ,  $k_i = .01$ .

A digital first order Butterworth filter is applied to the signals from the gyroscopes. Moreover the gyro's biases are estimated by a median filter, acting for twenty seconds with platform not floating, before the switching on of the attitude stabilization control.

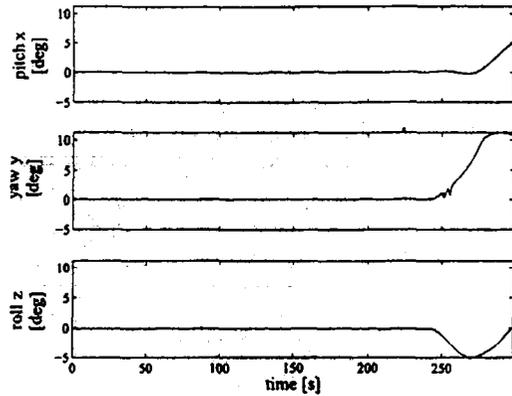
The attitude control software has been coded in Matlab-Simulink. The real time code was then automatically generated from the simulation code and uploaded to the on board computer, running a real time operating system (Mathworks Xpc).

Figures 9 report the angular positions and figure 10 reports the angular rate of the Three Axes Spacecraft Simulator during an experimental run of 300 s. In order to highlight the free motion of the spacecraft simulator under the effect of the disturbances, the stabilizing control has been switched off at  $time = 244$  s. The main disturbance torques acting on the spacecraft simulator are a residual unbalance between the center of mass of the system and the center of rotation of the air bearing, and the weight of a tiny wire carrying the electric power to the floating platform, visible in figure 7(b). The module of the disturbance torque has order of magnitude of  $\sim 0.01$  Nm.

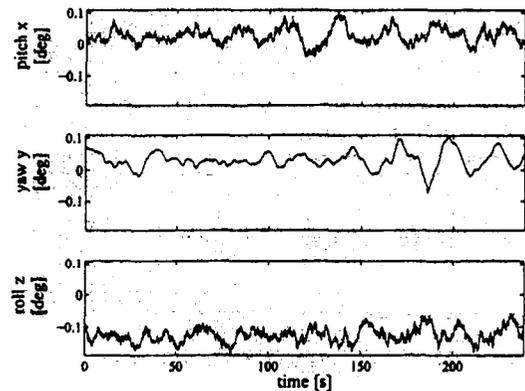
The maximum attitude error, during the presented test, was  $\sim 0.1$  deg and the maximum angular rate error  $\sim 0.02$  deg/s. The slow correction of the persistent error, especially evident around the roll axis (z), is due to the low value used for the integral gain. The maximum value of the applied control torque was  $\sim 0.03$  Nm, and the maximum speed reached by the reaction wheels was  $\sim 750$  rpm.

Tests have been carried out till a max duration of 600 s and have shown analogous results.

The obtained performances of the attitude stabilization control were very satisfying and, in particular, have allowed a full contemporaneous experimentation of the optical payload portion of the test-bed.



a) Complete measurement



b) Detail of figure (a)

Fig. 9 Experimental test: attitude of the three axes spacecraft simulator. The control is switched off at  $time = 244$  s.

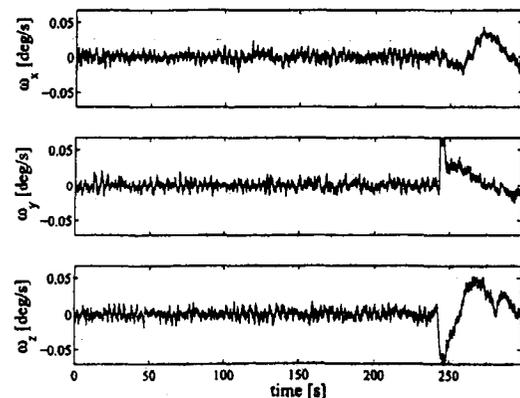


Fig. 10 Experimental test: angular rates of the three axes spacecraft simulator. The control is switched off at  $time = 244$  s.

#### IV Conclusions

The present paper focuses on several new recent developments in the researches regarding the Bifocal Relay Mirror spacecraft.

Simulations have been carried out on a refined dynamics model of the Bifocal Relay Mirror Spacecraft in order to preliminary validate and compare two different proposed control approaches. In particular, an independent control of fast steering mirrors and spacecraft attitude and an integrated control of transmitter fast steering mirror and spacecraft attitude have been investigated. The second approach gave better results in the presented simulations.

Moreover, experiments have been carried out on the spacecraft simulator of the NPS-AFRL Joint Laboratory at the Spacecraft Research and Design Center. The main tasks of the presented experiments were to validate a concept for the attitude stabilization control of the transmitter section of the Bifocal Relay Mirror spacecraft, together with the target acquisition-tracking-pointing and laser jitter rejection. The max attitude error, during the presented test, was  $\sim 0.1$  deg and the max angular rate error  $\sim 0.02$  deg/s. The obtained performances of the attitude stabilization control were very satisfying and, in particular, have allowed a full contemporaneous experimentation of the optical payload portion of the test-bed. Moreover the experimental tests carried out have demonstrated the effectiveness of the spacecraft simulator test-bed as an important validation tool, to be used in the following researches.

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test-bed is gratefully acknowledged.

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