Principle demonstration of fine pointing control system for inter-satellite laser communication

DONG YuHui1,2†, LIU HeShan1,2†, LUO ZiRen1, LI YuQiong1 & JIN Gang1*

1 National Microgravity Laboratory (NML), Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China;
2 University of Chinese Academy of Sciences, Beijing 100190, China

Received December 1, 2014; accepted January 22, 2015; published online January 30, 2015

Due to high data rates and reliability, inter-satellite laser communication has developed rapidly in these days. However, the stability of the laser beam pointing is still a key technique which needs to be solved; otherwise, the beam pointing jitter noise would reduce the communication quality or, even worse, would make the inter-satellite laser communication impossible. For this purpose, a bench-top of the fine beam pointing control system has been built and tested for inter-satellite laser communication. The pointing offset of more than 100 μrad is produced by the steering mirror. With beam pointing control system turned on, the offset could be rapidly suppressed to lower than 100 nrad in less than 0.5 s. Moreover, the pointing stability can be kept at 40 nrad for yaw motion and 62 nrad for pitch motion, when the received beam jitter is set at 20 μrad.

1 Introduction

Laser communication is thought to be the most promising future inter-satellite communication strategy because of its high transmitting speed and reliability [1–5]. During the operation of the inter-satellite laser communication system, how to maintain the precision and stability of the laser pointing direction is a critical problem that needs to be solved [3–8]. Being maximally suppressed by the disturbance reduction system, the residual satellite vibration, which originates from a variety of sources, such as solar radiation, residual magnetic field, static gravity imbalance and structural interactions, is still coupled into the detected laser beam. The heterodyne contrast and the received power which is decreased by the pointing jitter will seriously influence the communication quality. Therefore, the beam pointing control system between two distant satellites has become a major issue for those missions and should be suppressed to sub-micro-radian regime [9–13].

A fine laser pointing control system based on differential wave-front sensing (DWS) [14–17] is introduced in this paper which could be integrated with the inter-satellite laser communication system (see Figure 1). The pointing jitter can be well suppressed by a pair of beam pointing control systems in two satellites, which can guarantee the communication quality in the inter-satellite communication. This pointing control system is inherited from space-borne laser interferometer gravitational wave (G.W.) detection missions [18–22]. To explore the most attractive G.W.s, the space-borne G.W. antennas are designed to measure pico-meter displacement in a distance of $10^3$ to $10^7$ km [23–27]. Beam
pointing noise is one of the most prominent noises in long baseline space laser interferometer and mainly dominated by laser pointing jitter. Thus, the G.W. antennas require extremely high accuracy and stability for the laser beam pointing direction control \([28,29]\). Taking the evolved Laser Interferometer Space Antenna (eLISA) as an example, the laser pointing jitter should be suppressed to 10 nrad in a long period of \(10^2 \) to \(10^3 \) s \([30]\).

In this paper, a bench-top fine beam pointing control system is built and tested for inter-satellite laser communication based on the DWS technique. Under a closed loop, a static pointing offset larger than 100 \(\mu\)rad can be rapidly suppressed to 10 nrad within 0.5 s. Furthermore, we simulate a pointing jitter of 20 \(\mu\)rad in the laser pointing direction. After turning on the feedback pointing control system, the root mean square (RMS) of the pointing jitter for yaw and pitch motion has been reduced to 40 nrad and 62 nrad, respectively.

2 Experimental setups

To investigate the methodological laser beam pointing control system for inter-satellite laser communication, the heterodyne frequency generation part is essential shown in Figure 2(a). In this function part, a solid state laser at a wavelength of 1064 nm is used as the light source. After being divided by a beam splitter, the laser beams are frequency shifted by a pair of acoustic-optical modulators (AOMs), and the first-order Bragg diffracted beams with the maximum power are selected by the apertures. Then a pair of beams with stabilized heterodyne frequencies are generated and sent into the ultra-stable optical bench through fiber injected system as shown in Figure 2(b). The laser in red line used to simulate the transmitting laser is reflected by a steering mirror operated by the simulator; while the beam in green line represents the local laser. The two beams are superimposed and the relative angle is read out by the DWS angle-sensitive-system consisting of a quadrant photo detector (QPD) \([31,32]\) and a phasemeter (PM) (Figure 3). DWS is a well-known technique with high sensitivity. In small range, the DWS phase signals \(\Delta \theta\) between opposing halves of QPD can be approximated as \([17]\)

\[
\Delta \theta \approx \frac{16r}{3\lambda} \cdot \alpha = k \cdot \alpha,
\]

where \(\alpha\) is the relative wave-front tilt, \(r\) is the beam radius, \(\lambda\) is the laser wavelength and \(k\) is the conversion factor.

3 Calibration and experiments

Predicted by the DWS technique, the conversion factor \(k\) from geometrical angle to electrical phase difference should be initially calibrated by the experiment. Two degrees of freedom are required to depict the pointing jitter of the received light, where yaw motion indicates the horizontal misalignment and pitch motion presents the vertical fluctuation. In the experiment, the two degrees of freedom are calibrated independently. The steering mirror driven by a piezoelectric transducer (PZT) is steered from \(-300\) \(\mu\)rad to 300 \(\mu\)rad in the yaw (pitch) motion, when the pitch (yaw) motion is kept at zero. The laser beam pointing data read out by the DWS technique is shown in Figure 4.

As shown in Figure 4, the solid lines are the linear regression lines of the DWS pointing error. The correlation coefficients of the linear fittings for yaw and pitch motions are 0.99995 and 0.99996, respectively, which indicates a good linearity between the DWS signal and relative angles in the working range from \(-300\) \(\mu\)rad to 300 \(\mu\)rad. The con-
Figure 2 (Color online) Schematic diagram of the beam pointing control system. AOM: Acoustic-optical modulator, AP: Aperture, BS: 50:50 beam splitter, FI: Fiber injector, LP: Linear polarizer, P-Controller: Pointing controller, PM: Phasemeter, QPD: Quadrant photo detector, SM: Steering mirror and WP: Wedged plate.

Figure 3 (Color online) Picture of the ultra-stable optical bench of the beam pointing system.

Figure 4 (Color online) Linear fit for yaw motion and pitch motion.

version factors for yaw and pitch motions obtained from linear fitting curve are 5689 rad/rad and 4815 rad/rad. The different amplitudes of the conversion factor may originate from various elements, such as imperfect overlapping of two interfering beams, inhomogeneous spatial distribution of the phase, or non-perpendicularity between the laser beams and photo-detector. In addition to high conversion factor, the DWS angle measurement can suppress common mode noises, which makes the high accuracy angle measurement and control possible.

3.1 Beam pointing control with a pointing offset of 100 μrad

In order to verify the dynamic response of the pointing system in large pointing offset, an offset angle of more than 100 μrad for yaw motion and pitch motion is simulated by the steering mirror. After 20 s free running, the closed loop of the pointing control system is turned on, and its performance is shown in Figure 5.

As shown in Figure 5, from 0 and 20 s, the pointing offsets are larger than 100 μrad in yaw motion and pitch motion. When the pointing control system is working at 20 s, the average angle offsets are rapidly decreased to lower than 100 nrad for yaw and pitch motions in less than 0.5 s.

3.2 Beam pointing control with a 20 μrad jitter

Pointing stability is a significant parameter which will seriously influence the bit error rate for inter-satellite laser communication. In this experiment, a laser beam of which the peak to peak pointing jitter is 20 μrad is driven by the steering mirror. After 5000 s free running, the pointing control system begins to work and the data detected by DWS system is shown in Figure 6.

As shown in Figure 6(a), under the closed loop of the pointing control, the RMS of the pointing jitter is suppressed from 7.1 μrad to less than 40 nrad in yaw motion. Meanwhile, the RMS of the pitch jitter is controlled from 7.0 μrad to 62 nrad, which is available in Figure 6(b). Moreover, the average of the pointing data is lower than
100 nrad after the pointing control in yaw and pitch directions, respectively.

4 Conclusions

A bench-top of the feedback-based laser beam pointing system has been built and tested for inter-satellite laser communication. The DWS technique has been introduced to sense the relative wave-front tilt with high sensitivity and low noise. The offset pointing error of more than 100 µrad is produced by the steering mirror. With the beam pointing control system turned on, the offset has been rapidly suppressed to lower than 100 nrad for both yaw and pitch motions in less than 0.5 s, which indicates a good dynamic response. Moreover, the pointing stability can be kept at 40 nrad for yaw motion and 62 nrad for pitch motion, when the simulated received beam jitter is set at 20 µrad.

The environment of the inter-satellite laser communication is complicated and changeable. In the future, the simulated received beam jitter will be much closer to the real situation and the received laser power will be μW level. The following research will focus on the requirement of fine pointing control for inter-satellite laser communication in that situation.

This work was supported by the Space Science Research Projects in Advance (SSRPA: O930143XM1), and the Scientific Equipment Development and Research Project of Chinese Academy of Sciences (SEDRP: Y231411YB1).

1 Chan V W S. Optical space communications. IEEE J Sel Top Quantum Electron, 2000, 6: 959–975
2 Skormin V A, Tascillo M A, Busch T E. Demonstration of a jitter re-
jection technique for free-space laser. IEEE Aerosp Electron Syst Mag, 1997, 33: 568–576
3 Arnon S, Kopeika N S. Laser satellite communication network-vibration effect and possible solutions. Proc IEEE, 1997, 85: 1646–1661
4 Arnon S, Rotman S R, Kopeika N S. Performance limitations of a free-space optical communication satellite network owing to vibrations: heterodyne detection. Appl Opt, 1998, 37: 6366–6374
5 Ma J, Li X, Yu S, et al. Influence of satellite vibration on optical communication performance for intersatellite laser links. Opt Rev, 2012, 19: 25–28
6 Skormin V A, Busch T E, Givens M A. Model reference control of a fast steering mirror of a pointing, acquisition and tracking system for laser communications. Proc IEEE, 1995, 2: 907–913
7 Chen C C, Gardiner C S. Impact of random pointing and tracking errors on the design of coherent and incoherent optical intersatellite communication links. IEEE Tran Commun, 1989, 37: 252–260
8 Skormin V A, Tascillo M A, Busch T E. An adaptive jitter rejection technique applicable to airborne laser communication system. Opt Eng, 1995, 34: 1263–1268
9 Jono T, Takayama Y, Kura N, et al. OICETS on-orbit laser communication experiments. Proc SPIE, 2006, 6105: 610503
10 Held K J, Barry J D. Precision pointing and tracking between satellite-borne optical systems. Opt Eng, 1988, 27: 325–333
11 Spencer M G, Agrawal B N, Romano M, et al. Acquisition, tracking, pointing, and line-of-sight control laboratory experiments for a space-borne bifocal relay mirror. Proc SPIE, 2002, 4714: 54–64
12 Held K J, Barry J D. Precision optical pointing and tracking from spacecraft with vibrational noise. Proc SPIE, 1986, 0616: 160–173
13 Watkins R J. The adaptive control of optical beam jitter. Dissertation of Doctor Degree. Monterey: Naval Postgraduate School, 2004, 1–2
14 Anderson D Z. Alignment of resonant optical cavities. Appl Opt, 1984, 23: 2944–2949
15 Morrison E, Meers B J, Robertson D I, et al. Experimental demonstration of an automatic alignment system for optical interferometers. Appl Opt, 1994, 33: 5037–5040
16 Heinzel G, Wand V, García A, et al. The LTP interferometer and phasemeter. Class Quantum Grav, 2004, 21: 581–587
17 Sheard B S, Heinzel G, Danzmann K, et al. Intersatellite laser ranging instrument for the GRACE follow-on mission. J Geod, 2012, 86: 1083–1095
18 Dong Y H, Liu H S, Luo Z R, et al. Methodological demonstration of laser beam pointing control for space gravitational wave detection missions. Rev Sci Instrum, 2014, 85: 074501
19 Gong X F, Xu S, Bai S, et al. A scientific case study of an advanced LISA mission. Class Quantum Grav, 2011, 28: 094012
20 Liu H S, Dong Y H, Li Y Q, et al. The evaluation of phasemeter prototype performance for the space gravitational waves detection. Rev Sci Instrum, 2014, 85: 024503
21 Li Y Q, Luo Z R, Liu H S, et al. Laser interferometer used for satellite-satellite tracking: an on-ground methodological demonstration. Chin Phys Lett, 2012, 29: 079501
22 Liu H S, Dong Y H, Luo Z R, et al. Multi-channel phasemeter and its application in the heterodyne laser interferometry. Sci China Tech Sci, 2015, 58: dx: 10.1007/s11431-015-5770-y
23 Danzmann K, Bender P, Brillet A, et al. LISA pre-phase A report. 2nd ed. Max-Planck-Institut fur Quantenoptik Report No. MPQ 208. Garching, Germany, 1998: 47–51
24 Ni W T. ASTROD-GW: Overview and progress. Int J Mod Phys D, 2013, 22: 1341004
25 Harry G M, Fritschel P, Shaddock D A, et al. Laser interferometry for the big bang observer. Class Quantum Grav, 2006, 23: 4887–4894
26 Wang Y, Keitel D, Babak S, et al. Octahedron configuration for a displacement noise-cancelling gravitational wave detector in space. Phys Rev D, 2013, 88: 104021
27 Kawamura S, Nakamura T, Ando M, et al. The Japanese space gravitational wave antenna-DECIGO. Class Quantum Grav, 2006, 23: 125–131
28 Robertson D I, McNamara P, Ward H, et al. Optics for LISA. Class Quantum Grav, 1997, 14: 1575–1577
29 Bender P L. Wavefront distortion and beam pointing for LISA. Class Quantum Grav, 2005, 22: 339–346
30 Jenrich O, Binetruy P, Colpi M, et al. NGO revealing a hidden universe: opening a new chapter of discovery. NGO Assessment Study Report, 2011, 5–68
31 Joshi A, Rue J, Datta S. Low-noise large-area quad photoreceivers based on low-capacitance quad InGaAs photodiodes. IEEE Photonics Technol Lett, 2009, 21: 1585–1587
32 Cervantes F G, Livas J, Silverberg R, et al. Characterization of photoreceivers for LISA. Class Quantum Grav, 2011, 28: 094010