Real-Time Separation Atmospheric Tip-Tilt Signal from Lunar Surface

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Abstract: Considering atmospheric turbulence effects and returned photoelectron numbers on LLR, we think it’s time to compensate turbulence effects in real-time on the LLR, especially for the effects of atmospheric tip-tilt. In this paper, we present the computation method of atmospheric tip-tilt from the lunar surface, and the experiment results at Yunnan Observatory 1.2m telescope that use a small area near the retroreflector array on the lunar surface as an expanded source to detect and compute the atmospheric tip-tilt signal in real time.

Keywords: LLR, returned photoelectron numbers, real-time tip-tilt sensing and compensation

1. INTRODUCTION

Lunar laser ranging (LLR) represents the height of the single photon detection in which the received laser photoelectrons for one laser pulse emission by a 1m telescope on the ground are less than one.

If we consider the atmospheric turbulence effects, especially for the short term beam wander, the returned photoelectron numbers of Kunming station 1.2m laser ranging system for one laser pulse emission using Apollo 15 retroreflector array are: [1]

$$N_r=0.17\times(1/40 \sim 1/6) \qquad (1)$$

The term in brackets represents the effect of the short term beam wander for the laser beam on the LLR.

We may say it is sub-single photon detection.

When a laser beam propagates through the atmosphere, because of a random movement of the atmospheric turbulence, the index of refraction of the Earth’s atmosphere has a fluctuation. That results in a series of effects on the laser beam propagation. All these atmospheric turbulence effects have a time scale: several ms, and relate to the Fried’s coherence length r_o.

Fig.1 shows the relations of some atmospheric turbulence terms for the laser beam propagation and the r_o.

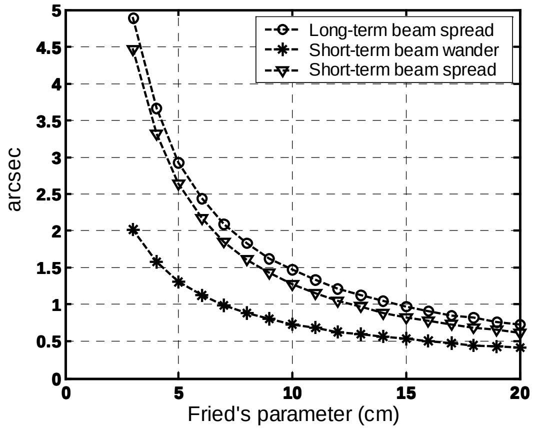

Fig. 1. Atmospheric effects for the laser beam at different r_o

Atmospheric turbulence also affect laser ranging accuracy with several mm to cm scale[1].
When returned laser photons are much less than 1 for one laser pulse firing, we need to consider a method to increase the returned photons. For current laser ranging, many aspects for increasing the returned photoelectron numbers have been considered. Using adaptive optics technique in the laser ranging is a way and proposed [2], especially for the LLR. Its purpose is to compensate atmospheric turbulence effects in real time, and to increase the returned photoelectron numbers on the lunar laser ranging.
For simple and effective, we choose to compensate the short- term wander that is caused by the atmospheric tip-tilt as the first step on the LLR, and near 87% wavefront distortion is caused by the tip-tilt[3]. That is to use the low order correction for the laser ranging, and to compensate the brackets factor in formula (1). The purpose is to increase the returned photoelectron numbers on the LLR.

2. ATMOSPHERIC TIP-TILT SENSING FROM MOON SURFACE

When a ground station performs the LLR, its telescope will point and track the retroreflector array on the moon surface. So the atmospheric tip-tilt information can only be obtained from a small area of the geomorphologic structure that is near the moon retroreflector. We use the absolute difference algorithm to track geomorphologic structure of the moon surface through the motion of the successive images.
First, a $N \times N$ pixels reference image $I_R(x, y)$ that is within the isoplanatic angle is sampled and stored in memory, and a time series $I_1(x, y)$;$I_2(x, y)$;…… $I_L(x, y)$ of two dimensionally resolved images of the same small area are sampled as live images. Then the absolute difference algorithm is used to determine the displacement between the reference image and the live images by computing the sum of the absolute values of the difference of them, for different relative shifts. For each $N \times N$ pixels live image $I_L(x, y)$, a $M \times M$ pixels window is extracted. This window of the live image is compared with the reference image at same positions. The absolute difference values $D(\delta x, \delta y)$ between them are given through the expression:

$$D(\delta x,\delta y)=\sum_{x=0}^{M-1}\sum_{y=0}^{M-1}\left|I_R(x+\delta x,y+\delta y)-I_L(x,y)\right| \tag{2}$$

The position(δx_{min}, δy_{min}) are obtained where $D(\delta x, \delta y)$ is minimum.
The tilt (T_x , T_y) can be determined using a parabolic interpolation. The Newton parabolic interpolation is used with a set of points $D(\delta x_{inx}-1, \delta y_{min})$, $D(\delta x_{min}, \delta y_{min})$, $D(\delta x_{min}+1, \delta y_{min})$ for the x-axis:

$$D(\delta x)=\alpha+\beta[\delta x-(\delta x_{min}-1)]+\gamma[\delta x-(\delta x_{min}-1)][\delta x-\delta x_{min}] \tag{3}$$

Using three point values to determine the parameters α, β, γ, when $D(\delta x)$ is maximum,
$dD(\delta x)/d\delta x=0$, this δx is the x component of the tilt, T_x:

$$T_x = \delta x_{\min} + \frac{1}{2} \cdot \frac{D(\delta x_{\min} - 1, \delta y_{\min}) - D(\delta x_{\min} + 1, \delta y_{\min})}{D(\delta x_{\min} - 1, \delta y_{\min}) + D(\delta x_{\min} + 1, \delta y_{\min}) - 2D(\delta x_{\min}, \delta y_{\min})} \tag{4}$$

Same as x-axis, the y component of the tilt, T_y is:

$$T_y = \delta y_{\min} + \frac{1}{2} \cdot \frac{D(\delta x_{\min}, \delta y_{\min} - 1) - D(\delta x_{\min}, \delta y_{\min} + 1)}{D(\delta x_{\min}, \delta y_{\min} - 1) + D(\delta x_{\min}, \delta y_{\min} + 1) - 2D(\delta x_{\min}, \delta y_{\min})} \tag{5}$$

3. TIP-TILT SENSING EXPERIMENT

Using Kunming SLR station 1.2m telescope, f = 6m, this experiment was done in 2003 with following device: 128×128 CCD, Frame rate: 419, 16μm×16μm for one pixel, 0.″55 /pixel Sampling area: near moon retroreflector array Apollo 11,Apollo14,Apollo15 and Lunakhod 2. Fig.2 show each one image around above arrays.

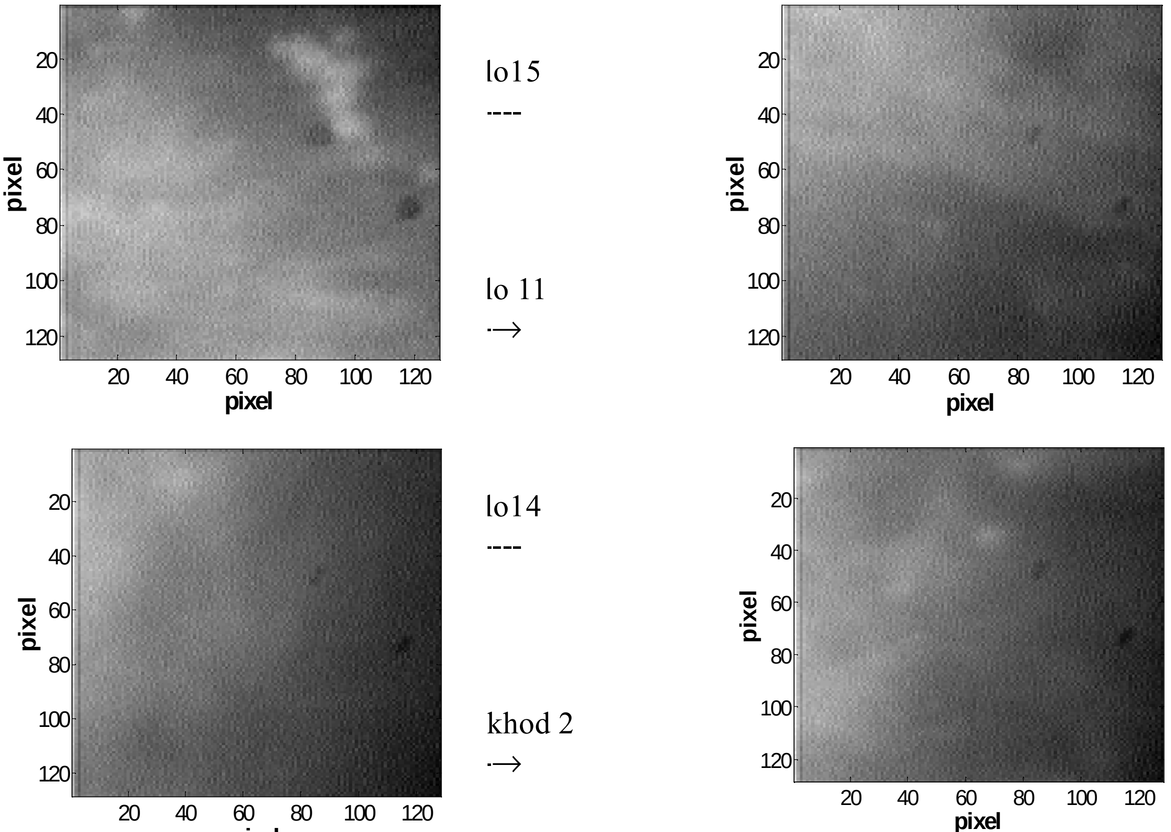

Fig.2. Lunar surface images near retroreflector array

Fig.3 and Fig.4 are computed atmospheric tip-tilt components using the absolute difference algorithm from the area near Apollo15 array.

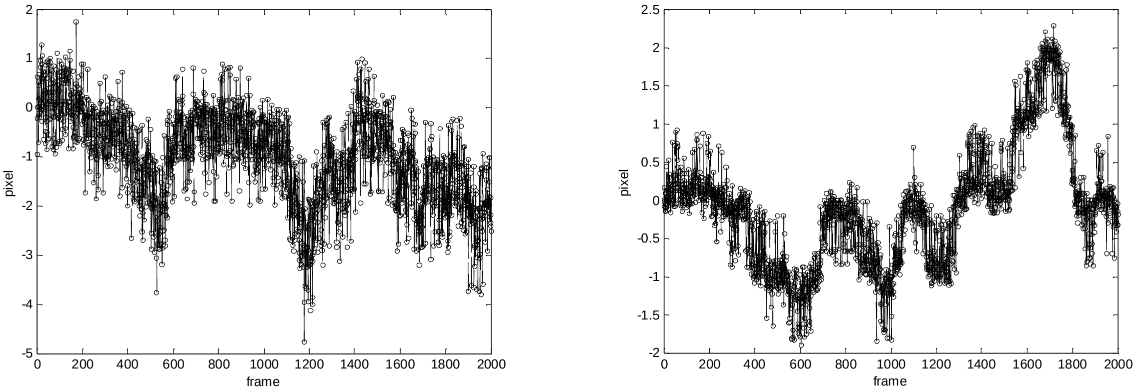

Fig.3. *x* and *y* component of tip-tilt with 16×16 pixels for Apollo15

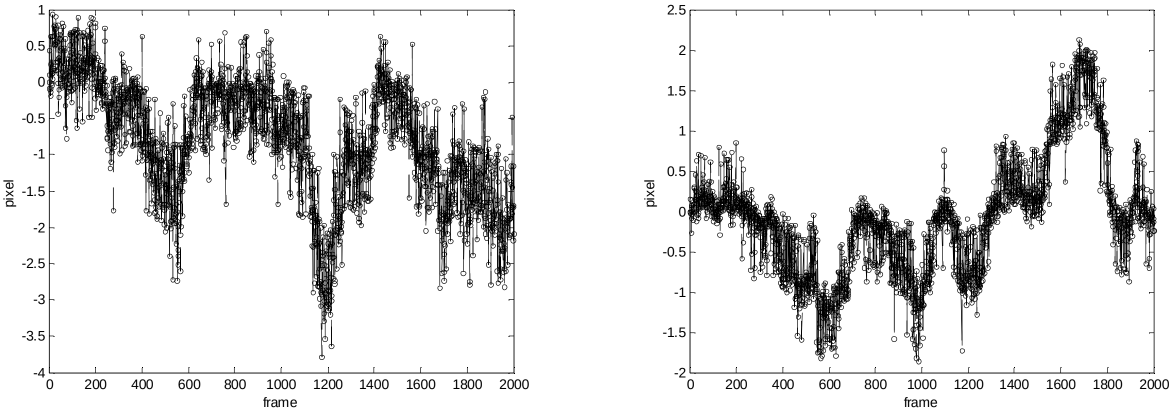

Fig.4. *x* and *y* component of tip-tilt with 32×32 pixels for Apollo15

For above proposal, the real-time property is a key factor for using. We also get following results:
When using a 32×32 pixel window to compute, it take 25 seconds to compute 2000 images,
i.e. 12.5ms/one image;
When using a 16×16 pixel window to compute, it take 6 seconds to compute 2000 images,
i.e. 3ms/one image, within atmospheric turbulence time scale.

4. TECHNICAL PLAN OF COMPENSATION TIP-TILT ON THE LLR

For the LLR, using a wavefront sensor and the absolute difference algorithm, the wavefront tip-tilt signal can be detected from the moon surface. That is to calculate the absolute difference values between a live image and a reference image those are taken from a same small area near the moon retroreflector in time sequence. Next is to separate and compute the atmospheric tip-tilt from these values, then using them to drive a fast tip-tilt mirror real-time (~ ms) to compensate atmospheric tip-tilt for the laser beam that will be emitted soon on the LLR.

For Kunming 1.2m laser ranging system, a tip-tilt detection part and a tip-tilt mirror have been built along optical path. It will perform the real-time tip-tilt compensation for the uplink and the downlink laser beam on the LLR.

Fig.5 is its optical layout for this technical plan.

When the system performs the LLR, according to the ephemeris of the moon retroreflector array, the retroreflector will be tracked by the telescope. Before starting a laser beam, the tip-tilt sensor is used to detect a series of images of the interested area near the moon retroreflector within the isoplanatic angle. M_4 is a dichroic mirror that reflects laser wavelength and passes other lights. When the tip-tilt signal is separated, it will be used to drive the tip-tilt mirror to perform a real-time tip-tilt compensation for a pulse laser beam that is emitted simultaneously.

The goal is to let the Gaussian laser beam hit the moon retroreflector accurately and centrally and let more laser photons return from it. It will compensate part of atmospheric turbulence effects on laser beam propagation, that is the brackets factor in formula (1). For about two second flying time, just before this pulse laser photon will be returned to the telescope, above process can be repeated. That will let the returned laser photons enter the receiver totally.

There are other key techniques for a ground LLR station: the pointing accuracy of the telescope (±1″), the divergence of 1″ for the uplink laser beam, and the compensation of the returned laser aberration [4].

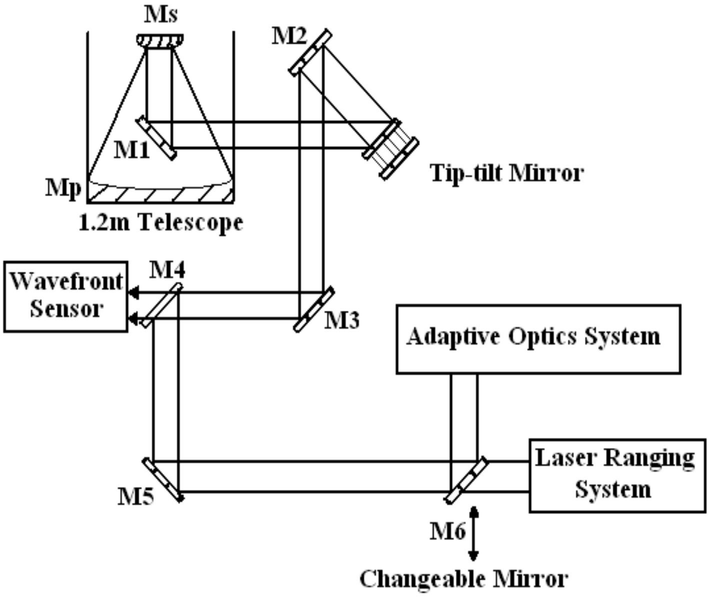

Fig.5.
Optical scheme of Kunming 1.2m LR system for tip-tilt correction

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