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

Xiong Yaoheng   Guo Rui

Yunnan Observatory, Chinese Academy of Sciences

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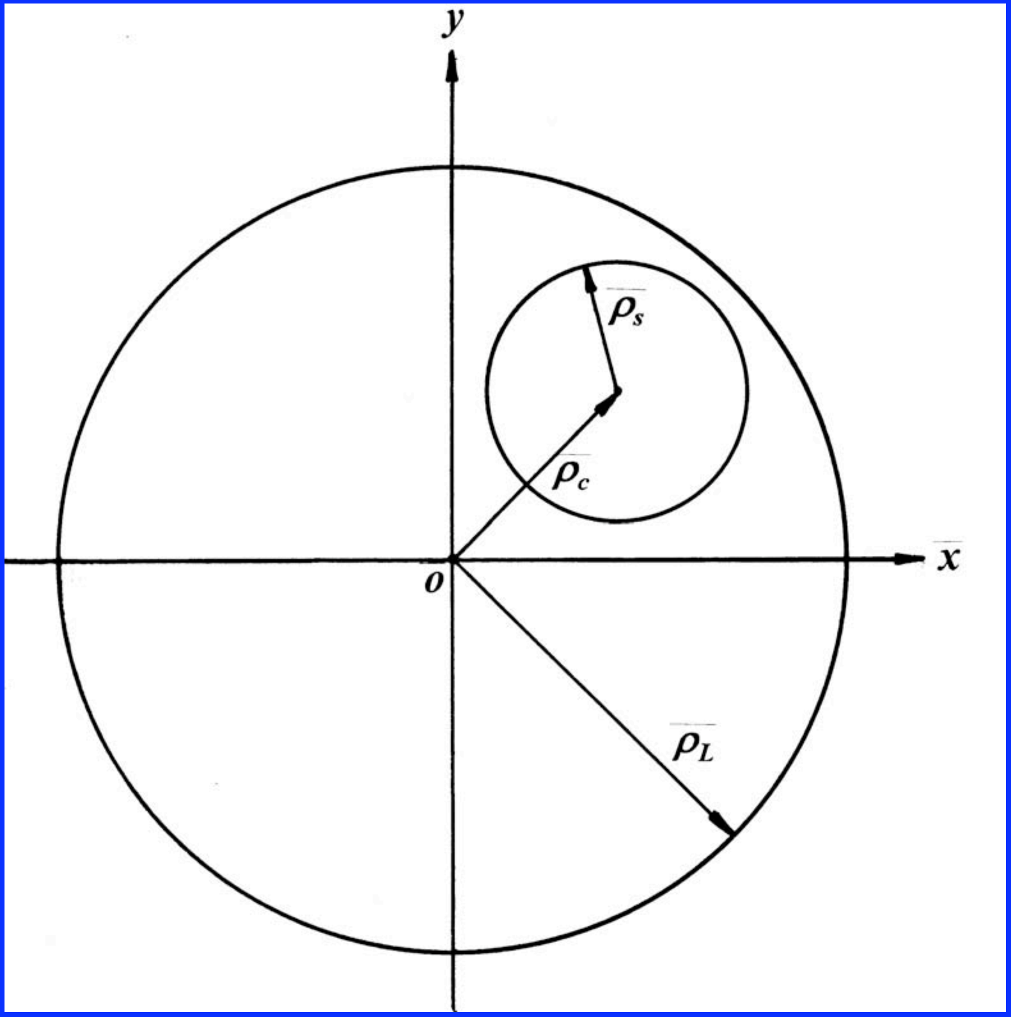
1. Atmospheric Turbulence Effects on Laser Beam Propagation



Laser beam at far-field

Short-term beam wander:

$$\langle \rho_C^2 \rangle = \frac{10.22 Z^2}{k^2 r_0^{\frac{5}{3}} D^{\frac{1}{3}}}$$

Short-term beam spread:

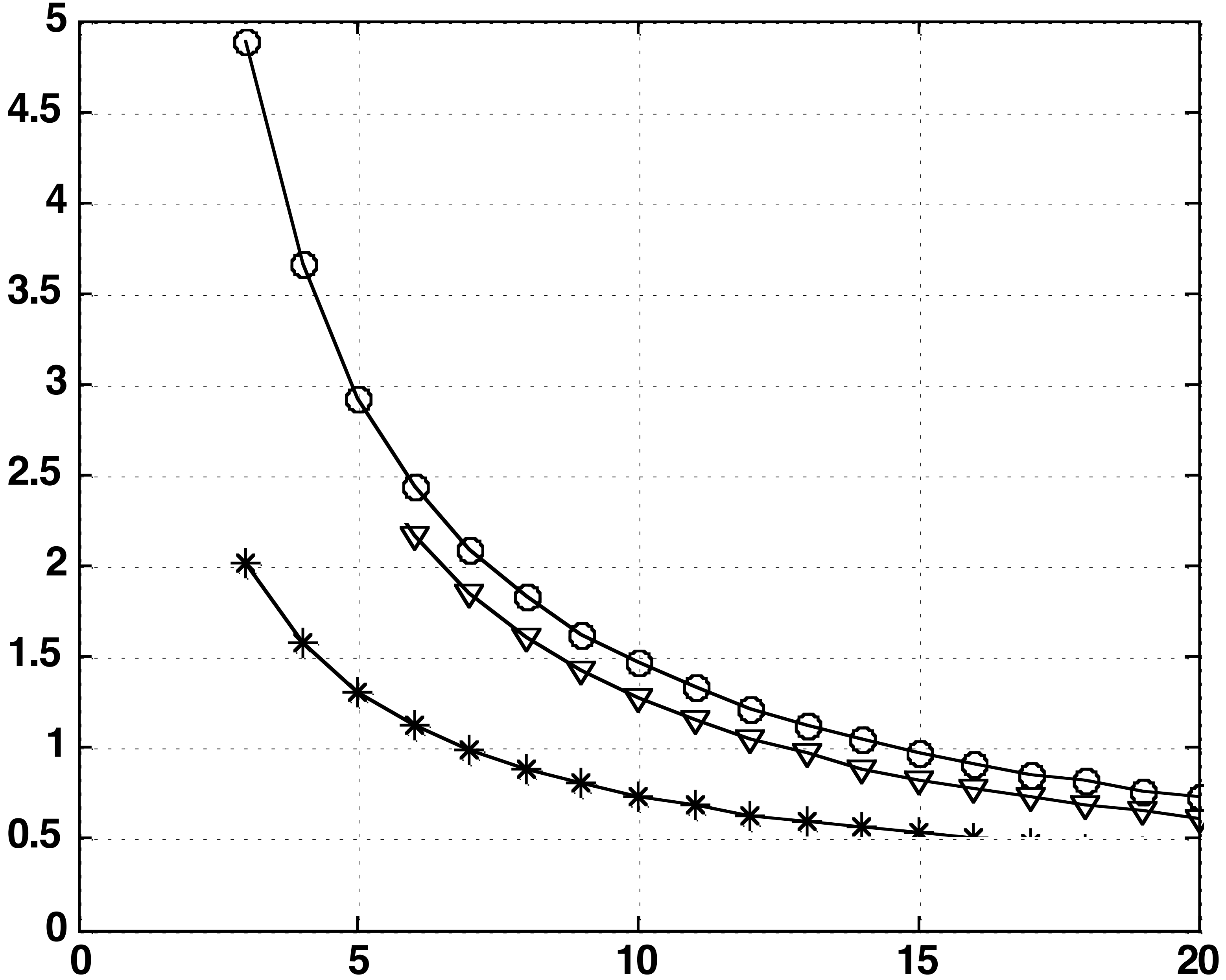
$$\langle \rho_S^2 \rangle = \frac{4Z^2}{k^2 D^2} + \frac{D^2}{4}\left(1 - \frac{Z}{F}\right)^2 + \frac{17.6 Z^2}{k^2 r_0^2}\left[1 - 0.48\left(\frac{r_0}{D}\right)^{\frac{1}{3}}\right]^{\frac{6}{5}}$$

Long-term beam spread:

$$\langle \rho_L^2 \rangle = \frac{4Z^2}{k^2 D^2} + \frac{D^2}{4}\left(1 - \frac{Z}{F}\right)^2 + \frac{17.6 Z^2}{k^2 r_0^2}$$

- Here,
  k wave number, D laser transmitter diameter
  Z laser propagation axis and coordinate
  F radius of curvature of laser beam
  r_o Fried's coherence length, 5 ~ 20 cm

- Method:
  Maxwell wave equation □ *Markov* approximation □ the second moment and the four moment (approximation) of the field □ mean square value of above terms


5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
5
10
15
20

2. Returned Laser Photoelectrons N_r

for one laser pulse firing:

$$N_r = \frac{4EN_0 A_m A_r T_a^2 T_t T_r \square\square}{\square^2 \left(\square_e^2 + \square_s^2\right) \square_m^2 R^4} \exp \left[\square \frac{\square_C^2}{\square_e^2 + \square_s^2} \right]$$

<u>Depend on turbulence terms to be considered</u>

here: $\square_e$ laser beam radius at target, determined by laser divergence

$\square_c$ short-term beam wander

$\square_s$ short-term beam spread

- If tilt is removed, the correction factor for the laser ranging is:

$$\frac{N_r}{N} = \frac{\square_e^2}{4\left(\square_e^2 + \square_s^2\right)} \exp\left[\square \frac{\square_C^2}{\square_e^2 + \square_s^2} \right]$$

- 1/40 ~ 1/6, depend on the turbulence

For Kunming station 1.2m laser ranging system on LLR:

N_r=0.17$\square$(1/40 ~ 1/6)

3. Detection and Computation of Tip-Tilt from Lunar Surface

Goal: to compensate atmospheric tip-tilt effect in real- time on LLR

Object: the extended light source

Method: When performing the LLR, its telescope will point the retroreflector array on the moon surface. Atmospheric tip-tilt signal can only be obtained from a small area of the geomorphologic structure that is near the moon retroreflector. That is to track geomorphologic structure of the moon surface through the motion of the successive images.

A N □ N pixels reference image $I_R(x, y)$ that is within the isoplanatic angle is sampled, and a time series $I_1(x, y)$£$I_2(x, y)$£□ □ $I_L(x, y)$ are sampled as live images.

To determine the displacement between reference image and live images by computing the sum of the absolute difference values of them. For each N □ N pixels live image $I_L(x, y)$, a M □ M pixels window is extracted. This central window of the live image is compared with the reference image. The absolute difference values D£®x, □y£©between them are given through the absolute difference algorithm:

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

The position (Δx_{min}, Δy_{min}) are obtained where D (Δx, Δy) is minimum. The tilt (T_x , T_y) can be determined using a parabolic interpolation.

$$T_x = \Delta x_{\min} + \frac{1}{2}\frac{D(\Delta x_{\min}-1,\Delta y_{\min}) - D(\Delta x_{\min}+1,\Delta y_{\min})}{D(\Delta x_{\min}-1,\Delta y_{\min}) + D(\Delta x_{\min}+1,\Delta y_{\min}) - 2D(\Delta x_{\min},\Delta y_{\min})}$$

$$T_y = \Delta y_{\min} + \frac{1}{2}\frac{D(\Delta x_{\min},\Delta y_{\min}-1) - D(\Delta x_{\min},\Delta y_{\min}+1)}{D(\Delta x_{\min},\Delta y_{\min}-1) + D(\Delta x_{\min},\Delta y_{\min}+1) - 2D(\Delta x_{\min},\Delta y_{\min})}$$

4. Experiment Results

Using Kunming SLR station 1.2m telescope

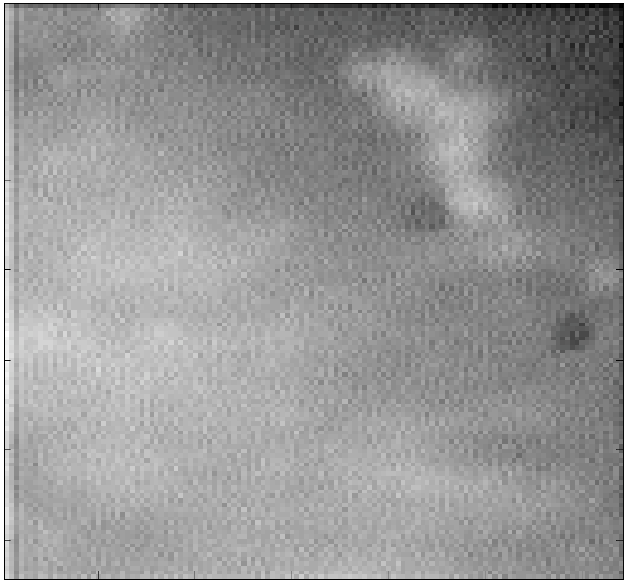
f = 6m

128□128 CCD, 16□ □16□ for one pixel

About 0.″55 /pixel   Frame rate: 419

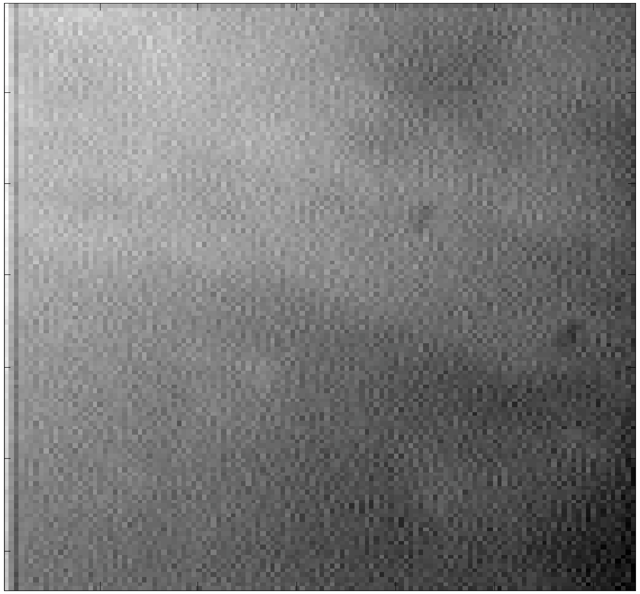
Sampling area: near the moon retroreflector array

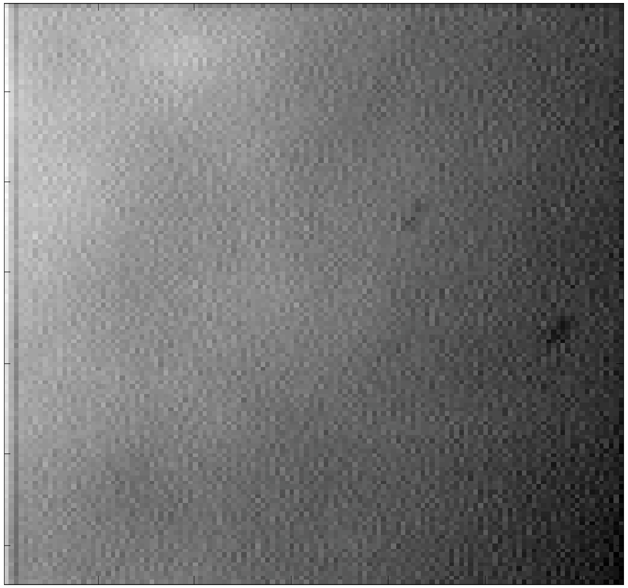
Apollo 11,Apollo14,Apollo15 and Lunakhod 2



Apollo15
□ -------

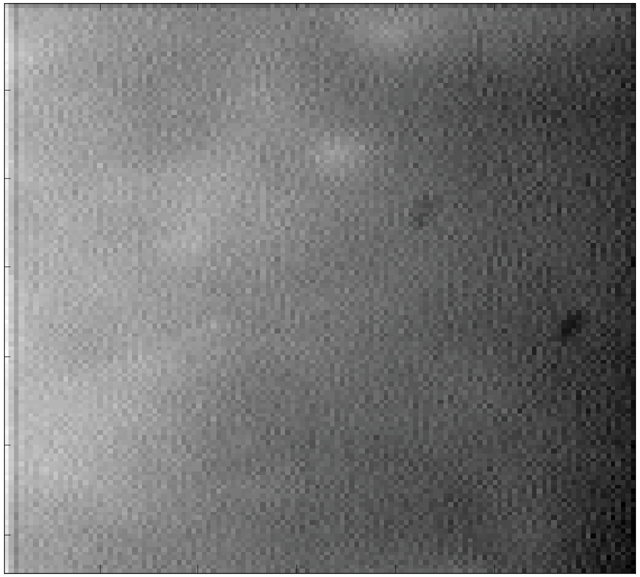
Apollo11
-------□

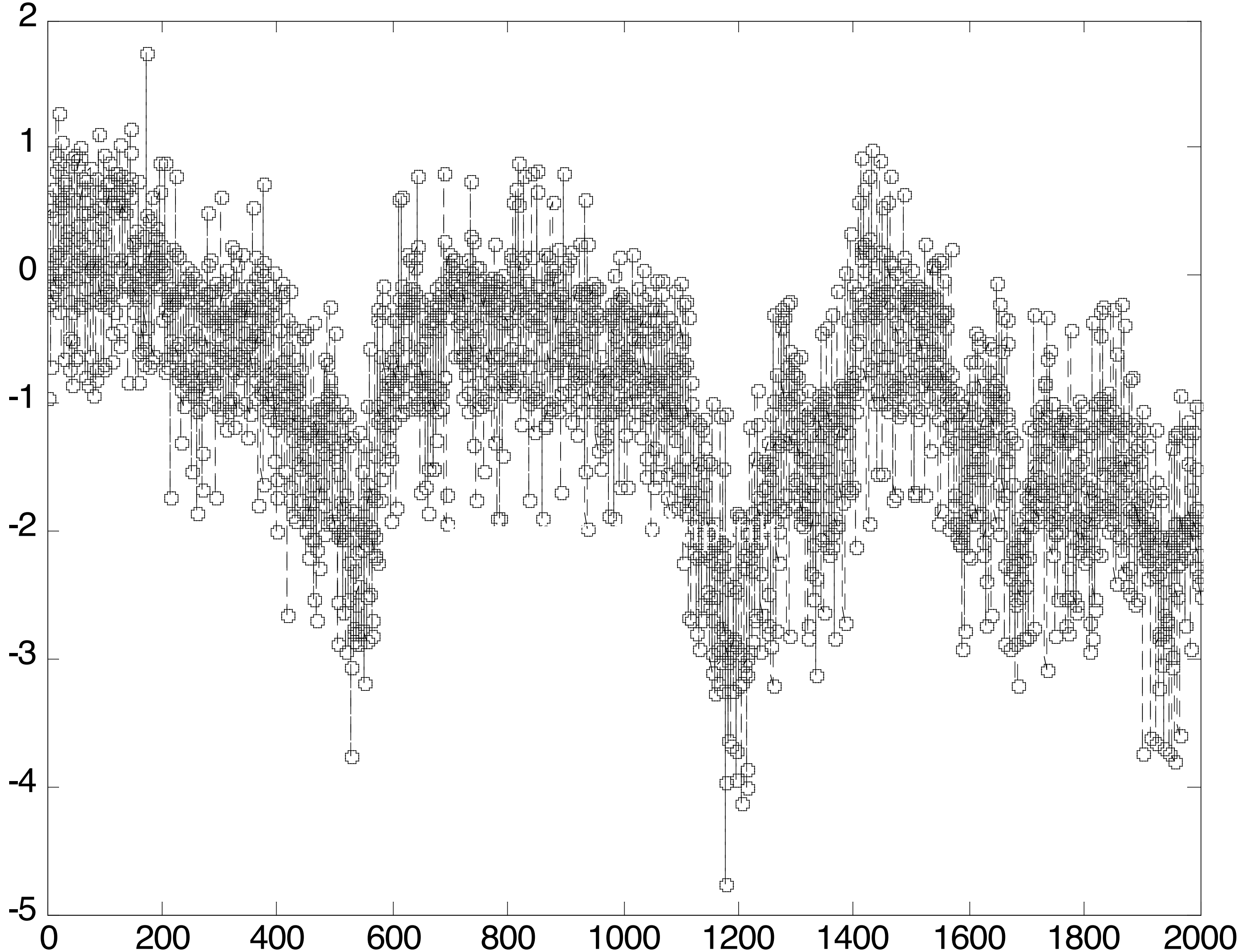




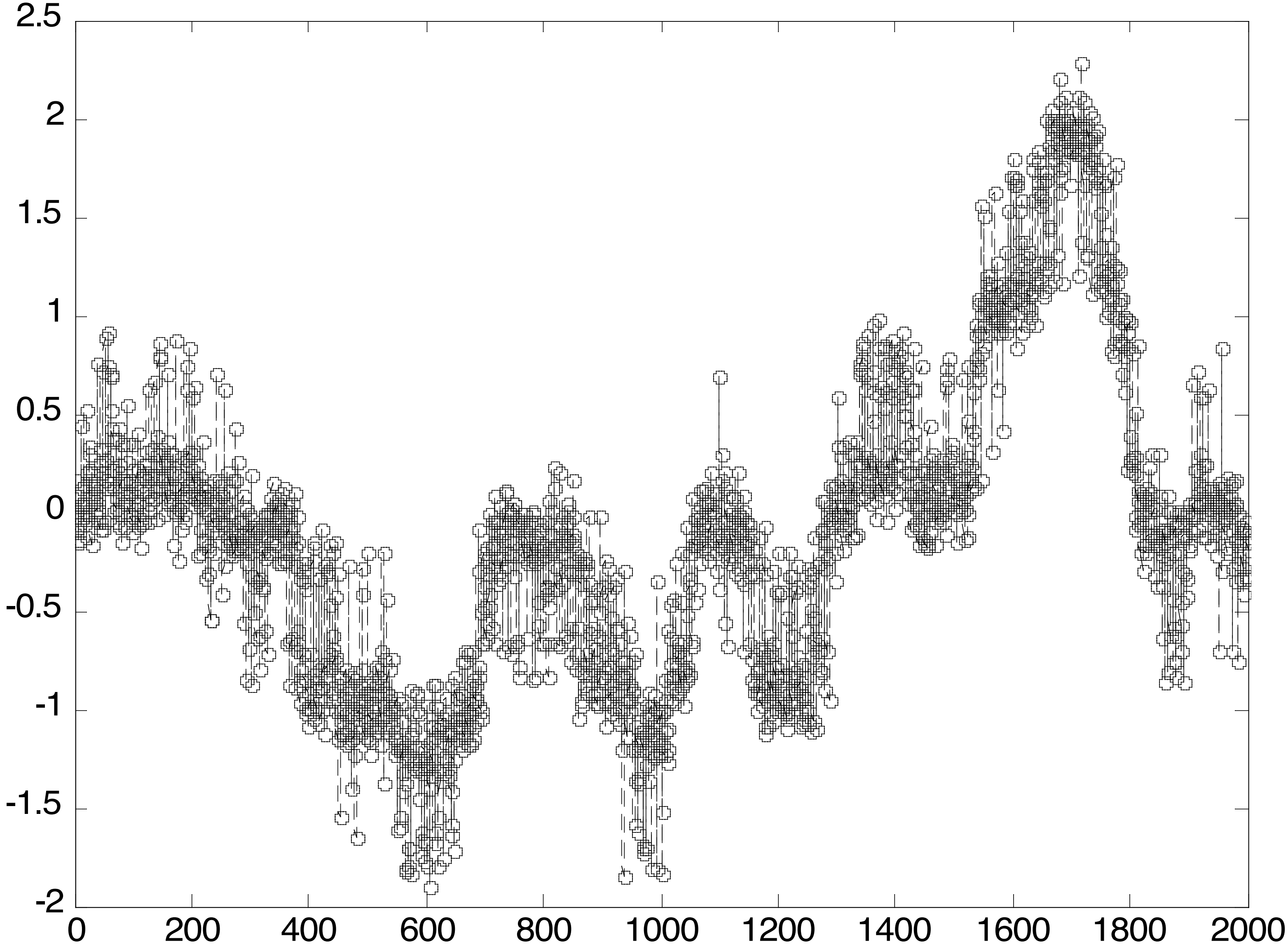
Apollo14
□ -------

Lunakhod
2-------□

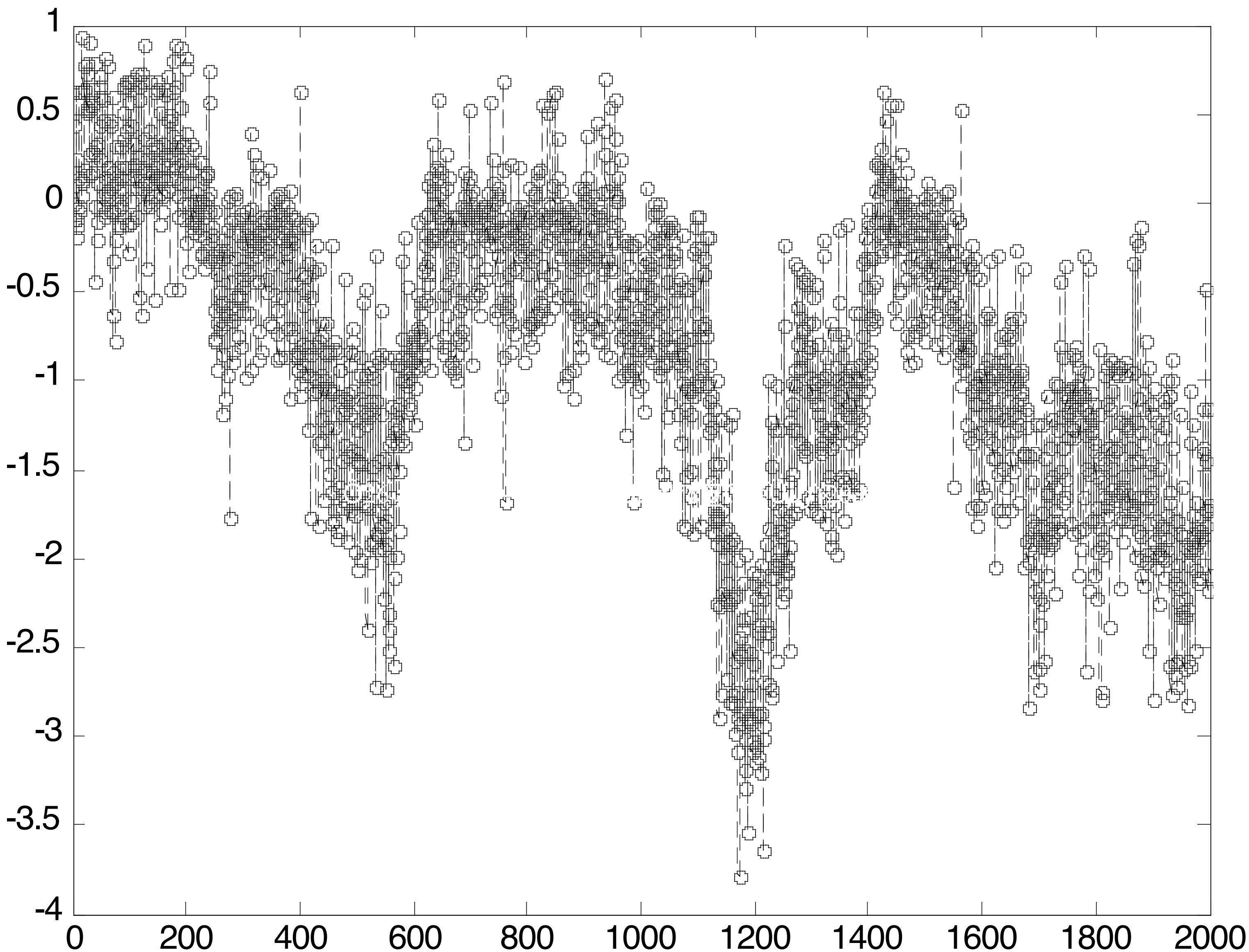




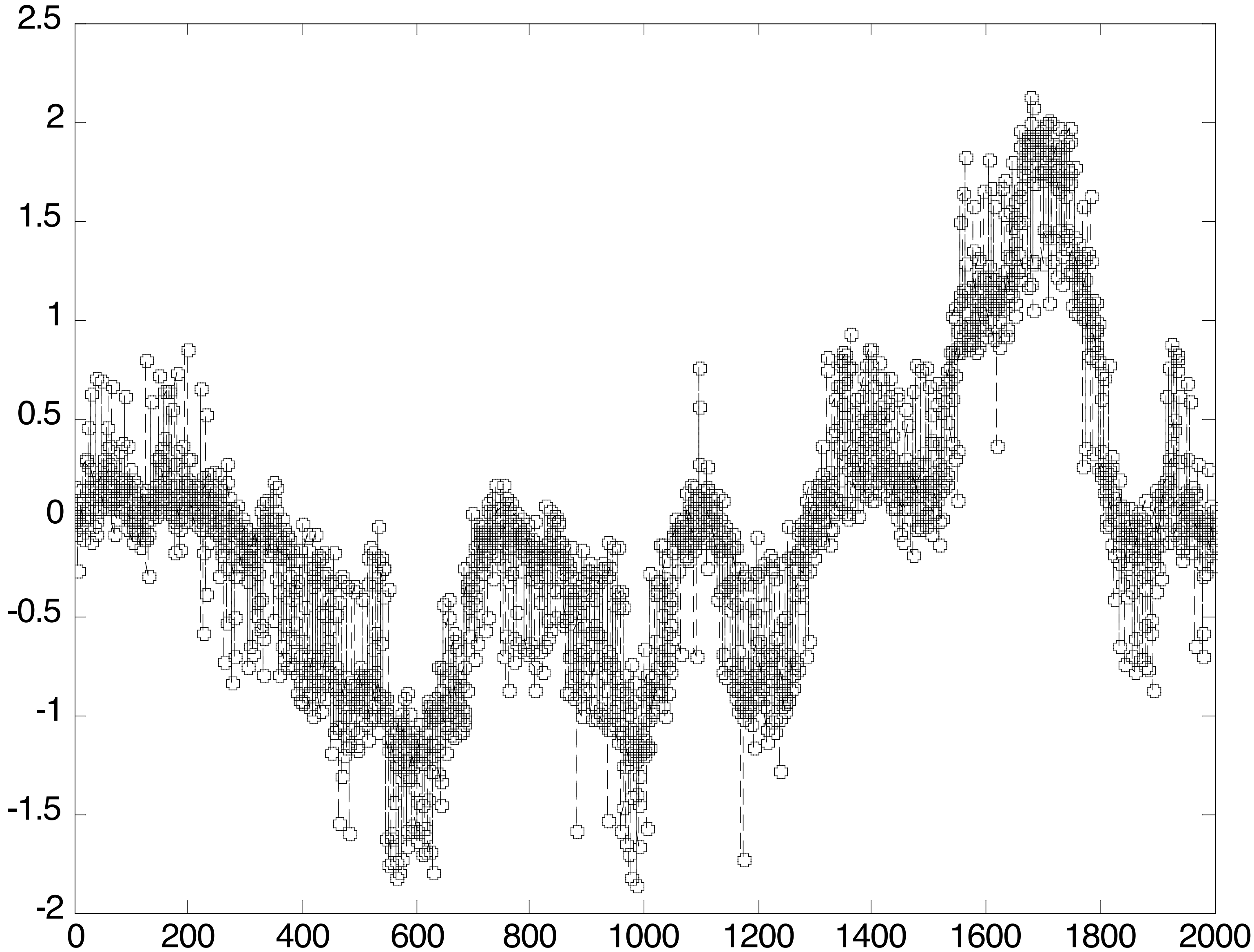
y component of tip-tilt , 16°¡16pixels Apollo15



x component of tip-tilt，16°¡16pixels Apollo15



y component of tip-tilt , 32°ȝ2 pixels Apollo15



x component of tip-tilt , 32°32 pixels Apollo15

Real-Time:

32°¡32 pixels window, take 25 seconds to compute 2000 images, □ 12.5ms/one image

16°¡16 pixels window, take 6 seconds to compute 2000 images, □ 3ms/one image

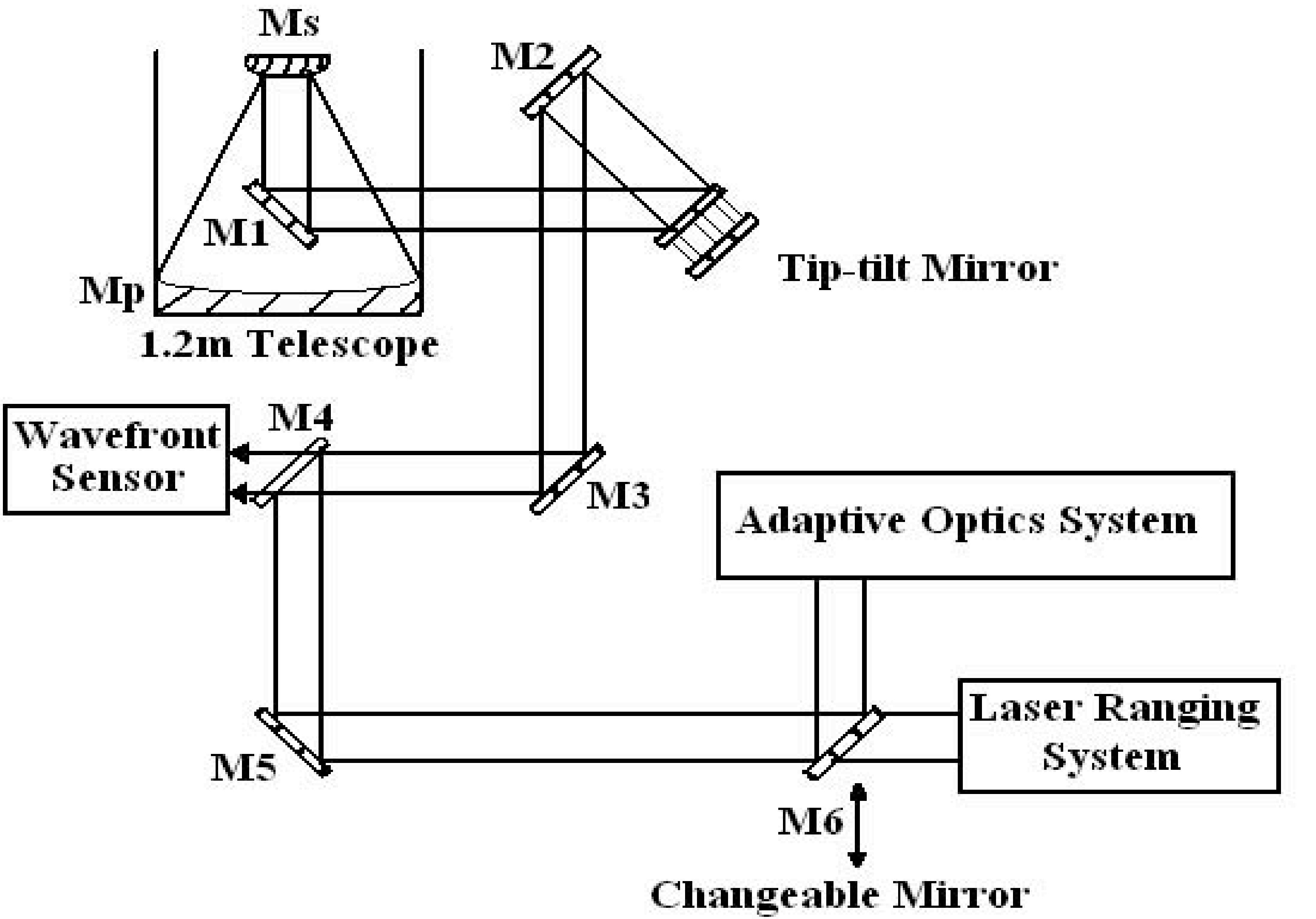
Conclusion:

Detection and separation of atmospheric Tip-Tilt signal real-time from Lunar surface is within the present technique, especially within the atmospheric turbulence scale.

5. Next Plan

- Apply grant for LLR (important)

- Combine the LR system and the AO system at 1.2m telescope, try to achieve real-time tip-tilt compensation for the laser beam on the LLR.



Optical Scheme of Kunming 1.2m LR System for Tilt Correction

Thanks