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Postprint of the Optimized Differential Image Motion Seeing Monitoring Method

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Abstract

Atmospheric seeing is an important indicator for evaluating the atmospheric optical quality of a site. The Differential Image Motion Monitor (DIMM) is widely used in seeing measurement operations for astronomical site selection both domestically and internationally; for example, the ESO DIMM has been applied in the site selection for the European Southern Observatory. This paper introduces an improved seeing measurement method—the Improved Differential Image Motion Monitor (I-DIMM) method. First, the structural design and seeing calculation method of I-DIMM are described in detail. Subsequently, simulated seeing measurements are conducted by configuring two telescopes with apertures of 0.36 m and 0.12 m. By comparing the measurement results of I-DIMM with those of the traditional DIMM, it is demonstrated that the I-DIMM seeing calculation method is more accurate than DIMM. Finally, the simulation results are analyzed, proving the advantages of I-DIMM over DIMM.

Full Text

Abstract

Atmospheric seeing is a critical metric for evaluating the optical quality of astronomical sites. The Differential Image Motion Monitor (DIMM) has been widely employed in site testing campaigns worldwide, exemplified by its use at the European Southern Observatory (ESO). This paper introduces an improved seeing measurement method called I-DIMM (Improved Differential Image Motion Monitor). We first describe the structural design of I-DIMM and its seeing calculation methodology in detail. Subsequently, through simulated measurements using telescopes of 0.36 m and 0.12 m apertures, we compare I-DIMM results with those from conventional DIMM. Both sets of simulations demonstrate that I-DIMM yields more accurate seeing measurements than traditional DIMM. Finally, we analyze the simulation results and highlight the advantages of I-DIMM over DIMM.

Keywords: I-DIMM; atmospheric seeing; site testing; DIMM

1. Introduction

The Fried parameter, or atmospheric optical coherence length r_0, is the key parameter for quantifying atmospheric seeing at astronomical sites. The differential image motion technique measures r_0 by tracking the relative positional variations of stellar images, effectively eliminating non-atmospheric factors to produce more accurate and reliable measurements. This principle forms the basis of the Differential Image Motion Monitor.

Currently, the most prevalent method for quantifying astronomical seeing is the Differential Image Motion Monitor (DIMM), proposed by Sarazin and Roddier in 1990 for ESO site testing [?]. This instrument consists of a 35 cm telescope, a mask with two sub-apertures, and a CCD detector. For a single target source passing through Earth' s atmosphere, DIMM measures the relative variance of wavefront arrival angles at two sub-apertures in the telescope pupil plane to determine the atmospheric seeing parameter r_0. Its primary advantage lies in eliminating non-atmospheric effects such as tracking errors from wind loading and instrumental vibrations, while providing sufficient spatial and temporal resolution for field site testing. Since the 1980s, DIMM has been deployed at numerous premier observatories and site surveys, including the La Palma Observatory [?], the Subaru 8 m telescope site selection [?], and the Lijiang Gaomeigu 2.4 m telescope site for Yunnan Observatory [?].

However, conventional DIMM employs a fixed mask aperture size, capturing only one set of stellar image displacement information per exposure for a fixed sub-aperture separation. Consequently, DIMM can only measure integrated atmospheric seeing and cannot profile seeing as a function of atmospheric height—a prerequisite for designing multi-conjugate adaptive optics systems. To address this limitation, the Multiple-Aperture Seeing Profiler (MASP) was introduced in 2015 [?] for daytime seeing measurements. MASP employs two 40 cm telescopes with binary stars as guide sources, analyzing atmospheric turbulence in multiple layers from 0–30 km to determine r_0. While MASP can extend turbulence measurement heights to 30 km (equivalent to a 112 cm telescope) and offers advantages in cost and mobility, it is overly complex for applications requiring only integrated r_0 measurements. Its dual-telescope configuration makes deployment cumbersome for general seeing monitoring.

This paper proposes I-DIMM (Improved Differential Image Motion Monitor), an enhanced method that modifies the conventional DIMM approach. Rather than using a pupil mask to create sub-apertures, I-DIMM selects two sub-apertures spaced 20 cm apart on the telescope pupil plane. By adopting the r_0 calculation methodology from MASP and applying differential processing to the stellar images from these sub-apertures, I-DIMM achieves higher measurement precision. Furthermore, by varying the separation between sub-apertures, I-DIMM can obtain r_0 values for different spacings, demonstrating superior accuracy particularly at smaller separations (relative to sub-aperture diameter).

2. I-DIMM System Description

The optical configuration of the ESO DIMM used for site testing [?] is illustrated in Figure 1 [Figure 1: see original paper]. Traditional DIMM systems typically place a mask with two sub-apertures (50–100 mm) at the entrance pupil of a small telescope (180–350 mm aperture), with a wedge prism in one sub-aperture to tilt the wavefront and produce non-overlapping dual images of the same target star. A detector records a series of instantaneous dual-image states, and the variance of their relative positions is used to calculate seeing. The conventional DIMM system used for comparison in this study follows this exact configuration, with specific parameters listed in Table 1 .

Table 1. ESO DIMM Parameters

Parameter	Value/Model
Telescope aperture	35 cm
Sub-aperture diameter D	10 cm
Pixel angular size	0.87'' $\times$ 0.87''
Intensified CCD	-

Our I-DIMM simulation employs a microlens array to segment the telescope pupil into multiple sub-apertures, as shown in Figure 2 [Figure 2: see original paper]. The linear array of valid Hartmann sub-apertures is numbered sequentially, as depicted in Figure 3 [Figure 3: see original paper].

In the I-DIMM system shown in Figure 3, nine Hartmann sub-apertures span the diameter, effectively dividing the telescope pupil into nine equal sub-apertures (numbered 1-9), each with a diameter of 4 cm—matching the sub-pupil diameter in DIMM (see Table 1). Within a single row of the Hartmann sub-aperture array, adjacent numbers represent apertures separated by one sub-aperture diameter ($1D$). By extension, sub-apertures with numbers differing by 2 have a separation of $2D$, and when the difference is 5, the separation is $5D$—equivalent to the 20 cm separation in conventional DIMM. This design achieves structural consistency between I-DIMM and DIMM systems. For any fixed sub-aperture separation, each row provides at least one combination. For example, in the configuration shown, sub-aperture pairs (1,2), (3,4), etc., each yield $1D$ separation, providing eight possible combinations for this spacing. Figure 4 [Figure 4: see original paper] illustrates the relationship between the number of available sub-aperture combinations and their separation for different diameters.

3. I-DIMM Calculation Theory

In conventional DIMM [?], the variance of differential image motion in the longitudinal direction L (along the sub-pupil center line) is expressed as:

$$\sigma_l^2 = 0.358\lambda^2 r_0^{-5/3} D^{-1/3}\left[1 - 0.541\left(\frac{d}{D}\right)^{-1/3}\right]$$

while in the transverse direction T (perpendicular to the sub-pupil center line) it is:

$$\sigma_t^2 = 0.358\lambda^2 r_0^{-5/3} D^{-1/3}\left[1 - 0.811\left(\frac{d}{D}\right)^{-1/3}\right]$$

Both variances can be expressed in terms of the total two-dimensional motion variance σ^2 for a single aperture:

$$\sigma^2 = 0.358\lambda^2 r_0^{-5/3} D^{-1/3}$$

Theoretically, assuming isotropic turbulence, the application of these formulas should satisfy the condition $S = d/D \geq 2$. Under this condition, equations (4) and (5) simplify to:

$$\sigma_{l,DIMM}^2 = \sigma^2\left[1 - 0.541 S^{-1/3}\right]$$

$$\sigma_{t,DIMM}^2 = \sigma^2\left[1 - 0.811 S^{-1/3}\right]$$

Although these approximations from [**?**] show good agreement with the expressions in [**?**] for large S, significant discrepancies emerge at smaller separations. For instance, when $S = 2$, the longitudinal differential motion variance deviates by only -0.2% from the exact value, while the transverse variance deviates by -17.3%. At $S = 3$, the transverse variance still shows a substantial deviation of -9.0%. To obtain more accurate r_0 estimates, we consider cases where S approaches zero, adopting the approximation from [**?**] used in MASP:

$$\sigma_l^2 = \sum_{n=1}^{N} F(d_n, h, \theta)\sigma^2(d_n, h, \theta)$$

$$\sigma_t^2 = \sum_{n=1}^{N} F(d_n, h, \theta)\sigma^2(d_n, h, \theta)$$

For a single guide star and evaluation of total r_0, we have $\theta = 0$ and $h = 0$, representing the integrated atmospheric turbulence above the telescope. Combining with $S = d/D$, equations (14) and (15) become:

$$\sigma^2_{l,IDIMM} = \sigma^2 \left[2I(0,0) - 2I(S,0) + I(2S,0)\right]$$

$$\sigma^2_{t,IDIMM} = \sigma^2 \left[2I(0,0) - 2I\left(S, \frac{\pi}{2}\right) + I\left(2S, \frac{\pi}{2}\right)\right]$$

For square sub-apertures, the function I is defined as [?]:

$$I(S,0) = \frac{1}{2}\left[1 - \frac{5}{3}S + \frac{1}{3}S^5\right] \quad \text{for } S \leq 1$$

$$I\left(S, \frac{\pi}{2}\right) = \frac{1}{2}\left[1 - \frac{5}{3}S + \frac{1}{3}S^5\right] \quad \text{for } S \leq 1$$

The function value is 0 when $S \geq 1$.

Tables 2 and 3 present the deviations of three r_0 calculation methods for various aperture separation ratios in both longitudinal and transverse directions. The deviations for I_{DIMM} are compared against Fried' s approximations, while those for I_{IDIMM} are compared against I_{DIMM}.

Table 2. Difference of Two-Dimensional Motion for Various Aperture-to-Separation Ratios in Longitude by Three Methods

S	Fried	$I_{DIMM}(S,0)$ % deviation	$I_{IDIMM}(S,0)$ % deviation

Table 3. Differences of Two-Dimensional Motion for Various Aperture-to-Separation Ratios in Transverse by Three Methods

S	Fried	$I_{DIMM}(S,\pi/2)$ % deviation	$I_{IDIMM}(S,\pi/2)$ % deviation

Figures 5 [Figure 5: see original paper] and 6 [Figure 6: see original paper] plot the two-dimensional motion relationships for the three methods across different aperture separation ratios in longitudinal and transverse directions, respectively. These figures clearly show that the improved I_{IDIMM} values are consistently smaller than I_{DIMM} in the longitudinal direction. In the transverse direction, when $S < 1.6$, I_{IDIMM} is smaller than I_{DIMM}, while the opposite holds for $S > 1.6$. Although I_{DIMM} represents simplified formulas for circular sub-apertures in the ESO DIMM, and I_{IDIMM} is derived for linear square sub-apertures, Tables 2 and 3 demonstrate that the difference between these two approximations is only about 2% at $S \geq 1.5$, indicating that aperture shape introduces negligible error.

3.1. Comparison of I-DIMM and DIMM at 20 cm Sub-Aperture Separation

We conducted simulations using the professional optical software YAO (widely recognized for simulating point spread functions under various atmospheric and source conditions). Running YAO in a Linux environment, we configured a 36 cm telescope with nine sub-apertures across its diameter (each 4 cm in diameter), matching the parameters of conventional DIMM [?]. This ensures that any differences in calculated r_0 values arise solely from the computational formulas rather than hardware disparities. Atmospheric turbulence parameters were set with an initial r_0 value of 0.1 m ($r_{0,std}$). The simulation generated a series of point spread function images mimicking DIMM' s differential image motion capture. Detailed parameters are listed in Table 4 .

Table 4. YAO Setup Parameters

Parameter	Value
Telescope aperture	0.36 m
Sub-aperture diameter D	0.04 m
Sub-aperture separation d	0.04–0.32 m
Pixel angular size	0.87'' × 0.87''
Point spread function images	2000 frames per set
Initial total r_0 setting	0.1 m
Wavelength	500 nm

Each simulation processed 2000 point spread function images, with 100 independent runs performed. Using a centroiding algorithm, we determined the coordinates of each sub-aperture' s image centroid in both L (along sub-pupil center line) and T (perpendicular to sub-pupil center line) directions. Applying the differential image motion algorithm, we calculated the atmospheric seeing parameter r_0 in both directions. Figures 7 [Figure 7: see original paper] and 8 [Figure 8: see original paper] present the r_0 values from 100 simulations at $S = 5$.

At a sub-aperture separation of 20 cm ($S = 5$), the I-DIMM measurements consistently yield r_0 values closer to the set value of 0.1 m than DIMM. In the longitudinal direction, I-DIMM' s mean r_0 is 0.1008 m (0.8% error), smaller than DIMM' s 1.6% error. In the transverse direction, I-DIMM measures 0.1026 m (2.6% error), outperforming DIMM' s 4.0% error. Figure 9 [Figure 9: see original paper] shows the total r_0 values from 100 simulations, where I-DIMM' s mean total r_0 is 0.1017 m (1.7% error), significantly better than DIMM' s 2.8% error. These results confirm that I-DIMM produces more accurate r_0 values than conventional DIMM.

3.2. Square Sub-Aperture Error Simulation

Section 3.1 demonstrated that I-DIMM' s calculation formulas improve accuracy. However, the traditional DIMM formulas were developed in 1990 when computational resources were limited and were optimized for circular sub-apertures, which may introduce bias when applied to our square sub-aperture simulations. Although Section 3 showed that the difference between I_{DIMM} and I_{IDIMM} formulas is only about 2% and thus negligible, we conducted additional simulations to exclude any error from Sarazin and Roddier' s circular sub-aperture formulas. In these tests, both methods used I-DIMM' s calculation formulas, differing only in that conventional DIMM processed only one pair (sub-apertures 1 and 6) at 20 cm separation, while I-DIMM processed four such pairs simultaneously (as shown in Figure 4). This means I-DIMM effectively analyzed 8000 point spread function images per simulation run—four times more data than DIMM. Table 5 presents the average total r_0 from 20 simulation runs.

Table 5. Average Total r_0 Results

Point spread function images per run	Method	Average total r_0	Error
2000	DIMM	0.1015 m	1.9%
2000	I-DIMM	0.1017 m	1.7%

Even when using identical formulas, I-DIMM' s processing of multiple sub-aperture combinations yields more precise results (1.7% error) than DIMM' s single-pair approach (1.9% error), demonstrating that increased sampling further enhances r_0 calculation accuracy.

3.3. Comparison at Smaller Sub-Aperture Separation Ratios

According to [?], DIMM requires $S \geq 2$, though many actual telescopes barely meet this criterion. For example, NOAO and ESO site testing programs [?] achieved only $S = 2$, while Taiwan's site survey [?] had $S = 1.6$. Smaller S values enable smaller telescope apertures, facilitating portable site testing operations. To evaluate I-DIMM' s performance at small separations, we analyzed cases where $S \leq 3$. Figures 10 [Figure 10: see original paper] and 11 [Figure 11: see original paper] show the mean r_0 values from 100 simulations at small S values.

In the longitudinal direction, I-DIMM consistently yields r_0 values closer to the set baseline than DIMM. Specifically, at $S = 1, 2, 3$, I-DIMM' s errors are 16.4%, 3.1%, and 0.7% respectively, all smaller than DIMM' s corresponding errors of 24.1%, 4.9%, and 1.9%. In the transverse direction at $S = 2, 3$, I-DIMM' s errors are 4.6% and 1.9%, outperforming DIMM' s 5.6% and 3.5% errors. Due to the monotonic relationship between I_{IDIMM} and I_{DIMM}, when $S < 1.6$, I-DIMM' s calculated r_0 values are more accurate than DIMM' s in both directions. Figure

12 [Figure 12: see original paper] confirms these findings with the average total r_0 values from 100 simulations.

4. Simulation of 0.12 m Telescope with I-DIMM

Using YAO, we simulated a 12 cm telescope with 4 cm sub-apertures and 8 cm separation ($S = 2$), with an initial r_0 setting of 0.03 m ($r_{0,std}$). Table 6 lists the detailed parameters.

Table 6. YAO Setup Parameters for 0.12 m Telescope

Parameter	Value
Telescope aperture	0.12 m
Sub-aperture diameter D	0.04 m
Sub-aperture separation d	0.08 m
Pixel angular size	1.3'' × 1.3''
Point spread function images	2000 frames
Initial total r_0 setting	0.03 m
Wavelength	500 nm

Applying the differential image motion method with equations (20) and (21), Figure 13 [Figure 13: see original paper] presents the average r_0 values from 20 simulation runs in both L and T directions.

At $S = 2$, I-DIMM' s r_0 values are consistently closer to the 0.03 m baseline than DIMM' s in both directions. The longitudinal r_0 is 0.0326 m (8.6% error) and transverse r_0 is 0.0303 m (0.9% error), both lower than DIMM' s errors of 10.5% and 1.8% respectively. I-DIMM' s total r_0 is 0.0314 m (4.7% error), superior to DIMM' s 6.1% error. This demonstrates that even with small telescopes and small sub-aperture separation ratios, I-DIMM provides more accurate total r_0 measurements than DIMM.

5. Conclusion

This paper has introduced I-DIMM (Improved Differential Image Motion Monitor), which calculates atmospheric seeing parameters r_0 using selected sub-aperture pairs on small telescopes. Through comprehensive comparison with conventional DIMM, we have demonstrated that I-DIMM' s calculation formulas produce more accurate r_0 values not only at the standard 20 cm sub-aperture separation but also at smaller separations. Particularly for separation ratios between 1 and 3, I-DIMM outperforms DIMM in both longitudinal and transverse directions with maximum errors around 5%. Regarding sub-aperture combinations, when processing equal numbers of stellar images at fixed separations, I-DIMM extracts information from multiple sub-aperture pairs per image (typically more than one), whereas DIMM yields only a single pair measurement, thereby further improving r_0 calculation precision.

Simulations with a 0.12 m telescope at $S = 2$ further validate I-DIMM' s superior accuracy over DIMM. This provides justification for using even smaller telescopes. I-DIMM' s requirement of only partial aperture combinations on small telescopes to obtain precise r_0 values significantly simplifies instrumentation, making it highly advantageous for portable seeing measurements and site testing in field conditions.

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