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TN:110 Mean Square Difference of G-Tilt for Two Square Apertures

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June 2000

ABSTRACT

Plans for quick-look data reduction involve forming an estimate of the value of r_0 based on the mean square difference of the G-tilts measured by two sub apertures of a standard type Hartmann sensor. Developing an r_0 value from such a mean square difference requires knowledge of the coefficient relating the two, with accommodation for the fact that the sub apertures are square (as distinct from the previously analyzed version of this method, for which the individual apertures were circular). The value of this coefficient is developed in this work.

1. Introduction

For quick-look data processing it is planned to form an estimate of the value of r_0 by calculating the mean square difference of the G-tilt values measured by a pair of sub apertures. Existing theory for this sort of approach to the determination of the value of r_0 tells us that the value of r_0 is proportional to the sub aperture size times the $-3/5$-power of the mean square difference of G-tilts divided by the square of the diffraction angle (*i.e.* divided by the square of the wave length over sub aperture size). For circular sub apertures the coefficient of proportionality has been known for a considerable time. However, no comparable result has been published for the case where the sub apertures are square—and that is what is needed for the quick-look data reduction since for that case the sub apertures are those of a standard type of Hartmann sensor, with square sub apertures. It is the objective of this work to develop the needed square sub aperture results.

The analysis will be conducted in the geometric optics limit, where the rays are considered to propagate along undeviating straight lines and there is no diffraction propagation effects converting atmospheric turbulence induced phase perturbations into intensity variations. I this case actual propagation analysis is not needed and we can simply make use of the nominal phase structure function expression, $\mathcal{D}_\phi(r)$, according to which the mean square phase difference measured at two points a distance r apart has a value of $\mathcal{D}_\phi(r) = 6.88\,(r/r_0)^{5/3}$.

We start in the next section with the development of expressions for the random difference of the G-tilt measured by two sub apertures. The section after that is concerned with the development from the random difference of G-tilts of an expression for the mean square value of that difference—an expression presented in terms of the phase structure function. The section following that introduces the above noted analytic formulation for the phase structure function, inserts that into the expression for the mean square difference of G-tilts, and proceeds to reduce that formulation to one which is suitable for numerical evaluation. The final section presents the numerical results.

2. Difference of G-Tilts

We consider a pair of wave square sub apertures, each having a size of ℓ-by-ℓ. Each of the sub apertures is aligned so that its sides are parallel to the x-axis or to the y-axis. The center-to-center separation of the two sub apertures has a component parallel to the x-axis of Δx and parallel to the y-axis of Δy. We shall use the notation $S(x, y)$ to denote a sub aperture of this type, one whose center is at the origin, with the value of $S(x, y)$ given by the equation

$$S(x,y) = \begin{cases} 1 & \text{if} \quad |x| \le \frac{1}{2}\ell \quad \text{and} \quad |y| \le \frac{1}{2}\ell \\ 0 & \text{if otherwise} \end{cases} . \tag{1}$$

The value of $S(x, y)$ is unity if the point specified by (x, y) is inside the square sub aperture and is zero if the point is outside the square sub aperture. Obvious then, since the area of the sub aperture is ℓ^2, we have

$$\iint dx'\, dy'\, S(x'-x, y'-y) = \ell^2 \,. \tag{2}$$

Introducing the notation k, where

$$k = 2\,\pi/\lambda \,, \tag{3}$$

to denote the wave number, and using the notation $\phi(x, y)$ to denote the turbulence induced phase perturbation, we recognize that the hight of the surface of constant phase at position (x, y) is given by $k^{-1}\,\phi(x,y)$. From this it follows that the G-tilt at the point (x,y) has x- and y-components of $\partial\left[\,k^{-1}\,\phi(x,y)\,\right]/\partial x$ and $\partial\left[\,k^{-1}\,\phi(x,y)\,\right]/\partial y$ respectively. From this it follows that the average G-tilt over a sub aperture whose center is at (x,y) has x- and y-components, $g_{\mathrm{X}}(x,y)$ and $g_{\mathrm{Y}}(x,y)$ respectively, given by the equations

$$g_{\mathrm{X}}(x,y) = \ell^{-2} \iint dx'\, dy'\, S(x'-x, y'-y) \left[\frac{\partial\left[\,k^{-1}\,\phi(\xi,\eta)\,\right]}{\partial \xi} \right]_{\substack{\xi=x' \\ \eta=y'}} , \tag{4a}$$

$$g_{\mathrm{Y}}(x,y) = \ell^{-2} \iint dx'\, dy'\, S(x'-x, y'-y) \left[\frac{\partial\left[\,k^{-1}\,\phi(\xi,\eta)\,\right]}{\partial \eta} \right]_{\substack{\xi=x' \\ \eta=y'}} . \tag{4b}$$

The difference of sub aperture average G-tilts measured by two sub apertures whose separation is $(\Delta x, \Delta y)$, the two components of which we denote by $\Delta g_{\mathrm{X}}(\Delta x, \Delta y)$ and $\Delta g_{\mathrm{Y}}(\Delta x, \Delta y)$ and define by the equations

$$\Delta g_{\mathrm{X}}(\Delta x, \Delta y) = g_{\mathrm{X}}(x+\Delta x, y+\Delta y) - g_{\mathrm{X}}(x,y) \,, \tag{5a}$$

$$\Delta g_{\mathrm{Y}}(\Delta x, \Delta y) = g_{\mathrm{Y}}(x+\Delta x, y+\Delta y) - g_{\mathrm{Y}}(x,y) \,, \tag{5b}$$

can be seen, making use of Eq. (4), to be expressible as

$$\begin{aligned} \Delta g_{\mathrm{X}}(\Delta x, \Delta y) = {} & k^{-1}\,\ell^{-2} \iint dx'\, dy'\, S(x'-x-\Delta x, y'-y-\Delta y) \left[\frac{\partial \phi(\xi',\eta')}{\partial \xi'} \right]_{\substack{\xi'=x' \\ \eta'=y'}} \\ & - k^{-1}\,\ell^{-2} \iint dx'\, dy'\, S(x'-x, y'-y) \left[\frac{\partial \phi(\xi',\eta')}{\partial \xi'} \right]_{\substack{\xi'=x' \\ \eta'=y'}} , \end{aligned} \tag{6a}$$

$$\begin{aligned} \Delta g_{\mathrm{Y}}(\Delta x, \Delta y) = {} & k^{-1}\,\ell^{-2} \iint dx'\, dy'\, S(x'-x-\Delta x, y'-y-\Delta y) \left[\frac{\partial \phi(\xi',\eta')}{\partial \eta'} \right]_{\substack{\xi'=x' \\ \eta'=y'}} \\ & - k^{-1}\,\ell^{-2} \iint dx'\, dy'\, S(x'-x, y'-y) \left[\frac{\partial \phi(\xi',\eta')}{\partial \eta'} \right]_{\substack{\xi'=x' \\ \eta'=y'}} . \end{aligned} \tag{6b}$$

By changing the variable of integration in Eq. (6a) from x' to $x'-\Delta x$, and using the notation x' to denote this new variable of integration—and in Eq. (6b) changing the variable of integration from y' to $y'-\Delta y$, and using the notation y' to denote this new variable of integration, we can recast Eq. (6) as

$$\begin{aligned} \Delta g_{\mathrm{X}}(\Delta x, \Delta y) = {} & k^{-1}\,\ell^{-2} \iint dx'\, dy'\, S(x'-x, y'-y) \left[\frac{\partial \phi(\xi',\eta')}{\partial \xi'} \right]_{\substack{\xi'=x'+\Delta x \\ \eta'=y'+\Delta y}} \\ & - k^{-1}\,\ell^{-2} \iint dx'\, dy'\, S(x'-x, y'-y) \left[\frac{\partial \phi(\xi',\eta')}{\partial \xi'} \right]_{\substack{\xi'=x' \\ \eta'=y'}} \\ = {} & k^{-1}\,\ell^{-2} \iint dx'\, dy'\, S(x'-x, y'-y) \left\{ \left[\frac{\partial \phi(\xi',\eta')}{\partial \xi'} \right]_{\substack{\xi'=x'+\Delta x \\ \eta'=y'+\Delta y}} - \left[\frac{\partial \phi(\xi',\eta')}{\partial \xi'} \right]_{\substack{\xi'=x' \\ \eta'=y'}} \right\} , \end{aligned} \tag{7a}$$

$$\Delta g_{\mathrm{Y}}(\Delta x, \Delta y) = k^{-1}\,\ell^{-2} \iint dx'\,dy'\,S(x'-x, y'-y)\left[\frac{\partial\phi(\xi',\eta')}{\partial\eta'}\right]_{\substack{\xi'=x'+\Delta x\\ \eta'=y'+\Delta y}}$$

$$- k^{-1}\,\ell^{-2} \iint dx'\,dy'\,S(x'-x, y'-y)\left[\frac{\partial\phi(\xi',\eta')}{\partial\eta'}\right]_{\substack{\xi'=x'\\ \eta'=y'}}$$

$$= k^{-1}\,\ell^{-2} \iint dx'\,dy'\,S(x'-x, y'-y)\left\{\left[\frac{\partial\phi(\xi',\eta')}{\partial\eta'}\right]_{\substack{\xi'=x'+\Delta x\\ \eta'=y'+\Delta y}} - \left[\frac{\partial\phi(\xi',\eta')}{\partial\eta'}\right]_{\substack{\xi'=x'\\ \eta'=y'}}\right\} . \quad (7b)$$

With this double result for the randomly varying difference of G-tilts in hand, we are now ready to turn to development of an expression for the mean square value of such differences. We take this up in the next section.

3. Development of an Expression for the Mean Square Difference of G-Tilts

Starting from Eq. (7) we can write for the mean of the square of each of the two components of the difference of the G-tilts measured by the two sub apertures, that

$$\left\langle \left[\Delta g_{\mathrm{X}}(\Delta x, \Delta y)\right]^2 \right\rangle = \left\langle \left(k^{-1}\,\ell^{-2} \iint dx'\,dy'\,S(x'-x, y'-y) \times \left\{\left[\frac{\partial\phi(\xi',\eta')}{\partial\xi'}\right]_{\substack{\xi'=x'+\Delta x\\ \eta'=y'+\Delta y}} - \left[\frac{\partial\phi(\xi',\eta')}{\partial\xi'}\right]_{\substack{\xi'=x'\\ \eta'=y'}}\right\}\right)^2 \right\rangle , \quad (8a)$$

$$\left\langle \left[\Delta g_{\mathrm{Y}}(\Delta x, \Delta y)\right]^2 \right\rangle = \left\langle \left(k^{-1}\,\ell^{-2} \iint dx'\,dy'\,S(x'-x, y'-y) \times \left\{\left[\frac{\partial\phi(\xi',\eta')}{\partial\eta'}\right]_{\substack{\xi'=x'+\Delta x\\ \eta'=y'+\Delta y}} - \left[\frac{\partial\phi(\xi',\eta')}{\partial\eta'}\right]_{\substack{\xi'=x'\\ \eta'=y'}}\right\}\right)^2 \right\rangle . \quad (8b)$$

Carrying out the squaring process, writing the variables of integration in one of the two versions of the double integral thus formed as x'' and y'' (in place of x' and y'), changing the notation from ξ' to ξ'' and from η' to η'' in the integrand of that same double integral, and then making a quadruple integral of the product of two double integrals, we can recast Eq. (8) as

$$\left\langle \left[\Delta g_{\mathrm{X}}(\Delta x, \Delta y)\right]^2 \right\rangle = k^{-2}\,\ell^{-4} \iiiint dx'\,dx''\,dy'\,dy''\,S(x'-x, y'-y)\,S(x''-x, y''-y) \times \left\langle \left\{\left[\frac{\partial\phi(\xi',\eta')}{\partial\xi'}\right]_{\substack{\xi'=x'+\Delta x\\ \eta'=y'+\Delta y}} - \left[\frac{\partial\phi(\xi',\eta')}{\partial\xi'}\right]_{\substack{\xi'=x'\\ \eta'=y'}}\right\} \times \left\{\left[\frac{\partial\phi(\xi'',\eta'')}{\partial\xi''}\right]_{\substack{\xi''=x''+\Delta x\\ \eta''=y''+\Delta y}} - \left[\frac{\partial\phi(\xi'',\eta'')}{\partial\xi''}\right]_{\substack{\xi''=x''\\ \eta''=y''}}\right\} \right\rangle , \quad (9a)$$

$$\left\langle \left[\Delta g_{\mathrm{Y}}(\Delta x, \Delta y)\right]^2 \right\rangle = k^{-2}\,\ell^{-4} \iiiint dx'\,dx''\,dy'\,dy''\,S(x'-x, y'-y)\,S(x''-x, y''-y)$$

$$\times \left\langle \left\{ \left[\frac{\partial \phi(\xi',\eta')}{\partial \eta'} \right]_{\substack{\xi'=x'+\Delta x \\ \eta'=y'+\Delta y}} - \left[\frac{\partial \phi(\xi',\eta')}{\partial \eta'} \right]_{\substack{\xi'=x' \\ \eta'=y'}} \right\} \right.$$

$$\left. \times \left\{ \left[\frac{\partial \phi(\xi'',\eta'')}{\partial \eta''} \right]_{\substack{\xi''=x''+\Delta x \\ \eta''=y''+\Delta y}} - \left[\frac{\partial \phi(\xi'',\eta'')}{\partial \eta''} \right]_{\substack{\xi''=x'' \\ \eta''=y''}} \right\} \right\rangle . \quad (9b)$$

At this point it is appropriate to introduce the phase structure function, $\mathcal{D}_\phi(x,y)$, noting that it can be considered to be defined by the equation

$$\mathcal{D}_\phi(\xi'-\xi'',\eta'-\eta'') = \left\langle \left[\phi(\xi',\eta') - \phi(\xi'',\eta'') \right]^2 \right\rangle . \quad (10)$$

Expanding the squaring operation we can rewrite this as

$$\mathcal{D}_\phi(\xi'-\xi'',\eta'-\eta'') = \left\langle \left[\phi(\xi',\eta') \right]^2 - 2\,\phi(\xi',\eta')\,\phi(\xi'',\eta'') + \left[\phi(\xi'',\eta'') \right]^2 \right\rangle . \quad (11)$$

Noting that quite obviously

$$\frac{\partial^2 \left[\phi(\xi',\eta') \right]^2}{\partial \xi'\,\partial \xi''} = 0\,, \quad (12a)$$

$$\frac{\partial^2 \left[\phi(\xi'',\eta'') \right]^2}{\partial \xi'\,\partial \xi''} = 0\,, \quad (12b)$$

we can see that it follows from Eq. (11) that

$$\frac{\partial^2 \mathcal{D}_\phi(\xi'-\xi'',\eta'-\eta'')}{\partial \xi'\,\partial \xi''} = -2 \left\langle \frac{\partial \phi(\xi',\eta')}{\partial \xi'}\,\frac{\partial \phi(\xi'',\eta'')}{\partial \xi''} \right\rangle , \quad (13a)$$

$$\frac{\partial^2 \mathcal{D}_\phi(\xi'-\xi'',\eta'-\eta'')}{\partial \eta'\,\partial \eta''} = -2 \left\langle \frac{\partial \phi(\xi',\eta')}{\partial \eta'}\,\frac{\partial \phi(\xi'',\eta'')}{\partial \eta''} \right\rangle . \quad (13b)$$

If we substitute Eq. (13a) into Eq. (9a), and Eq. (13b) into Eq. (9b), we see that we obtain results which can be written as

$$\left\langle \left[\Delta g_{\mathrm{x}}(\Delta x,\Delta y) \right]^2 \right\rangle = -\tfrac{1}{2}\, k^{-2}\, \ell^{-4} \iiiint dx'\,dx''\,dy'\,dy''\, S(x'-x,y'-y)\, S(x''-x,y''-y)$$

$$\times \left\{ \left[\frac{\partial^2 \mathcal{D}_\phi(\xi'-\xi'',\eta'-\eta'')}{\partial \xi'\,\partial \xi''} \right]_{\substack{\xi'=x'+\Delta x \;\; \xi''=x''+\Delta x \\ \eta'=y'+\Delta y \;\; \eta''=y''+\Delta y}} \right.$$

$$- \left[\frac{\partial^2 \mathcal{D}_\phi(\xi'-\xi'',\eta'-\eta'')}{\partial \xi'\,\partial \xi''} \right]_{\substack{\xi'=x'+\Delta x \;\; \xi''=x'' \\ \eta'=y'+\Delta y \;\; \eta''=y''}}$$

$$- \left[\frac{\partial^2 \mathcal{D}_\phi(\xi'-\xi'',\eta'-\eta'')}{\partial \xi'\,\partial \xi''} \right]_{\substack{\xi'=x' \;\; \xi''=x''+\Delta x \\ \eta'=y' \;\; \eta''=y''+\Delta y}}$$

$$\left. + \left[\frac{\partial^2 \mathcal{D}_\phi(\xi'-\xi'',\eta'-\eta'')}{\partial \xi'\,\partial \xi''} \right]_{\substack{\xi'=x' \;\; \xi''=x'' \\ \eta'=y' \;\; \eta''=y''}} \right\} , \quad (14a)$$

$$\Big\langle \big[\, \Delta g_{\mathrm{Y}}(\Delta x, \Delta y) \big]^2 \Big\rangle = -\tfrac{1}{2}\, k^{-2}\, \ell^{-4} \iiiint dx'\, dx''\, dy'\, dy''\, S(x'-x, y'-y)\, S(x''-x, y''-y)$$

$$\times \Bigg\{ \left[\frac{\partial^2 \mathcal{D}_\phi(\xi'-\xi'', \eta'-\eta'')}{\partial\eta'\,\partial\eta''} \right]_{\substack{\xi'=x'+\Delta x \\ \eta'=y'+\Delta y}\ \substack{\xi''=x''+\Delta x \\ \eta''=y''+\Delta y}} - \left[\frac{\partial^2 \mathcal{D}_\phi(\xi'-\xi'', \eta'-\eta'')}{\partial\eta'\,\partial\eta''} \right]_{\substack{\xi'=x'+\Delta x \\ \eta'=y'+\Delta y}\ \substack{\xi''=x'' \\ \eta''=y''}}$$

$$- \left[\frac{\partial^2 \mathcal{D}_\phi(\xi'-\xi'', \eta'-\eta'')}{\partial\eta'\,\partial\eta''} \right]_{\substack{\xi'=x' \\ \eta'=y'}\ \substack{\xi''=x''+\Delta x \\ \eta''=y''+\Delta y}} + \left[\frac{\partial^2 \mathcal{D}_\phi(\xi'-\xi'', \eta'-\eta'')}{\partial\eta'\,\partial\eta''} \right]_{\substack{\xi'=x' \\ \eta'=y'}\ \substack{\xi''=x'' \\ \eta''=y''}} \Bigg\}. \tag{14b}$$

To proceed beyond this point we need to be explicite about the turbulence induced phase perturbation statistics, *i.e.* we have to introduce an analytic expression for the phase structure function, $\mathcal{D}_\phi(x, y)$. We develop these results in the next section.

4. Incorporating an Expression for the Phase Perturbation Statistics into the Formulation

Ignoring the diffraction/propagation induced conversion of turbulence generated phase perturbation into intensity variations, the phase structure function, $\mathcal{D}_\phi(x, y)$, has a form such that we can write

$$\mathcal{D}_\phi(\xi'-\xi'', \eta'-\eta'') = 6.88\, r_{\mathrm{o}}^{-5/3} \big[\, (\xi'-\xi'')^2 + (\eta'-\eta'')^2 \big]^{5/6} . \tag{15}$$

From this it follows that

$$\frac{\partial^2 \mathcal{D}_\phi(\xi'-\xi'', \eta'-\eta'')}{\partial\xi'\,\partial\xi''} = 6.88\, r_{\mathrm{o}}^{-5/3} \frac{\partial}{\partial\xi''} \Big\{ \tfrac{5}{6} \big[\, (\xi'-\xi'')^2 + (\eta'-\eta'')^2 \big]^{-1/6} \big[\, 2\,(\xi'-\xi'')\, \big] \Big\}$$

$$= 6.88\, r_{\mathrm{o}}^{-5/3} \Big\{ \tfrac{5}{6} \big(-\tfrac{1}{6}\big) \big[\, (\xi'-\xi'')^2 + (\eta'-\eta'')^2 \big]^{-7/6} \big[\, 2\,(\xi'-\xi'')\,(-1) \big] \big[\, 2\,(\xi'-\xi'') \big]$$

$$+ \tfrac{5}{6} \big[\, (\xi'-\xi'')^2 + (\eta'-\eta'')^2 \big]^{-1/6} \big[\, 2\,(-1) \big] \Big\}$$

$$= -6.88 \big(\tfrac{5}{3}\big)\, r_{\mathrm{o}}^{-5/3} \frac{\tfrac{2}{3}\,(\xi'-\xi'')^2 + (\eta'-\eta'')^2}{\big[\, (\xi'-\xi'')^2 + (\eta'-\eta'')^2 \big]^{7/6}} , \tag{16a}$$

$$\frac{\partial^2 \mathcal{D}_\phi(\xi'-\xi'', \eta'-\eta'')}{\partial\eta'\,\partial\eta''} = -6.88 \big(\tfrac{5}{3}\big)\, r_{\mathrm{o}}^{-5/3} \frac{(\xi'-\xi'')^2 + \tfrac{2}{3}\,(\eta'-\eta'')^2}{\big[\, (\xi'-\xi'')^2 + (\eta'-\eta'')^2 \big]^{7/6}} . \tag{16b}$$

We shall substitute Eq. (16a) into Eq. (14a), and Eq. (16b) into Eq. (14b), and at the same time will introduce a change of the variables of integration—changing from x' and x'' to x_+ and x_-, and changing from y' and y'' to y_+ and y_-, where

$$x_+ = \tfrac{1}{2}\,(x' + x'')\,, \qquad x_- = x' - x''\,, \tag{17a}$$

$$y_+ = \tfrac{1}{2}\,(y' + y'')\,, \qquad y_- = y' - y''\,. \tag{17b}$$

Ancillary relations are

$$x' = x_+ + \tfrac{1}{2}\,x_-\,, \qquad x'' = x_+ - \tfrac{1}{2}\,x_-\,, \tag{18a}$$

$$y' = y_+ + \tfrac{1}{2}\,y_-\,, \qquad y'' = y_+ - \tfrac{1}{2}\,x_-\,, \tag{18b}$$

$$dx'\,dx'' = dx_+\,dx_-\,, \tag{18c}$$

$$dy'\,dy'' = dy_+\,dy_-\,. \tag{18d}$$

Making the substitutions from Eq. (16) into Eq. (14), changing the variables of integration, and making use of the ancillary relationships presented in Eq. (18), we can write

$$\begin{aligned}\Big\langle \big[\,\Delta g_{\mathrm{X}}(\Delta x, \Delta y)\big]^2\Big\rangle &= \left(\tfrac{1}{2}\right) 6.88 \left(\tfrac{5}{3}\right) r_{\mathrm{o}}{}^{-5/3}\, k^{-2}\, \ell^{-4} \iiiint dx_+\, dx_-\, dy_+\, dy_- \\ &\times S\big(x_+ + \tfrac{1}{2}\,x_- - x, y_+ + \tfrac{1}{2}\,y_- - y\big)\, S\big(x_+ - \tfrac{1}{2}\,x_- - x, y_+ - \tfrac{1}{2}\,y_- - y\big) \\ &\times \left\{ \frac{\tfrac{2}{3}\,x_-{}^2 + y_-{}^2}{\big[\,x_-{}^2 + y_-{}^2\big]^{7/6}} - \frac{\tfrac{2}{3}\,(x_- + \Delta x)^2 + (y_- + \Delta y)^2}{\big[\,(x_- + \Delta x)^2 + (y_- + \Delta y)^2\big]^{7/6}} \right. \\ &\qquad \left. - \frac{\tfrac{2}{3}\,(x_- - \Delta x)^2 + (y_- - \Delta y)^2}{\big[\,(x_- - \Delta x)^2 + (y_- - \Delta y)^2\big]^{7/6}} + \frac{\tfrac{2}{3}\,x_-{}^2 + y_-{}^2}{\big[\,x_-{}^2 + y_-{}^2\big]^{7/6}} \right\}, \end{aligned} \tag{19a}$$

$$\begin{aligned}\Big\langle \big[\,\Delta g_{\mathrm{Y}}(\Delta x, \Delta y)\big]^2\Big\rangle &= \left(\tfrac{1}{2}\right) 6.88 \left(\tfrac{5}{3}\right) r_{\mathrm{o}}{}^{-5/3}\, k^{-2}\, \ell^{-4} \iiiint dx_+\, dx_-\, dy_+\, dy_- \\ &\times S\big(x_+ + \tfrac{1}{2}\,x_- - x, y_+ + \tfrac{1}{2}\,y_- - y\big)\, S\big(x_+ - \tfrac{1}{2}\,x_- - x, y_+ - \tfrac{1}{2}\,y_- - y\big) \\ &\times \left\{ \frac{x_-{}^2 + \tfrac{2}{3}\,y_-{}^2}{\big[\,x_-{}^2 + y_-{}^2\big]^{7/6}} - \frac{(x_- + \Delta x)^2 + \tfrac{2}{3}\,(y_- + \Delta y)^2}{\big[\,(x_- + \Delta x)^2 + (y_- + \Delta y)^2\big]^{7/6}} \right. \\ &\qquad \left. - \frac{(x_- - \Delta x)^2 + \tfrac{2}{3}\,(y_- - \Delta y)^2}{\big[\,(x_- - \Delta x)^2 + (y_- - \Delta y)^2\big]^{7/6}} + \frac{x_-{}^2 + \tfrac{2}{3}\,y_-{}^2}{\big[\,x_-{}^2 + y_-{}^2\big]^{7/6}} \right\}. \end{aligned} \tag{19b}$$

We note that in the integrands of Eq. (19) the only dependence on the x_+- and y_+-variables of integration is contained in the square aperture defining $S(x, y)$-functions. This suggests that we consider those two integrations separately, defining the function $\Lambda(x_-, y_-)$ by the equation

$$\Lambda(x_-, y_-) = \ell^{-2} \iint dx_+\, dy_+\, S\big(x_+ + \tfrac{1}{2}\,x_- - x, y_+ + \tfrac{1}{2}\,y_- - y\big)\, S\big(x_+ - \tfrac{1}{2}\,x_- - x, y_+ - \tfrac{1}{2}\,y_- - y\big)\,. \tag{20}$$

This function, $\Lambda(x_-, y_-)$, can be seen to correspond to the fractional overlap of two squares, each of size ℓ-by-ℓ, with a center-to-center separation of (x_-, y_-). It is easy to see that the fractional overlap is such that

$$\Lambda(x, y) = \begin{cases} \big(1 - |x|/\ell\big)\,\big(1 - |y|/\ell\big) & \text{if} \quad |x| \le \ell \quad \text{and} \quad |y| \le \ell \\ 0 & \text{if otherwise} \end{cases}\,. \tag{21}$$

Making use of Eq. (20) we can recast Eq. (19) as

$$\left\langle \left[\Delta g_{\mathrm{X}}(\Delta x, \Delta y) \right]^2 \right\rangle = 6.88 \left(\tfrac{5}{6}\right) r_{\mathrm{o}}^{-5/3} \, k^{-2} \, \ell^{-2} \iint dx \, dy \, \Lambda(x,y)$$
$$\times \left\{ \frac{\frac{2}{3} x^2 + y^2}{\left[x^2 + y^2 \right]^{7/6}} - \frac{\frac{2}{3} (x + \Delta x)^2 + (y + \Delta y)^2}{\left[(x + \Delta x)^2 + (y + \Delta y)^2 \right]^{7/6}} - \frac{\frac{2}{3} (x - \Delta x)^2 + (y - \Delta y)^2}{\left[(x - \Delta x)^2 + (y - \Delta y)^2 \right]^{7/6}} + \frac{\frac{2}{3} x^2 + y^2}{\left[x^2 + y^2 \right]^{7/6}} \right\}, \quad (22a)$$

$$\left\langle \left[\Delta g_{\mathrm{Y}}(\Delta x, \Delta y) \right]^2 \right\rangle = 6.88 \left(\tfrac{5}{6}\right) r_{\mathrm{o}}^{-5/3} \, k^{-2} \, \ell^{-2} \iint dx \, dy \, \Lambda(x,y)$$
$$\times \left\{ \frac{x^2 + \frac{2}{3} y^2}{\left[x^2 + y^2 \right]^{7/6}} - \frac{(x + \Delta x)^2 + \frac{2}{3} (y + \Delta y)^2}{\left[(x + \Delta x)^2 + (y + \Delta y)^2 \right]^{7/6}} - \frac{(x - \Delta x)^2 + \frac{2}{3} (y - \Delta y)^2}{\left[(x - \Delta x)^2 + (y - \Delta y)^2 \right]^{7/6}} + \frac{x^2 + \frac{2}{3} y^2}{\left[x^2 + y^2 \right]^{7/6}} \right\}. \quad (22b)$$

Making use of Eq. (21) this can be rewritten as

$$\left\langle \left[\Delta g_{\mathrm{X}}(\Delta x, \Delta y) \right]^2 \right\rangle = 6.88 \left(\tfrac{5}{3}\right) r_{\mathrm{o}}^{-5/3} \, k^{-2} \, \ell^{-2} \int_{-\ell}^{+\ell} dx \int_{-\ell}^{+\ell} dy \, (1 - |x|/\ell) \, (1 - |y|/\ell)$$
$$\times \left\{ \frac{\frac{2}{3} x^2 + y^2}{\left[x^2 + y^2 \right]^{7/6}} - \frac{\frac{2}{3} (x + \Delta x)^2 + (y + \Delta y)^2}{\left[(x + \Delta x)^2 + (y + \Delta y)^2 \right]^{7/6}} \right\}, \quad (23a)$$

$$\left\langle \left[\Delta g_{\mathrm{Y}}(\Delta x, \Delta y) \right]^2 \right\rangle = 6.88 \left(\tfrac{5}{3}\right) r_{\mathrm{o}}^{-5/3} \, k^{-2} \, \ell^{-2} \int_{-\ell}^{+\ell} dx \int_{-\ell}^{+\ell} dy \, (1 - |x|/\ell) \, (1 - |y|/\ell)$$
$$\times \left\{ \frac{x^2 + \frac{2}{3} y^2}{\left[x^2 + y^2 \right]^{7/6}} - \frac{(x + \Delta x)^2 + \frac{2}{3} (y + \Delta y)^2}{\left[(x + \Delta x)^2 + (y + \Delta y)^2 \right]^{7/6}} \right\}. \quad (23b)$$

Making use of Eq. (3) to replace the wave number dependence, *i.e.* the k-dependence, by a wave length dependence, *i.e.* a λ-dependence, and replacing the variables of integration, x and y by variables of integration corresponding to x/ℓ and y/ℓ —only still using the notations x and y to denote the variables of integration, we can recast Eq. (23) as

$$\left\langle \left[\Delta g_{\mathrm{X}}(\Delta x, \Delta y) \right]^2 \right\rangle = 6.88 \left(\tfrac{5}{3}\right) (2\,\pi)^{-2} \left(\ell / r_{\mathrm{o}}\right)^{5/3} \left(\lambda/\ell\right)^2 \int_{-1}^{+1} dx \int_{-1}^{+1} dy \, \left(1 - |x|\right) \left(1 - |y|\right)$$
$$\times \left\{ \frac{\frac{2}{3} x^2 + y^2}{\left[x^2 + y^2 \right]^{7/6}} - \frac{\frac{2}{3} (x + \Delta x/\ell)^2 + (y + \Delta y/\ell)^2}{\left[(x + \Delta x/\ell)^2 + (y + \Delta y/\ell)^2 \right]^{7/6}} \right\}, \quad (24a)$$

$$\left\langle \left[\Delta g_{\mathrm{Y}}(\Delta x, \Delta y) \right]^2 \right\rangle = 6.88 \left(\tfrac{5}{3}\right) (2\,\pi)^{-2} \left(\ell / r_{\mathrm{o}}\right)^{5/3} \left(\lambda/\ell\right)^2 \int_{-1}^{+1} dx \int_{-1}^{+1} dy \, \left(1 - |x|\right) \left(1 - |y|\right)$$
$$\times \left\{ \frac{x^2 + \frac{2}{3} y^2}{\left[x^2 + y^2 \right]^{7/6}} - \frac{(x + \Delta x/\ell)^2 + \frac{2}{3} (y + \Delta y/\ell)^2}{\left[(x + \Delta x/\ell)^2 + (y + \Delta y/\ell)^2 \right]^{7/6}} \right\}. \quad (24b)$$

Expressed in this form the results are ready for numerical evaluation. We present this and the consequent numerical results in the next section.

5. Numerical Evaluation and Results

The numerical evaluation of the integrals in Eq. (24), which will yield the results we desire is relatively straight forward. There are only two complications that need to be dealt with. The first of these concerns a divergence of the integrand at the origin, *i.e.* at $(x, y) = (0, 0)$. It can be seen that this divergence is of the form of $r^{-1/3}$, where r is the distance from the origin. It is easy to see that the integration, if we could undertake it analytically, would have no problem with such a weak divergence. Unfortunately a numerical approach to the evaluation of the integral will not be able to pass so easily over this divergence. Since the divergence of the integrand does not actually make a significant contribution to the value of the integral in our numerical evaluation we suppress the divergence by replacing the value of the integrand at the origin with the average of the value of the integrand at the four nearest points for which the integrand is calculated. This eliminates/takes care of the first of the two problems.

The second problem in the numerical integration process has to do with the fact that with $\Delta x = 1$ [or $\Delta y = 1$, or $\Delta x = 1$ and $\Delta y = 1$] the integrand will take a 0/0 form at $(x, y) = (-1, 0)$ [or at $(x, y) = (0, -1)$, or at $(x, y) = (-1, -1)$]. Examining the integrand we can see that the contribution to the value of the integral from the vicinity of such a point is zero. Accordingly in the numerical evaluation we force the value of the integrand to be zero at such points.

We list here the computer program, written in the MATLAB programming language and called **Calc01**, used to evaluate the integrals in Eq. (24).

Calc01

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Script, called Calc01, used to develop numerical results for the G-tilt
% mean square difference as given by Eq.(25).
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

Del=[1 1.2 1.5 2 2.5 3:25];
N=length(Del);
MSD=NaN*ones(2,N);
C=6.88*(5/3)/(2*pi)^2;
[x,c]=simpson(100,1,-1);
x=x+1e-10;
cc=c'*c;
num=length(x);
mid=(num+1)/2;
x=ones(num,1)*x;
y=x';
for n=1:N
  W=(1-abs(x)).*(1-abs(y));
  Q1=(2/3)*x.^2+y.^2;
  Q2=(x.^2+y.^2).^(7/6);
  Q3=(2/3)*(x+Del(n)).^2+y.^2;
  Q4=((x+Del(n)).^2+y.^2).^(7/6);
```

```
  integrand=W.*(Q1./Q2-Q3./Q4);
  if Del(n)==1
    ii=find(isnan(integrand));
    integrand(ii)=0;
  end
  integrand(mid,mid)=(integrand(mid+1,mid)+integrand(mid-1,mid) ...
                      +integrand(mid,mid+1)+integrand(mid,mid-1))/4;
  MSD(1,n)=C*dblsum(cc.*integrand);
end

for n=1:N
  W=(1-abs(x)).*(1-abs(y));
  Q1=x.^2+(2/3)*y.^2;
  Q2=(x.^2+y.^2).^(7/6);
  Q3=(x+Del(n)).^2+(2/3)*y.^2;
  Q4=((x+Del(n)).^2+y.^2).^(7/6);
  integrand=W.*(Q1./Q2-Q3./Q4);
  if Del(n)==1
    ii=find(isnan(integrand));
    integrand(ii)=0;
  end
  integrand(mid,mid)=(integrand(mid+1,mid)+integrand(mid-1,mid) ...
                      +integrand(mid,mid+1)+integrand(mid,mid-1))/4;
  MSD(2,n)=C*dblsum(cc.*integrand);
end

dbllin(Del,MSD(1,:),Del,MSD(2,:),':')
print -deps fig1
```

Calculation are carried out by this program for the two cases where the separation is parallel to either the x-axis or the y-axis and the component of tilt considered is either parallel to or perpendicular to the separation. Results are generated for separations as small as ℓ and as large as $25\,\ell$ (where ℓ is the size of a sub aperture).

For convenience in presenting the results we introduce the two functions $\mathcal{F}_{\|}(\Delta/\ell)$ and $\mathcal{F}_{\perp}(\Delta/\ell)$, which we define by the equations

$$\mathcal{F}_{\|}(\Delta/\ell) = 6.88\left(\tfrac{5}{3}\right)(2\,\pi)^{-2}\int_{-1}^{+1} dx \int_{-1}^{+1} dy\,\big(1-|x|\big)\big(1-|y|\big) \times \left\{ \frac{\frac{2}{3}\,x^2+y^2}{\left[\,x^2+y^2\,\right]^{7/6}} - \frac{\frac{2}{3}\left(x+\Delta/\ell\right)^2+y^2}{\left[\,\left(x+\Delta/\ell\right)^2+y^2\,\right]^{7/6}} \right\}, \quad (25a)$$

$$\mathcal{F}_{\perp}(\Delta/\ell) = 6.88\left(\tfrac{5}{3}\right)(2\,\pi)^{-2}\int_{-1}^{+1} dx \int_{-1}^{+1} dy\,\big(1-|x|\big)\big(1-|y|\big) \times \left\{ \frac{x^2+\frac{2}{3}\,y^2}{\left[\,x^2+y^2\,\right]^{7/6}} - \frac{\left(x+\Delta/\ell\right)^2+\frac{2}{3}\,y^2}{\left[\,\left(x+\Delta/\ell\right)^2+y^2\,\right]^{7/6}} \right\}. \quad (25b)$$

Comparing this with Eq. (24) we can see that

$$\left\langle \left[\Delta g_{\mathrm{X}}(\Delta,0) \right]^2 \right\rangle = \left(\ell/r_0\right)^{5/3} \left(\lambda/\ell\right)^2 \mathcal{F}_{\parallel}(\Delta/\ell)\,, \tag{26a}$$

$$\left\langle \left[\Delta g_{\mathrm{Y}}(\Delta,0) \right]^2 \right\rangle = \left(\ell/r_0\right)^{5/3} \left(\lambda/\ell\right)^2 \mathcal{F}_{\perp}(\Delta/\ell)\,. \tag{26b}$$

It is the functions $\mathcal{F}_{\parallel}(\Delta/\ell)$ and $\mathcal{F}_{\perp}(\Delta/\ell)$ that the computer program evaluates. The computer generated results are shown in Fig. 1, and listed in Table 1.

Figure 1. Mean Square Tilt Difference Separation Dependance Functions, $\mathcal{F}_{\parallel}(\Delta/\ell)$ and $\mathcal{F}_{\perp}(\Delta/\ell)$

The notation Δ represents the center-to-center separation of two equal size and parallel square sub apertures. The separation is parallel to one of the sides of a square. The notation ℓ represents the length of a side of one of the squares. The solid curve shows the results for the component of tilt parallel to the separation, *i.e.* for $\mathcal{F}_{\parallel}(\Delta/\ell)$, while the dotted line curve shows the results for the component of tilt perpendicular to the separation, *i.e.* for $\mathcal{F}_{\perp}(\Delta/\ell)$.

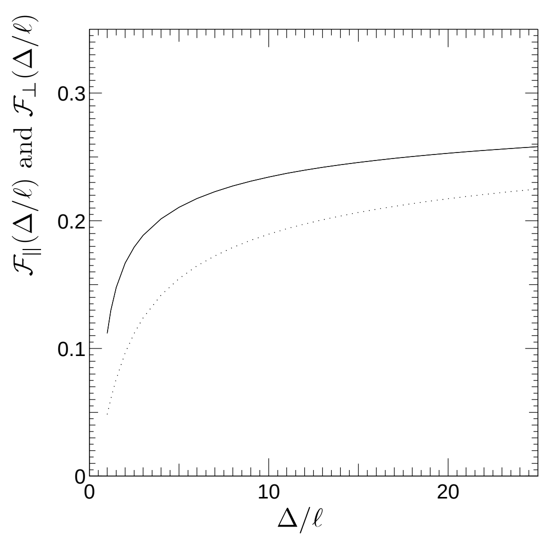

Table 1		
Mean Square Tilt Difference Separation-Dependence		
Δ/ℓ	$\mathcal{F}_{\parallel}(\Delta/\ell)$	$\mathcal{F}_{\perp}(\Delta/\ell)$
1.0000	0.1119	0.0484
1.2000	0.1298	0.0605
1.5000	0.1479	0.0761
2.0000	0.1669	0.0965
2.5000	0.1794	0.1119
3.0000	0.1886	0.1239
4.0000	0.2015	0.1418
5.0000	0.2106	0.1547
6.0000	0.2174	0.1646
7.0000	0.2228	0.1726
8.0000	0.2273	0.1791
9.0000	0.2310	0.1847
10.0000	0.2343	0.1895
11.0000	0.2371	0.1937
12.0000	0.2396	0.1974
13.0000	0.2418	0.2008
14.0000	0.2439	0.2038
15.0000	0.2457	0.2065
16.0000	0.2474	0.2090
17.0000	0.2489	0.2113
18.0000	0.2503	0.2134
19.0000	0.2517	0.2154
20.0000	0.2529	0.2173
21.0000	0.2540	0.2190
22.0000	0.2551	0.2206
23.0000	0.2561	0.2221
24.0000	0.2571	0.2236
25.0000	0.2580	0.2249

PUBLIC AFFAIRS SECURITY AND POLICY REVIEW WORKSHEET

(See page 2 for instructions)

1. DATE NEEDED: 11/6/2023

2. SUBMITTER REFERENCE NO.: O-2253

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***5. DOCUMENT TITLE**

TN:110 Mean Square Difference of G-Tilt for Two Square Apertures

***6. CONFERENCE/EVENT/PUBLICATION/WEBSITE/PUBLIC WEB URL**

Defense Technical Information Center https://dtic.mil/

***7. EVENT/PUBLICATION DATE:** 12/4/2023

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If a PIA, enter the contract # below and the Approval Officer must sign in Block 18 or 19. **For AFOSR,** provide the LRIR and name of program officer below. **For 6.x** include the Work Unit # (WU) and work unit manager's name (WUM) below. **For Other** specify below.

This work was produced June 2000. We cannot locate the contract, or work unit information because this is so old. Any rights held should have reverted to the government in the last 23 years. Please get in contact with me if more

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PUBLIC AFFAIRS OFFICER

CASE NUMBER

Block 14 - Explanation (Continued):

REFERENCES: Electronic Code of Federal Regulations / Export Administration Regulations Database / U.S. Munitions List (Part 121) / The Commerce Control List
Int'l Traffic In Arms Regulations (ITAR) / AFMAN 16-201 / DoDI 5230.24 / AFI 61-201 / AFI 35-101 (Chapter 9) / AFMAN 35-101 (Chapter 8) / AFRLI 35-102 / AFRLI 61-113

INSTRUCTIONS FOR COMPLETING THE SECURITY AND POLICY REVIEW WORKSHEET

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