文章编号：1001-3806(2011)02-0234-04

双程传输中粗糙面散射场统计特性的研究

武颖丽，吴振森
(西安电子科技大学 理学院，西安 710071)

摘要：为了研究激光散斑对目标探测的影响，采用广义惠更斯-菲涅耳原理，进行了双程传输中激光束照射远场目标时在接收平面上散斑的统计特性的理论分析，导出了汇聚光束及准直光束照射情况下散斑场的互相关函数、平均散射强度以及强度协方差的表达式。结果表明，随着波束特征半径以及传输距离的减小，会聚波束照射时接收平面上散斑场的互相关函数下降迅速，而准直波束正好相反，总体上准直波束比会聚波束下降要快得多；强度协方差函数的变化规律与互相关函数的变化规律基本一致。

关键词：散射；粗糙面散射；激光散斑；强度协方差；双程传输
中图分类号：O436.2 **文献标识码**：A **doi**:10.3969/j.issn.1001-3806.2011.02.025

Study on statistical characteristics of rough surfaces scattering in double transmission

WU Ying-li, WU Zhen-sen
(School of Science, Xidian University, Xi'an 710071, China)

Abstract: In order to study the effect of laser speckle on target detection, according to the extended Huygens-Fresnel principle, statistical properties of the speckle scattered from the rough surfaces in the far field were analyzed in double transmission. Analytical expressions for the correlation function and covariance of the speckle intensity were derived under the illumination of focused beam and collimated beam. The results indicate that under the illumination of focused beam, the speckle intensity correlation function of the receiver surface is decreased fast with the laser beam waist and transmission distance decreasing. However, under the illumination of collimated beam, the speckle intensity correlation function of the receiver surface is decreased fast with the laser beam waist and transmission distance increasing. In the whole, it decreased fast under the collimated illumination than focused illumination. The change rule of intensity covariance is identical with the speckle intensity correlation function.

Key words: scattering; rough surface scattering; laser speckle; intensity covariance; double transmission

引 言

通过研究散射体随机粗糙面的激光散射特性，可以获取目标激光雷达散射截面、散射功率、距离像、激光距离多普勒像等信息。激光雷达就是利用粗糙面与激光散射特性及机理去探测目标。DAINTY 认为在激光与粗糙面相互作用的过程中存在激光散斑效应，而激光散斑对目标探测与识别有较大影响[1]。当激光束从粗糙的目标表面反射时，粗糙目标将对散射回波产生很大影响，人们已对相干光和部分相干光产生的散斑图案的统计特性作了广泛的研究[2-5]。GUO 分析了激光散斑效应对激光雷达探测性能的影响，给出了远场情况下接收物镜所采集激光散斑数的表达式[6]。GUO 从理论角度研究了利用高斯光束照射远场目标时，激光散斑的统计特性，导出了散射光场的自相关函数和光强度二阶矩的解析表达式，计算了激光散斑的面积[7]。WANG 根据目标随机粗糙面激光散射特性，研究了运动目标的散射强度协方差函数及功率谱密度统计特征[8]。而实际中激光雷达与目标之间的距离通常很远，传输距离以及激光光束特性将对接收平面上散射回波信号产生很大影响。基于此，作者从广义惠更斯-菲涅耳原理出发，研究了在双程传输情况下激光束照射远场目标在接收平面上散斑的统计特性。

1 接收平面处散斑场的互相关函数、平均散射强度的计算

在研究激光雷达对目标的成像时，激光雷达是利用激光先向目标发射一个探测信号，然后将其接收到的从

作者简介：武颖丽(1975-)，女，副教授，现主要从事散斑测量及其信号处理的研究。
E-mail: ylwu@xidian.edu.cn.

收稿日期：2010-05-06；收到修改稿日期：2010-06-10

目标反射来的信号与发射信号作比较，以获得目标的有关信息。而信号从目标经传输过程中将引起激光散斑效应。图 1 为激光束双程折叠式传输示意图。

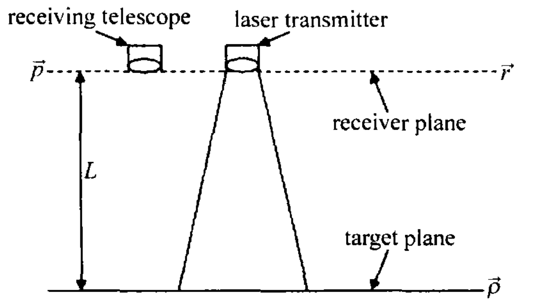

Fig. 1　Diagram of laser beam retraced transmission in the free space

假定激光源和目标的尺寸远小于传输距离 L，接收机与光源之间的距离大于源的尺寸，同时假定目标是漫射体，设源的振幅分布为[9]：

$$u_0(\vec{r}) = u_0\exp\left[-\frac{r^2}{2\alpha_0^{\,2}} - \frac{\mathrm{i}kr^2}{2F}\right] \quad (1)$$

式中，$\vec{r}$ 表示发射机孔径平面的 2 维坐标矢量，α_0 为波束的特征半径，k 为自由空间波数，F 为聚焦宽度，u_0 为常数。假设目标的尺寸远大于波束孔径，应用广义惠更斯-菲涅耳原理，入射到目标上任一点的复振幅可以表示为：

$$u(\vec{\rho}) = \frac{k\mathrm{e}^{\mathrm{i}kL}}{2\pi\mathrm{i}L}\int u_0(\vec{r})\exp\left(\frac{\mathrm{i}k|\vec{\rho}-\vec{r}|^2}{2L}\right)\mathrm{d}\vec{r} \quad (2)$$

式中，$u(\vec{\rho})$ 为入射到目标 $\vec{\rho}$ 处的场，$\vec{\rho}$ 为目标平面上的 2 维坐标矢量。联合(1)式、(2)式得到：

$$u(\vec{\rho}) = \frac{k\mathrm{e}^{\left[\mathrm{i}k\left(L+\frac{\rho^2}{2L}\right)\right]}u_0}{2\pi\mathrm{i}L}\int\exp\left[-\frac{r^2}{2\alpha_0^{\,2}} + \frac{\mathrm{i}k}{2L}\left(1-\frac{L}{F}\right)r^2 - \frac{\mathrm{i}k}{L}\vec{\rho}\cdot\vec{r}\right]\mathrm{d}\vec{r} \quad (3)$$

式中，当 $L=F$ 和 $F\rightarrow\infty$ 时，分别对应于会聚波束和准直波束入射的结果。

把波束照射的目标等效为一个源，再次利用广义惠更斯-菲涅耳原理及对偶原理，接收点 $\vec{p}$ 处的场可以写为：

$$u(\vec{p}) = \frac{k\mathrm{e}^{\left[\mathrm{i}k\left(L+\frac{p^2}{2L}\right)\right]}}{2\pi\mathrm{i}L}\int u(\vec{\rho}) \times \exp\left[\frac{\mathrm{i}k}{2L}(\rho^2 - 2\vec{p}\cdot\vec{\rho})\right]\mathrm{d}\vec{\rho} \quad (4)$$

则目标平面上散斑场的互相关函数为：

$$\Gamma(\vec{\rho}_1,\vec{\rho}_2) = \langle u(\vec{\rho}_1)u^*(\vec{\rho}_2)\rangle = \left(\frac{k}{2\pi L}\right)^2\exp\left[\frac{\mathrm{i}k(\rho_1^{\,2}-\rho_2^{\,2})}{2L}\right]\times\iint\langle u_0(\vec{r}_1)u_0^{\,*}(\vec{r}_2)\rangle\times\exp\left\{\mathrm{i}k\left[\frac{r_1^{\,2}-r_2^{\,2}}{2L} - \frac{\vec{\rho}_1\cdot\vec{r}_1 - \vec{\rho}_2\cdot\vec{r}_2}{L}\right]\right\}\mathrm{d}\vec{r}_1\mathrm{d}\vec{r}_2 \quad (5)$$

当 $\vec{\rho}_1=\vec{\rho}_2$ 时，互相关函数即为平均散射强度，因此，目标平面的平均散射强度由(5)式可以写为：

$$\langle I(\vec{\rho})\rangle = \langle|u(\vec{\rho})|^2\rangle = \left(\frac{k}{2\pi L}\right)^2\times\iint\langle u_0(\vec{r}_1)u_0^{\,*}(\vec{r}_2)\rangle\exp\left\{\frac{\mathrm{i}k}{2L}\left[(r_1^{\,2} - r_2^{\,2}) - 2\vec{\rho}\cdot(\vec{r}_1-\vec{r}_2)\right]\right\}\mathrm{d}\vec{r}_1\mathrm{d}\vec{r}_2 \quad (6)$$

接收平面上两点的互相关函数为：

$$\Gamma(\vec{p}_1,\vec{p}_2) = \langle u(\vec{p}_1)u^*(\vec{p}_2)\rangle = \left(\frac{k}{2\pi L}\right)^2\times\exp\left[\frac{\mathrm{i}k(p_1^{\,2}-p_2^{\,2})}{2L}\right]\iint\langle u(\vec{\rho}_1)u^*(\vec{\rho}_2)\rangle\times\exp\left\{\mathrm{i}k\left[\frac{\rho_1^{\,2}-\rho_2^{\,2}}{2L} - \frac{\vec{p}_1\cdot\vec{\rho}_1 - \vec{p}_2\cdot\vec{\rho}_2}{L}\right]\right\}\mathrm{d}\vec{\rho}_1\mathrm{d}\vec{\rho}_2 \quad (7)$$

显然当 $\vec{p}_1=\vec{p}_2$ 时，互相关函数为平均散射强度，因此，接收点处的平均散射强度可以写为：

$$\langle I(\vec{p})\rangle = \langle|u(\vec{p})|^2\rangle = \left(\frac{k}{2\pi L}\right)^2\iint\langle u(\vec{\rho}_1)u^*(\vec{\rho}_2)\rangle\exp\left\{\frac{\mathrm{i}k}{2L}\left[(\rho_1^{\,2} - \rho_2^{\,2}) - 2\vec{p}\cdot(\vec{\rho}_1-\vec{\rho}_2)\right]\right\}\mathrm{d}\vec{\rho}_1\mathrm{d}\vec{\rho}_2 \quad (8)$$

根据漫射目标假设，由于波束从漫射目标反射的非相干性，散射波束在目标上从一点到另一点有相位延迟，入射波束的横向相关长度稍大于目标表面的相关距离，这时源可认为是一朗伯源，则有：

$$\langle u(\vec{\rho}_1)u^*(\vec{\rho}_2)\rangle = \beta\langle I(\vec{\rho}_1)\rangle\delta(\vec{\rho}_1-\vec{\rho}_2) \quad (9)$$

将(9)式带入(8)式得：

$$\langle I(\vec{p})\rangle = \beta\left(\frac{k}{2\pi L}\right)^2\int\langle|u(\vec{\rho}_1)|^2\rangle\mathrm{d}\vec{\rho}_1 \quad (10)$$

根据能量守恒定律，指数项平均值为 1，所以接收处的平均散射强度可简写为：

$$\langle I(\vec{p})\rangle = \beta\left(\frac{k}{2\pi L}\right)^2\int\langle|u(\vec{\rho})|^2\rangle\mathrm{d}\vec{\rho} \quad (11)$$

而由半球的朗伯散射，同样可得平均散射强度：

$$\langle I\rangle = \frac{P_z}{\pi L^2}\int\langle|u(\vec{r})|^2\rangle\mathrm{d}\vec{r} \quad (12)$$

式中，P_z 为总功率。

比较(11)式、(12)式可得 $\beta=4\pi/k^2$。有：

$$\langle|u(\vec{\rho})|^2\rangle = \left(\frac{k}{2\pi L}\right)^2 u_0^{\,2}\times\iint\exp\left[-\frac{r_1^{\,2}+r_2^{\,2}}{2\alpha_0^{\,2}} - \frac{\mathrm{i}k}{L}\vec{\rho}\cdot(\vec{r}_1-\vec{r}_2)\right]\mathrm{d}\vec{r}_1\mathrm{d}\vec{r}_2 \quad (13)$$

将 $\beta=4\pi/k^2$ 代入(7)式，得接收平面上两点间的互相关函数为：

$$\Gamma(\vec{p}_1,\vec{p}_2) = \frac{1}{\pi L^2}\exp\left[\frac{\mathrm{i}k(p_1^{\,2}-p_2^{\,2})}{2L}\right]\times$$

$$\int\langle I(\vec{\rho})\rangle\exp\left[-\frac{\mathrm{i}k}{L}(\vec{p}_1-\vec{p}_2)\cdot\vec{\rho}\right]\mathrm{d}\vec{\rho} \quad (14)$$

将(13)式带入(11)式,并利用 Fourier-Bessel 积分,可以得到:

$$\langle I(\vec{p})\rangle = \frac{{u_0}^2{\alpha_0}^2}{L^2} \quad (15)$$

显然在接收平面上任一点的平均强度仅与波束特征半径、入射场及接收机和目标之间的距离有关。

对(13)式进一步推导(会聚波束):

$$\langle I(\vec{\rho})\rangle = \langle |u(\vec{\rho})|^2\rangle = \left(\frac{k}{L}\right)^2 |u_0|^2\frac{{\alpha_0}^2}{2}\times \int_0^{\infty}\mathrm{J}_0\left(\frac{k}{L}\rho r\right)\exp\left(-\frac{r^2}{4{\alpha_0}^2}\right)r\mathrm{d}r \quad (16)$$

式中,$\mathrm{J}_0(\ )$为零阶贝塞尔函数。

因此有:

$$\Gamma(\vec{p}_1,\vec{p}_2) = \frac{1}{\pi L^2}\left(\frac{k}{L}\right)^2{u_0}^2\frac{{\alpha_0}^2}{2}\int\mathrm{d}\vec{\rho}\int_0^{\infty}\mathrm{J}_0\left(\frac{k}{L}\rho r\right)\times \exp\left[-\frac{r^2}{4{\alpha_0}^2}-\frac{\mathrm{i}k}{L}\vec{\rho}\cdot\vec{p}\mp\frac{\mathrm{i}k({p_1}^2-{p_2}^2)}{2L}\right]r\mathrm{d}r = \frac{2k^2}{L^4}{u_0}^2\frac{{\alpha_0}^2}{2}\int_0^{\infty}\rho\mathrm{d}\rho\int_0^{\infty}\mathrm{J}_0\left(\frac{k}{L}\rho r\right)\mathrm{J}_0\left(\frac{k}{L}\rho p\right)\times \exp\left[-\frac{r^2}{4{\alpha_0}^2}+\frac{\mathrm{i}k({p_1}^2-{p_2}^2)}{2L}\right]r\mathrm{d}r \quad (17)$$

式中,$p=|\vec{p}_1-\vec{p}_2|$。利用 Fourier-Bessel 积分公式:

$$\int_0^{\infty}\rho\mathrm{J}_0\left(\frac{k}{L}r\rho\right)\mathrm{J}_0\left(\frac{k}{L}\rho p\right)\mathrm{d}\rho = \left(\frac{L}{k}\right)^2\frac{1}{\sqrt{rp}}\delta(r-p) \quad (18)$$

(17)式可简化为:

$$\Gamma(\vec{p}_1,\vec{p}_2) = {u_0}^2\frac{{\alpha_0}^2}{L^2}\exp\left[-\frac{p^2}{4{\alpha_0}^2}\mp\frac{\mathrm{i}k({p_1}^2-{p_2}^2)}{2L}\right] = \langle I(\vec{p})\rangle\exp\left[-\frac{p^2}{4{\alpha_0}^2}+\frac{\mathrm{i}k({p_1}^2-{p_2}^2)}{2L}\right] \quad (19)$$

当入射波束为准直波束时,互相关函数可表达为:

$$\Gamma(\vec{p}_1,\vec{p}_2) = \langle I(\vec{p})\rangle\exp\left\{-p^2\times \left[\left(\frac{1}{2\alpha_0}\right)^2+\left(\frac{k\alpha_0}{2L}\right)^2\right]+\frac{\mathrm{i}k({p_1}^2-{p_2}^2)}{2L}\right\} \quad (20)$$

2 接收平面处散斑场的强度协方差函数、强度方差的公式推导

对协方差函数的分析,可得出关于散射光场的统计特性。而目标平面处的强度协方差函数可定义为:

$$C_{\mathrm{i}}(\vec{\rho}_1,\vec{\rho}_2) = \langle I(\vec{\rho}_1)I(\vec{\rho}_2)\rangle - \langle I(\vec{\rho}_1)\rangle\langle I(\vec{\rho}_2)\rangle \quad (21)$$

(21)式中等号右边第 1 项为强度的自相关函数,利用广义惠更斯-菲涅耳原理可表示为:

$$C_{\mathrm{i}}(\vec{\rho}_1,\vec{\rho}_2) = \langle I(\vec{\rho}_1)I(\vec{\rho}_2)\rangle - \langle I(\vec{\rho}_1)\rangle\langle I(\vec{\rho}_2)\rangle = \left(\frac{k}{2\pi L}\right)^4\iint\langle u_0(\vec{r}_1)u_0^*(\vec{r}_2)u_0(\vec{r}_3)u_0^*(\vec{r}_4)\rangle\times \exp\left\{\frac{\mathrm{i}k}{2L}\left[({r_1}^2-{r_2}^2+{r_3}^2-{r_4}^2)-2(\vec{\rho}_1\cdot\vec{r}_1+\vec{\rho}_1\cdot\vec{r}_2-\vec{\rho}_2\cdot\vec{r}_3+\vec{\rho}_2\cdot\vec{r}_4)\right]\right\}\mathrm{d}\vec{r}_1\mathrm{d}\vec{r}_2\mathrm{d}\vec{r}_3\mathrm{d}\vec{r}_4 - \left(\frac{k}{2\pi L}\right)^4\iint\langle u_0(\vec{r}_1)u_0^*(\vec{r}_2)\rangle\langle u_0(\vec{r}_3)u_0^*(\vec{r}_4)\rangle\times \exp\left\{\frac{\mathrm{i}k}{2L}\left[({r_1}^2-{r_2}^2+{r_3}^2-{r_4}^2)-2(\vec{\rho}_1\cdot\vec{r}_1+\vec{\rho}_1\cdot\vec{r}_2-\vec{\rho}_2\cdot\vec{r}_3+\vec{\rho}_2\cdot\vec{r}_4)\right]\right\}\mathrm{d}\vec{r}_1\mathrm{d}\vec{r}_2\mathrm{d}\vec{r}_3\mathrm{d}\vec{r}_4 \quad (22)$$

当$\vec{\rho}=0$时,$C_{\mathrm{i}}(\vec{\rho})=C_{\mathrm{i}}(0)={\sigma_{\mathrm{i}}}^2$,${\sigma_{\mathrm{i}}}^2$为强度方差。同理,在接收平面处的强度协方差函数为:

$$C_{\mathrm{i}}(\vec{p}_1,\vec{p}_2) = \langle I(\vec{p}_1)I(\vec{p}_2)\rangle - \langle I(\vec{p}_1)\rangle\langle I(\vec{p}_2)\rangle \quad (23)$$

(23)式中等号右边第 1 项为强度的自相关函数,为了求解强度的协方差,首先要求解强度的自相关函数。在此只考虑目标表面的不规则程度远大于入射波波长的情况。

$$B_{\mathrm{i}}(\vec{p}_1,\vec{p}_2) = \langle I(\vec{p}_1)I(\vec{p}_2)\rangle = \langle u(\vec{p}_1)u^*(\vec{p}_1)u(\vec{p}_2)u^*(\vec{p}_2)\rangle \quad (24)$$

在这种情况下,散射光场服从高斯统计,为了计算方便,对$C_{\mathrm{i}}(\vec{p})$利用联合高斯假设,在接收平面上光强度的自相关函数与入射光场自相关函数有如下关系:

$$B_{\mathrm{i}}(\vec{p}_1,\vec{p}_2) = \langle u(\vec{p}_1)u^*(\vec{p}_1)\rangle\langle u(\vec{p}_2)u^*(\vec{p}_2)\rangle + \langle u(\vec{p}_1)u^*(\vec{p}_2)\rangle\langle u^*(\vec{p}_1)u(\vec{p}_2)\rangle = \langle I(\vec{p}_1)\rangle\langle I(\vec{p}_2)\rangle + |\Gamma(\vec{p}_1,\vec{p}_2)|^2 \quad (25)$$

$$C_{\mathrm{i}}(\vec{p}_1,\vec{p}_2) = B_{\mathrm{i}}(\vec{p}_1,\vec{p}_2) - \langle I(\vec{p}_1)\rangle\langle I(\vec{p}_2)\rangle = |\Gamma(\vec{p}_1,\vec{p}_2)|^2 \quad (26)$$

当$\vec{p}=0$时,$C_{\mathrm{i}}(\vec{p})=C_{\mathrm{i}}(0)={\sigma_{\mathrm{i}}}^2$。

3 数值分析

综上所述,给出了接收平面处互相关函数、平均散射强度、强度协方差与强度方差的计算公式,下面对其互相关函数和强度协方差函数进行数值计算。

图 2 中给出了会聚波束和准直波束入射时,在不同入射波束特征半径下的互相关函数。从图中可以看出,随着波束特征半径的减小,会聚波束的互相关函数下降迅速,准直波束正好相反,总体上准直波束比会聚波束下降要快得多。

会聚波束和准直波束入射时,在不同传输距离下

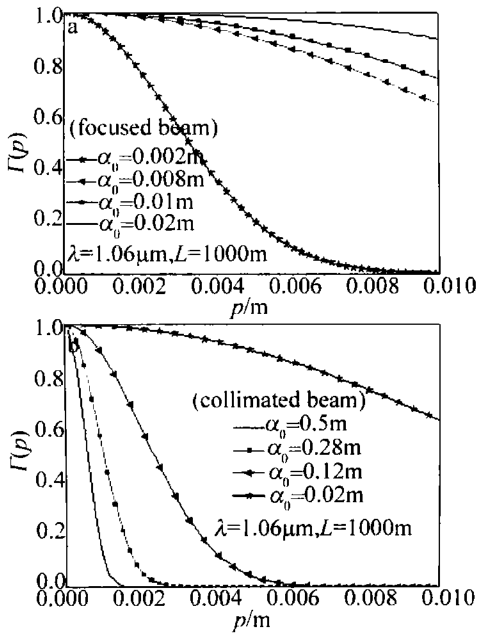

Fig. 2　Change of the speckle intensity correlation function as p under the illumination of the laser beam with different waist

的互相关函数见图 3。从图中可以看出，随着传输距

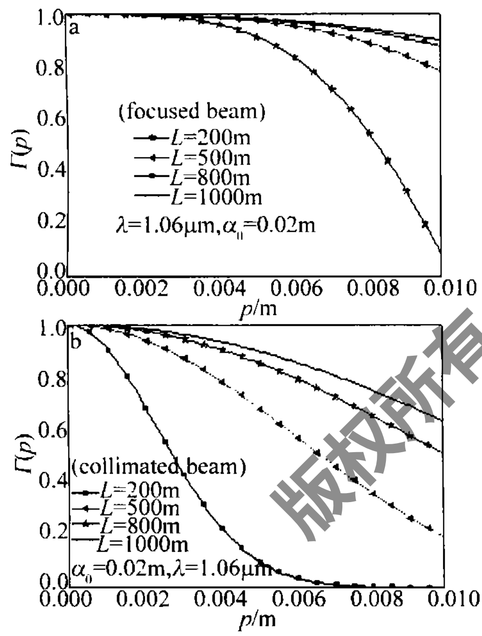

Fig. 3　Change of the speckle intensity correlation function as p under different transmission distance

离的减小，会聚波束与准直波束的互相关函数随之下降，总体上准直波束比会聚波束下降要快得多。

会聚波束和准直波束分别入射时，在不同入射波束特征半径下的协方差函数见图 4。可以看出，随着波束特征半径的减小，会聚波束的协方差函数下降迅速，准直波束正好相反，总体上准直波束比会聚波束下降要快得多。

图 5 中分别给出了会聚波束和准直波束入射时，在不同传输距离下的协方差函数。从图中可以看出，随着传输距离的减小，会聚波束与准直波束的协方差函数

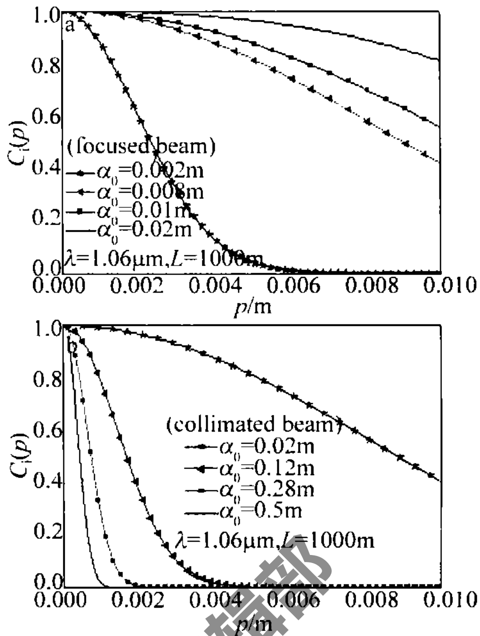

Fig. 4　Change of intensity covariance as p under the illumination of the laser beam with different waist

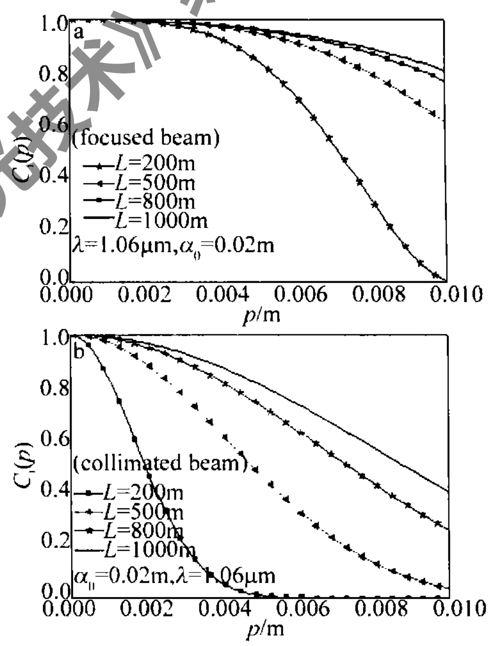

Fig. 5　Change of intensity covariance as p under different transmission distance

随之下降，总体上准直波束比会聚波束下降要快得多。

4　结　论

采用广义惠更斯-菲涅耳原理推导了激光束折叠式双程传输，接收处散斑场的互相关函数、平均散射强度、强度协方差以及强度方差，计算了激光波长为 1.06μm，不同入射波束特征半径、不同传输距离条件下，会聚波束和准直波束的互相关函数和强度协方差函数随接收处两点间距离的变化情况。结果表明，随着波束特征半径的减小，会聚波束的互相关函数下降

（下转第 241 页）

度从 5μm 增加至 10μm，微坑直径从 161μm 降至 134μm。

参 考 文 献

[1] KLIGERMAN Y, ETSION I, SHINKARENKO A. Improving tribological performance of piston rings by partial surface texturing[J]. Journal of Tribology,2005, 127(3):632-638.

[2] RYK G, KLIGERMAN Y, ETSION I, *et al.* Experimental investigation of partial laser surface texturing for piston-ring friction reduction [J]. Tribology Transactions,2005,48(4):583-588.

[3] TOMANIK E. Friction and wear bench tests of different engine liner surface finishes[J]. Tribology International,2008, 41(11):1032-1038.

[4] RYK G, KLIGERMAN Y, ETSION I, *et al.* Experimental investigation of laser surface texturing for reciprocating automotive components [J]. Tribology Transactions,2002,45(4):444-449.

[5] KOVALCHENKO A,AJAYI O,ERDEMIR A, *et al.* The effect of laser surface texturing on transitions in lubrication regimes during unidirectional sliding contact[J]. Tribology International, 2005, 38(3): 219-225.

[6] KRUUSING A. Underwater and water-assisted laser processing: part 2——Etching, cutting and rarely used methods [J]. Optics and Lasers in Engineering,2004,41(2):329-352.

[7] DUBEY A K, YADAVA V. Experimental study of Nd: YAG laser beam machining-an overview [J]. Journal of Materials Processing Technology, 2008,195(1/3):15-26.

[8] ZHANG H, XU W, WANG J. Investigation of a novel hybrid process of laser drilling assisted with jet electrochemical machining[J]. Optics and Lasers in Engineering, 2009, 47(11):1242-1249.

[9] TUNNA L, KEARNS A, O'NEILL W, *et al.* Micromachining of copper using Nd: YAG laser radiation at 1064,532 and 355nm wavelengths[J]. Optics & Laser Technology, 2001, 33(3):135-143.

[10] LI L, CHARA C. Chemical assisted laser machining for the minimisation of recast and heat affected zone[J]. CIRP Annals-Manufacturing Technology, 2004, 53(1):175-178.

[11] LIU D H. Laser drilling[J]. Laser Journal,1992,13(3):151-155 (in Chinese).

(上接第237页)

迅速，准直波束正好相反，总体上，准直波束比会聚波束下降要快得多。在不同传输距离下时，随着传输距离的减小，会聚波束与准直波束的互相关函数随之下降，总体上，准直波束比会聚波束下降要快得多。强度协方差函数的变化规律与互相关函数的变化规律基本一致。这样，激光光束特点以及对应的传输距离对激光雷达目标探测及识别散斑的效应的影响就有了理论依据，这对激光雷达目标成像过程中散斑噪声的消除有一定的应用价值。

参 考 文 献

[1] DAINTY J C. Laser speckle and related phenomena[M]. Springer: Berlin Press,1975: 10-77.

[2] DAINTY J C. Progress in optics XIV [M]. North-Holland: Amsterdam Press,1976:1-70.

[3] BRIERS J D. Laser doppler and time-varying speckle: Reconciliation [J]. Journal of the Optical Society of America,1996,13(2):345-350.

[4] YANG H, YANG X L. Analysis of characteristics of light propagation through clouds and Monte Carlo simulation[J]. Laser Technology, 2008,32(5):477-479(in Chinese).

[5] LI Y Y, SUN D S. Study of clouds multiple scattering influences on lidar measurement[J]. Laser Technology,2008,32(6):611-638(in Chinese).

[6] GUO G J, SHAO Y. Rough surfaces induced speckle effect s on detection performance of pulsed laser radar[J]. Acta Physica Sinica, 2004,53(7):2089-2093(in Chinese).

[7] GUO G J, SHAO Y. Statistical properties of the back-scattered signal from ground in laser radar applications [J]. Acta Physica Sinica, 2002,51(2):228-233(in Chinese).

[8] WANG M J. Statistical characteristics of the laser scattering intensity's covariance on the horizontally moving and rotating targets[J]. Infrared and Laser Engineering,2008,37(5):810-813(in Chinese).

[9] GUO G J, LI Sh K, TAN Q. Statistical properties of laser speckles generated from far rough surfaces[J]. International Journal of Infrared and Millimeter Waves,2001,22(8):1177-1191.