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研究论文

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基于相位校正的分布式光纤大探测孔径多维定位

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摘要 分布式光纤多维定位对于周界安防、地震速报、目标跟踪等应用有着十分重要的意义。地震源或空气中声源波长与光纤探测孔径为同一量级，光纤传感通道无法对波场进行密集采样，难以实现精准定位。为了消除光纤大探测孔径对目标源多维定位的影响，提出了一种基于相位校正的分布式光纤大探测孔径多维定位方法。首先建立了光纤传感通道对目标源的响应模型，分析了光纤阵列相位误差来源，根据目标源预估计位置对光纤阵列采样信号进行相位校正；然后对校正后的信号进行空间谱估计并采用多次迭代降低定位误差。现场初步实验结果表明，所提方法能够有效实现对目标源的二维定位，定位结果与实际测量位置的误差为 1.1 m。该方法可用于既有光缆，提高了分布式光纤传感系统在实际应用中的定位能力。

关键词 光纤光学；分布式声波传感；阵列信号处理；目标定位

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1 引言

分布式光纤声波传感（DAS）技术是一种新型传感技术，利用光纤中背向瑞利散射的相干效应[1-4]，可以监测光纤沿线任意位置的物理量变化。DAS 技术凭借其可动态在线监测、大范围密集测量、方便布设免维护等独特优势得到了广泛应用。近年来，铁路安全监控[5]、周界安防[6]、地震监测[7]等实际应用对目标源多维定位提出了更高要求。然而，大多数 DAS 技术只能提供目标源沿光纤轴向的一维位置信息，缺少目标源与光纤横向距离信息，无法实现多维空间定位，阻碍了 DAS 技术发挥实用价值。因此，目标源多维定位是当前分布式光纤传感应用中亟待解决的问题。

当前的目标源定位方法可以分为两大类：一是基于到达时间差（TDOA）的目标源定位方法，二是基于阵列信号处理（ASP）的目标源定位方法。基于到达时间差的定位方法原理简单，计算量小，实时性好，是应用最广的技术之一。然而，该算法定位精度受时延估计影响较大，时延估计存在误差时定位精度较差。实际应用中需要对算法做进一步优化来满足定位精度的需求，如 Ding 等[8]提出了一系列 TDOA 优化方法对与光纤横向距离大于 60 m 的振动源实现了精准定位，定位误差小于 5 m。基于阵列信号处理的定位算法已被广泛应用于雷达、声呐等领域，该类算法又包括波束形成和空间谱估计两种。波束形成技术是通过多个传感阵元以特定的空间排列接收和分析目标源的位置信息，根据传感阵列在各方向的输出功率判断目标源来向。Fang 等[9]利用特殊设计的超灵敏光纤声学传感器，结合相位变换加权可控响应功率（SRP-PHAT）方法实现了无人机的轨迹监测和角度估计，测向方位角误差约 1.47°；Muñoz 等[10]通过稀疏波束形成空间滤波提高信噪比，利用改进的双曲三角法和 8.63 km 的光纤阵列实现了定位误差约为 3.06 m 的振动源定位。波束形成方法在实际应用中往往要求高信噪比和大阵列孔径，且需要一些环境噪声和目标源的先验知识，而这些先验知识很难准确获得。空间谱估计技术是另一种基于阵列信号处理的定位算法，该算法利用信号子空间和噪声子空间正交的特性，具有很高的估计精度和角度分辨力。Cao 等[11]利用多重信号分类（MUSIC）空间谱估计算法实现了误差为 0.7 m 的水下近场目标源定位，目标信号波长和单信道探测孔径之比为 25∶1；Liang 等[12]将光纤密集缠绕在圆柱体空腔结构压缩了光纤探测孔径，实现了空气介质中声源二维和三维定位，目标信号波长和压缩后单信道探测孔

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径之比为100:1。这些工作中信道探测孔径远小于目标信号波长，可以被视为点式传感器。然而，DAS受系统空间分辨率限制，基于既有光缆的单信道探测孔径在10 m量级，与目标信号波长相当，难以直接利用空间谱估计方法来实现目标源多维定位。另外，压缩信道探测孔径需要特殊设计的传感单元，结构复杂，不便于大规模推广应用。

为了解决目标源多维定位存在的上述问题，本文提出一种基于相位校正的DAS多维定位方法。通过分析光纤传感通道对目标源的响应原理及阵列相位误差来源，提出了一种阵列相位校正方法，并通过实验验证了所提定位方法的有效性。现场实验结果表明，经过阵列相位校正，DAS探测相位可以直接利用空间谱估计方法得到目标源定位，且经过多次迭代空间谱估计算法和校正相位，定位结果的距离误差显著下降。迭代次数增加至3次时定位结果达到最小误差1.1 m。所提方法解决了TDOA方法定位精度差的问题和大探测孔径对空间谱估计算法的影响，有助于提升DAS实际应用中利用既有光缆实现定位的能力。

2 基本原理

2.1 DAS传感通道响应和阵列相位偏差

DAS将一根光纤等效为一组传感器阵列，如图1所示，每个传感通道的长度为Δl，两个相邻传感通道间距为d，传感阵列孔径为L。DAS传感通道对外界的响应要考虑波场在传感通道内的梯度分布。不同于点式传感器，DAS传感通道的探测相位为传输波产生的应变梯度在传感通道范围内的积分[1,12]。在近场条件下[13]，传感通道对目标源的响应如图1所示，第i个传感通道的探测相位可以表示为

$$\varphi_{\tau_i}(R_1,\theta_1)=\int_{(i-1)d}^{(i-1)d+\Delta l}\frac{1}{\sqrt{R_1^2+x^2-2R_1x\sin\theta_1}}\exp\left(-\mathrm{j}k\sqrt{R_1^2+x^2-2R_1x\sin\theta_1}\right)\mathrm{d}x, \tag{1}$$

式中：R_1和θ_1分别为目标源相对于第一个传感通道初始位置$x_{1,0}$的距离和方位角；k为目标信号的波数。

DAS等效阵列的探测相位可以像点式传感阵列一样表示为向量形式$\left[\varphi_{\tau_1},\varphi_{\tau_2},\cdots,\varphi_{\tau_N}\right]$，其中$N$为传感通道的个数。然而，等效相位点$\tau_i$在每个传感通道的位置无法确定，不能直接采用点式传感器的空间谱估计方法来获得高精度的目标源定位。

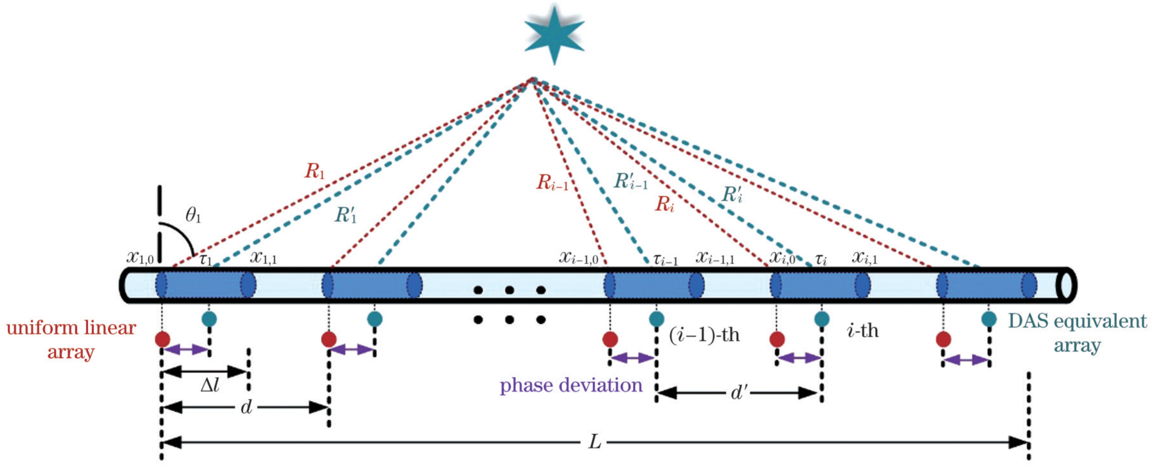

图1 DAS目标源近场响应示意图

Fig. 1 Schematic diagram of DAS target source response in near field

由于均匀线性阵列（ULA）结构简单，阵列参数方便确定，空间谱估计中通常选取ULA为接收阵列。为了将DAS光纤阵列映射为一个分布式ULA，选取每个传感通道的初始位置作为ULA的传感单元，则第i个ULA传感单元的相位可以表示为

$$\varphi_{x_{i,0}}(R_1,\theta_1)=\frac{1}{\sqrt{R_1^2+(i-1)^2d^2-2R_1(i-1)d\sin\theta_1}}\exp\left(-\mathrm{j}k\sqrt{R_1^2+(i-1)^2d^2-2R_1(i-1)d\sin\theta_1}\right)。 \tag{2}$$

由式(1)和式(2)，第i个DAS传感通道等效探测相位与第i个ULA传感单元相位的偏差可以表示为

$$\delta\varphi_i(R_1,\theta_1)=\mathrm{angle}\left[\varphi_{\tau_i}(R_1,\theta_1)\right]-\mathrm{angle}\left[\varphi_{x_{i,0}}(R_1,\theta_1)\right]。 \tag{3}$$

据此可将DAS等效阵列的探测相位校正为ULA相位，进而直接利用传统的空间谱估计方法实现目标源高精度定位。

2.2 阵列相位校正和目标源定位

由式(3)可知，相位偏差$\delta\varphi_i$是R_1与θ_1的函数，因此阵列相位校正需要首先预估计目标源的位置$(\hat{R}_1,\hat{\theta}_1)$。本文所提方法流程主要包括位置预估计、阵列相位校正和高精度定位三个主要处理步骤。其中，位置预估计是指利用不同传感通道的相位时延，通过TDOA方法预估目标源位置；阵列相位校正是指根据目标源预估计位置计算探测相位偏差并进行校正；高精度定位是指对相位校正后的信号利用MUSIC方法进行多维定位。

为了获得目标源的预估计位置，本文采用了TDOA方法[14]。假设光纤第一个传感通道的起始位置为参考点，则第i个传感通道到目标源位置之间的距离可以近似表示为

$$R_i=\sqrt{R_1^2+(i-1)^2d^2-2(i-1)R_1d\sin\theta_1}\text{，}\tag{4}$$

第i个光纤传感通道相对于参考点的信号时延可以表示为

$$\delta t_{(1,i)}=(R_1-R_i)/v\text{，}\tag{5}$$

式中：v为目标源传输波的速度。

TDOA需要至少三个传感通道信号延迟参与定位。由式(4)和式(5)可得到目标源的一个预估计位置$(\hat{R}_{1i},\hat{\theta}_{1i})$。为了提高预估计位置精度，选取$N$个传感通道组合参与TDOA，最后的预估计位置$(\hat{R}_1,\hat{\theta}_1)$取每个传感通道组合TDOA估计结果的平均值，即$\hat{R}=\left(\sum_{i=1}^{N}\hat{R}_{1i}\right)/N,\hat{\theta}=\left(\sum_{i=1}^{N}\hat{\theta}_{1i}\right)/N$。

利用预估计位置$(\hat{R}_1,\hat{\theta}_1)$根据式(3)进行阵列相位校正，校正后的阵列相位可表示为$\Phi(t)=[\varphi_{\tau_1}-\delta\varphi_1,\varphi_{\tau_2}-\delta\varphi_2,\cdots,\varphi_{\tau_N}-\delta\varphi_N]$。将校正后的信号用MUSIC方法[15]进行空间谱估计，其算法原理是将阵列采样数据$\Phi(t)$的协方差矩阵$\mathfrak{R}$进行特征值分解，分离出信号子空间$\boldsymbol{U}_{\mathrm{S}}$和噪声子空间$\boldsymbol{U}_{\mathrm{N}}$，利用阵列方向向量$\boldsymbol{a}(r,\theta)$与噪声子空间$\boldsymbol{U}_{\mathrm{N}}$正交的特性，构造空间谱函数$P_{\mathrm{MUSIC}}(r,\theta)$进行谱峰搜索，对应的极大值为目标源估计位置$(R_1,\theta_1)$。值得一提的是，当目标源在近场条件下时，谱峰搜索需要遍历角度和距离二维解空间，空间谱函数表示为

$$P_{\mathrm{MUSIC}}(r,\theta)=\frac{1}{\boldsymbol{a}(r,\theta)^{\mathrm{H}}\boldsymbol{U}_N\boldsymbol{U}_N^{\mathrm{H}}\boldsymbol{a}(r,\theta)}\text{，}\tag{6}$$

其中，均匀线性阵列的方向向量$\boldsymbol{a}(r,\theta)$可以表示为

$$\boldsymbol{a}(r,\theta)=\left[\frac{1}{R_1}\mathrm{e}^{-\mathrm{j}kR_1}\quad\frac{1}{R_2}\mathrm{e}^{-\mathrm{j}kR_2}\quad\cdots\quad\frac{1}{R_M}\mathrm{e}^{-\mathrm{j}kR_M}\right]^{\mathrm{T}}\text{。}\tag{7}$$

将得到的目标源定位(R_1,θ_1)作为预估计位置$(\hat{R}_1,\hat{\theta}_1)$继续进行阵列相位校正，校正后的信号再次用MUSIC方法进行空间谱估计，多次迭代，可以提高目标源的定位精度，最终得到高精度的目标源定位。

2.3 多维定位误差

为了定量描述所提方法的定位精度，将目标源估计位置(R_1,θ_1)转换为光纤轴向和光纤垂向两个方向的距离，计算与实际位置(R_0,θ_0)距离的RMSE。多维定位的均方根误差R_{rmse}可以表示为

$$R_{\mathrm{rmse}}=\sqrt{(R_1\cos\theta_1-R_0\cos\theta_0)^2+(R_1\sin\theta_1-R_0\sin\theta_0)^2}\text{。}\tag{8}$$

将R_{rmse}作为定位精度的评价指标，该指标描述了估计位置和实际位置在光纤轴向和光纤垂向两个维度的距离偏差[16]。R_{rmse}的值越小，表示目标源估计位置距离实际位置越近，定位精度越高。

3 实验结果

采用相位敏感光时域反射计(Φ-OTDR)的DAS技术进行验证实验，如图2(a)所示。现场测试使用的光缆长度约为50 m，埋于地下0.5～0.8 m。光缆由支

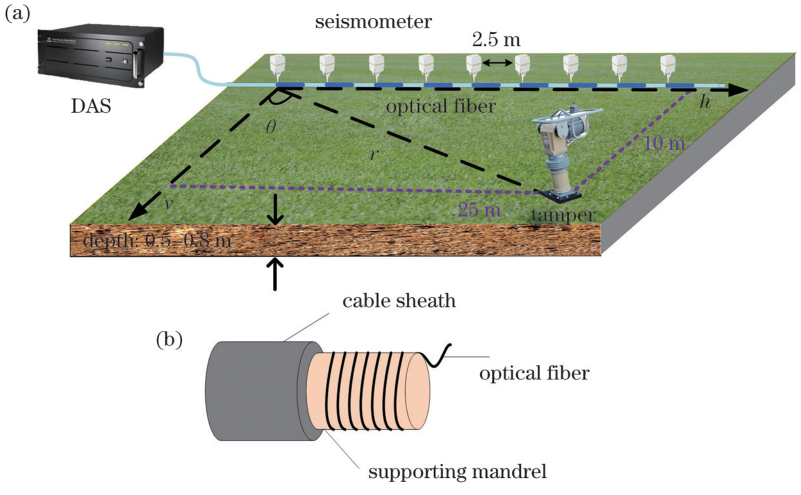

图2 验证实验。(a)目标源定位实验设置；(b)光缆结构示意图

Fig. 2 Confirmation experiment. (a) Experiment setup of target source localization test; (b) structure of optical cable

撑芯轴、专用抗弯曲光纤(芯径80 μm,外径165 μm)和光缆护套组成,如图2(b)所示。光纤按1∶7.5的比例缠绕在光缆上,缠绕间隙约为1 cm,该光缆可通过绕包机等自动化设备进行制备。10 m的光纤空间差分长度对应光缆1.33 m的传感通道,2.5 m的传感通道间距对应18.75 m的光纤。DAS系统脉冲宽度为20 ns,对应的空间分辨率为2 m。探测脉冲的重复频率为5 kHz。在近场条件下[13],将固定振动频率的打夯机作为目标源进行扰动测试,其振动频率为10 Hz。选取光纤第一个传感通道的起始位置作为参考点,打夯机与探测光纤的垂向距离为10 m,沿光纤轴向距离为25 m;相对参考点的直线距离r为26.9 m,方位角θ为68°。

对DAS采集的信号进行10 Hz窄带滤波和归一化预处理,不同传感通道的信号延迟如图3所示。将两个地震计(SmartSolo)间隔10 m放置,用夯土机在两个地震计的延长线上施加扰动,利用广义互相关函数(GCC)方法[17]估计两个地震计探测信号时延,计算得到实验场地的地震波传播速度约为110 m/s。为了得到目标源预估计位置,分析了传感通道数目和位置对TDOA估计精度的影响。选择不同数目的传感通道参与TDOA估计,预估计位置误差$R_{\rm rmse}$随传感通道数目变化呈现随机性,如图4所示。另外选择相同数目、不同位置的传感通道参与TDOA估计,结果也相差较大,如表1所示。这与实验场地传输介质均匀性[18]或光缆的布设状态有关。实验中选择多个传感通道组合参与TDOA估计,每个组合包含3个不同位置的传感通道,最终得到的目标源预估计位置为多个传感通道组合TDOA估计的平均值,目标源预估计位置为(29.73 m, 58.11°)。

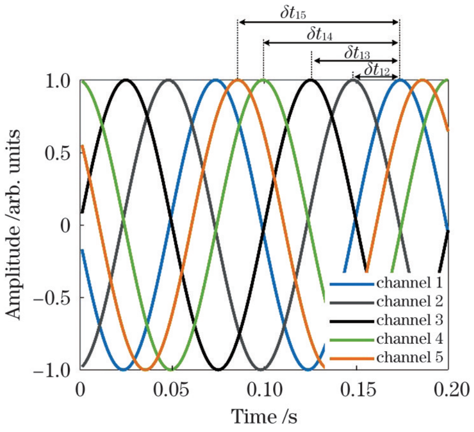

图3　不同传感通道间的时间延迟

Fig. 3　Delay among different sensing channels

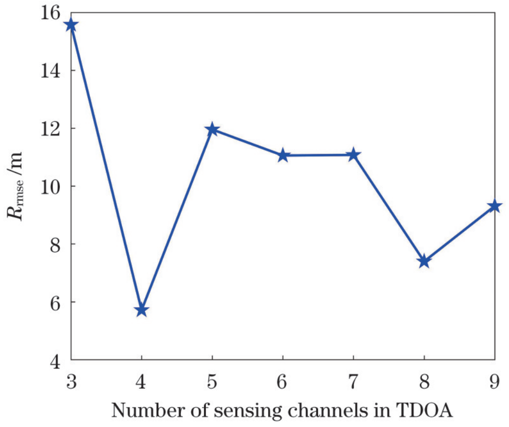

图4　不同数目的传感通道TDOA预估计结果

Fig. 4　TDOA pre-estimation results for different numbers of sensing channels

表1　3个不同传感通道TDOA预估计结果

Table 1　TDOA pre-estimation results of three different sensing channels

Sensing channels group	Distance r /m	Angle θ /(°)
[1,2,3]	9.6490	65.8268
[1,3,5]	16.9083	61.4332
[1,4,7]	19.3817	64.6476
[1,5,9]	40.0215	53.4207
[1,7,9]	37.7996	54.2196
[1,8,9]	54.6337	49.0911
Average	29.7323	58.1065

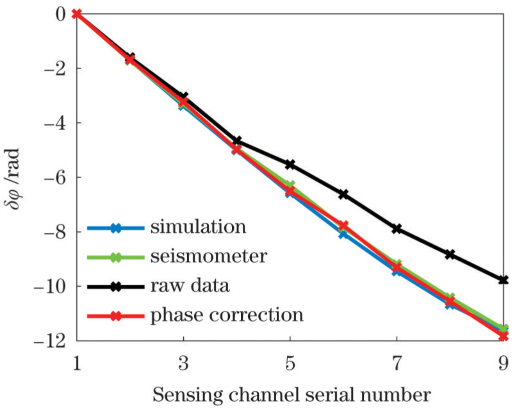

图5　传感阵列相移

Fig. 5　Phase shift of sensing array

根据目标源预估计位置对DAS阵列采集的信号进行相位校正。图5中黑色曲线和红色曲线对比了相位校正前后的DAS阵列相移,蓝色曲线根据式(2)仿真了DAS阵列相位校正后的相移,绿色曲线为地震计阵列测量相移。结果显示,校正前的DAS阵列相移(黑色曲线)与点式传感器阵列相移(蓝色曲线)之间存在偏差,而校正后的DAS阵列相移(红色曲线)与点式传感器阵列相移相比有很好的一致性,说明阵列相位校正方法有效地补偿了DAS探测孔径带来的相位偏差。

利用MUSIC算法[15]对DAS阵列采集的信号进行空间谱估计,图6对比了DAS阵列相位校正前后的定

位结果。结果显示：相位校正前的阵列信号受大探测孔径影响，空间谱估计有多个杂散峰，无法得到准确的目标源位置估计；相位校正后的阵列信号空间谱估计能够得到一个清晰的谱峰，实现了目标源位置估计。该实验结果说明本方法消除了光纤探测孔径对分布式光纤定位的影响，能够将光纤传感阵列等效为点式传感器阵列，进而可由校正后的DAS信号利用空间谱估计算法实现目标源定位。

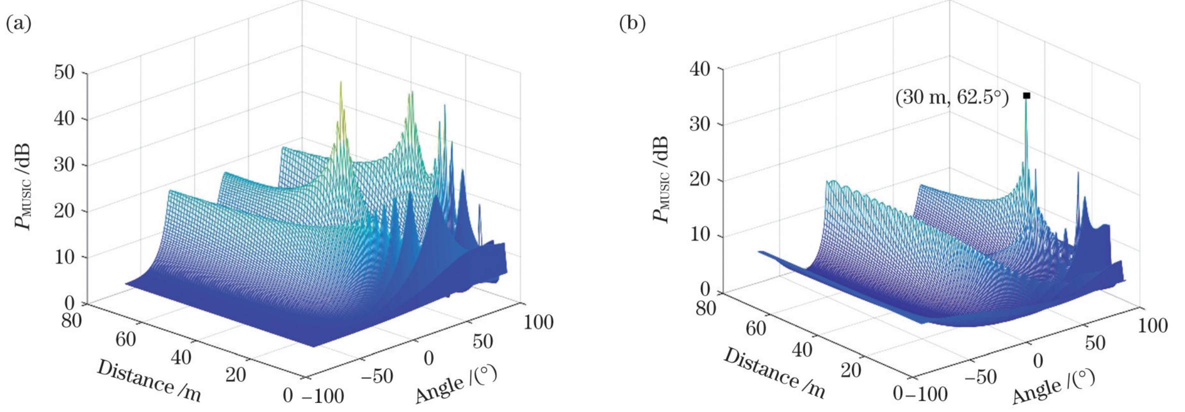

图 6　空间谱估计。(a)相位校正前；(b)相位校正后

Fig. 6　Spatial spectrum estimation. (a) Before phase correction; (b) after phase correction

将空间谱估计得到的结果作为预估位置继续用于阵列相位校正和高精度定位，目标源定位误差随MUSIC算法迭代次数的变化如图7所示。结果显示：随着MUSIC算法迭代次数的增加，经过校正的DAS阵列相移与ULA相移之间的偏差越来越小，目标源定位误差逐步减小；当MUSIC算法迭代次数增加至3次时，定位误差趋于稳定，此时随着MUSIC算法迭代次数的增加定位结果不再发生变化，达到最优化的定位结果，最小距离误差为1.1 m。此外，可以通过增大阵列孔径[10]、阵型校正[19]、优化空间分辨率[20]等方法，进一步提升定位精度。

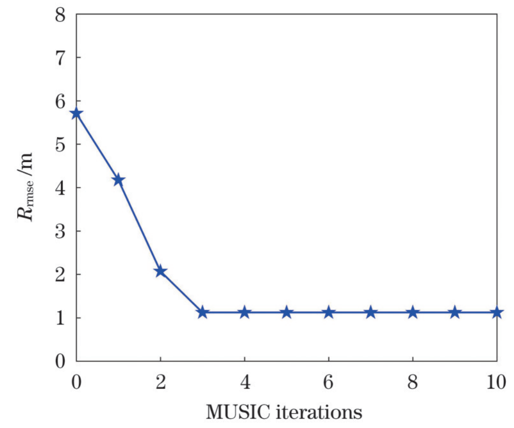

图 7　R_{rmse}随MUSIC迭代次数的变化

Fig. 7　Change of R_{rmse} with MUSIC iterations

经过多次空间谱算法迭代，最终的目标源空间谱估计定位结果如图8(a)所示，定位结果相对参考点的直线距离r为28 m，方位角θ为67.5°。同时将目标源位置转换到直角坐标系内，图8(b)比较了目标源现场位置、预估计位置及定位结果。定位结果与现场位置接近，说明该方法有效地消除了光纤探测孔径对空间谱估计算法的影响，能够在目标信号波长与探测孔径相差较小的情况下实现目标源多维定位；同时相较于TDOA算法得到的预估计位置，所提方法大幅降低了定位误差。

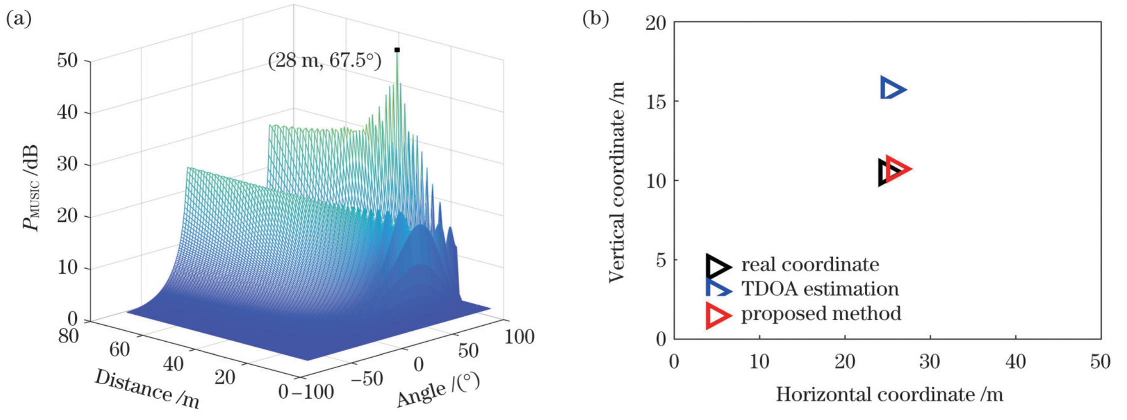

图 8　目标源定位结果。(a)空间谱估计；(b)直角坐标系中的位置

Fig. 8　Localization results of target source. (a) Spatial spectrum estimation; (b) locations in rectangular coordinate system

本方法弥补了TDOA算法定位精度差的不足，而且解决了空间谱估计在大探测孔径情况下不适用的问题。如表2所示，在波长孔径比（WAR）为8∶1的情况下，实现了相对误差4.09%的定位结果，有望利用既有光缆实现WAR大于8∶1以上的目标源定位。该方法的定位性能边界由许多因素决定。可实现的最远探测距离受限于两个方面：一是可探测目标源的距离r和光纤阵列长度L要满足近场关系[13]，即$r < 2L^2/\lambda$，其中λ为目标源信号波长；二是信噪比，由DAS系统灵敏度和目标源共同决定。光纤阵列长度由阵元数量、阵元间距及阵元孔径决定。阵元数量多、光纤阵列长度长有助于提高定位精度，但需要考虑信噪比和运行时间的限制。阵元间距应满足$d \leqslant \lambda/2$且大于系统脉冲宽度。针对周界安防、地震监测等不同应用场景，光纤阵列长度在几十米至几十千米量级不等。

表2　所提算法与其他算法定位结果对比

Table 2　Comparison among proposed method and existing methods

Method	Ref.	Layout requirement	WAR	Relative error /%
TDOA optimization	[8]	—	5∶1	8.30
Sparse beamforming (ASP)	[10]	Large array aperture (8.63 km)	7∶1	0.83
MUSIC (ASP)	[12]	Wound fiber	100∶1	34.48
MUSIC (ASP)	[11]	—	25∶1	3.14
Proposed	—	—	8∶1	4.09

4 结　　论

本文提出了一种分布式光纤目标源多维定位方法，消除了光纤传感信道大探测孔径对空间谱估计算法的影响，解决了既有光缆无法对声源或地震源准确定位的问题。实验结果表明，TDOA方法对地震源定位精度较差，但可以用于位置预估计。DAS采集信号根据目标源预估计位置进行相位校正，校正后的DAS阵列相移与点式传感器阵列相移有很好的一致性，能够直接通过空间谱估计方法获得目标源多维定位。通过多次迭代空间谱估计算法和校正相位，定位误差显著下降，最小定位误差为1.1 m，实现了目标源高精度多维定位。

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Distributed Optical Fiber Multi-Dimensional Localization with Large Detection Aperture Based on Phase Correction

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Abstract

Objective Distributed acoustic sensing (DAS) has been widely applied in railway safety monitoring, perimeter security, seismology, and other fields. The high precision target source multi-dimensional localization is important for these applications. However, most implementations of DAS provide the position of detected sources as a function of distance within the one-dimensional axial space along the sensing fiber, and the transversal distance between the detected sources and the sensing fiber is unclear, which hinders the process of DAS practical applications.

The current target source localization methods can be divided into two categories: one is based on time difference of arrival (TDOA) algorithm, and the other is based on array signal processing (ASP) method. The ASP methods include beamforming and spatial spectrum estimation. The positioning accuracy of TDOA algorithm is poor, and the beamforming method often requires high signal-to-noise ratio, large array aperture, and *a priori* knowledge of the environmental noise and target source which is difficult to obtain accurately.

The spatial spectrum estimation method is based on the orthogonal property of signal subspace and noise subspace, and has high estimation accuracy and angle resolution. Cao *et al.* used multiple signal classification (MUSIC) algorithm to locate the underwater near-field target source with an error of 0.7 m, and the ratio of signal wavelength to detection aperture was 25∶1. Liang *et al.* realized sound source location in the air medium by wrapping the optical fiber densely around the cylindrical cavity structure, and the ratio of signal wavelength to detection aperture was 100∶1. In these studies, the channel detection aperture is much smaller than the signal wavelength and sensor can be regarded as a point sensor. However, DAS is limited by the spatial resolution, and the single-channel detection aperture of the existing optical cable is 10 m, which is comparable with the target signal wavelength, so it is difficult to directly use the spatial spectrum estimation method to achieve multi-dimensional target source localization. In addition, the channel aperture compression requires a special design of the sensor unit, and the structure is complex, so it is not easy for large-scale application.

In this paper, we propose a multi-dimensional target source localization method for DAS by correcting fiber array phase deviation. The proposed method can eliminate the influence of DAS large detection aperture, and the high precision target source multi-dimensional localization can be obtained by common optical cables.

Methods To eliminate the influence of DAS large detection aperture, the phase correction method is proposed. First, the DAS sensing channel response is analyzed and the phase deviation between DAS equivalent array and distributed uniform linear array (ULA) is calculated. Then, the TDOA algorithm is used to obtain pre-estimation location of target source for array phase correction. The effects of sensing channel number and position on TDOA estimation are studied. Multiple sensing channel groups are used for TDOA estimation, and the final pre-estimation location is the average value of estimation results of all those groups. After that, the corrected signal is used for spatial spectrum estimation by MUSIC method, and a higher precision target source localization can be obtained. Then, the array phase is corrected according to the MUSIC estimation and the MUSIC algorithm is iterated. The effect of MUSIC algorithm iterations on the root-mean-square error (RMSE) is studied.

Results and Discussions The proposed method can realize multi-dimensional localization of target source, and the preliminary experiment verifies that the minimum RMSE of localization result is 1.1 m. The proposed target source localization method contains three major processing stages: localization pre-estimation, array phase correction, and high precision localization. The pre-estimation accuracy of TDOA is uncorrelated with the number of sensing channels, and the TDOA pre-estimation of the sensing channels at different locations is quite different, which may be related to the uneven transmission medium and inconsistent cable deployment conditions. Multiple sensing channel groups are used for TDOA pre-estimation, and the final pre-estimation location is the average value. The result of TDOA pre-estimation is (29.7 m, 58.1°), and the RMSE is 5.7 m. The DAS detected phase is corrected according to the pre-estimation location, and the corrected DAS detected phase is used for spatial spectrum estimation by MUSIC method to obtain a multi-dimensional target source localization. In the experiment, the RMSE of localization result can be effectively reduced by increasing the iterations of MUSIC algorithm. When the iteration number is increased to three, the RMSE reaches a minimum value, and a high precision target source multi-dimensional localization result can be obtained. The final localization result is (28 m, 67.5°), and the RMSE is 1.1 m. The proposed method enables that the detected signal of DAS sensing channel can be accurately located using ASP method directly. Moreover, compared with TDOA pre-estimation, the localization accuracy is greatly improved.

Conclusions In the present study, a multi-dimensional target source localization method for distributed acoustic sensing is proposed, which is suitable for common communication fiber in a wide range of applications. Due to the large detection aperture of DAS, there is a phase deviation between DAS equivalent array and uniform linear array. The DAS detected phase is corrected by the proposed phase correction method, and the target source can be accurately located using ASP method without shrinking the sensing channel aperture. The principle of array phase deviation is analyzed and the feasibility of the proposed localization method is preliminarily verified. Compared with previous DAS target multi-dimensional localization studies, the proposed method does not require special structures to wind the optical fiber and shrink the sensing channel aperture, greatly simplifying the system complexity. The RMSE of localization result can be effectively reduced by increasing the iterations of MUSIC algorithm. The proposed method provides a simple and effective means for DAS target source multi-dimensional localization. It is believed that the proposed method will improve DAS localization performance in actual applications, such as intrusion detection and earthquake monitoring.

Key words fiber optics; distributed acoustic sensing; array signal processing; target localization