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# A bistatic sodar for precision wind profiling in complex terrain

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1     **A bi-static sodar for precision wind profiling in**  
2                                   **complex terrain**

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## Abstract

A new ground-based wind profiling technology, a scanned bistatic sodar, is described. The motivation for this design is to obtain a ‘mast-like’ wind vector profile in a single atmospheric column extending from the ground to heights of more than 200 m. The need for this columnar profiling arises from difficulties experienced by all existing lidars and sodars in the presence of non-horizontally-uniform wind fields, such as found generically in complex terrain. Other advantages are described, including improved signal strength from turbulent velocity fluctuations, improved data availability in neutral atmospheric temperature profiles, improved rejection of rain echoes, and improved rejection of echoes from fixed (non-atmospheric) objects. Initial brief field tests indicate that the scattered intensity profile agrees with theoretical expectations, and bistatic sodar winds are consistent with winds from standard mast-mounted instruments.

33

## 34 1. Introduction

35 In the last few years the use of surface-based remote sensing for wind energy has come to  
36 be the preferred method of obtaining wind profiles in the vicinity of large turbines  
37 (Upwind, 2011). The useful instruments comprise two types: lidars, which use laser light  
38 scattered from naturally occurring atmospheric particulates; and sodars, which use  
39 audible sound scattered from atmospheric turbulence (Emeis, 2010). Wind components  
40 are sensed through the Doppler frequency shift of the light or sound caused by the  
41 movement of the target particles or turbulence in the radiated volume above the  
42 instrument. Although continuous systems exist, such as the ZephIR lidar (Natural Power,  
43 2010), nearly all lidars and sodars are pulsed, and the position in the atmosphere from  
44 which the scattering occurs is determined by time-of-flight of the returning signal. Both  
45 the optical and the acoustic instruments are faced with the challenge of low received  
46 signal levels compared with background noise.

47 All commercial versions of lidars and sodars are ‘mono-static’, by which is meant  
48 that the transmitter and receiver are co-located, and energy from the scattering volume is  
49 scattered through 180°. This has the advantage of compactness, and the instruments are  
50 more readily deployed in the field because the single instrument package is self-  
51 contained. However, Doppler shift from a moving target requires that there be a  
52 component of the motion either in the transmitter-target line or in the target-receiver line.  
53 This means that, to sense three Cartesian coordinate wind components, at least three

54 beams of light or sound have to be transmitted upward and at least two of these must be  
 55 non-vertical.

56 For a sound beam transmitted in the direction  $\mathbf{T}$  and scattered energy received  
 57 from direction  $\mathbf{R}$ , the measured Doppler shift can be written in scaled form as

$$58 \quad \mu = -\frac{c \Delta f}{2 f_T} = \frac{1}{2} \left( \frac{\mathbf{T}}{|\mathbf{T}|} + \frac{\mathbf{R}}{|\mathbf{R}|} \right) \cdot \mathbf{V} \quad (1)$$

59 where  $c$  is the speed of sound,  $\Delta f$  the Doppler shift,  $f_T$  the frequency of the transmitted  
 60 sound, and  $\mathbf{V} = (u, v, w)$  the wind velocity vector (Bradley, 2007). In the mono-static  
 61 case,  $\mathbf{T} = \mathbf{R}$ , and three measurements would give

$$63 \quad \mu_b = u_b \sin \theta_b \cos \phi_b + v_b \sin \theta_b \sin \phi_b + w_b \cos \theta_b \quad b = 1,2,3 \quad (2)$$

64 where  $\theta_b$  and  $\phi_b$  are the zenith and azimuth angles of the  $b^{\text{th}}$  beam direction. If  $u_b = u$ ,  $v_b =$   
 65  $v$ , and  $w_b = w$  for  $b = 1,2,3$ , then the equations can be solved for the Cartesian wind  
 66 components  $u$ ,  $v$ , and  $w$ .

#### 68 *a. Wind estimation errors in complex terrain*

69 Solving (2) for  $(u, v, w)$  requires the assumption of horizontal homogeneity of the wind  
 70 field, which is probably sufficiently valid above flat terrain, but seldom valid over  
 71 complex terrain. The  $u$  components  $u_1$ ,  $u_2$ , and  $u_3$ , for example, are in general different  
 72 because they are the values of the  $u$  component in three different volumes. Generally it is  
 73 the components directly above the instrument which are required, since this gives ‘mast-  
 74 like’ wind profiles. Bradley (2008) has developed a potential flow model for estimating  
 75 remote sensing errors over a bell-shaped hill. The fractional error in estimating the wind  
 76 speed for a 3-beam sodar sited on the crest of the hill, with beam 1 facing downwind, is

77 
$$\frac{\hat{V}}{V_0} - 1 \approx -2\eta^2 \frac{z}{H} \approx -5G_{\max}^2 \frac{z}{H} \quad (3)$$

78  
 79 where  $z$  is the height of the sensing volume above the hill crest,  $H$  is the hill height,  $\eta$  is  
 80 the ratio of hill height to hill half-width at half-height, and  $G_{\max}$  is the maximum gradient  
 81 of the bell-shaped hill. The fractional error is negative because the maximum speed is  
 82 directly above the instrument in this case, and the beam directed in the direction of the  
 83 flow underestimates. So for a hill of maximum gradient 0.1, and with  $z = H$ , a 5% error in  
 84 wind estimation is predicted. This is comparable to the error measured in practice in  
 85 complex terrain (Behrens et al., 2011, Bradley et al., 2011), and is unacceptably high for  
 86 wind energy applications. Note that this error is generic across all sodars and lidars, and  
 87 is insensitive to the beam zenith angle  $\theta$ .

88 Bingol et al. (2009) have proposed a correction method using a flow model  
 89 (Wasp). However, the reason for doing the *in situ* remote sensing measurements is  
 90 because the available flow models are considered insufficiently reliable in complex  
 91 terrain. This raises the question of whether correcting inaccurate measurements using  
 92 inaccurate models is a useful approach.

93 One approach to the distributed sensing volume problem is to expand the wind  
 94 component variations in the horizontal using Taylor series (Bradley et al., 2011). For  
 95 example, the  $u$  component expands as

96 
$$u(\mathbf{T}) = u(\mathbf{Z}) + [(\mathbf{T} - \mathbf{Z}) \bullet \nabla] u|_{\mathbf{Z}} + \dots \quad (4)$$

97 The correct component above the instrument is  $u(\mathbf{Z})$ , and the error term contains  
 98 the vector distance  $\mathbf{T} - \mathbf{Z}$  horizontally between the sample volume and the point above the  
 99 instrument. Note that this expansion *does not* include  $\mathbf{R}$ . What this means is that,

100 provided transmission is vertical (i.e.  $\mathbf{T} = \mathbf{Z}$ ), there are no corrections due to horizontal  
101 wind shear. But from (1), a mono-static instrument with  $\mathbf{T} = \mathbf{Z}$  can only sense  $\mathbf{Z} \bullet \mathbf{V} = w$ .  
102 The main rationale for the work described in this publication is to describe a remote  
103 sensing system in which  $\mathbf{T} = \mathbf{Z}$  but  $\mathbf{R} \neq \mathbf{T}$ . Systems in which  $\mathbf{R} \neq \mathbf{T}$  are called ‘bi-static’,  
104 and necessarily have separated transmitter and receivers, as shown in Figure 1.

105 *b. Previous bi-static sodar designs*

106 The Doppler shift and scattering cross section for bi-static sodars were analysed by  
107 Thompson and Coulter (1974) and by Wesely (1976). Early experiments with bi-static  
108 sodars are described by Coulter and Underwood (1980) and Underwood (1981) for the  
109 Risø-78 experiment. For this experiment there were two bi-static sodars, as shown in  
110 Figure 2. Bi-static system (a) transmitted at 1 kHz, and system (b) at 1.6 kHz. Both  
111 systems operated in ‘staring’, or non-scanning, mode (the tilted beams had a fixed zenith  
112 angle of  $60^\circ$ ), but the overlap between the vertical beam and the tilted beams was from  
113 about 90 to 200m height, allowing for profiling over this height range with pulsed  
114 transmission. Both systems were pulsed, defining an instantaneous sensing volume of  
115 depth of about 17m. Comparisons with tower measurements 260m distant are shown in  
116 Figure 3. Although 30 minute averages were used, the uncertainties in the bi-static wind  
117 measurements are rather large. Values of the structure function parameter for turbulence  
118 velocity fluctuations,  $C_V^2$  were also measured at a height of 130m. The azimuth and  
119 elevation angles could be changed manually but this took around 4 minutes.

120 Mastrantonio et al. (1986) also presented some preliminary results of use of a  
121 staring mode bi-static sodar which could be used simultaneously with a 3-axis monostatic  
122 sodar, and Mathews et al. (1986) explored refractive acoustic path bending effects for bi-

123 static sodars. Mouldsley and Cole (1993) extended the earlier analyses to give a general  
 124 radar equation for bi-static sodars. Zinichev et al. (1997) have described a very large bi-  
 125 static system having transmitter-receiver separations of 400m.

126 Mikkelsen et al.(2007) have described ‘Heimdall’, a continuous-transmission  
 127 staring-mode bi-static sodar design. This operated with vertical transmission at 4 kHz and  
 128 a single receiver beam of 45° zenith angle at a separation distance of 60m. The combined  
 129 temperature structure function parameter  $C_T^2$  and velocity structure function  $C_V^2$   
 130 measurements agreed with mast measurements to within an order of magnitude, which is  
 131 reasonable, given various system uncertainties. It was noted that only 25% of the  
 132 received scattered energy was expected to be from temperature fluctuations.

133 Figure 4 shows a spectrum from the Heimdall bi-static sodar. The direct signal  
 134 from the transmitter to the receiver is obvious in the sharp spectral peak at 3960 Hz. The  
 135 remainder of the spectral hump is comprised of two broad bell-shaped spectral peaks.  
 136 The broader spectral peak to the left is due to the vertically transmitted pulse. Note that it  
 137 is much broader than the direct signal spectrum because of the wide range of scattering  
 138 angles for this continuous system. There is also a second broader peak, partly underlying  
 139 the direct signal peak and slightly to its right. This is due to a diffraction side lobe from  
 140 the dish antenna used. Given that  $f_T = 3960$  Hz, and the peak at the left is at 3920 Hz (for  
 141  $\theta=0$ ),  $u/c = (40/3960)R/D$ , where  $R = (D^2+z^2)^{1/2}$  is the distance from receiver to sensing  
 142 volume, and  $D$  is the distance from the receiver to the point below the sensing volume.  
 143 The half-width of the left-hand spectral peak is about 50 Hz, so the range of scattering  
 144 angles, expressed as  $\Delta\theta$ , is



$$145 \quad \Delta\theta = \frac{50}{3960} \frac{1}{\frac{u}{c} \left(1 + \frac{z}{R}\right)} = \frac{50}{3960} \frac{D}{\frac{40}{3960} (R+z)} = 1.25 \frac{D}{R+z} \quad (5)$$

146           Here  $D = z$ , so  $\Delta\theta = \pm 30^\circ$ , which emphasizes the need for bi-static SODARs to be  
 147 pulsed systems. The broad peak at the right, at 3970 Hz, will be from a side-lobe at about  
 148  $27^\circ$  from the vertical. Side lobes at such angles readily exist since they will generally be  
 149 within the angular pass region of acoustic baffles. For mono-static SODARs such a side  
 150 lobe would be unlikely to cause problems, but in the case of this bi-static system it is  
 151 significant.

152           Very recently AQS (2010) have announced a commercial ‘common volume’  
 153 configuration comprising three interconnected sodars each having tilted beams which  
 154 intersect at a common volume in staring mode. A typical configuration is quoted as  
 155 having the three beams all with zenith angle  $\theta = 15^\circ$ , the common volume at height  $z =$   
 156 100m, and the three sodar units each separated from the point on the ground beneath the  
 157 sensed volume by a distance of  $D = 26$ m. The system is pulsed, giving better definition of  
 158 the sensed volume. Winds can be obtained only from a single height. Previous bi-static  
 159 designs discussed above, and the design by Shamanaev(2003), all used fixed angle  
 160 antennas, with the limitation of a rather confined height range.

161           From these examples of previous work it is clear that bi-static sodar systems do  
 162 give wind profiles, but that (1) they should allow for a non-staring (i.e. scanned) mode, or  
 163 a multiple fan-beam staring mode, so as to give a broad height range, and (2) they should  
 164 be pulsed so that problems with direct and diffracted beam reception are avoided, and so  
 165 that the height range of the sensed volume is not so extensive. The design described  
 166 below accommodates to these requirements.

## 167 2. Bi-static sodar design principles

168 Both the Doppler shift and the received amplitude are different for a bi-static system  
 169 compared with a mono-static sodar. While any configuration of three beams could be  
 170 used (such as the AQS configuration), if the atmosphere is to be scanned in a column, it  
 171 is more convenient to have one beam pointing vertically, since then only two beams need  
 172 be scanned. We will concentrate discussion on a single vertical transmission beam and  
 173 two tilted receiving beams, with the two planes defined by each tilted beam and the  
 174 vertical being orthogonal, as in Figure 5.

### 175 *a. Signal Amplitude*

176 Scattered acoustic power  $P_R$  is given by:

$$177 \quad P_R \propto \frac{\sin^2 \beta}{(1 + \sin \beta)^{11/6}} \frac{e^{-\alpha r}}{r^2} \left[ C_T^2 + 3.66(1 - \sin \beta) \frac{T^2}{c^2} C_V^2 \right] \quad (6)$$

178 where  $r = z + (D^2 + z^2)^{1/2}$  is the total sound path distance,  $c$  is the speed of sound in air,  $T$   
 179 the absolute air temperature,  $\alpha$  the absorption coefficient,  $C_V^2$  and  $C_T^2$  are turbulent  
 180 structure function parameters, and  $\beta = \tan^{-1}(z/D)$  the elevation angle from the receiver to  
 181 the sensing volume (Bradley, 2007). Bi-static SODARs have greater sensitivity than  
 182 mono-static SODARs because of the extra contribution from  $C_V^2$ , especially in neutral  
 183 conditions when  $C_T^2$  vanishes.

### 184 *b. Sensitivity to scattering from rain*

185 Acoustic scattering from rain drops for typical SODAR wavelengths is in the Rayleigh  
 186 regime, and has an angular dependence of  $(\sin \beta - 2/3)^2$ , as discussed by Bradley and

187 Webb (2002). This has a minimum at  $\sin\beta = 2/3$  or  $\beta=42^\circ$ , whereas from Equation (6),  
 188 the scattering from velocity fluctuations peaks at  $\beta=35^\circ$ . This means that, for much of the  
 189 bi-static profile, the angular scattering patterns of turbulence and rain favour the  
 190 scattering from turbulence.

191 The scattered energy amplitudes from temperature and velocity fluctuations are  
 192 shown in Figure 6 for  $D= 30\text{m}$  and for  $D = 50\text{m}$ , together with the scattering pattern from  
 193 rain.

#### 194 *c. Doppler winds*

195 From (1), the bi-static equivalent of (2) is

$$196 \quad \begin{aligned} \mu_b &= \frac{u}{2} \cos\beta \cos\phi_i + \frac{v}{2} \cos\beta \sin\phi_i + \frac{w}{2}(1 + \sin\beta) \quad b = 1,2 \\ \mu_3 &= w \end{aligned} \quad (7)$$

197 with the solution, for  $\phi_1 = \phi_2 - 90^\circ = \phi$ ,  
 198

$$199 \quad \begin{aligned} u &= [2(\mu_1 \cos\phi - \mu_2 \sin\phi) - (1 + \sin\beta)\mu_3(\cos\phi - \sin\phi)] / \cos\beta \\ v &= [2(\mu_1 \sin\phi + \mu_2 \cos\phi) - (1 + \sin\beta)\mu_3(\cos\phi + \sin\phi)] / \cos\beta \\ w &= \mu_3 \end{aligned} \quad (8)$$

200  
 201 For example, if  $\phi=0$ , the coefficient of  $u$  in  $\mu_1$ , which is proportional to the  
 202 Doppler shift in beam 1 from the  $u$  component, is greater than the corresponding mono-  
 203 static Doppler shift up to the height of 83m if the bi-static spacing  $D = 50\text{m}$ , and the  
 204 mono-static beam zenith angle is  $\theta=15^\circ$ .

205 The Doppler contribution from  $w$  in beams 1 and 2 is always larger than the  
 206 mono-static case. This increased Doppler helps discriminate against echoes from fixed  
 207 objects around the sodar. For example, assume a hard reflecting surface is at a range of  
 208 20 m and the atmospheric scattered signal is of the same amplitude as that from the fixed

209 surface. For a horizontal wind speed component of  $2 \text{ m s}^{-1}$  in the plane of a beam, and  
 210 with a pulse duration of 0.1 s, a transmitted frequency of 4500 Hz, a mono-static beam  
 211 zenith angle of  $15^\circ$ , and a bi-static baseline of  $D = 50 \text{ m}$ , Figure 7 shows the  
 212 corresponding Doppler spectra for a mono-static sodar and a bi-static sodar. The much  
 213 improved resolving power of the bi-static system is evident.

#### 214 *d. Scanning geometry*

215 Sodars normally have a pulse duration of about  $\tau=0.1\text{s}$ , corresponding to a height  
 216 resolution of  $\Delta z = c\tau/2 = 17\text{m}$ . In the case of a scanning, pulsed, bi-static design, the  
 217 pulse height will define the sensing volume height, but for maximum signal gain the  
 218 beam width of the scanned beam should not be so large that much of the sensitive beam  
 219 area is outside the pulsed volume. The antenna for typical sodars has a diameter  $L$  of  
 220 between 0.5m and 1.0m, and the width of the sodar beam, from peak to the first null, is  
 221 about

$$222 \quad \Delta\beta = \frac{2\pi}{kL} = \frac{c}{Lf_T} \quad (9)$$

223 where  $k$  is the acoustic wavenumber and  $f_T$  is the transmitted frequency. For  $f_T = 4500 \text{ Hz}$ ,  
 224  $\Delta\beta = 2.7^\circ$  for  $L = 0.8\text{m}$ . At 80m height, for example, the diameter of this beam would be  
 225 about 15m, or close to the typical height extent defined by the pulse duration. Figure 8  
 226 shows schematically how the sampling volume is defined by the product of three  
 227 Gaussian spatial functions: one for the transmitted beam, one for the received beam, and  
 228 one for the transmitted pulse.

229 For example, if  $f_T = 4500$  Hz,  $L = 0.8$  m,  $D = 50$  m, and a Gaussian pulse is used  
 230 having a temporal standard deviation of 0.02s, the sampling volumes at 30, 50 and 80m  
 231 are as shown in Figure 9.

232 Given the above, a reasonable design starting point is to have the scanned  
 233 receiving arrays about 1m in length. For a prototype bi-static receiver, we have used  
 234 Motorola KSN1005A super-horn tweeters as microphones. These have a diameter of  $d =$   
 235 0.085m and, because our multi-channel data loggers have 12 channels, we used  $M = 12$  of  
 236 these microphones in a linear array, giving a length  $L = 0.935$ m. In order to limit the  
 237 lateral extent of the sensitivity, we used a 12x3 array, with each row of three  
 238 microphones connected in parallel to a low-noise preamplifier. This gave a lateral half-  
 239 beamwidth of 12.7°.

240 The pointing direction of each microphone array is controlled by adding a  
 241 progressive phase shift  $\Delta\phi$  to each row down the length of the linear array of  
 242 microphones (Bradley, 2007). In order to obtain best sensitivity, each array is mounted on  
 243 a tripod and aimed at a height  $z_0$ , at an elevation angle of  $\beta_0$ .

244 The pointing elevation angle,  $\beta_g$  to the centre of a range gate sampling volume at  
 245 height  $z_g$ , is

$$246 \quad \beta_g = \beta_0 + \sin^{-1} \frac{\Delta\phi}{kd} \quad (10)$$

$$247 \quad \frac{\Delta\phi}{kd} = \frac{D}{(D^2 + z_0^2)^{1/2}} \frac{z_g - z_0}{(D^2 + z_g^2)^{1/2}} \quad (11)$$

#### 248 *e. Scanning implementation*

249 The voltage output  $s_m(t_i)$  from microphone  $m$  ( $m = 1, 2, \dots, M$ ) is recorded at times  $t_i =$   
 250  $i\Delta t$  ( $i=1, 2, \dots, N$ ) with time  $t = 0$  being the start of the transmission of the acoustic pulse.

251 The first scattered sound from the air just above the transmitter arrives at the receiver  
 252 array at time  $t_0 = D/c$ . Signals from a range gate at height  $z_g \pm \Delta z_g/2$  arrive between time  
 253  $[(z_g - \Delta z_g/2) + \{D^2 + (z_g - \Delta z_g/2)^2\}^{1/2}]/c$  and  $[(z_g + \Delta z_g/2) + \{D^2 + (z_g + \Delta z_g/2)^2\}^{1/2}]/c$  or, say,  $i = i_g,$   
 254  $i_g + 1, \dots, i_g + (N_g - 1)$ . Within this time period, the phased array receiver needs to be staring  
 255 at this sensing volume, which is achieved by applying the correct incremental phase shift  
 256 across the array microphone elements.

257 All of this processing can be done *after* recording the whole time series  $s_m(t_i)$ .

258 Delays of any precision can be applied through Fourier transforms.

$$\begin{aligned}
 S'_{mg}(f) &= \int_{t_{i_g}}^{t_{i_g} + (N_g - 1)\Delta t_g} s_m(t - m\Delta t_g) e^{j2\pi f t} dt \\
 259 \quad &= \left( e^{jm \frac{f}{f_T} \Delta \phi_g} \right) \int_{t_{i_g} + m\Delta t_g}^{t_{i_g} + (N_g - 1)\Delta t_g + m\Delta t_g} s_m(t^*) e^{j2\pi f t^*} dt^* \\
 &= P_{mg}(f) S_{mg}(f)
 \end{aligned} \tag{12}$$

260  
 261 where  $\Delta t_g = \Delta \phi_g / (2\pi f_T)$ . We select the  $\Delta t_g$  by selecting the range gate limits. This in turn  
 262 determines  $N_g$ . For a sampling frequency  $f_s = 1/\Delta t = 12$  kHz, and  $\Delta z_g = 30$  m, we get  $N_g =$   
 263 1059, and the other range gate parameters shown in Table 1. The time delays are small  
 264 compared with  $\Delta t$ , emphasizing the need (at lower sampling frequencies) of using Fourier  
 265 delays rather than indexing into the time series table. Note that the beam steering time  
 266 delays are so small that they do not need to be accounted for in the Fourier integral (or  
 267 indexing for each spectrum). The last column in Table 1 is the velocity increment  
 268 corresponding to the frequency increment in the Fourier transform. Once these  
 269 parameters are determined, the  $M$  Fourier transforms  $S_{mg}(f_i)$  are found for this range gate.  
 270 Each complex spectral component from  $S_{mg}$  is then multiplied by the complex number

271  $P_{mg}(f_i)$  to form the complex spectrum  $S'_{mg}$ . Finally, the  $M$  spectra are summed to obtain  
 272 the spectral components  $Q$  of the phased array at range gate  $g$ .

$$273 \quad Q_g(f_i) = \sum_{m=1}^M P_{mg}(f_i) S'_{mg}(f_i) \quad (13)$$

274 This spectrum is analyzed to find the frequency  $f_T + \Delta f_g$  of the spectral peak, and hence to  
 275 calculate  $\mu_g = -c\Delta f_g / f_T$ .

### 276 *f. Beam sensitivity*

277 The overall amplitude response of the phased array is

$$278 \quad G \frac{\sin\left[\frac{M}{2}kd\{\sin(\beta - \beta_0) - \sin(\beta_g - \beta_0)\}\right]}{\sin\left[\frac{1}{2}kd\{\sin(\beta - \beta_0) - \sin(\beta_g - \beta_0)\}\right]} \quad (14)$$

279 where  $G$  is the angular sensitivity of an individual microphone at an off-axis angle of  $\beta$ -  
 280  $\beta_0$ . For the prototype we used Motorola KSN1005A tweeters as microphones, which have  
 281 an intensity pattern which can be approximated by  $\cos^5(\beta - \beta_0)$ . The array intensity  
 282 sensitivity pattern is shown in Figure 10. There are in general two main interference  
 283 peaks, but the unwanted one of these is pointed well away from the position of the  
 284 scattered sound, at the time the array is staring at the sensing volume. The -3 dB  
 285 beamwidth is  $\pm 2^\circ$ .

287 The transmitter dish antenna and horn sensitivity have been measured at 3500 Hz  
 288 (Mikkelsen et al., 2007) with a -3 dB beamwidth of  $\pm 3^\circ$ . At 4500 Hz the beamwidth  
 289 would be expected to be about  $\pm 2^\circ$ . In the horizontal plane the beamwidth is  $\pm 8^\circ$ , giving  
 290 reasonable latitude in pointing toward the column being sensed.

### 291 3. Hardware design

292 The prototype bi-static system comprises a horn and parabolic dish reflector transmitter,  
293 and two identical phased-array receivers. This configuration of a single transmitter which  
294 transmits sound vertically, and multiple inclined phased array receivers, is chosen  
295 because other configurations, such as a single vertically-pointing receiver and multiple  
296 inclined transmitters require more power and the use of multiple transmit frequencies. A  
297 master PC generates the transmitted signal, sent to the horn through a power amplifier.  
298 The master PC receives signals from one of the phased array receivers (Unit 1), and also  
299 generates a trigger signal which is sent to a slave PC. The slave PC controls sampling  
300 from a second phased-array receiver (Unit 2). All timing is therefore controlled by the  
301 master PC.

302 Each receiver array consists of 12 rows each containing 3 microphones (actually  
303 KSN1005A superhorn tweeters used as microphones). The voltage outputs from each  
304 group of 3 microphones are summed. This has the effect of confining the lateral  
305 (azimuth) receiver sensitivity, while also cancelling some of the random noise. Each of  
306 the 12 grouped outputs is amplified, using a low-noise preamplifier, and band-pass  
307 filtered. Digitization is achieved using a Data Translation DT9836 usb module, which can  
308 sample the 12 channels simultaneously at up to 225 kHz (see Fig. 11). The dish antenna  
309 and each receiver are mounted on stand with adjustable zenith angle (see Fig. 12).

### 310 4. Field test

311 A short field test was conducted to check the basic amplitude and Doppler behavior  
312 described above.



313 *a. Scanning bi-static sodar  $C_T^2$  and  $C_V^2$  profiles*

314 The prototype bi-static system was set up at the Riso test facility at Høvsøre, Denmark,  
 315 with a single transmitter and two phased array receivers. The receivers were each 38 m  
 316 from the transmitter, with the transmitter-receiver lines at right angles. Receiver Unit 1  
 317 had hay bales on three sides, as an acoustic shield. Unit 2 and the transmitter had no  
 318 shielding.

319 The variation of scattered amplitude with height is shown in Fig. 13, using  
 320 continuous transmission so that the beam steering selectivity could also be tested.  
 321 Consequently, the large amplitude lobe near the ground comes from the direct signal, but  
 322 gives an indication that the angular selectivity of the scanning receiver has a half-width of  
 323 10 m at the ground, or  $15^\circ$ . However, this apparent beam width is mostly due to the pulse  
 324 length being equivalent to 8.5 m. The expected profile is also shown, based on Eqs. (6)  
 325 and (14), and assuming that  $T^2 C_V^2 c^{-2} C_T^{-2}$  has a constant value of 50 (see Mouldsley et al.,  
 326 1981, for typical measured values of  $C_V^2$  and  $C_T^2$ ). The unknown overall antenna gain for  
 327 the expected profile is arbitrarily chosen, but this does not affect the profile shape. In  
 328 practice the profile results from a convolution, with the sharp nulls in the beam pattern  
 329 smoothed out.

330 The measured profile closely matches that expected, allowing some confidence in  
 331 being able to retrieve individual  $C_T^2$  and  $C_V^2$  profiles. To do this, receiver Unit 1 was  
 332 placed near the transmitter, facing upward. Because  $\beta_1 = 90^\circ$ , only  $C_T^2$  is recorded by  
 333 Unit 1. Unit 2, still at 38 m from the receiver and scanning, recorded a combination of

334 the two structure function parameters. The receiver antennas, while identical, are not  
 335 calibrated absolutely but, from Eqn. (6)

336

$$337 \quad \frac{P_2}{P_1} = 2^{23/6} \frac{\sin^4 \beta}{(1 + \sin \beta)^{23/6}} e^{-\alpha D(1 - \sin \beta) / \cos \beta} \left[ 1 + 3.66(1 - \sin \beta) \frac{T^2}{c^2} \frac{C_V^2}{C_T^2} \right] \quad (15)$$

338 allowing the ratio  $C_V^2 / C_T^2$  to be estimated as a function of height  $z = D \tan \beta$ . Since this  
 339 experiment does not relate directly to precise wind profiling in complex terrain, the  
 340 results will be reported elsewhere.

#### 341 *b. Scanning bi-static sodar velocity profiles*

342 A comparison was available against mast instruments at 44 m, 60 m, and 77 m.  
 343 Fig. 14 shows the mast instrument wind speed record for a three-hours period including a  
 344 period during which bistatic recordings were being made. Fig. 15 shows the wind speed  
 345 profile averaged over six 1-second soundings starting at 14:10. For this short run, the  
 346 error bars are quite large, partly because each spectrum is 1024 points from signals  
 347 sampled at 12 kHz, which gives 85 ms for the duration of each spectrum and frequency  
 348 intervals of 12 Hz, equivalent to a velocity interval of nearly  $3 \text{ m s}^{-1}$ . An improved  
 349 velocity resolution and smaller error bars are obtained by averaging over many more  
 350 samples.

## 351 5. Conclusions

352 We have described the design and brief field tests of the first scanned bistatic sodar. This  
 353 new technology potentially has significant advantages over previous bistatic sodars, all of  
 354 which used a ‘staring mode’ in which wind data could only be obtained from a confined

355 height range. The main motivation for designing a scanning bistatic sodar, described in  
356 the first section, is to avoid errors arising in all current sodars and lidars when they  
357 sample non-horizontally-uniform winds. This situation arises generically in complex  
358 terrain and, without a solution such as the new bistatic sodar, wind estimates in such  
359 regions are considerably compromised.

360 The result is single-column, or ‘mast-like’ sampling of the wind profile. But there  
361 are other advantages which we have identified. These include

- 362 • improved SNR because of the extra scattering from velocity fluctuations
- 363 • much improved performance in neutral lapse conditions, where the turbulent  
364 temperature fluctuation contrast is low
- 365 • improved rejection of rain echoes through an advantageous scattering pattern
- 366 • larger Doppler shift reducing the possibility of erroneous velocity estimates  
367 arising from echoes from fixed structures

368 We describe the relevant theory for each of these factors, and how to design a  
369 scanning sodar which has good spatial resolution. In particular, it is important to use a  
370 pulsed system to avoid the multiple overlapping spectra experienced by the Heimdall  
371 sodar (Mikkelsen, 2007). In fact, the pulse length largely determines the vertical  
372 resolution in the scanned bistatic system. The spectral processing needs to be done rather  
373 carefully, and certainly is rather more complicated than for a monostatic system.  
374 Nevertheless, we found all spectral processing, and post-sampling beam steering, can  
375 readily be completed in MATLAB in a small fraction of the profiling time, and  
376 effectively gives real-time performance.

377 A prototype scanning bistatic sodar was designed using a dish antenna transmitter  
378 and 12 x 3 arrays of microphones for the receivers. The baseline used in our experiments  
379 was 38 m, but this is somewhat arbitrary and there should be further exploration of the  
380 optimum configuration. No acoustic baffles (except for crude use of some hay bales)  
381 were used in our prototype. We would expect significant improvements in performance  
382 if properly-designed acoustic shielding was used.

383 Very preliminary experiments are described. The profile of the turbulent  
384 scattering intensity is found to closely approximate what we expect from theory, giving  
385 some confidence in the instrument design and scanning. Comparisons were performed  
386 against mast-mounted instruments, and the velocity profile obtained with the bistatic  
387 sodar agreed with the ‘standard’ instruments to within measurement uncertainties.

388 We are now progressing to designing microphone-based arrays as an optional  
389 addition to a monostatic sodar. This configuration will allow both monostatic and bistatic  
390 configuration to operate simultaneously, or sequentially, thereby providing considerable  
391 self-checking of the instrument, since the two velocity estimation schemes are quite  
392 different.

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442 sodar based on 15-meter overall review radiotelescopes. *Radiophys Quant Opt.*, **40**, 877-  
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444

445 TABLE 1. Typical parameters for  $f_s = 12\text{kHz}$ ,  $D = 50\text{ m}$ ,  $z_0 = 60\text{ m}$ , and a design vertical  
 446 resolution of 20m.

$z_g$ [m]	$\Delta t_g$ [ $\mu\text{s}$ ]	$i_g$	$\Delta u$ [ $\text{m s}^{-1}$ ]
20	-125	353	1.0
50	-21	1412	1.4
80	30	2471	2.0
110	58	3529	2.6
140	74	4588	3.3
170	85	5647	3.9
200	92	6706	4.6
160	82	5294	3.7
180	88	6000	4.1
200	92	6706	4.6

447

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461 the response for a mono-static sodar. Also shown (circles) is the response from rain, with  
462 arbitrary scaling.

463 FIG. 7. Sensitivity to spectral corruption due to echoes from fixed objects. Typical sodar  
464 a parameters are used, as described in the text, and the hard reflecting surface is at a  
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479 speeds from mast instruments (crosses).

480

Fig 1

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Fig 2

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Fig 3

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Fig 4

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Fig 5

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Fig 6

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Fig 7

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Fig 8

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Fig 9

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Fig 10

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Fig 11

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Fig 12  
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Fig 13

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Fig 14

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Fig 15

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