State of the art of wind remote sensing

Elforsk rapport 11:20

Lasse Johansson, Johan Hansson, Jenny Lundén June 2011

Vindforsk Energimyndigheten ELFORSK

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Preface

Remote sensing techniques for measuring wind are becoming increasingly used for wind turbine applications. SODAR (SOnic Detection And Ranging) and LIDAR (Light Detection And Ranging) are used for site assessment studies, after-control and research projects. The type of terrain and under which turbulence conditions the techniques can be used are matters under discussion. How to compare remote sensing data to in-situ measurements like data from cup anemometers is another issue under discussion.

In order to shed light on the status of remote sensing techniques project V-352 has been carried out within the Swedish wind energy research programme Vindforsk-III.

The work has been carried out as a literature study, a state of the art description and a work shop where users of remote sensing techniques shared their experiences.

The work was carried out by the wind power department of Vattenfall Power Consultant AB and the result is presented in this report.

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Comments on the work and the final report have been given by a reference group with the following members: Anton Andersson and Francesco Sottini from E.ON Climate and Renewables, Daniel Marmander from Triventus, Kristoffer Lager from O2 Vindkompaniet and Daniel Gustafsson from Vattenfall Vindkraft

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Sammanfattning

I rapporten redovisas en litteraturstudie kring fjärrmätning av vind. Resultaten från denna sammanfattas i en lägesrapport. Inom projektet hölls ett seminarium om fjärrmätning av vind. Diskussioner från detta seminarium redovisas i rapporten. I sammanfattningen redovisas även projektets slutstater.

1.1 Litteraturstudium

Litteraturstudien visar att de teoretiska frågeställningarna kring sodar är mer utmanande än motsvarande kring lidar. De förra har bland annat därför lockat till mer teoristudier än de senare. Orsaken är kortfattat att sodar använder en tusentals gånger längre våglängd än lidar. Detta ger mer komplicerade diffraktionseffekter, växelverkan med luftreflektorerna är mer komplex, vågutbredningen i ett rörligt medium är mer komplex, lufttemperaturen påverkar resultatet och så vidare. Sodarteori är därför också ett svårt område inom vilket användaren är utlämnad till egen förkovran.

Omkring 2005 genomfördes det så kallade EU-WISE-projektet där ett antal forskare studerade sodarer från ett flertal aspekter. Kontentan av studierna var att sodar inte kan användas som ett fristående, pålitligt mätinstrument för högprecisionsmätning av vind utan att kompletteras med en permanent låg mätmast bredvid. Slutsatsen baserades bland annat på jämförelser mellan sodarer och skålkorsanemometrar samt principiella överväganden och metodstudier. Bara några år senare, runt 2009, kom ett antal renommerade vindenergiinstitut med en rad rapporter, beställda av instrumenttillverkare, där slutsatsen var att sodarer håller tillräckligt hög precision för att kunna användas fristående från och i stället för konventionella skålkoppsanemometrar i höga master. Samma institut kom ungefär samtidigt med en rad rapporter där man, med något undantag, är minst lika positiva till lidarinstrumentens mätnoggrannhet. Rapporterna bygger på korttidsförsök i enklast tänkbara terräng, nämligen platta gräsmarker. Vi noterar:

- att det är intressant att provresultaten och tolkningarna utfaller så olika på endast några få år,
- att alla test har utförts i terräng och förhållanden som ligger långt ifrån de förhållanden som instrumenten skulle utsättas för i fält i Sverige,
- att instrumentens praktiska funktion avseende strömförsörjning, frakt och så vidare, inte utvärderas i den litteratur vi funnit.

Ett mycket aktuellt problem inom fjärrmätning med såväl sodar som lidar, är så kallade orografifel. De uppstår när mätinstrumentet tolkar dopplerskiften från en krökt eller accelererad luftströmning som om de härrör från en konstant strömning. Litteraturstudien och våra egna beräkningar visar att orografiska effekter kan ge stora fel i vindstyrka; 5-10 %. Orografifel eller rättare sagt metoder att hantera dem är ännu relativt outvecklade, men, föremål för stort intresse och snabb utveckling.

I litteraturstudien har vi huvudsakligen koncentrerat oss på modernt material, yngre än tio år, eftersom teknik och användande av fjärranalysmetoder utvecklas så snabbt. Den ymnigaste källan har varit rapporter från olika forsknings-/konsultföretag, vilka dels provat utrustningar av olika fabrikat men också deltagit i större forskningsprojekt med allmänna mål inom vindfjärrmätning som teori och tekniska specialstudier. Den gängse vetenskapliga litteraturen, tidskriftsartiklar, har i mindre utsträckning belyst metoder och tekniker för fjärranalysmätning. Istället står där själva mätresultatens meteorologiska tillämpningar i fokus. Vi har vidare utvärderat den stora och lättillgängliga mängd konferenspresentationer och liknande som finns, men med något undantag inte funnit något användbart material där eftersom det är i stort sett ogranskat och fjärmat från sitt sammanhang. Vi har sökt intensivt efter material på tyska och spanska men tyvärr endast funnit den sistnämnda källtypen: sparsamt kommenterade presentationer.

1.2 Lägesrapport, ”state-of-the-art”

För fjärrmätning av vind finns idag två metoder: akustisk (sodar) och optisk (lidar). Den förra har utvecklats under närmare femtio år, varav de senaste fem-tio åren även mot instrument specialiserade på atmosfärens så kallade friktionsgränsskikt, det vill säga det understa hundratalet metrarna. Lidarer har i jämförelse betydligt färre år på nacken och de är följaktligen stadda i en något snabbare teknisk och praktisk utveckling.

De flesta sodarer arbetar efter principen med styrd lob, vilket innebär att ljudet kan riktas åt olika håll genom en elektroniskt fasstyrd facetthögtalare. En alternativ teknisk princip, genom vilken den i Sverige dominerade AQ500 utmärker sig, är den med tre oberoende fasta högtalare/antenner. Utförandemässigt synes sodarerna för övrigt konvergera mot ungefär samma utförande, vilket du kan studera i rapportens instrumentgalleri. Sodartillverkarna har sökt få fram fristående, transportabla enheter med egen energiförsörjning, uppvärmda antenner med mera.

Lidarerna idag är antingen, likt sodarer, pulsade eller så har de har variabelt optiskt höjdfokus. Lidarer har lägre eller mycket lägre höjdupplösning av vinden än sodarer, vilket delvis förklarar att de har lägre eller mycket lägre brusnivå än sodarer. Lidarer har inte fått ett så enhetligt utförande som sodarer (se fotogalleriet), utan användaren måste själv mer eller mindre bygga ihop en fungerande enhet, skydda den mot stöld och så vidare. Vår slutsats är att lidarinstrument inte ännu är fältmässiga. Det vill säga att de inte klarar svenskt klimat eller att arbeta problemfritt utan tätt och omfattande underhåll.

När det gäller användning av fjärrmätinstrument står olika avnämares intressen i viss mån mot varandra:

- projektören vill ha en billig och snabb mätning av medelvinden,
- turbinleverantören vill ha så mycket korrekta mätningar av turbulens och vindskjuvning som möjligt,
- investeraren vill ha en exakt vindresursskattning som ger låg investeringsrisk.

I vindbranschen råder delade meningar om värdet av fjärrmätdata. Man kan inte utgå från att det är en i alla läger accepterad metod för vindmätning. Tvärtom bedömer vi att det är det låg sannolikhet att ett projekt, baserat endast på fjärrmätdata, kan fullbordas. I rapporten listar vi ett antal påståenden och frågor om fjärrmätning som vi ofta stöter på. Vi ger våra kommentarer till dem.

Det finns för närvarande inte någon standard för hur fjärrmätinstrument skall användas. Ett förarbete till en sådan Recommended Practice finns i form av ett utkast, Moore (2010), vilket kan bli grunden till fortsatt arbete mot en Recommended Practice inom IEA. Vår bedömning är att Moore (2010) är för generell för att vara direkt tillämpbar för en vanlig användare av fjärrmätinstrument. Däremot kan den tjäna som riktlinje för en projektörs egen formulering av konkreta riktlinjer.

Mätning av turbulens med fjärrmätinstrument är problematisk. Det finns principiella skillnader mellan fjärrmätare och skålkorsanemometrar vid turbulensmätning vilket vi beskriver i rapporten och det finns även praktiska problem som har med mättekniken att göra. Under brukarmötet framfördes i linje med detta synpunkten att en sodar inte kan användas för turbulensmätning. I rapporten redovisar vi kortfattat varför och hur mätningar av både medelvind och turbulens mätt med fjärrmätinstrument måste korrigeras för att bli jämförbar med skålkorsanemometermätningar.

Vägen till framgångsrika mätningar med sodarer och lidarer är kunskap, såväl teoretisk som praktisk. Detta uttrycks i de flesta källor vi använt oss av och överensstämmer med våra egna erfarenheter.

1.3 Brukarmöte – ”Workshop”

Vi ordnade ett brukarmöte, till vilket Vindforsks medlemmar var inbjudna, den 10:e mars 2011 i Göteborg. Projektörer, konsulter och en turbintillverkare bidrog med ett brett spektrum av aspekter på användning av och nytta med fjärrmätinstrument. I rapporten redovisas bidragen genom våra anteckningar och bilder från presentationerna.

Efter mötet står det klart att praktiska frågor kring instrumentens funktion är viktiga. De måste klara lång drifttid utan omfattande krav på underhåll, snö och kyla och så vidare. Flera deltagare redovisade fall där mätkampanjer inte givit önskat resultat på grund av bristande driftsäkerhet eller funktion hos instrumenten.

En annan mycket viktig aspekt är svårigheterna att få fram information om hur mätningarna behandlas genom filtrering och olika medelvärdesbildningar innan användaren får tillgång till dem som utdata. Viss kritik uttrycktes mot instrumenttillverkarnas hemlighållande av sådana uppgifter.

1.4 Slutsatser

Rapportens slutsatser sammanfattas som:

- Det saknas idag, maj 2011, en standard eller norm för hur fjärrmätning av vind skall utföras. Detta gäller för såväl sodarer som lidarer. Moore & Bailey (2010) har sammanställt rekommendationer för sodarmätning (vilka förväntas bli grunden för en framtida IEA Recommended Practice på området). Enligt vår mening är dock rekommendationerna alltför vaga för att vara användbara för den praktiskt verkande vindprojektören.
- Fjärrmätinstrument blir alltmer använda för vindprospektering och alltmer erkända av vindbranschens aktörer. Instrumenten är emellertid fortfarande omstridda och vissa aktörer litar inte på data insamlade med dem. Man kan alltså inte utgå från att mätningar gjorda med fjärrmätinstrument automatiskt kommer att godkännas, utan man bör försäkra sig om detta innan mätningar påbörjas.
- Fjärrmätinstrumentens kvalitet och renommé har förbättrats drastiskt under de senaste fem åren. Under vissa villkor, vilka varierar med instrumenttyp och mätmiljö, kan användaren av fjärrmätinstrument, genom publicerade prov av dem, åberopa starkt stöd för att resultaten är tillförlitliga (t.ex. gräsmark), medan i andra situationer saknas sådant stöd (t.ex. skog).
- Idag är sodarer avgjort mer lämpade för praktiskt användning i fält än lidarer. De förra klarar skogs- och vinterförhållanden samt drift under längre tid utan tillsyn, medan de senare snarast är prototyper som kräver stora insatser från användaren vad gäller såväl uppbyggnad som underhåll. Lidarer förefaller å andra sidan ha något lägre mätbrus och högre dataåterbäring än sodarer.
- Enligt vår erfarenhet bidrar fjärrmätinstrument till en högre projektkvalitet om de används på rätt sätt. De numeriska modeller för vindberäkningar som finns idag ger mycket allvarliga felskattningar av vindresursen. Fjärrmätinstrument – i kombination med vanliga mätmaster – ger säkrare skattning av vindresursen, vilket ger bättre lönsamhet och lägre risk än vindmodellering.
- En nödvändig förutsättning för framgångsrikt bruk av fjärrmätinstrument är kunskap. Utan sådan kunskap kan användaren inte skatta mätfelen, tillämpa rätt korrektioner av mätningarna eller förstå de fenomen som observeras. Kunskap om meteorologi, akustik/optik samt statistik är ett minimikrav.

1.5 Upphovsmännens ställning

Rapportförfattarnas har inte och har inte haft någon form av bidning till, avtal med eller uppdrag åt någon av de leverantörer av fjärrmätinstrument som förekommer i denna rapport.

Summary

Due to the rapid development of remote sensing, the literature survey focussed on the latest ten years. Sodar and lidar theory is a popular theme in literature and it suggests that lidar is physically simpler than sodar due to the vast difference in wavelength giving fewer complications for the lidar. On the other hand, the available lidars are less mature instruments from a practical point of view than most sodar makes.

Around 2005, a series of evaluations came to the conclusion that a sodar is not an instrument accurate enough to be used in standalone mode. Instead, a short conventional meteorological mast with a cup anemometer permanently installed next to the sodar for its calibration, is necessary for accurate measurements. Only a few years later, another series of reports were issued by renowned research/consultancy firms stating that both sodars and lidars are indeed accurate enough to be used standalone. No mast necessary!

We note that many of the latter reports were ordered by the remote sensor firms and that the comparisons were carried out in extremely simple terrain, not representing the conditions met in a typical Swedish wind energy project.

In the state-of-the-art part of this report we provide some comparisons of lidars and sodars along with commented advantages and drawbacks of remote sensing technique. There is no doubt that remote sensing is still not accepted by everyone in the wind business, a fact that every user must take into account and evaluate.

For example, using the sodar as a turbulence measuring instrument is not always straightforward. We exemplify briefly why some deviations compared to cup anemometer data occur and how they could be remedied.

We organised a workshop in Göteborg the 10th of march 2011 with a focus on remote sensor use. The participants contributed with a wide spectrum of user need and experience and gave a valuable outcome. Minutes of the workshop are found in the report. For a remote sensor user, practical issues such as the stand-alone-capacity or need for maintenance are most important. Also, giving reliable data despite snow, low temperatures and a long winter is an absolute requirement of a remote sensor for use in Sweden.

A big problem for a user is that the signal processing is not transparent. Filtering and averaging procedures are applied to the data but not disclosed for the user. This contributes to cast some doubt on the quality and expertise of the sodar products and their manufacturers.

The authors of the report have no attachments in terms of present or past assignments for any of the instrument suppliers mentioned in this report.

Conclusions in summary are:

- At the time of writing, May 2011, there is no standard for remote sensing of wind neither for sodars nor lidars. Moore & Bailey (2010) have compiled recommendations for sodar measurements (which are expected to be the foundation for a future IEA Recommended Practice in this area). In our opinion however, the recommendations are still to loose to be of use for the practising wind resource investigator.

- Remote wind sensors are being increasingly more used and more acknowledged by the different wind business parties. The instruments are however still under debate and some do not trust the data collected with them. Thus, one can not assume that data collected with remote sensors will be automatically recognized, but one must try to ensure that they will before the measurements commence.
- The quality and reputation of remote sensors have improved considerably in the last five years. Under some conditions, which vary with the instrument type and the measurement conditions, the user can obtain strong support for quality through a number of trials made (e.g. flat grassland), whereas in other conditions such support is lacking (e.g. forest).
- Today, sodars are more suited for use in field conditions than lidars. The former are available in models capable of working in forest and winter conditions for periods of time, whereas the latter are rather prototypes requiring large effort from the user in setting-up and maintaining them. Lidars on the other hand appear to have somewhat less measurement noise and higher data yield than sodars.
- In our opinion, remote sensors contribute greatly to a higher project quality if used correctly. The numerical modelling tools available are most limited and give very serious errors in the wind resource estimate. Remote sensors – combined with masts – can give a much more accurate estimation and thus higher profit and lower risk than numerical wind modelling alone.
- A necessary prerequisite for the successful use of remote sensors is knowledge. Without it the user can not estimate the measurement errors nor apply corrections appropriately or understand the phenomena which are observed. Knowledge in meteorology, acoustics/optics and statistics are the minimum requirements.

Innehåll

2 Literature review

2.1 Choice of material

We have surveyed the following periodicals for material on remote sensing: Boundary layer meteorology, Meteorologische Zeitschrift, Journal of atmospheric and oceanic technology, Quarterly journal of the royal meteorological society and DEWI Magazin. Most of the material was however found in the form or technical reports, e.g. by ECN, Deutsche Windguard, RISØ or NREL.

Due to the rapid development in the wind remote sensing area, only material younger than ten years was considered, except for one or two papers. Papers focussing more on boundary layer issues, wind modelling etc than on the lidars/sodars themselves have been excluded. Also, sales material or 'manufacturers evaluating themselves' –type material has been left out. We have read and evaluated some Master theses/Exjobb, but in our opinion one could not require of a student to produce material with the insight into the problems and solutions needed to contribute in a state-of-the-art context.

2.2 Theory

Apparently lidars have not attracted as much interest as sodars in wind energy literature. The explanation for this may partly be that the lidar is a more recent wind measurement instrument than sodar. The first sodar applications in meteorology appear in the 1960-ies whereas lidars seem to have emerged only in the last decade; 2000-2010.

Also, differences due to the measurement principles are favourable to lidars in some respects. Most prominently, the beam-forming equipment (optics) and the beam in a lidar have sizes which are thousands of wavelengths. Opposite to this, in a sodar the beam-forming parts (the antenna or the antenna array) and the beam is much smaller in size; only a few wavelengths. Issues such as diffraction of the measurement beam, movement and temperature effects on the air are more pronounced for sodars than for lidars thereby attracting more theoretical investigations.

The most popular topic in the material is sodar theory. One of the most cited papers is Antoniou et al (2003) which covers several aspects of sodar theory relevant to wind energy applications. The paper, on which several subsequent studies are modelled, covers the internal workings of (mainly phased array) sodars, the sodar equation and signal processing issues. Comparison with cup anemometry is treated extensively and a selection of differences in wind speed between cups and sodars is explored, as well as some of the common error factors for sodars. The paper does not cover antenna theory in any detail.

Antenna theory is well-covered in Bradley (2007). This book also covers a lot of what may be desired on signal-processing and different kinds of sodar measurement errors when compared to cup anemometers; more on theory than on application. The text is also focussed on phased array systems, although ‘antenna dish’ systems such as AQ500 is mentioned. The book approaches sodars generally; 3-beam, 5-beam, RASS etc and has no special emphasis on wind energy applications. Large parts of the material in this book is also found in WISE A, B and C (2005) by the EU-WISE project (WISE = wind energy sodar evaluation).

Common to many treatises on sodar and, to some extent, lidar theory is that they try to deal with or compare instruments with a variety of forms. The results may be quite general and therefore difficult to apply to a specific instrument. For example, theory for a phased array sodar with a vertical beam is not easily applicable to another instrument. There is a need for studies of particular instruments with a wider scope than just the remote sensor versus cup perspective – a genre to which we now turn.

2.3 Evaluation and calibration of wind remote sensors

The second most popular theme in the literature is comparison of sodars and lidars to cups alias “mechanical anemometry”.

In experimental physics, calibration of instruments is one of the most fundamental parts of an experiment. If an instrument cannot be calibrated it has close to no value, since the experimental results can then not be compared and checked. Verifiable experiments are a cornerstone of science as are calibrated instruments to the wind energy business.

The main problem of calibrating sodars and lidars is the size of the measurement volume. They do not fit a wind tunnel or a similar controlled environment as cup anemometers do. Instead they must be operated outdoor in a variable, unpredictable and not completely measurable environment. A problem – highlighted in WISE B and many other studies – is that sodar calibration against (calibrated) cup anemometers cannot give a higher precision than the cup anemometers themselves. Also, calibrating in real wind against a nearby mast or another remote sensing device incurs other problems such as distance and interference from the surroundings.

The report WISE A (2005) is a comprehensive sodar evaluation, already slightly outdated due to the rapid development of remote sensing in the wind industry. It is a summary of two other reports, WISE B (2005) concerning power performance measurements with sodar and WISE C (2005?) on sodar calibration.

2.3.1 WISE A

The summary report, WISE A, also contains a chapter on ‘application of sodars in difficult circumstances’. In this chapter, the following important points on methodology are raised:

- One disadvantage with sodar is the complex data treatment and the numerous factors that influence the result.
- Since the manufacturers often do not disclose the internal data processing to the clients, the decision if data can be used or not, is up to the operator and her experience.

As we shall see later, the last point was the main issue of the final discussion on the workshop, §4.14.

WISE A advocates stand-alone systems with built in power and simple data transfer i.e. rather GSM than for example satellite. Some practical difficulties are mentioned such as rodents [gnagare] attacking cables, snow in the antenna, high energy consumption, sabotage and noise but the reader is rather more invited to identify with such nuisances than offered advice on how to ease them.

Some of the recommendations of the WISE project are compactly summarised in this table:

7.8 Recommendations

The main recommendation based on the research done in the WISE project is the use of a small and sufficiently instrumented meteo mast to calibrate Sodar systems simultaneously during the measurements. To carry out power performance measurements with a Sodar and simultaneous calibration with a lower meteo mast the following steps are recommended:

1. Install the Sodar according to the instructions of the manufacturer.
2. Install the 30-40m meteo mast sufficiently equipped with top and reference anemometer and sensors for wind direction, precipitation, temperature and air pressure, (all instruments traceably calibrated).
3. Start the measurements and synchronise the two systems in time.
4. Check data during the measurements for possible influences of fixed echoes, background noise, speaker degradation and improper parameter settings.
5. After the end of the measurements, collect all points in a database.
6. Filter away all the erroneous data points from both met mast and Sodar and keep only simultaneous points.
7. Filter away all the SNRs below and above a given threshold.
8. Verify that the cup anemometer has been working satisfactorily.
9. Verify that outliers in the Sodar are due to precipitation.
10. Find the regression of the relation between Sodar and cup.
11. Filter all outliers outside a certain band.
12. Find the slope of the regression relation again between the Sodar and the cup.
13. Calibrate the wind direction of the Sodar using the mast direction for the low height.
14. Apply the relations at the hub height for the cup and the wind direction.
15. Apply the relation for pressure and temperature using the adiabatic relation and the pressure change with height.

Excerpt from WISE A.

2.3.2 WISE B

In WISE b commercial sodar systems are evaluated for power performance tests by three renowned consultants: ECN, WINDTEST and RISØ. The evaluations are done at the three test sites of the institutes. The sites and the instrumentation are described in detail. The sites are very similar being flat, open grassland which represent simple conditions.

Large differences between the sodar measurements and conventional cup anemometers are found. The differences are regarded as errors, i.e. the cup anemometer data is seen as correct. By the use of short, 40 m, met masts <u>permanently</u> located next to the sodars and a calibration procedure, the errors can be reduced considerably.

The report concludes that the uncertainties in the sodars, still after calibration, are larger than with conventional cup anemometers. They state that:

"The uncertainty of the sodar will never be smaller than the uncertainty of the cup anemometers used for the calibration [of the sodars]…".

WINDTEST and RISØ find deviations of 4 % between sodar and mast calculated annual energy <u>production</u>, but the <u>uncertainties</u> calculated from sodar data is 10-30 % higher than cup anemometer uncertainties. Their conclusion is that:

"The sodar shall in principle work as a tool for extrapolation of measured data from the met mast height to a higher hub height."

WISE B has a detailed section on error analysis, both of the cup anemometers and the sodar measurements. The ISO (1993) standard, "GUM", is applied. Together with the comprehensive documentation of the measurements, we regard this as an authoritarian and reliable account. It must be noted that:

- the experiments were carried out in a simple landscape and thus low turbulence levels,
- the application was power performance calculations,
- only phased array sodars were evaluated (Aerovironment 4000 by RISÖ and ECN, Scintech SFAS by WINDTEST).

2.3.3 WISE C

In WISE C the theoretical framework is detailed, treating selected error sources. Several parties have contributed to the work reported but it is not quite clear how the investigations have been harmonized, which would have been desirable from a methodological perspective. Flat grassland terrain – the Høvsøre test site – was used for all three instruments: Aerovironment 4000, Metek PCS2000 and Scintech SFAS, all phased array sodars.

WISE C shows that different sodar models need different error analysis and treatment since errors, to some extent, are model-specific. The degree of detail decreases towards the end of the report which is unfortunate since the most important results are found there. The authors present an "*extremely important finding*", suggesting that there is no difference in terms of accuracy when comparing sodar to cup and cup to cup. They arrive to this by studying the difference in measured wind speed by a sodar 70 meters away from a mast with cup anemometers and by studying the difference between two cup anemometers in the mast, one 20 meters above the other. They conclude that "*The implication is that the SODAR is measuring winds to at least as high a reliability as the mast cup anemometers*."

In chapter eight, a number of valuable results and recommendations are given. The need for a permanent low calibration mast with cup anemometers is underlined. Two of the sodars exhibited height independent calibration parameters and could obtain wind speed to 'within 1 %', whereas the third instrument had a height dependent calibration, making data at high altitudes uncertain. Without calibration all sodars had significant errors, above 5 % on wind speed.

The need for filtering the data to remove erroneous parts is stressed in this and other papers. For example, some sodars are sensitive to rain and so rainy periods must be removed or corrected. However, the question of conditioning problems is not mentioned. In our experience, conditioning is unavoidable if certain weather types are removed. Precautions must be taken.

The error budget below is from WISE C:

8.1 SODAR Error budget

The various errors examined in Section 3 may be combined to provide an error budget for SODAR measurements of wind speed. In summary, the various error contributions are

ID	Source	Parameter	Slope error $\frac{\hat{u}}{u}-1$	Parameter range	Error range
1	Temperature	ΔT [K]	$+\frac{\Delta T}{2T}$	±20 K	± 3 %
2	Out of level	$\Delta\varphi$ [radian]	$-\frac{1}{2}(\Delta\varphi)^2$	±15° (±0.3 rad)	-3.5 % to 0 %
3	Fixed echoes	Δx [m]		0 to 500 m	0 to -100%
4	Rain	R [mm/h]		0 to 50 mm/h	20 - 30 m s^{-1}
5	Beam spread	σ_φ [radian] φ [radian]	$+2\frac{\sigma_\varphi^2}{\sin^2\varphi}$	4°-8° (0.07-0.14 rad) 15°-24° (0.26-0.42 rad)	+6 % to +25 %
6	Beam drift	u/c	$\pm\sqrt{2}\frac{u}{c}$	0 to ±0.06	0 % to ±8.5 %
7	Beam separation	$\rho(\Delta x)$	$-(1-\rho)$	0.8? to 1	-20 % to 0 %
8	Vector averaging	z_0 [m] z [m]	$\frac{1}{2\left(\ln\frac{z}{z_0}\right)^2}$	0.01 to 2 m 10 to 1000 m	0 to 10 ?
9	Peak position	$\sigma_{\Delta f}$ [Hz] φ [radian] f_T [Hz]	$\pm\frac{c}{\sqrt{2}\sin\varphi}\frac{\sigma_{\Delta f}}{f_T}$	±0.5 Hz 15°-24° (0.26-0.42 rad) 1000 to 6000 Hz	0 to 10

Table 9. Error sources and estimates for SODARs

All except for the error 9 can be systematic (rain and fixed echo errors vary with conditions, but when present can lead to persistent errors which are non-random).

Excerpt from WISE C. Some entries in this table pertain to phased array sodars only.

2.3.4 Hansen (2006) and Bradley (2008a)

Hansen et al (2006) reports similar findings as in WISE C, namely that the sodar as a standalone instrument is not accurate enough, but with a complementary low mast, a resource assessment with sodar is possible. The sodar used in the study required a high level of maintenance. The sodar had problems measuring winds above 15 m/s and during rain. The rain biasing is treated by an ‘assumption of randomness’ i.e. not treated.

Bradley (2008a) suggests a very interesting calibration method potentially circumventing the fundamental calibration problem described in §2.3. It is a kind of self-calibration without the need for an independent instrument such as a mast mounted cup anemometer. The method is adapted to a sodar with one vertical beam in addition to slanting beams. The article is however quite theoretical and the promising approach is not developed into a practical method nor evaluated.

2.3.5 Lidar evaluation

A compact evaluation of two lidar models is found in Courtney et al. (2008). The paper presents the Windcube and the Zephir instruments in some detail and compares different aspects of them, commenting on the problems of comparing to cup anemometers. Measurements (very simple terrain) were performed and the results seem positive. Some practical issues, for example lidar sensitivity to fog and low clouds, are treated. The authors have a high degree of confidence in the lidar technique, both over cup anemometers and sodars.

2.4 Evaluation of individual instruments by third parties

We have found a number of third party evaluations of remote sensors. The evaluating companies come to more positive conclusions on the usability and accuracy of the tested instruments than for example WISE B and Hansen (2006) do.

2.4.1 Triton sodar evaluated by NREL

Scott et al (2010) used data from a Second Wind Triton sodar unit and from an 80 m meteorological mast located 200 m away. An operating wind farm with about a dozen turbines was located to the north of the met mast and the sodar. The study uses 6,5 months worth of data. The landscape is mostly flat with low vegetation.

The data was not collected by NREL themselves but by a third party cooperating with the sodar manufacturer. NREL follows the manufacturers guidelines for sodar evaluation, Walls (2009). They conclude among other things that "*At 80m, the difference in average wind speeds between the Triton and the meteorological tower was 2.1%*" and that "*The percent of valid data … was greater than 95% at 80m and was approximately 81% at 120m*".

2.4.2 Triton sodar evaluated by ECN

The test site is an experimental wind farm in flat grassland. Verhoef et al (2009) follow the manufacturers guidelines for sodar evaluation, Walls (2009). Three months worth of data was evaluated.

The authors are very positive in their evaluation and conclude among other things that "*The percent of valid data measured by the Triton is approximately … 92% at 80 meter and 88% at 100 meter*". They write:

"In the analysis we performed the Triton shows comparable uncertainty to conventional anemometry. Our initial conclusion is that the Triton can be considered as a valid stand alone system for wind resource assessments, especially given the industries tendency towards higher hub heights."

2.4.3 AQ500 sodar evaluated by ECN

Verhoef et al (2010). The test site is an experimental wind farm in flat grassland (same site as the ECN/Triton evaluation described in §2.4.2). As far as we can see the authors follows nearly the same procedure for the AQ500 evaluation as for the Triton evaluation (Walls (2009)) although it is not stated explicitly. One month worth of data was evaluated.

The authors are very positive in their evaluation and conclude that "*The percentage of valid data measured by the AQ500 is approximately … 99.3% at 80 meter and 99% at 100 meter*." They write:

"In the analysis we performed the AQS shows comparable uncertainty to conventional anemometry. Our initial conclusion is that the AQS can be considered as a valid stand alone system for wind resource assessments, especially given the industries tendency towards higher hub heights."

2.4.4 Windcube evaluated by Deutsche Windguard

Albers (2008). The test site was flat, open grassland. 20 days worth of data was evaluated. For methodology the author refers to internal standards, guidelines and quality management systems without further details.

The author is very positive in his evaluation and concludes that "…*Windcube reached a good data availability in 98,7 m measurement height between 86,6 % and 96,5 % depending on the definition of availability*" and that "*The deviations of the horizontal wind components as measured by the windcube and the cup anemometers are within the range of the standard uncertainty of cup anemometer measurements.".*

2.4.5 Windcubes evaluated by Risø

Gottshall & Courtney (2010). The test site was a flat, open grassland. 8 weeks worth of data was collected with three windcubes but only 5 % or about 3 days could be used due to disturbed winds. The authors do not refer to a verification guideline or similar. The evaluation is detailed in the report; it is similar to the other evaluation methodologies cited in this section.

The authors come to the following conclusion: "*The verification results confirm that the tested WindCubeTM units do not show any severe abnormal behaviour for the test period and may be considered as satisfactorily performing systems*." Unlike in the other evaluations they point out that that "*The results are however only valid in flat terrain with truly homogeneous flow, and they cannot be applied to measurements in conditions significantly differing from that such as complex terrain*."

2.4.6 Triton an Windcube evaluated by RES

Campbell (2011). The test site is a flat, uncomplicated grassland with some clusters of trees. The sodar and the lidar were 13 m apart and about 70 m away from an 80 m tall met mast. Almost one month worth of concurrent data during the summer was available. Different filtering strategies are described and applied. Campbell refers to the guideline by Walls (2009).

The author concludes that "*there is excellent agreement between the fixed mast, the Triton and the WINDCUBE. There is excellent linearity, correlation and very low scatter*."

2.4.7 ASC model 4000 Sodar evaluated by GWU-Umwelttechnik and WINDTEST

Warmbier et al (2007). The sodar was compared to cup anemometers in a 50 m tall mast at two sites, one "almost flat" agricultural landscape and the other consisting of a 2 by 1 km plateau in an agricultural and low-vegetation landscape (no maps or photos). Four to five months worth of data was collected at each site.

The authors find an "excellent" correspondence between the sodar and (ultrasonic) anemometers in the mast. The authors conclude that: "*If operated properly SODARs are a powerful alternative and in some applications also a meaningful complement to wind measurements with a mast*."

2.4.8 Zephir lidar

Kindler et. al. (2007). The lidar was compared with tall mast measurements for three months (120 m mast) onshore and five months (103 m mast) offshore. The authors conclude: "*The results returned from this study have shown that the QinetiQ system is very capable of returning good quality results in both an offshore and onshore environment*."

2.5 Complex terrain

Effects on remote sensing devices in complex terrain are discussed in many texts. The obvious reason is that many wind energy projects are in complex terrain and not in the simple ones in which sodar and lidar devices are evaluated, as we saw in section 2.4.

One could distinguish two types of terrain complexity: orography and roughness. In the literature, the former is studied in most detail whereas roughness effects are not investigated as much, although effects thereof may influence the results reported.

Orography leads to acceleration of the flow of air over the instrument, creating a varying wind field. A remote sensor must however 'assume' that the flow is constant which leads to a misinterpretation of the Doppler pattern and to an incorrectly estimated wind speed.

Roughness effects will not be able to change the wind locally in the same manner but may give vertical gradients and turbulence that affect the wind speed estimate through mechanisms described later in §3.10.1.

Bingöl et al (2008 and 2009) give a simplified derivation of the flow and geometry considerations that give effects from orography on a conically scanning lidar and try to apply RISØ software to correct the error. They find errors of 4 to 7 % on wind speed in a complex mountainous site.

Bradley (2008b) applies an analytical potential flow mimicking the flow over a ridge for a somewhat more general range of instruments. His approach has the great advantage of allowing some insight into how steepness and the other characteristics of orography influence the error. He finds wind speed errors from 5 % and up to 20 % and concludes that orography errors are generally larger for lidars because they have a larger zenith angle (beam tilt from the vertical) than sodars.

3 State of the art

3.1 Available techniques

3.1.1 Types of sodars

Only sodars for wind energy applications are considered in this report.

Two main groups of sodar antennas exist; phased array antennas [styrd lob] and dish, usually 3-beam antennas. One advantage with phased arrays is that the beam can be pointed arbitrarily, for example upwards (to zenith), which might be of importance in some applications. A drawback is that the phased array beam direction is temperature dependent which must be corrected for, Bradley (2007), WISE C §3.3. A dish-antenna does not suffer from this, but on the other hand it is more complicated mechanically and, as far as we have seen, only one slanting, three beam model exists.

For the lidar and sodar performance, at least as important as low error levels are the practical issues. The sodar must be a self-contained, stand-alone system including energy supply, data storage and transmission and de-icing facilities. It must be transportable also to remote places in rough terrain. Presently we know of a few such systems; AQ Systems AQ500, Second Wind Triton, Scintech/TORAGON WindCollector2, Atmospheric Research & Technology VT-1 and Atmospheric Systems 4000WE (formerly Aerovironment). This list may not be complete! A picture gallery is found later in this report.

3.1.2 Types of lidars

In this report, we regard lidars mounted in a turbine hub as special applications rather than standard solutions and we have purposely excluded them from this report.

Wind energy lidars have two working principles; pulsed lidars (Windcube and Galion) or variable focus height (ZephIR). The latter principle incurs also a height dependent probe length, which could be a disadvantage.

The lidar can be conically scanning or it can have discrete beam directions or other scanning patterns.

Lidars mostly depend on precision optics with moving parts, thus susceptible to mechanical wear, jamming etc. The aperture is smaller than for a sodar and so it could more easily be blocked by obstacles such as leafs or particles such as frost or simply buried in snow. Some kind of aperture cleaning, moving mechanism (with cleaning fluid) is probably necessary for a lidar to work for a longer period without maintenance although not all models seem to be equipped with such.

As far as we can see, none of the commercially available lidars are stand-alone units. The units are small and light and thus easy to transport and handle. On the other hand, they are easy to steal. We have not seen any transportation solutions. Separate energy supply is offered by some manufacturers. Please see below for some lidar pictures and judge for yourself their versatility.

3.2 Advantages and drawbacks of remote sensors

We have collected often expressed opinions for and against remote sensors as bullets below. *Our short comments are after each bullet – the comments express our view.*

Often the following is said in favour of remote sensors (RS):

- RS allow a quick initial assessment of the wind resource on a location since, ideally, one must only park the device, start it and wait.

RS allow an initial assessment of the wind resource. It is necessary to have a measurement plan in order to achieve a reliable data material. The plan must take into consideration the micro-meteorology of the area and basic statistical requirements. It is necessary to follow up on the measurements on a weekly basis to ensure that the RS is working properly.

- RS can be deployed at more locations within a site than tall masts usually can.

Given enough time and with a good measurement plan, RS are good complements to one or more tall masts on site.

- A RS measurement campaign gives a more reliable wind estimate than numerical modelling.

Numerical modelling is unreliable, especially linear models applied in a forested and/or hilly terrain. RS will give substantially improved resource estimates and lead to lower risk in revenue calculations.

- RS are the future of wind energy assessment

This remains to bee seen. Meteorological masts will probably be around for a long time. RS will probably improve a lot in the coming years. The user experience will improve RS application.

As drawbacks of RS, the following is heard

- It is not bankable

True. Standalone RS is not trusted for revenue and risk calculations.

- RS technique is accurate enough for reliable wind resource assessments

This is the view of the makers of RS and of the recent tests by consultants that we have reviewed in §2.4. It was however not the view of the WISE consortium some years ago, as reported in §2.3. RS should be used in combination with high-quality hub height cup anemometer measurements. Corrections to RS-data should be applied, §3.10.

- RS do not measure turbulence correctly

There are problems, theoretical and practical, in obtaining the same turbulence values with RS as with cup anemometers (§3.10.1a). The RS-value is biased which becomes important in high turbulence and should be corrected to compare with cup anemometers ((§3.10.1b). However, the requirements in terms of exactness are lower on turbulence than on mean wind speed which must be taken into consideration too. Again, RS should be used in combination with high-quality hub height mast measurements. Refer to §3.7 for more on turbulence.

- The RS theory as well as the practical application is difficult and there are no guidelines apart from (biased) RS-supplier advice.

Clear-cut guidelines are still missing. The user must familiarize herself with the sometimes difficult literature on RS. A deeper understanding of theory is a must in order to know what corrections to apply to the measurements to make them comparable to the cup anemometer which is still the de-facto *standard instrument in wind energy.*

- Lidars are very expensive and easy to steal

Lidars typically cost 2-3 times more than sodars. We have to date not seen any stand-alone application with cover, wheels, power solution etc. The user must take action herself against theft.

- Lidars are only for indoor use (i.e. sensitive)

Lidars are potentially sensitive to snow and ice, leafs and particles carried by the air. Like sodars they are not maintenance free instruments. With a proper and probably high maintenance level, they will work.

- Sodars emit noise and gets ruined by thugs

Sodars emit audible tones. In quiet situations inviting to outdoor activities, such as a still summer night, the sodar can be heard over distance, especially by younger persons – older people seldom hear these high tones very well. If the sound is received as a nuisance or not largely depends on the attitude of the listener to the planned wind farm project. A sodar reveals itself by the sound so it is not easy to hide from thugs. Sturdy locks, removal of the wheels and of attractive loose parts such as solar panels are some countermeasures. GPS-trackers and video surveillance are others. A contracted neighbour is the best method according to our experience.

- Sodars are heavy and require at least a tractor or a helicopter for installation

This is true, unless there is a road to the deployment position.

- RS don't make it through a Swedish winter

Certainly not without maintenance and a close watch on the data.

Of course, the above opinions were shaped through practical experiences as well as gossip-type ones. What is true is that remote sensors are debated and that different parties in the wind energy business value them differently because they have different needs:

- The <u>project developer</u> wants a cheap and quick resource assessment

- The turbine supplier wants extensive and correct data on turbulence and wind shear
- The investor/bank wants an exact resource assessment for a low-risk investment

3.3 Sodar versus lidar

In Cattin et al (2010) an interesting field measurement campaign with both sodar and lidar was reported. We note that the comparison appears to have taken place in a high-altitude mountainous region which could explain (through low aerosol content) the low lidar data yield reported. Needless to say, the post processing needs and some other issues are probably model-specific, but since comparisons like this are rare, we have chosen to include the basic finding in the table from their report.

SODAR	LIDAR - ZephIR
- Decreasing data availability with height	+ High data availability until 150m
+ Good data availability for low winds	- Low data availability for winds <4m/s
- Low data availability for winds >20m/s	+ High data availability for winds >20m/s
- Careful post-processing needed	+ Little post-processing needed
- Careful use of absolute values	+ Absolute values seem ok?
+ High vertical resolution (10m)	- Only five height levels
+ Fast GSM download	- Very slow (expensive!!) GSM download
- Moderate transport and installation	+ Relatively easy transport and installation
- High energy consumption	+ Moderate energy consumption
- Sound Emission	+ No sound emission
+ Moderate Costs	- High costs

From Cattin et al. (2010). The sodar apparently is an Aerovironment 4000(?) – a phased array sodar.

3.3.1 Sodar

Until recently, sodars were not recommended as standalone instruments from an uncertainty point of view. This was pointed out in studies from around 2005, §2.3. These studies recommend a 30-40 m permanent meteorological mast – with high quality sensors – located next to the sodar during the entirety of the measurements campaign.

Even more recently, beginning 2009, a number of instrument evaluations, reviewed in §2.4, that seem to relax the requirement for a closely neighbouring and permanent mast for calibration. Although this looks very promising, it must be recognized that several of the evaluations were carried out as assignments for the sodar/lidar manufacturers, and in some cases, according to schemes set up by them. The tests were all carried out in very simple terrains.

3.3.2 Lidar

The lidar has had less time to evolve as a wind energy instrument than the sodar. Consequently, less material, evaluations and experience with lidar has accumulated than with sodar. Also, the existing lidar systems seem less practical in terms of stand-alone solutions.

Lidar and sodar physics are quite different due to differences in wavelength, signal speed and observational sample size. The lidar has no problems with diffraction and external noise. On the other hand the probe length is bigger than that of a sodar and, for one model, height dependent, more on this is found in § 3.10 below. The larger zenith angle of standard lidars will give larger orographic errors.

A lidar typically costs two or three times as much as a sodar, not counting differences due to peripherals such as power supply, transport and protection facilities etc.

3.4 Acceptance of remote sensing

Remote sensing is just beginning to gain some acceptance for wind resource assessment and power performance verification. There is however a long way to go before a general acceptance as a tool with a bankable performance. Several actors in the wind energy industry are negative towards remote sensors or at least of some applications of them. Thus, the remote sensor user needs to consider the validity of the measurements already <u>before</u> measuring and to consider the opinion of the end-user, be it a bank, a turbine supplier or the company board.

Among turbine manufacturers there are different opinions. Some manufacturers are satisfied with climatic condition assessments partly based on remote sensing whereas others are reluctant to consider such data at all. These discussions however turn out not to be as black and white as it may appear. As is often the case in Sweden, the measured data may be scarce and of poor quality in combination with complicated terrain. Since some modelling tools fail to even roughly predict the conditions over the entire site, sodar data is often accepted in such cases as a more or less informal decision support.

Banks and other investors less often have a strong opinion on the measurement techniques for the revenue estimates. Instead, for small projects in a known wind resource environment, they sometimes rely on the calculations of the client and thus on his recommendations on remote sensing. Most often however, and always for large projects, the bank will have the project evaluated by one or two consultants external to the client. Consultants too, are divided in the opinion on remote sensors. Our impression is nevertheless that most consultants carefully point out the potential uncertainty and flaws of remote sensors and underline the need for high quality on-site mast measurements.

The International Energy Agencies (IEA) sodar workgroup writes: "*It can be demonstrated that, in the absence of influences such as fixed echoes, sodar has an inherent accuracy that is comparable to anemometry in the field, and therefore, if certain conditions are met, sodar data should be bankable. Those conditions include verification of the individual sodar's performance by the methods discussed … in this document*", cited from Moore & bailey (2010).

We have noted a cultural component in the opinion on remote sensing. For example, in Sweden the sodar use is widespread and many project developers strive to motivate the use of sodars to their investors. Sodar is a popular instrument also in Germany and in USA. In Great Britain however, we note a prevalent doubt in sodars but a confidence in lidars. Lidars are also preferred to sodars in France and Spain.

3.5 Market survey

Below we have made a picture gallery on all remote sensors for wind energy that we have found. The pictures are mostly from manufacturers sales material and have been chosen so that the reader could get an impression of the complete solution or usability.

We have not researched prices, but generally lidars are much more expensive than sodars even without power generation and other necessary peripherals.

Second Wind sodar model Triton.

Two AQ Systems model AQ500 sodars.

Atmospheric Systems sodar model 4000WE.

Scintech / TORAGON sodar model WindCollector2.

Atmospheric Research & Technology LLC sodar model VT-1. Note the anemometer, apparently 4-6 m high, and the tube mast in the background.

Zephir lidar, total height ca 2 m.

Windcube lidar.

Galion lidar.

3.6 The view of the International Energy Agency (IEA) on remote sensing

An IEA Topical Expert Meeting was held in October of 2009. At the meeting, a document “Recommended Practices for the Use of Sodar in Wind Energy Resource Assessment” was discussed. We have studied the fifth draft version, dated July 2010, Moore & Bailey (2010). The document can be said to describe the view of the IEA working group. Recent communication, Avia (2011), indicate that the draft version will be final in a near future with some, apparently minor, modifications.

We have no information on the status of the corresponding document concerning lidar.

Moore & Bailey (2010) is a general document. It contains a selection of aspects on sodar use and some recommendations. The document is not usable as a guide line for practical sodar usage. Rather it may be one of more starting points for the development of such practical guidelines, in-house in a consultancy company for example.

In an appendix, “A Protocol for Verification of Remote Sensing Instrument Performance” is found. The name implies that the protocol is equally applicable to sodars and lidars.

3.7 Measuring turbulence

The sodar as an instrument for turbulence measurement is debated. More than some turbine suppliers are reluctant to use sodar turbulence or refuse to do so.

The turbulence is not an as high-precision parameter as the mean wind speed. It is neither possible nor necessary to determine it as accurately as the mean.

The problem of measuring turbulence with remote sensors is described below in §3.10.1a. A bias correction which might be required in high turbulence environments is given in §3.10.1b.

3.8 Influence of weather

Several sources stress that lidars are sensitive to fog and low aerosol content and that sodars could be sensitive to rain, se §3.10.3j,k below. We have not seen any quantification of such sensitivity or even mention of it in the manufacturers specification, although some manufacturers recommend that precipitation periods be filtered out.

Cold weather has a profound effect on remote sensors. The power supply and the antenna heating seem to be the most critical things. A petrol engine can easily run into problems in low temperatures when it must be cold-started every day or so. Running it continuously is not feasible either. The antenna can be filled with snow which could melt, freeze again and deform the antenna shape so that it does not work. Although sodar manufacturers are trying to invent clever solutions, there is presently no alternative to active maintenance and looking after the instruments and very careful examination of the data to detect errors.

Presently, we know of no lidar solution that can be deployed in conditions such as during Swedish winter.

3.9 Successfully using remote sensing

A key component in the successful use of remote sensing in wind energy is knowledge. Still today, most applications in this area to some extent imply pioneering work, the result of which must be analysed with respect to accuracy if it is to be further used for bankable projects.

Studying the proposed “Protocol for Verification of Remote Sensing Instrument Performance” appended to Moore & Bailey (2010), it is obvious that the sodar user must possess knowledge in

- physics (acoustics, wave theory)
- meteorology and
- statistics.

We would like to add to this list also

- measurement technique and
- signal processing theory and application.

In the case of lidars also

- optics and knowledge of laser

must be added.

As many sources have pointed out, closeness to data from high-quality cup anemometry is also required for successful use of remote sensors. However, it is up to the remote sensor user to obtain this closeness, in other words, to make probable that the remote sensor data are correct in each case.

3.10 Differences between cup anemometers and remote sensors

We have tried to ease the reading of this section by dividing the differences into three groups roughly by their character. The first group is mainly due to measurement principles, the second to technical solutions and the third deals with differences due to practical circumstances.

See also the error budget in §2.3.3.

3.10.1 Differences due to measurements principles

a) Point measurements versus volume measurements

A cup anemometer has a size of the order of 10 cm. In contrast to this, at 100 meters above ground, a monostatic remote sensor with a zenith angle of 15 degrees measures the wind flow in an area enclosed in a circle with a diameter of 54 m. This may be defined as the size of the virtual sensor of the remote measurement device. It is thus more than 500 times the size of a cup anemometer.

The measurement beam, be it laser or sound, also has a certain size which in both cases is bigger than the cup arrangement of the anemometer.

Since the wind speed is random it must be summarized in the form of statistical measures such as its average and standard deviation. At 100 meters above ground, the turbulent structures of the wind have length scales from a millimetre and upwards to a few hundred meters. (The upper limit is diffuse since the difference between “turbulence” and “gust” is undefined.) During one ten-minute period, the air typically moves 3 to 10 kilometres which means that the air is renewed 30000 to 100000 times in the cup anemometer measurement volume and 50 to 200 times in the remote sensor volume. Loosely speaking, there is a sufficiently large sample of independent wind measurements passing through both sensor types for the mean wind speed to be a reasonably stable measure. Therefore the issue of spatial averaging due to the large size of the virtual sensor of a remote sensing device is not so severe because large volumes of air are sampled anyway during the standard ten minute measurement period, if the sampling is complete. If the sampling is incomplete, that is, if 50 or 75 percent or more of the observations in the sample are missing, spatial and temporal averaging will be poor. The result will then be highly random too.

The turbulence measurement is more difficult to interpret. The mere concept of turbulent intensity defined as the coefficient of variation (standard deviation divided by the mean) in a small, cup anemometer volume (about one litre) is difficult to compare to non-simultaneous measurements in more than one big volume (thousand cubic metres) separated by tens of meters, as for remote sensors. We have only found one study relating to this and it is a conference presentation, Schlipf et al (2010). That presentation is not straightforward to interpret but could mean that turbulent scales below 50-200 meters could be less well resolved. Even considering the inertia effects on a cup anemometer, giving underspeeding and/or overspeeding, the difference in resolution ability between a remote sensor and a cup anemometer would be huge.

The conclusion is that (in good conditions) a cup anemometer and a remote sensor measure much the same mean wind speed but quite different turbulence.

Vertical volume averaging-effects are discussed later in the 'probe length' section 3.10.2.

b) Vector and scalar wind averages

A properly mounted cup anemometer, being independent of wind direction, gives a number of <u>scalar</u> wind speed measurements; 600 per ten minutes if a sampling frequency of 1 Hz is used. The logger averages these over ten minutes.

A remote sensor on the other hand, usually calculates <u>vector</u> wind values which are then averaged over ten minutes. The scalar (anemometer) and the vector (remote sensor) averages are respectively

$$U_s = \overline{\sqrt{u^2 + v^2}}$$

$$U_v = \sqrt{\overline{u}^2 + \overline{v}^2}$$

where u and v are the individual measurements (an ensemble) during a ten-minute period. An overbar signifies average.

It is easily seen that these two averages are different, that the vector average is always lower and that the difference increases with the turbulence intensity.

We note that all the third part evaluations, § 2.4, were performed in low-turbulence environments on average, giving small differences due to this effect. We also note that conditions in Sweden are usually more turbulent, which means that the difference is larger.

Thus, it is necessary to apply a correction to sodar and lidar winds in order to obtain values that are comparable to cup anemometer values.

It is not an error that causes the vector mean to differ from the scalar mean, but it is an error to use a vector mean as if it was a scalar mean.

Having said that, for economy of expression we will acknowledge the fact that the industry standard is the scalar mean wind speed and phrase the adjustment as a <u>correction of vector mean</u> to obtain a scalar mean.

Bradley (2007) and other authors provide a correction to apply to vector (sodar/lidar) mean wind speed to translate it into a scalar (cup) value. However, as the turbulence is derived from the roughness length, which is not very precise, the resulting formula is unreliable. In Clive (2008), the turbulent intensity is used to derive a vector/scalar factor, which makes more sense since the remote sensor actually measures the turbulence, let be to a lower accuracy than the mean wind speed. However, a less plausible wind distribution was assumed (uniform direction on an interval).

Instead we assume that the wind speed is normally distributed during each averaging period, normally ten minutes. This is observationally supported by high-frequency sonic anemometer measurements. In this case, the vector/scalar mean ratio may be calculated simply as

$$\frac{U_{s,i}}{U_{v,i}} \approx 1 + \frac{1}{2}\sigma_i^2$$

which is correct to σ^3, where σ is the true horizontal turbulent intensity as opposed to the sample turbulent intensity. (In this section, the word variance is used as a synonymous to the square of the "turbulent intensity" = standard deviation divided by mean wind speed. We note that it is not quite correct in physics language but accepted in the wind business.) The index *i* signifies that the formula is valid for ten-minute observation number *i*. Substituting for σ^2 the sample variance s^2 will give a reasonable approximation, as long as the turbulence is not severe. Another condition for the use of the formula is that the number of (vector) samples constituting the mean is not too low; at least 30 individual sodar or lidar "shots" are required. This illuminates the problems that occur if the remote sensor manufacturer does not provide the sample size information as an output from the instrument!

For high turbulence levels, the turbulent intensity bias must also be considered

$$s_{s,i}^2 \approx s_{v,i}^2(1 + s_{v,i}^2)$$

correct to s^5. s_s and s_v are the measured sample scalar and vector variances respectively.

These formulas should be applied point-wise, i.e. for all observations in the time series. We call this the canonical correction. It often happens that the remote sensor produces fewer (or much fewer) values of turbulence than of mean wind speed. Applying corrections of this type may then lead to a considerable data loss, in turn probably leading to biased wind speed estimates since loss of turbulence data is probably conditioned on wind speed, either directly or through the atmospheric conditions. On the other hand, not correcting the remotely sensed wind speed will lead to an under estimation of the wind resource.

One approach is to replace σ_i^2 (i.e. $s_{v,i}^2$) by $\overline{\sigma}^2$. The corrections then become constant and can be evaluated for all available wind speed means. This so-called naïve correction however is an under-estimation of the canonical correction. It can be shown that a better choice is to assume that σ is normally distributed with mean $\overline{\sigma}$ and variance β^2. The correction then becomes

$$\frac{U_{s,i}}{U_{v,i}} \approx 1 + \frac{1}{2}(\overline{\sigma}^2 + \beta^2).$$

An obvious improvement of this formula is to let the right hand side depend on U, thereby taking conditioning into account – with the drawback of making the application more complicated.

c) Acoustic travel time

The wind speed is only one order of magnitude smaller than the speed of sound in air; the former is roughly 5 to 20 m/s and the latter 330 m/s, a relation 1/60 to 1/15. As a consequence, the air parcel reflecting the sound will move slightly as the sound moves through the air. This is not accounted for in the schoolbook derivation of the Doppler effect on/by a moving sender/receiver. In WISE C (2005) see §3.4, this so-called beam-drift error is given for a three beam sodar using the vertical wind component:

$$\left|\frac{\delta U}{U}\right| = \frac{U\sqrt{2}}{c}\tan\varphi$$

where $\delta U/U$ is the maximum relative wind speed error. U and c are the wind and sound speed respectively and φ is the zenith angle. As a handy but rough estimate, the max relative error is:

$$\frac{\delta U}{U} = \pm\frac{U}{1000}.$$

It evaluates to around one percent and depends on the wind direction.

The (pulsed) lidar does not have this problem since the air hardly moves at all during the very short travel time of the measurement pulse; the ratio U/c is about 1/30 000 000.

3.10.2 Differences due to measurement technique

d) Probe length

A sodar and a pulsed lidar emit measurement pulses. The pulse is reflected and received. The signal processor ‘slices’ the received signal and analyses each slice which corresponds to one level above ground. We would like to have very narrow slices so that we could determine exactly from which level it comes. That would give us a good *vertical resolution* of the wind speed, i.e. an exact wind profile. However, a very narrow slice contains very little information, so the value of the wind speed in a too narrow slice is very uncertain. This imposes the contradicting requirement for thick slices. These constitute an uncertainty relation; there is a trade-off between vertical resolution and wind speed accuracy.

The thickness of a slice is sometimes called “probe length”, especially in the lidar context. If the probe length is too large, we will not know at which height a sodar or a lidar value is valid. For instance, if the probe length is 20 meter is the 100 meter value a mean between 90 and 110 meter? Is it a weighted mean? Perhaps it is actually the wind from 85 to 105 meter?

Defining now the wind speed error as the difference between the remote sensor wind and the cup anemometer wind we may conclude:

- the error increases with the probe length
- the error increases with the wind shear.

An approximate relationship, assuming a wind power law, $U \propto z^{\alpha}$, and a uniform weighting function across the probe length, L, is:

$$\frac{\delta U}{U} \approx \frac{\alpha(\alpha-1)}{16(\alpha+1)}\left(\frac{L}{z}\right)^2$$

where the relative error is $\delta U/U$ at measurement height z. We see that the error is negative for $\alpha < 1$ i.e. for realistic α. For a probe length of 20 m and $\alpha = 0{,}3$ we get an error of about –0,5 % at z = 100 m.

The main problem here is to find out the real probe length and the weighting function. The suppliers do not supply this information. Some suppliers concoct own algorithms that combine information from neighbouring levels, thus actually increasing the probe length effect, i.e. smearing out the wind profile.

As far as we have been able to find out, the probe length effect has not been studied experimentally. A brief comparison of mean winds from continuous and pulsed lidars is found in Mikkelsen (2009). The presentation concludes with an interesting calculation of the vertical averaging error of a Zephir (continuous) and a Windcube (pulsed) as a function of height.

e) Temperature effects

The speed of light is very weakly dependent on temperature. The direct temperature effects on lidar must therefore be negligible. Of course, the practical performance may be strongly temperature dependant, but this is not the issue in this section.

The speed of sound increases by about 5 % between –10°C and +20°C, thus there is an important dependence. For phased array systems, the zenith angle will increase with temperature. The reason is that the beam is formed by creating an interference pattern by phase controlling many loudspeakers. The sound beam angle depends on the relation between loudspeaker distance and the wavelength. Since the sound speed changes with air temperature, so will the wavelength and thus the beam angle, see for example Bradley (2007). This must be accounted for by measuring the temperature and using it in the wind speed calculations in a correct way, alternatively, the sodar must adjust the phase control to temperature compensate.

A dish antenna sodar is not affected by this; the zenith angle is temperature independent.

Another temperature effect has to do with travel time. In warm air, the travel time is less than in cold. The sodar must compensate for this to determine accurately the height from which the echo comes, i.e. the measurement height. If not compensated the echo would come from a higher level in warm air. Since the wind usually increases with height, the wind would be overestimated in warm air due to this travel time effect.

The Doppler shift is also temperature dependent. In air, the following approximation holds for, δf/f, the relative Doppler shift

$$\frac{\delta f}{f} \approx \frac{2V}{c-V}$$

where V is the wind speed (projected on the beam direction) and c is the sound speed. In warm air c is higher and so the Doppler shift, δf/f, decreases even if V remains the same. Thus, the sodar would underestimate the wind speed in warm air due to this Doppler shift change effect.

Obviously and fortuitously, these two effects counter act each other. If a power law for the wind profile is assumed, the contributions can be summed up, simplified and expressed as:

$$\frac{\delta U}{U} \approx (\alpha - 1)\frac{\delta c}{c}$$

or, if expressed in terms of temperature error, δT, instead

$$\frac{\delta U}{U} \approx \delta T\,\frac{(\alpha - 1)}{550}.$$

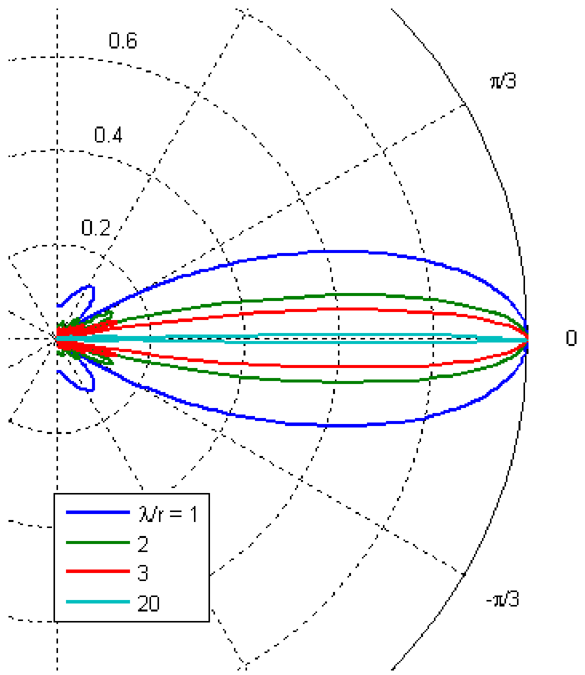
As above, δU/U is the relative wind speed error and α is the power law exponent. For example, suppose that the sodar thermometer measures +25°C, but that the real air temperature is +10°C so that $\delta T = T_{real} — T_{sodar}$ = —15°C. Assuming an α = 0,3 gives δU/U = +0,02 meaning that the sodar overestimates the wind speed by 2 %. This magnitude of error could easily occur if the sodar thermometer is unsuitably mounted, see § 3.10.3 below.

f) Antenna aperture

Both sodars and lidars have an 'aperture' i.e. an opening through which radiation (waves) is transmitted and received. The aperture of a lidar is the lens, the sodar aperture is the phased array surface or the antenna dish combined with the opening in the antenna housing. A typical lidar aperture is a few centimetres. The lidar wave length is roughly 1 μm or 0,0001 cm. Thus the aperture is 50 000 times larger than the wavelength. This enables a very good directivity; the laser beam goes in a straight line and does not spread (diffract). In everyday physics, this is also the reason to why it is possible to hear but not to see 'around a corner'.

On the other hand, a typical sodar uses a wavelength of around 10 cm whereas the aperture is a few times larger; 30 to 100 cm. Such a small (in terms of wave length) aperture results in a significant spreading (diffraction) of the sound. It does not travel as a narrow beam but spreads to the sides in complicated patterns with a main lobe and side lobes. The same thing applies to the sound received; the sodar 'hears' sound from multiple directions.

The difference in sodar and lidar beam width is illustrated in the figure below.



The blue curve is the directivity of an aperture with a diameter equal to the wavelength; λ/r = 1. The directivity is the wave amplitude in a direction divided by the amplitude on the aperture normal (to the right in this figure). The blue curve shows that the sound waves are emitted in a wide sector – and received from the same sector. The green and red curves correspond to bigger apertures which gives a narrower sector thus better directivity – approximately sodar size apertures. The turquoise curve is for a much bigger opening/smaller wavelength through which the waves go almost as a straight beam. In reality, the lidar aperture is many times wider than this.

In this respect, lidars and sodars are very different instruments and, potentially, lidars experience fewer complications.

For a particular sodar however, the aperture issues are constant and independent of external factors such as wind speed and temperature. Thus, it should be possible to compensate for aperture/diffraction errors. We have however, not seen this aspect explicitly treated by any sodar manufacturer.

The interesting topic of diffraction is treated in Bradley (2007) and in any standard wave physics text.

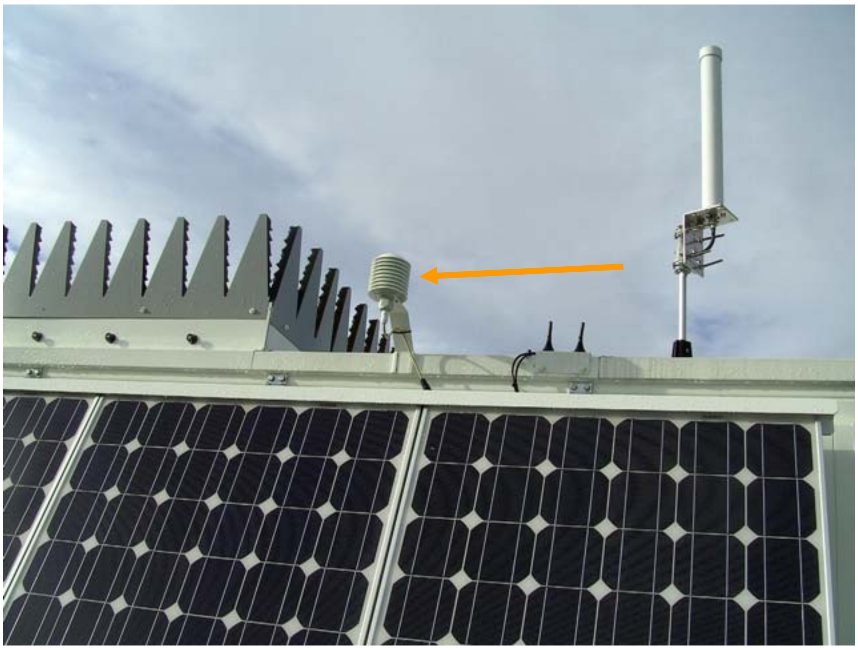
3.10.3 Differences due to practical circumstances

g) Thermometer mounting

Temperature effects on cup anemometers are icing which is also a strong function of air moisture. The icing behaviour of cup anemometers is unpredictable and could result in over- or underestimation. Some cup anemometer models have lubrication that freezes or becomes more viscous resulting in under estimation of the wind speed. Certainly, these effects must be considered in cup-sodar/lidar comparisons.

Sodars must be temperature compensated because the air sound speed varies with temperature as detailed in 3.10.2. If the sodar is placed where it gets much warmer or colder than the mean temperature in the air up to the measurement height, this will introduce a certain error, §3.10.1c.

- Avoid leed [läade] and sunny places such as the north side of a forest clearing [glänta], or occasional positive temperature deviations of 5-10^{o}C can be expected.
- Avoid pit holes in the terrain in which very cold air will accumulate in the winter, or occasional negative temperature deviations of 10-15^{o}C can be expected.
- The thermometer of the sodar must be placed on its shadowed side. With the mounting as in the figure below, positive temperature deviations of 15-20^{o}C can occur.



A thermometer in a radiation shield (arrow) is mounted above a black, southward facing surface. Very large errors will occur whenever the sun shines. On the back of the machine in the shadow is a much better place.

h) Tilting sensor

The tilt error for any remote sensor is

$$\frac{\delta U}{U} \approx -\frac{1}{2}(\delta\varphi)^2$$

where $\delta\varphi$ is the error in zenith angle (in radians!), see e.g. Bradley (2007). Note that a tilting instrument will give a too low speed.

- Place the sensor on firm ground. Iced earth [tjäle] will move when it thaws which must be taken into consideration.
- Check horizontation before and after the deployment with a separate vattenpass.

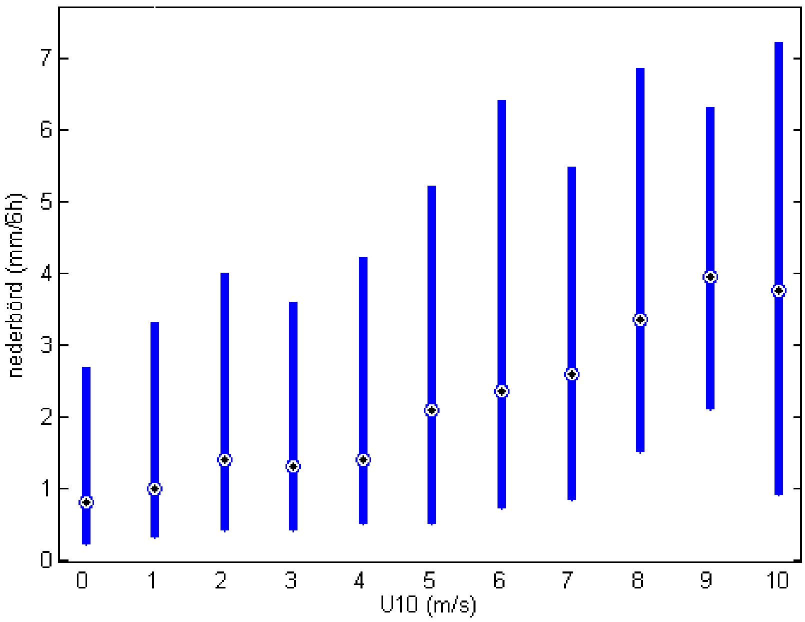
i) Distance mast-sodar

When comparing/calibrating a remote sensor against a met mast, the separation distance must be as small as possible to minimise effects of them not measuring the same wind. If closeness can not be achieved, the deviations must be estimated which is difficult.

j) Rain or snow

For example Moore & Bailey (2010) point out that sodars could be sensitive to rain. The rain drops have another speed than the wind and thus the sodar echo is a combination of rain-drop echo and air-echo. We have not been able to find a study of this phenomenon. Instead all sources that treat this issue recommend that sodar data during rain should be excluded. This, in turn, requires a rain gauge be installed with the sodar. Since precipitation has pronounced small-scale patchiness, a remote rain gauge will not suffice.

However, deleting “rainy wind data” from the material will insert a bias in the mean wind speed estimate if rain and wind are correlated. In dry places, this will not make an important difference but in a rainy location the bias could be significant. In the figure below, we can see that there is a correlation between precipitation (rain and snow) and wind speed (at 10 m above ground). There is more precipitation at higher wind speed. Now, excluding rain means lowering the mean wind speed. The picture is just a coarse statistics for Göteborg. A rainier place will show stronger effects. For example, Borås has some 30 days with more than 10 mm precipitation per year, with November having more than double the amount of april. With this uneven distribution of eliminated data, intra-annual varying wind speed biases will be introduced.



The dots show the median of the six-hourly precipitation for SMHI Göteborg A (at Skansen Lejonet) versus the wind speed. The blue lines connect the 25 and 75-percentiles. Only observations > 0,1 mm/6 h are included. Despite the coarse resolution of this observational material, a connection between precipitation and wind speed is apparent. Observations courtesy of SMHI.

k) Fog or clouds

Little is known (or at least written) about the sensitivity of lidars to fog and low clouds/cloud base. Therefore, the lidar user must estimate the effects of these herself and include in the products derived from the observations. In places with frequent orographic fog, such as the Swedish mountains [fjällen], conditioning effects will be significant. Furthermore, professional observation of these weather parameters requires special and quite expensive meteorological instruments which probably are inaccessible to next to all. Finally, like precipitation, fog and cloud vary widely over short distance.

l) Signal processing

In Moore & Bailey (2010) in appendix § 3.3 and WISE c (2005) § 5.3 it is underlined that the signal processing and data filtering must be adequately known in order to use the resulting wind and turbulence data. For instance, if one does not know the number of individual samples that make up one ensemble (from which the mean and standard deviation are calculated) it is not possible to calculate the standard uncertainty.

We recognize that the instrument manufacturers seek to develop user-friendly solutions in terms of hardware and software and that this means trying to find a middle-way between on one hand requiring the user to make advanced settings and choices in terms of operation and data processing and on the other hand, making the instrument fool-proof by choosing settings for the user leaving few or no options.

The black-box approach is however a problem that hampers development of application of both sodars and lidars. The instrument developers may be unwilling to reveal what they see as the inner workings of their products while attempting to enable the instruments to work in different regimes with respect to weather, orography, turbulence etc. At the same time, the instrument users will probably see more real, varying and challenging situations than the developers and so for the user it is most handicapping not knowing settings, filtering and data processing when interpreting the measurements and possibly comparing to cup anemometers.

In our opinion, this slows down the rate of improvement of the instruments and hampers the trust and use of them.

m) Noise

We have not found very much written on this topic. In her presentation, Ylva Malmberg reports interesting findings in this respect, §4.2. Naturally, an acoustic instrument is sensitive to the frequencies which it uses to measure the wind. Usually the frequency range is 2500-4500 Hz or, in wavelength, 13 to 7 centimeters, or d’’’’ (key 78 on an ordinary 88 key piano) to beyond c’’’’’ (key 88).

Generally, fixed noise sources that emit in the frequency range above should potentially disturb the measurements. Episodic noise, from cars on a road for example, has less potential impact and the impact must decrease with decreasing traffic intensity. Therefore it has a diurnal cycle.

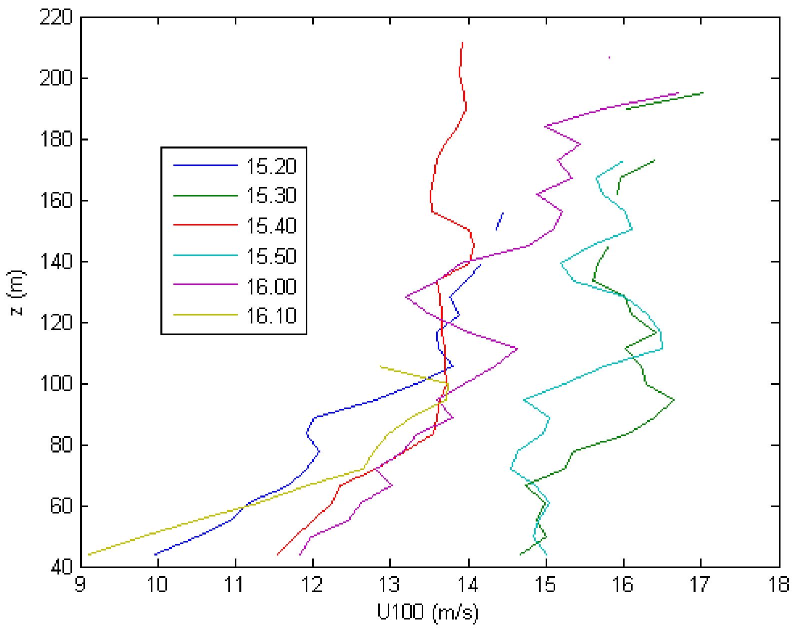
In §4.1 in Moore and Bailey (2010) some further notes are given on the noise topic.

n) Unknown effects

All cup anemometer, sodar and lidar observations must be scrutinized for oddities. Physically impossible situations such as super critical shear or speed spikes must be found and deleted from the time series before they are put to further use. As a general rule of thumb, the error in the statistics of not deleting erroneous observations is larger than of the holes that they leave.

An experienced analyst who masters applied meteorology and hydrodynamics is necessary to detect, understand and appropriately treat strange data.

In the picture below we can see a very common pattern. Unstable profile features are ubiquitous. It is not possible to judge whether these highly improbable features really exist or if they are just a result of small-sample size because the sodar does not report sample size.



An example of wind speed profiles, six ten-minute values during an hour. Some of the gradients, e.g. the dent at 130 m 16.00, represent unstable and thus highly unlikely flow situations. Could it be that these mean profiles actually represent a small sample of a few minutes or less?

4 Workshop

From the presentations below it is apparent that knowledge on the use of remote sensors is growing rapidly but that there is a huge potential for improvement. A lot of the effort so far has actually not in been using the remote sensors operationally but to compare them with cup anemometers and with one another – analogous to the focus of the remote sensor literature, §2. Opposite to the literature however, the interest of the contributors on the workshop is much more focussed on practical usability and accuracy than on theory and extensive deviation studies.

The conditions and locations reported by the contributors contrast sharply to the instrument evaluations in §2.4 above. The latter were all very simple terrain, power grid connection, theft protection and so on, whereas in the real applications none of these conditions existed. Our impression is therefore that the scientific and technical literature, project reports etc are inadequate in this respect and, for further progress in remote sensing, it must be completed by consorted efforts from the user community. No user or instrument developer or researcher alone can develop remote sensor usage skill effectively.

Most, but not all speakers this day, the 10th of march 2011, were reporting findings and experience connected to the sodar AQ500 by AQSystems.

Below we present the contributions based on the minutes taken by the VPC team. A few illustrations have been selected from some of the presentations.

4.1 Johan Hansson, Vattenfall Power Consultant

Field experiments with two AQ500 sodars have been conducted to learn more about measurement errors due to orography and to find a method to estimate the error. The field experiment was carried out in the following way,

- Two sodars were placed side by side at a flat terrain location.
- One sodar was turned 60^{o} at a flat terrain location.
- One sodar was turned 60^{o} and tilted 7^{o}, at a flat terrain location illustrated in the figure below.
- The sodars were placed next to a steep hill slope with the sound beams 60^{o} apart

The preliminary results show that the variability of the wind speed difference between the instruments is significant. Careful statistical analysis will be required to detect the comparatively subtle orographic effects that we are looking for. The first lesson learned is that is necessary to have big enough samples – long enough time series – in order to separate noise from effect!

Sodars at the field experiment in Sweden. The photograph is taken from Johans presentation.

4.2 Ylva Malmberg, Rabbalshede Kraft

Rabbalshede Kraft owns 12 sodars that are used as a complement to meteorological masts during winter and at larger sites. They also use sodar to verify turbines and energy yield at their wind farms. Based on their experience, Ylva Malmberg pointed out some factors to obtain useful measurements:

- Choose a suitable place to put the sodar at a site.
- Continuous follow-up and quality control of the wind data.
- Quickly fix problems when they occur.
- Routine maintenance of the sodar.

She also shared some experience with data loss due to the different background factors listed below

- Influence of background noise close to roads with heavy traffic caused data loss but no mean wind speed error.
- Influence of the electrical supply that cause vibrations. Caused data loss but not mean wind speed error.
- Problems with snow and ice in the antenna.
- Placing the sodar close to trees influences the calculated wind speed and cause data loss but at levels that are less important for wind farm calculations (50 – 60 m).

4.3 Anton Andersson, EON Climate & Renewables

EON use sodar as a complement to met masts and point out that the location for the sodar should be selected with great care. Anton reported that approximately the same correlation between two cup anemometers placed 20 m vertically apart in a met mast is found when comparing sodar and cup anemometer, and discussed conclusions that could be drawn from that.

He also demonstrated a storm event during which the met mast was unaffected while the sodar was loosing data.

EON is planning field campaigns in flat terrain as well as in complex to evaluate the performance of different remote sensing instruments; ZephIR, WindCube, AQ500 and Triton.

4.4 Esben Haldrup Eriksen, Vestas

Vestas own four lidars, two ZephIR (2007) and two WindCube (2008).

The lidars are used for assessment of extreme winds, power curve evaluations and to investigate problematic sites in the view of turbine functionality. Esben talked about the future for remote sensing in Vestas and that reliability is of great importance. Other things are:

- IEC approval is crucial; bankability, resource measurements and power curves.
- Turbulence measurements to better understand the turbulence measured with remote sensing instruments.
- Complex terrain, this is the place for using remote sensing.

Vestas does not use lidars for site wind resource assessment.

4.5 Kristina Lindgren, O2

O2 have considerable experience in sodar, owning 24 units of AQ500. Kristina talked about AQ Systems upgrades of their data collecting program, SODWIN-MCOM. The first version (2008) required 3 % correction of the wind speed. This correction was included in the next version (2009). In the latest version (2010) the wind speed has less spikes and is more evened out in time. According to AQ Systems this modification is based on their experience and done in order to resemble met mast measurements.

Kristina also showed problems with the temperature probe and noted that it should be possible to verify the measured temperature. The conclusions from Kristinas presentation are

- It is important to have information about the version of the data collection program that is used since it includes filters with secret inner workings
- Even though the mean wind speed values calculated with different program versions are similar, details in the time series differ. In order to get consistent time series, all data should be downloaded anew when a new version of the program is released. As a precaution, it is

recommended to save the raw data for future versions of the data collection program.

4.6 Linn Rognlien, Statkraft

Statkraft wants the lowest possible uncertainty in their revenue calculation. To achieve this they use several met masts in each project area, located in forested areas.

Beginning in 2007 Statkraft have tested AQ500 sodars by placing them close to 60 m met masts and have experienced

- good sodar-mast wind speed correlation, 0,97 (in mild weather)
- significant difference in mean wind speed
- low data yield from sodar
- much higher (50 %) wind shear from sodar
- technical problems and snow cause sodar data loss
- acceptable correspondence between sodar and mast in mild weather but not satisfactory during cold periods

The conclusion is that a lot was learned about handling the sodar but it was not usable in the project.

In 2010 Statkraft have begun evaluating a more recent version of the AQ500 sodar. Results are pending.

4.7 Daniel Gustavsson, Vattenfall Vindkraft

Vattenfall Vindkraft has considerable experience with remote sensing instruments owning 27 sodars and two lidars.

Daniel presented a study comparing remote sensing instruments and cup anemometers. The main conclusions from the study are

- Lidar measurements correspond well cup to anemometers at all heights. Overall, the lidar showed 2 % higher wind speed than the cup anemometer at 150 m.
- Sodar measurements correspond well to cup anemometer for heights relevant to wind farm purposes. Large deviation was seen above 150 m.
- Daniel recommended the 50-150 m configuration for the AQ500 as this gives the best vertical resolution and data availability.
- Since lidar and cup anemometer show good agreement, it was assumed that the sodar overestimated the wind speed above 150 m.

Daniel also shared his practical experience with lidar; there are several issues such as problems with electrical supply, broken components and computer failures. The same problem does not appear twice. In total there were 5-6 months worth of useful data from the two year period of measurements.

4.8 Jesper Knudsen, Ownpower

When comparing sodar to cup anemometer in met masts it is often assumed that the latter have low errors – even as low as the calibration certificate would imply. However, cup anemometers are frequently improperly mounted. The mast can be iced and thereby act as a compact body giving a stronger lee-effect that else. Non-heated and poorly heated anemometers may not reveal in an obvious way that they give quite erroneous data. Two pictures from the presentation illustrating these effects are shown below.

As success factors Jesper listed the following

- Using different instrument techniques and makes, redundance is achieved and the possibility to detect errors. For example sonic and different types of cup anemometers could be used in the same mast.
- Maintenance and surveillance of the data is necessary to prevent, detect and combat data (quality) loss
- The measurement length must be adequate
- One should minimize vertical and horizontal extrapolation as well as the extension of the time series to a long-time reference period
- Maximize the overlap between measurements and production

An iced mast with instruments mounted on a boom. From Jesper Knudsens presentation.

The cup of a Thies First Class captured in an instant showing snow accumulated in the cup. From Jesper Knudsens presentation.

4.9 Pia Hjalmarsson, Stena Renewable

Pia presented a project managers view on the use of remote sensing instruments. Some of the motivations for using sodar are the flexibility of the system and that it is quick and easy to place on a site. The first year (2009) gave a lot of experience, however some users guidelines could be helpful. Pia lists the following pros and cons

- Easy to install on a site.
- Cheap compared to met masts.
- Quickly put out on a site, no permissions needed other than from the land owner.
- Require a large amount of maintenance.
- Snow and ice in the antenna during winter.
- The maintenance is time consuming.
- Limited of knowledge in interpreting sodar data

4.10 Johan Welander, Vattenfall Services Nordic AB

Johans organisation has about 30 sodar-operation-years (AQ500) and 1,5 lidar-operation-years (WindCube). Based on this he presented the following experiences

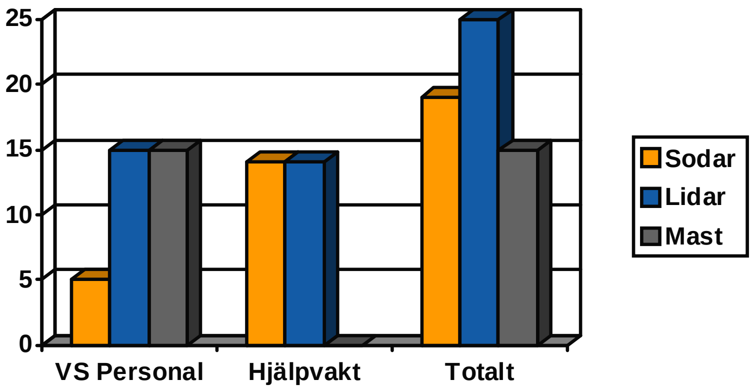
Sodar

- Low power consumption; 2 liters diesel/day, none with solar panels April-September
- a diesel heated antenna, solar panels, big fuel tank, big antenna, de-charging protector, temperature-humidity probe
- the supplier gives good service and has a large assortment of spare parts which are delivered promptly

Lidar

- high power consumption; 8 liters diesel/day
- works ok with 220 V grid connection
- unprotected on site
- good web-solution
- expensive
- two people needed for lifting

Johan presented the comparison below of sodar, lidar and mast maintenance requirement.



Number of service visits per year and unit. VS personnel, other personnel [Hjälpvakt].

4.11 Peter Schelander, Vattenfall Power Consultant

Peter started his presentation talking about wind variations on different horizontal scales. Concerning large scale variations, above 100 kilometers or so, the meteorological research community has gained experience over more than a century. Extensive research on small scale processes began around half a century ago. Both fields of research have earned much of its knowledge from observations. There is a limited knowledge of variation on the kilometre scale, which is significant for wind farms. Meso and micro scale modelling has not been able to satisfactorily reproduce the large variations which we are now are able to observe, much thanks to the use of mobile remote sensing.

Mobile remote sensing systems such as sodar and lidar have thereby already shown that they are valuable instruments for the wind energy community. The largest uncertainty in energy yield calculations is due to the horizontal extrapolation performed by models. This uncertainty can be reduced by using mobile remote sensing systems on more than one location at the site. At the same time we learn more about the local wind climate at the site.

Peter continued to say that we like to believe the model description of the reality as relatively smooth, but that Nature itself possesses a large variability even on short distances even at relatively uncomplicated sites.

Good measurements reduce the uncertainty, mobile remote sensing systems is the way to go!

4.12 Daniel Marmander, Triventus Consulting

There are several reasons to why sodar is not fully accepted by financers and turbine manufacturers Daniel said. For example: conservatism and the fact that the remote sensing technology is still young in the wind energy community. Several problems are not due to the sodar technology itself, but with use and handling of the instruments, unsuitable placement such as on soft ground causing the sodar to tilt.

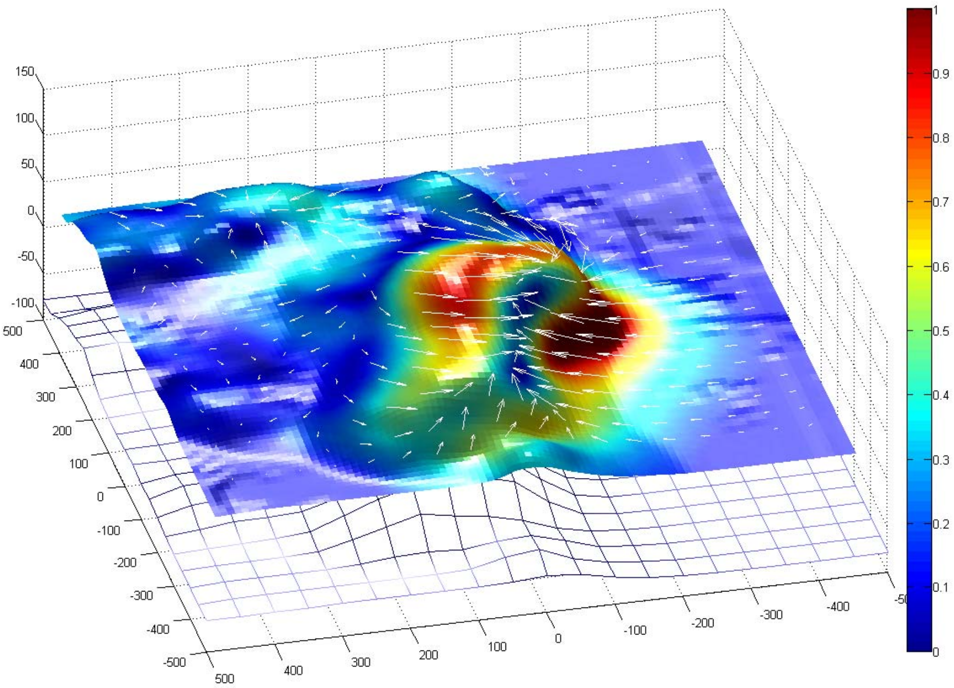
Daniel pointed out that the same requirement on validation is needed for sodars as for cup anemometers. He exemplified that the calibration procedure and outcome for the dominating sodar make in Sweden, AQ500, is poorly documented.

4.13 Lasse Johansson, Vattenfall Power Consultant

The influence of orography on remote sensors is a hot topic now. Monostatic remote sensors use the spatial distance between measurements volumes to deduce the air flow, as opposed to cup anemometers which measure the wind speed in a minute volume of air. Remote sensors rely on the assumption that the flow is constant – an assumption which is clearly violated if the flow accelerates, for example due to its curvature above a hill. The violation leads to an error in the wind velocity delivered by the remote sensor. The error is exemplified in the picture below.

The detailed computation of the error is quite difficult. Lasse expects debate if a large correction is applied to data from a remote sensor campaign. Corrections of 10 % in mean wind speed leading to changes in AEP of 20-25 % will be doubted unless supported by measurements. Even a 5 % correction will be quite difficult to accept. Was the correction computed and applied correctly? If yes – please prove it!

For now, the way to go is firstly to avoid places where the ‘orography error’ is too big and secondly to locate and install the remote sensor so as to minimise the error. For this, a simple expression for the error, portable into the forest or up on the mountain is needed. This is the goal of our current research.



The colored surface and the arrows show the magnitude and direction of the sodar wind velocity error on the 100 m surface above a mountain indicated by the mesh below. The colorscale, m/s, is given on the right. The undisturbed wind speed is 10 m/s from lower right. The maximum error is about 1 m/s or 10 % of the wind speed for this wind direction.

4.14 Minutes on the closing session

The following questions were discussed at plenum at the end of the workshop.

Several participants pointed out the need for more transparency in the filtering and processing of the data. The fact that the manufacturers keep the specifics of the treatment of data a secret limits the reliability and usefulness of the data and in effect limits the use and development of remote sensing, compare §3.10.3l.

- Data should not only be available in processed form but also as raw data with no filtering or averaging applied.
- Statistical specification such as the number of observations per ten minute average must be available or basic error estimates cannot be done.

- The factory calibration procedure and documentation must be improved.

We have seen several examples on how remote sensors can be used. But what should remote sensors, especially sodars, not be used for? One participant argued that sodar (AQ500) does not correctly estimate turbulence. Again, the signal processing and data treatment was brought to discussion. There was a general feeling that clarifying this issue is necessary for the future of remote sensing.

5 Conclusions

The main conclusions of the report can be summarized as:

- At the time of writing, May 2011, there is no standard for remote sensing of wind neither for sodars nor lidars. Moore & Bailey (2010) have compiled recommendations for sodar measurements (which are expected to be the foundation for a future IEA Recommended Practice in this area). In our opinion however, the recommendations are still to loose to be of use for the practising wind resource investigator.
- Remote wind sensors are being increasingly more used and more acknowledged by the different wind business parties. The instruments are however still under debate and some do not trust the data collected with them. Thus, one can not assume that data collected with remote sensors will be automatically recognized, but one must try to ensure that they will before the measurements commence.
- The quality and reputation of remote sensors have improved considerably in the last five years. Under some conditions, which vary with the instrument type and the measurement conditions, the user can obtain strong support for quality through a number of trials made (e.g. flat grassland), whereas in other conditions such support is lacking (e.g. forest).
- Today, sodars are more suited for use in field conditions than lidars. The former are available in models capable of working in forest and winter conditions for periods of time, whereas the latter are rather prototypes requiring large effort from the user in setting-up and maintaining them. Lidars on the other hand appear to have somewhat less measurement noise and higher data yield than sodars.
- In our opinion, remote sensors contribute greatly to a higher project quality if used correctly. The numerical modelling tools available are most limited and give very serious errors in the wind resource estimate. Remote sensors – combined with masts – can give a much more accurate estimation and thus higher profit and lower risk than numerical wind modelling alone.
- A necessary prerequisite for the successful use of remote sensors is knowledge. Without it the user can not estimate the measurement errors nor apply corrections appropriately or understand the phenomena which are observed. Knowledge in meteorology, acoustics/optics and statistics are the minimum requirements.

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