The use of Signals of Opportunity for the Measurement of Atmospheric Refractivity

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***Abstract*— The next generation of high-resolution numerical weather models require fine-scale (1-5 km) measurements of water vapour over large areas (>20,000 km^2). Existing observing techniques such as GPS are not able to meet these requirements. This paper discusses the feasibility of a novel technique for measuring atmospheric refractivity by the reception and processing of digital radio and television signals (DAB & DVB-T). This technique is step towards the realization of a wide-area water vapour sensor network made possible by the soon-to-be widespread availability of digital broadcast signals. The paper presents an error analysis and preliminary results.**

I. Introduction

The development of new high-resolution numerical weather prediction (NWP) models is being driven by the need to provide improved warning of severe weather. Key to the successful exploitation of these models is input data on the appropriate spatial and temporal scales which can be assimilated. In particular data on moisture in the boundary layer is currently lacking. This is important because the convergence of moisture at low-levels is linked to the initiation of severe storms. It has been noted that that the forecasting of convective initiation requires knowledge on 2-5 km scales [1]. Furthermore, it has been shown that even small differences in boundary layer temperature (≈1°C) and moisture (≈1 g kg^{-1}) can make the difference between no initiation and intense convection [2].

There are relatively few conventional sensors able to provide moisture measurements in the free atmosphere. The GPS water vapour technique uses dual-frequency receivers (cost £10,000-£15,000) to estimate the vertically-integrated water vapour [3] The Met Office operates a network of 120 such receivers, the data from which are routinely assimilated. However, while the data are useful there is a critical need for higher spatial and temporal resolution data within the boundary layer for both atmospheric science and for the development of future NWP. It is difficult to derive higher spatial information, of the order of a few km, without a very dense network of GPS receivers which would be prohibitively expensive. Furthermore, the application of tomographic techniques to estimate water vapour density fields from GPS data although improving have had only limited success (e.g., [4, 5, 6]. This is partly attributable to the geometry (the receivers are generally at similar heights) and partly because of the significant difficulty in estimating meaningful slant-path delay to individual satellites [7]. The vertical and horizontal spatial information that can be estimated from GPS is weak and is diluted because of the significant space-time averaging inherent in the processing. Other sensors technologies such as radiosondes, ground and space-borne microwave radiometers (with the exception of the new compact radiometers under development [8]) are either considerably more expensive and/or cannot meet the horizontal and vertical spatial and temporal resolution requirements for the new NWP models.

This paper proposes a new low-cost sensor based on the opportunistic reception of broadcast radio signals to address this need (target cost <£1000). Since the sensors are passive receivers their power consumption is low and could potentially be met from off-grid sources, e.g., solar. The receiver and signal processing requirements could be easily met with commercial-off-the-shelf components. The main advantage over GPS is that individual path delays can be directly measured, the effects of scintillation are minimal and there is obviously no error due to the ionosphere. In the longer term, the aim is to deploy a network of such sensors. Using the data from the entire network inverse imaging techniques similar to those developed for rainfall [9] can be used to derive two-dimensional, time-evolving boundary-layer moisture fields.

II. Signals of Opportunity for Remote Sensing

The use of broadcast digital radio signals for atmospheric monitoring has been proposed by Coleman et al., (2008) [10]. Although there are many radio signals that could potentially be used, in this paper we will consider only DAB and DVB-T. The reason for this is that both have desirable signal properties: phase/frequency synchronisation symbols which can be tracked and good autocorrelation properties. The former allows the signal phase to be readily tracked and the latter allows the separation of individual transmitters in the same frequency allocation.

The basic principle is similar to that used to estimate water vapour using dual-frequency GPS measurements. The propagation velocity of radio signals such as GPS, DAB and DVB-T depends on the refractive index of the air, which is a function of pressure, temperature and water vapour density (humidity). Changes in the water vapour density along the path lead to changes in the propagation velocity. This change in turn manifests itself in an additional delay in the arrival of the signal compared to what might be expected based on the geometric path. The change in the refractive index along the path with time can be observed by measuring the changes in the relative phase between the transmitter and receiver. In typical UK Summertime boundary layer conditions, short-term changes in refractivity are dominated by changes in humidity. In GPS terminology this is known as the "wet" delay. Although there will undoubtedly be some change in both pressure and temperature along the path depending on the length, it is the humidity that will show the most variation. In common with the GPS technique, a more precise correction for the pressure and temperature related hydrostatic delay can be made using surface measurements.

Although the basic concept is straightforward the technique poses a number of significant technical challenges. Preliminary experiments made at University of Bath using a receiver developed by University of Adelaide for passive radar studies suggest that the transmitters do not have the required level of phase stability for direct measurements of phase. Instead, difference techniques have been proposed whereby phase differences between pairs of stations can be used. The disadvantage of this technique is that it requires precise synchronisation between receivers.

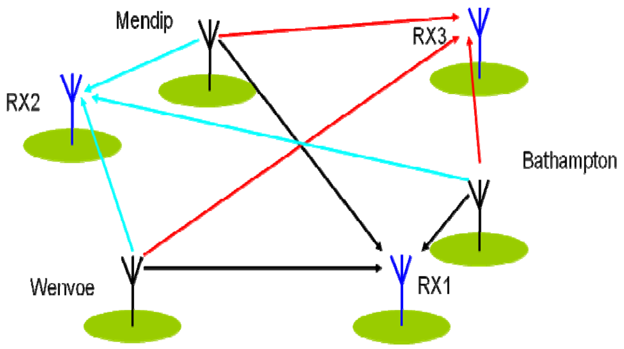

Figure 1: Schematic illustration of the basic concept. Transmitters are located at Wenvoe, Mendip and Bathampton. Receivers are RX1, RX2 and RX3 and yield integrated refractivity data which can be either inverted using tomographic or directly assimilated into NWP models.

The proposition here is that it is possible using a network of passive sensors, receiving DAB and DVB-T broadcasts, to measure path-averaged refractivity. Such a network would be very inexpensive to produce and run compared to dual-frequency GPS and radiosonde stations. Depending on the application these data could either be assimilated directly into NWP or the data inverted using a tomographic approach in real-time for science applications e.g., field campaigns. The long-term vision would be for an extensive grid of receivers with path-averaged refractivity estimated for all possible pairs of receivers from all transmitters (shown schematically in Fig 1). It could also be imagined that some paths could be across short sea-crossings or estuaries where few observations currently exist.

A. *Signal availability*

In the UK there is an extensive transmitter network for DAB (digital audio broadcast radio) and DVB-T (digital video broadcast for terrestrial transmission). The BBC national transmitter network currently comprises 148 DAB transmitters and 87 DVB-T transmitters (source: www.ofcom.gov.uk). In addition to these BBC sites there are 137 DAB transmitters operated by Digital One broadcasting other national services e.g., Classic FM. By the end of the Digital Switchover in 2012 digital radio and television signals will be able to be received almost everywhere in the UK. Critically, the transmissions are relatively stable in frequency and often locked to, or are traceable to, rubidium or caesium frequency standards.

Figure 2 Bathhampton DAB and DVB-T transmitter near Bath. Left: transmitter tower. Right: close-up of array.

Key to the success of the technique is the wide visibility of good line-of-sight signals. To assess the likely visibility of the signals we have considered a parabolic equation modelling approach [11] in conjunction with data from the SRTM database [12] and refractivity data taken from the UK Met Office UM (Unified Model) a mesoscale numerical weather prediction model.

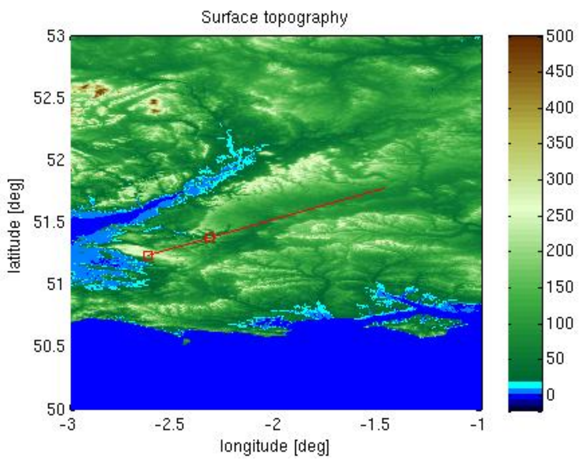

Figure 3: Surface topography along line of sight from Mendip (left square) to University of Bath (right square). Red line indicates direction of path loss calculation.

Figure 3 shows the surface topography in the South West of the UK, while the parabolic equation model derived path-loss is shown in Fig. 4. Note that the propagation is strongly dependent on the vertical refractive index structure.

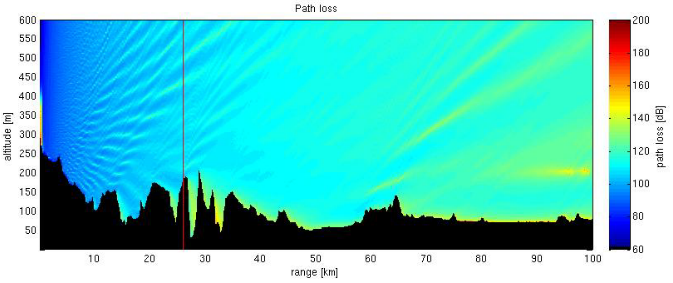

Figure 4: Vertical slice through terrain (as shown in Fig. 2.). Mendip transmitter is located at range=0 km. Vertical line at 27 km shows location of University of Bath.

B. Measurement principle and error analysis

The basic measurement principle is that of change in signal phase associated with change in the effective refractive index along the propagation path. The refractivity of the atmosphere in *N*-units can be written as:

$$N = \frac{77.6p}{T} + 3.73\times10^{5}\frac{e}{T^{2}}, \qquad (1)$$

where p is atmospheric pressure (hPa), T is temperature (K) and e is the partial pressure of water vapour (hPa). The refractivity is related to the refractive index n via:

$$N = (n-1)\times10^{6} \qquad (2)$$

The phase-shift ϕ, over a path length d, for a signal with a free-space wave-number $k_0 = 2\pi/\lambda$, in a medium of refractive index n is given by $\phi = d(k_0 n)$. Rewriting the partial pressure of water vapour e in terms of water vapour density the phase shift as a function of path length and water vapour density can be found (Table 1)

TABLE 1: DAB & DVB-T SIGNALS AND THEIR ASSOCIATED SENSITIVITY TO WATER-VAPOUR DENSITY

Signal	Frequency (MHz)	Wavelength (wave-number)	WV sensitivity $^\circ$ km^{-1} g^{-1} m^{3}
DAB	220-225	1.35m (4.65 m^{-1})	1.6
DVB-T	470-890	0.337m (18.64 m^{-1})	6.5

Given that the uncertainty in the measurement of phase is largely independent of frequency (say typically $< 0.1^\circ$) this would appear to favour larger wave-numbers as these have more sensitivity to water vapour. However, DAB has better coverage than DVB-T and the free-space loss and other losses due to diffraction are smaller. In the case of very long links the phase might be expected to "wrap-around". However, since the changes in phase are expected to be gradual it is straightforward to un-wrap the phase. The estimation of signal phase due to the propagation path assumes that both the transmitted phase and the phase of the receiver sampling clock are sufficiently stable over the measurement period.

C. Time and frequency stability

Key to the success of the technique is accurate estimation of change in signal phase. For a single receiver this relies on stable transmitter phase. Where this is not the case the technical challenge is ensuring sufficiently accurate relative timing between the pair of receivers to which the double-differencing technique is applied. Using two low-cost single-frequency GPS receivers separated by 20 km, relative time differences of <1.5 ns over 24h have been obtained [13]. In this approach the receivers observe at a common set of high-elevation satellites which reduces the ionospheric and tropospheric errors. A 1.5 ns error translates to a 24h phase error at DAB frequencies of 120° compared to the water vapour sensitivity of 35°g^{-1}m^{3}, making estimation of water vapour challenging. However, using GPS to discipline a high-quality oven-compensated oscillator the short-term error can be reduced. The oven-compensated clock in the preliminary work has an Allan variance $<1\times10^{-12}$ in 10,000s (~3h). Similar approaches are used in VLBI (Very-Long-Baseline-Interferometer) radio astronomy where the challenges are similar [13]. Further reduction in error could be achieved by using dual-frequency GPS receivers and carrier phase processing [14]. These techniques can reduce the error to <100 ps in 24h.

III. PHASE ESTIMATION APPROACHES

Three potential algorithms have been conceived. An outline of each is as follows:

A. Autocorrelation/cross-correlation phase:

This method works with the raw complex signal and requires no demodulation of the DAB or DVB-T signals. If the transmitter phase is sufficiently stable the complex autocorrelation of the signal can be used to determine the changes in phase along the path. If the transmitter phase is not sufficiently stable, as is likely, two receivers are required and the signals cross-correlated. These methods are essentially the same as those used in GPS pseudo-range and carrier phase estimation. Like GPS techniques, using a pair of receivers allows the removal of common-mode errors such as transmitter phase-offsets (double differencing). Additionally in a single-frequency-network (SFN) such as DAB and DVB-T all transmitters broadcast the same data at the same time which means that signals from multiple transmitters at different ranges can be separated in the time domain (provided no two transmitters lie on an ellipse the foci of which are the two receiver locations). This means a pair of receivers can determine phase to all transmitters that are receivable.

B. Autocorrelation amplitude

A further method for indirectly determining information about the vertical structure of refractivity is to exploit anomalous propagation. Consider the situation shown schematically in Fig. 5. Under standard conditions only the signal from TX1 is received at RX. However as the refractive index conditions change the signal from TX2 becomes visible. Furthermore, changes in the vertical refractive index structure would also be expected to change the angle of arrival of the signal which may provide further information on the refractive index.

This method is similar to the estimation of the self-ambiguity function in radar applications. In the case of fixed transmitter and receiver antennas (no Doppler) and ignoring the effects of moving scatterers, this amounts to the calculation of the complex autocorrelation of the received sampled time-series data:

$$R(m) = \frac{1}{K}\left|\sum_{k=1}^{K} x(k)(x(k-m))^*\right|, \quad (3)$$

where *R(m)* gives the autocorrelation at the m^{th} lag.

In a single frequency network this gives rise to maxima at zero range and at the ranges (lags) of other transmitters. As the vertical and horizontal refractive index structure changes, multipath and anomalous propagation lead to changes in the auto correlation. Although information on the refractive index structure is contained within this data, its' retrieval is even more complicated than direct demodulation of the phase symbols.

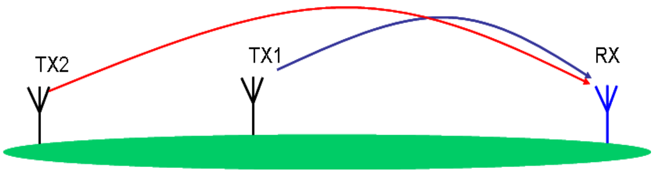

Figure 5: Schematic illustration of the effects of anomalous propagation. As the vertical and horizontal refractive index structures change the relative signal strengths from TX1,TX2 and the angles-of-arrival at the receiver, RX could be expected to change.

C. Pilot symbol tracking:

This algorithm is the most complex since it requires some demodulation of the signals to recover the in-built synchronisation (pilot) symbols. This method is however potentially the most reliable since it may offer better immunity to interference. The DAB signal contains a ≈1 ms synchronisation symbol in every ≈96 ms data frame. From this a carrier burst can be extracted and the changes in phase tracked using a phase-locked-loop. Similar techniques can be applied to DVB-T signals which have permanent synchronisation pilot symbols rather than the periodic ones in DAB. Like the auto-correlation method double-differencing can be applied and transmitters can be likewise isolated in the time domain based on their range differences.

IV. Preliminary Results

To test the ideas proposed in this paper some preliminary tests have been conducted. The test equipment consisted of a log-periodic antenna pointed towards the Mendip transmitter, a narrow-band anti-aliasing band-pass filter and a 105 M-samples s^{-1} 14-bit ADC and digital receiver (GE/ICS ICS-554).

The 222.064 MHz DAB signal was sub-sampled, digitally down-converted and streamed to disk. A low phase-noise signal generator (Rhode & Schwarz SMIQ03B) phase-locked to a GPS disciplined rubidium oscillator (Stanford Research PRS10) was used to provide a low-jitter ADC sample clock (Allan variance < 2×10^{-12} over 100s). Figure 6 shows the anti-alias filter response (left); the DAB spectrum received from the antenna on the University of Bath roof shows several multiplexes (right). A single multiplex is selected at 222.064MHz by the digital-down converter to produce complex baseband data which is re-sampled at 2.048MHz (which is a fundamental timing frequency of DAB).

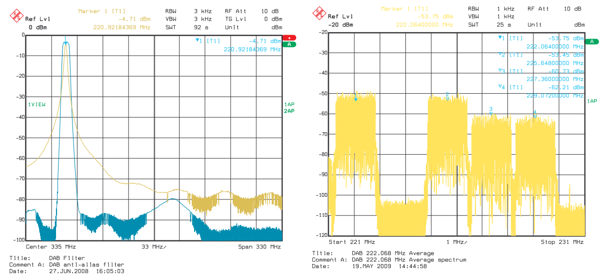

Figure 6: Anti-alias bandpass filter response (left). OFDM DAB multiplexes as seen from roof-top antenna at University of Bath.

As an example, the complex baseband signals are shown in Fig. 7. The null symbol of ≈1 ms can be clearly seen at around 11 ms.

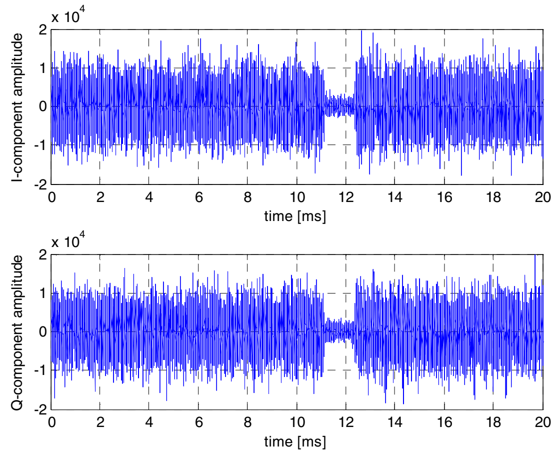

Figure 7: complex (in-phase and quadrature) baseband data showing null symbol at 11 ms, the null symbol is repeated every frame (96 ms).

The synchronization symbol immediately follows the null symbol. The precise location of the null symbol can be easily determined using an envelope detector as shown in Fig. 8.

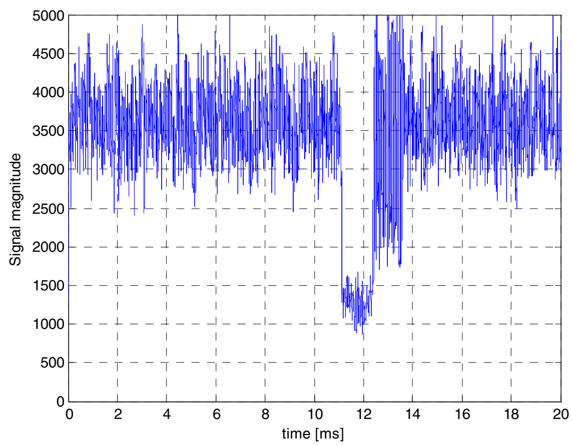

Figure 8 Envelope of the DAB symbol showing the null (≈11-12 ms) and synchronisation symbols (≈12-13 ms).

The envelope detector function is implemented as a low-pass filtered version of the complex amplitude data. The synchronization symbol can be seen immediately following the null symbol. The null symbol consists of a repeated constant-amplitude zero auto-correlation sequence (CAZAC). A carrier burst can be recovered from the synchronization symbol by mixing the synchronization symbol with a conjugated replica of the CAZAC sequence to recover a carrier burst. The carrier bust can then be tracked to determine the signal phase using a digital phase locked loop or some other form of phase estimator.

Figure 9 shows the auto-correlation (self-ambiguity function at zero-Doppler) evaluated over 50 frames (at approximately 20 ms intervals) between 17:00 - 21:00 UTC on 15/01/2009. The strongest signals, shown in red/orange/yellow, correspond to the ranges of the main transmitter sites. Note that in addition to the single frequency transmissions from Bath (~0 km) and Mendip (~25 km) weaker signals from other transmitters are occasionally visible, as are other structures. Changes in the autocorrelation amplitude can be seen to occur over time and can be attributed to changes in the vertical structure of refractivity causing changes in ray-bending.

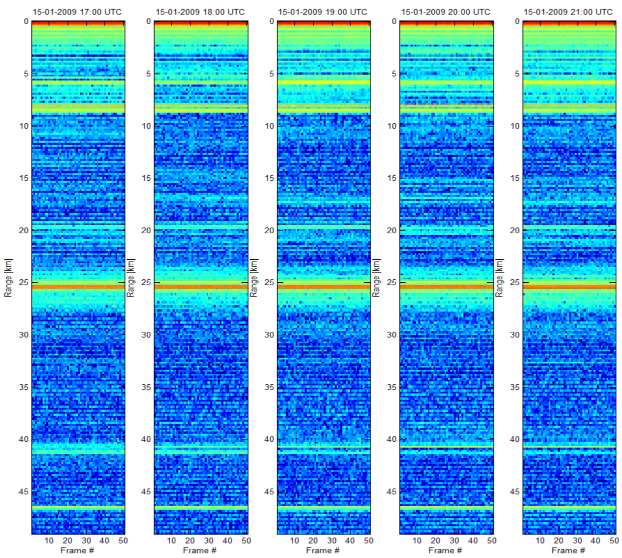

Figure 9: Zero-Doppler slices through self-ambiguity function showing variation in transmitter visibility (indirectly related to the vertical refractive index structure)

V. CONCLUSIONS

The feasibility of using opportunistic reception of DAB and DVB-T signals for the determination of refractivity has been investigated. The signal properties of both DAB and DVB-T signals have been shown to be suitable for the estimation of phase on the radio path. Three techniques have been developed that can be used to retrieve refractivity related information from the DAB signals. The most promising technique based on synchronization-symbol phase-tracking has been demonstrated using DAB transmissions from Mendip to Bath. Many problems still remain with the techniques developed. Most of the filtering and integration time-constants have been empirically determined. In order to remove the effects of phase jumps in the transmitter signal the analysed events have to carefully selected and heavily filtered.

Further work will consider differencing techniques as a means to remove the effects of transmitter phase drift.

ACKNOWLEDGMENT

Part of the work present here was supported by the UK Met Office. We thank the Met Office and the BADC for the numerical weather prediction model data used in this study. The authors would like to thank and acknowledge the efforts of Mr Heath Yardley, University of Adelaide who performed much of the development of the bandpass filters and acquisition software used to collect the data in this paper.

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