Remodulation of DVB–T signals for use in Passive Bistatic Radar

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***Abstract*— Passive Bistatic Radar employs a local communications transmitter as an illuminator. A template for matched–filtering is obtained by steering a beam at the transmission source. However this signal is subject to sensor noise and may also contain delayed attenuated copies of the transmitted signal. Demodulation and remodulation of the signal provides a clean template, however this also removes transmitter effects, resulting in a less than ideal mismatched filter. Estimation of the carrier drift allows transmitter effects to be re–introduced to the template signal and results in ambiguity surfaces of improved quality.**

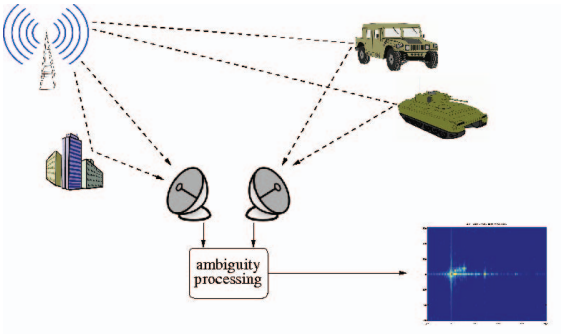


Fig. 1. Passive Bistatic Radar

I. Introduction

A Passive Bistatic Radar (PBR) system employs an Illuminator Of Opportunity (IOO) as a signal source. Typical IOOs include terrestrial radio or television transmitters. Recent work [1], [2], [3] has employed Terrestrial Digital Video Broadcast (DVB–T) transmitters as the IOO. Benefits of PBR over conventional monostatic radar include reduced hardware costs and the ability to operate covertly.

A complication of PBR is that one does not have knowledge of the transmitted signal. In order to perform ambiguity processing one must therefore obtain a correlation template by steering a beam at the transmitter. This template will not be pristine due to the presence of receiver noise. Furthermore reflections from objects in the same beam, or strong returns which leak into the main beam, result in attenuated delayed copies of the transmitted signal being present in the template. Receiver noise can be dealt with during matched filtering by integrating over a suitably large interval, but the presence of delayed copies will cause "ghost" ambiguities to appear in the output. A further complication particular to DVB–T is due to the insertion of redundant data into the framing structure. This causes range ambiguities as the signal has significant autocorrelation at certain lags and Doppler shifts.

One can demodulate the received template signal and recover the transmitted data bits. These can then be remodulated to form a pristine template signal devoid of receiver noise and delayed copies. This study demonstrates how to compose a template signal for ambiguity processing in PBR via demodulation and reconstruction of the transmitted signal. Use of reconstructed templates is shown to yield improved performance over the use of raw line–of–sight templates.

II. Method

A. Demodulation

The Australian Standard for DVB–T transmission [4] specifies the means by which a binary video data stream has Forward Error Correction (FEC) applied, is mapped to constellation symbols, and inserted into a DVB–T symbol.The underlying modulation of DVB–T is Orthogonal Frequency Division Multiplexing (OFDM), in which individual constellation symbols are used to modulate one of a set of orthogonal sinusoidal carriers. Certain carriers are used to transmit pilot information. A constant ± 1 value is transmitted exclusively at each of a set of designated Continual Pilot Carriers (CPC), and every fourth symbol at a set of designated Scattered Pilot Carriers (SPC). These carriers are transmitted at a higher average power than the data carriers. Some carriers are used for Transmission Parameter Signalling (TPS), in which a string of bits containing a synchronisation pattern and some information about the underlying coding method being used is transmitted as DBPSK over one frame.

Baseband modulation is efficiently performed by taking a symbol of OFDM data (*ie* a set of constellation symbols) and applying an inverse Fourier transform to obtain timeseries. A guard band is added to each symbol timeseries via circular extension. This redundancy helps to combat intersymbol interference.

The sequel describes the algorithms used for demodulation of DVB–T signals in this study. We do not claim that these algorithms are optimal. However they are simple and work sufficiently well with the data at hand.

Demodulation of DVB–T first requires synchronisation in

time and frequency: That the initial sample of a symbol be located, and the carriers be properly aligned. Synchronisation consists of several sub–steps. The fractional frequency offset f_f is the offset in frequency required to make all carriers lie on centre–bin of the Fourier transform, and the coarse time offset t_c is the delay to the initial sample of an OFDM symbol. These can both be estimated by exploiting the redundancy in the guard band between OFDM symbols. The received signal s is correlated with a copy of itself, delayed by the number of samples in the useful part of the symbol N_u. This is then arranged into blocks having the total length of an OFDM symbol $N_u + N_g$, where N_g is the number of samples in the guard band.

$$y(n) = s(n) \otimes s(n + N_u) \tag{1}$$

$$z(i, j) = y(i + (j - 1)(N_u + N_g)) \tag{2}$$

Since the beginning of a symbol will be correlated with redundant data, the corresponding row of z will be nearly constant, and t_c can be estimated as the row index (delay) which minimises the standard deviation across columns (symbols). The phase of elements of this row corresponds to the fractional frequency offset, which may be estimated by averaging.

$$\hat{t}_c = \arg\min_i \text{std}\left\{\angle z(i, 1), \angle z(i, 2), \ldots\right\} \tag{3}$$

$$\hat{f}_f = \frac{1}{2\pi}\angle \sum_{k=1}^{K} z(i, k) \tag{4}$$

The coarse frequency offset f_c is the offset in frequency required to make each carrier line up in its correct bin. The received data is corrected for f_f and t_c, blocked in to symbols and Fourier transformed. f_c is then estimated by examining the evolution of phase in the CPC pilot bins $\{p_1, p_2, \ldots p_L\}$, in a manner similar to that presented in [5].

$$P(k) = \sum_{i=1}^{L} S(k + p_i, 1) \times S^*(k + p_i, 2) \tag{5}$$

$$\hat{f}_c = \arg\max |P(k)| \tag{6}$$

Intra–sample offset introduces a frequency–dependent phase error. This is estimated by comparing the value in each CPC bin to its expected value (± 1) and solving a linear equation.

$$z = 2\pi \begin{bmatrix} f_{c_1} & 1 \\ f_{c_2} & 1 \\ \vdots & \vdots \end{bmatrix} \begin{bmatrix} \hat{t}_e \\ \phi_i \end{bmatrix} \tag{7}$$

where

$$z_j = S(c_j, \cdot)/E\left\{S(c_j, \cdot)\right\} \tag{8}$$

The received signal may be sampled at a slightly different rate due to disparities between the transmitter and receiver clocks. Such disparities will result in the received signal being sampled at an incorrect rate, causing symbol phase to change over time. Assuming that the clock rate difference is constant, the number of extra cycles experienced by a CPC carrier over one symbol is

$$x_p = \frac{f_p + f_v}{f_s + f_e} N \tag{9}$$

where f_s is the receiver's sampling rate, f_e is the apparent difference (error) between the local sample rate and the transmitter's, and f_p is the pth CPC frequency. f_v is residual fine–frequency offset error. x_p is observed as a phasor on 2π

$$\tilde{x}_p = 2\pi(x_p - [x_p]) \tag{10}$$

One can then determine the unknown parameters by forming an observation vector

$$z_j = \angle \sum_k S(c_j, k + 1)/S(c_j, k) \tag{11}$$

and using a numerical optimisation tehnique to find $\hat{f}_v$ & $\hat{f}_e$.

Alignment to the start of a frame is performed by extracting data from TPS bins and correlating the observed sequence with the 16–bit sync sequence which marks the start of a frame.

The power occuring in each CPC bin is estimated by averaging power in these bins across a frame. The same is done for each SPC bin, using only the symbols in which they are present (every fourth symbol). Average power at non–pilot bins is estimated by interpolation. Equalisation is then performed by scaling each bin by the estimated power.

In the present study one is not especially interested in the recovery of the transmitted message. All that is required for remodulation is the transmitted constellation symbols. Provided that the SNR is not prohibitively low, one may dispense with the error correction by simply making a hard decision about the transmitted symbols after equalisation.

B. Remodulation

Having obtained error–free constellation symbols, an ideal template signal is formed by constructing new OFDM symbols and modulating them via inverse DFT. Some improvement may be made by modulating the designated pilot sinusoids at a lower power than is specified by the standard. This can suppress range and Doppler sidelobes in the radar ambiguity output which occur due to temporal redundancy in the pilot channels [3].

A single DVB–T symbol (at 8K mode) endures for 1.2 ms; a frame of 68 symbols therefore lasts for 0.078 s. The transmitter's carrier frequency can drift significantly over timeframes of this length, causing each OFDM symbol in the transmission to experience different relative phase shifting. The actual transmitted signal may thus be markedly different from the ideal reconstructed template signal. If r is the length–N_u vector of received samples in a whole symbol of DVB–T data, and $\tilde{s}$ is the vector of demodulated and reconstructed LOS template samples, then an estimate of the constant phase offset between them during this symbol is

$$\hat{\phi} = \angle r^H \tilde{s} \tag{12}$$

In order to provide a better–matched filter template this symbol phase difference is estimated at each symbol period and reintroduced to the template signal.

$$\tilde{s}_k = \tilde{s}_k e^{-i\hat{\phi}_k} \tag{13}$$

One might achieve better performance if one considered that the residual phase error varied continuously over each symbol and attempted to track this. However we find that estimating a constant error over each symbol independently works sufficiently well for our purposes.

When decoding DVB–T for communications it is not necessary to make specific considerations for transmitter effects like clock rate differences since one is only interested in extracting the underlying information. The remodulation of a DVB–T signal in a manner which preserves transmitter effects is a problem which is wholly specific to radar.

C. Processing

A data signal and a LOS signal are synchronously captured, digitised and recorded by the radar. Analysis of the LOS signal determines the precise subsample offset to the start of a frame, and the precise frequency offset to centre the carriers in the correct bins. Both the LOS signal and the data signal are shifted in time and frequency to account for these offsets. The constant sample–rate error is estimated, and the LOS signal is resampled accordingly. The LOS signal is then equalised. The complex values in all bins are corrected by rounding to the nearest constellation symbol. This corrected LOS data is remodulated in one of three ways:

1) Symbols are Fourier transformed and cyclically extended as per normal OFDM processing. This is how the signal would be remodulated for communications purposes, and serves as a baseline.
2) As above, then the clock error is reintroduced by resampling the signal at the original apparent rate. This attempts to account for disparity between transmitter and receiver clocks, modelling any difference as constant over the duration of a frame.
3) As above, but nonlinear clock phase is accounted for by post-processing each symbol timeblock (eqs. 12–13). This models the clock difference as varying between symbols.

Ambiguity processing is performed by filtering the data signal with the remodulated LOS signal at various frequency offsets.

III. Demonstration

Some real PBR data was collected, using an Australian DVB–T transmitter as the IOO. Collection was performed using a custom receiver that was designed (primarily using Commercial Off the Shelf (COTS) components) and built by the Defence Science and Technology Organisation (DSTO) of Australia. The receiver, which belongs to the eXperimental Phased Array Radar (XPAR) project, digitises and extracts RF signals to a recording device for offline digital signal processing. The XPAR receiver RF chain down-converts the received signal from up to 16 independent elements to a 175MHz nominal Intermediate Frequency (IF). Each array element has a separate 14-bit Analogue-to-Digital converter (ADC) that allows the IF signal to be digitised at 100MS/s. The XPAR system then uses COTS chipsets to digitally down-convert the IF signal to baseband where the samples are stored on a large non-volatile disk in 32-bit complex values. The IOO was 8K mode OFDM, using 64–QAM modulation symbols, and a carrier frequency in the vicinity of 560 MHz. A LOS reference signal was formed by manually steering a radar receiver towards this transmitter.

Two distinct data sets, comprising returns from different targets, were recorded and processed.

A. Data set 1

An ambiguity plot, formed by correlating the raw LOS signal with the received data signal, is presented in fig. 2. The integration time was equal to the duration of 4 DVB–T frames (0.31 seconds). The direct–path mainlobe is apparent at zero lag and zero Doppler. In addition there is significant return from an extended moving target (a train) at a close range. There is also an obvious ghost return manifesting in the location opposite the target in the range–Doppler plane (highlighted region in lower left).

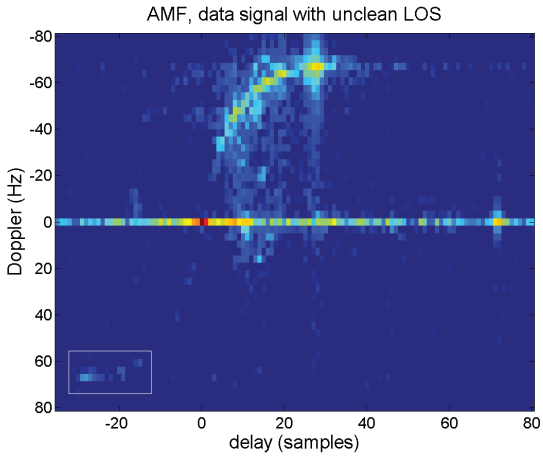


Fig. 2. Ambiguity surface, LOS signal template

The LOS signal is demodulated to constellation symbols and remodulated. This remodulated signal is used to produce the ambiguity plot in fig. 3. The reason for this clearly poor result is that the transmitter clock varies with respect to that of the receiver. The remodulated signal, produced with the receiver's clock, is not properly matched to the transmitted signal.

The disparity between transmitter and receiver clock manifests as a marching phase error in the transmitted signal. It is assumed that the clock rate varies in an approximately linear fashion over the integration period. The demodulation performs coarse sample frequency correction by fitting a linear frequency model to the observed phase error. This phase error is re-introduced to the remodulated signal in order that it be better matched to the transmission. The result of ambiguity

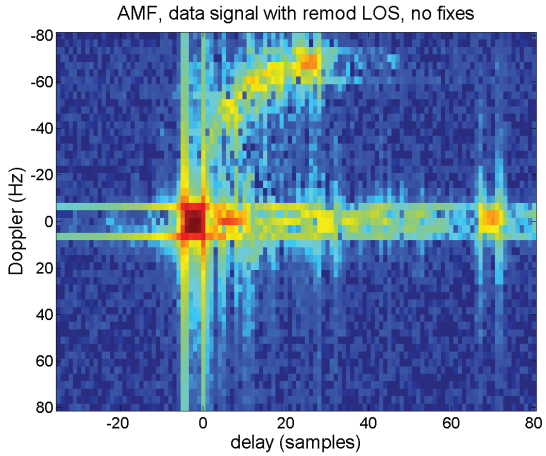


Fig. 3. Ambiguity surface, remodulated LOS signal template

processing with this modified template is presented in fig. 4. Observe that the ghost return has been suppressed, but also that significant power is leaking from the returns (mostly notable at the main return).

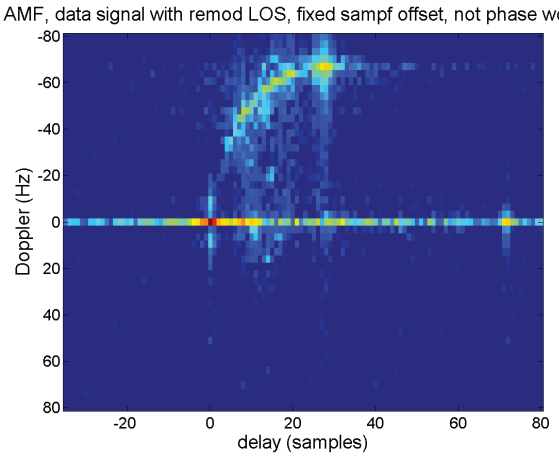


Fig. 4. Ambiguity surface, remodulated LOS signal, accounted for linear phase error

This residual power leakage is caused due to errors in estimation of the clock disparity. The disparity is not strictly linear but "wobbles", causing slight errors in carrier frequency. This error is estimated on a symbol–by–symbol basis and re–introduced to the remodulated signal. The ambiguity surface produced with this template is presented in fig. 5. Observe that there is no longer any power leakage due to signal mismatch and that the ghost return remains suppressed.

The phase–corrected remodulated template produces improved resolution in ambiguity surfaces. Consider the plot of the zero–range (*ie* main return) slice of the ambiguity surfaces (fig 6). The slice produced with the fully corrected LOS template (green dashed line) produces a mainlobe which is about 10 dB better (with respect to its vicinity) than the

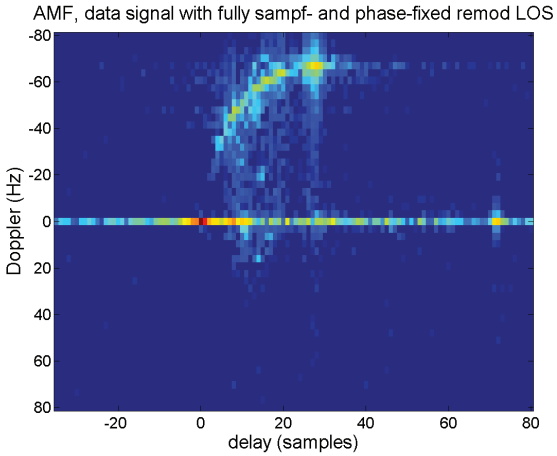


Fig. 5. Ambiguity surface, remodulated LOS signal, accounted for total phase error

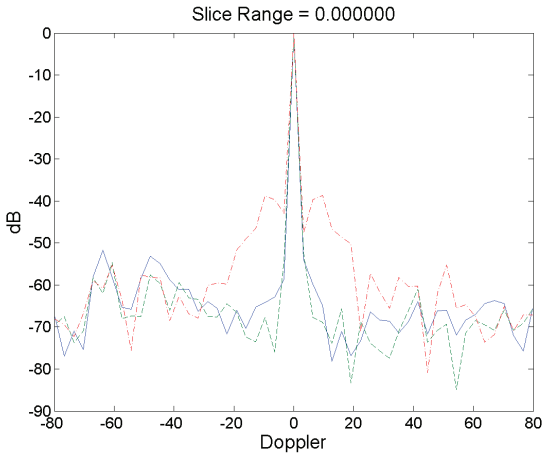


Fig. 6. Zero–range slice of ambiguity surfaces

mainlobe produced by the raw LOS template (solid blue line). The mainlobe produced by the linear–offset corrected template (red dashdot) has significant sidelobes flanking the mainlobe.

B. Data set 2

The second data set used the same IOO as the first. However in this trial a different target was present, and the data signal was pre–processed for clutter removal prior to ambiguity processing. A Wiener filter was used to estimate the main zero–Doppler return and this was then cancelled from the return signal. This had the effect of reducing the noise floor but also exposed many low–power returns.

An ambiguity surface was computed with this preprocessed data and a LOS signal. The low–range component of this, which encompassed all major target returns, is shown in fig. 7. The LOS signal was demodulated and remodulated, having phase errors estimated and reintroduced to the remodulated signal on a symbol–by–symbol basis, and also having pilot carriers modulated at a slightly lower power as described in [3]

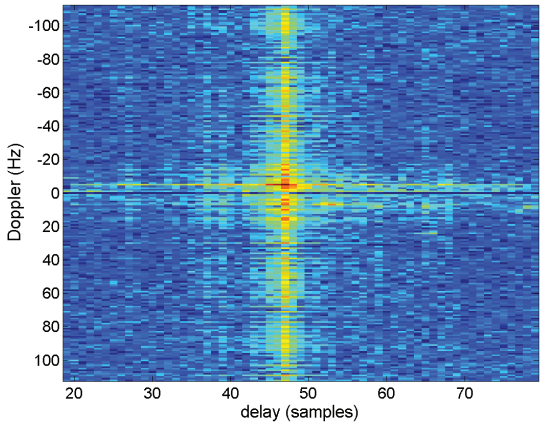


Fig. 7. Ambiguity, set 2, low range, unprocessed LOS signal

to mitigate ambiguities inherent in the DVB–T frame structure. The low–range component of the ambiguity surface computed with this remodulated LOS signal is shown in fig. 8. Observe

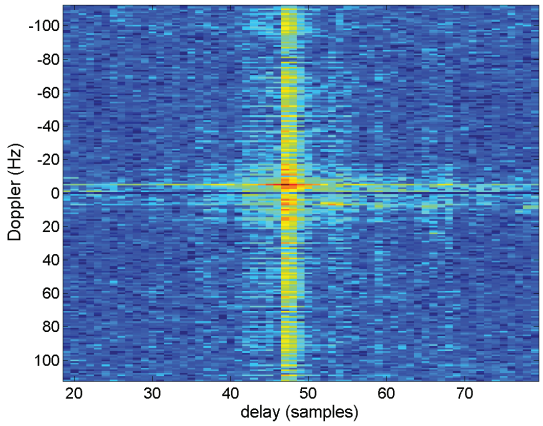


Fig. 8. Ambiguity, set 2, low range, demod–remod LOS signal

that the sidelobes are heavily mitigated by the demod–remod process, particularly those on the near side of the main return.

A second range section of the ambiguity surface is shown in fig. 9. Here a sidelobe due to DVB–T frame structure is present, and its extent in range is exacerbated by impurities in the LOS signal. Remodulation of the LOS signal with attenuated pilot power completely removes these sidelobes, evident in fig. 10.

IV. Summary

This study has demonstrated that ambiguities arising in PBR processing with DVB–T signals can be ameliorated via demodulation and remodulation of the reference signal. Radar–specific concerns must be addressed when remodulating the reference in order to ensure it is well matched to the transmitted signal. In particular, care must be taken to accurately

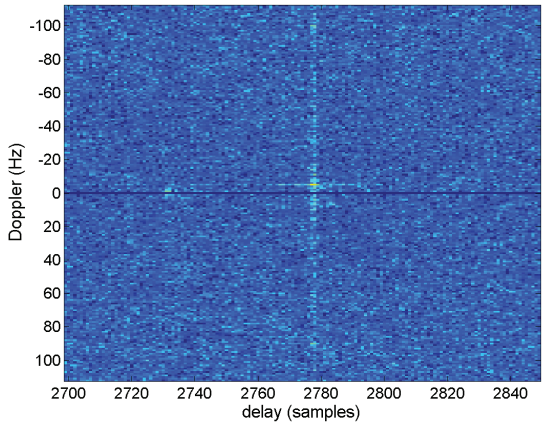


Fig. 9. Ambiguity, set 2, range vicinity of sidelobe, unprocessed LOS

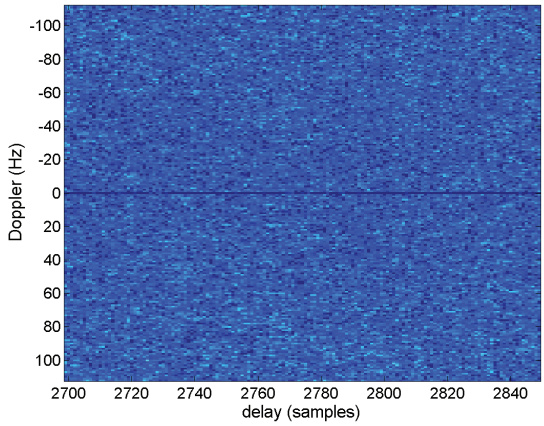


Fig. 10. Ambiguity, set 2, range vicinity of sidelobe, demod–remod LOS

model the disparities in carrier frequency which arise due to differences between the transmitter and receiver clocks.

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