

Characterisation of Narrowband HF Channels in the Mid and Low Latitude Ionosphere

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ABSTRACT

The performance of an HF digital radio system is strongly affected by the response of its various protocols to short-term (sub-hourly) variations in the ionosphere. There is a very limited choice of models of this variation. Channel simulators based on the Watterson 2-path model (ITU-R F.1487) are commonly relied upon for modem testing, system design and modelling. Limited DSTO trials in the past have cast doubt on the validity of the Watterson model in the Australian mid-latitude region. In addition to fading errors, the Watterson model introduces further errors by ignoring variations in the group delay due to diffuse multi-path propagation.

These concerns provided the impetus to conduct an extensive and rigorous trial to measure the narrow-band channel impulse response (CIR) at mid latitudes as well as the highly dynamic low latitude region of the ionosphere. A variety of low and mid-latitude narrowband HF channels were probed during a 14 day campaign in April 2006. Channel response measures such as Doppler shift and spread, group-delay spread, and signal fading statistics were used to identify a small set of similar channels by fuzzy clustering the response variables. By including or omitting other factors such as the carrier frequency, time of day, path information, ionospheric electron density profile parameters, and the maximum usable frequency from oblique ionospheric sounding on coincident paths, it is possible to establish various physical dependencies and derive a small selection of typical CIR records that define the cardinal channel types in the geographic region.

In this paper the authors describe the trial, the measurements and the analysis methods used to characterise and statistically analyse the short-term properties of individual channel records and to cluster the channels into a manageable set of cardinal channel types. Important analysis results from the first campaign are presented.

1.0 INTRODUCTION

The performance of an HF digital radio system is strongly affected by the response of its various protocols to short-term (sub-hourly) variations in the ionosphere. There is a very limited choice in models of this variation. Channel simulators based on the Watterson 2-path model [1] are commonly relied upon for modem testing, system design and modelling. Limited DSTO trials in the past have cast doubt on the validity of the Watterson model, at least in the Australian mid-latitude region. Subsequent DSTO LONGFISH trials [2], designed to investigate protocol behaviour, provided further practical evidence of the impact of slowly fading live channels on the data link and transport-layer protocols. In addition to fading errors, the Watterson model introduces further errors by ignoring variations in the group delay due to diffuse multi-path propagation.

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Characterisation of Narrowband HF Channels in the Mid and Low Latitude Ionosphere

Figure 1 illustrates the region of greatest ionospheric variability to the north of Australia. This is the low-latitude region bounded by the equatorial anomalies at $\sim\pm 20^\circ$ Magnetic latitudes. In order to characterise HF modem performance the ionosphere needs to be characterised taking into account the highly dynamic low-latitudes as well as the more stable mid-latitude regions.

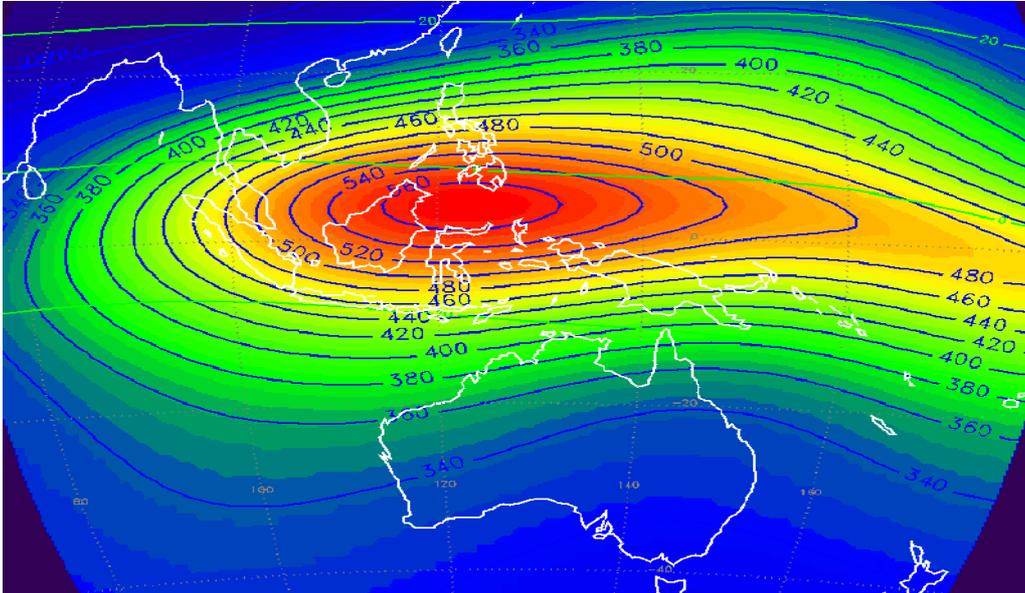


Figure 1 Typical “height” of maximum electron density for the ionosphere in the Australian region at 0300UT during January near solar maximum.

Little experimental evidence exists to validate or replace the Watterson model in the Australian region. Indeed, there are very few measurements of the typical group-delay and Doppler spreads to be expected on mid and low-latitude paths. Various authors, for example Warrington *et al* [3], Angling *et al* [4], and Warrington *et al*. [5], have conducted HF channel characteristics experiments at high latitudes using the DAMSON system described in Davies *et al* [6] and Cannon *et al* [7]. Cannon *et al* [8] have reviewed some of the pre-2000 activities using DAMSON. In the review they mention observations over Thailand in 1997 which were presented in 2000. These are some of the few observations of HF channel scattering functions near the equatorial. The channel scatter form of measurements, as provided by the Damson system, is extremely useful in characterising the varied dispersion effects of the ionosphere on HF communications signals. To fully characterise the ionospheric variations relevant to modern modem design and HF communications networks such observations are required over a large area and over a generous time period.

It is the intention of DSTO to remove the reliance on the Watterson model for the propagation path component of HF communications link modelling by developing a set of typical “real” ionospheric channels with known temporal and spatial applicability. This will have immediate application in optimising the design of the Australian Modernised HF Communication Network (MHFCS), a large narrow-band HF sky-wave digital radio network being built for the Australian Defence Force.

With these objectives in mind an extensive and rigorous ionospheric channel characterisation trial (CCT) has been set in motion. The experimental setup will be described in Section 2.0, followed by a description of the analysis procedures in Section 3.0 and preliminary results in Section 4.0. Finally, preliminary conclusions and further analyses will be discussed in Section 5.0.

2.0 CHANNEL CHARACTERISATION TRIAL

2.1 The Paths

The aim of the channel characterisation trial (CCT) is to measure the narrow-band channel impulse response (CIR) at mid latitudes as well as the highly dynamic low latitude (equatorial) region of the ionosphere. The CCT involves eleven sites in Australia and its neighbouring countries. 130,000 10-min measurements of the CIR are being obtained on 24 paths with four frequency sets (28 different frequency allocations) over four, two-week campaigns spanning a 12 month period to capture diurnal and seasonal variations.

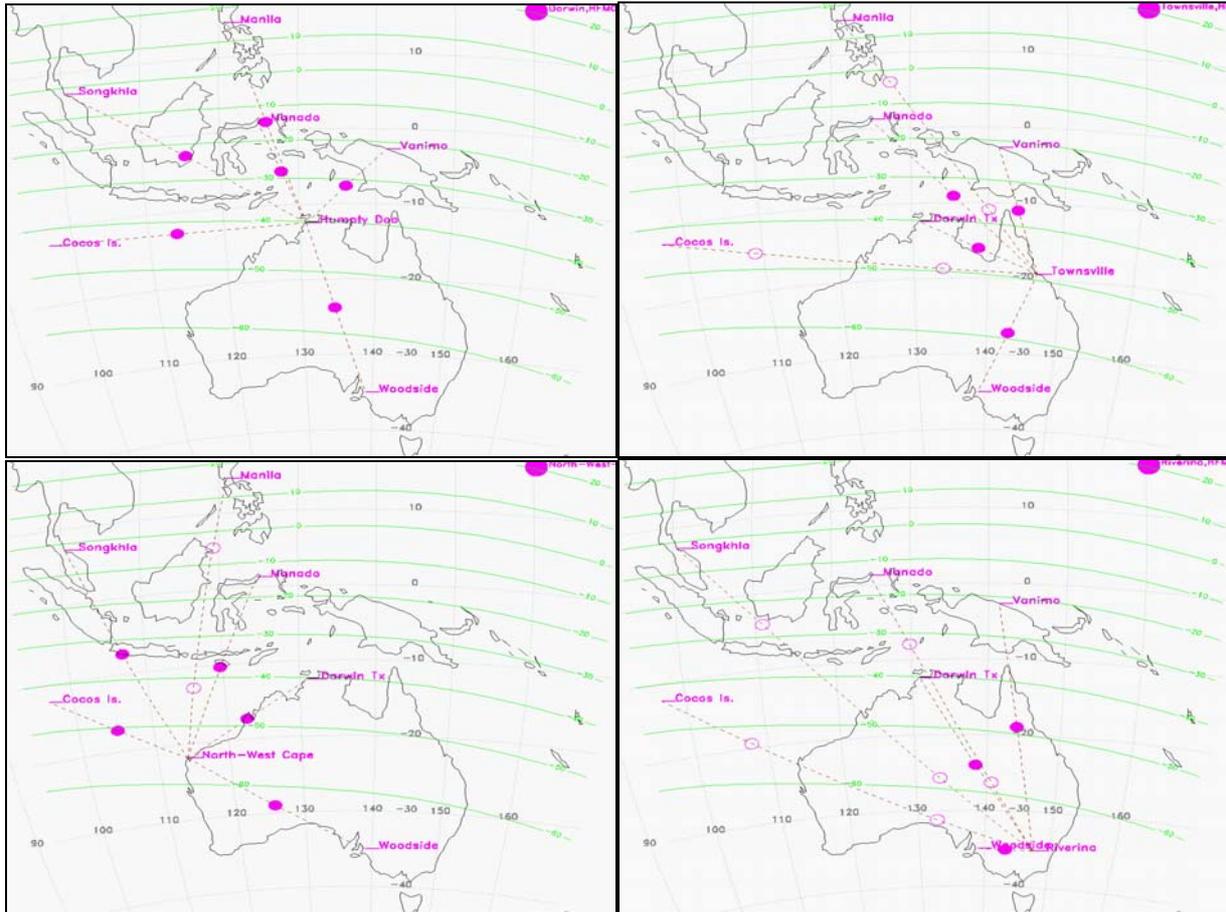


Figure 2 Paths for the four receivers used in the HF Channel Characterisation Trial. Magnetic dip latitudes are shown in green. Filled magenta circles indicate one-hop ionospheric “reflection” points while the open circles indicate approximate two-hop “reflection” points for paths beyond typical one-hop range.

There are four receive sites in Australia, one near each of Darwin, Townsville, Learmonth and Wagga. Each receiver station listens to 6 of the possible 7 transmitters. The transmitter-receiver paths are shown in the four panels in Figure 2. The transmitter-receiver pairs provide a mixture of long and short, east-west, north-south, mid and low latitude paths.

The first CCT campaign commenced in April 2006. Due to time and resource constraints, the transmitters at Songkhla and Manila could not be set up for use in this campaign.

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2.2 The Channel Probe Transmission

Each transmitter radiates a maximum of 50W using omnidirectional broadband HF antenna. The transmitters are on a schedule of events which consist of the channel probe transmissions, oblique sounding transmissions and GPS synchronisations. The oblique sounding transmission is a continuous linear FMCW sweep through the entire HF band. The channel probe transmission waveform on the other hand is a 3.6 kHz narrow-band linear FM “chirp” (see Figure 3). The chirp dwells on a given frequency channel for 10 to 15 minutes. Over a period of an hour each transmitter will cycle through 4 HF channels (frequencies) for the channel probe transmissions, 4 oblique sounding transmissions, and 4 GPS synchronisations. The cycle then repeats every hour.

The four channel probe frequencies were chosen to allow good propagation over a 24 hour period. It is expected that the lowest and highest frequencies will only propagate for half of any 24 day, whereas the two middle frequencies should provide useful information for most of each 24 period.

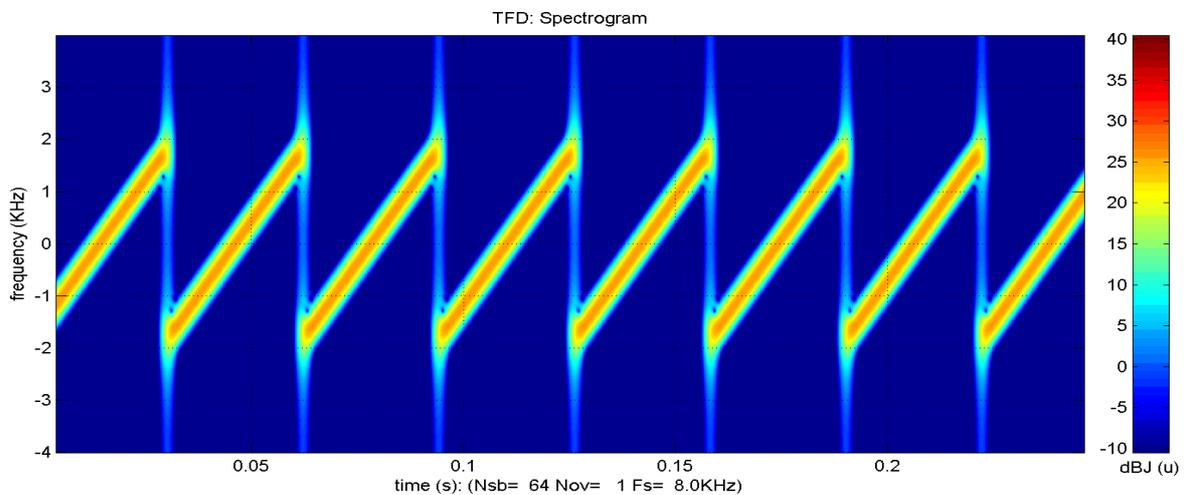


Figure 3 Time-series of the transmitted channel probe signal shown in the frequency domain during loop-back testing for calibration. The sweep is from low to high frequencies, with an “infinite” flyback causing the energy distortions seen.

The channel probe signal allows Doppler processing and derivation of range information so that a channel scatter function (CSF) can be determined. The CSF is essentially the Fourier transform of the CIR function. For calibration the transmitted signal was captured using a wideband digital receiver in a loop-back test, and spectral purity information collected. The CSF for one of the loop-back tests is shown in Figure 4. It can be seen that the transmitter produces time-delay artefacts at zero Doppler but at energies that are \sim -60dBJ less than the main signal (the red dot centred at zero Doppler and zero time delay). There are other spurious in Doppler space but these too are more than 60dB down in energy.

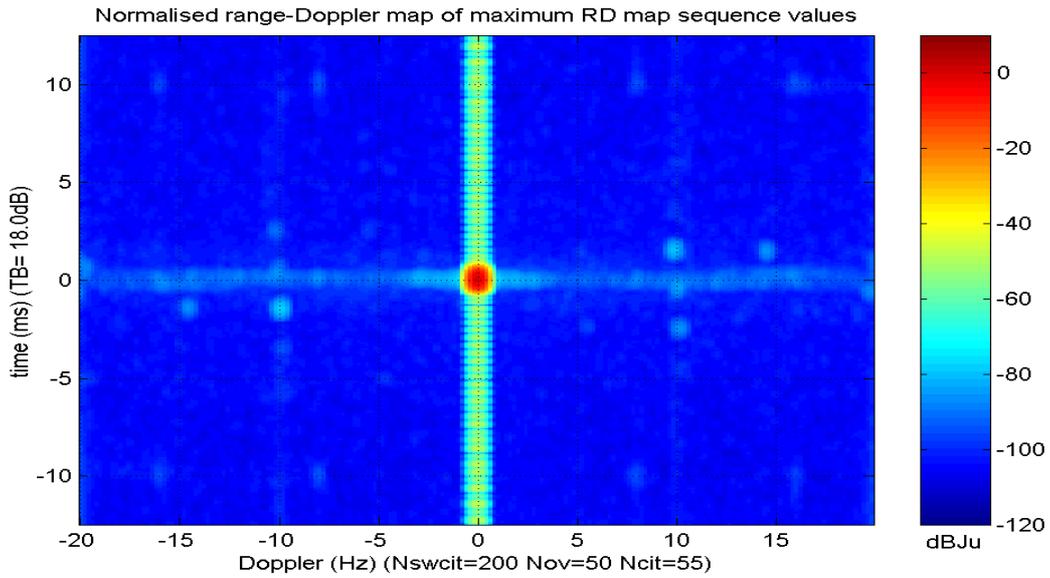


Figure 4 Testing the spectral purity of the transmitted channel probe signal during calibration loop-back testing.

2.3 Signal and Noise

Besides capturing the propagation effects on the channel signal, the CCT will also monitor the noise environment. Figure 5 shows the 16 kHz receiver pass band. The receiver pass band is set up so that the channel probe transmission is in a band near one end and a similar 3.6 kHz band at the other end is used to simultaneously assess the noise environment. The two bands are digitally separated during the analysis stage then processed independently.

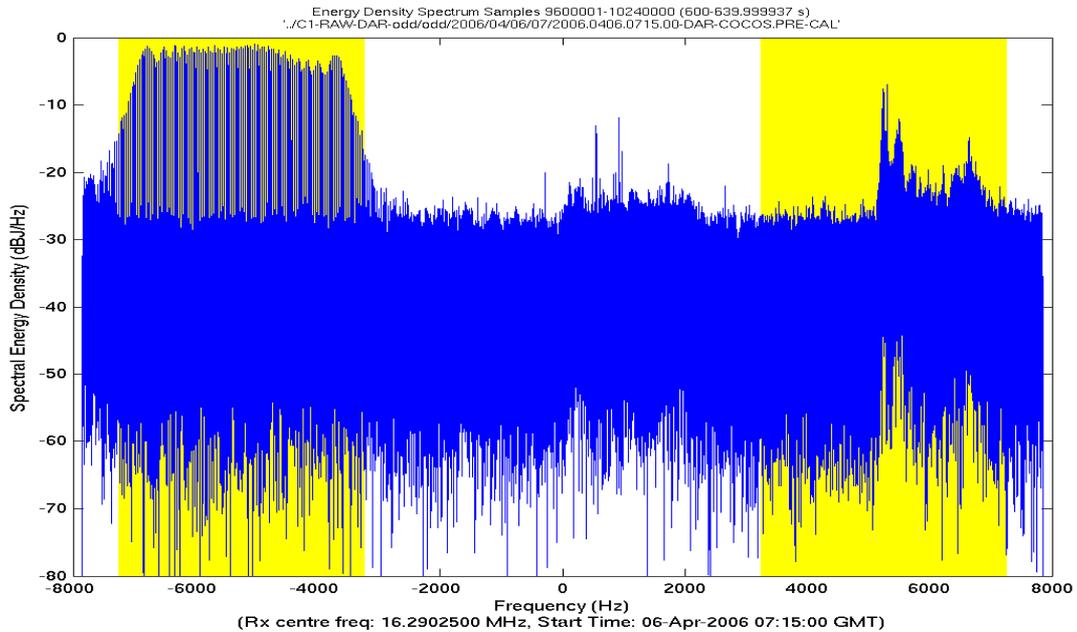


Figure 5 The receiver bandpass showing the signal and noise sub-bands (yellow).

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2.4 Ancillary Ionospheric Information

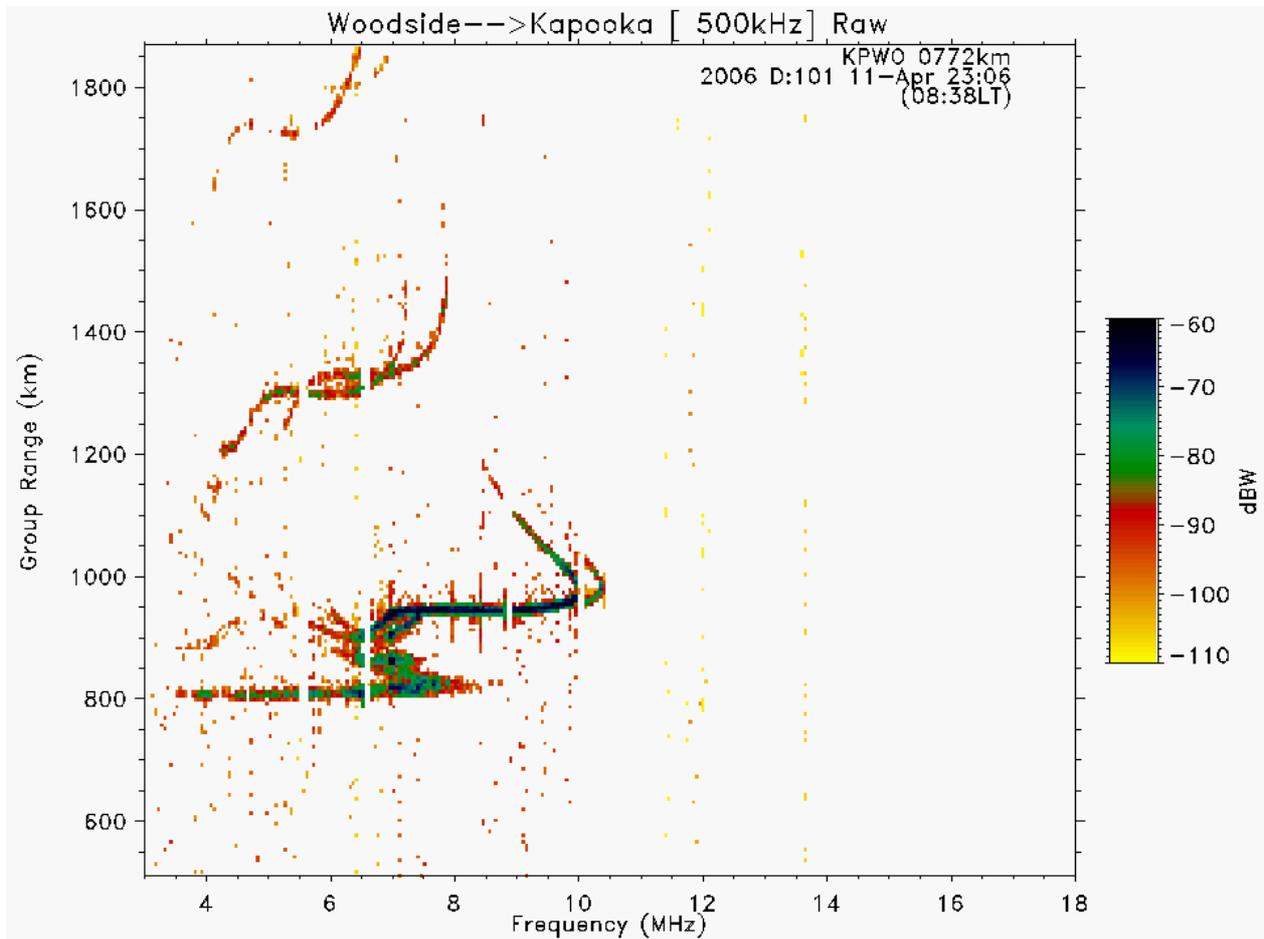


Figure 6 An example oblique ionogram for the Darwin to Townsville path.

The oblique transmissions from the CCT transmitters are received on equipment that is collocated with the channel probe receivers. An example of the ionograms collected is shown in Figure 6. This example is an ionogram received at the Kapooka (Riverina) site from the Woodside transmitter near Adelaide. Although the ionograms are only collected every 15 minutes for any given path they provide evidence for the mode structures and allow unambiguous identification of the propagating layers, such as the presence of sporadic E, one- or two-hop F modes, *etc.*

Real-time data driven ionospheric model information is used to estimate the midpoint electron density profiles for input into the cluster analysis. Figure 7 shows the estimated electron density along the great-circle path from Darwin to Riverina (the actual quantity displayed is the plasma frequency, which is related to the square-root of the electron density).

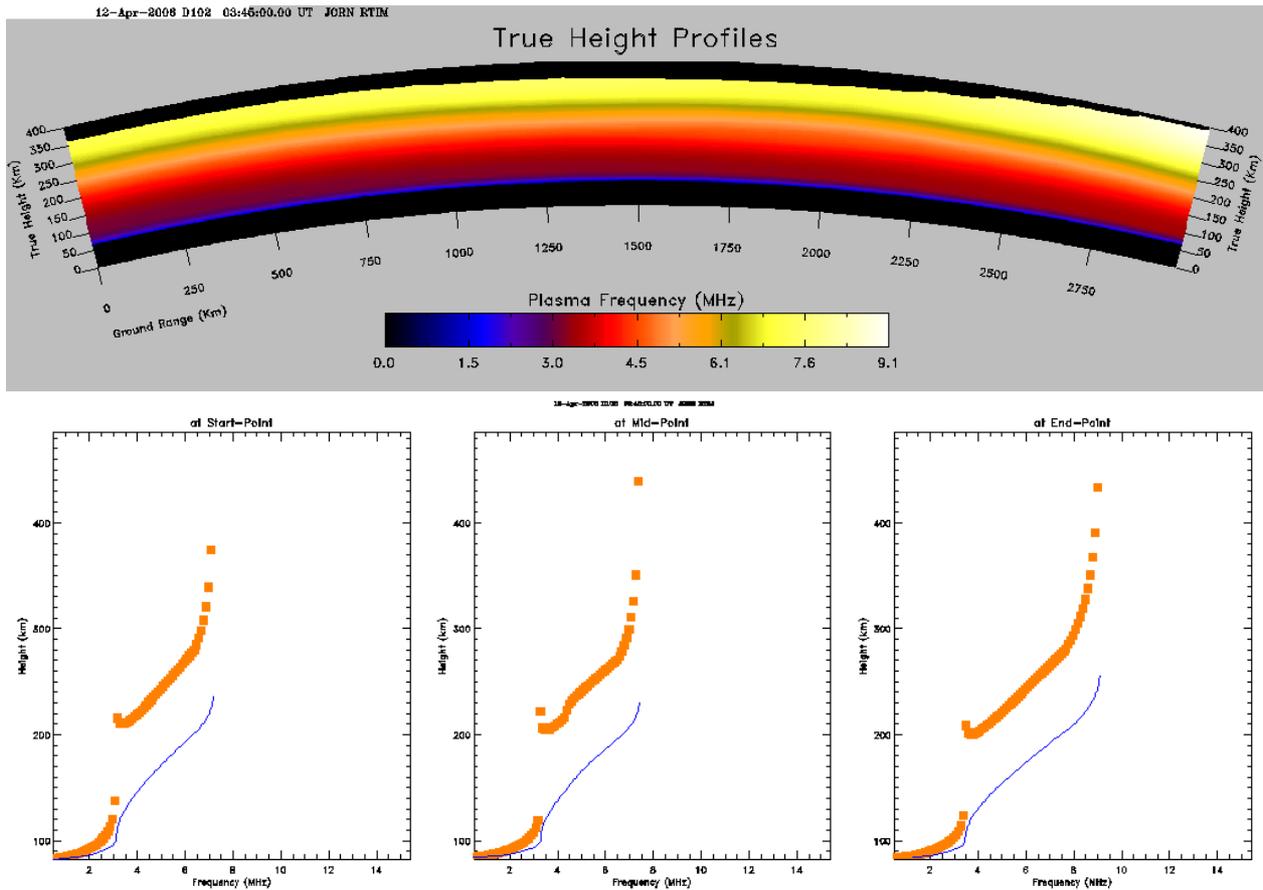


Figure 7 Electron density profiles along a single path estimated from a real-time ionospheric model. The top panel shows the estimated plasma frequencies along the great-circle path from Riverina on the left to Darwin on the right. The lower panel shows the estimated virtual heights as would be received by a vertical incidence sounding (orange symbols), along with the derived electron density profile expressed as a plasma frequency.

3.0 THE ANALYSIS

The prime analysis objective is to provide a small set of ionospheric channels, with known probabilities of occurrence, that cover the full span of the Australian region and conditions, to be used for channel simulation experiments. To achieve this outcome there are several intermediate objectives. These broadly are to:

- Measure the time-varying channel impulse responses;
- Determine various statistics of the propagation path, including propagation path loss, path delay, Doppler spectrum and scatter function;
- Determine noise statistics, including amplitude and level crossing distributions, amplitude and phase spectrum, power spectrum and autocorrelation function;
- Fit noise and path loss data to mathematical and statistical models;
- Classify the channels from their statistical characteristics as well as key parameters derived from ionospheric soundings (such as the MUF, layer heights and mode structure) and physical conditions (e.g. path geometry, frequency) using mathematical clustering techniques such as Fuzzy Clustering;
- Determine the statistics of the clusters, including probability of cluster membership, cluster location and spread.

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3.1 Data reduction

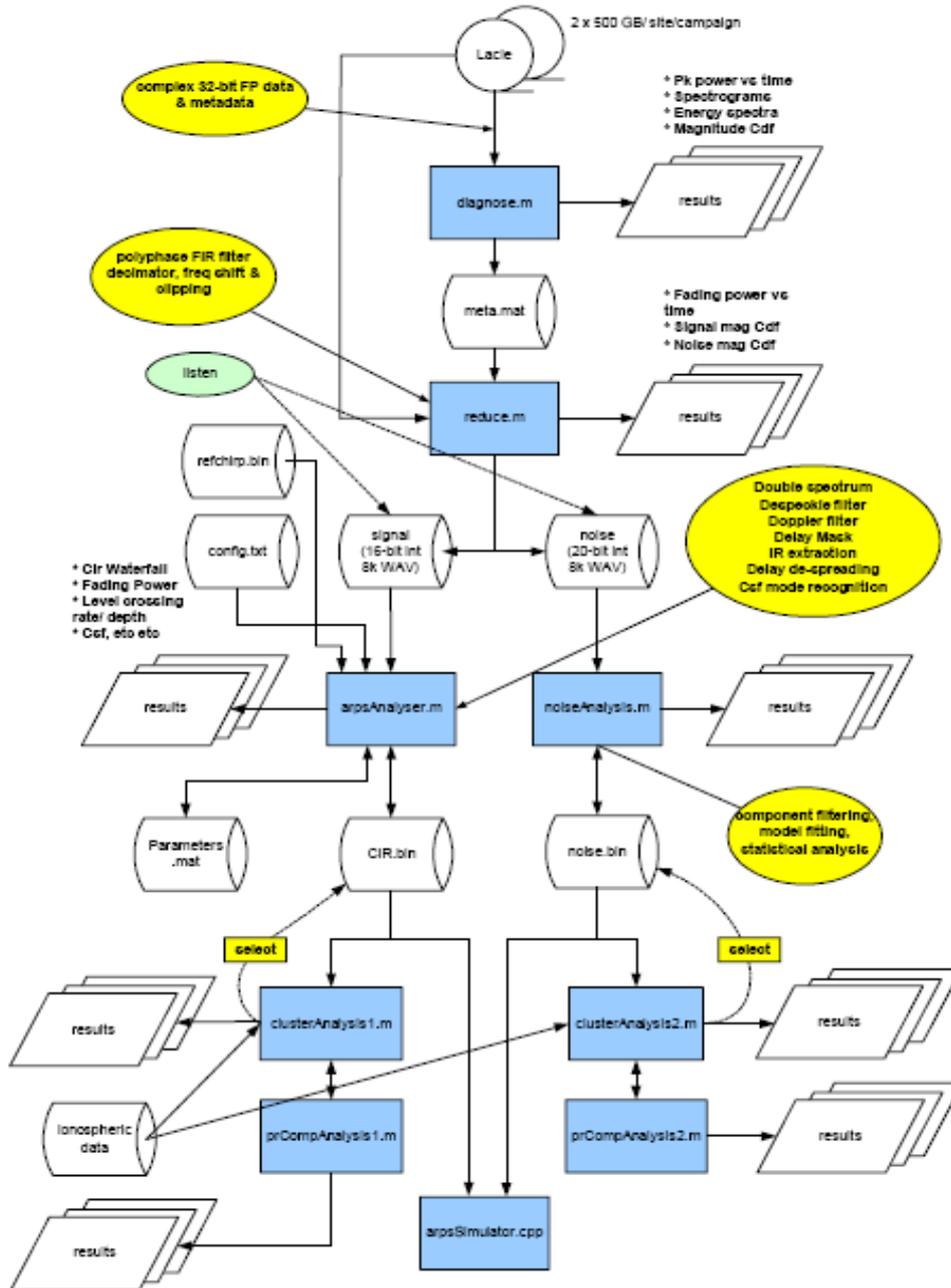


Figure 8 Data Reduction and Analysis flowchart

Figure 8 shows a flow-chart of the analysis process. The analysis was performed using shell scripts and compiled Matlab routines run on fast Xeon server class machines under Linux. The raw data was retrieved from the remote sites on removable media. The raw-data volume was approximately 900GBytes for each of the sites. A quick-look analysis allowed identification of poor data through either low signal-to-noise power ratio or man-made interference. This allowed the data to be prioritised for further analysis.

The raw data was saved on site as 32bit floating point complex data with a 16 kHz bandwidth sampled at 16kHz. A data reduction step of polyphase FIR filtering and clipping reduced this single complex time-series to two real time-series. One containing coincident 4 kHz narrowband noise as an 8 kHz 24bit wav format file, and the other containing the 4 kHz narrowband signal as an 8 kHz 16bit wav format file. This reduced the data volume to approximately 30% of the original as well as separating the signal and noise channels.

Specialised analyses then produced statistics and channel impulse response (CIR) files suitable for the cluster analysis.

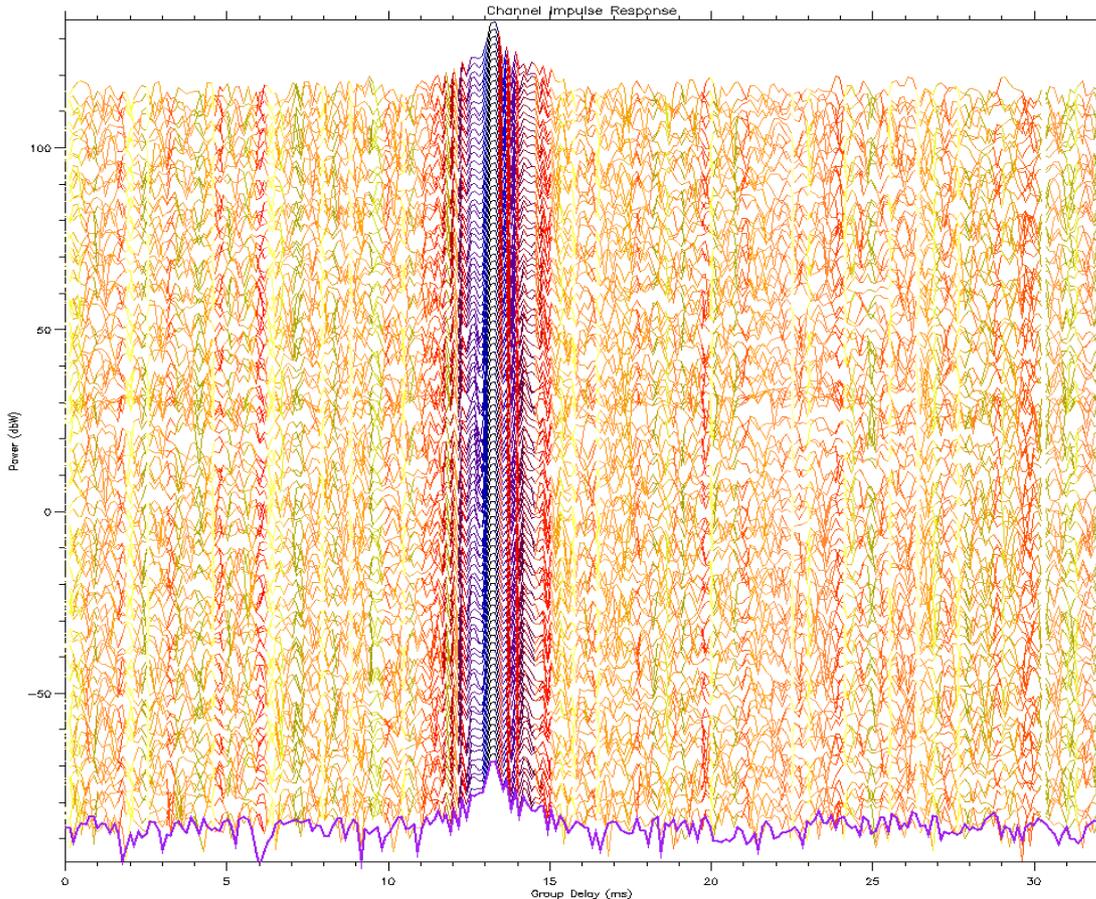


Figure 9 Example Channel Impulse responses (Powers in dBW)

Examples of the time-series of the channel impulse response are shown in Figure 9 as a waterfall display. There is one CIR estimate for every 32 millisecond sweep, giving 18000 over the 10 minute data run. From the CIR a channel scatter function (CSF) can be produced. A typical CSF is shown in Figure 10. For this figure a coherent integration time (CIT) of the full ~10 minutes was used. As the ionosphere is expected to be changing over the 10 minute period this CSF is expected to have additional broadening in group delay and Doppler over and above what a HF modem would be expected to see. Modems typically integrate for only a few seconds, hence fading and other channel statistics have been derived from 2 second CIT scatter functions.

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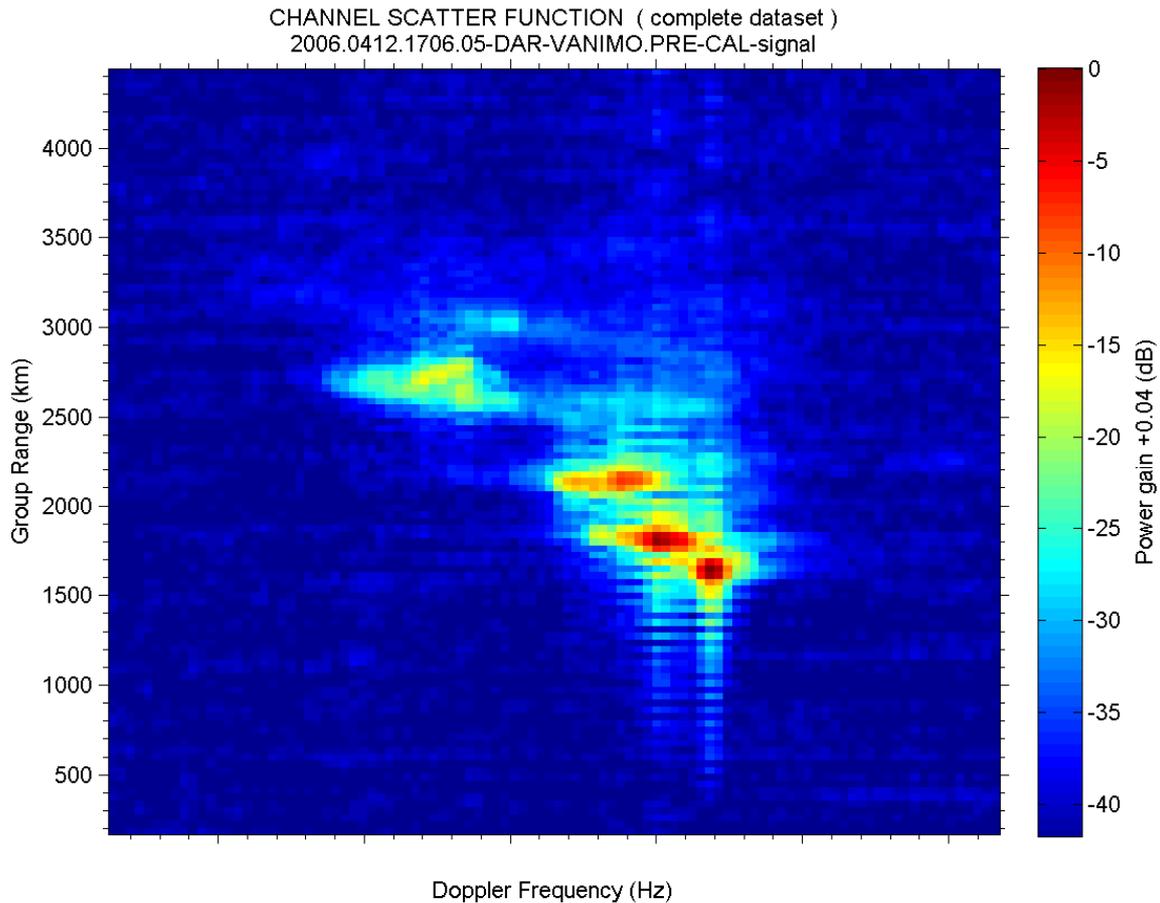


Figure 10 Channel Scatter Function using a full 10 minute coherent integration time. At this stage the Doppler axis is only relative Doppler. Major ticks are 1 Hz apart.

3.2 Clustering

All measured parameters related to propagation conditions and possibly affecting modem data rates are possible cluster factors. Many of the factors that could be used for the cluster analysis will not contribute additional information. This is because many environmental parameters are highly correlated. The success of cluster analysis relies on the correct choice of independent parameters that describe the entire variability space.

The details of the cluster analysis used in this study will be presented in a subsequent paper.

4.0 PRELIMINARY RESULTS

The first of several planned trials was completed in late April, 2006. Although much useful data was collected during this first trial, many problems were also identified. Most of these are logistical issues and will not be dealt with in this paper.

The trial collected over 850Gb of data relating to 28841 individual 10-15 minute data runs. Although a thorough statistical analysis is continuing, some preliminary results are now presented.

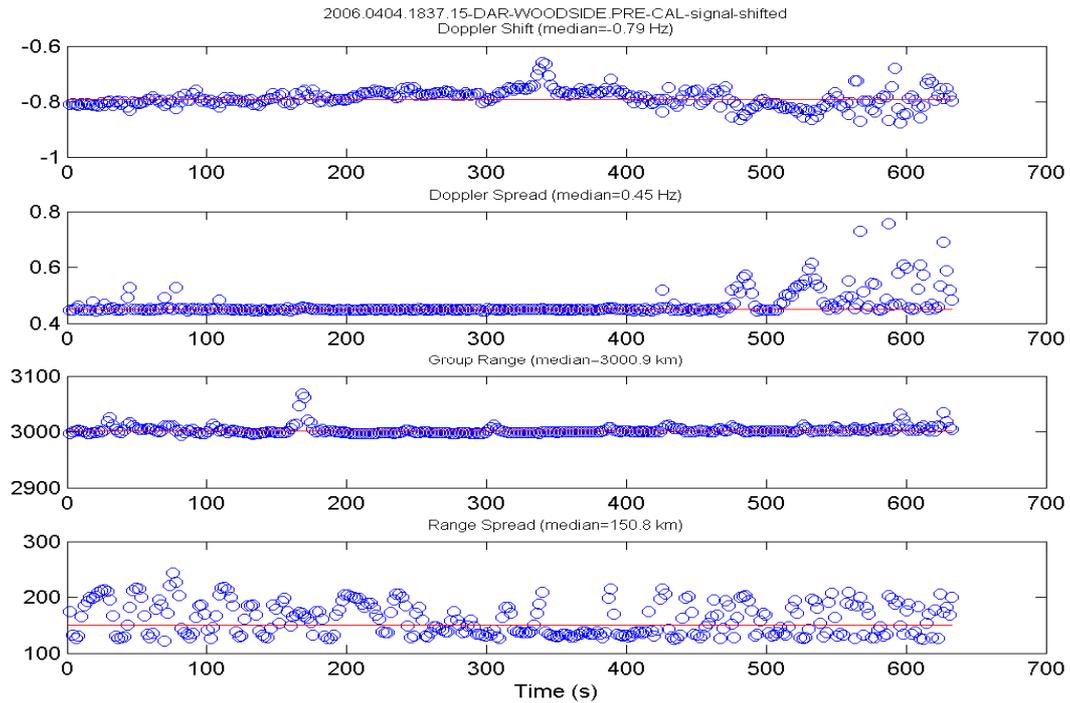


Figure 11 Doppler and Group range statistics for a single path

Two second CIT channel scatter functions were produced, with a 50% overlap, across the entire run. From these CSF ordered statistics were calculated in Doppler space, having summed over group-delay space. The integrated Doppler profile gave measures of the median Doppler shift and the Doppler range that contained 90% of the energy (Doppler spread). The same procedure was used for the group-delay information, where the integration was across Doppler space. The time-series of these statistics are shown in Figure 11 for a single path. We can see that there is a disturbance occurring late in the time-series causing a greater spread over Doppler. The range spread exhibits a beating pattern throughout the 10-minute collection period. Further analysis will tell whether this is usual for this path or time-of-day.

An important channel characteristic for HF communications is the amplitude fading behaviour. The limited analysis of the trial data set shows a wide variety of fading behaviour. Cluster analysis will determine the associations of these behaviours with time-of-day, paths *etc.* The correlated behaviour of a single path is shown in Figure 12. For this example the correlation time is of the order of 40 seconds. Some data sets have shown correlation times as short as 0.3 seconds. Signal-to-noise ratio is of course an important factor in this correlation time.

Figure 13 shows statistics of the fade duration on the same dataset shown in Figure 12. The top panel shows the cumulative distribution of time-series power, with the bottom panel showing the mean duration for the power to be less than the corresponding envelope power. For this example the fade duration is of the order of 5 seconds for many threshold power settings. Again, other datasets give widely different results. The complex correlated interactions controlling this behaviour are under investigation.

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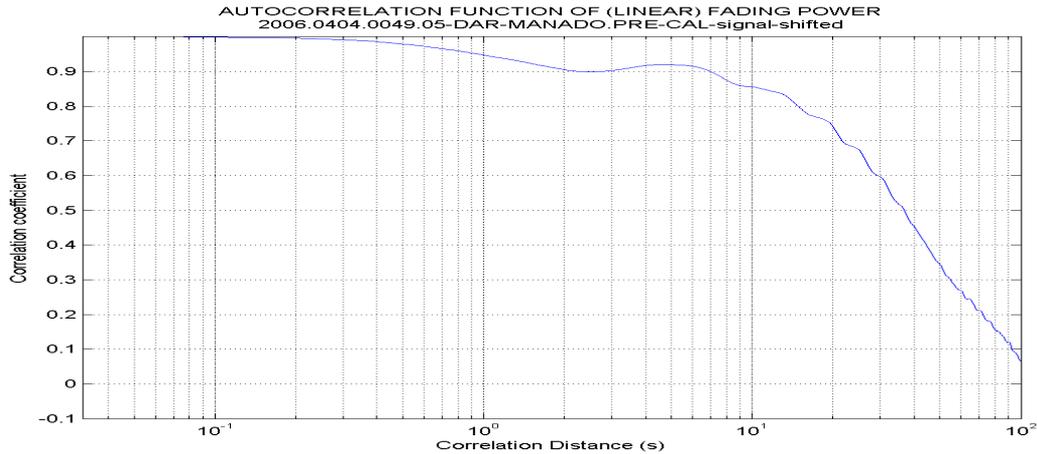


Figure 12 An example Autocorrelation of received power.

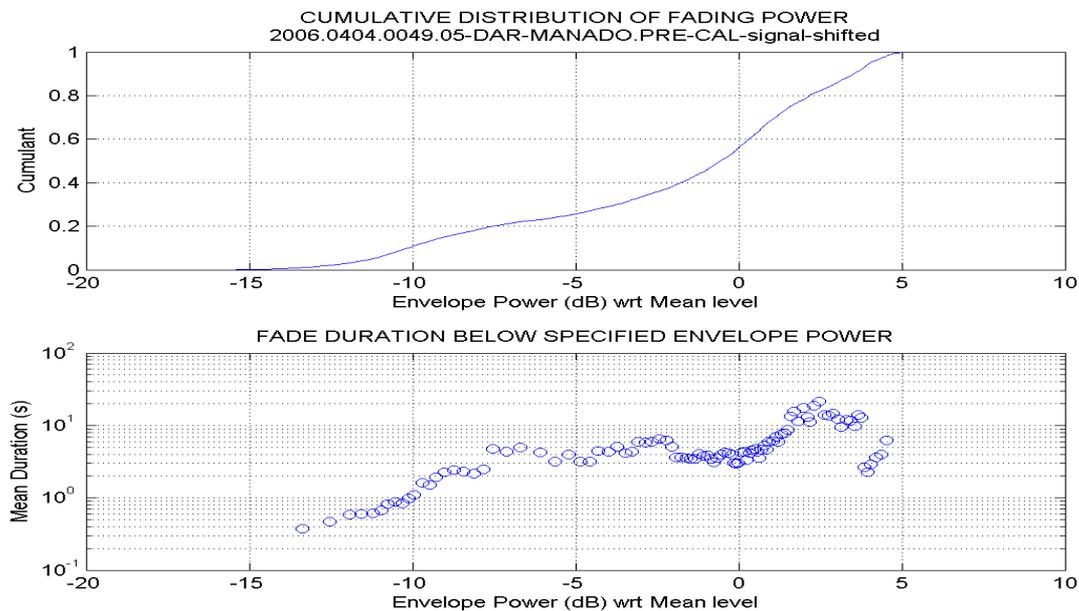


Figure 13 An example of Fade duration

5.0 CONCLUSIONS

This paper describes an extensive Australian trial to determine the HF skywave channel characteristics in the Australasian region. The goal of the trial is to set the framework to determine how current HF modems perform using real ionospheric channels. The experimental setup has been described and preliminary results presented.

There is much work to be done to understand the statistical relationship between the many correlated ionospheric parameters. Cluster analysis will be performed on the data using ionospheric and signal parameters specially chosen to reflect the entire variability space with as little cross-correlation amongst the parameters as possible. The details of the cluster analysis and the results will be presented at a later stage.

6.0 ACKNOWLEDGEMENTS:

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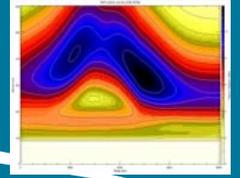
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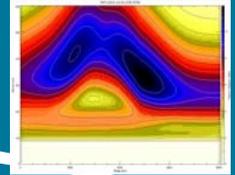
¹ Intelligence Surveillance Reconnaissance Division

² Information Networks Division



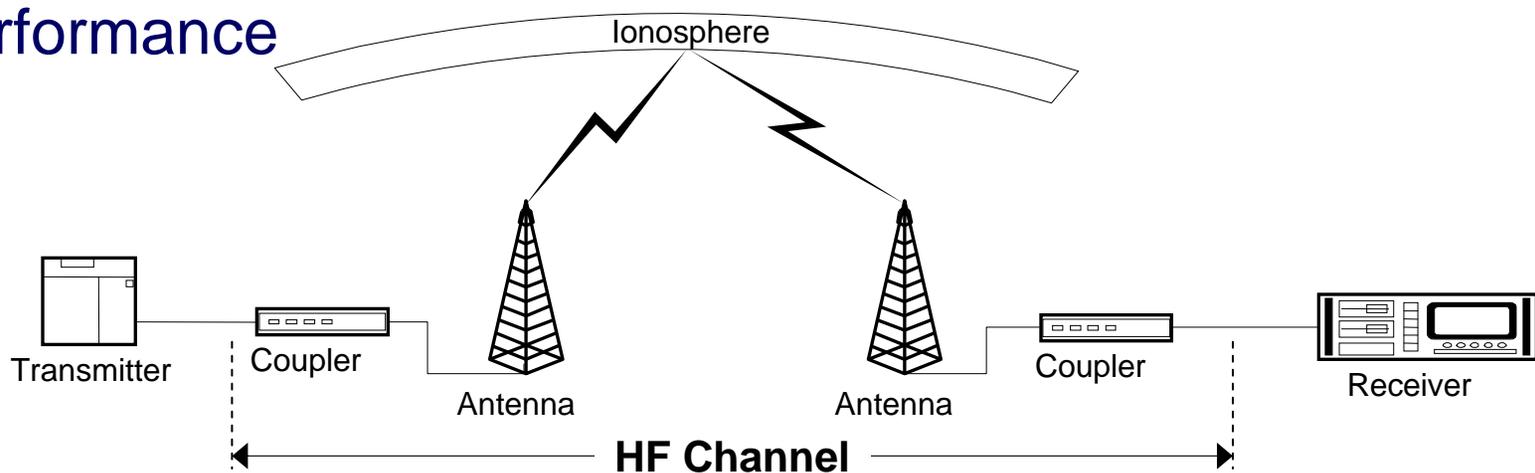
Introduction

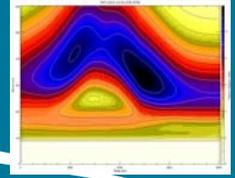
- Background
- HF Channel Characterisation Trial
- The Data
- The Analysis
- The next steps



Modernised HF Communication System [MHFCS]

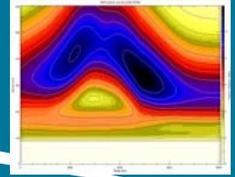
- ADF Asset
- Networked system
- HF Modems for Voice and Data
- System Performance Model vital for predicting performance
- The “HF Channel” is a part of the HF communications system that introduces attenuation, multiplicative and additive noise.





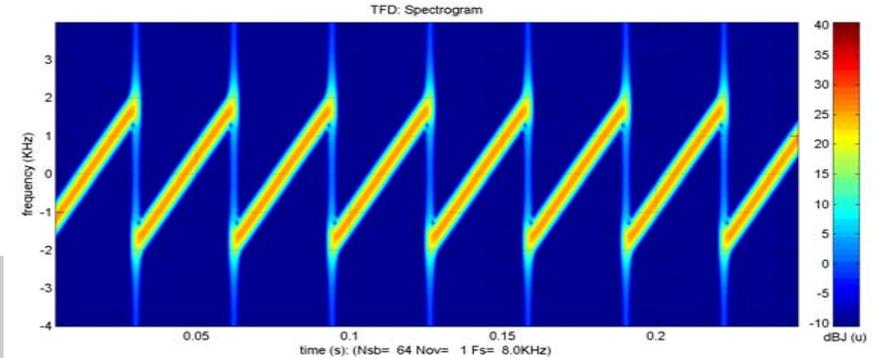
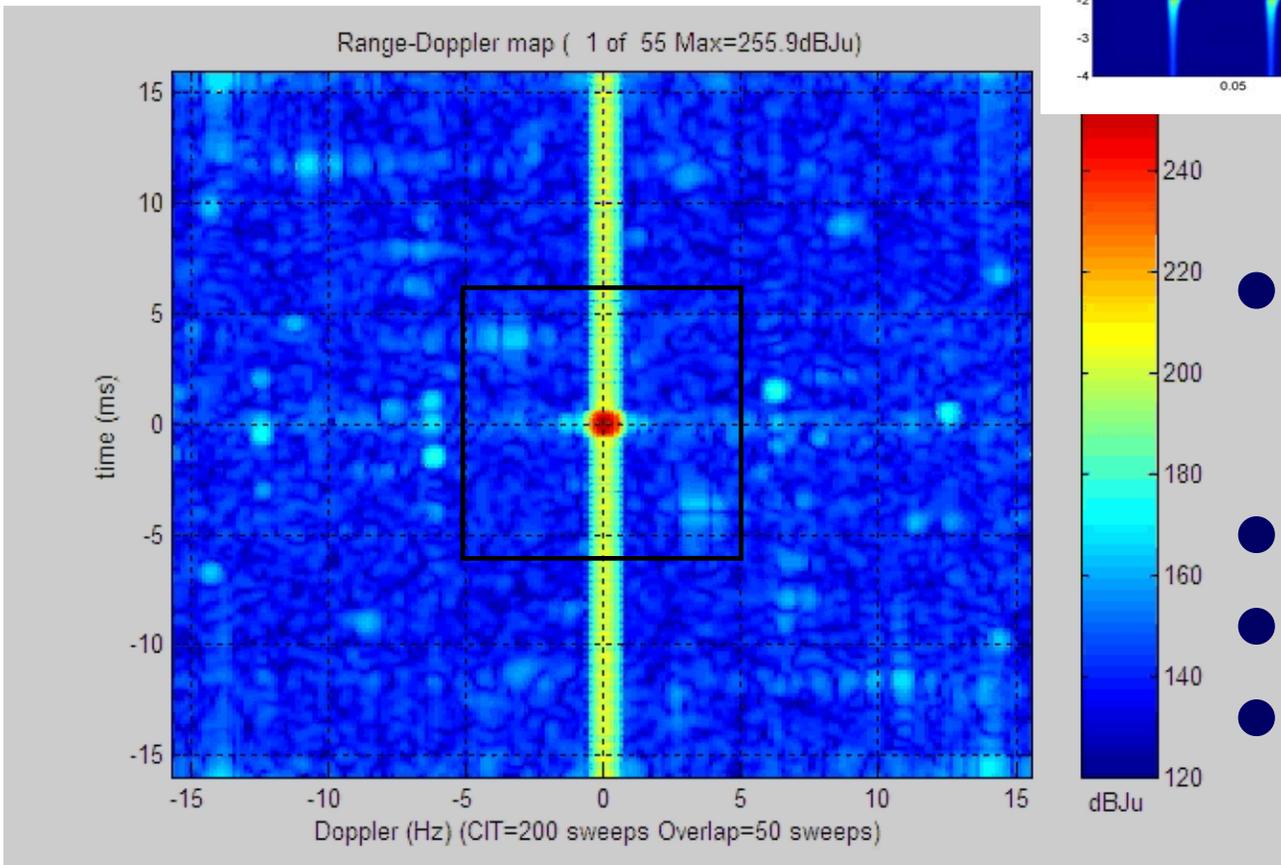
HF Channel Characterisation Trial

- The aim of this trial is to undertake measurements of the characteristics of real HF communications channels in the Regions of interest to the ADF in order to:
 - validate the HFMOD system performance model
 - validate design assumptions used in HFMOD.
 - Allow testing of realistic protocol and modem behaviour
- This is an attempt to understand the real HF Channel variability in our region.
- Addresses the important issues of:
 - How often do conditions in our region go outside the bounds used in the MHFCS design and modeled in the SPM ?
 - How is the MHFCS performance affected by these real variations ?
 - Are the MHFCS SNR predictions reasonable ?

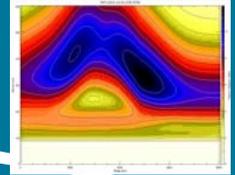


The Transmitters

Tx loopback test

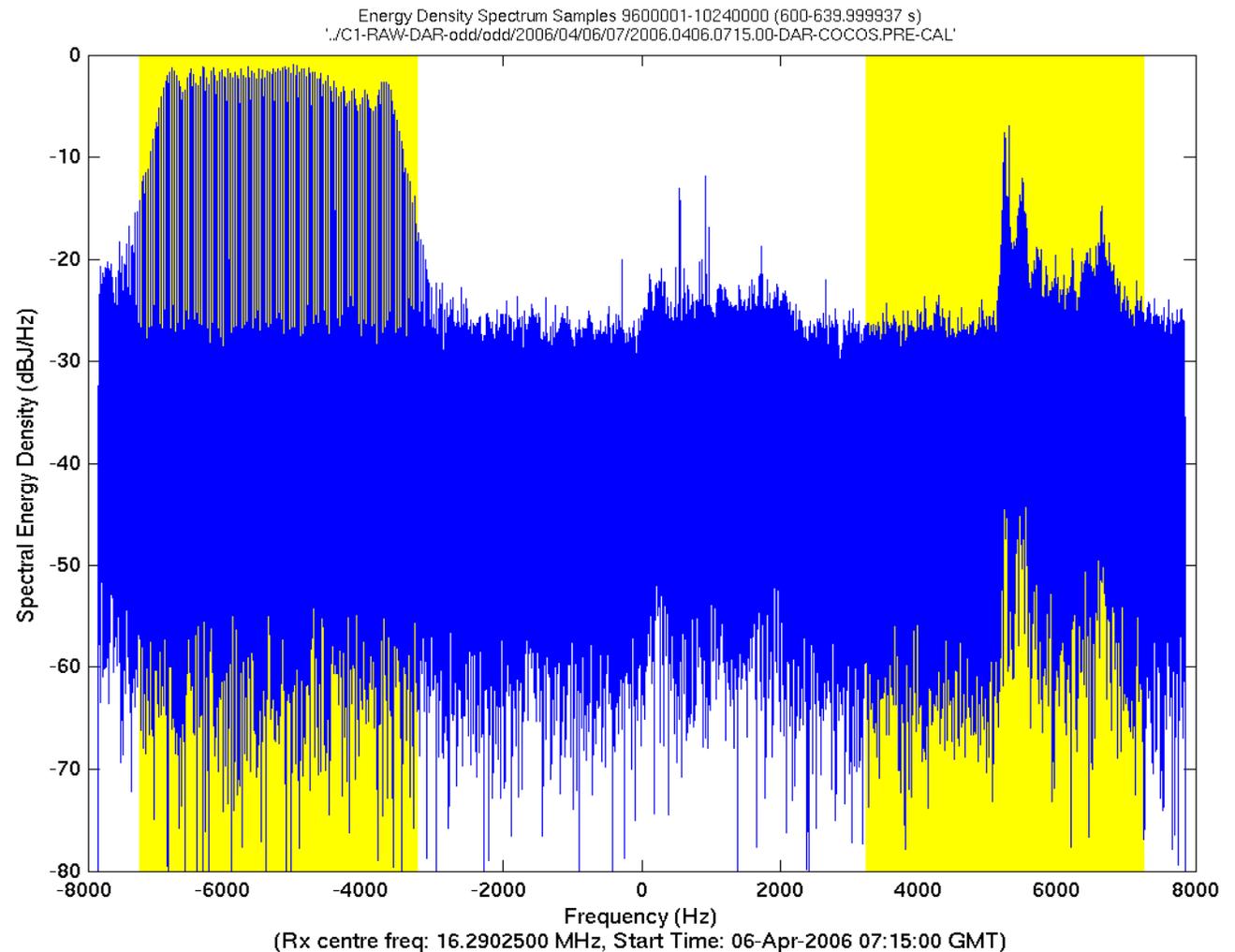


- Repetitive FMCW sweep across 3.6kHz band
- 4 frequency / hr / Tx
- 24hr / day
- ~14days



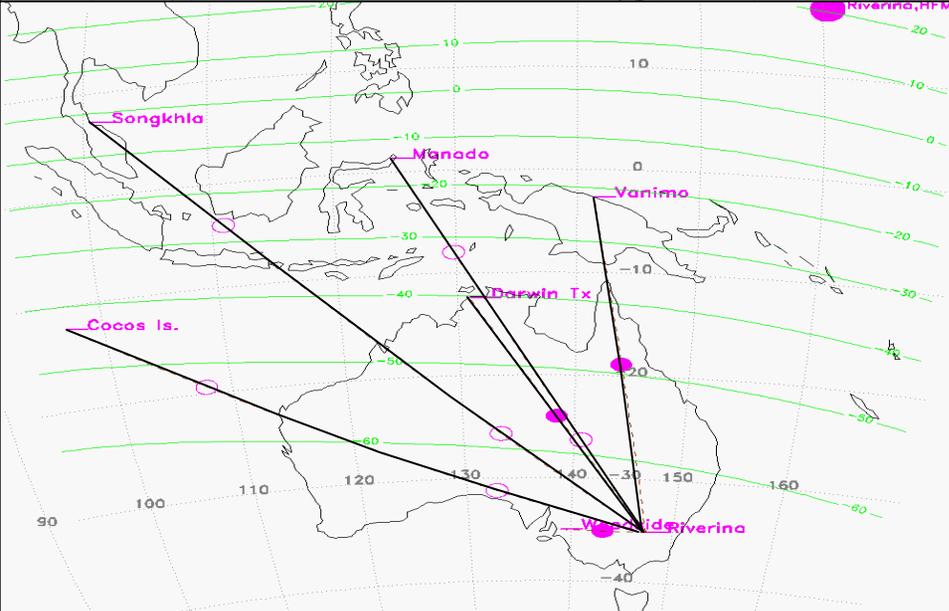
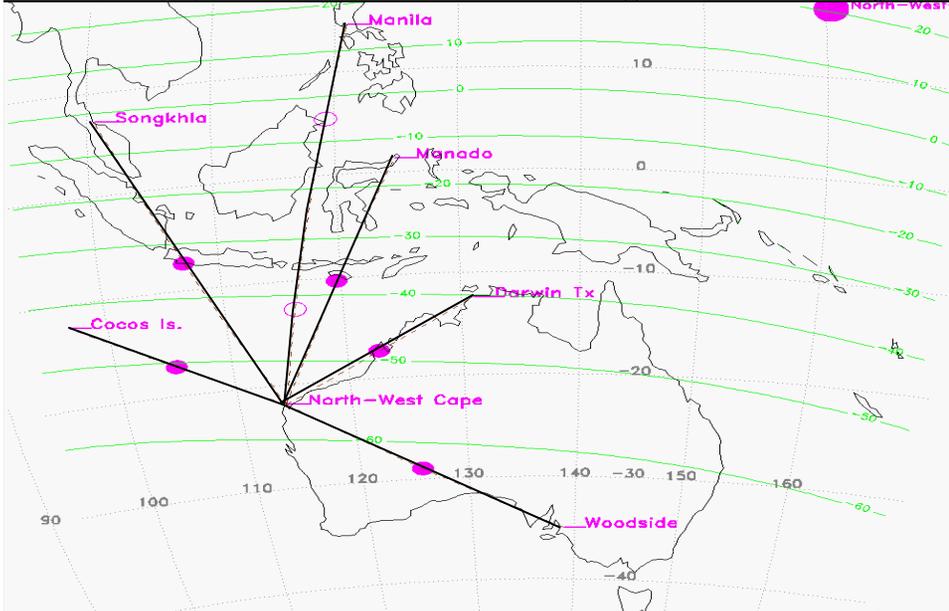
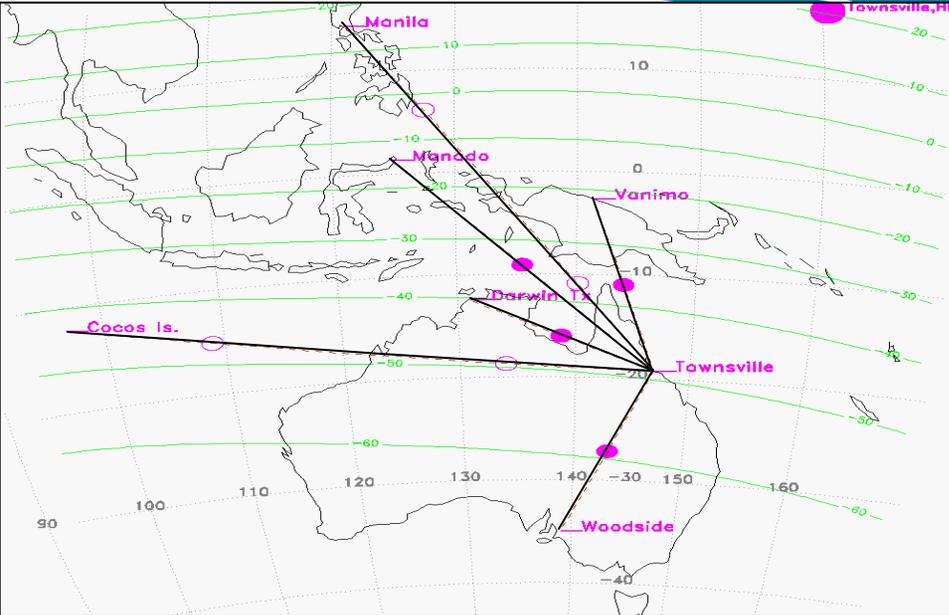
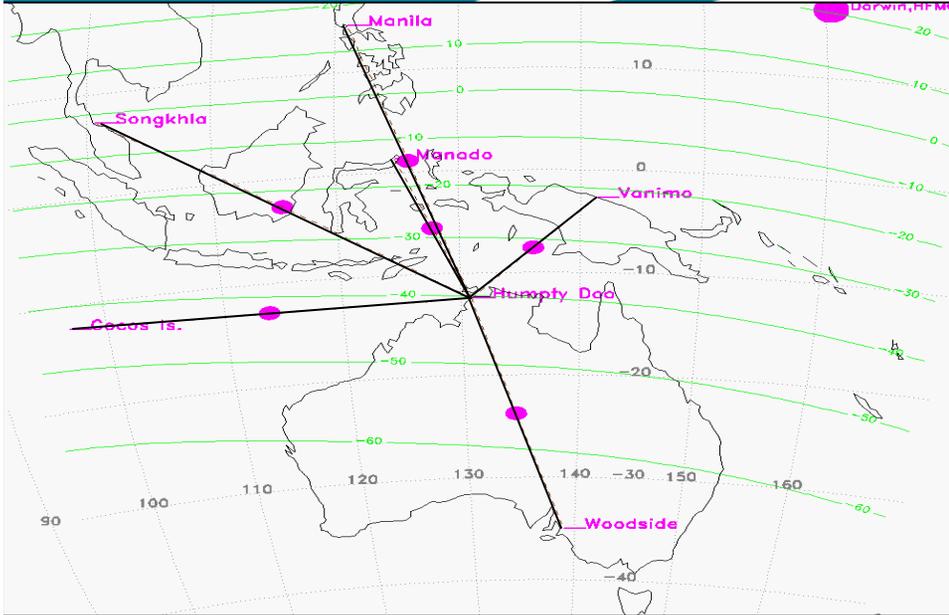
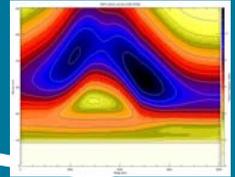
The Receivers

- Wideband Digital
- C1, 3/4 Rx, 5/7 Tx
- Campaign 1,
 - 28841 data runs
 - 10-15 Min each
 - 850 GB



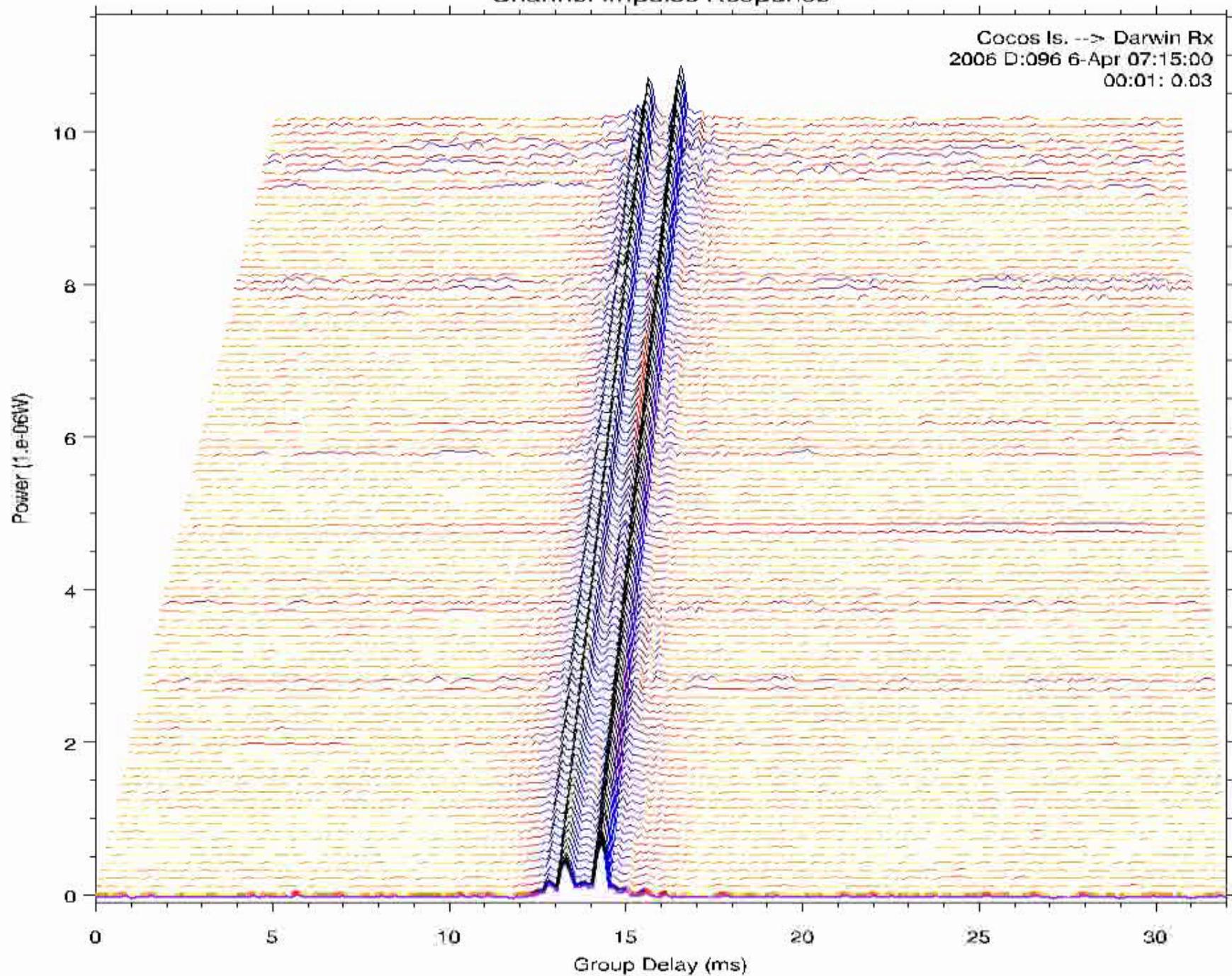


The Paths



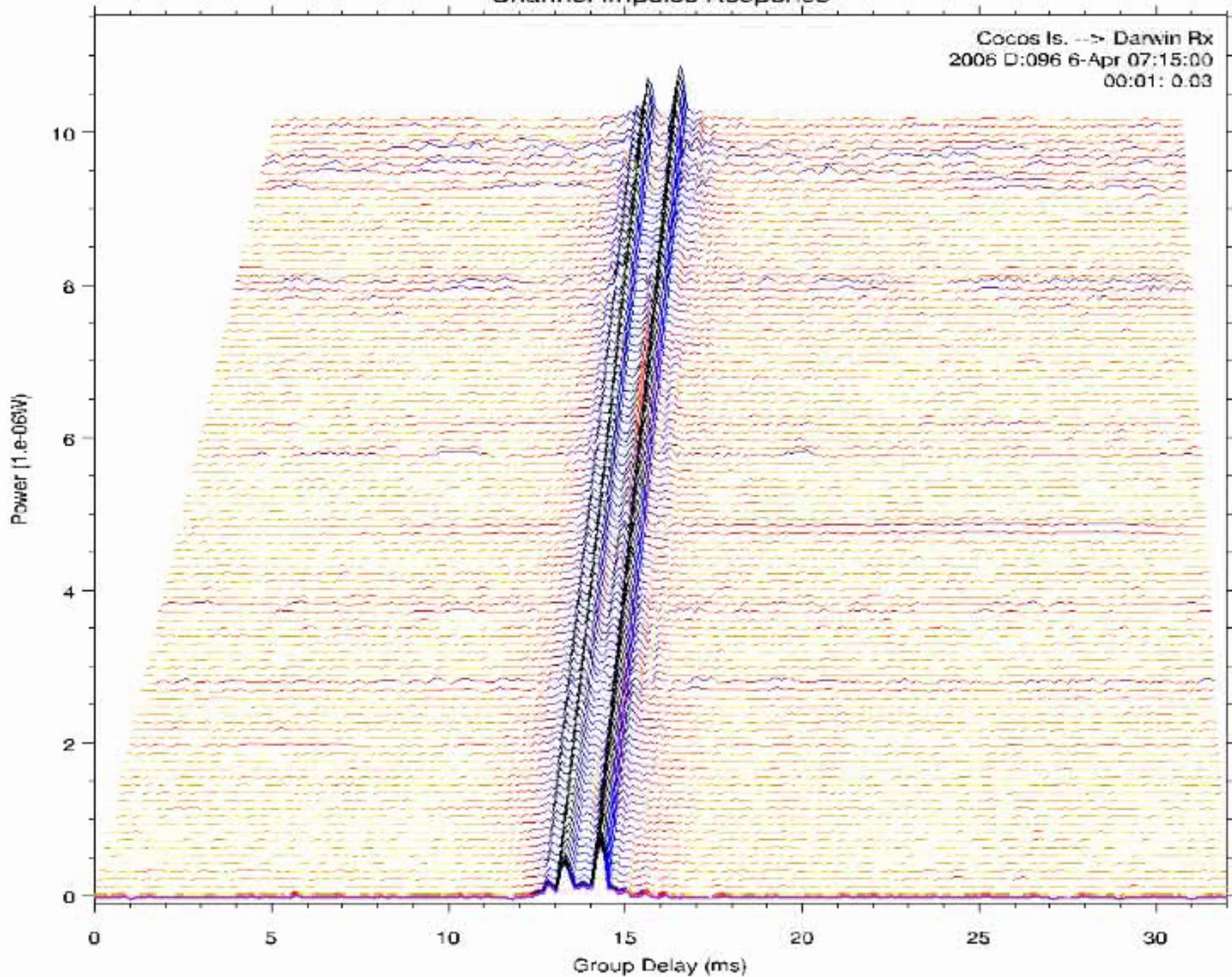
Channel Impulse Response

Cocos Is. --> Darwin Rx
2006 D:096 6-Apr 07:15:00
00:01: 0.03

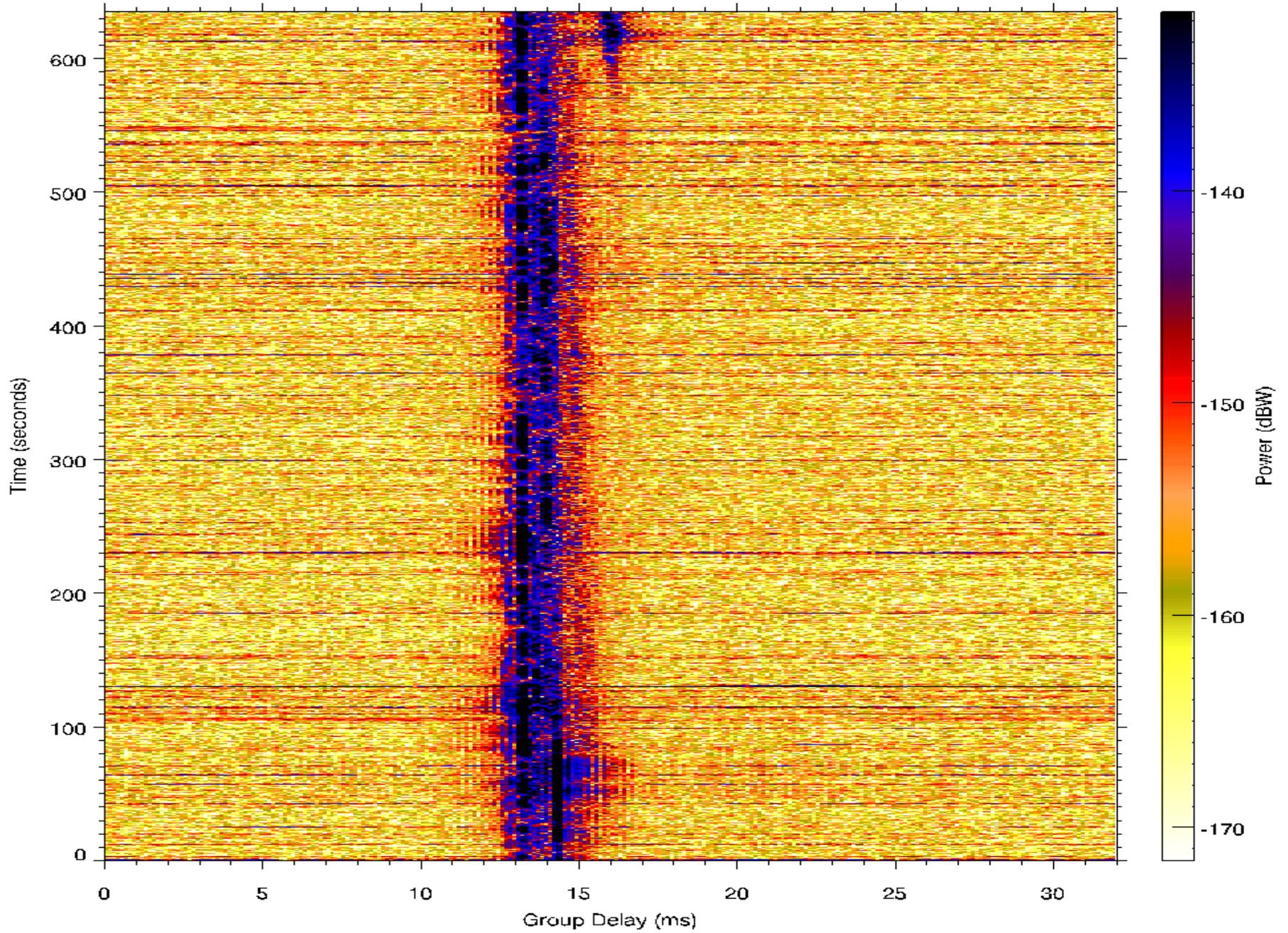


Channel Impulse Response

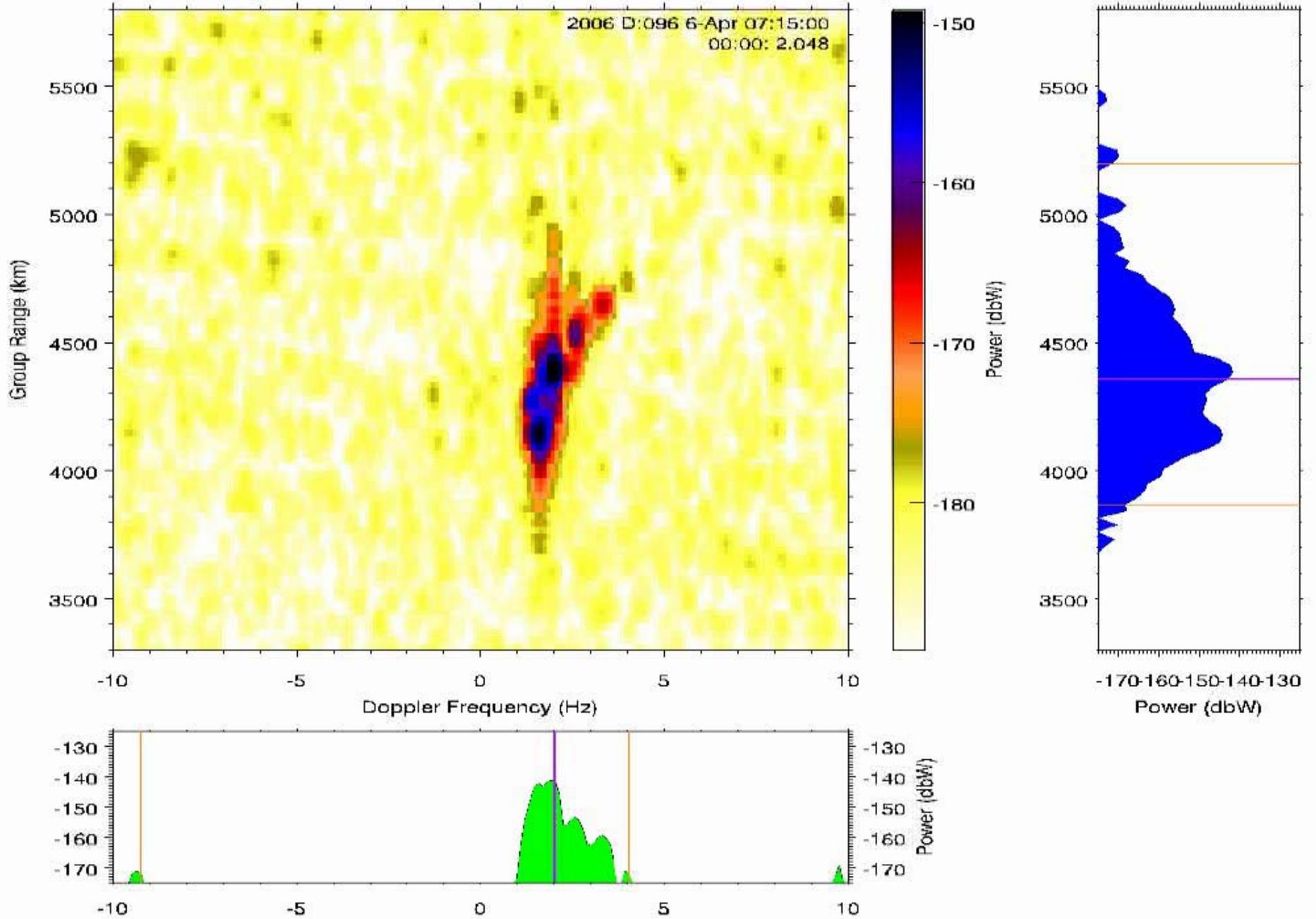
Cocos Is. --> Darwin Rx
2006 D:096 6-Apr 07:15:00
00:01: 0.03



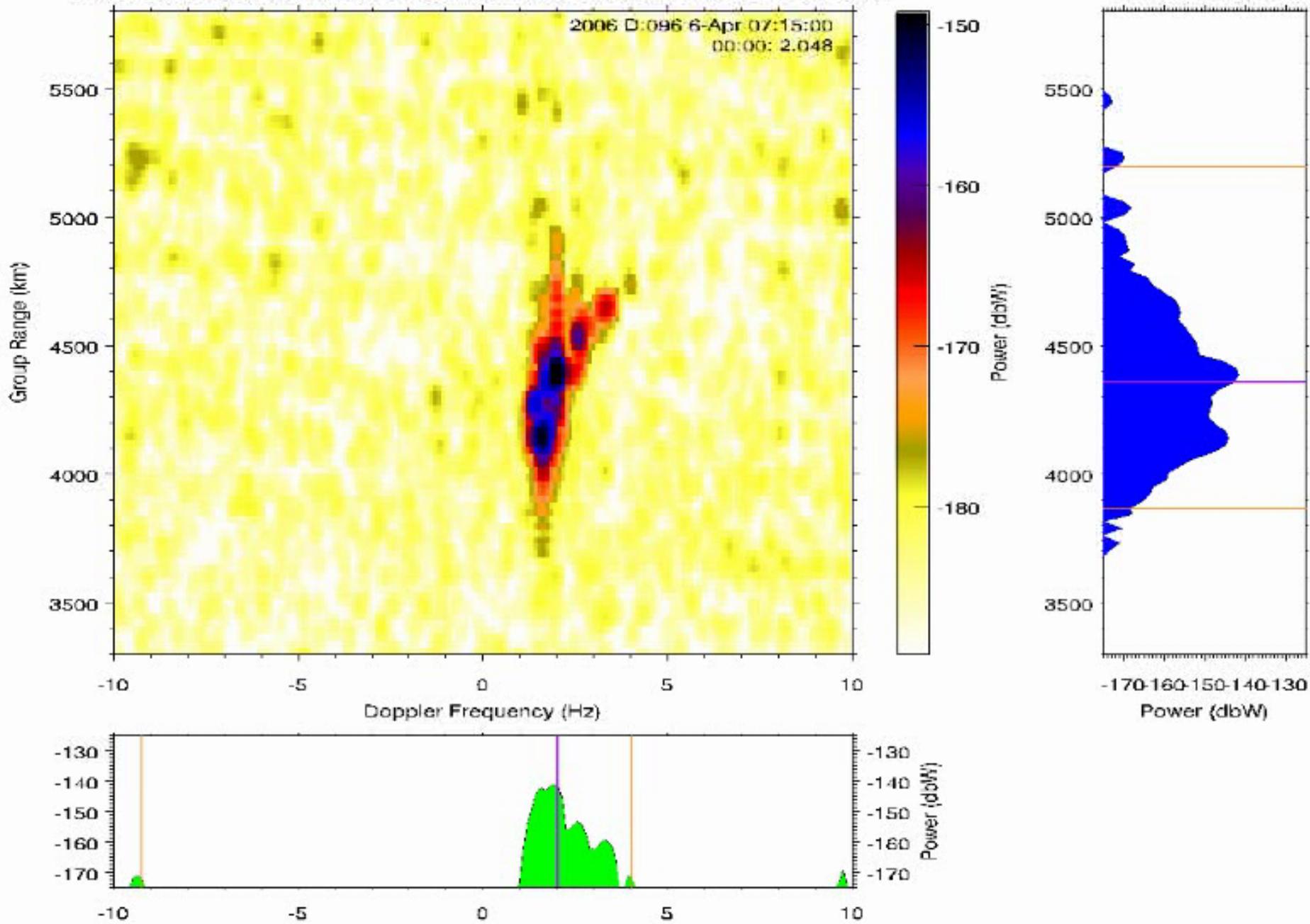
Cocos Is. --> Darwin Rx
2006 D:096 6-Apr 07:15:00 Channel Impulse Response

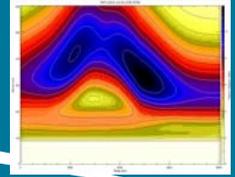


Cocos Is. --> Darwin Rx
2006 D:096 6-Apr 07:15:00 Channel Scatter Function (8.192 sec CIT)

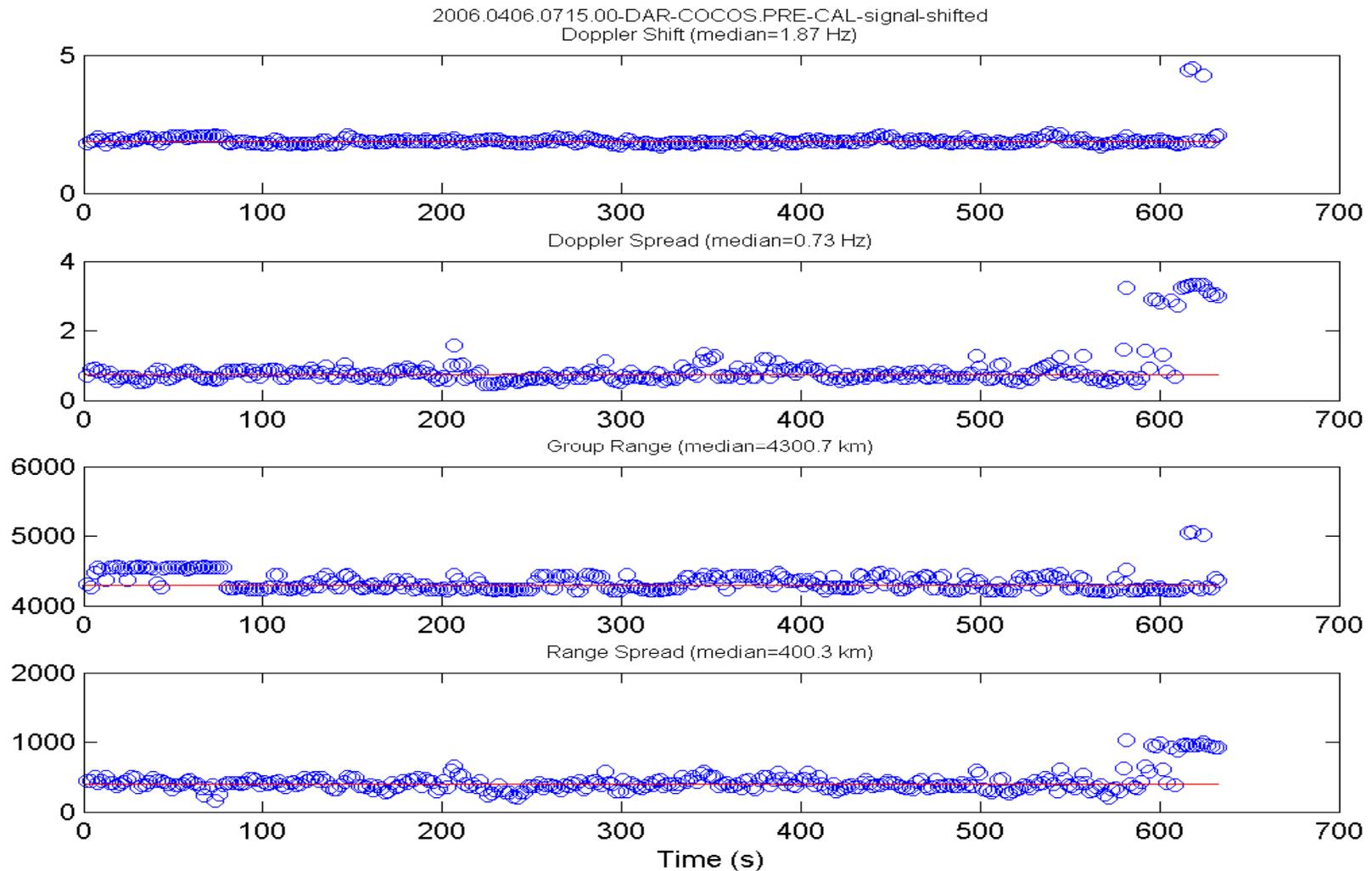


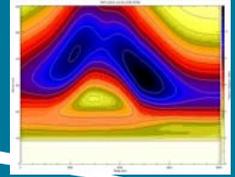
Cocos Is. --> Darwin Rx
2006 D:096 6-Apr 07:15:00 Channel Scatter Function (8.192 sec CIT)





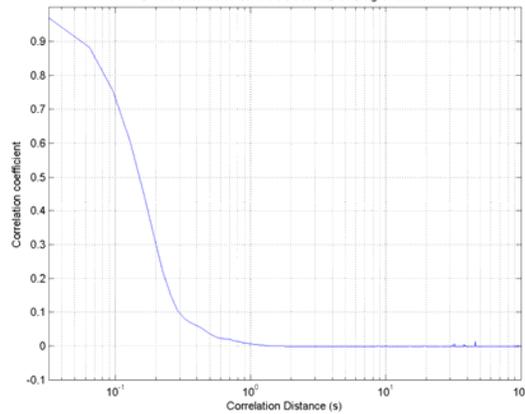
Doppler and Group Statistics



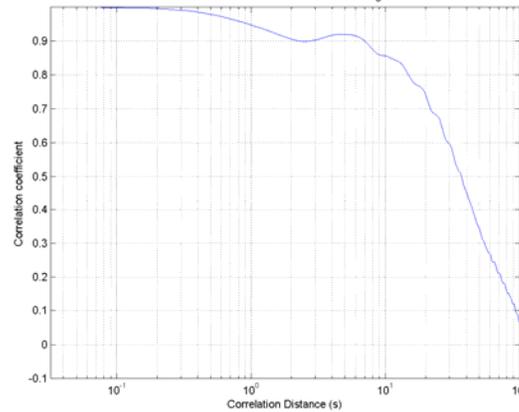


Fading Statistics

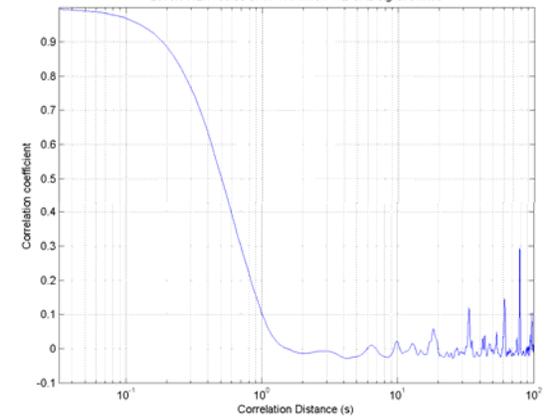
AUTOCORRELATION FUNCTION OF (LINEAR) FADING POWER
2006.0406.0715.00-DAR-COCOS.PRE-CAL-signal-shifted



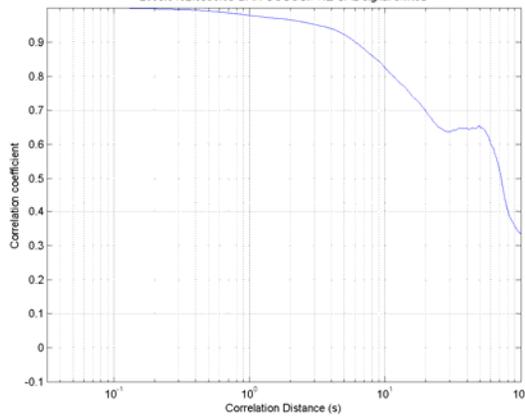
AUTOCORRELATION FUNCTION OF (LINEAR) FADING POWER
2006.0404.0049.05-DAR-MANADO.PRE-CAL-signal-shifted



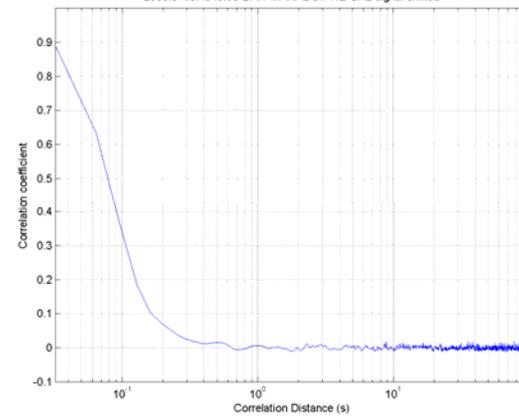
AUTOCORRELATION FUNCTION OF (LINEAR) FADING POWER
2006.0412.1706.05-DAR-VANIMO.PRE-CAL-signal-shifted



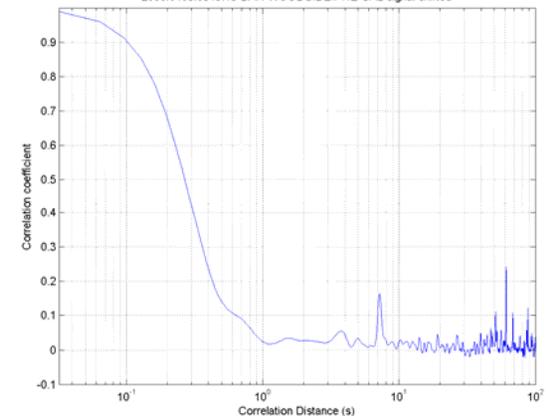
AUTOCORRELATION FUNCTION OF (LINEAR) FADING POWER
2006.0402.0530.05-DAR-COCOS.PRE-CAL-signal-shifted

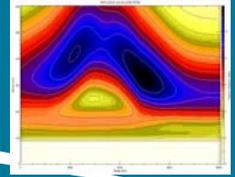


AUTOCORRELATION FUNCTION OF (LINEAR) FADING POWER
2006.0405.1349.05-DAR-MANADO.PRE-CAL-signal-shifted



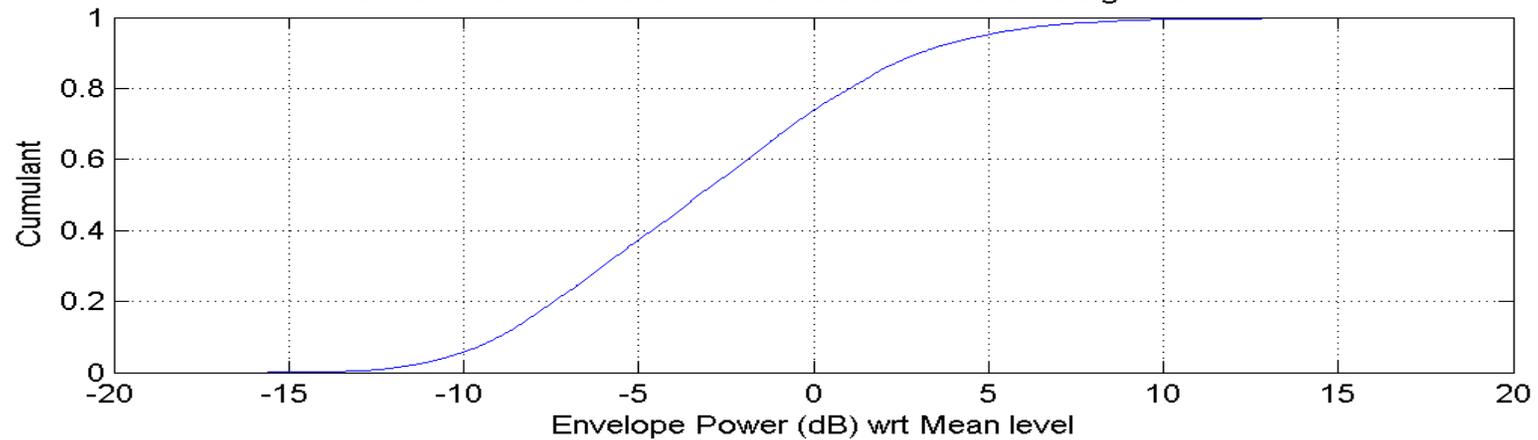
AUTOCORRELATION FUNCTION OF (LINEAR) FADING POWER
2006.0403.0919.15-DAR-WOODSIDE.PRE-CAL-signal-shifted



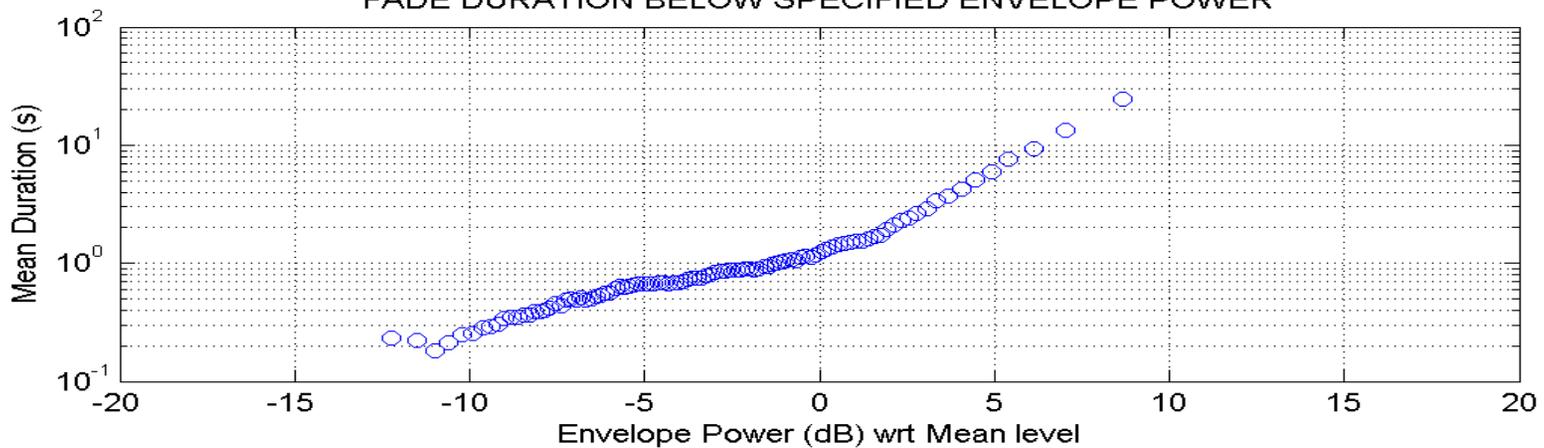


Fading Statistics

CUMULATIVE DISTRIBUTION OF FADING POWER
2006.0403.0919.15-DAR-WOODSIDE.PRE-CAL-signal-shifted



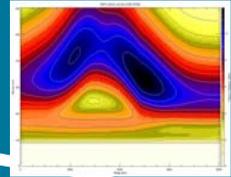
FADE DURATION BELOW SPECIFIED ENVELOPE POWER





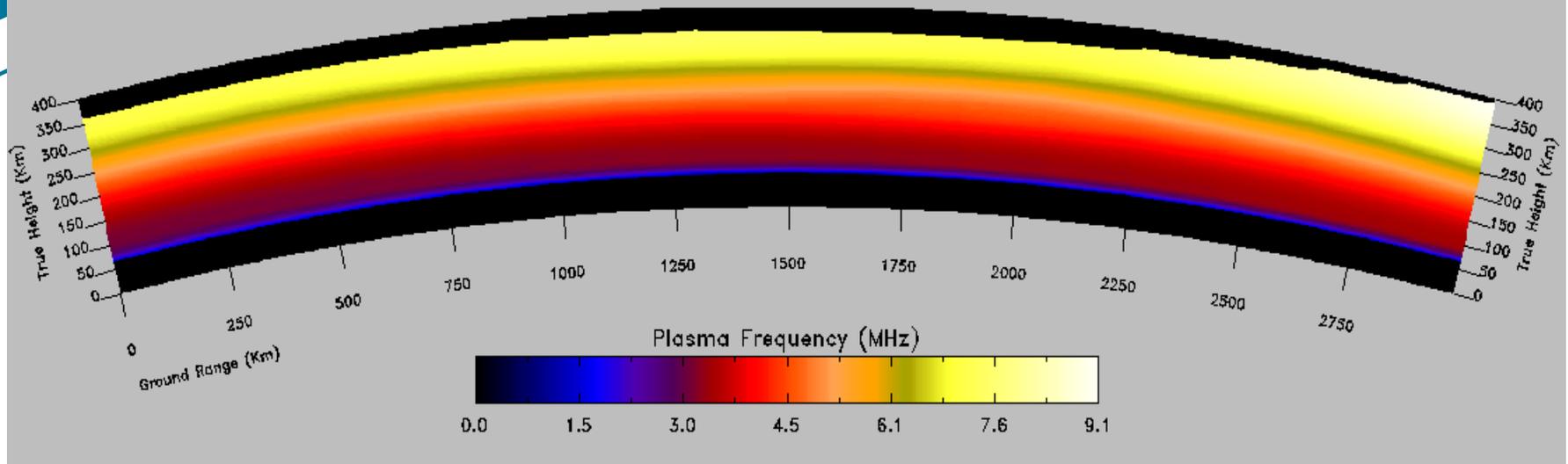
Australian Government
Department of Defence
Defence Science and
Technology Organisation

Ionospheric Slice

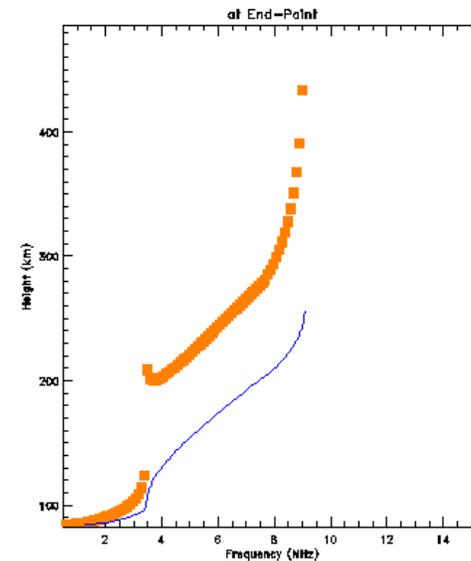
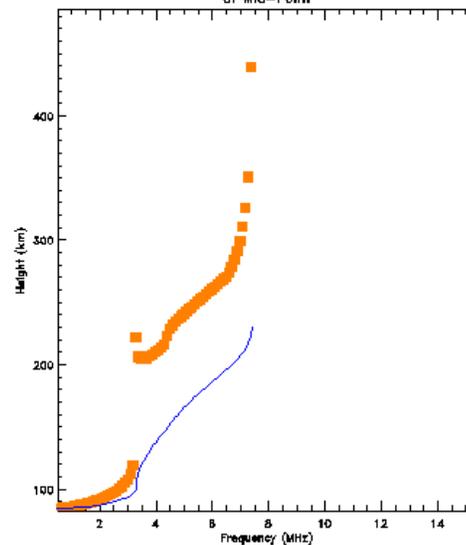
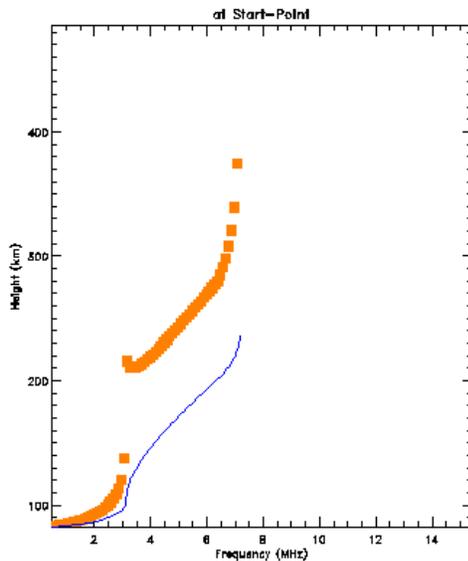


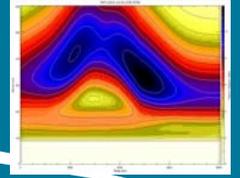
12-Apr-2008 D102 03:45:00.00 UT JORN RTIM

True Height Profiles



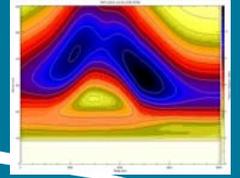
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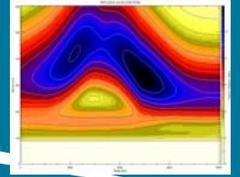
Clustering

- Path characteristics
 - Rx/Tx range separation, magnetic lat/lon
 - magnetic lat/lon, dip, dec for Mid-point and multi-hop points
- Daily characteristics
 - Solar activity
- Run-by-Run variations
 - Frequency
 - Local Time-of-day at Mid-point and multi-hop points
 - Magnetic activity: DST index
 - Ionospheric strength at Mid-point and multi-hop points
 - Fading depths and rates
 - Doppler and Group-delay shifts and spreads
 - Noise environment, SNR



The Next Steps

- Tuning the Cluster analysis
- Closer look at the NOISE environment
- Determine Groupings: %time/%coverage
- Choose “typical” channel for specified time and spatial coverage
- Use typical channels for REPLAY SIMULATION of HFMOD protocols for traffic / performance analysis
- Campaigns
 - 1) April 2006
 - 2) July 2006
 - 3) October 2006
 - 4) January 2007



Acknowledgements

- DSTO technician David M. Sutton: installing and maintaining the equipment and liaising with the staff at the remote transmitter and receiver sites;
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- LAPAN in Bandung: maintenance of the Manado transmitter;
- The Royal Thailand Navy Communications Department: maintenance of the Songhkla transmitter;
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