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DSTO-TR-1505

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Intelligence, Surveillance and Reconnaissance Division
Information Sciences Laboratory

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ABSTRACT

To maximise target signal to noise ratio, the Jindalee Facility Alice Springs (JFAS) Over-the-Horizon Radar (OTHR) requires frequency channels that are free from radio frequency interference (RFI). Prior to 2000, to achieve this objective the radar operators were reliant on Clear Channel Advice (CCA) which is derived primarily from the Frequency Management System's (FMS) Spectrum Monitor (SM). Due to limitations of the SM, the operators were forced to use an HF communications receiver to check CCA, which could be a time consuming and inaccurate process. As part of a major upgrade of the FMS in 1999, a Passive Channel Evaluator (PCE) subsystem was added to remove or reduce the need to use the communications receiver. This report contains a description of the signal processing algorithms used to determine if PCE data contains RFI and the results of testing these algorithms with the JFAS radar.

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The Radio Frequency Interference Detection Algorithms for the Jindalee Facility Alice Springs Passive Channel Evaluator

Executive Summary

The primary purpose of the JFAS (Jindalee Facility Alice Springs) Over-the-Horizon radar is to detect air and surface targets. Target signal to noise ratio (SNR) is optimised by using radar carrier frequencies that provide good propagation to the region of interest and that are free from radio frequency interference (RFI). To achieve this objective, the radar operators use Clear Channel Advice (CCA) which is derived primarily from the Frequency Management System's (FMS) Spectrum Monitor (SM). CCA determines every two minutes, at 2 kHz resolution, whether channels in the HF band are currently "clear channels" fit for use by the radar. Due to limitations of the SM, prior to 2000, the operators were forced to use an HF communications receiver to check CCA, which could be a time consuming and inaccurate process. As part of a major upgrade of the FMS in 1999, a Passive Channel Evaluator (PCE) subsystem was added to remove or reduce the need to use the communications receiver.

The main use of the PCE is to automatically evaluate channels nominated by the Frequency Advice algorithms used by a radar operator to implement a radar task. By passively dwelling on frequencies provided by CCA, the PCE vets prospective radar frequencies before they are recommended for use by the radar. The PCE mimics the response of the main radar (in passive mode) by using the same dwell parameters and the same signal processing as the main radar. The PCE has eight receivers and collects data simultaneously on the eight FMS directional beams. By providing more sensitivity than the SM as well as Doppler information, the PCE is expected to overcome most of the shortcomings of CCA based on the SM.

DSTO's Intelligence, Surveillance and Reconnaissance Division (ISRD) volunteered to produce the signal processing algorithms to determine if PCE data contain RFI and consequently developed a suite of software to examine and process PCE data in ISRD. Although the other FMS Upgrade subsystems became operational in 2000, the PCE was not available for scientific assessment until early in 2002. At that time, ISRD tested the performance of the PCE and found that the initial implementation of both the user interface and the signal processing algorithms were not ready for operational use. ISRD recommended and subsequently tested changes to both the user interface and the signal processing algorithms. The PCE was declared ready for operational use at the end of 2002.

This document provides a brief description of the PCE and the way in which the RAAF 1RSU operators are expected to use it. The major thrust of this document is the PCE signal processing algorithm suite describing the types of interference these algorithms aim to detect and how this is achieved. Potential improvements to these algorithms are also discussed.

Authors

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Brett Northey is a Defence Scientist in the Electromagnetics and Propagation Group of the Intelligence, Surveillance and Reconnaissance Division. He graduated from the University of Adelaide in 1994 with a Bachelor of Science degree (Honours) and was awarded a Master of Science degree in 1998.

He joined DSTO in 1995 and has worked in several areas in relation to the Jindalee over-the-horizon radar Frequency Management System, such as HF background noise and spectral occupancy, the Passive Channel Evaluator, and Surface Mode Frequency Advice.

Philip S Whitham
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Phil studied for both his B.Sc (Hons) in Physics and his Ph.D at the University of Tasmania. His Ph.D was in the field of radio astronomy and that led to his recruitment to the Jindalee Over-the-Horizon Radar Project at the Defence Science and Technology Organisation (DSTO) at Edinburgh.

Phil came to Adelaide in 1978 and, apart from two years in Canberra in the mid 1980s, has been working on over-the-horizon radar ever since. He has worked in the fields of radar control, radar signal processing, propagation management and the effects of the ionosphere on the radar. His current research interests include the use of expert systems for radar control and several topics in ionospheric physics.

Contents

1. Introduction

The primary purpose of the JFAS (Jindalee Facility Alice Springs) Over-the-Horizon radar is to detect air and surface targets. To do this, target signal to noise ratio (SNR) is optimised by using radar carrier frequencies that provide good propagation to the region of interest and are free from radio frequency interference (RFI). The radar management software used to determine such frequencies use data gathered by the radar's Frequency Management System (FMS). In particular, data from the FMS Background Noise Monitor (BNM) and Spectrum Monitor (SM) are combined to determine, at 2 kHz resolution, whether channels in the HF band are currently occupied or unoccupied. Channels listed in a Forbidden Frequency Table are deemed to be occupied regardless of signal level. The unoccupied channels are declared to be "clear channels" fit for use by the radar by a Clear Channel Advice algorithm based, inter alia, on how long they have been unoccupied. The Clear Channel Advice algorithm has been documented by Hutchinson (1995) and the JFAS FMS subsystems have been described in detail by Earl and Ward (1987).

The design of the SM is such that each 2 kHz channel is only examined for a very brief time during the two minutes it takes to complete a 5 to 45 MHz scan. Thus channels, which may have been declared clear by the Clear Channel Advice algorithm, can contain intermittent RFI. For this reason, prior to accepting one of these "clear channels" for use by the radar, the radar operator uses an Icom HF communications receiver to check if the channel is free from RFI. For the purposes of this report, this receiver will be referred to as "the Icom". If the operator discovers that recommended channels are occupied, the Icom is used to examine further channels. This is a common phenomenon, especially during night-time operations, and can result in long delays between requesting frequency advice for a radar task and starting the task. Additionally, the SM and the Icom both use omni-directional antennas that do not have the directional gain of the main radar receive antenna so channels found to be clear by both the SM and the Icom can still contain RFI. Further, the SM does not have the ability to utilise Doppler information, which is important in determining if RFI would be harmful to target detection.

As part of a major upgrade of the JFAS Frequency Management System in 1999, a new subsystem was installed called the Passive Channel Evaluator (PCE). The PCE is designed to remove or reduce the reliance on the Icom, by passively dwelling on frequencies provided by the Clear Channel Advice algorithm. The PCE mimics the response of the main radar (in passive mode) by using the same radar dwell parameters and the same signal processing as the main radar. The PCE has eight receivers and collects data simultaneously on the FMS directional beams. Thus by providing better directional gain and Doppler information, the PCE should solve some of the shortcomings of clear channel advice based on the SM. The main use of the PCE is to automatically evaluate channels nominated by the Frequency Advice algorithms used by a radar operator to implement a radar task.

ISRD volunteered to produce the signal processing software to determine if PCE data contain RFI and consequently developed a suite of software to examine and process PCE data in ISRD. Although the other FMS Upgrade subsystems became operational in 2000, the PCE was not available for scientific assessment until early in 2002. At that time, ISRD tested the performance of the PCE and found that the initial implementation of both the user interface and the signal processing algorithms were not ready for operational use. ISRD recommended and subsequently tested changes to both the user interface and the signal processing algorithms. The PCE was declared ready for operational use at the end of 2002.

This document provides a brief description of the PCE and the way in which the RAAF 1RSU operators are expected to use it. The major thrust of this document is the PCE signal processing algorithms describing the types of interference these algorithms aim to detect and how this is achieved. Potential improvements to these algorithms are also discussed.

2. Brief Description of the PCE

The JFAS FMS consists of several modular subsystems that collect environmental data relevant to ionospheric propagation. The data collected by the FMS subsystems are used to provide the main radar with advice on what parameters radar tasks should use to attain optimum performance for a given mission. Several of the FMS subsystems use the "FMS array" and omni-directional antennas located at the radar receive site to collect their data. The FMS array produces eight directional beams, numbered 0 to 7, covering a 90-degree segment NW of the radar receive site. Beam 0 is directed towards the West and beam 7 towards the North. The PCE is a passive system that collects data from either the eight FMS beams or seven of the beams and an omni-directional antenna.

When the radar operator requests frequency advice for a radar task, the PCE is tasked to examine the channels recommended by the automatic clear channel and frequency advice algorithms. The PCE data or "dwells" are generated using the following parameters where the radar operator can adjust the default values of these parameters:

a. the centre frequency of the channel (default: proposed radar frequency)
b. the bandwidth of the channel (default: radar task's bandwidth)
c. the duration of each PCE dwell (default: radar task's dwell time)
d. the number of dwells the PCE will collect on each candidate channel (1-5, default: 3)
e. the FMS beams to use (default: the eight directional beams)
f. waveform parameters (default: same as the radar task)
g. number of range cells (default: same as the radar task)

Very similar data processing to that used by the main radar is applied to the PCE data. The data are deramped against a linear sawtooth FM waveform with the same parameters (bandwidth, waveform repetition frequency (WRF) and number of sweeps) as the radar task for which clear channel advice has been sought. After deramping, the data are subjected to range and Doppler processing. The number of range cells retained after processing is the same as the radar task. An example of PCE processed data, consisting of a dwell for each FMS beam, is shown in Figure 1 where the data are displayed in range-Doppler format. The range resolution is inversely proportional to the bandwidth of the deramping waveform and the Doppler resolution is proportional to the WRF divided by the number of sweeps, i.e. Doppler resolution is inversely proportional to the coherent integration time. Since the data are range processed, it can be displayed with a range dimension, but it should be noted that features in the data do not necessarily correspond to signals coming from the ranges indicated on the PCE display.

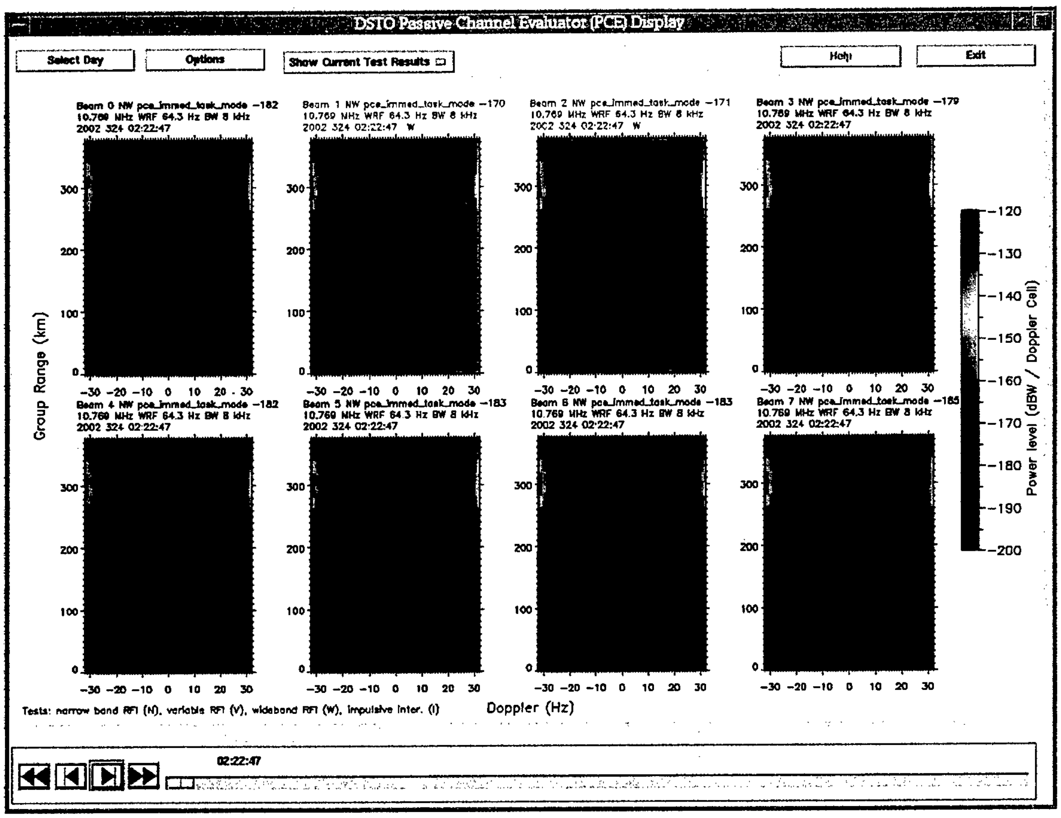

Figure 1: The ISRD PCE display is shown. The dwells for FMS beams 1 and 2 have enhanced noise floors and so are labelled W to indicate they contain wideband RFI.

Figure 1 is a screen capture of the ISRD PCE display, which is part of the suite of software that was developed in ISRD to evaluate the PCE signal processing algorithms, and is almost identical to the JFAS PCE range-Doppler display available in the operations room at the JORN Coordination Centre (JCC) at the RAAF Edinburgh Base in South Australia. Information is displayed above each dwell providing the source (FMS beam number), the FMS segment (NW (default), NE, SE or SW), the PCE mode (see Section 3), the noise level for the dwell (see Section 4.3), the dwell's frequency, WRF, bandwidth and run time. Finally, there is a label that indicates if the PCE signal processing algorithms found RFI in this particular dwell. The label is blank (no RFI found) or N (narrow-band RFI) or V (variable RFI) or W (wideband interference). When the algorithms detect RFI all of the dwell text information is displayed in red; text information for dwells without RFI is displayed in black.

3. PCE Concept of Operations

This section is based on the PCE Operational Concepts Document (OCD 2002) that was developed jointly by the OTHR Systems Project Office (OTHRSPO) and ISRD. The three modes of operation for the PCE are the Immediate Task mode (checking the channels recommended by automatic frequency advice for a radar task), the Immediate Channel mode (checking a specific channel) and the Manual Frequency mode (searching for clear channels in a specified band). The way the PCE is used for any given radar task will depend on whether the frequency advice algorithms recommend any clear channels, whether the PCE agrees that these channels are clear and the urgency of the task.

3.1 Immediate Task Mode

When frequency advice is requested for a task, up to five "clear" channels are provided for a non-frequency agile task or for each footprint for a frequency agile task. In Immediate Task mode, the PCE will automatically examine these channels until one "PCE clear" channel is found for a non-agile task or for each of the footprints of an agile task. A PCE option allows all channels recommended by frequency advice to be checked, with the operator able to halt this operation at any stage. As PCE advice becomes available, the order of the channels is sorted to show the best frequencies first, i.e. PCE clear channels, followed by any containing impulsive interference followed by any containing wideband RFI followed by any containing variable RFI and finally any containing narrow-band RFI.

In difficult conditions when the PCE advises that none of the recommended channels are free of RFI, the five channels are still shown sorted as above with their RFI flag next to them. In this situation, it is envisaged that the radar operator will either use the Icom to double check these frequencies or use the PCE to search for a PCE clear channel using the Manual Frequency mode.

In the initial implementation of the PCE, it will only be used to recommend against the use of channels that frequency advice claimed are clear but which PCE signal processing determined are occupied. The Icom will still be used as a final check that a selected channel is clear. However, when the PCE has been fully tested and accepted, it is anticipated that the Icom will no longer be required. It is important to note that JORN does not provide an Icom-type receiver for the radar operators, so testing the JFAS system with a view to no longer using the Icom is important for JORN. (JORN does provide a PCE and its concept of operations is very similar to that of the JFAS PCE.)

3.2 Immediate Channel Mode

Immediate Channel Mode will provide the radar operator with the option to send a single channel to the PCE for immediate evaluation. This mode may be implemented from either the list provided by frequency advice or the PCE Scan Display – see Figure 2.

3.3 Manual Frequency Mode

In very difficult conditions when no clear channels are found by frequency advice, prior to the introduction of the PCE, the radar operator would have had to do a manual search using the Icom. The Manual Frequency mode of the PCE provides an alternative way of searching for clear channels. When the radar operator selects PCE Manual Frequency Mode, the PCE will search for clear channels of a specified bandwidth in a specified band of the HF spectrum. In addition to the PCE parameters described in Section 2, the following parameters apply in Manual Frequency Mode:

a. start frequency for the search
b. the spectrum band to search (default: 1 MHz)
c. the bandwidth of the required clear channel (default: 2 kHz)
d. the size of the step for each scan (default: 2 kHz)
e. continue or stop on finding a clear channel (default: continue)

When the step size for the scan is less than the bandwidth of the required clear channels, consecutive dwells overlap in frequency. This provides a better chance (at the expense of time) of identifying any available channels of the requested bandwidth. If the step size is equal to the PCE dwell bandwidth, then there is no overlapping of candidate channels. The operator can also specify that the search be confined to areas of the spectrum that clear channel advice has declared clear (the default) or the search can be set to the entire specified band except for channels in the Forbidden Frequency Table. When a PCE clear channel is located, it will be provided to the operator with the option to immediately stop the search or to continue through to the end of the band. The results of the search are also provided by colour coded vertical lines on a copy of the radar operator's clear channel display - see Figure 2.

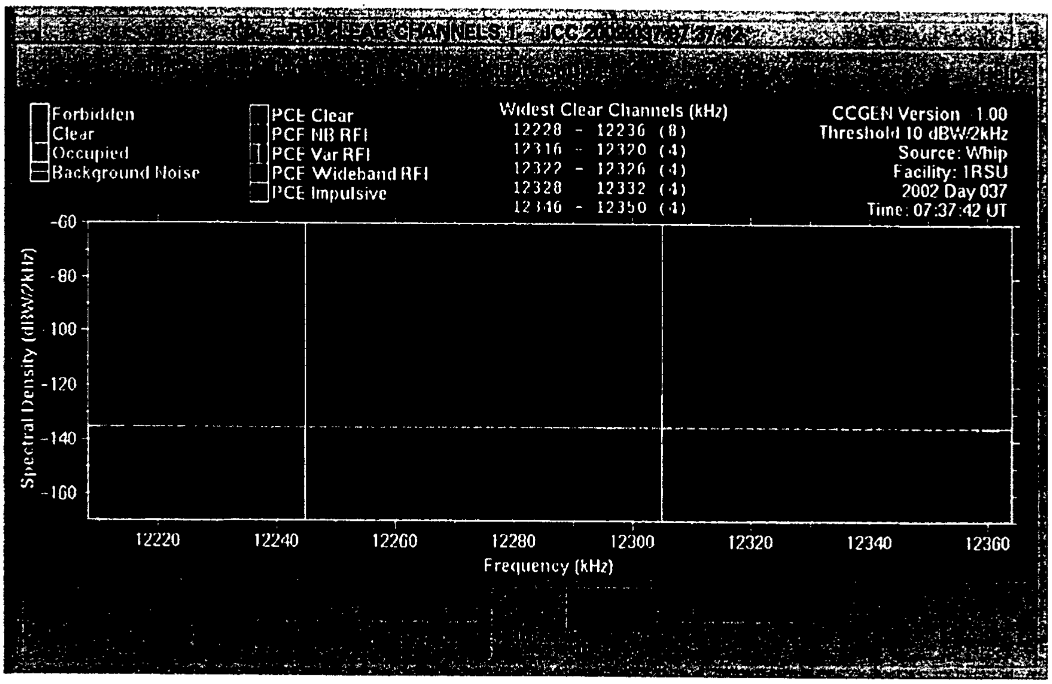

Figure 2: The JFAS PCE Scan Display with PCE channel status flags as vertical lines indicating the types of RFI detected.

If a PCE Manual Frequency mode search fails to find any clear channels, the operator could examine the PCE dwell display to investigate whether any of the channels have been incorrectly declared as containing RFI. The operator could double check a result by resubmitting a channel to the PCE using PCE Immediate Channel mode. The only other alternative is to search again for smaller bandwidth channels.

4. The PCE Signal Processing Algorithms

The key outcome required of the PCE is for it to reliably detect whether channels are clear (or not) for use by the main radar. It should detect occupied channels and advise against their use, so that the radar SNR can be optimised and also so other users of the HF spectrum will not be adversely impacted. If RFI is present in a given channel, then a PCE dwell at that frequency will exhibit similar characteristics to that "seen" by a radar dwell at the same frequency if the PCE and radar use the same signal processing. By collecting sets of PCE dwells on a frequency channel, the PCE can be used to determine whether the channel is occupied to an extent that will adversely affect the performance of the radar. To automate this process, algorithms are applied to PCE dwells, to classify any RFI that may be in the dwells. The algorithms look for narrow-band RFI, variable RFI, wideband RFI and impulsive interference. Each of these types of interference and the respective algorithms are discussed in the following sub-sections. These are the most common forms of RFI encountered during OTHR operations. The order of the tests is the narrow-band RFI test first, then the variable RFI test and then the wideband RFI test. The impulsive interference test uses the data from the wideband RFI test. If one of these tests finds RFI in a given dwell, then the remaining tests are not applied to that dwell.

4.1 Narrow Band RFI (N)

For the purpose of this report, narrow-band RFI is defined as a RFI signal having a bandwidth significantly less than both the PCE's waveform bandwidth and WRF. RFI signals are incoherent with the PCE waveform so they appear spread across all range cells but being narrow with respect to the WRF they result in coherent Doppler processing. An example of a PCE dwell containing a narrow-band RFI signal is shown in Figure 3. This is a PCE dwell in range-Doppler format. The colour scale indicates the power in dBW/Doppler cell. This example is from FMS beam 6 for a run at 12.265 MHz at 09:04:22 on day 035 in 2002. The WRF was 64.3 Hz and the bandwidth was 2 kHz.

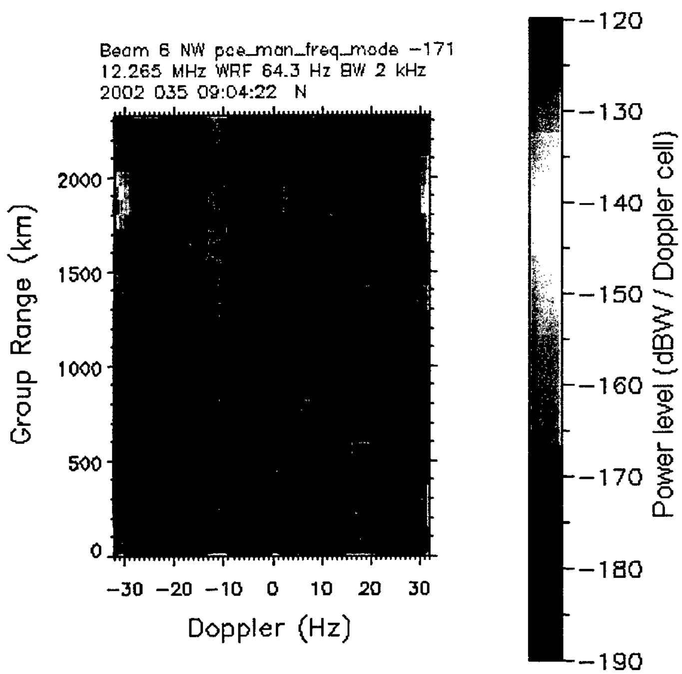

Figure 3: Example of narrow-band interference.

The narrow-band RFI test looks for at least one "Doppler slice" (i.e. all range cells at a given Doppler) that has relatively constant power levels that are well above the noise floor of the dwell. Dwells that contain narrow-band RFI are labelled "N" on the PCE displays.

The details of the algorithm used in the narrow-band RFI test are as follows. For each Doppler slice, determine if the power level of every range cell is within a specified threshold (*NB_threshold_1*) of the power levels of its two neighbouring range cells. For each Doppler slice that satisfies the above criteria, determine if the power level in every range cell of that Doppler slice exceeds a specified level (*NB_threshold_2*) above the noise floor of the dwell. (The calculation of the dwell noise floor is discussed in Section 4.3). Narrow-band RFI is declared to be present in the dwell, if for any Doppler slice satisfying both of the above criteria, more than a specified number of the range cells in the slice vary in their signal level by less than a specified amount (*NB_threshold_3*).

The values of the parameters used in this test are: *NB_threshold_1*: 30 dB, *NB_threshold_2*: 7 dB, *NB_threshold_3*: 2 dB and the specified number of range cells is $1/9^{th}$ of the total number in the slice less 1.

It should be noted that even though a dwell found to contain narrow-band RFI may be for an FMS beam that is not in the direction of the prospective radar task, the channel will not be declared clear for use by the radar because radar transmissions via antenna pattern side-lobes could interfere with this HF user.

4.2 Variable RFI (V)

An example of another manifestation of RFI is shown in Figure 4. This type of signal appears coherent in Doppler and partially coherent in the range dimension. It therefore manifests itself on a range-Doppler display in a similar manner to narrow-band RFI but with only partial spreading in range. The partial spreading is believed to be caused by the signal's demodulated frequency components overlapping the edge of the PCE pass-band (Reference: Personal Communication: Dr. Mike Turley, ISRD, DSTO). This type of RFI is sufficiently different from the narrow-band RFI case that a separate test is required to detect it. For the purpose of this report, this type of RFI is referred to as variable RFI and is denoted by a "V" on the PCE displays.

The details of the algorithm used in the variable RFI test are as follows. The bottom third, middle third and top third of the range cells in each Doppler slice are examined separately to determine if there is a smooth variation in the power from range cell to range cell. The criterion for "a smooth variation" is that the variation from cell to cell is less than *V_threshold_1*. If for any given Doppler slice, if a *large fraction* of any of its three range brackets satisfy the smooth variation criterion and the average power in the range bracket is more than *V_threshold_2* above the noise floor of the dwell, then the dwell is deemed to contain variable RFI.

The values of the parameters used in this test are: *V_threshold_1*: 3 dB, *V_threshold_2*: 10 dB and the *large fraction* of range cells in a range bracket is 23/24.

If the above test does not detect variable RFI, it is then repeated with *V_threshold_2* decreased to 7 dB. If the number of range brackets, for the entire dwell, that satisfy the criteria for variable RFI exceeds 1/8th the total number of Doppler slices, then the dwell is deemed to contain variable RFI. The intention of the second pass of the test is to catch stripes of low power variable RFI that are spread in Doppler.

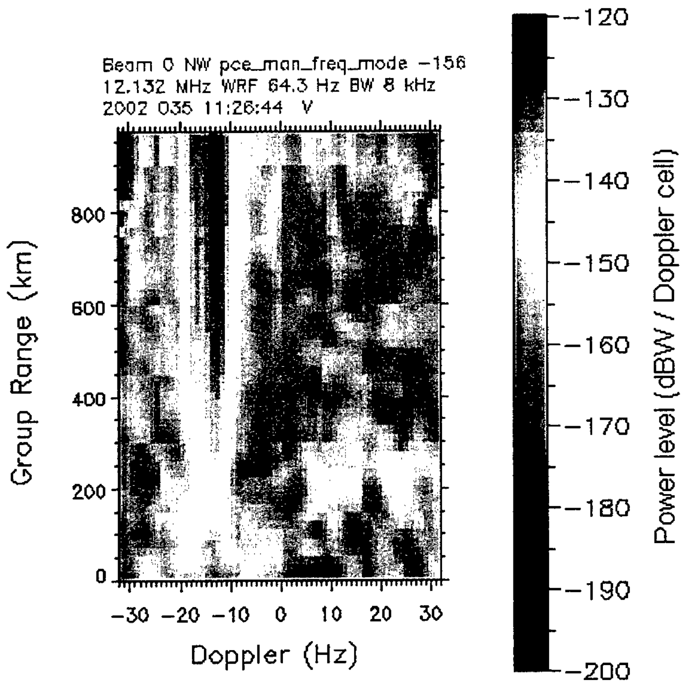

Figure 4: This dwell has been flagged as containing variable RFI, where there is interference over some of the range cells, in a narrow-band in Doppler.

It is noted that variable RFI is often seen in PCE dwells recorded using the PCE Manual Frequency mode, but is rarely seen in PCE dwells collected in Immediate Task mode or in main radar dwells. It is believed that the reason for this is due to the smaller number of retained range cells in Immediate Task mode in which the number of range cells retained is deliberately set to be the same as the main radar. In Manual Frequency mode, the number of retained cells is the maximum possible number of range cells (i.e. PCE receiver BW divided by the WRF).

4.3 Wideband RFI (W)

For the purpose of this report, wideband RFI is defined as a RFI signal having a bandwidth similar to or larger than the PCE dwell's WRF. RFI signals are incoherent with the PCE waveform so they will be spread across all range cells and because they are wide with respect to the PCE's WRF, this will result in incoherent Doppler processing and they will also be spread in Doppler. Spreading in both the range and Doppler dimensions will raise the noise floor of the PCE dwell. This is the basis of the wideband RFI test. PCE dwells containing wideband RFI are denoted by a "W" on the PCE displays. An example of a PCE dwell with wideband RFI is shown in Figure 5.

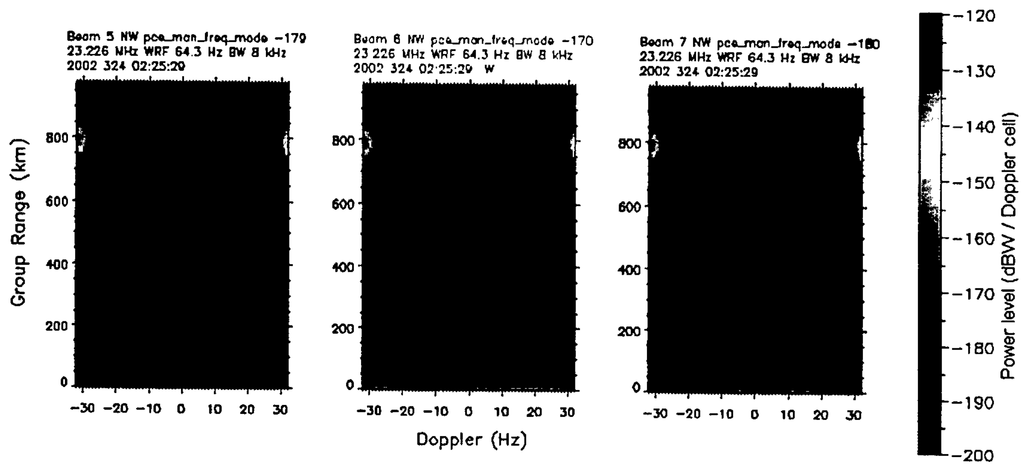

Figure 5: The beam 6 dwell is flagged as containing wideband RFI (label W). Although this dwell is clearly contaminated compared with the dwells from neighbouring beams, the wideband RFI test is based on a comparison with the BNM data for the same FMS beam (and closest time and frequency).

The details of the algorithm used in the wideband RFI test are as follows. First, the noise floor of each PCE dwell is determined by an algorithm that iteratively divides the dwell into an increasingly larger number of smaller rectangles (in range-Doppler space) and computes the median power level for each rectangle. For each iteration, the minimum of these values is deemed the background level. This process continues until the background level changes by less than 2 dB from one iteration to the next or for a maximum of sixteen iterations. The background level at the conclusion of this iterative process is deemed the noise floor for the dwell (Barnes *et al.* 1993).

This noise floor is then compared with the most recent noise level recorded by the FMS Background Noise Monitor (BNM) system (for the relevant 200 kHz band and FMS beam), after scaling the BNM value (dBW/Hz) to the same units as the PCE dwell value (dBW/Doppler cell). If the noise floor of the PCE dwell is more than *W_threshold_1* above the BNM value, then the dwell is considered to have an enhanced noise floor and declared as having wideband RFI and is labelled "W". As in the mini-radar Elevated Noise Floor algorithm, which was the basis for this PCE algorithm, *W_threshold_1* currently varies as a function of frequency and time of day:

$$W\_threshold\_1 = 4 + y\ dB$$

where y = (30 - $freq_{MHz}$)/5 plus an increment of 1 dB for times between 7 and 9 UT or between 22 UT and 24 UT, 2 dB for times between 9 and 11 UT or between 21 and 22 UT and 3 dB for times between 11 and 21 UT. However, this variation may not be appropriate for the PCE and is currently being investigated.

4.4 Impulsive Interference (I)

As noted in Section 2, the PCE normally collects multiple PCE dwells when examining a candidate channel. The default is three sets, which are referred to as triplets, in which case there are three dwells at the same frequency for each FMS beam, i.e. 24 dwells for a given frequency. If wideband RFI (i.e. an enhanced noise floor) is detected in one of the dwells for a given FMS beam but is not detected for the other two dwells for that beam in the triplet, then rather than containing a wideband interferer, the dwell is considered to contain impulsive interference and is labelled "I" in the final presentation to the radar operator, i.e. the frequency advice display which provides details of prospective radar channels. This is discussed further in Section 4.7

4.5 Other Forms of RFI

There are additional forms of RFI that appear in PCE data for which the exact causes are not known, but the important requirement at this stage is to trap and flag the most serious and common interferers and that is achieved by the previously discussed algorithms. Figure 6 is an example where there appears to be RFI which is not detected by the current PCE signal processing algorithms. The horizontal band of enhanced noise could be caused by a genuine external signal that is similar to the PCE deramping waveform, but there is a suspicion that it is generated by the PCE itself. Such dwells appear so infrequently that they are not considered to warrant further investigation.

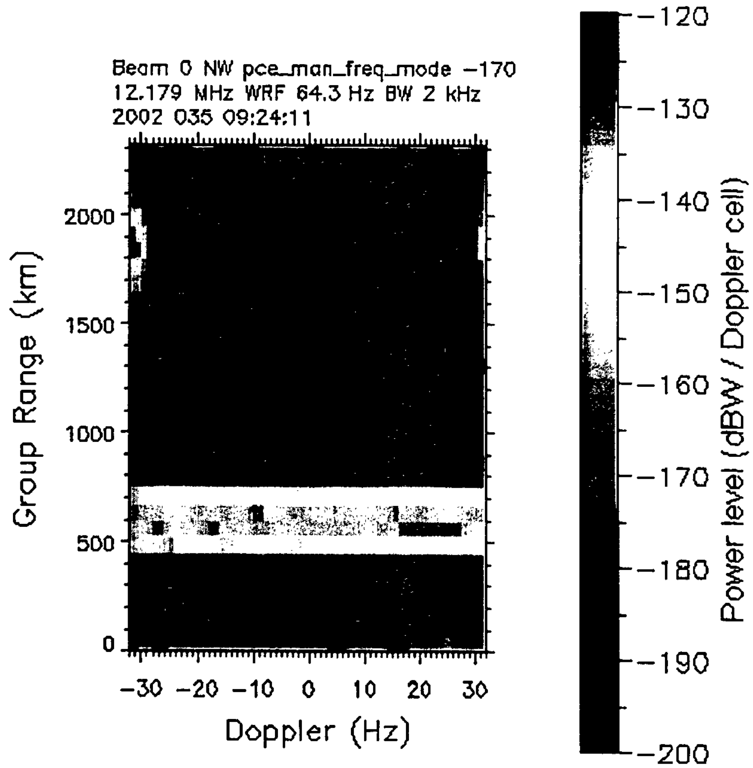

Figure 6: This dwell contains a horizontal band of enhanced noise but it is not flagged by any of the existing tests.

4.6 Algorithm modifications

The initial version of the PCE signal processing algorithms used the same algorithms and parameter values employed by the mini-radar subsystem (Barnes *et al.* 1993) and was found to perform poorly for PCE data. Consequently modifications, based on an analysis of PCE data collected at the JCC on days 024, 025, 035 and 037 in 2002, were made to the algorithms. The algorithms described in the preceding sections of this report are the current (modified) version. Details on how the algorithms were optimised for detecting RFI in PCE data are provided in Appendix A. Software developed in ISRD allows a user to display the RFI detection results found for JFAS PCE data at the JCC (and written into the PCE data file headers) or the results from re-running the data through modified algorithms. The software also allows a large quantity of data to be automatically run through the RFI detection algorithms thus enabling comparisons of the results of different algorithms and/or parameters.

All the data collected from early in 2002 were analysed again in ISRD using the modified suite of PCE signal processing algorithms. The results collated for all runs are shown in Table 1. The numbers of dwells flagged by each test are shown both as absolute numbers and as a percentage of all the dwells. It can be seen that the narrow-band RFI test was made much *less* sensitive and that the variable and wideband RFI tests were made much *more* sensitive. Overall, the total percentage of individual dwells being flagged as containing RFI increased from 42% to 46%. The number of PCE candidate channels in which RFI was detected (in the dwells from at least one FMS beam) increased from 76% to 83%. It is noted that a large proportion of the data used in this analysis was either randomly collected from the HF spectrum or deliberately focused on occupied channels, so these percentages can not be interpreted as the quantity of clear channels that radar operator can expect following the introduction of the PCE.

Table 1: The results of the PCE tests, collated across all runs for days 024, 025, 035 and 037 in 2002, before and after the algorithm changes were made.

Test Changes	# Runs	# Flagged Runs	# Dwells	# Flagged Dwells	N Flagged	V Flagged	W Flagged
Before	3203	2447 (76%)	25624	10722 (42%)	9143 (36%)	287 (1%)	1292 (5%)
After	3203	2659 (83%)	25624	11915 (46%)	3833 (15%)	3615 (14%)	4467 (17%)

It should also be noted that where the success in algorithms detecting RFI is considered, the process of deciding between success or failure can be subjective, as even experts cannot guarantee a frequency is clear based on a visual examination of the PCE dwell display. Only immediately using the radar on that frequency provides a rigorous test but that is impractical given the large data quantities involved and the limited radar time available. The decisions made on success rates described above are based on feedback from experts backed up by actual testing with the radar.

4.7 Final decision on whether a channel is clear

In early May 2002, the modified PCE algorithms were tested at the JCC. The frequencies examined were those that would be used for realistic radar operations. Agile frequency advice was requested for the radar tasks. Passive radar dwells were collected and these showed that the PCE was successfully detecting interference missed by the Icom (or only heard when the Icom's receiver gain was set to maximum, which is not a practical operating procedure). Dr Mike Turley, from ISRD, used several tools from SPARTA (a signal processing and display package developed in ISRD) to examine the radar data and compare this with PCE data. In general, good agreement was obtained between the types of RFI reported by the PCE and that observed in the radar data. However, at times the PCE algorithm, used to make a final decision about whether a candidate channel was clear or occupied, was too sensitive - i.e. it was declaring channels, considered to be clear by experts, to be occupied. For example, when triplets are collected across the eight FMS beams, 24 PCE dwells are analysed and if one dwell for one beam was flagged as containing variable RFI, then the channel was being declared occupied, which was considered to be too sensitive. It was suspected that these single occurrences of variable RFI were caused by impulsive interference. Following this testing, the algorithm determining the final result for a candidate channel was changed. The current implementation is described below.

As noted in Section 2, PCE dwells can be collected in sets from one to five with the default (and recommended) being three sets. The RFI algorithm tests, described in the preceding sections, make decisions on each individual dwell, but the final result for the candidate channel depends on the number of dwells collected and what combination of RFI flags occurred.

For sets of n dwells (where n = 2 to 5):

- if **any** dwell on **any beam** has N then the channel is flagged as occupied: N (narrow-band RFI)

- if **all n** dwells on **the same beam** have V then the channel is flagged as occupied: V (variable RFI)

- if **all n** dwells on **the same beam** have W then the channel is flagged as occupied: W (wideband RFI)

- if **all n** dwells on **the same beam** have a **combination** of V and W then the channel is flagged as occupied: W (wideband RFI)

- if there is a combination of V and W across the n*8 dwells but if no particular beam suffered from V or W in **all n** of the set, then the channel is flagged as unoccupied: I (impulsive interference)

For sets of just one dwell per FMS beam (which is not recommended operationally):

- if any dwell is flagged N then the channel is labelled as occupied (N)

- if any dwell is flagged V then the channel is labelled as occupied (V)

- if any dwell is flagged W then the channel is considered unoccupied and labelled as I (impulsive interference).

Where a channel satisfies the above criteria to be labelled with more than one of the N, V, W or I flags, then the label actually used is the first in this list (i.e. N is considered the most important, then V, then W, then I).

The implementation of this algorithm and the RFI detection algorithms were successfully tested at the JCC by ISRD in November 2002. Between May 2002 and November 2002, following recommendations by ISRD, the PCE operator interface was also improved. A variety of changes were implemented for the JFAS PCE range-Doppler display, the PCE clear channel display, the PCE manual scan GUI and the main frequency advice results display. The key changes are detailed in Appendix B. These modifications improve the integration of the PCE with the other tools available to the radar operators thus making the total system easier to use. The PCE was declared ready for operational use at the end of 2002.

5. Potential PCE Enhancements

The direction of any future work on the PCE will depend on whether ISRD focuses its efforts on improving the JFAS PCE or uses it purely as a testbed for the JORN PCEs. At the time of writing the way ahead is not clear, but a list of potential improvements for the JFAS PCE is provided below.

- An improvement to the display of PCE dwells in range-Doppler format would be to show the dwells relative to the ambient noise spectral density, as measured by the BNM. This would reduce the need for a radar operator to change the colour scale regularly (as the operator examines candidate channels at different parts of the HF spectrum).

- It is possible under difficult environmental conditions that no PCE clear channels will be found, in which case some sort of ranking could be performed on the occupied channels, so that the least worst are shown first. What defines "least worse" would depend on the operational situation. If the task is extremely high priority, then it may be necessary to operate in a channel that has a narrow-band user. (Narrow-band RFI can be better handled by the radar signal processing than wideband RFI.) Another important consideration is the direction of the RFI. If it is strong but in a different direction to the proposed task, then this may reduce the importance of that RFI. It probably won't degrade the radar's performance, but consideration of the effect of the radar sidelobes on the other user will be required.

- Ranking could also be used to distinguish the degree of RFI contamination for the same RFI type. For example, the narrow-band and variable RFI algorithms use thresholds that the power in areas of the dwells must exceed before a channel is classed as containing RFI. Several passes could be made with the algorithms, using different thresholds. For the wideband RFI test, the level of the dwell's background noise above the BNM level could be used to rank the level of contamination.

- Impulsive interference suppression in radar signal processing uses the early stage data (the initial time series) to look for large peaks that do not occupy all sweeps thus permitting corrupted data from impulsive interference to be removed. This suppression algorithm is not used by the PCE because detecting impulsive interference is currently one of the goals of the PCE. However, a future enhancement may be to make use of this algorithm as an alternative method to detect impulsive interference. Use of multiple dwells (e.g. triplets) may then no longer be necessary (thus speeding up the clear channel vetting stage). It may be reasonable to take this a step further and remove the impulsive interference from the PCE dwells which would allow the PCE to test for the man-made forms of RFI.

- The current implementation of automatic frequency advice attempts to find five clear channels based on SM data and then the PCE advises whether they are clear or occupied. In difficult environmental situations when the PCE declares that all five of these channels are occupied, it would be preferable if the frequency advice algorithm provided all SM clear channels (instead of just five) within specification (i.e. in the case of air advice, within ± 10% of the optimum frequency). The PCE could then work through the list until at least one clear channel has been found.

- Once a channel has been selected by the operator and is being used by the radar, a PCE mode could be provided whereby it continues to monitor the channel, to check if it is still free from RFI. This PCE mode is available for the JORN radars.

- When a radar operator is not tasking the PCE, it could revert to a background task whereby it checks channels cleared by the SM but not currently being used by the radar. This could be used to provide feedback to the SM and to speed up calls to frequency advice (because potential radar channels would have already been vetted by the PCE).

- It is anticipated that wideband digital receivers will eventually replace the functionality of both the SM and PCE. In the meantime, using such receivers in conjunction with the PCE should permit further modification and fine tuning of the PCE signal processing algorithms.

6. Summary

The introduction of the PCE into JFAS is intended to ensure that frequencies recommended by the radar management automatic frequency advice algorithms are clear, thus improving the JFAS radar performance and minimising interference to other HF users. The PCE should also eliminate or significantly reduce the time intensive process of operators having to "listen", using the Icom receiver, to prospective channels. To meet these objectives, ISRD designed a suite of RFI detection algorithms to analyse the PCE data. The PCE signal-processing algorithms are designed to detect narrow-band, wideband and variable RFI and impulsive interference.

Following a period of data collection in early 2002, changes were made to these algorithms that led to a decrease in the sensitivity of the narrow-band RFI test and an increase in the sensitivity of the variable and wideband RFI tests. Radar time in early May 2002 was used to prove that these changes resulted in good agreement between RFI reported by the PCE and what was actually seen in radar dwells. During this period the algorithm, which combines the results from the RFI tests on multiple dwells collected from the eight FMS beams, was found to be too sensitive and this led to changes in this final algorithm. The current version of the PCE signal processing algorithms were successfully tested at the JCC in November 2002 and the PCE was declared ready for operational use at the end of 2002.

Following recommendations from the authors, the PCE operator interface was also improved in 2002. A variety of changes were implemented for the JFAS PCE range-Doppler display, the PCE clear channel display, the PCE manual-scan GUI and the frequency advice results display. With time, it is anticipated that the radar operators will gain confidence in the PCE and the Icom receiver will become redundant.

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Appendix A: Optimising the RFI Detection Algorithms

As noted in the body of the report, the initial versions of the PCE signal processing algorithms were based on algorithms used to identify corrupt mini-radar dwells. PCE data were collected during ISRD JFAS radar time at the JCC in January and February of 2002. The data were moved to ISRD and used to modify the algorithms so they were optimised for detecting RFI in PCE data. A detailed description of the algorithm modifications is provided in this appendix.

The main code containing the PCE algorithms is *MR8_Bad_Test*. As it is part of the MR software suite, any changes that needed to be integrated into ISRD software or the JFAS baseline required the code to be changed so thresholds specific to the PCE or MR could be used.

A program called *PCE_Test_Day* was written in ISRD which dumps the RFI flags for each beam for each run. At the end of the output file a summary is provided listing the number of runs containing at least one flagged dwell, the total number of N dwells (i.e. the total number of dwells that were flagged N, which can be up to eight (one for each beam) per run), and similarly the total number of V and W dwells. The total number of dwells in the day can be obtained from looking at the last run of the log (the dwells are numbered starting from zero) and multiplying by eight.

A.1. Narrow Band RFI (the N test)

The narrow band RFI test was found to be firing far too often, picking up very faint signals or random noise in the dwell. The threshold level above the noise floor *(NB_threshold_2)* was originally set to 1 dB. Tests were done on 2002 day 035 data with *NB_threshold_2* set to 3 dB and 7 dB. It was found that increasing the threshold (i.e. requiring levels from an interferer to be stronger) significantly decreased the number of *runs* in which dwells were flagged as containing RFI. The number of individual dwells flagged as having narrow band RFI dropped substantially. However, increasing the threshold higher than 7 dB started to allow dwells through that clearly contained narrow band interference, so the final choice was *NB_threshold_2*: 7dB.

Table 2 shows that as the threshold increased from 1 to 7 dB, the percentage of runs in which no dwells were flagged as containing RFI decreased from 9% to 31% and the percentage of individual dwells containing RFI dropped from 39% to 16%. However, in decreasing the sensitivity to N, more dwells are subjected to the subsequent RFI tests (when a test fires, further tests on the same dwell are bypassed). So decreasing the number of dwells detected in the N-test led to an increase in the number detected by the V and W tests; i.e. although a dwell was no longer deemed to have narrow band RFI, it could then be found to have a *different type* of RFI. An examination of the data indicated that the V and W labels more accurately described the RFI type than the original N labels.

Table 2: A summary of bad data flagging on all dwells collected on 2002 035, with NB_threshold_2 varied in the N test.

NB_threshold_2	# Runs	# Flagged Runs	# Dwells	# Flagged Dwells	N flagged	V flagged	W flagged
1 dB	835	760	6680	3122	2622	105	395
3 dB	835	677	6680	2511	1879	175	457
7 dB	835	575	6680	1878	1078	289	511

A.2. Re-examination with Reduced N - Improving the W Test

After the N test was optimised, the data were re-examined. The main failing was found to be the wideband RFI (W) test; it was not rejecting enough dwells. The criterion for a dwell being rejected is that the measure of the noise floor in the dwell must be greater than a certain threshold *(W_threshold_1)* above the noise floor as determined by the background noise monitor.

The threshold used in the equivalent mini-radar algorithm varies depending on frequency and time of day, being larger for lower frequencies and at night when there tends to be more variation in the noise levels and when the Clear Channel Advice has more difficulty finding truly clear channels (Barnes *et al.* 1993). Such frequency and time of day variations in the threshold were designed to prevent a large percentage of the night-time MR dwells being rejected because of enhanced noise floors. Such latitude may not be appropriate for the PCE where an unbiased view of how clear a channel is should be presented to the radar operator. As noted in Section 4.3, this issue is subject to current investigation.

For the current implementation, the threshold variations for frequency and time-of-day have been left in, but the absolute level was reduced. The base threshold used for all times and frequencies (before allowances made) was 12 dB. The threshold was changed to 7 dB and then 4 dB, and the data re-subjected to the tests (with the new *N test* parameter *NB_threshold_2* in place). The results are shown in Table 3 for two data sets. Data set 1 was 2002 035 09:02:05 to 09:04:25, typically around 12 MHz. Data set 2 was 2002 035 11:44:18 to 11:54:05, around 24 and 25 MHz.

Table 3: A manual examination of the success rate in detecting enhanced noise floors for two data sets and for three different levels of the W test base threshold.

W Test Base Threshold	# Dwells	True +ve	False +ve	False -ve
12 dB -> data set 1	400	32	1	106
12 dB -> data set 2	384	1	0	21
12 dB -> total	784	33	1	127
7 dB -> data set 1	400	57	1	81
7 dB -> data set 2	384	12	0	10
7 dB -> total	784	69	1	91
4 dB -> dataset 1	400	134	1	4
4 dB -> dataset 2	384	16	0	6
4 dB -> total	784	150	1	10

Even when manually examining the data, it can be very difficult to determine whether a dwell is suffering from a wideband interferer. An example of where a superficial examination of the PCE data might lead to the conclusion that a wideband user is present in some beams was seen in 2002 035 11:44:18 UT. Around sunset the BN was becoming strong at about 24 MHz on beams 1 and 2, whereas this increase was yet to occur in beam 0. This directional variation made the noise floor of beams 1 and 2 appear enhanced compared with beam 0, but it was simply the natural variation, not an interferer.

Without passing the data through all the signal processing steps, the determination of what is an enhanced noise floor can be somewhat subjective. The conclusions made in tuning the algorithm are based on two considerations: what the actual noise floor would appear to be, based on BNM data, and examination of PCE dwells close in time on the same frequency and beam (e.g. triplets). A balance had to be struck between not letting too many enhanced noise floor dwells get through (false negatives) while not incorrectly (or over-sensitively) rejecting dwells (false positives).

Although the very nature of HF noise means there will be variation even in very small time scales, if successive dwells are collected at the same frequency (e.g. triplets) then a *significant* increase in the noise floor between dwells can be taken as an unnatural elevation (or possibly impulsive interference such as lightning), and this method was used when examining some of the data. Doing so dramatically increased the number of dwells being described as false negatives, i.e. it was felt many dwells had enhanced noise floors and were not being detected by the 12 dB threshold case.

Another major factor is the issue of being operationally practical. The sensitivity of the PCE means that if you collect enough dwells, or dwell long enough, or have extremely sensitive algorithms, you will find some form of RFI in virtually every channel you examine. This effect is also observed when using the Icom and stepping through all the modulations and increasing the audio volume. It is clearly not practical to reject all these channels. Although it is by no means intended to deliberately use a channel occupied by other users, consideration must be given to setting the detection threshold level so that a suitable false alarm rate is achieved. As such, base thresholds below 4 dB were not considered. In the lenient 12 dB threshold case, for many dwells, the above factors made it difficult to determine whether to flag them as false negatives or true negatives. This subjectivity made it hard to compare manual examination results for the three base thresholds tested. Nevertheless, Table 3 can be used as a good guide to the success or otherwise of the W test.

The results obtained across all data collected on day 035 (periods covering 0900 to 1200 UT), are shown in Table 4. With the threshold at 12 dB, 28% of all dwells collected in day 035 data were flagged as occupied (8% with wideband RFI). At 7 dB this number increased to 36% (15% with wideband RFI) and to 44% for 4 dB (23% with wideband RFI). Although this is a large fraction of the dwells collected, the PCE was generally set to dwell on all frequencies in the set band, not just channels already labelled as clear by the Clear Channel Advice, and in fact there was often an emphasis on occupied channels, so this is not a concern. Note that these results were based on the algorithms before the changes were made to the variable RFI test (as discussed in A.3).

Table 4: Wideband RFI test results obtained over all data collected on 2002 day 035 with the base threshold set at three different levels.

W Test Base Threshold	# Runs	# Flagged Runs	# Dwells	# Flagged Dwells	N flagged	V flagged	W flagged
12 dB	835	575	6680	1878	1078	289	511
7 dB	835	655	6680	2388	1078	289	1021
4 dB	835	716	6680	2909	1078	289	1542

At this stage, the relatively strict base threshold of 4 dB will be used for the W test, as wideband RFI is deemed to be more damaging to radar performance than narrow band interference, which can be handled reasonably well by the signal processing. The wideband RFI test now usually correctly indicates an enhanced noise floor, but if 4 dB is not the optimal value then it may need to be a little larger, allowing more dwells to pass. For all these tests, further data collection may be useful, but the real test will come during 1RSU radar operations.

A.3. Variable RFI Test

The variable RFI test is applied to PCE dwells after the narrow band RFI test, but before the wideband RFI test. It was firing far less often than the N and W tests, and a qualitative review of collected data indicated that it almost never tripped incorrectly (false positives tended towards zero, true positives almost always correct) and that it tripped successfully in a lot of the genuine cases (false negatives fairly low). However, there were still quite a few dwells getting through that had RFI that one might expect to be caught by the V test, so it was investigated further leading to the final version of the variable RFI test which was described in Section 4.2.

Quantitative data of success and failures was not collated. However a thorough examination of 2002 days 024, 025, 035 and 037 showed that this relatively successful test had been improved; the rate of false positives had not increased and the rate of false negatives had decreased.

Appendix B: Improvements to the PCE functionality and Operator interface

Several changes to the PCE-radar interface were recommended by the authors and implemented by the OTHRSPO to improve the integration of the PCE with the other tools used by the radar operators. These should make the PCE easier to use and therefore it is more likely to be accepted by the operators. The key changes are described below.

- On the PCE manual scan GUI, the number of dwells that could be collected in a set was changed from 1 - 3 to 1 - 5. This is useful in developmental work and also for testing a channel more thoroughly. The default operation remains at using three sets.

- The coloured lines to indicate the type of RFI were difficult to distinguish on the PCE clear channel display. Changes were made so that green is used for clear, blue for impulsive interference, red for narrow band RFI, yellow for variable RFI and pink for wideband RFI.

- On the PCE range-Doppler display, the RFI algorithm labels are displayed (e.g. N for narrow band RFI). When scanning through the data, it was difficult to spot differences between the labels. To draw attention to dwells other than those declared clear, the entire dwell label was changed to the same colour used for this type of RFI on the PCE clear channel display.

- After the PCE has evaluated the channels returned from a frequency advice request, the channels for each region are now re-ordered (if necessary) so that clear channels are shown first, then channels with impulsive interference, then channels with wideband RFI, then channels with variable RFI and last those with narrow band RFI are displayed; i.e. operators are presented with the channels in the order which provides the best chance of selecting a clear channel and not interfering with other users.

- When frequency advice is initially obtained for a radar task, the frequencies and PCE based RFI flags are shown. When frequency advice is accepted (so the frequency-advice window closed), the frequencies chosen for each footprint can then be re-displayed by left mouse button clicking on the frequency area of the radar-tasking table but the PCE flags were not being made available. This has been changed so the PCE flags associated with channels appear in both frequency-advice displays.

- The original PCE manual scan interface made it difficult to scan a single channel. An easier method was developed, allowing the operator to either manually enter the same minimum and maximum frequency, or use the mouse to select the frequency from the PCE clear channel display. If this feature is used regularly, further work may be required to improve this aspect of the interface.

- The PCE data structures and algorithms were based on existing mini-radar software. A variety of software changes were recommended and implemented, mainly involving separating the PCE from the MR. This including ensuring that data written to the PCE headers were truly PCE data, not MR, and vice versa. Flags were added to the RFI testing algorithms to differentiate between tests for MR and PCE data, so that the tests could be modified in the PCE case.

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19. ABSTRACT

To maximise target signal to noise ratio, the Jindalee Facility Alice Springs (JFAS) Over-the-Horizon Radar (OTHR) requires frequency channels that are free from radio frequency interference (RFI). Prior to 2000, to achieve this objective the radar operators were reliant on Clear Channel Advice (CCA) which is derived primarily from the Frequency Management System's (FMS) Spectrum Monitor (SM). Due to limitations of the SM, the operators were forced to use an HF communications receiver to check CCA, which could be a time consuming and inaccurate process. As part of a major upgrade of the FMS in 1999, a Passive Channel Evaluator (PCE) subsystem was added to remove or reduce the need to use the communications receiver. This report contains a description of the signal processing algorithms used to determine if PCE data contains RFI and the results of testing these algorithms with the JFAS radar.

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