Australian Government

Department of Defence
Science and Technology

High Range Resolution Backscatter Sounder Ionograms

David J Netherway, Michael J Whitington and Robert S Gardiner-Garden

National Security and ISR Division
Defence Science and Technology Group

DST-Group-TR-3477

ABSTRACT

Backscatter ionograms have been routinely collected for thirty years in support of the Jindalee Over-The-Horizon-Radar and Jindalee Operational Radar Network. Backscatter sounder ionograms display the power received as a function of time delay (usually expressed as group range) and transmitted frequency after radio-wave signal transmission from an antenna, propagation via the ionosphere, backscattered reflection from the Earth's surface and further propagation via the ionosphere to the receive antenna. Routine practice has been to process and retain data at a range resolution of 48.8 km and frequency resolution of 200 kHz. This resolution was set to accommodate equipment, signal processing, communications and data storage capability at the time (the 1980s). This paper describes methods used for high range resolution processing (6.1 km for 3 frequencies per 100 kHz) of the same raw data including superior radio frequency interference rejection. These superior ionograms make many additional propagation features more clearly visible.

Produced by

National Security and ISR Division
Defence Science and Technology Group
PO Box 1500
Edinburgh SA 5111

Telephone: 1300 333 362

April 2018
AR-017-160

High Range Resolution Backscatter Sounder Ionograms

Executive Summary

Backscatter ionograms have been routinely collected for thirty years in support of the Jindalee Over-The-Horizon-Radar (OTHR) and Jindalee Operational Radar Network (JORN). Backscatter sounder (BSS) ionograms display the radio-wave signal power received, as a function of range, after backscattered reflection from the Earth's surface for frequencies in the high frequency (HF) band. Routine practice has been to process and retain data at a resolution of 48.8 km and 200 kHz. This resolution was set to accommodate equipment, signal processing, communications and data storage capability at the time.

This paper describes methods used for high range resolution processing (6.1 km for 3 frequencies per 100 kHz) of the same raw data including superior radio frequency interference rejection. These superior ionograms make many additional propagation features more clearly visible.

The techniques described here were completed in 2008 and are being further developed for inclusion in a programme of enhancements to JORN.

This page is intentionally blank.

Authors

David J Netherway
National Security and ISR Division

Dr Netherway obtained his PhD in Physics from The University of Melbourne (1982) in the field of crystallography and electron diffraction. After several years tutoring Materials Science at the University of Adelaide he joined Defence Science and Technology (DST) in 1984 working on high frequency Over-the-Horizon Radar (OTHR). In 1990 he joined the Australian Craniofacial Unit working on computed tomography and craniofacial morphology. Then in 2006 he returned to DST and OTHR where he is currently working on ionospheric radiowave propagation.

Michael J Whitington
National Security and ISR Division

Mr Michael Whitington, Bachelor of Applied Science (in Computer Studies) from University of South Australia, worked for 7 years in Software and Electronic Engineering related to control systems for remote area Power Generation, before joining DST in 1988. He has been involved in many aspects of Over-the-Horizon Radar during his long career including tracking, signal processing and environmental measurement.

Robert S Gardiner-Garden
National Security and ISR Division

Dr Gardiner-Garden started life as a scientist with a Bachelor of Science (Honours) from Sydney University in Applied Mathematics (1982) and PhD from Princeton University in Geophysical Fluid Dynamics (Physical Oceanography) (1987). After nearly 10 years as an academic oceanographer he joined Defence Science and Technology Group in 1996 in what was then the High Frequency Radar Division. For the last 20 years he has worked on various aspects of ionospheric and radar modelling and data analysis focused on understanding and improving the accuracy of Australias Over-the-Horizon Radars.

This page is intentionally blank.

Contents

This page is intentionally blank

1. Introduction

Backscatter sounder ionograms (BSI) indicate the ionospheric propagation conditions as a function of group range and transmitted frequency. Essentially a signal, swept linearly in frequency through the HF band, is transmitted, propagated via the ionosphere, backscattered from the earth's surface and received via further propagation through the ionosphere. One half of the time delay between transmission and reception of a backscattered signal is taken as the group range of the scatterer. This is the distance a signal would travel at the speed-of-light in a vacuum in that time. The time delay is proportional to the difference frequency between the transmitted and received signals due to the linearly swept frequency of the signal. For a continuum of scatterers of similar backscatter coefficient, the returned power indicates the efficacy of ionospheric propagation as a function of group range and frequency.

The main features of the Alice Springs Jindalee backscatter sounder system have been described by Earl and Ward, 1987. Since 1987 there have upgrades to extend the 6–30MHz frequency range to 5–45 MHz, to simultaneously receive signals from each of the 8 beams, and changes to signal processing parameters. Determination of background noise and detection of radio frequency interference (RFI) contamination has been facilitated by the use of a 'guard-band' generated by advancing in time the local replica of the transmitted signal, with which the received signal is mixed or correlated, to give negative ranges from which there cannot be backscatter.

Without mitigation, radio frequency interference has a significant deleterious impact on the quality of backscatter ionograms (Figure 1). Earl, 1991 introduced an algorithm based on producing 48 spectra, each covering 3 kHz within a 200 kHz band. By rejecting RFI contaminated spectra and averaging the remaining data the quality of the ionograms was markedly improved (Figure 2). The use of a 3 kHz bandwidth for the spectra gave a range resolution of approximately 50 km. However, the signal is coherent over approximately 74 kHz of the band so the range resolution could be reduced to approximately 2 km. At this resolution many other approaches to RFI rejection are available. In addition, the beam width at 15 MHz is approximately 240 km at a range of 2000 km so the value of high range resolution is a consideration.

This paper discusses processing of the Alice Springs backscatter sounder data for higher range resolution than has been the common practice since the 1980s.

2. Standard Processing

The HF band is swept from 5 MHz to 45 MHz at 125 kHz/s. The signal is phase continuous over 73.728 kHz, but subdivided into 24 by 3.072 kHz blocks for spectral analysis. The signal resumes every 100 kHz. The base-band of the receiver is digitized at a sampling rate of 13.021 kHz, and spectral analysis is performed on 320 samples with a coherent integration time of 24.6 ms giving 48 spectra every 200 kHz (Figure 1). Each spectrum gives an estimate of the returned signal power as function of range. For each 200 kHz frequency cell in the band, RFI contaminated spectra are rejected and the rest averaged (Earl, 1991). If all spectra within the 200 kHz are rejected then interpolation of adjacent data can be performed if the gap is not too large.

The final product is 8 ionograms, one for each beam direction, each with 200 kHz resolution in frequency and 48.8 km resolution in range, with a range depth of 12 493 km.

In this paper BSS beams are numbered from 1 to 8 instead of the earlier convention for the Jindalee Facility Alice Springs (JFAS) of numbering from 0 to 7. Only BSS data from JFAS is considered in this paper where the standard range resolution is 48.8km rather than the 50.0 km of the other two JORN BSS sites.

A calibration signal of known power, injected at the receiver input at a specified base band frequency offset, is used to scale the data to account for any losses or gains in the processing chain. The power of each spectrum is scaled so that the power in the calibration range cell matches the known injected power.

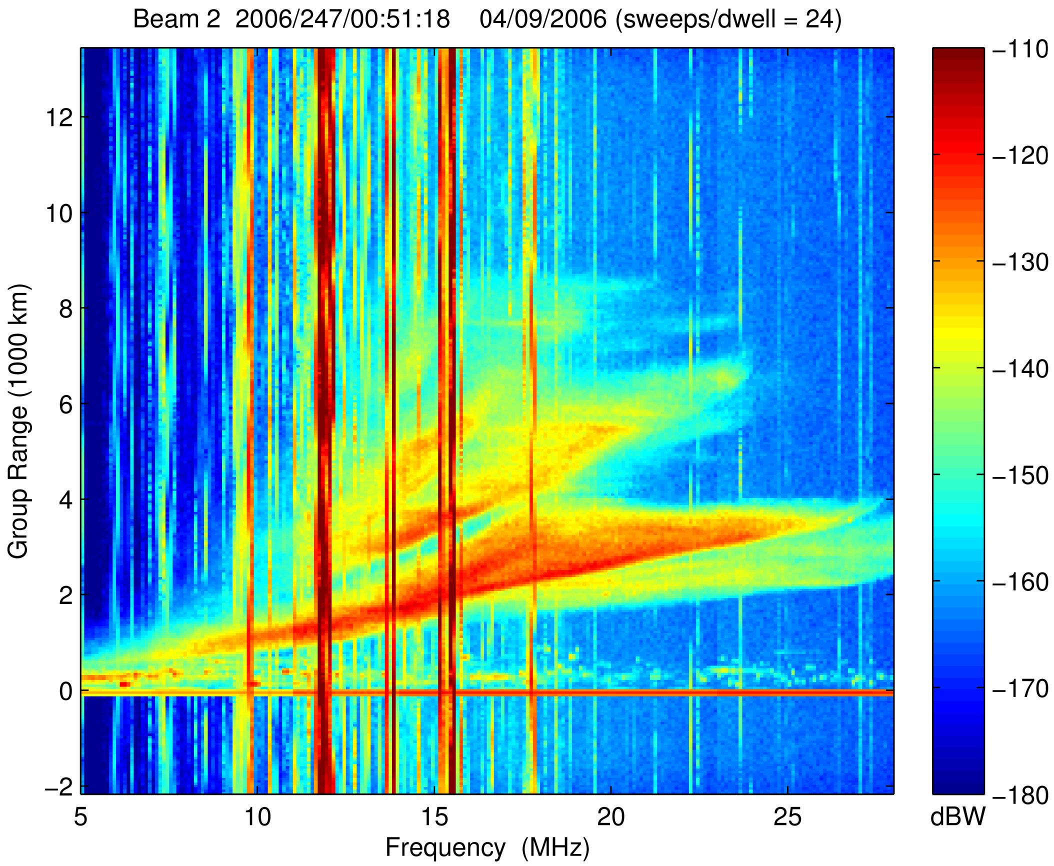

Figure 1. Backscatter ionogram created using the standard processing without RFI rejection. The vertical lines are the unwanted RFI signals contaminating the data. The horizontal line at -24.4 km is the injected calibration signal. The other main sources of power are the desired backscattered signal and potentially azimuthal side-lobe power.

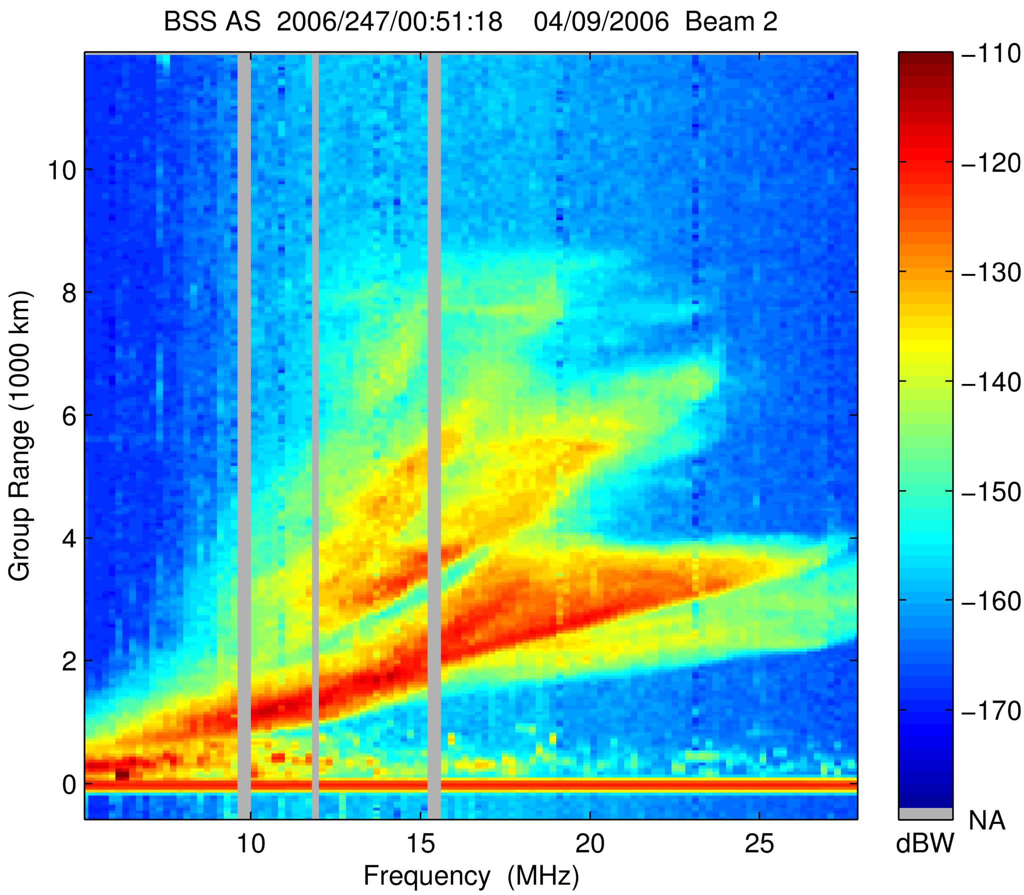

Figure 2. Standard processing removes RFI by excluding contaminated spectra from 48 in a 200 kHz band and taking the average of the remainder. If the number of remaining spectra is less than 6 all the data is excluded (grey vertical bands) and interpolation from neighbouring good frequencies is subsequently performed (not done in this figure). The standard resolution is 200 kHz by 48.8 km.

3. High Resolution Processing

3.1 Overview

With increased processing power and storage capacity, high resolution processing has become possible where spectral analysis and RFI rejection can take place using all 7680 complex samples of the phase coherent signal that covers 73.728 kHz of every 100 kHz of the swept band. There is a trade-off between resolution in range or frequency. For example, a Fourier transform of each set of 7680 samples provides one spectrum with range resolution 2 km every 100 kHz. Processing the data in blocks of 2560 samples provides clutter power estimates with range resolution 6.1 km for 3 frequencies spaced at 24.576 kHz every 100 kHz. The terminology used here refers to the coherent part of the signal as a dwell and the range processed block as a sweep so that in this case the data is processed as “3 sweeps per dwell”.

3.2 Processing without RFI rejection

A Fourier transform of all 7680 phase coherent time domain samples gives the highest range resolution. As is common practice, a taper is applied to the samples before Fourier transformation to reduce range side-lobes, and for all the processing discussed here a Hann window was used. An example is shown in Figure 3. Note the characteristic speckle and the significant RFI. The corresponding time domain signal is shown in Figure 4. The backscatter ionograms shown in this section and the next, prior to clean-up of the calibration signal, have a simple scaling scheme whereby the ionogram is scaled so that the median calibration signal level in the processed calibration range cell is equal to the median injected calibration signal. The slowly varying calibration signal, except for occasional steps, is handled in a later section.

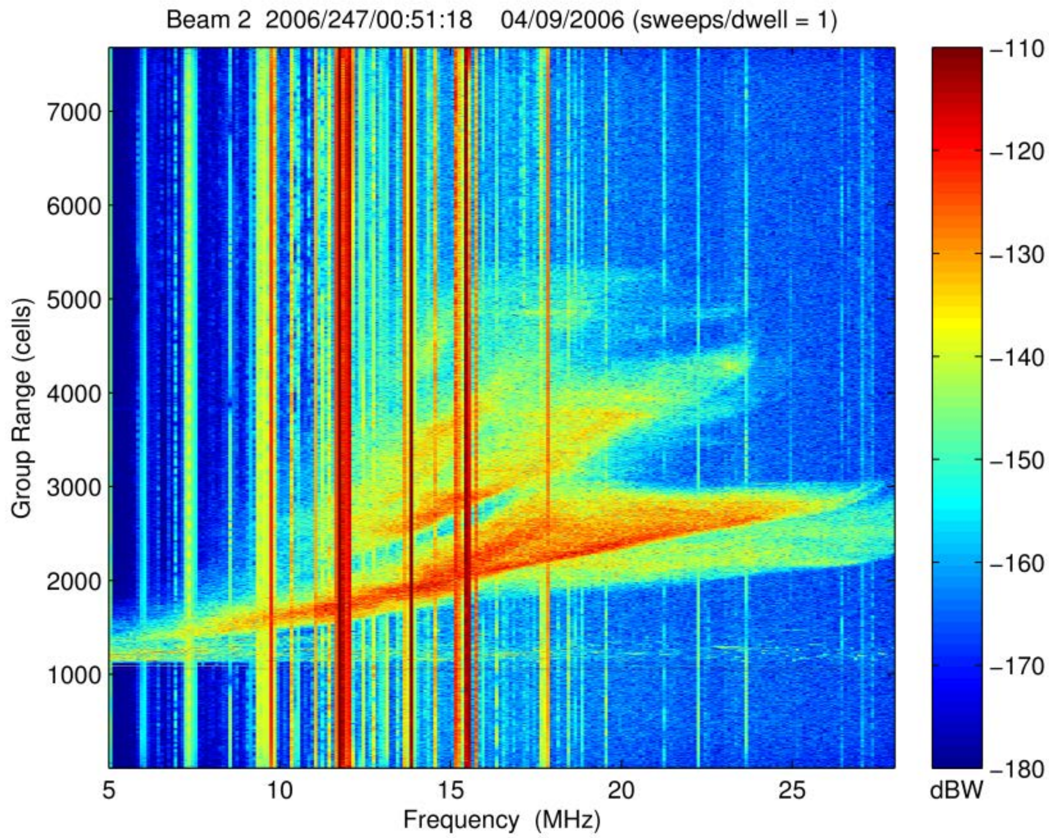

Figure 3. BSS data processed for maximum range resolution (2 km) with 7680 range cells by 230 frequency cells. Significant RFI is evident

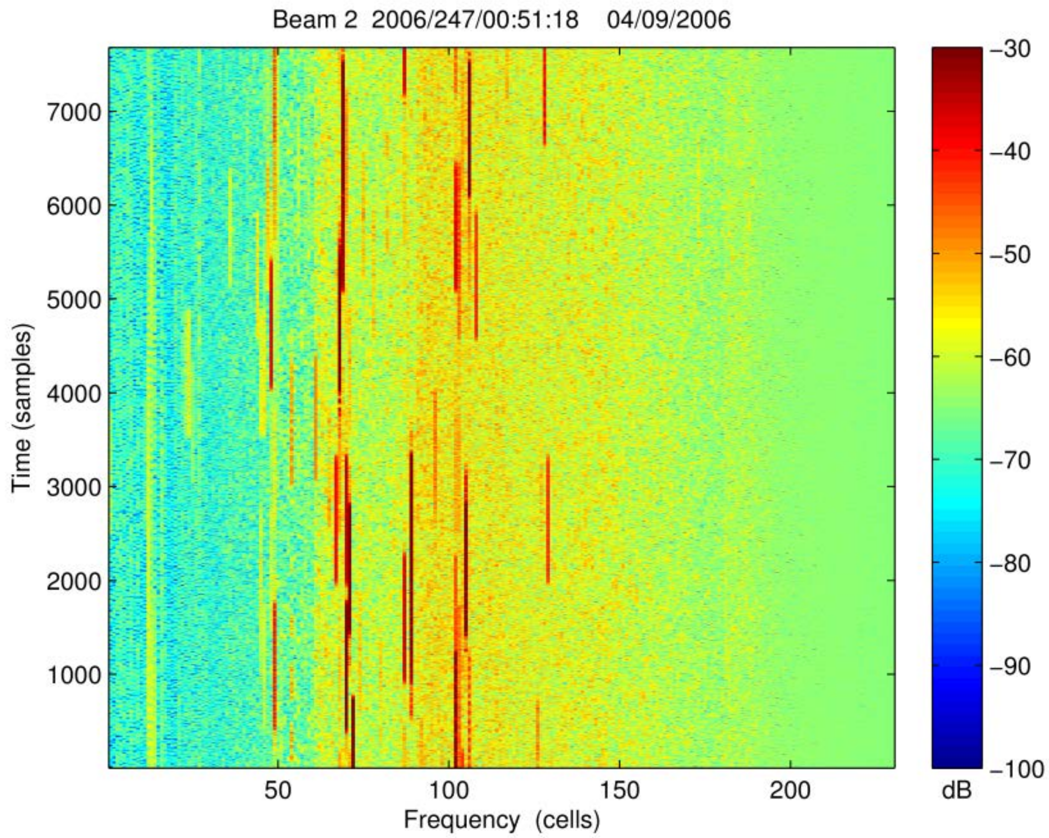

Figure 4. Time domain signal corresponding to Figure 3

3.3 RFI rejection

The scheme employed here for RFI mitigation for high resolution BSS processing is based on the fact that the sum of 2 offset Hann windows reproduces and represents the entire original time series. This means we can take a time series, window and FFT it and after alteration we can reconstruct the original time series (where it is not altered) by applying an inverse FFT. The scheme is a two pass process.

The first pass divides the 7680 coherent samples of each dwell (using the terminology described at the end of section 3.1) into 192 overlapped sets of 80 samples to yield 192 spectra within each 100 kHz of the HF band. A Hann taper is applied to each sample before Fourier transforming (see, for example, Figure 5 where a time series of 240 samples is subdivided into overlapped time series). An example of the resulting spectra is shown in Figure 6 and Figure 7 where the cell spacing is 195 km by 384 Hz. The frequency band swept per cell is 768 Hz, twice the frequency sample spacing. Narrow band RFI appears as diagonal interference with slopes corresponding to the sweep rate of the BSS. At the edges of the dwell there is no overlap for half a sweep, but this is handled later by adding in a suitably Hann weighted copy of the original time series data.

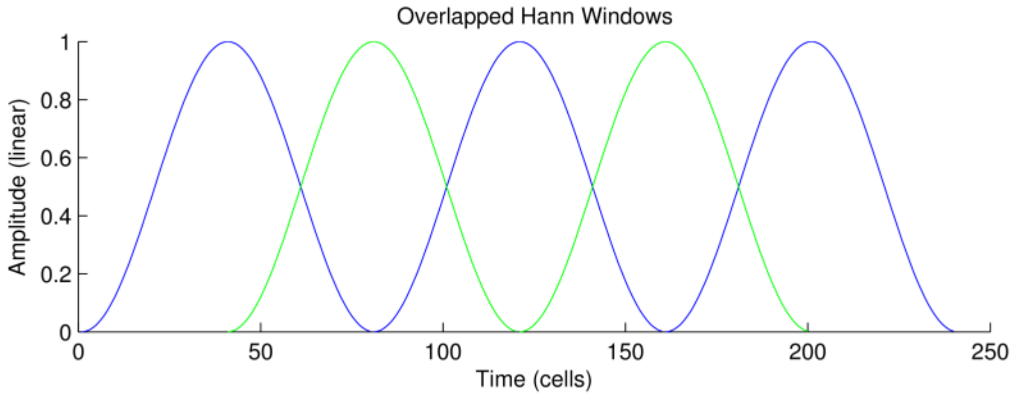

Figure 5. *A 240 sample time series multiplied by overlapped Hann (sine squared) windows would produce 5 segments of 80 samples for spectral analysis. At each time cell the original signal is the sum of the 2 overlapped components*

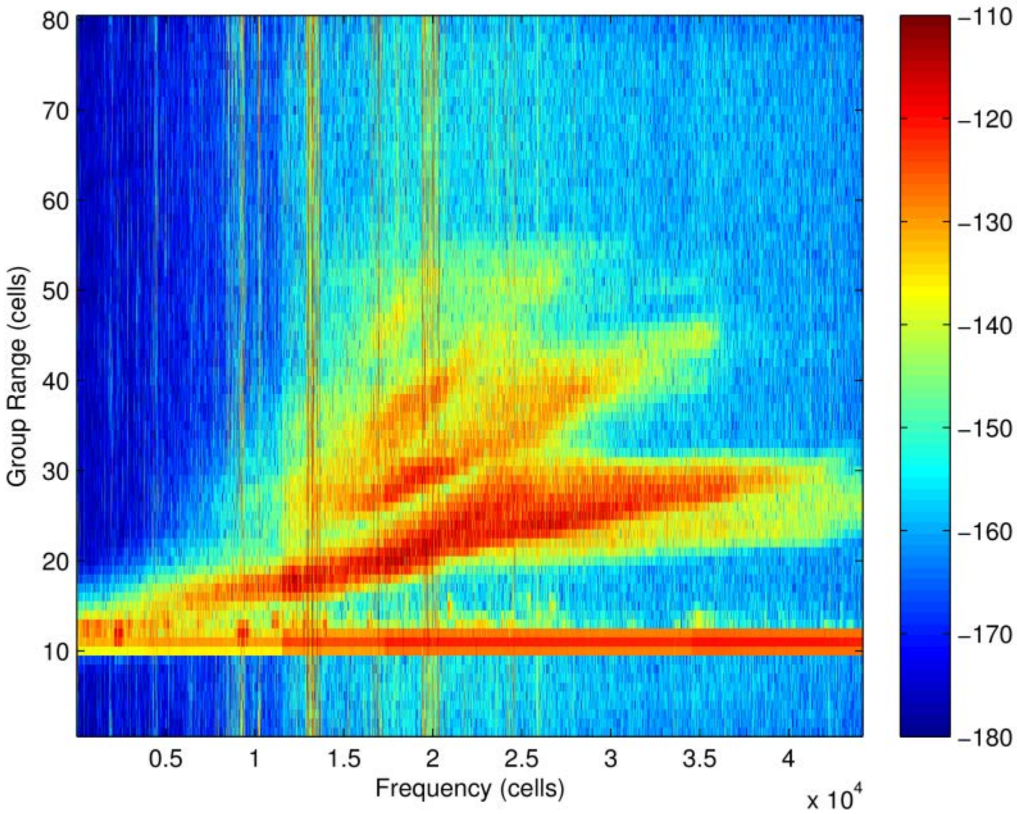

Figure 6. *The 192 overlapped time series per 100 kHz yield an ionogram with very high frequency resolution*

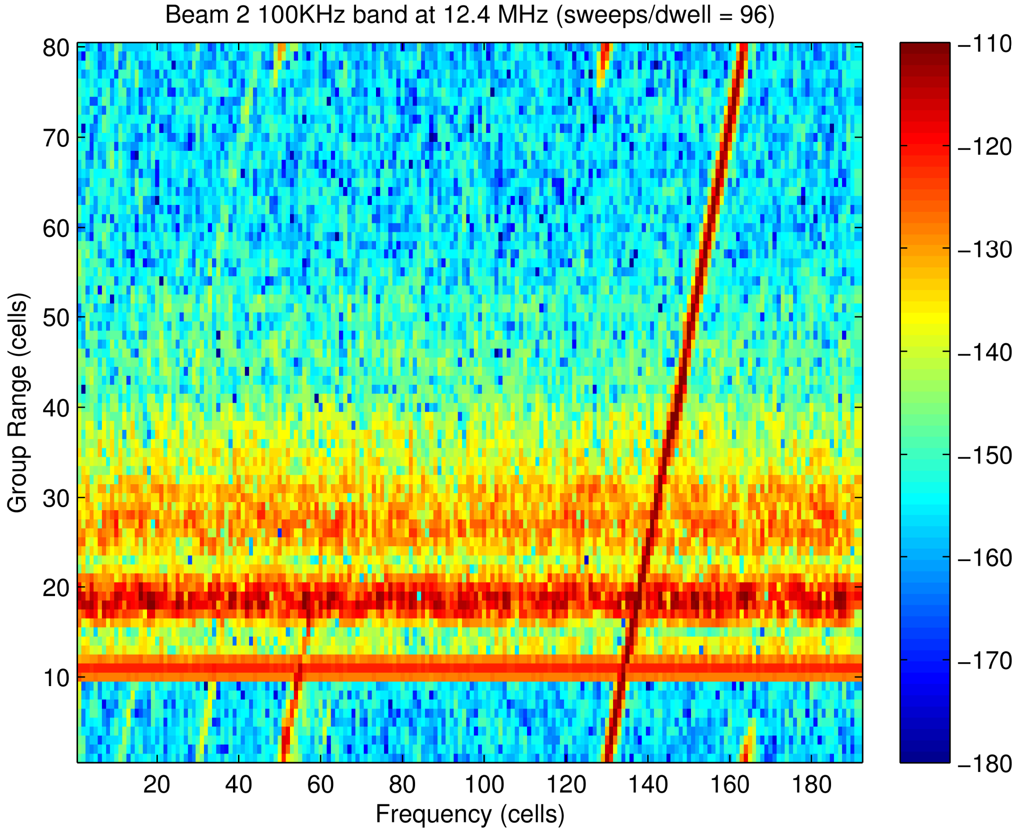

Figure 7. The 192 spectra for one dwell starting at 12.4 MHz. The resolution is approximately 195 km by 384 Hz. The calibration signal is visible at range cell 11. The diagonal lines are narrow band RFI, transmitted at fixed frequencies but have slopes here corresponding to the sweep rate of the BSS.

The RFI at each frequency extends only a few range cells so is amenable to excision from the data in this domain. RFI detection is carried out by setting a suitable detection threshold (10 dB) above the background clutter (and/or noise) power. The background clutter power was determined, at each frequency and range cell, as the median power across a window of ±300 kHz, or ±3 dwells. Rather than determine a computationally costly moving median at the resolution of the frequency samples (384 Hz), a median was determined for each dwell (effectively one value for each 100 kHz of the band). See, for example, Figure 8. The extent of the window for determination of the median was diminished at the edges of the band to form non-centred medians. Some residual RFI is visible at a few frequencies in this figure indicating that the RFI was sufficiently strong and spread at these frequencies to contaminate estimates of the background RFI free noise.

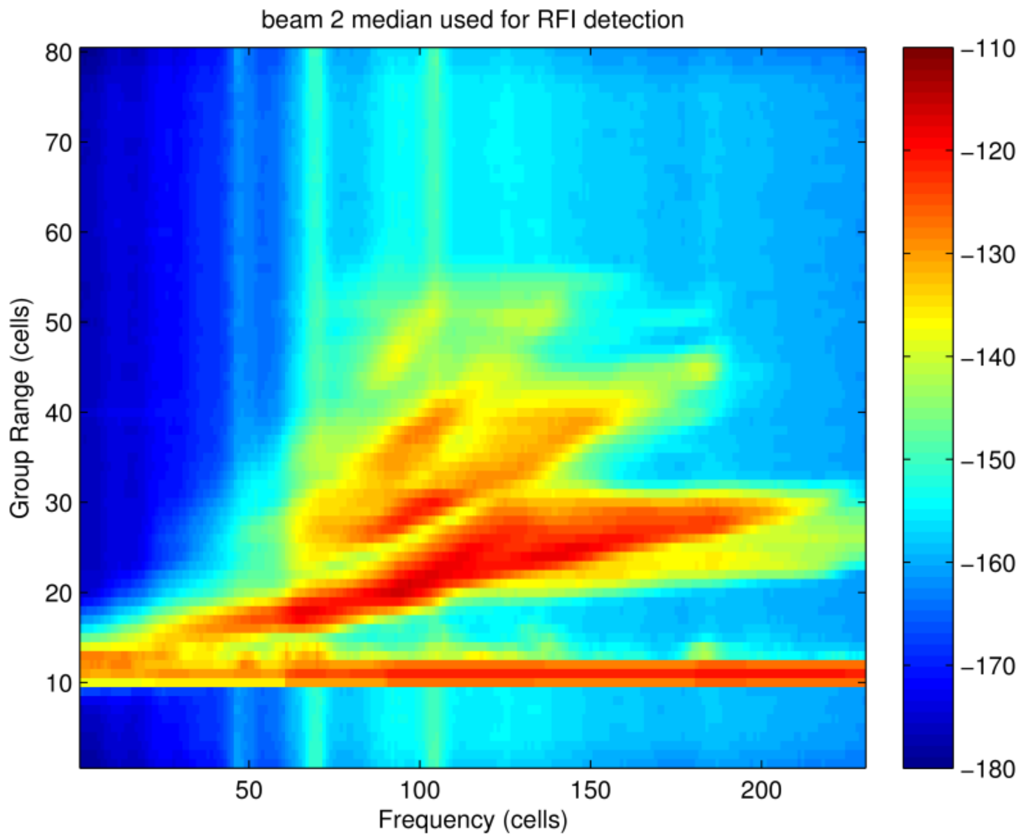

Figure 8. Median ionogram used for RFI detection. The resolution of this ionogram is 195 km by 100 kHz. Some residual RFI is visible.

Signals that exceeded the median clutter power by more than 10 dB were deemed to be unwanted RFI and were selected for excision (Figure 9). The detected RFI was removed by setting the complex frequency (in this case range) domain signal to zero at the RFI and tapering the 3 edge range cells (Figure 10) using taper weights [0.1 0.5 0.9].

Impulsive noise will raise the power level for all 80 range cells and, if sufficiently strong so as to exceed the threshold for detection, will cause the entire 80 samples at a particular frequency (of band width 384 Hz) to be zeroed.

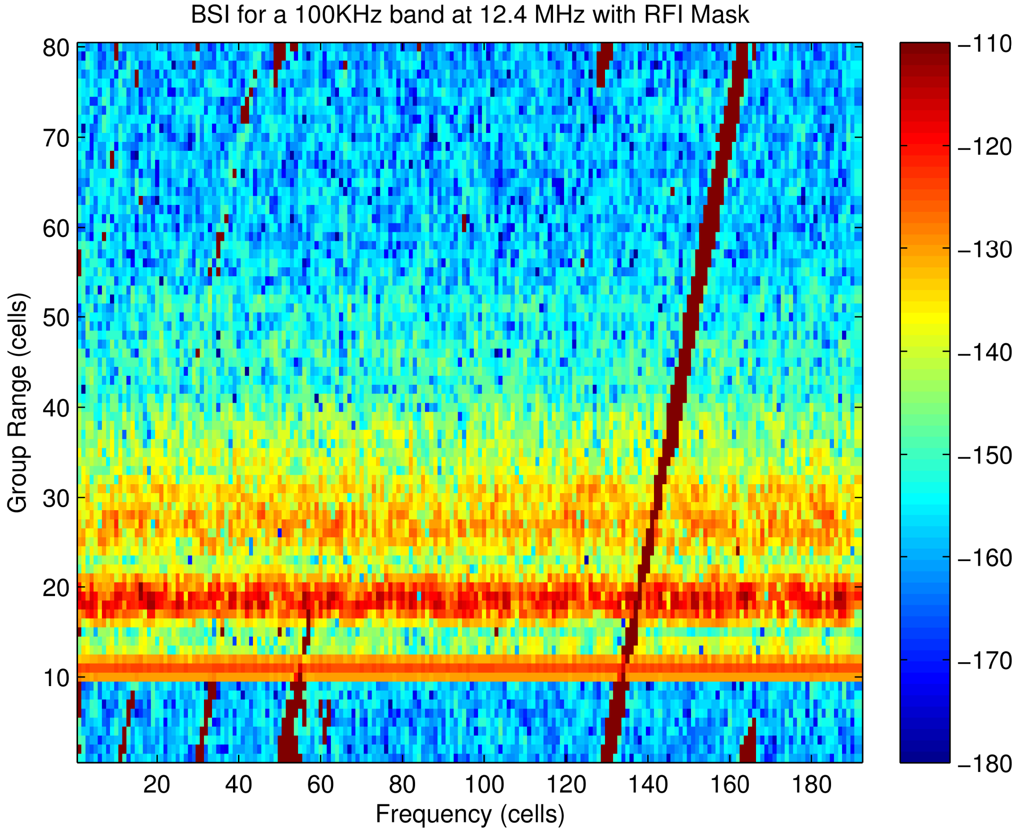

Figure 9. Location of RFI detected (dark red) for excision for the same dwell as Figure 7

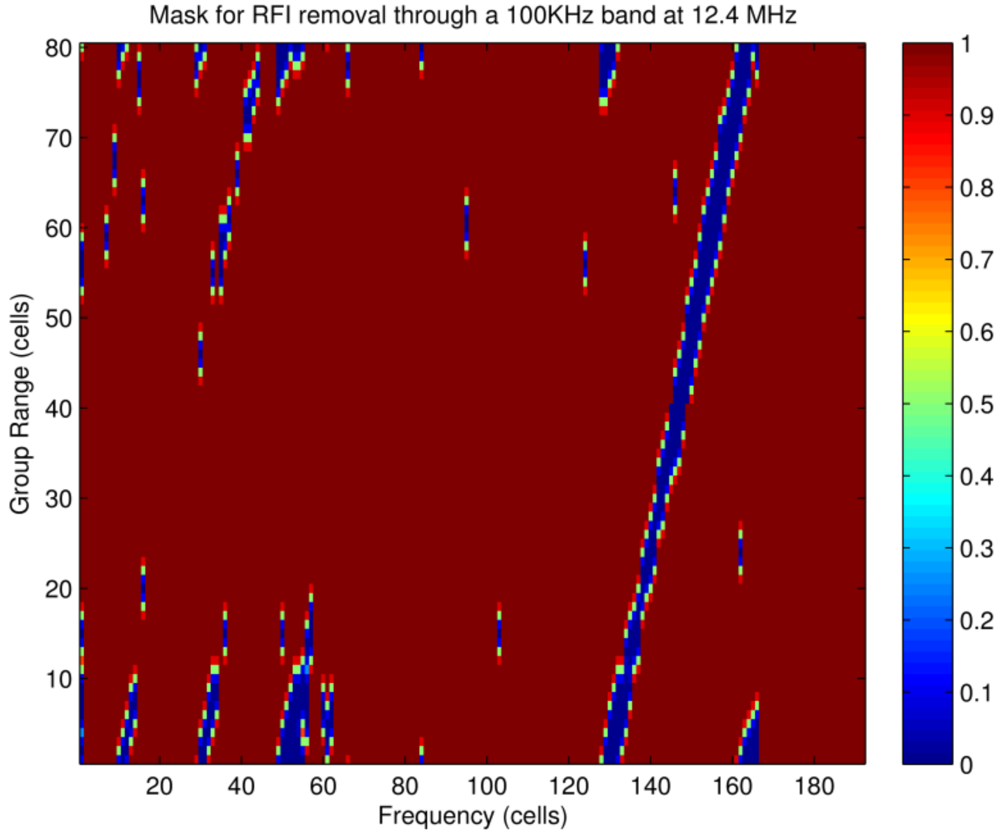

Figure 10. The tapered notches created for RFI excision corresponding to Figure 9

The inverse Fourier transform then produces a time domain signal without the RFI. The signal at this stage has overlapped components, being the inverse transform of 192 spectra per dwell of 80 samples. Each of these time domain segments has the envelope of the Hann window that was applied before range forming via Fourier transform. Examination of Figure 5 shows that simply adding the corresponding signals from the overlapped inverse Fourier transforms will reconstitute the required time domain signals because the sum of sine squared and cosine squared is unity. At the beginning and end of each dwell the power has the shape of half the Hann window used for RFI processing because there is no overlap for the end half sweep. To mitigate this unwanted taper, an appropriately Hann window tapered copy of the original signal before RFI removal was added for the first and last half sweeps of the dwell. Hann windows applied in subsequent processing will diminish the effect of any RFI in the edge regions. The reconstructed time domain signal at the end of the first pass of RFI removal is shown in Figure 11 and this corresponds to an updated version of Figure 4. The updated ionogram corresponding to Figure 3 is shown in Figure 12, processed using 3 coherent non-overlapped time series per dwell to give range resolution 6.1 km and 3 frequencies per 100 kHz.

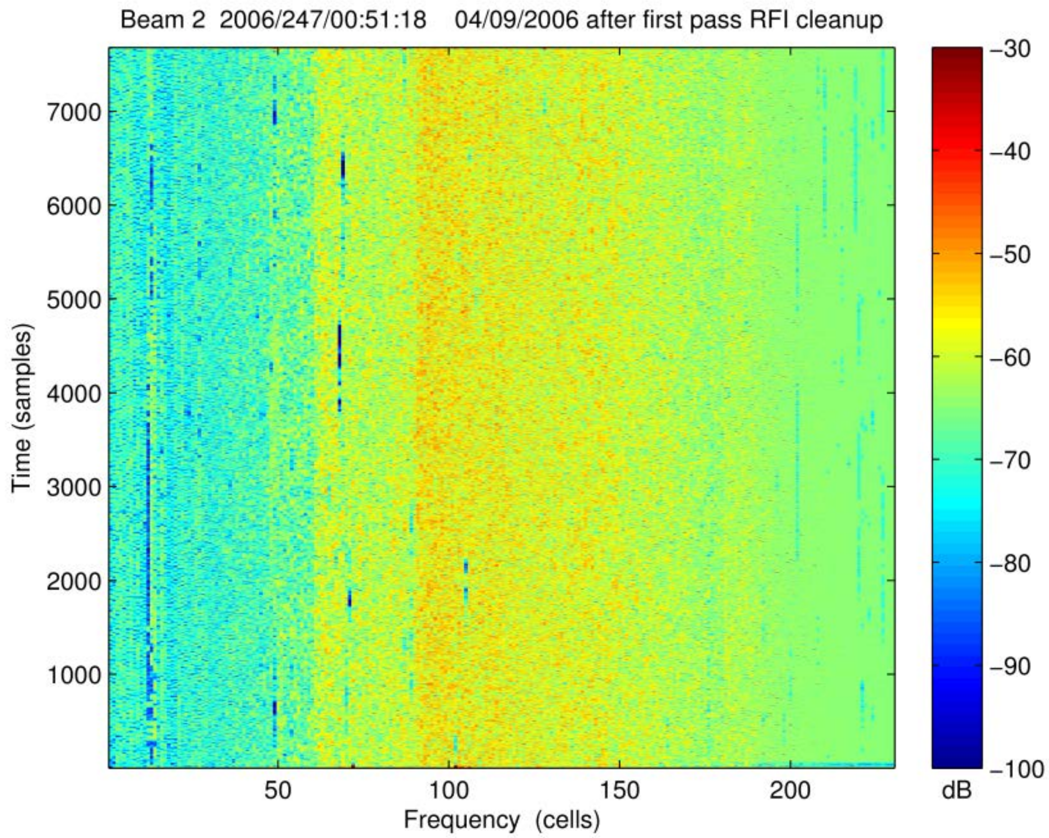

Figure 11. Received power in the time domain after first pass RFI removal

At the end of the first pass the BSI has been cleaned of the large RFI signals but due to the necessity of coarse range resolution to get high frequency/time resolution some residual RFI remained around large signals, such as the calibration signal, to give a "feathered" appearance. Linear interpolation was tried across the RFI in the range dimension of Figure 9 and this reduced the 'feathering" but was less effective at removing RFI. Further work with interpolation may be of benefit but will not be pursued here.

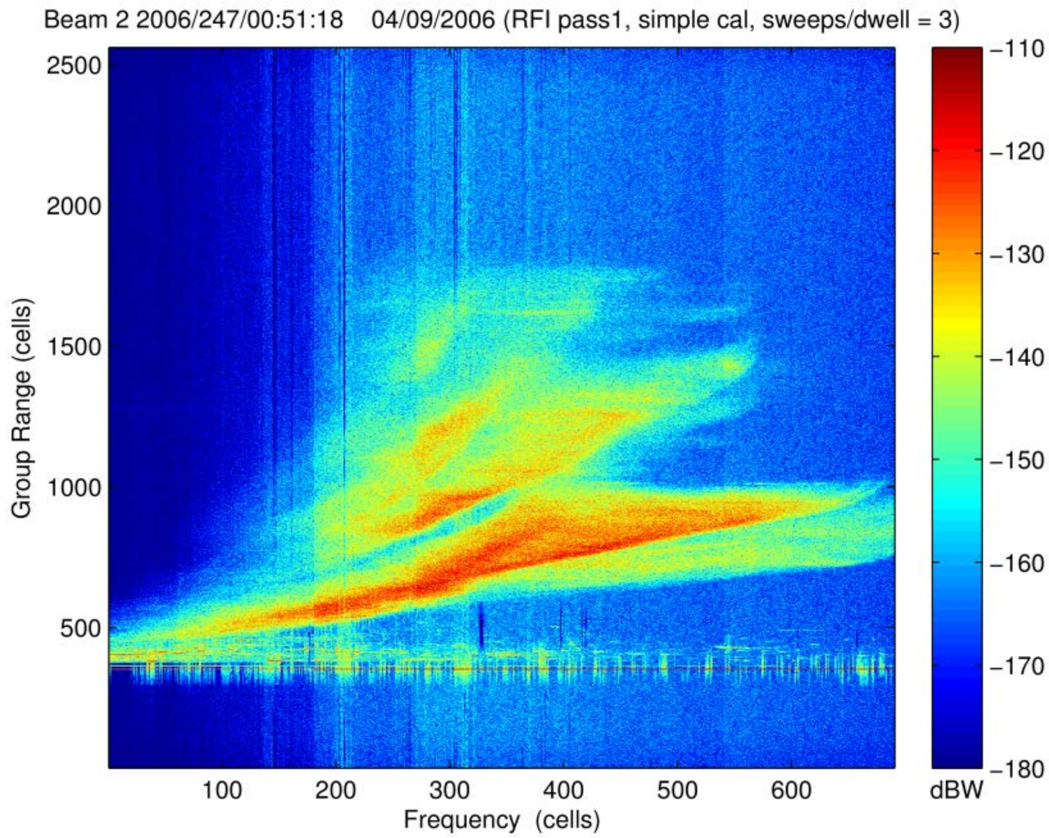

Figure 12. BSI after first pass of the RFI clean-up algorithm reprocessed to 2560 range cells and 3 frequency cells per 100 kHz to give 690 frequency cells across the 5-28 MHz band

In the second pass of the RFI rejection algorithm the data is processed with a higher range resolution than the first pass. This time the dwell is regarded as 12 sweeps in duration where the 7680 coherent samples of the dwell are partitioned into 24 (twice the number of sweeps per dwell) overlapped sets of 640 samples to yield 24 spectra within each 100 kHz of the HF band. Again, a Hann taper is applied to each sample before Fourier transforming. An example of the resulting spectra is shown in Figure 13 and Figure 14 where the resolution is 24.4 km by 3.072 kHz and the number of frequency cells is 24x230 = 5520 for the 5-28 MHz band.

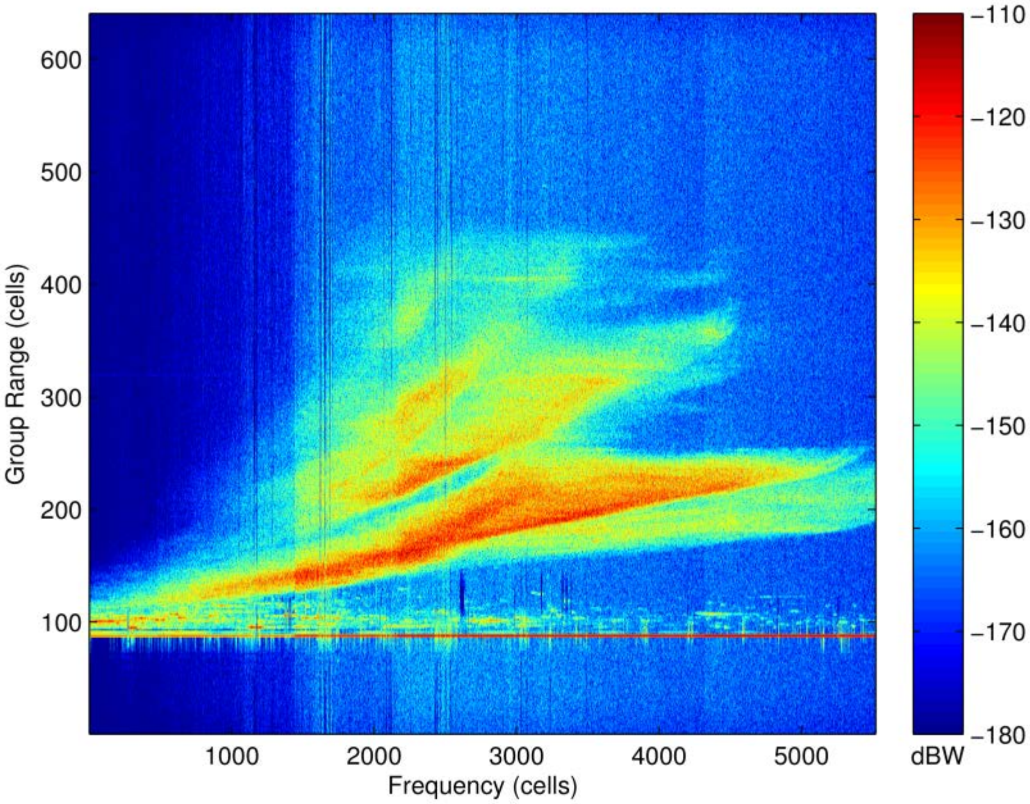

Figure 13. The first pass BSI reprocessed to 640 range cells and 24 frequency cells per 100 kHz for the second pass. Residual RFI remaining after the first pass of RFI mitigation algorithm appears as "feathering" on large signals such as the calibration signal

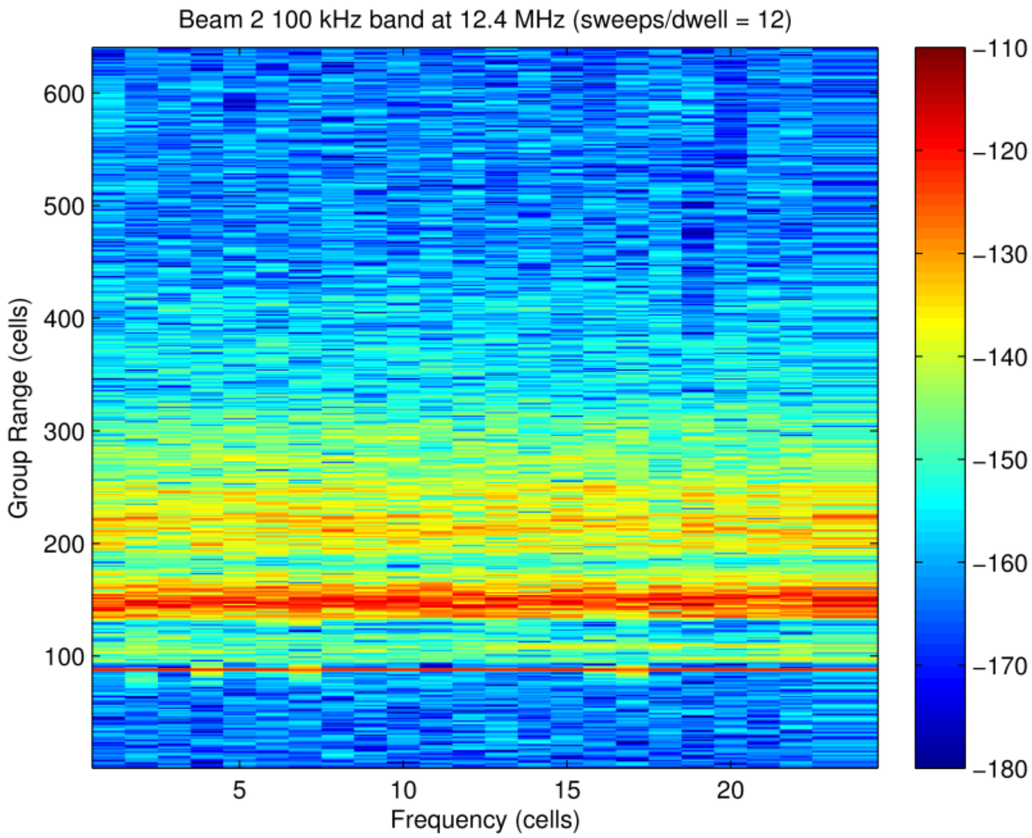

Figure 14. BSI at 12.4 MHz after processing to 640 range cells and 24 frequency cells per 100 kHz. Residual RFI remaining after the first pass of RFI mitigation algorithm appears as "feathering" and can be seen here attached to the calibration signal in frequency cells 4, 7 and 17

In the second pass the residual RFI is detected against a median background. In a similar fashion to the first pass, the background power is estimated, at each frequency and range cell, as the median power across ±200 kHz, or ±2 dwells, at that range cell. The threshold for detection of the residual RFI was also set at 10 dB above the background clutter power.

In the dwell starting at 12.4 MHz that we have been looking at in a number of figures, there is only light residual RFI, as can be seen in Figure 15, but Figure 16 shows another zoomed up region where the "feathering" has been identified and masked. Not all visible feathering is detected when the estimated background power is raised by extensive RFI, for example around frequency cells 1100 and 1600 in Figure 16.

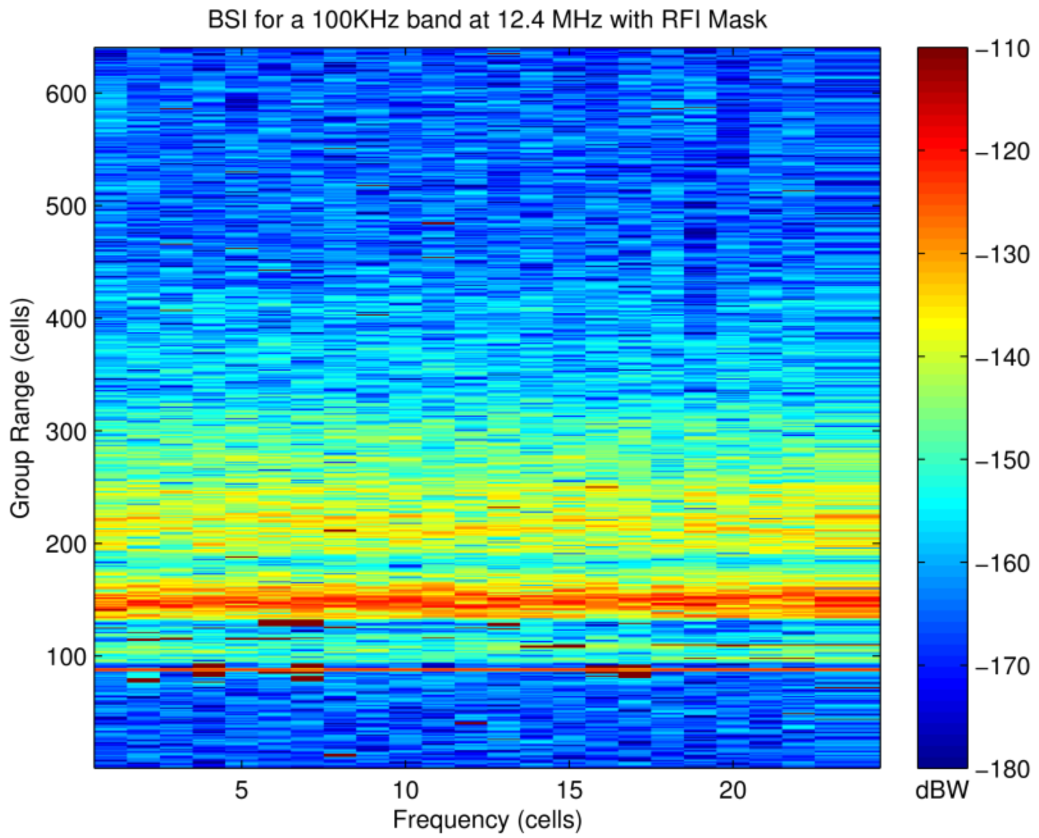

Figure 15. BSI at 12.4 MHz, processed for second pass RFI removal. The data to be removed is coloured dark red, the colour of the maximum display power.

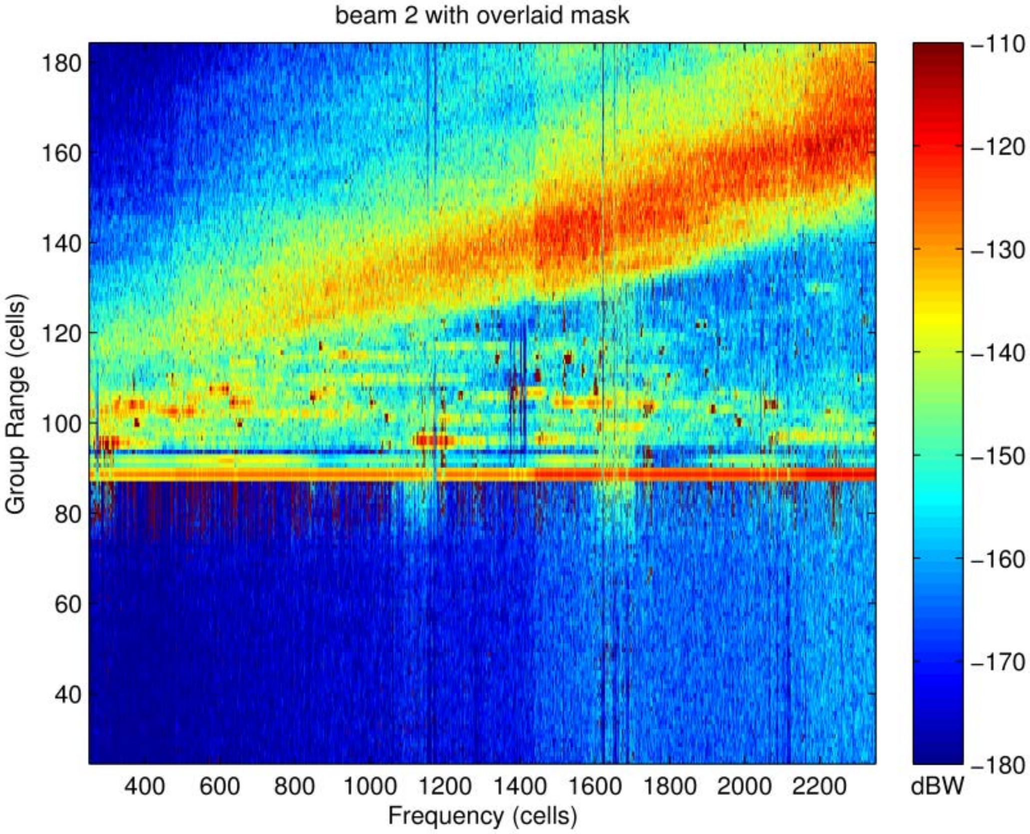

Figure 16. Zoomed region of BSI where substantial "feathering" has been detected for removal

A tapered mask was again created to remove data found contaminated. But in this second pass, the removed data was replaced with a median of the neighbouring data. For each dwell (i.e. every 100 kHz) the median "range" spectra were determined across 500 kHz (±2 dwells) except at the edges where the kernel was truncated. While the median was used in the processing here, zeroing the contaminated data using the tapered mask is the preferred option. Aside: *The median was calculated over the real and imaginary components separately then recombined into a complex "median" sequence. The starting phase of the "range" spectra would likely be different for each frequency cell. If the signals were random then the median formed in this way would be expected to be zero.*

After the second pass masking of the RFI, inverse Fourier transformation and coalescence of the overlapped regions, the time domain signal appears as in Figure 17 for comparison with Figure 4, the original RFI contaminated signal and with Figure 11, the time domain signal after the first pass. After subsequent Fourier transformation of 2560 sample sweeps (3 sweeps per dwell) the BSI looks like Figure 18, where again the calibration has been kept simple – a single median calibration signal was used for each beam. The feathery attachments to the calibration signal have been reduced and comparison of the detail between Figure 19 and Figure 20 shows that level of the detected RFI was reduced where it extends away from the calibration signal (e.g. near frequency cells 275-285).

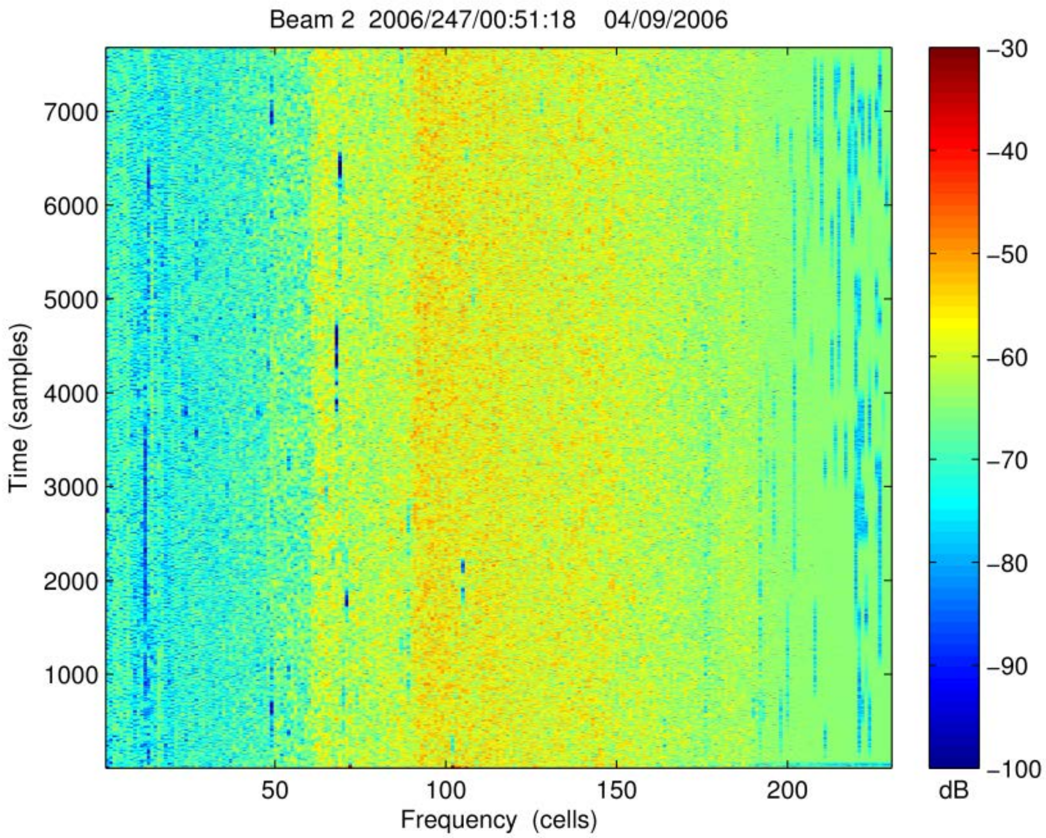

Figure 17. Time domain data corresponding to Figure 4 after RFI removal

The calibration signal is substantially degraded by RFI removal because the tapered edges of the RFI removal notches cut into it. Cleaning of the calibration signal is discussed in the next section.

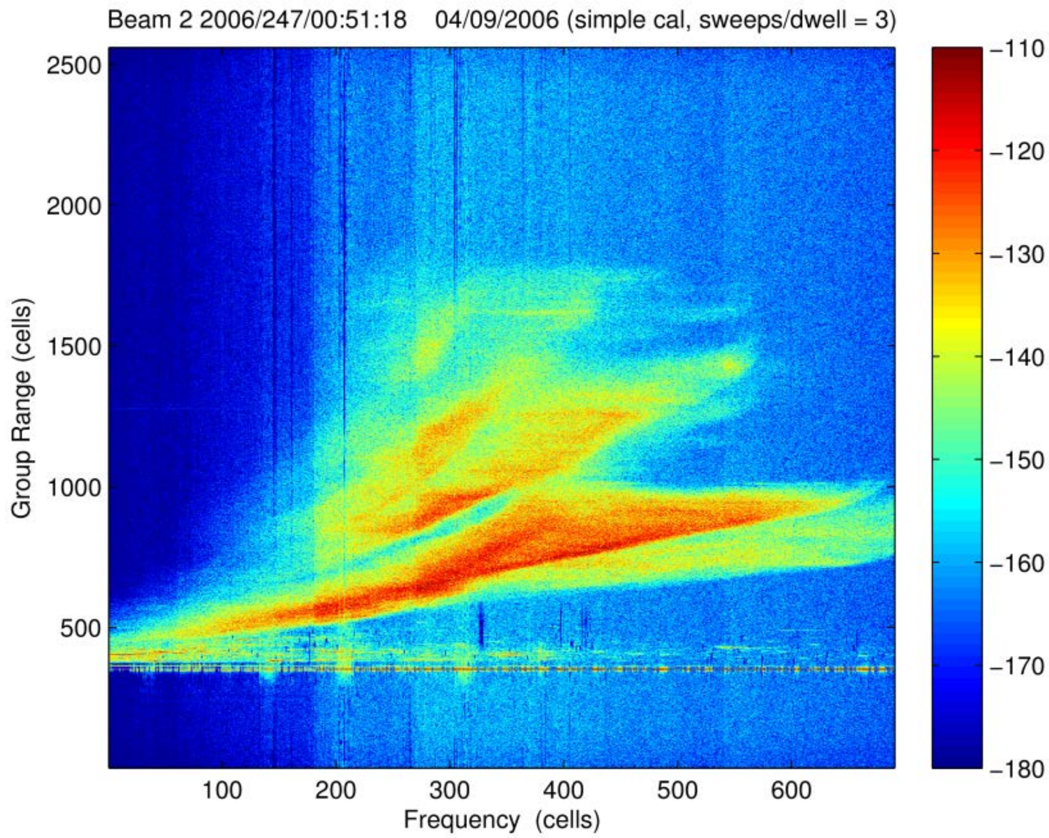

Figure 18. Backscatter ionogram after the second pass of the RFI removal algorithm but with only simple calibration at this stage. On comparison with Figure 12 it can be seen that the feathery remains of RFI attached to the calibration signal have been reduced.

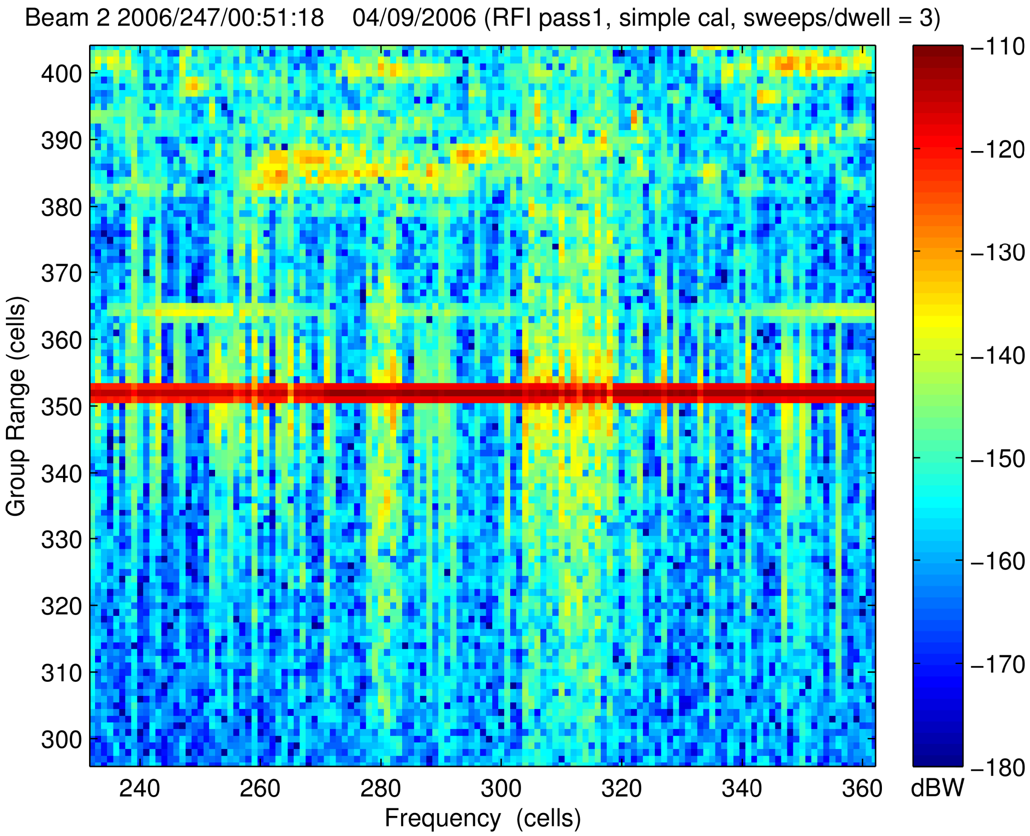

Figure 19. Zoomed BSI after the first pass of the RFI removal algorithm showing detail around the calibration signal for comparison with Figure 20

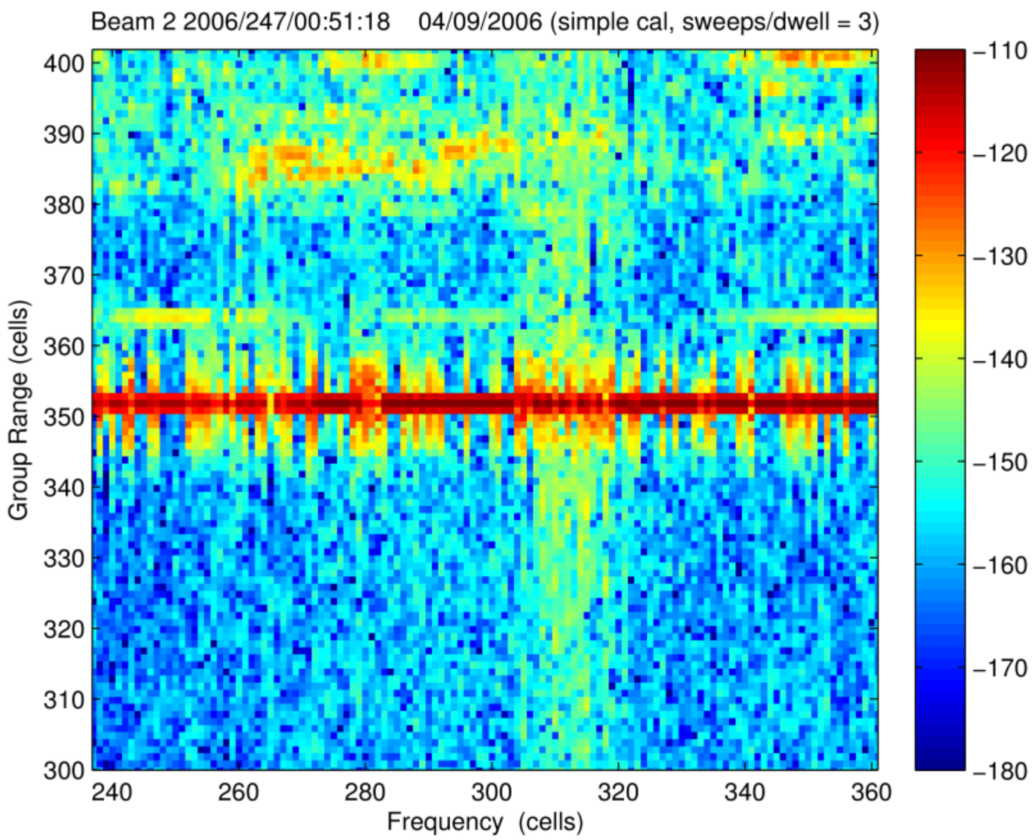

Figure 20. After the second pass of the RFI removal algorithm, on comparison with Figure 19, the residual RFI extending away from the calibration signal has been reduced, but the integrity of the calibration signal has been adversely affected and there are more artefacts close to the calibration signal

After RFI mitigation and processing at one sweep per dwell to achieve the highest range resolution (2 km) (Figure 21) the ground wave at half the transmitter-receiver site separation of 100 km is clearly visible, spread across two range cells at 48.9 and 50.9 km. Also visible are quasi-vertical incidence O and X traces at a one-way group range of approximately 300 km, consistent with propagation via the F2 layer.

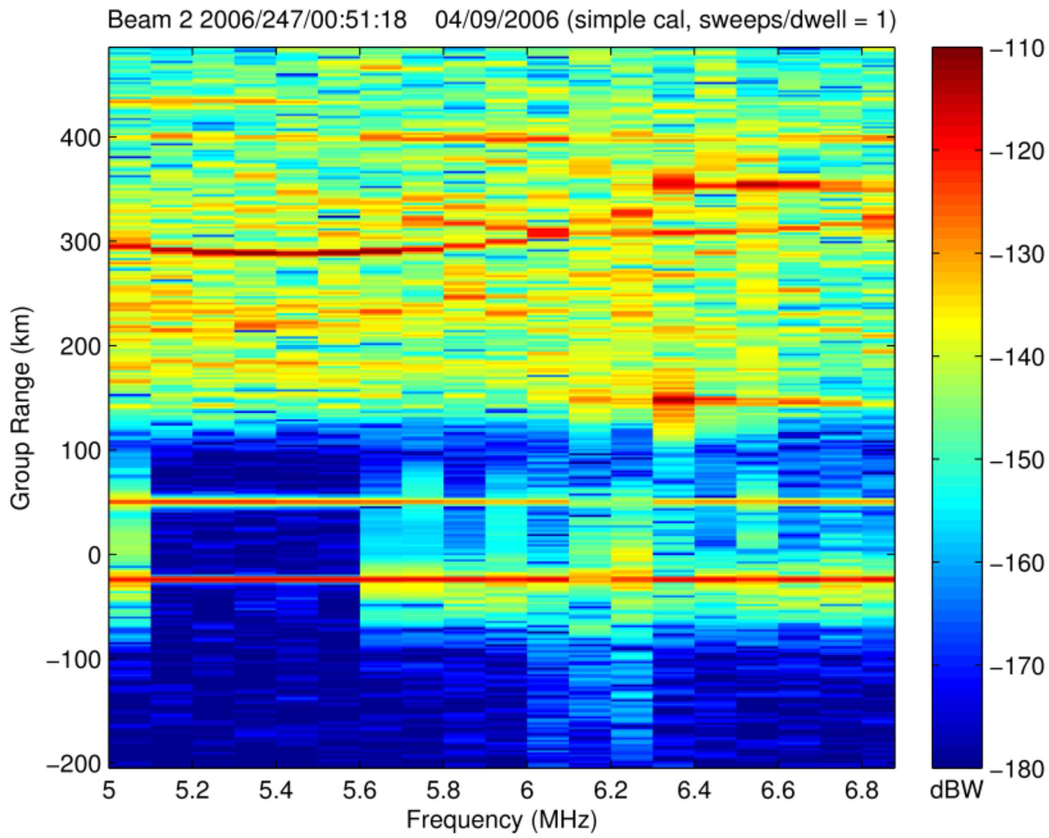

Figure 21. Highest range resolution BSI (2 km by 100 kHz) zoomed to show the calibration signal at -24.4 km, the ground wave at 49.9 km and quasi-vertical incidence F2 O and X traces at approximately 300 km (in amongst other signals).

3.4 Calibration signal

The calibration signal in the ionogram is frequently contaminated by RFI and may be further degraded by the RFI rejection algorithm. For this reason the calibration signal is separately processed and cleaned of RFI using the original raw data, processed according to the final target resolution. Here the final target resolution is achieved by processing the raw data using 3 sweeps per dwell or, in other words, using non-overlapped 2560 time samples at 3 frequencies per 100 kHz. This gives a range resolution of 6.1 km. Overlapped processing would give 5 frequencies per 100 kHz.

Examination of the calibration signal strength as a function of frequency for a single beam (Figure 22) shows that between antenna/receiver steps (where filters switch) the signal strength varies slowly except where there is contamination by RFI.

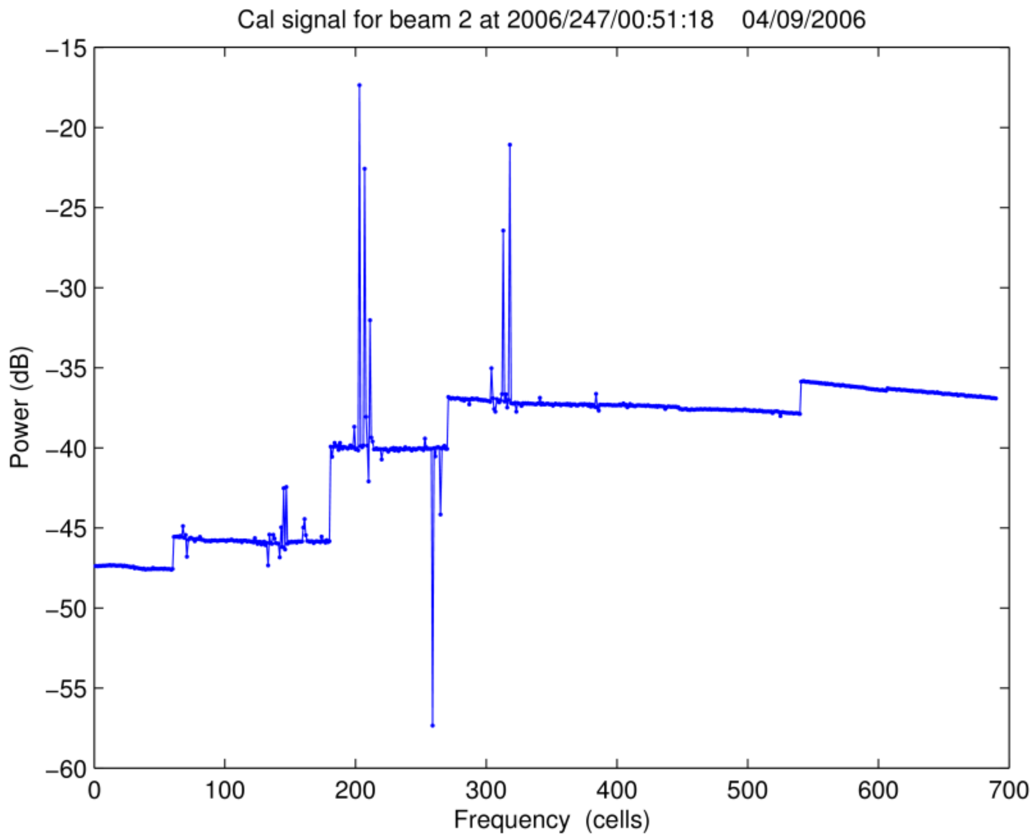

Figure 22. RFI is frequently strong enough to contaminate the calibration signal.

The guard band in the backscatter ionograms is the region of negative range cells below the calibration signal where there can be no backscattered signal power. The guard band was used to estimate both the RFI level and the background noise level. First the median guard-band signal (noise + RFI) level was estimated as the median (over the range dimension) of the guard band at each frequency and each BSS beam. The background noise (excluding RFI) was then estimated by subsequently taking the median over each 500 kHz band (median of medians). Similarly the noise floor for each 500 kHz band was estimated as the minimum guard-band signal over each 500 kHz band (minimum of medians). The median difference between the background noise and the noise floor over the whole 5-45 MHz HF band for each beam gave a measure of noise variation for each beam. Thresholds for detection of RFI contamination in each 500 kHz band were set as the noise floor plus twice the noise variation.

Calibration signal data at frequencies where there was RFI contamination were excluded. Replacement with linearly interpolated values from good data at lower and higher frequencies was considered but a problem with this method would be that if the RFI masks a step in the calibration signal then linear interpolation would be from one step to another. To avoid this problem the median calibration signal (over good values only) in each 1 MHz band was used to replace the contaminated data. The reason for using 1 MHz steps is that observation showed that the steps occurred on 1 MHz boundaries. A refinement would be to find out where the steps occur and take them into account directly. Figure 23 shows an example of some of the measures used for cleaning the calibration signal.

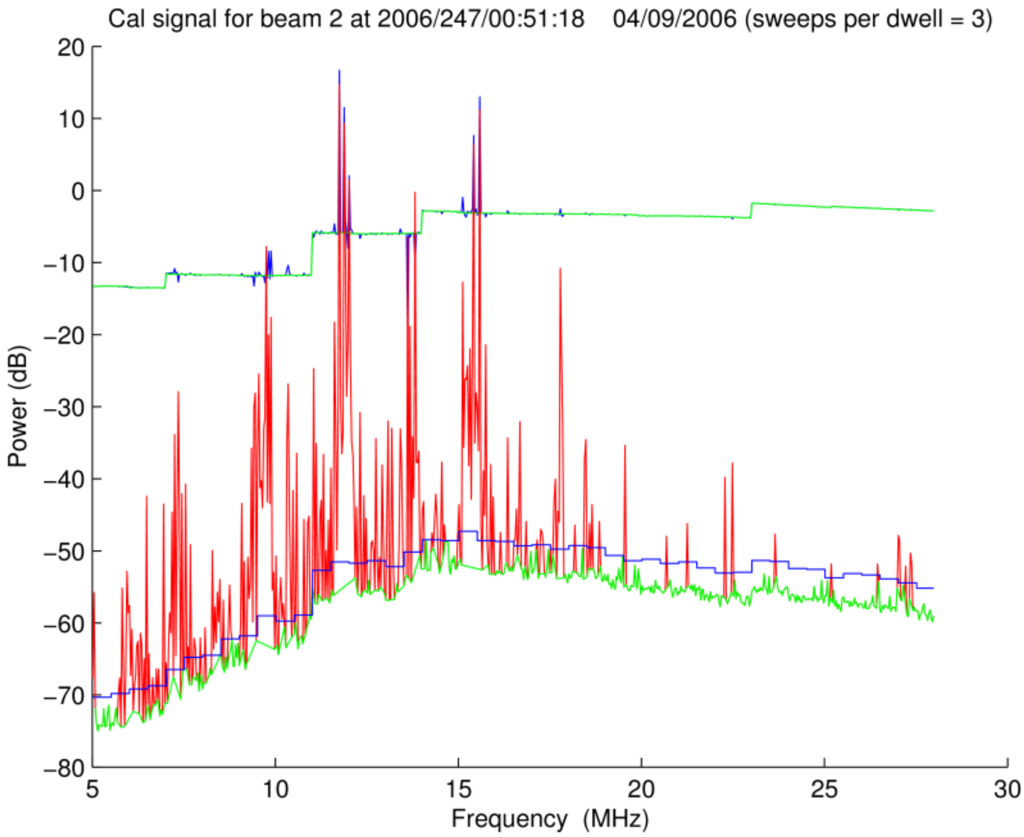

Figure 23. RFI contamination of the calibration signal. The upper blue curve is the uncleaned RFI contaminated calibration signal. The upper green curve gives the cleaned calibration signal, mostly superimposed on the original signal. The red line gives the median guard-band signal when the RFI detection threshold was exceeded. The lower blue curve gives the threshold for detection of RFI contamination, while the lower green curve gives the noise levels that were below the RFI detection threshold.

Ionograms were then scaled according to the differences between the cleaned calibration signal and the recorded reference calibration signal levels in order to produce a cleaned calibrated BSI (see Figure 24).

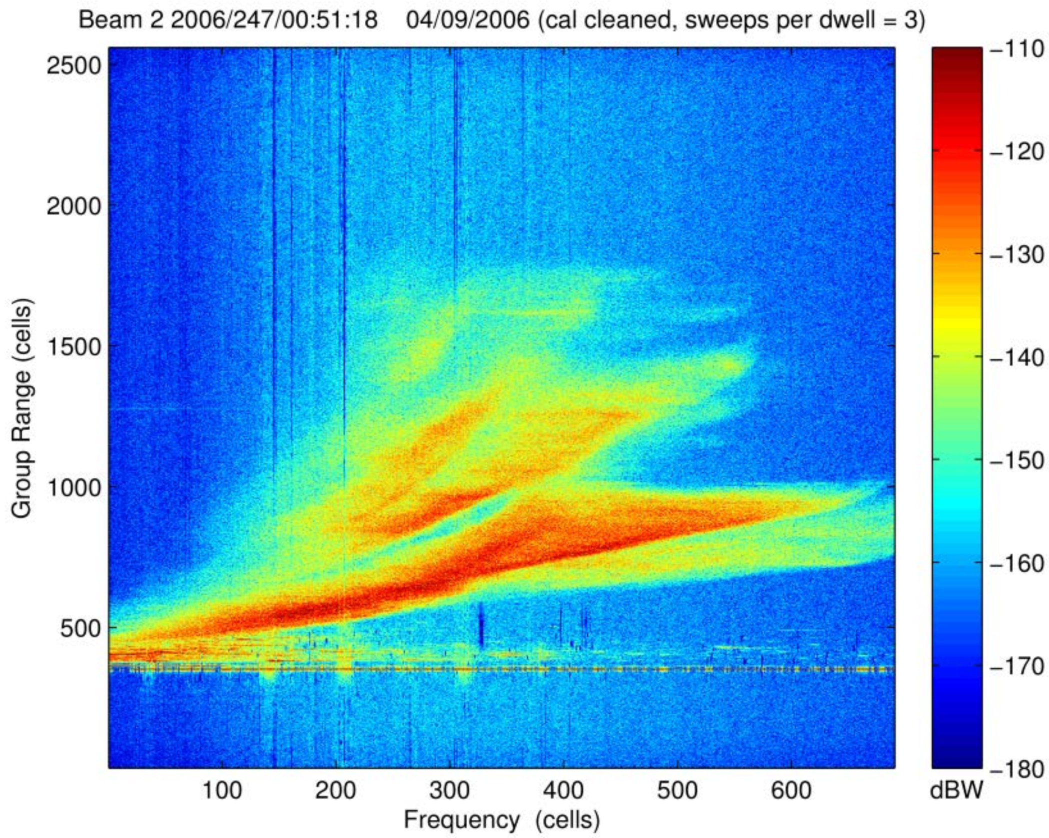

Figure 24. Final RFI cleaned and calibrated backscatter ionogram at a resolution of 6.1 km by 3 frequencies per 100 kHz (based on the same data as the standard image presented in Figure 2).

3.5 Pass-band

For standard processing only the central 80% of range cells are retained because of roll off at the edge of the receiver pass-band. This is optional for the high resolution processing.

3.6 Incoherent Integration

For comparison with the standard processing and for evaluation of suitable final resolutions it was found useful to integrate range and/or frequency cells. In order to keep the colour scale the same for direct comparison for different levels of integration, it was decided to scale the clutter power levels to correspond to the range cell size of the standard processing (48.8 km).

The raw BSS data collected for high resolution evaluation was processed to provide BSIs at a resolution of 6.1 km by 3 frequencies per 100 kHz. The processing steps were RFI removal, range-forming at 3 sweeps per dwell (6.1 km range resolution) and calibration as presented in the previous sections. A variation would be to use overlapped sampling to give 5 frequencies per 100 kHz. Then taking a median or mean over these 5 would yield further data reduction to a frequency sampling of the HF band at 100 kHz but maintaining the 6.1 km range resolution.

From the pre-processed data, BSIs could be generated at range resolutions that were multiples of 6.1 km by summing the power over the appropriate number of adjacent cells and at various frequency resolutions by averaging the power over adjacent frequency cells. The data for Figure 25 was processed to provide the standard 48.8 km by 200 kHz resolution for comparison with Figure 2.

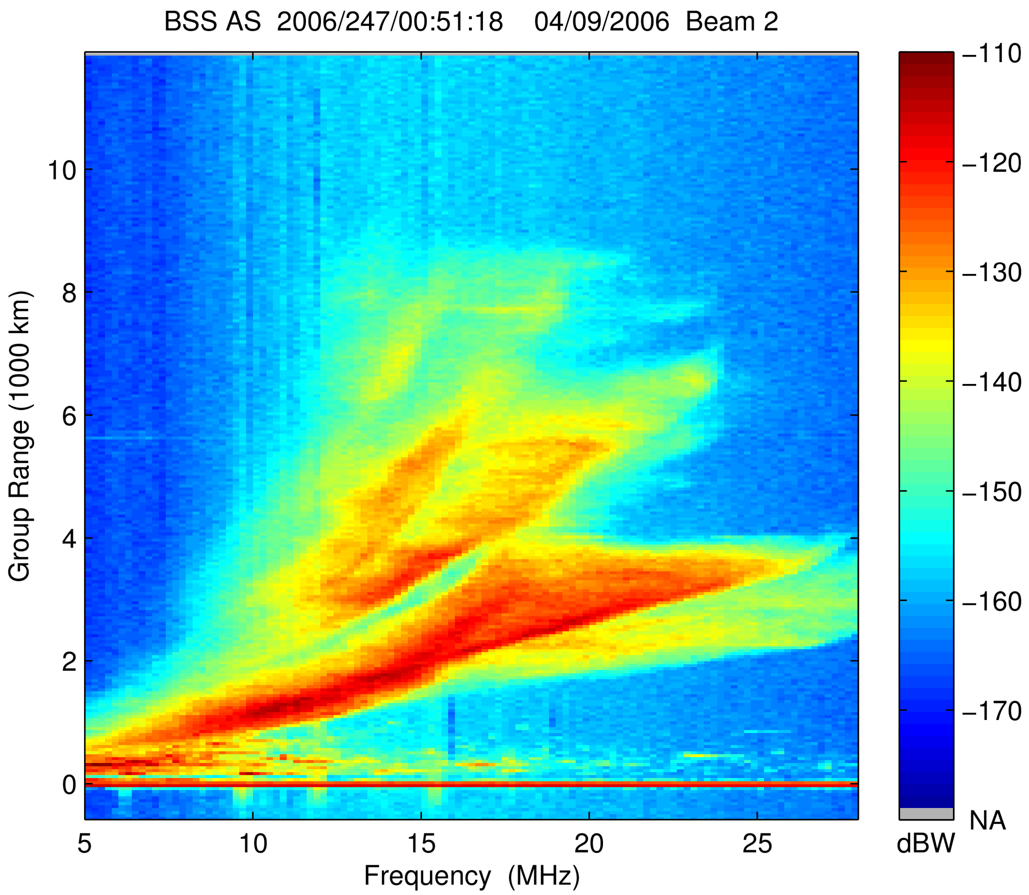

Figure 25. High resolution backscatter ionogram processed to have the standard resolution of 48.8 km by 200 kHz. Note the substantially cleaner appearance on comparison with Figure 2.

Certainly with incoherent integration of range cells, meteor trails are confined to one range cell rather than being spread by the range forming window over a number of samples.

Naturally the higher range resolution reveals details of features that would otherwise be merged. For example, when sporadic E (Es) is present the multi-hop quasi-vertical incidence (QVI) Es can be resolved at the higher range resolution as can be seen on comparison of Figure 26 and Figure 27.

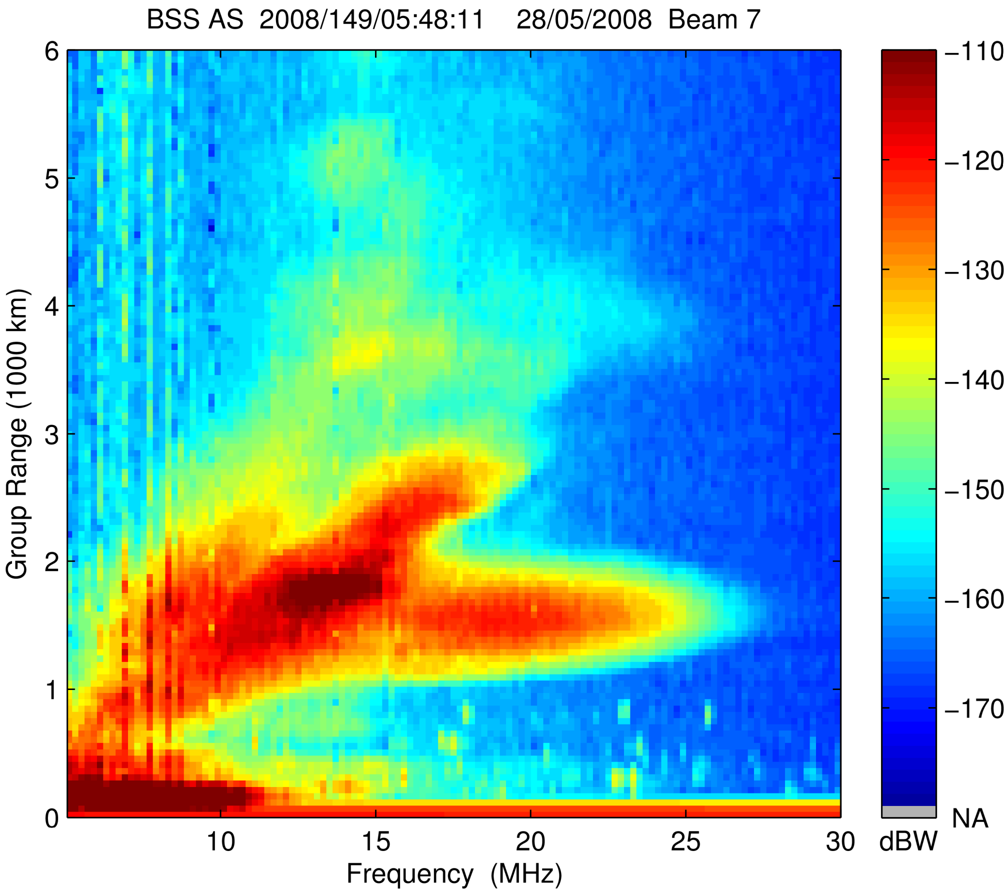

Figure 26. Standard backscatter ionogram with resolution 48.8 km by 200 kHz showing Es propagation from ranges 1000 to 2000 km. At close range, 100 to 300 km just beyond the calibration signal, there are unresolved quasi-vertical incidence traces.

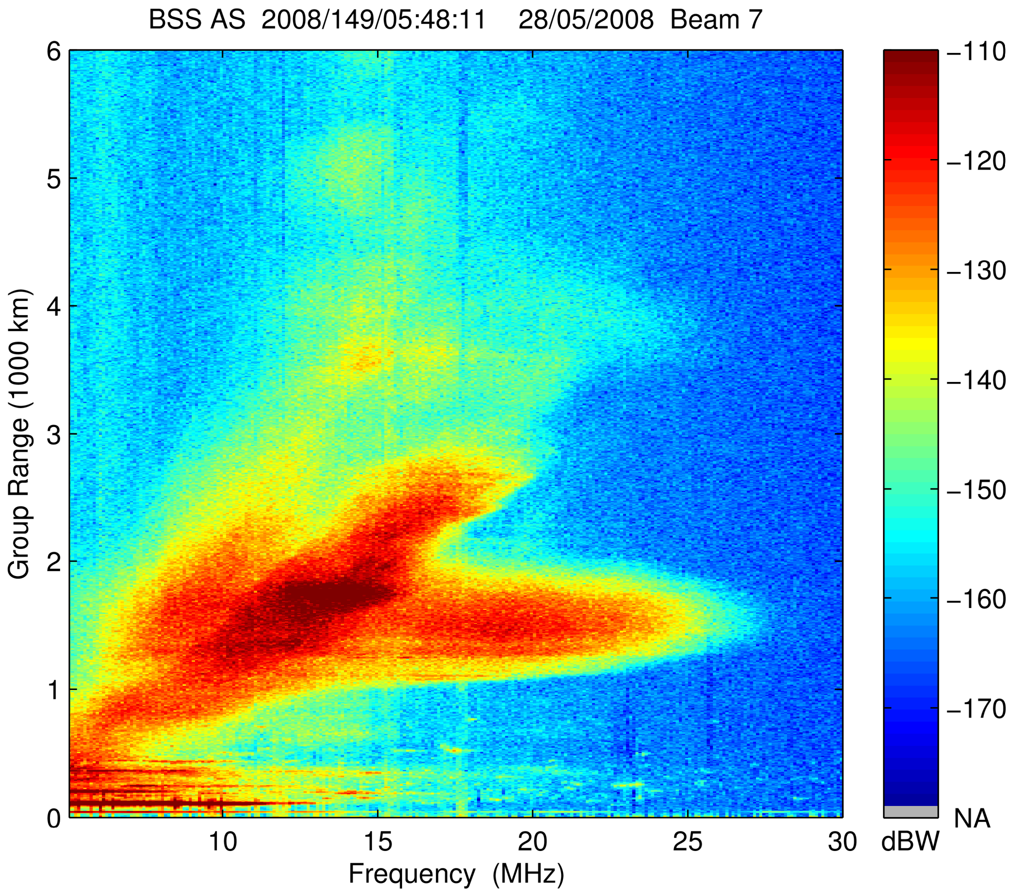

Figure 27. High resolution backscatter ionogram with pixel resolution 6.1 km by 100 kHz showing Es both from backscatter at 1000-2000 km and from multi-hop QVI at close range. Also visible is the ground wave return at 50 km. The calibration signal is just off the bottom of the image at -24.4 km.

3.7 Processing Time

The examples in this document were produced using MATLAB 2007b on the hfr-desk03 computer of ISRD with the following configuration: "SMP x86_64 Intel(R) Xeon(R) CPU E5320 @ 1.86GHz GNU/Linux". A spot check of RFI mitigation time gave 192 s to process all 8 beams at 3 sweeps per dwell returning 5 frequencies per 100 kHz (using overlapped sequences). Added to this was 18 s to load the data (subsequent loads from buffers took 4 s). Time to save the data to file was not measured. To keep up with data collection the entire processing time should be within the time it takes for one sweep of the HF band. The frequency range for the above test was from 5 to 35 MHz and this would allow 4 minutes.

The raw test data used for the examples given here, for days 2006/233 and 2006/247, were collected with only the standard processing operating in real time. This enabled collection at a rate of 1 run every 3.5 minutes over the frequency band 5-28 MHz. At the time the VHF band was not available.

The processing times given here are only an indication because efficiency was not a major design parameter for the experimental code. The system activity was also not known at the time of the test.

For provision of timely frequency advice to radar operators, faster processing of the BSS data would be preferable. After beam forming each beam is processed independently so could be processed concurrently. Every indication is that this processing could be executed in real time.

3.8 Extended Time Periods

In order to identify potential problems that might surface when applying high resolution processing to a variety of data, the available data (about 3 days) was processed and examined. Summary images were produced that gave backscattered power as a function of group range and time for selected frequencies. Additionally variations with respect to the number of incoherently averaged pixels were performed to visually check image quality.

The slope of the leading edge in Figure 24 is approximately 12 km per 100 kHz. This means that averaging over 200 kHz will potentially blur LE features on a scale of 24 km.

Figure 28 and Figure 29 give a visual comparison of the standard processing and the high resolution processing for the same pixel size over a 24 hour period as a function of range and time at 13.1 MHz. Even though the cell size is the same the high resolution processing produced an image that appears crisper, the edge of the backscattered power cleaner and the meteor echoes less spread in the range dimension, these being confined to one or two range cells.

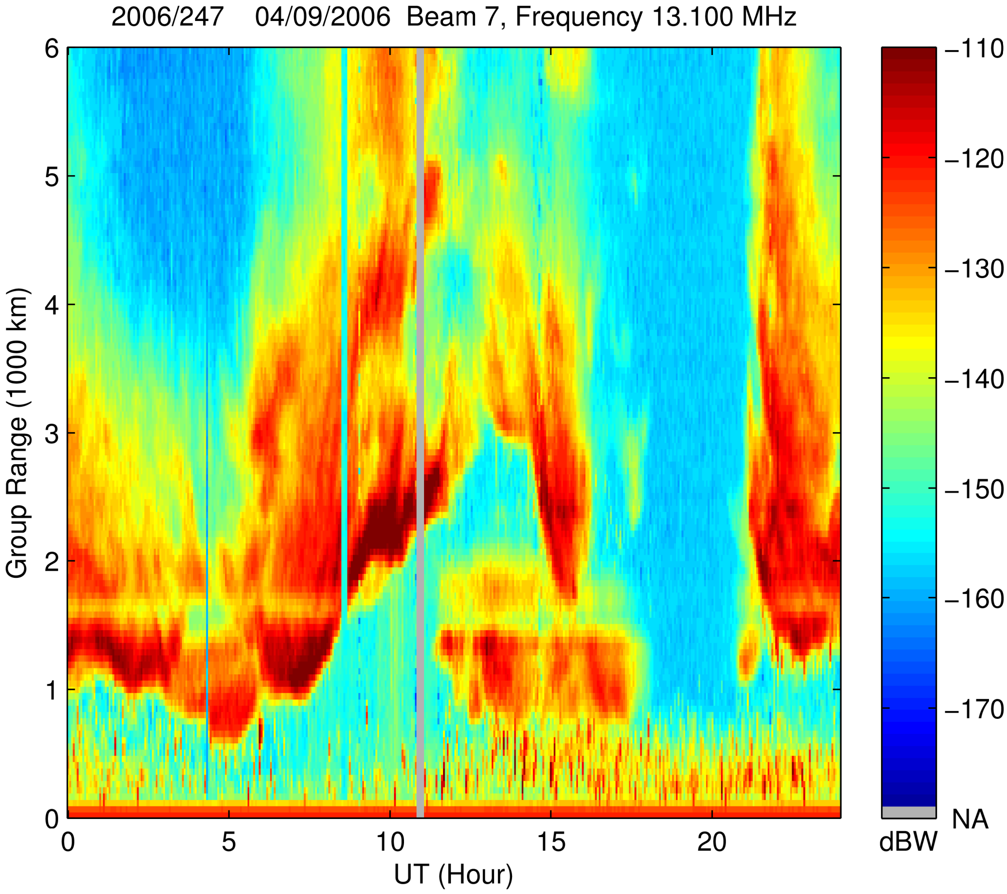

Figure 28. Backscattered power as a function of group range at 13.1 MHz for a 24 hour period using the standard processing at resolution 48.8 km by 200 kHz. .The bulk of the backscattered power from 1000 to 4000 km was due to propagation via the F2 layer. The power in front of the F2 leading edge from approximately 0300 – 0600 UT and 1200-1800 UT at ranges 800 km to 1800 km was due to Es propagation. The many transient returns at ranges from approximately 100 to 800 km were predominantly from meteor trail backscatter. Also evident is the reduction in backscattered power at approximately 1600 km for the F2 propagation and at a slightly shorter group range for Es propagation, as expected from a reduced earth's surface backscatter coefficient at a fixed ground range. At this frequency there was no night-time propagation from 1800-2000 UT.

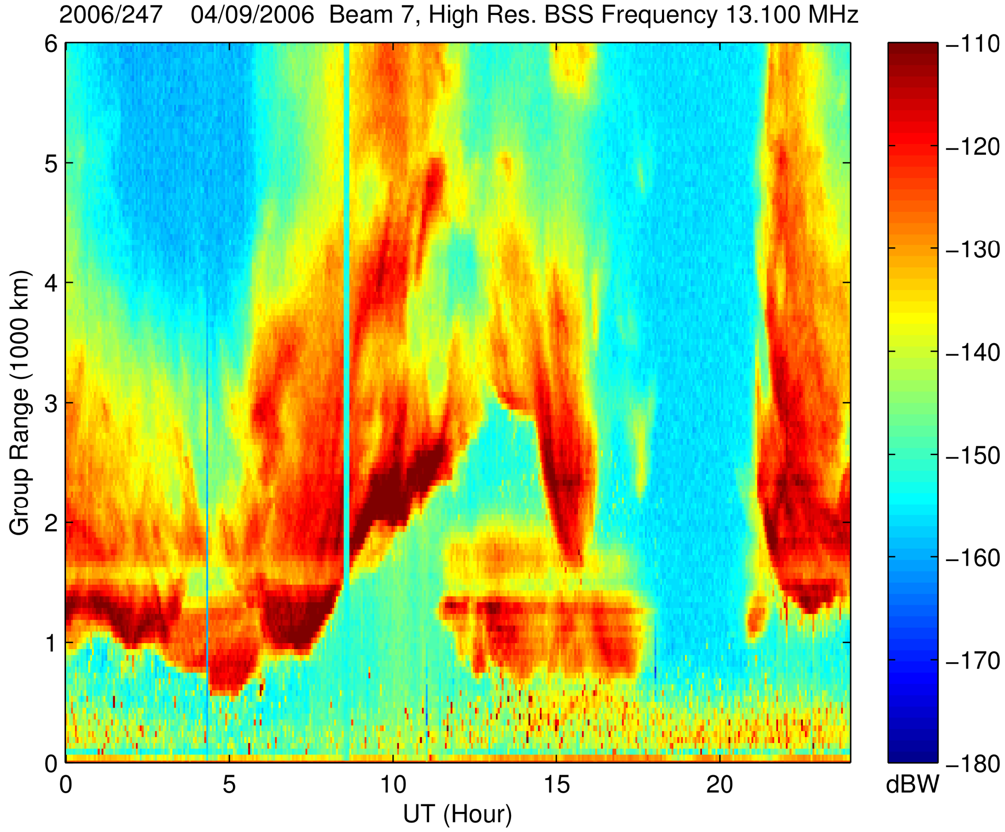

Figure 29. Backscattered power as a function of group range at 13.1 MHz for a 24 hour period using high resolution processing and incoherent averaging to the standard resolution of 48.8 km by 200 kHz. Even though the resolution is the same as for the standard processing used for Figure 28, the image appears crisper, the edge of the backscattered power is cleaner and the meteor echoes are visibly less spread in the range dimension, being confined to one or two range cells.

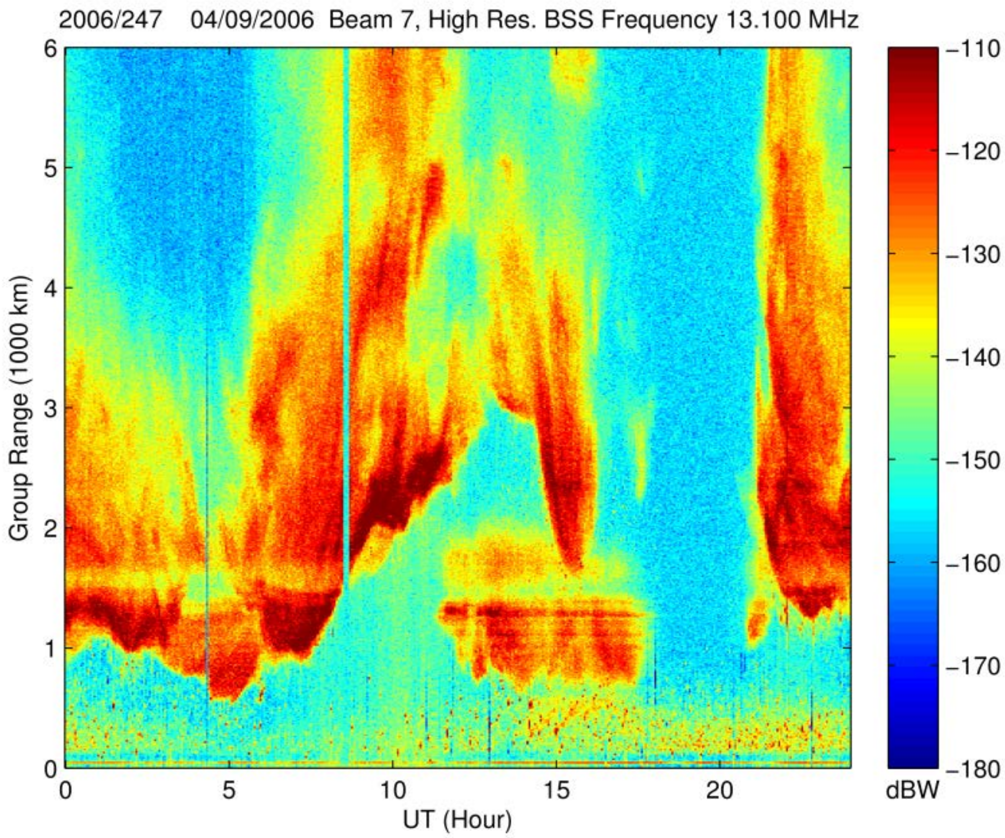

Figure 30. Backscattered power as a function of group range at 13.1 MHz for a 24 hour period (using high resolution processing to a resolution of 6.1 km by 100 kHz). In comparison with Figure 29 the power edges are cleaner and the meteor echoes are even more tightly confined in range, spread across 3 range cells that are one eighth the size. The calibration signal at -24.4 km is now not spread into the first few positive range cells and the ground wave at 50 km has become visible. Just above the ground wave there is a drop in backscattered power until approximately 100 km where direct backscatter from meteor trails starts to occur. Very fine lines of focussing are now visible behind the leading edge, for example, at approximately 0200 UT. However, the visibility of some features benefited from the spatial integration and now these appear more speckled and harder to see.

Figure 30 shows that at higher resolution (6.1 km by 100 kHz) some features become more distinct but that other larger scale features appear more speckled and perhaps harder to delineate. By integrating over 6 frequency samples to 200 kHz resolution (Figure 31) some of the benefits of integration are regained without loss of range resolution. If overlapped processing were used integration would be over 10 frequency cells. But, as stated earlier, if the slope of the leading edge is of the order 12 km per 100 kHz, 100 kHz would seem to be an appropriate frequency resolution for range processing to 6.1 or 12.2 km.

The range-time backscatter power for another time period is given at standard resolution in Figure 32 and at higher range resolution in Figure 33 where much more detail regarding ionospheric propagation is evident. Only day-time high resolution data was available for this day, 2006/233.

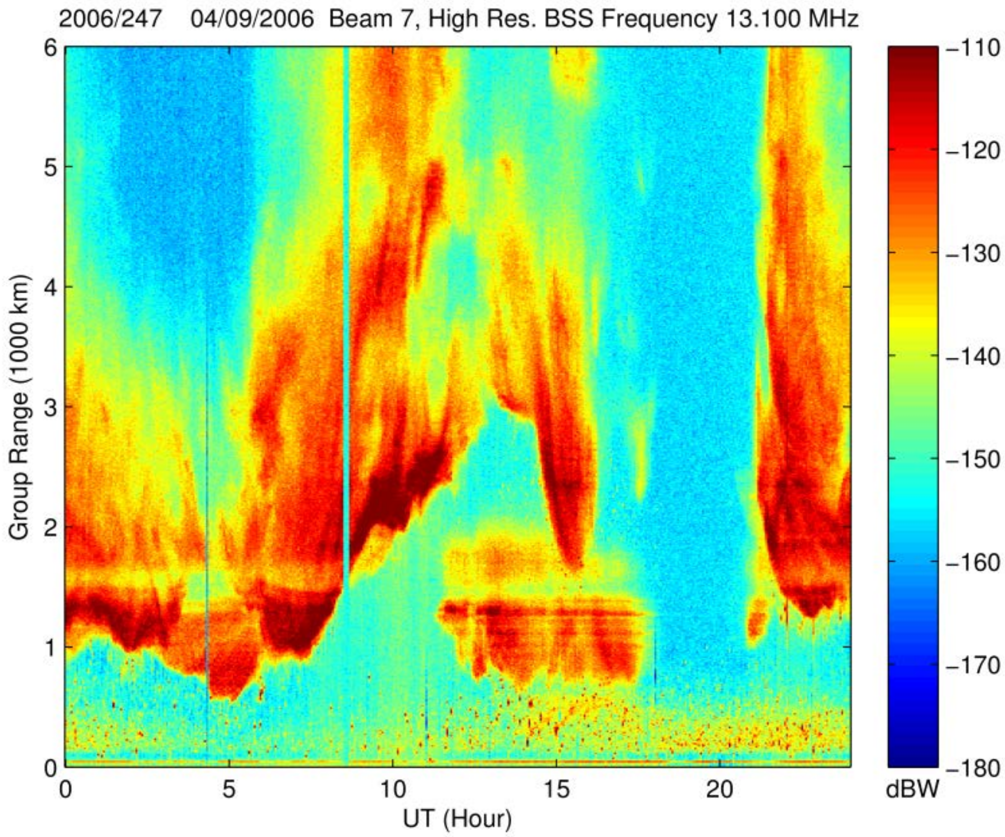

Figure 31. Incoherently averaging the power over 6 frequency samples to resolution 6.1 km by 200 kHz reduces both the noise and backscattered power variance, as expected, without an obvious loss of clarity. In fact the higher power backscatter just inside the leading edge is better defined, for example, at around 0630 UT.

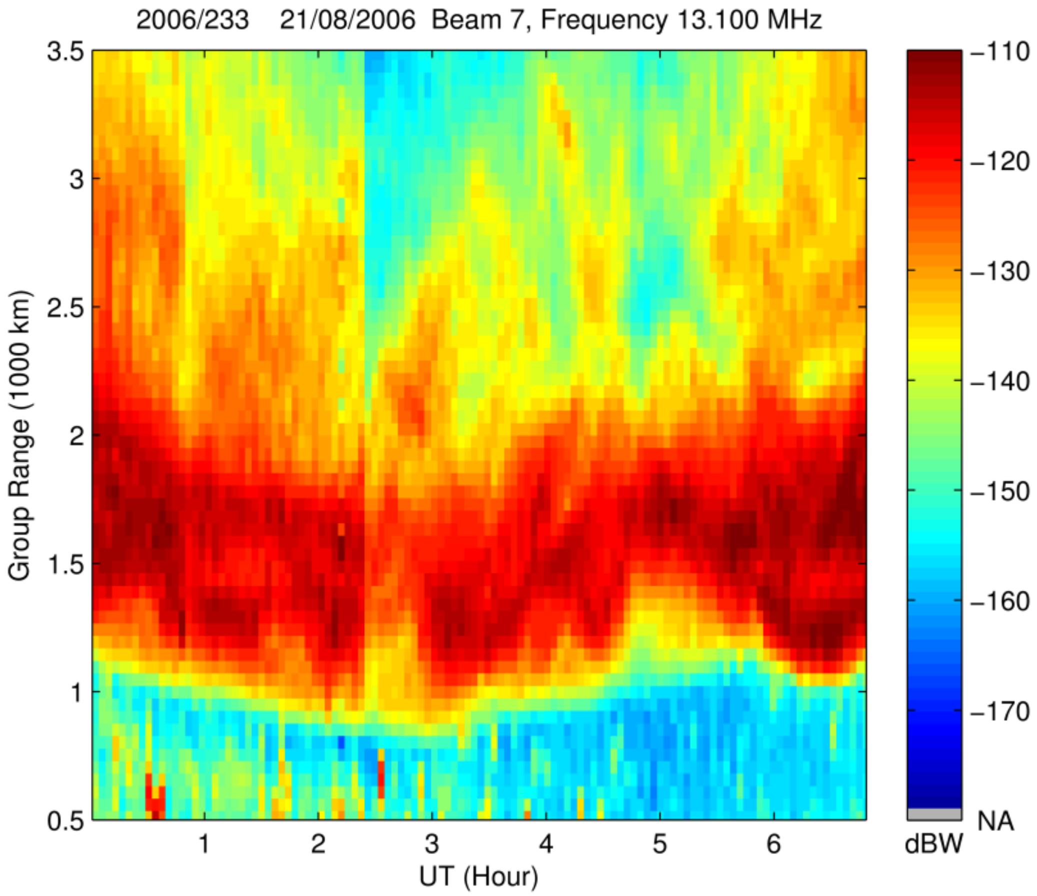

Figure 32. Backscattered power obtained from standard BSS processing at resolution 48.8 km by 200 kHz for comparison with Figure 33.

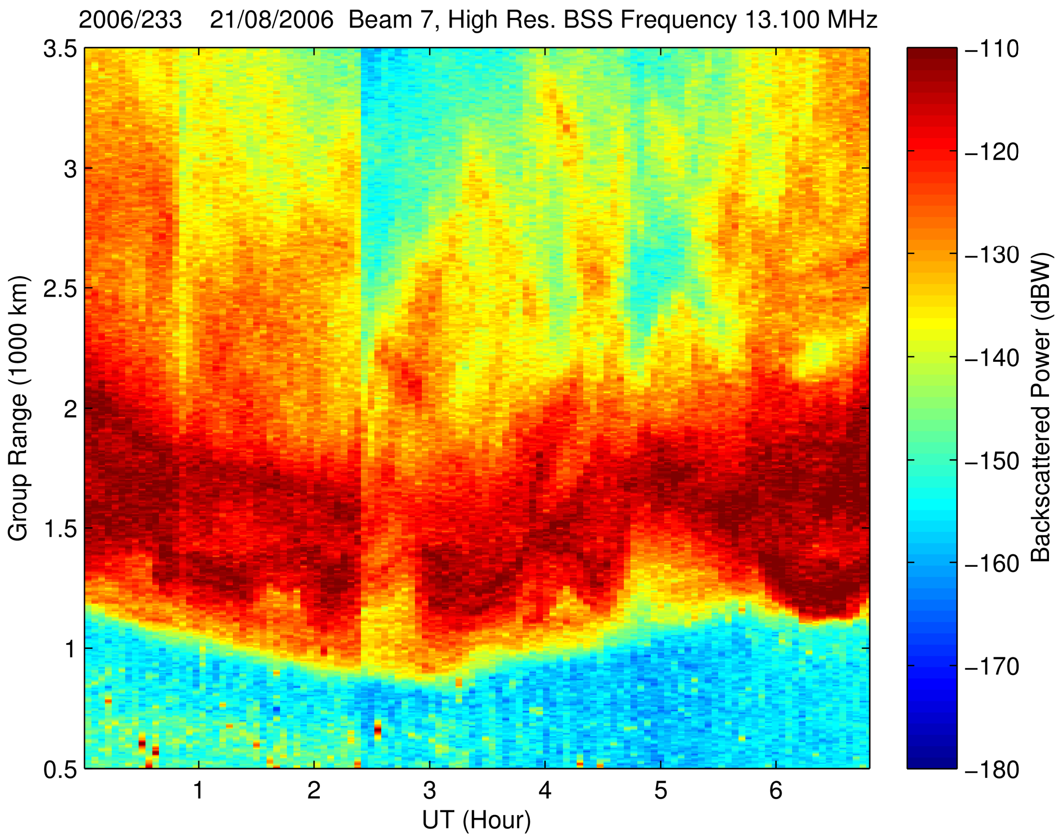

Figure 33. Backscattered power obtained from high resolution processing to resolution 6.1 km by 200 kHz showing the greater detail visible on comparison with the standard processing of Figure 32.

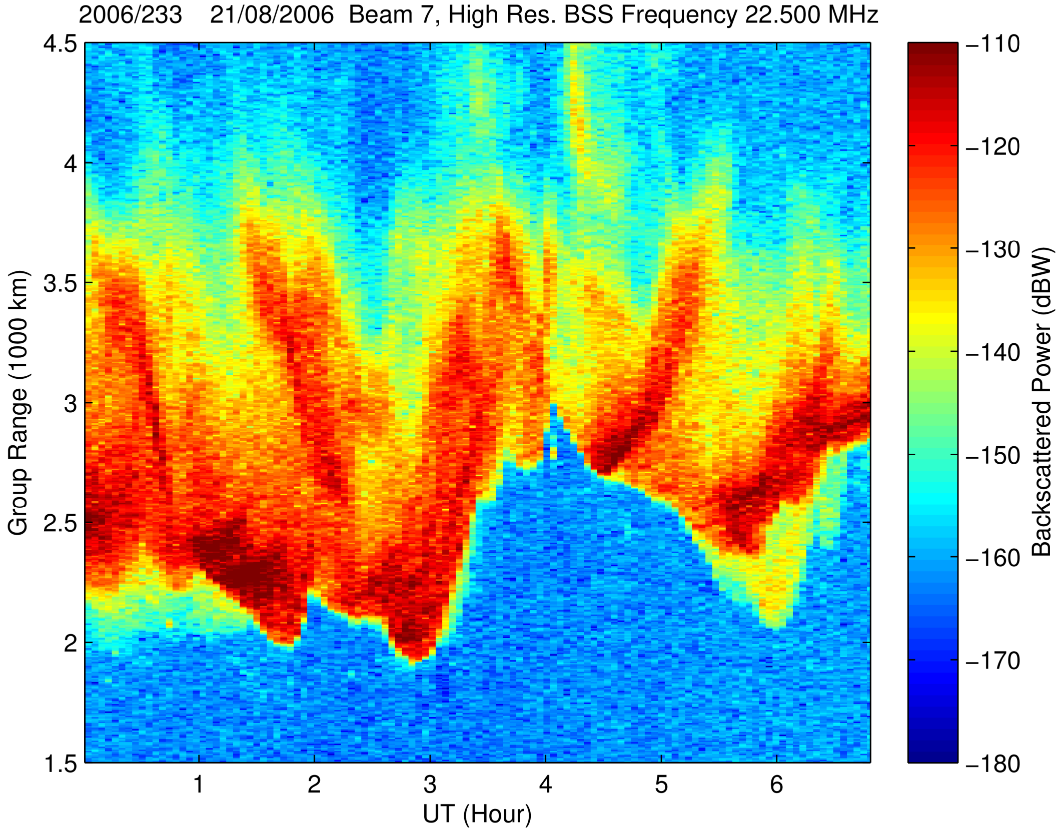

Figure 34. At 22.5 MHz most of the propagation shown here is beyond the E horizon. Visible in this image are regions of focussed power at longer ranges than the leading edge. The high resolution processing (at 6.1 km by 100 kHz) shows the detail of the progression of the regions of focus with time.

At a higher frequency, 22.5 MHz, interesting structure behind the leading edge becomes visible (Figure 34) and appear related to ionospheric disturbances where regions of focussed power move first inward, toward the leading edge and then outward, away from the leading edge. The outward propagation of focussed power is more apparent in this single frequency-time slice of the data at around 0500 UT, than in the corresponding whole BSI at this single time (Figure 35).

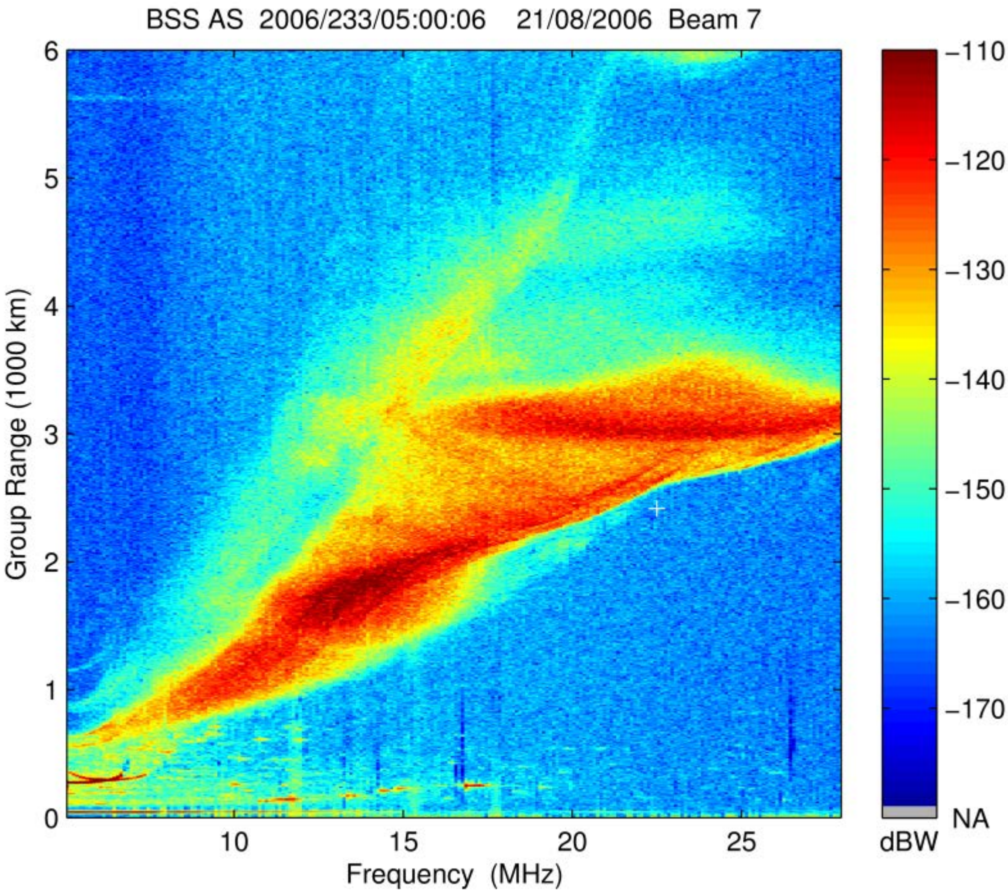

Figure 35. At 22.5 MHz there is a region of focussed power at approximately 3000 km, a few hundred km beyond the LE at approximately 2700 km. Also visible are QVI F2 O and X traces, possibly the 2 hop QVI traces, the ground wave at 50 km,, an Es LE out to about 2000 km, and O-X splitting of the F2 LE. The resolution of the image is 6.1 km by 100 kHz.

4. Conclusion

This paper has introduced a method for producing substantially higher resolution backscatter ionograms from the existing equipment at JFAS through modification of the signal processing. The method takes advantage of the fact that the data is coherent 24 times longer than used by the standard processing in order to mitigate RFI and retain the higher range and frequency resolution available. The processing load is substantially increased, requiring Fourier and inverse Fourier transforms of length 2560 instead of the standard 320, but possible in real time using current computing power.

5. References

Earl, G. F. and Ward, B. D. (1987) The frequency management system of the Jindalee over-the-horizon backscatter HF radar, *Radio Science*, **22**, 275-291.

Earl, G. F. (1991) An algorithm for the removal of radio frequency interference in ionospheric backscatter sounding, *Radio Science*, **26**, 661-670.

DISTRIBUTION LIST

High Range Resolution Backscatter Sounder Ionograms

David J Netherway, Michael J Whitington and Robert S Gardiner-Garden

DEFENCE

Task Sponsor

OC WASS SPO

S&T Program

Chief of National Security and ISR Division
Research Leader: Dr Gordon Frazer
Task Leader: Dr Sam Davey
Science Team Leader: Dr Trevor Harris
Dr Michael Turley
Dr David Holdsworth

Author(s):
Dr David Netherway
Mr Michael Whitington
Dr Robert Gardiner-Garden

<table>
<tr><td colspan="3">DEFENCE SCIENCE AND TECHNOLOGY GROUP
DOCUMENT CONTROL DATA</td><td colspan="3">1. DLM/CAVEAT (OF DOCUMENT)</td></tr>
<tr><td colspan="3">2. TITLE

High Range Resolution Backscatter Sounder Ionograms</td><td colspan="3">3. SECURITY CLASSIFICATION (FOR UNCLASSIFIED LIMITED RELEASE USE (U/L) NEXT TO DOCUMENT CLASSIFICATION)

Document (U)
Title (U)
Abstract (U)</td></tr>
<tr><td colspan="3">4. AUTHOR(S)

David J Netherway, Michael J Whitington, Robert S Gardiner-Garden</td><td colspan="3">5. CORPORATE AUTHOR

Defence Science and Technology Group
PO Box 1500, Edinburgh SA 5111</td></tr>
<tr><td>6a. DST GROUP NUMBER

DST-Group-TR-3477</td><td colspan="2">6b. AR NUMBER

AR-017-160</td><td colspan="2">6c. TYPE OF REPORT

Technical report</td><td>7. DOCUMENT DATE

April 2018</td></tr>
<tr><td colspan="2">8. OBJECTIVE ID</td><td colspan="2">9.TASK NUMBER

AIR 17/550</td><td colspan="2">10.TASK SPONSOR

OC WASS SPO</td></tr>
<tr><td colspan="3">11. MSTC

High Frequency Radar</td><td colspan="3">12. STC

Geophysical Phenomena and Performance Assessment</td></tr>
<tr><td colspan="3">13. DOWNGRADING/DELIMITING INSTRUCTIONS</td><td colspan="3">14. RELEASE AUTHORITY

Chief, National Security and ISR Division</td></tr>
<tr><td colspan="6">15. SECONDARY RELEASE STATEMENT OF THIS DOCUMENT

Approved for public release

OVERSEAS ENQUIRIES OUTSIDE STATED LIMITATIONS SHOULD BE REFERRED THROUGH DOCUMENT EXCHANGE, PO BOX 1500, EDINBURGH, SA 5111</td></tr>
<tr><td colspan="6">16. DELIBERATE ANNOUNCEMENT

No limitations</td></tr>
<tr><td colspan="6">17. CITATION IN OTHER DOCUMENTS

Yes</td></tr>
<tr><td colspan="6">18. RESEARCH LIBRARY THESAURUS

Ionosphere, Radar Measurement, Digital signal processing, High frequency radio propagation, High frequency radar</td></tr>
<tr><td colspan="6">19. ABSTRACT

Backscatter ionograms have been routinely collected for thirty years in support of the Jindalee Over-The-Horizon-Radar and Jindalee Operational Radar Network. Backscatter sounder ionograms display the power received as a function of time delay (usually expressed as group range) and transmitted frequency after radio-wave signal transmission from an antenna, propagation via the ionosphere, backscattered reflection from the Earth's surface and further propagation via the ionosphere to the receive antenna. Routine practice has been to process and retain data at a range resolution of 48.8 km and frequency resolution of 200 kHz. This resolution was set to accommodate equipment, signal processing, communications and data storage capability at the time (the 1980s). This paper describes methods used for high range resolution processing (6.1 km for 3 frequencies per 100 kHz) of the same raw data including superior radio frequency interference rejection. These superior ionograms make many additional propagation features more clearly visible.</td></tr>
</table>