Very low latitude whistler-mode signals: Observations at three widely spaced latitudes

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Key Points:

- Man-made whistler-mode signals with delays ~50-100 ms are confirmed to have propagated on very low latitude paths
- Such signals are observed continuously for up to 11 hours a night, exhibiting stable transequatorial guiding
- These signals are readily observable if either transmitter or receiver is at a low latitude (~20°) but both need not be at low latitudes

Abstract

VLF radio signals with travel times ~100 ms were observed continuously for up to ~11 hours at night on Rarotonga (Cook Islands, ~21°S) at 21.4 kHz from US Navy transmitter NPM, Hawaii (~21°N). These signals travelled in the whistler-mode on well-defined paths, though not field-aligned ducts, through the ionospheric *F* region, and across the equator reaching altitudes ~700-1400 km depending on time of night. These same signals were also observed simultaneously in Dunedin (46°S), New Zealand, with very nearly the same travel times but with somewhat lower amplitudes and occurrence rates, consistent with the whistler-mode part of the propagation being at very low latitudes. Both sets of signals had similar Doppler shifts, typically tens of mHz, but sometimes up to a few hundred mHz, being positive during most of the night, while the whistler-mode group delays decreased due to both the shortening of the path and the decay of the near equatorial ionosphere, but negative near dawn when the Sun's rays start ionizing the *F* region. The signals are not observable during the day, fading out during dawn, due to increasing attenuation from the increasing electron density, and hence increasing collisions, in both the *D* and *F* regions. Similar weaker NPM signals were also seen at Rothera (68°S). In addition, similar 24.8 kHz signals were seen from the more distant NLK (Seattle, ~48°N) at Rarotonga, though clearly weaker than from NPM, but not at Dunedin.

1. Introduction

Traditional whistlers originate from wideband 2-30 kHz radio waves radiated from the brief (<< 1ms) electrical currents in lightning strokes in the Earth's atmosphere. These radio waves then propagate upwards from near the ground into the Earth's ionosphere and magnetosphere. They are typically propagated along magnetic field aligned ducts of enhanced (~10%) plasma (and hence electron) density crossing the equatorial plane, descending again and exiting the ionosphere into the opposite hemisphere from which they entered. Because the signals are travelling through a magnetoionic plasma their velocities are markedly less than the speed of light in vacuo and their group delays are frequency dependent. When the resulting signals are received by a simple antenna and audio amplifier, they are heard as a descending audio whistling tone lasting ~0.5 s or more and so have been long known as 'whistlers' (e.g., Helliwell, 1965; Storey, 1953). For example, for a typical entry, and hence exit, geomagnetic latitude of 55°, the top of the path is at L = 3 - i.e., 3 Earth radii from the Earth's center, or 2 Earth radii, ~12800 km, above the Earth's surface. Such normal ducted whistlers are common at least in the range L = 2-4 or more. If, instead, the source of the ~2-30 kHz radio waves travelling along such a path is a single frequency from say a ground based man-made transmitter, rather than a lightning flash, then the resulting narrowband signals are known as whistler-mode signals (e.g., Helliwell, 1965; Thomson, 1975, 1981; Clilverd et al., 1993).

While the substantial majority of whistlers and whistler-mode signals at mid- and high latitudes almost certainly require guiding in geomagnetic field-aligned ducts to reach the ground in the opposite hemisphere, at L-values less than ~2 (geomagnetic latitude ~45°) the enhancements needed for such ducting become increasingly very much stronger than the ~10% needed at mid-latitudes as the *L*-value decreases. At very low latitudes, ~10°-20° geomagnetic, the enhancements required for inter-hemispheric ducted propagation are so high, that is >>100% (Singh and Tantry, 1973; see also Hasegawa et al., 1978), that true geomagnetic field-aligned ducting, in a tube of such enhanced ionization, becomes very unlikely. However, Andrews (1978), building on an earlier satellite study by Scarabucci (1970), used ray-tracing at night at latitudes ~11°-12°, in the absence of both field-aligned ducts and significant horizontal electron density gradients. He showed that the ambient horizontal refractive index gradients in the Earth's ionosphere, mainly those in the *F* region due to the low latitude geomagnetic field geometry, are typically of the right size to bend the VLF wave normals (though not field-aligned) towards the equator so that, with the help of the ambient vertical electron density gradients at higher altitudes, they become approximately horizontal when crossing the equatorial plane (at heights ~700 km). These gradients then bend the wave symmetrically down again so that the signals exit into the Earth-ionosphere waveguide, and hence to the ground, in the opposite hemisphere. These natural guiding refractive index gradients are thus partly due to vertical electron density gradients, particularly at the top of the path, but are also strongly contributed to by the changing geomagnetic field gradients in the ionosphere at the very low latitudes on either side of the equator (Thomson, 1987b).

Thomson (1987a) reported that whistler-mode signals from US Navy transmitter NPM (21.4°N, 158°W, Hawaii) were commonly observed at Dunedin, New Zealand (46°S, 170.5°E) in 1983/84 on 23.4 kHz with group delays of ~75-160 ms and typical Doppler frequency shifts of tens of mHz up to ~ ± 240 mHz. Thomson (1987b), also using ray tracing, suggested that late in the night, when there would normally be little or no natural horizontal electron density gradients, these NPM-Dunedin signals travelled on a ~10°N-10°S path very similar to the path postulated by Andrews (1978). Thomson then showed that the measured whistler-mode group delays agreed with those calculated from the ray tracing using appropriate typical values of *foF*2 (~5.5 MHz) at 10° latitude together with an appropriate electron density height profile, but found that, early in the night, the typical much higher *foF*2 (~9.3 MHz) would give calculated delays significantly higher than the measured delays. However, also early in the night, there are natural horizontal electron density gradients in the *F2* region, directed towards the equator, effectively left over from the daytime equatorial anomaly or fountain effect, which allow a non-ducted whistler-mode path from ~20°N to 20°S (Singh, 1976, and references therein). Following Singh (1976), Thomson (1987b), using further ray tracing with these horizontal electron density gradients typical of early in the night, also found that slightly higher latitude unducted paths, up to ~ 20°, were enabled and that these, when used with the lower *foF*2 to be expected there, e.g., ~7.2 MHz at ~ 20°, gave calculated delays which agreed very much better with those measured for the NPM-Dunedin path.

Although Thomson (1987b) concluded that these signals were very low latitude whistler-mode signals of the type ray-traced by Singh (1976), Andrews (1978) and Thomson (1987b), there were no corresponding observations from any site other than Dunedin to confirm this. Here we present simultaneous observations, and their implications, of such VLF signals from transmitters NPM, Hawaii, and NLK, Seattle (48°N, 122°W), received at Rarotonga (21°S, 160°W) and Dunedin (46°S) in 1996, plus some similar non-simultaneous observations from Rothera, Antarctica (67.6°S, 68.1°W) in 2009. Having fixed, powerful, nearly continuously operating transmitters as the source, as opposed to intermittent lightning, enables certainty and simplicity in source location and in whether the presence or absence of received signals is due to the source or to the path conditions. Because ducted propagation at very low latitudes still has some support (e.g., Chen et al, 2017; Gokani et al., 2015; Singh et al., 2014), we use our results, including the longevity of our signals, to re-examine the evidence for non-ducted propagation. By measuring the Doppler shifts of the received signals from fixed frequency transmitters we are able not only to see path changes more dynamically but also, for the first time, to distinguish longitudinally separated paths by their different frequency shifts.

2. Receiving Technique

The signals from the VLF transmitters were received on crossed vertical loops, oriented approximately north/south and east/west, at each of the three sites reported on here, Dunedin (New Zealand), Rarotonga (Cook Islands), and Rothera (Antarctica). The raw data are available in Thomson et al. (2019). The two transmitters used were the US Navy's NLK in Seattle radiating on 24.8 kHz and NPM in Hawaii on 21.4 kHz. NPM was previously on 23.4 kHz including for the 1983/84 data discussed above; from April 1996, and so for all the NPM observations presented here, NPM was on 21.4 kHz. For both transmitters, for all of the observations discussed here, their radiation was modulated with 200 baud MSK (Minimum Shift Keying). The bit period, and so the smallest group delay resolution block, is thus 1/200 s = 5 ms, though the group time accuracy can often be interpolated to < 5 ms.

At all the receiving sites the direct subionospheric signal is much stronger than both the atmospheric noise and any indirect signals, such as the whistler-mode signals discussed here. Each receiver, one for each transmitter, locks onto both the carrier, e.g., 21.4 kHz or 24.8 kHz, and the modulation frequency, 200 Hz, of the (dominant) subionospheric signal. During each 5-ms modulation period, the transmitter is effectively transmitting only one of four possibilities; the computer part of the receiver is programmed to take one ADC sample in each 5-ms period and recognize which one of the four possibilities was being used in that 5-ms modulation period and to keep a running mean of the amplitude for each of these four over the last several modulation periods. After each 5-ms analog sample is taken, it is stored in the direct series (so 200 s^{-1}) and then the appropriate running mean (i.e., the subionospheric signal) is subtracted from it leaving a small residue signal containing noise and any indirect (e.g., whistler-mode) signal which is stored in the indirect series (so also 200 s^{-1}). A cross-correlation is then performed between this indirect (whistler-mode plus noise) signal series and the (delayed) direct series to determine how much indirect signal is present at each group delay. Further details can be found in Thomson (1981, 1985); note however, in Thomson (1981), as NLK was then using 100-baud MSK (on 18.6 kHz), the references to 10-ms bit periods there correspond to the 5-ms bit periods here. As was also shown in Thomson (1981), the technique also enables the determination of the Doppler frequency shifts, typically from tens of mHz up to ~500 mHz with respect to the direct subionospheric signal, of the whistler-mode signals received at each group delay. The description of the technique for determining these frequency shifts is independent of whether the MSK modulation is 100 or 200 baud.

A sketch map showing the locations of the transmitters and receivers used for the observations reported here is shown in Figure 1. This figure also includes an approximate projection on the Earth's surface of the very low latitude whistler-mode paths discussed here. Figure 2 shows these same paths (based on Thomson, 1987b) but as functions of distance in Earth radii, from the center of the Earth, compared with the field-aligned path of a regular, ducted, mid-latitude whistler or whistler-mode path from Seattle to Dunedin, NZ.

3. Observations

3.1 Observations of NPM (Hawaii, 21°N) at Rarotonga and Dunedin

Figures 3 and 4 show observations of whistler-mode and other indirect signals received at Rarotonga (left side panels) and Dunedin (right side panels) from transmitter NPM in Hawaii on 21.4 kHz on 4 of the 10 nights of observation in the period 28 Aug – 6 Sep 1996 UT. Similar plots for the other 6 nights can be found in the Supporting Information. In each panel, the position on the vertical axis shows the arrival delay, 0.0-0.9 s = 0-900 ms, of the indirect signal relative to the arrival time of the (subionospheric) direct signal at the receiver. The color of each small block indicates the amplitude of the indirect signal during its 15-minute integration period, used for all the observations here; the color scale is shown at the top left of Figure 3, with green representing the smallest most marginally significant signals, often just noise, through to blue representing the strongest highly significant signals. Because, as discussed above, the transmitter modulation is 200 baud with a bit period of 5 ms, each resolution block is 5 ms (vertically). The group delay resolution of each signal is thus limited by this 5 ms increment; however, quite often, if needed, the group delay can be interpolated down to 1-2 ms. The time of day, in hours UT, is shown on the horizontal axis at the bottom of each panel. Approximately, 12 UT is midnight for the paths used here, in the central Pacific Ocean; midnight at both Rarotonga and NPM is ~1 h before 12 UT while midnight at Dunedin is ~1 h after 12 UT.

The very low latitude whistler-mode signals, which are the prime focus of this report, can be clearly seen between ~6 UT and ~17 UT, i.e, mainly during the night, particularly at Rarotonga, with group delays of ~100 ms, tending to decrease by a few tens of ms during the night as the path (entry/height) slowly changes and the very low latitude ionosphere slowly decays (Thomson, 1987b). The indirect signals with constant delays ~10-45 ms are from mountain range reflections, particularly here, at ~30 ms, from the Rocky Mountains in the western USA/Canada (Thomson, 1985, 1989). The indirect signals showing at delays ~0.3-0.6 s at Dunedin, but not at Rarotonga, between ~12-16 UT on 6 September, in Figure 4, (and on 30, 31 August, and 2 September in Figures S1 and S2 in the Supporting Information) are regular mid-latitude whistler-mode signals. The 'signals' near the top of each panel at delays of 0.925, 0.945 and 0.965 s are from calibration signals intentionally injected during recording at these delays. For NPM at Dunedin, these were 2, 3 and 5 ADC (analog-to-digital converter) units corresponding to approximately 1.2, 1.8 and 3.0 μV/m respectively. For comparison, the daytime direct subionospheric amplitude of NPM at Dunedin was ~300-400 μV/m, depending on time of day etc. The corresponding direct nighttime amplitude is somewhat lower and rather unpredictably variable ~100-200 μV/m. For NPM at Rarotonga the calibrations were 1, 2 and 4 ADC units corresponding to about 1.8, 3.7 and 7.5 μV/m respectively, while the direct signal was ~1000 μV/m. The amplitudes of the direct signals at Dunedin and Rarotonga were measured on site with a calibrated portable loop system (Thomson, 1993; Thomson et al., 2018, and references therein).

The apparent variability of the amplitudes of the calibration signals seen occasionally in many panels is due to changes in the background noise level, due to either atmospheric or man-made sources; these same changes can often also be seen in the apparent amplitudes of the other indirect signals because the apparent amplitudes of all the indirect signals depend on the background noise level. This is due to the residual signal being reduced to one bit for computational efficiency (Thomson, 1985). Hence any changes in the apparent amplitudes of the indirect signals in the plots must be compared with the calibration amplitudes at the top of the plots at the same time to determine if the apparent indirect signal amplitude changes are real or due to changing noise levels. For example, the apparent sudden whistler-mode amplitude drop at Rarotonga on 6 September just after ~15 UT, in Figure 4, is almost certainly due to an increase in noise because the calibrations, and the mountain reflections, show a similar apparent amplitude decrease. In contrast, at Dunedin on 6 September the sudden drop in whistler-mode amplitude near 09 UT is almost certainly real since the calibrations and the mountain reflections show no such change.

A qualitative to semi-quantitative estimate of the relative amplitudes of the low-delayed (~100 ms) whistler-mode signals received at Rarotonga and Dunedin can now be made. Firstly, even without taking the calibrations into account, the ‘stronger’ colors of the Rarotonga signals, plus their greater occurrence rate (number of hours of observation each day), and their being clearly detected on all 10 nights at Rarotonga but not, or only barely, detected on 3 of the 10 nights at Dunedin is suggestive that the signals at Rarotonga were on average a factor ~2 stronger than at Dunedin. Secondly, after taking into account the calibrations given above in this section (in µV/m for 2 adc units), the gain at Rarotonga was a factor of $3.7/1.2 \approx 3$ lower than at Dunedin.

Hence, the (~100-ms delayed) whistler-mode signals when received at Rarotonga appear to have average amplitudes greater than those of the simultaneous signals received at Dunedin by a factor ~6. Hence the observed average low-delayed whistler-mode signal amplitudes at Rarotonga (21°S) can thus be estimated to be greater than those simultaneously observed at Dunedin (46°S) by ~15 ± 6 dB. Clearly this implies that the exit points of the signals from the ionosphere are much nearer Rarotonga than Dunedin, consistent with the ray-tracing exit latitude calculations of 10°-20°S of Thomson (1987b).

As can be seen in Figures 3 and 4, and in Figures S1-S3 in the Supporting Information, the very low latitude whistler-mode signals, and hence their propagation paths, are often continuous for many hours, particularly at Rarotonga where, on 3 and 4 September, in Figures 3 and S3, they last continuously for >~11 hours and ~10 hours respectively. This is in contrast to some studies made using lightning generated natural whistlers at low latitudes, where lifetimes ~1 hour, for the presumed field-aligned ducts, have been estimated (e.g., Hayakawa et al., 1983; Hayakawa and Ohta, 1992; Singh, 1993). At mid-latitudes, whistler duct lifetimes have been estimated theoretically, and found experimentally, to be many hours, up to ~1 day (e.g., Thomson (1978) and references therein). However, any ducts at low latitudes would need much greater enhancements, >~100%, compared with ~10% at mid-latitudes for trapping and this, together with their being much shorter, would result in their enhancements decaying away into the lower *F* region very much faster.

As noted earlier in this section, the signal delays in the plots, such as in Figure 3, are relative to the arrival time of the direct, subionospheric signal at the receiver. This explains, with the aid of Figure 1, why the Rarotonga whistler-mode delays are very similar to those at Dunedin. Firstly, most of the ~100 ms of each delay is in the whistler-mode section of the path and, although, as shown in Figure 1, the two whistler-mode paths may be slightly separated in longitude, they and their travel times are likely to be very similar with such a small separation. Secondly, subionospheric travel is at ~3 x 10^8 m/s; so, for example, the ~4.7 Mm between NPM and Rarotonga takes only ~16 ms, Finally, as illustrated in Figure 1, most of the subionopheric delays are at least approximately common to both the direct and indirect (whistler-mode) paths. If, for example, the Rarotonga receiver were moved 3 Mm to the south, the travel times of both direct and indirect paths would increase by ~10 ms but the (relative) delays of the whistler-mode signals in the plots would not change at all.

3.2 Observations of NLK (Seattle, 48°N) at Rarotonga and Dunedin

Figure 5 shows observations of whistler-mode (and other indirect signals) from transmitter NLK in Seattle on 24.8 kHz received at Rarotonga (left side panels) and Dunedin (right side panels) for two of the 10 nights, 2 and 3 Sep 1996 UT. Plots for NLK at Rarotonga and Dunedin for the rest of the 10-night study period, 28 Aug – 6 Sep 1996, can be found in the Supporting Information.

For NLK at Rarotonga, very low latitude whistler-mode signals can again be seen with delays of ~100 ms but are clearly weaker in amplitude than those from NPM at Rarotonga at the same times, in Figures 3 and S2. The direct subionospheric amplitude for NLK at Rarotonga was ~200 µV/m and the calibrations were 2, 4 and 6 ADC units corresponding to approximately 1.2, 2.4 and 3.6 µV/m respectively. Not only do the plot and calibration intensities indicate that the NLK very low latitude whistler-mode signals are markedly weaker at Rarotonga than those from NPM, but also no such signals from NLK could be detected at all on 2 of the 10 nights (30 August and 6 September) whereas such NPM signals were strong on all 10 nights. This is consistent with NPM (21°N) being much closer to path entry (~10-20°N from the ray-tracing) than NLK (48°N); i.e., this is consistent with the low-delayed (~100-ms) signals propagating in the whistler-mode on a very low latitude path (from 10-20°N).

No low-delayed (~100-ms) signals were detectable from NLK (48°N) at Dunedin (46°S) in the 10 days considered here nor on any other occasion over a much longer period of several years; this too is consistent with these signals entering the ionosphere at very low latitudes (~10-20°N to ~10-20°S) because the transmitter to duct-entry distance is much greater for NLK (48°N) than for NPM (21°N). It is worth noting that on all of the 10 nights here there were clear, regular mid-latitude, whistler-mode signals from NLK received at Dunedin while at Rarotonga these signals were clearly seen on only 3 out of the 10 nights, i.e., 2, 5 and 6 September, and even then over shorter times. This is likely due to these regular whistler-mode signals re-entering the Earth-ionosphere waveguide far south of Rarotonga with predominantly poleward directed launch angles.

3.3 Observations of NPM (21°N) at Rothera (Antarctica, 68°S) and Dunedin

VLF recordings are also made at the British Antarctic Survey base, Rothera, on Adelaide Island just off the west coast of the Antarctic Peninsula, shown in Figure 1. The receiving technique used there is very similar to that used at Dunedin and Rarotonga but such recordings of NPM did not begin until 2009, after which some very low latitude whistler-mode signals were observed despite the high latitude of the receiver (~68°S). An example is shown in Figure 6 where the simultaneous recordings of NPM at Dunedin on 21 Sep 2009 UT are also shown for comparison. As can be seen in the two left panels, the very low latitude signals have rather similar delays at both locations, e.g., ~120 ms at ~10 UT; however, these signals appear stronger, at least on this day, and are observable for much longer at Dunedin (~4 Mm from a likely NPM signal exit point near 10°-20° S) than at Rothera (~8.5 Mm from a broadly similar exit point). The signals fading much earlier at Rothera, from ~11 UT, is likely largely due to the (gradually) increasing subionospheric attenuation at the Rothera end of the path starting from sunrise at Rothera ~1030 UT. The two right-hand panels of Figure 6 show the Doppler shifts of the signals at the two receivers at ~10 UT (21 Sep 2009); they are broadly similar at an average of ~ -20 mHz, consistent with the group delays slowly increasing, as can be seen for both locations in the left two panels near 10 UT.

3.4 Doppler-shift Observations and Paths for Rarotonga and Dunedin

The electron number density in the *F* region of the ionosphere typically slowly decays during the night because of lack of ionizing radiation; recombination of the electrons with ions typically exceeds any replenishment from the plasmasphere, particularly in low latitude regions. This can be seen rather clearly in Figure 3 for 29 Aug 1996 UT where the very low latitude whistler-mode group delay at Rarotonga decreases steadily from ~10 UT until ~16 UT, just before dawn. This group delay then starts to increase again as direct EUV radiation from the rising Sun becomes able to produce new free electrons, particularly by ionizing neutral atomic oxygen in the ionosphere's *F* region, through which the NPM signals pass. This, in turn, produces not only more group delay but also more phase delay (more wavelengths in the ionosphere) resulting in negative Doppler shifts in the received signals. These Doppler shifts come almost entirely (>>99%) from the whistler-mode parts of the paths because the subionospheric parts are very phase-stable (e.g., Thomson et al., 2014). Examples of these for two 15-minute intervals, centered on 1630 UT and 1645 UT on 29 Aug 2009 can be seen in Figure 7 both for Rarotonga (left panels) and Dunedin (right panels) where the Doppler shifts are all negative. An interesting feature here is that the Doppler shifts at these two times at Rarotonga, ~ -215 mHz and ~ -215 mHz, are clearly different from (more negative than) those of the simultaneous signals at Dunedin, ~ -150 mHz and ~ -110 mHz. This clearly implies that the whistler-mode path of the NPM-Rarotonga signals must have been at least slightly different from the whistler-mode path of the NPM-Dunedin signals. Specifically, this means that if the signals were (longitudinally) ducted, they could not have been in the same duct; they would have had to have been in (longitudinally) separated ducts. If, as seems more likely, the signals were not longitudinally ducted, but were guided only in latitude (*L*-value) as ray-traced by Andrews (1978) and by Thomson (1987b), then these Doppler difference observations can be readily accounted for by the Dunedin whistler-mode path being predominantly a little west, perhaps by only 5-10° in longitude, of the Rarotonga whistler-mode path, thus making the Rarotonga path later after sunrise, tending to give rise to the greater Doppler shift.

On 3 September 1996 at 1530 UT and 1545 UT a somewhat similar situation occurred except that the whistler-mode signal amplitude falls below detection earlier (~1615 UT) and just before any increasing group delay would be evident. At these two earlier times, and so earlier in the sunrise period, the Doppler shifts on the more western

Dunedin path were observed to be positive due to the sunrise production having not yet begun; in contrast, on the Rarotonga path (further east) the Doppler shifts were near zero at 1530 UT and negative at 1545 UT as the sunrise began to produce new electrons. A plot similar to Figure 7 but for 3 September can be seen in Figure S4 in the Supporting Information. Similarly, on 4 September 1996, the Doppler frequency shifts on the Dunedin path changed from positive (~ +40 mHz) at 1530 UT to negative (~ -60 mHz) at 1600 UT, while for the Rarotonga path the trend was in the same direction, as the sunrise advanced, but the shifts were more negative, changing from near zero at 1530 UT to ~ -160 mHz at 1600 UT (Figure S5). Again the different, more negative, frequency shifts observed on the Rarotonga paths relative to those on the Dunedin paths strongly indicate that, if ducted, the signals could not both have propagated in the same duct but their very similar group delays imply they have very similar path latitudes (*L*-values), again consistent with guiding only in latitude (*L*-value). Earlier in the night, as illustrated in the example plot for 3 September in Figure 8, the Doppler shifts on the two paths are typically fairly similar. This is probably because only near sunrise are the Doppler shifts changing with longitude sufficiently rapidly that differences in longitude of 4-8° (15-30 minutes separation in local time, as here) are likely to result in observable differences in Doppler shifts on the two paths. We note that, in Figure 8, the Doppler shift values for Rarotonga in the periods ~0830-1100 UT and 1230-1530 UT may have reduced accuracy because, although the signal to noise ratio was good, the signal appeared simultaneously in many Doppler channels making it difficult to reliably interpolate a mean value.

4. Discussion

4.1 Comparison with Natural Lightning-Generated Whistlers

The group travel time, *t*, of (natural, lightning-sourced) whistlers, as a function of frequency, *f*, particularly at low latitudes, follows the Eckersley dispersion law, $t\sqrt{f} = D$, where *D* is a constant (in $s^{1/2}$) referred to as the dispersion of the whistler (e.g. Helliwell, 1965). The dispersion of each individual whistler is thus a convenient measure of its travel times, being effectively averaged over its range of times and frequencies. Thus it is convenient to convert the (NPM-Rarotonga) whistler-mode group travel times here into dispersions for comparing with very low latitude natural whistlers. Over the 10 days of observations, 28 August to 6 September 1996, the average whistler-mode group delay for NPM-Rarotonga was found to be ~74 ms at 1600 UT (using the 9 out of 10 days when the signal was visible at/near 1600 UT) and ~102 ms at 0900 UT (7 out of 10 days). These group delays are relative to the received subionospheric signal and so must be increased by the subionospheric travel times between the entry and exit points of the (ionospheric/plasmaspheric) whistler-mode path to get the whistler-mode group travel times. From Thomson (1987b), this entry-exit subionosperic path at 16 UT is likely to be between ~±10° latitude which corresponds to ~8 ms delay, while at 09 UT, ±20° and 15 ms respectively are likely more appropriate. Hence the NPM-Rarotonga group travel times and dispersions in the whistler-mode become 74+8 = 82 ms at 16 UT, and 102+15 = 117 ms at 09 UT. Thus the NPM-Rarotonga dispersions during the period from 09 to 16 UT (= ~2230-0530 LT) decreased from 17.1 $s^{1/2}$ to 12.0 $s^{1/2}$, where f = 21400 Hz, the frequency of NPM.

As discussed below, very low latitude (< 20° geomagnetic) natural whistlers have been observed and closely studied in India, China and southern Japan, where the geomagnetic equator is ~10° north of the geographic equator. Geomagnetic latitudes are used here in the following for convenience. These studies conclude (1) the very low latitude whistler occurrence rates peak after midnight, towards dawn, and (2) their night-time dispersions generally decrease during the night.

In China, during the winters of 1979/80 - 1982/83 (Bao et al., 1983; Liang et al., 1985), whistlers were observed at 3-5 sites between 6°-19°N, mainly ~01-07 LT with highest occurrence rate at 03-06 LT at Zhanjiang, 10°N, where the dispersion reduced with time to a mean minimum of ~12.5 $s^{1/2}$ at ~05 LT. Whistlers with the same dispersion were simultaneously observed at two or more of these 5 sites; spectrograms of an example seen simultaneously with a dispersion of 12.3 $s^{1/2}$ at 4 sites over the range 6°-19°N are shown. Similarly, in January 1988, Xu et al. (1989) and Hayakawa et al. (1990), also in China, 0-4 LT, using nearly the same stations, found dispersions of 10-15 $s^{1/2}$ which were again often single-valued at all 3 of their stations. The exit regions were found, by direction finding, to be confined to 10°-14°N. The occurrence peaked at Zhanjiang, 10°N, and the direction finding showed the whistlers arriving in the zenith only at Zhanjiang. The highest occurrence rate was on 5 Jan 1988, at ~0200-0330 LT, when the dispersion was single-valued at 10.5 $s^{1/2}$ at all 3 stations; a higher dispersion of 12 $s^{1/2}$ was also seen only at Wuchang, 19°N, during this period.

In India, in 2010-2011, mainly December-April, Gokani et al. (2015) and Singh et al. 2012) found the average of the 1863 post midnight (0030-0530 LT) whistler dispersions was 12.1 $s^{1/2}$ at Allahabad (~16°N). For premidnight (1930-0030 LT) and evening (1430-1930 UT) there were 12 whistlers averaging 15.7 $s^{1/2}$ and 92 whistlers averaging 18.2 $s^{1/2}$ respectively.

In southern Japan, for October 1974 to January 1976, at Okinawa (15°N), Ondoh et al. (1979) reported a markedly higher whistler occurrence rate post-midnight (up until about dawn) than pre-midnight. During the period 23-06 JST (~2230-0530 LT), the average observed dispersion decreased from 16 $s^{1/2}$ to 11 $s^{1/2}$. As noted above the NPM-Rarotonga dispersions reported here over the same LT range decreased from ~17 $s^{1/2}$ to ~12 $s^{1/2}$. The international 13-month smoothed sunspot number was ~11 at the time of the 1996 NPM-Rarotonga measurements and ~25 for the Okinawa whistlers (1974-76). Kotaki et al. (1977) observed whistlers, during the 8-day period 29 Jan - 6 Feb 1976, at both Okinawa and further south at Ishigaki Island (13°N) finding similar dispersions, ~14 $s^{1/2}$, including at least one simultaneous whistler, with dispersion 13 $s^{1/2}$, and a slightly higher occurrence rate at Ishigaki Island.

4.2 Whistler-mode Observations with Perpendicular Loops

Both Araki et al. (1972) and Andrews (1974, 1978) noticed slightly Doppler-shifted weak signals on loop antennas which had been successfully oriented to null out, and so be perpendicular to the paths of, the direct subionospheric signals from their VLF transmitters, NWC, northwest Australia, received at Uji in Japan for Araki et al., and NLK, Seattle, received in both Rarotonga and New Zealand for Andrews. These signals appeared definitely Doppler shifted but by only ~2-10 mHz (predominantly 3-4 mHz), much less than the Doppler-shifts of tens to a few hundred mHz reported here. Hence they do not appear to be the same signals as the very low latitude whistler-mode signals reported here which were received most strongly on loops oriented approximately parallel to the transmitter-receiver path, i.e., oriented for near maximum subionospheric reception. Recently Chen et al. (2017) observed very low latitude whistlers at Suizhou, China (21.8°N geomagnetic) using a loop antenna oriented east-west with average dispersions (over 7 nights in the period 8 Feb – 2 March 2016) falling from 22 to 17 $s^{1/2}$ from 0 to 06 LT. All these reductions in dispersion of ~ 5 $s^{1/2}$ in ∼6 hours (in China, Japan, India and here) correspond to a reduction in group time at 21.4 kHz of $5/(21400)^{1/2}$ = 34 ms in 6 h ≡ 34 x 1.85 = 63 ms reduction in phase time (Thomson, 1987ab) in 6 h ≡ 21400 x 0.063/(6 x 3600) = 62 mHz average Doppler shift which is very similar to the Doppler-shifts reported here and by Thomson (1987a) but much larger than those reported by Araki et al. and Andrews. A typical Andrews observed Doppler-shift was ~3 mHz or ~1/20 of the ~60 mHz of the regular very low latitude whistler-mode signals reported here from Rarotonga and Dunedin. This is perhaps suggestive that the Andrews observed signals might possibly have something like 1/20 of the group delay (~100 ms) of our very low latitude whistler-mode signals: i.e., ~5 ms. The cross-correlation technique which we used at Rarotonga and Dunedin would not work well, if at all, with delays as short as ~5 ms; so, although our technique works very well for our very low latitude whistler-mode signals, it seems unable to contribute to elucidating the signals observed by Araki et al. (1972) and Andrews (1974, 1978).

4.3 The Paths of the Very Low Latitude Whistlers and Whistler-mode Signals

Andrews (1974, 1978) may not have been observing signals similar to (our) very low latitude whistler-mode signals, but his ray-tracings (Andrews 1978, 1979) were correctly determining for the first time the naturally occurring (non-field-aligned) path of these very low latitude whistler-mode signals, ~ 10°-10°, at least late at night when there is virtually no horizontal electron density gradient in the (*F2*) ionosphere. Earlier Singh (1976) had shown by ray tracing, in an ionosphere with a suitable horizontal electron density gradient, that a non-field-aligned path for whistler mode signals, ~20°-20°, inter-hemispheric ground-to-ground, could exist. Later, Thomson (1987b) found that the decrease in group time observed, ~140-100 = ~40 ms, during the night, 09-15 UT, for very low latitude whistler-mode signals from NPM recorded at Dunedin, New Zealand, was clearly too small to be explained by decay of the night ionosphere alone; this decay change, ~180-100 = ~80 ms, based mainly on the large *foF2* decay observed at ~10° latitude, would be much too great. However, early in the night, a (Singh-type) path at ~20°-20°, where *foF2* is much lower than at 10° early in the night, decaying/drifting to an (Andrews-type) path near 10°-10° late at night, when the *foF2* at 10° has greatly reduced, was able to quantitatively explain the observed reduction in group delay during the night.

While Singh (1976), Andrews (1978, 1979) and Thomson (1987b) used two-dimensional ray tracing and a dipole geomagnetic field, Liang et al. (1985) used the IGRF field and three-dimensional ray tracing to successfully model their very low latitude whistlers exiting near Zhanjiang, 10°N geomagnetic, 21.3°N geographic. As they say, their non-ducted results are capable of explaining satisfactorily their observational data obtained at very low latitudes. Their entry and exit latitudes are about 20° apart, consistent with ~10°-10° geomagnetic paths.

However, some uncertainty seemed to continue as to whether this very low latitude propagation really was being guided, on a non-field-aligned path, by the fairly natural ionospheric electron density and geomagnetic gradients or was being guided, at least somewhat like mid-latitude whistlers, on geomagnetic-field-aligned ducts of enhanced electron density. By monitoring wave-normal angles on the FR-1 satellite orbiting at 750 km altitude, Cerisier (1973) was able to detect ducted propagation at mid-latitude

L-values, but could find no ducted propagation for low latitudes where *L* <~1.7. Any very low latitude ducts would need very high enhancements (~400% even at moderately low latitudes of 25°, Singh and Tantry, 1973) and might need to be unrealistically narrow, ~10 km (see also Hasegawa et al., 1978; Hayakawa et al., 1990; Hayakawa and Ohta, 1992). Very low latitude whistler echoes had been observed: Hayakawa et al. (1990) found up to 10% of very low latitude whistlers showed echoes; Liang et al. (1985) even observed the same very low latitude whistler with echo simultaneously at both Zhanjiang (10°N geomagnetic) and Wuchang (19.4°N geomagnetic). At mid- and high latitudes, echoes require ducts to keep both whistler and echo on the same path; however, at low latitudes, the fixed non-ducted path, say 10°-10°, could well serve the same role. At very low latitudes, if the whistler needed to penetrate the *D* region to reflect from the ground, and so echo, the attenuation would likely be too great but if it reflected from the steep vertical gradients at the bottom of the *F* region this would be avoided. Ohta et al., (1997) and Ohta and Hayakawa (2000), using 3-D, IGRF ray tracing and the non-ducted (~10°-10°) path, came to the general conclusion that it is possible to reproduce the one-hop and three-hop whistlers with the observed dispersion ratio of 1:3. Singh and Hayakawa (2001) conclude that for "the propagation mechanism of low latitude and equatorial whistlers, it is clear that most of the low-latitude workers in India, China, and New Zealand have favored non-ducted propagation for low- and very-low-latitude whistlers. Even the Japanese workers, who were the first to realize that the propagation mechanism of these whistlers was not fully understood, have lately favored the non-ducted mode. Thus there is now a consensus about the propagation mechanism of these whistlers among the various workers."

The DEMETER satellite at a height of ~700 km has recorded in a single world map the average penetration of signals from VLF transmitters at night during the 3 years 2006-2008 (Parrot et al., 2009, Figure 1). More recently, the ZH-1 satellite has recorded similar clear signals at heights ~500 km (Zhao et al, 2019, Figure 3). Although many of these signals will not reach the ground again, some of those showing on NPM's longitude in the equatorial region may well include those propagating as reported here.

Thus, as supported by the discussions in this section and as displayed by the observations in Figures 3 and 4 (and S1-S3), there is a very salient whistler-mode path at very low latitudes crossing the equator. The signals are guided in latitude (L-value) by refractive index gradients caused by geomagnetic gradients and ambient electron density gradients, both horizontal and vertical. As depicted in Figure 2, the resulting paths are not magnetic field aligned, nor constrained in longitude, and so are not ducted in the conventional sense. Early in the night, the significant, natural, horizontal, equatorward electron density gradient, results in paths having entry/exit regions near latitudes ±20° with ~1400 km peak altitude, while late in the night, when the natural horizontal electron density gradients fall to near zero, the paths have entry/exit regions near latitudes ~±10° with ~700 km peak altitude as shown in Figure 2. Despite this well-defined whistler-mode propagation path being at such very low latitudes, signals from VLF transmitters can propagate to, or be received at, locations many thousands of km from the low latitude entry or exit regions, showing how unique and dominant this path is.

Bearing in mind the path geometries illustrated in Figures 1 and 2, and the very low latitude whistler-mode signals being unconstrained in longitude, some estimates can now be calculated for the relative amplitudes at Rarotonga and Dunedin, and compared with observations. As the waves leave the transmitter (NPM at 21°N) they spread out azimuthally, at least initially, subionospherically in the Earth-ionosphere waveguide (height ~ 85 km), in particular towards the South. Neglecting any reflection losses at the upper (ionospheric) and lower (ocean) boundaries for the moment, at range ρ (say ~500 km) from NPM, the radiated power will have spread out uniformly onto the sides of an imaginary vertical cylinder of radius ρ and circumference $2\pi\rho$ in the waveguide, and so the outward power flux will be inversely proportional to ρ. For larger distances (>>500 km), account needs to be taken of the curvature of the Earth (radius, R_E) and so the circumference of the appropriate ('small circle') cylinder at a 'great circle' range ρ from NPM is $2\pi R_E \sin(\rho/R_E)$, resulting in the flux being inversely proportional to $R_E \sin(\rho/R_E)$ rather than to ρ.

After leaving NPM and spreading azimuthally (southwards) the waves reach the region 10°-20°N where some of them enter the, longitudinally unconstrained, whistler-mode path passing southwards over the equator returning to the Earth-ionosphere waveguide in the conjugate region 10°-20°S. During this propagation, inside the ionosphere, say ~14°N to 14°S, the waves continue to spread azimuthally but likely at a much slower rate due to the much higher refractive index (>~10) on this whistler-mode part of the path. On returning to the Earth-ionosphere waveguide, these ~southward travelling waves, due (essentially) to Snell's Law, will continue to spread in azimuth at a rate similar to those waves which did not enter the whistler-mode path but which continued subionospherically in the Earth-ionosphere wave guide towards

Rarotonga and Dunedin. Hence, an estimate of the relative attenuation, due to the azimuthal spreading of the very low latitude whistler-mode waves, for NPM-Rarotonga and NPM-Dunedin, can be made by using, as a proxy, the corresponding subionospheric signals. For these the ratio, NPM-Rarotonga/NPM-Dunedin, from above, is $\sin(\rho_2/R_E)/\sin(\rho_1/R_E)$ where ρ_2 = 8.1 Mm and ρ_1 = 4.7 Mm are the respective great circle distances, except that both these distances need to be reduced by ~3 Mm to allow for the ±14° whistler-mode part of the paths where the refractive index is high and so where there is little effective azimuthal spreading. This ratio thus becomes sin(5.1/6.4)/sin(1.7/6.4) = 2.72; i.e., the amount by which the amplitude is expected to be lower at Dunedin relative to Rarotonga, due to azimuthal spreading, is $10 \log_{10}(2.72)$ = 4.3 dB. In addition to this, there is, of course, the *D* region (reflection) attenuation due to the longer path (~3.5 Mm) from the exit region to Dunedin compared with that to Rarotonga. Using the US Navy waveguide propagation code, 'Modefinder', this attenuation (at night with *H'* = 85 km and β = 0.6 km^{-1}, Thomson et al., 2007) can be estimated as ~3 dB/Mm giving ~3.5 × 3 + 4.3 ≈ 15 ± 4 dB. This compares quite well with the observed ~15 ± 6 dB, from section 3.1 above, for the observed amplitude difference between Dunedin and Rarotonga for the very low latitude whistler-mode signals.

If the whistler-mode signals had exited from a conventional, longitude-constrained (~circular) duct, at say 0.5 Mm = 500 km north of Rarotonga, there would have been an amplitude difference between Rarotonga and Dunedin, due to azimuthal spreading, now from this exit point, of $\sin(\rho_2/R_E)/\sin(\rho_1/R_E) \equiv 8.7$ dB, where now ρ_2 = 4 Mm and ρ_1 = 0.5 Mm, compared with 4.3 dB above for the non-ducted, longitude unconstrained path. Thus, if the signals had been ducted, the calculated, non-ducted

~15 dB above would increase to 8.7–4.3 + 15 = ~19 ± 4 dB, agreeing somewhat less closely with the observed ~15 ± 6 dB. More generally, this 8.7–4.3 = ~4 dB lower loss for non-ducted propagation will contribute to signals from the very low latitude paths tending to be observable further from their exit regions than those from conventional (mid-latitude) whistler ducts.

5. Summary and Conclusions

VLF radio signals on 21.4 kHz are commonly received in Dunedin, NZ, from NPM (21.4°N, 158°W, Hawaii) not only on the direct, subionospheric, very phase stable, 8.1 Mm great circle path, but also, at night, on indirect paths involving whistler-mode propagation. The most prominent of these latter signals arrive at Dunedin with low delays of ~50-150 ms. They are concluded to propagate via a transequatorial, non-field-aligned, very low latitude, whistler-mode path entering the ionosphere 10°-20°N (south of NPM), refracting to near horizontal over the equator, at heights ~1000 km, depending on time of night, and then further refracting nearly symmetrically downwards to exit the ionosphere essentially conjugate to the entry point, followed by subionospheric propagation to Dunedin. For ten days, recordings were also made simultaneously on Rarotonga (21°S, 160°W, near NPM's conjugate), where these low-delayed indirect signals were received on the same days with essentially the same delays at the same (UT) times as at Dunedin. However, the Rarotonga signals showed significantly higher amplitudes and were detectable for significantly longer periods nearly every night, compared with those on the same night at Dunedin consistent with the assumed very low latitude whistler-mode path exiting much nearer to Rarotonga (21°S) than Dunedin (46°S). Fairly recently Cohen et al. (2012) reported that the Helliwell (1965) calculations of VLF ionospheric absorption (between the Earth's surface and the plasmasphere may be too low by 20-100 dB; the amplitude observations, in section 3.1 here, of NPM to Rarotonga after passing through the ionosphere twice (i.e., up and down) may be useful for providing an experimental upper limit for the attenuation for full-wave VLF transionospheric modeling (see also Zhao et al., 2017).

The signals at both the Dunedin and Rarotonga receivers were Doppler-shifted usually by very similar amounts, typically a few tens of mHz, but sometimes up to ~300 mHz, at the same (UT) times. However, near (NPM-Rarotonga) dawn, when the Doppler shifts turn negative as the Sun starts to ionize the (NPM-Rarotonga) ionosphere again, the Doppler shifts at Rarotonga tend to be more negative, implying that the Rarotonga-received path is a little further to the east of the Dunedin-received path; this, in turn, implies that the whistler-mode paths, although constrained in latitude are not constrained in longitude, and so are not conventionally, field-aligned ducted.

At Dunedin, normal, mid-latitude, whistler-mode signals from NLK (48°N, 122°W, Seattle) are very common at night (with delays ~300-700 ms) but low-delayed (~100 ms) whistler-mode signals from NLK are too weak to be detected at Dunedin. However, they were seen at Rarotonga, and only to a slightly lesser extent than the corresponding low-delayed signals from NPM seen at Dunedin. NLK radiates slightly less power than NPM, NLK has a slightly higher frequency giving slightly more ionospheric attenuation, and Rarotonga is slightly noisier than Dunedin. This near comparability of NPM-Dunedin and NLK-Rarotonga is consistent with the assumed very low latitude whistler-mode path; for NPM-Dunedin, the transmitter is close to the very low latitude entry area but the receiver is far from the path exit area giving a similar result to that for NLK-Rarotonga where the receiver is close to path exit but the transmitter is far from the path entry. Provided the transmitter, e.g. NPM at 21°N latitude, is fairly close (i.e., within direct line of sight from the ground to the night *D* region entry at ~85 km altitude, i.e., ~1000 km ≡ ~10° latitude) to the path entry, it is here observed that the very low latitude whistler-mode signals can be detected up to ~9 Mm away, i.e., at Rothera, 68°S in the Antarctic. This is consistent with the study of Allcock and McNeill (1966) on mid-latitude whistler-mode duct entry and exit distances from their transmitters and receivers.

Natural whistlers exhibit essentially the same dispersions as man-made whistler-mode signals at very low latitudes and almost certainly have the same whistler-mode paths (~10°-20°). Two- and three-hop echoes are not uncommon for whistlers but do not seem to occur for whistler-mode signals from man-made transmitters because the latter are at higher frequencies (~20 kHz) resulting in higher attenuation in the *F* region (Thomson, 1987b) which must be multiply traversed. However, whistler-mode signals from a man-made transmitter come from a continuous, constant source showing that the path can last for many hours, up to most, or all, of the night: e.g., on 3 and 4 September 1996, at Rarotonga, the propagation is continuous for 11 and 10 hours respectively. In contrast, as discussed in Section 3.1, many estimates of the possible lifetimes of (assumed) very low latitude whistler ducts are much less than this, making field-aligned ducting very unlikely at these low latitudes. Non-ducted propagation increases the value of the VLF delay and frequency-shift measurements because they are then representative of the normal ambient equatorial plasma density rather than that of highly enhanced plasma, likely by up to several hundred percent. It is interesting to note that if the transmitter is at low latitude, such as NPM at 21° N, then the equatorial F-region can be monitored from anywhere up to a few Mm from NPM's conjugate. Conversely and more importantly, if the receiver is at a low latitude, such as Rarotonga at 21° S, then signals from a number of transmitters in the opposite hemisphere can be used, such as NPM and NLK as here.

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References

Allcock, G. McK. & McNeill, F.A. (1966). The reception of whistler mode signals at a point remote from the transmitter's magnetic conjugate point. *Journal of Geophysical Research*, *71*(9), 2285-2294. https://doi.org/10.1029/JZ071i009p02285

Andrews, M. K. (1974). Small Doppler shifts on low latitude transequatorial path VLF signals. *Journal of Atmospheric and Terrestrial Physics*, *36*(2), 335–341. https://doi.org/10.1016/0021-9169(74)90052-X

Andrews, M. K. (1978). Non-ducted whistler-mode signals at low latitudes. *Journal of Atmospheric and Terrestrial Physics*, *40*(4), 429–436. https://doi.org/10.1016/0021-9169(78)90174-5

Andrews, M. K. (1979). On whistlers with very low dispersion. *Journal of Atmospheric and Terrestrial Physics*, *41*(2), 231–235. https://doi.org/10.1016/0021-9169(79)90016-3

Araki, T., Naito, Y., & Kato, S. (1972). Detection of whistler mode signals from VLF transmitter in Australia. *Report of Ionosphere and Space Research in Japan*, *26*, 69-78.

Bao, Z, Wang, T., Xu, J., Chen, S., & Liang, B. (1983). Characteristics of low-latitude whistlers and their relation with *foF2* and magnetic activity. *Advances in Space Research*, *2*(10), 223-226. https://doi.org/10.1016/0273-1177(82)90395-7

Cerisier, J. C. (1973). A theoretical and experimental study of non-ducted VLF waves after propagation through the magnetosphere. *Journal of Atmospheric and Terrestrial Physics*, *35*(1), 77-94. https://doi.org/10.1016/0021-9169(73)90217-1

Chen, Y., Ni, B., Gu, X., Zhao, Z., Yang, G., Zhou, C., & Zhang, Y. (2017). First observations of low latitude whistlers using WHU ELF/VLF receiver system. *Science China Technological Sciences*, *60*(1), 166-174. https://doi.org/10.1007/s11431-016-6103-5

Clilverd, M. A., Thomson, N. R., & Smith, A. J. (1993). The influence of ionospheric absorption on mid-latitude whistler-mode signal occurrence from VLF transmitters. *Journal of Atmospheric and Terrestrial Physics*, *55*(10), 1469–1477. https://doi.org/10.1016/0021-9169(93)90112-C

Cohen, M. B., Lehtinen, M. G., and Inan, U. S. (2012). Models of ionospheric VLF absorption of powerful ground transmitters. *Geophysical Research Letters*, *39*(24). https://doi.org/10.1029/2012GL054437

Gokani, S. A., Singh, R., Cohen, M. B., Kumar, S., Venkatesham, K., Maurya, A. K., Selvakumaran, R., & Lichtenberger, J. (2015). Very low latitude (L = 1.08) whistlers and correlation with lightning activity. *Journal of Geophysical Research: Space Physics*, *120*(8), 6694–6706. https://doi.org/10.1002/2015JA021058

Hasegawa, M., Hayakawa, M., & Ohtsu, J. (1978). On the conditions of duct trapping of low-latitude whistlers. *Annales de Geophysique, 34*(4), 317-324.

Hayakawa, M., & Tanaka, Y. (1978). On the propagation of low-latitude whistlers. *Reviews of Geophysics and Space Physics*, *16*(1), 111-123. https://doi.org/10.1029/RG016i001p00111

Hayakawa, M., Tanaka, Y., Okada, T., & Ohtsu, J. (1983). Time scales for the formation, lifetime and decay of low latitude whistler ducts. *Annales Geophysicae 1*(6), 515–518.

Hayakawa, M., Ohta, K., & Shimakura, S. (1990). Spaced direction finding of nighttime whistlers at low and equatorial latitudes and their propagation mechanism. *Journal of Geophysical Research*, *95*(A9), 15,091-15,102. https://doi.org/10.1029/JA095iA09p15091

Hayakawa, M., & Ohta, K. (1992). The propagation of low-latitude whistlers: a review. *Planetary and Space Science*, *40*(10), 1339-1351. https://doi.org/10.1016/0032-0633(92)90090-B

Helliwell, R. A. (1965), *Whistlers and related ionospheric phenomena*, Stanford, California.

Kotaki, M., Ondoh, T., Murakami, T., & Watanabe, S. (1977). Characteristics of low-latitude whistlers as observed at Okinawa, Japan. *Journal of the Radio Research Laboratories*, *24*(115), 117-135.

Liang, B., Bao, Z, & Xu, J. (1985). Propagation characteristics of night-time whistlers in the region of equatorial anomaly. *Journal of Atmospheric and Terrestrial Physics*, *47*(8-10), 999–1007. https://doi.org/10.1016/0021-9169(85)90079-0

Ondoh, T., Kotaki, M., Murakami, T., Watanabe, S., & Nakamura, Y. (1979). Propagation characteristics of low-latitude whistlers. *Journal of Geophysical Research*, *84*(A5), 2907-2104. https://doi.org/10.1029/JA084iA05p02097

Ohta, K., Nishimura, Y., Kitagawa, T., & Hayakawa, M. (1997). Study of propagation characteristics of very low latitude whistlers by means of three-dimensional ray-tracing computations. *Journal of Geophysical Research*, *102*(A4), 7537-7546. https://doi.org/10.1029/96JA03633

Ohta, K., & Hayakawa, M. (2000). Study of Three-dimensional ray-tracing for very low latitude whistlers, taking into account the latitudinal and longitudinal gradients of the ionosphere. *Journal of Geophysical Research*, *105*(A8), 18,895-18,900.

Parrot, M., Inan, U. S., Lehtinen, N. G. & Pincon, J. L. (2009). Penetration of lightning MF signals to the upper ionosphere over VLF ground-based transmitters. *Journal of Geophysical Research*, *114*(A12). https://doi.org/10.1029/2009JA014598

Scarabucci, R. R. (1970). Satellite observations of equatorial phenomena and defocusing of VLF electromagnetic waves. *Journal of Geophysical Research*, *75*(1), 69-84. https://doi.org/10.1029/JA075i001p00069

Singh, B., & Tantry B. A. P. (1973). On ducting of whistlers at low latitudes. *Annales de Geophysique*, *29*(4), 561-568.

Singh, B. (1976). On the ground observation of whistlers at low latitudes. *Journal of Geophysical Research*, *81*(13), 2429-2432. https://doi.org/10.1029/JA081i013p02429

Singh, B., & Hayakawa (2001). Propagation modes of low- and very-low-latitude whistlers. *Journal of Atmospheric and Solar-Terrestrial Physics, 63*(11), 1133-1147. https://doi.org/10.1016/S1364-6826(00)00218-2

Singh, R. P. (1993). Whistler studies at low latitudes: A review. *Indian Journal of Radio and Space Physics*, *22*(3), 139-155.

Singh, R., Cohen, M. B., Maurya, A. K., Veenadhari, B., Kumar, S., Pant, P., Said, R. K., & Inan, U. S. (2012). Very low latitude (L = 1.08) whistlers. *Geophysical Research Letters*, *39*, L23102. https://doi.org/10.1029/2012GL054122

Storey, L. R. O. (1953). An investigation of whistling atmospherics. *Philosophical Transactions of the Royal Society of London*, *A246*(908), 113-141. https://doi.org/10.1098/rsta.1953.0011

Thomson, N. R. (1975). Whistler mode signals: Group delay by crosscorrelation. *Geophysical Research Letters*, *2*(10), 451-452. https://doi.org/10.1029/GL002i010p00451

Thomson, N. R. (1981). Whistler mode signals: Spectrographic group delays. *Journal of Geophysical Research*, *86*(A6), 4795-4802. https://doi.org/10.1029/JA086iA06p04795

Thomson, N. R. (1985). Reflection of VLF radio waves from distant mountain ranges. *Journal of Atmospheric and Terrestrial Physics*, *47*(4), 353-362. https://doi.org/10.1016/0021-9169(85)90015-7

Thomson, N. R. (1987a). Experimental observations of very low latitude man-made whistler-mode signals. *Journal of Atmospheric and Terrestrial Physics*, *49*(4), 309–319. https://doi.org/10.1016/0021-9169(87)90027-4

Thomson, N. R. (1987b). Ray-tracing the paths of very low latitude whistler-mode signals. *Journal of Atmospheric and Terrestrial Physics*, *49*(4), 321–338. https://doi.org/10.1016/0021-9169(87)90028-6

Thomson, N. R. (1989). Re-radiation of VLF radio waves from mountain ranges. *Journal of Atmospheric and Terrestrial Physics*, *51*(4), 339-349. https://doi.org/10.1016/0021-9169(89)90084-6

Thomson, N. R. (1993). Experimental daytime VLF ionospheric parameters. *Journal of Atmospheric and Terrestrial Physics*, *55*(2), 173-184. https://doi.org/10.1016/0021-9169(93)90122-F

Thomson, N. R., Clilverd, M. A. & McRae, W. M. (2007). Nighttime ionospheric *D* region parameters from VLF phase and amplitude. *Journal of Geophysical Research*, *112*(A7). https://doi.org/10.1029/2007JA012271

Thomson, N. R., Clilverd, M. A., & Rodger, C. J. (2014). Low-latitude ionospheric *D* region dependence on solar zenith angle. *Journal of Geophysical Research: Space Physics 119*(8), 6865-6875. https://doi.org/10.1002/2014JA020299

Thomson, N. R., Clilverd, M. A., & Rodger, C. J. (2018). Quiet daytime Arctic ionospheric *D* region. *Journal of Geophysical Research: Space Physics, 123*, 9726–9742. https://doi.org/10.1029/2018JA025669

Thomson, N. R., Clilverd, M. A., & Rodger, C. J. (2019). Very low latitude whistler-mode data. https://doi.org/10.5281/zenodo.3381090

Thomson, R. J. (1978). The formation and lifetime of whistler ducts. *Planetary and Space Science 26*(5), 423-430. https://doi.org/10.1016/0032-0633(78)90064-8

Xu, J. S., Tian, M., Tang, C.C., Hayakawa, M., Ohta, K., & Shimakura, S. (1989). Direction finding of night-time whistlers at very low latitudes in China: preliminary results. *Planetary and Space Science 37*(9), 1047-1052.

Zhao, S. F., Liao, L., Zhang, X.M. (2017). Trans-ionospheric VLF wave power absorption of terrestrial VLF signal. *Chinese Journal of Geophysics*, *60*(8), 3004-3014. http://www.geophy.cn/EN/10.6038/cjg20170809

Zhao, S., Zhou, C., Shen, X. H., & Zhima, Z. (2019). Investigation of VLF transmitter signals in the ionosphere by ZH-1 observations and full-wave simulation. *Journal of Geophysical Research: Space Physics, 124,* 4697–4709. https://doi.org/10.1029/2019JA026593

Figure Captions

Figure 1. The two VLF transmitters (red circles with dots: NLK and NPM) and the three receiving sites (black circles with dots: Rarotonga, Dunedin and Rothera) used for the very low latitude whistler-mode observations. The dark blue lines and shading indicate the approximate surface projections of the ionospheric whistler-mode paths and region (darker shading for earlier in the night, say ~09 UT, lighter shading for later, say 15 UT, see text for details). The lighter blue lines show the subionospheric parts of these paths.

Figure 2. Very low latitude whistler-mode signals follow near the solid blue line early in the night drifting to the solid red line late at night, with peak altitudes of ~1400 km and ~700 km respectively. The dashed red and purple lines indicate the connecting subionospheric parts of the paths from transmitters NPM and NLK to receivers at Rarotonga and Dunedin. The dotted red and blue lines are geomagnetic field lines shown for comparison with these red and blue non-field-aligned paths. In contrast, the long solid blue-green line indicates a regular, ducted, field aligned, whistler-mode path from transmitter NLK (48°N) to a receiver at Dunedin (46°S), New Zealand (peak altitude ~10,000 km).

Figure 3. VLF signals from the 21.4-kHz US Navy transmitter NPM on Hawaii (~21°N) recorded simultaneously at Rarotonga (~21°S, left panels) and Dunedin (~46°S, right panels) on 29 Aug and 3 Sep 1996 UT (top and bottom panels, respectively). The vertical axis in each panel shows the group delay of each received signal, 0.0 – 0.9 s, while the horizontal axis shows the time of arrival in hours UT (12 UT ~ midnight LT for Dunedin/Rarotonga/NPM). The amplitudes of the signals are color coded in line with the color bar at top left, with green smallest and blue largest. The very low latitude whistler-mode signals can be clearly seen at ~100 ms (~0.1 s)

delay, strongest at ~09-17 UT at Rarotonga. The three horizontal color bars at the top of each panel (> 0.9 s delay) are amplitude calibrations explained in the text.

Figure 4. Same as for Figure 3 except that for 28 Aug and 6 Sep 1996. These are the only nights (2 out of 10) when the very low latitude whistler-mode signals were seen earlier at Dunedin than at Rarotonga. On 6 Sep 1996, this may well be due to the higher noise level at Rarotonga early in the night. As well as the very low latitude whistler-mode signals with delays ~100 ms at Dunedin and strongest at Rarotonga, note also the (weak) regular, mid-latitude, whistler-mode signals at Dunedin at delays of ~ 0.75 s at ~06-07 UT and 0.5-0.6 s at ~12-15 UT on 28 Aug 1996.

Figure 5. Same as for Figure 3 except that for NLK at Rarotonga and Dunedin on 2 and 3 Sep 1996. The very low latitude whistler-mode signals (delays ~100 ms) are visible at Rarotonga only, though weaker than for NPM at Rarotonga (see Figure 3 above for 3 Sep 1996, and the Supporting Information for 2 Sep 1996). Note that no very low latitude whistler-mode signals from NLK are detectable at Dunedin. However, regular, mid-latitude whistler-mode signals are clearly observable with delays ~0.3-0.5 s, ~06-15 UT.

Figure 6 Very low latitude whistle-mode signals from NPM (Hawaii) simultaneously received at Dunedin (46°S) and Rothera (68°S). The two left-hand panels show the group delays (as in Figure 3) as a function of UT on 21 Sep 2009. The two right hand panels show the Doppler shifts at ~10 UT on 21 Sep 2009.

Figure 7. Doppler shifts of very low latitude whistler-mode signals from NPM (Hawaii) simultaneously received at Rarotonga, 21°S (left two panels), and Dunedin, 46°S (right two panels), at 1630 UT (top two panels) and 1645 UT (bottom two panels) on 29 Aug 1996.

Figure 8. Doppler shifts of very low latitude whistler-mode signals from NPM (Hawaii) simultaneously received at Rarotonga and Dunedin, NZ, on 3 Sep 1996 UT. After ~1530 UT, the negative values and the increasing differences between the shifts at the two sites are likely due to sunrise (arriving first on the Rarotonga path), and the slightly different path longitudes (~6°). See text for further discussion.

xxx

Figure 1.

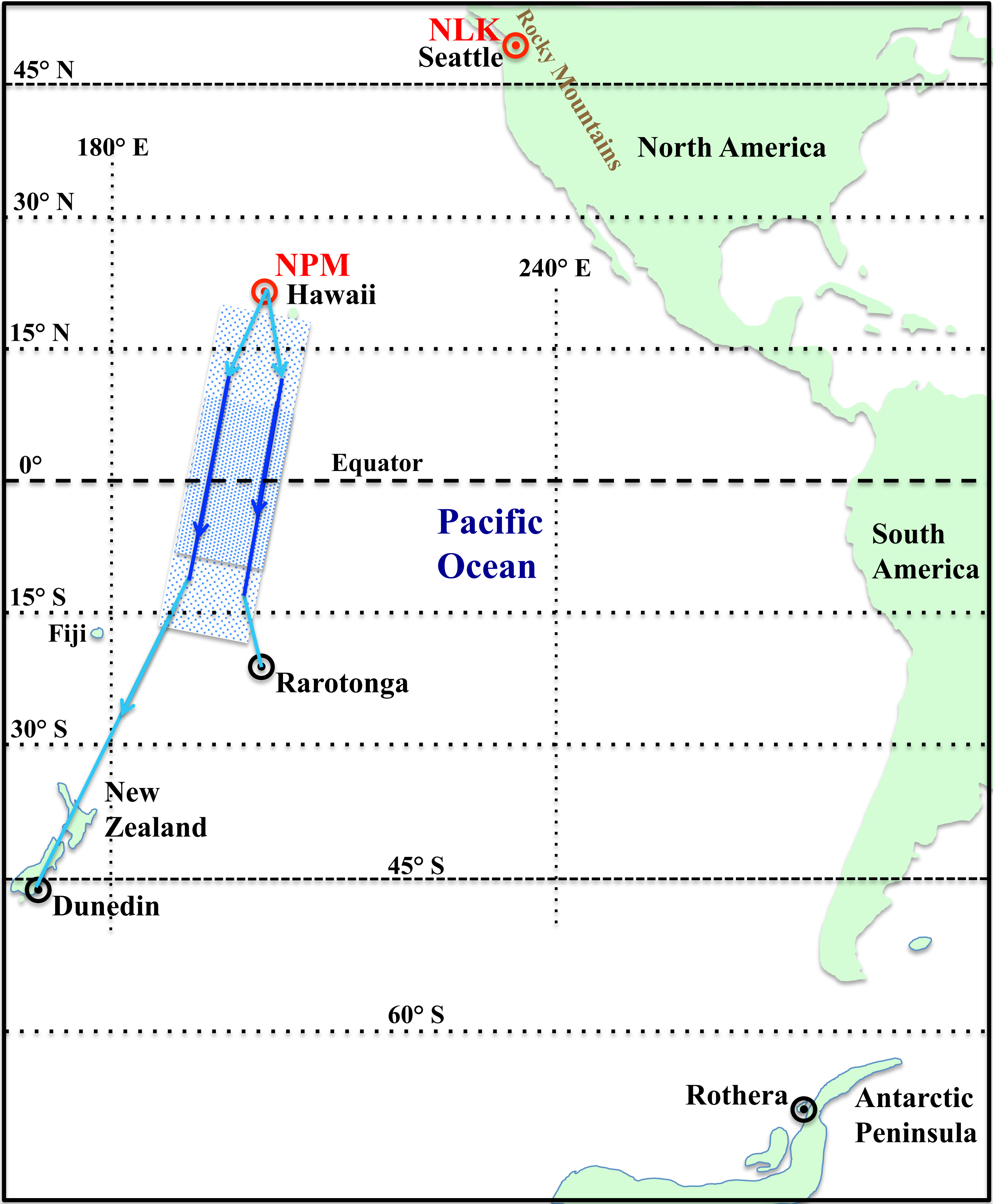

NLK
Seattle
Rocky Mountains
45° N
180° E
North America
30° N
NPM
Hawaii
240° E
15° N
0°
Equator
Pacific
Ocean
South
America
15° S
Fiji
Rarotonga
30° S
New
Zealand
45° S
Dunedin
60° S
Rothera
Antarctic
Peninsula

Figure 2.

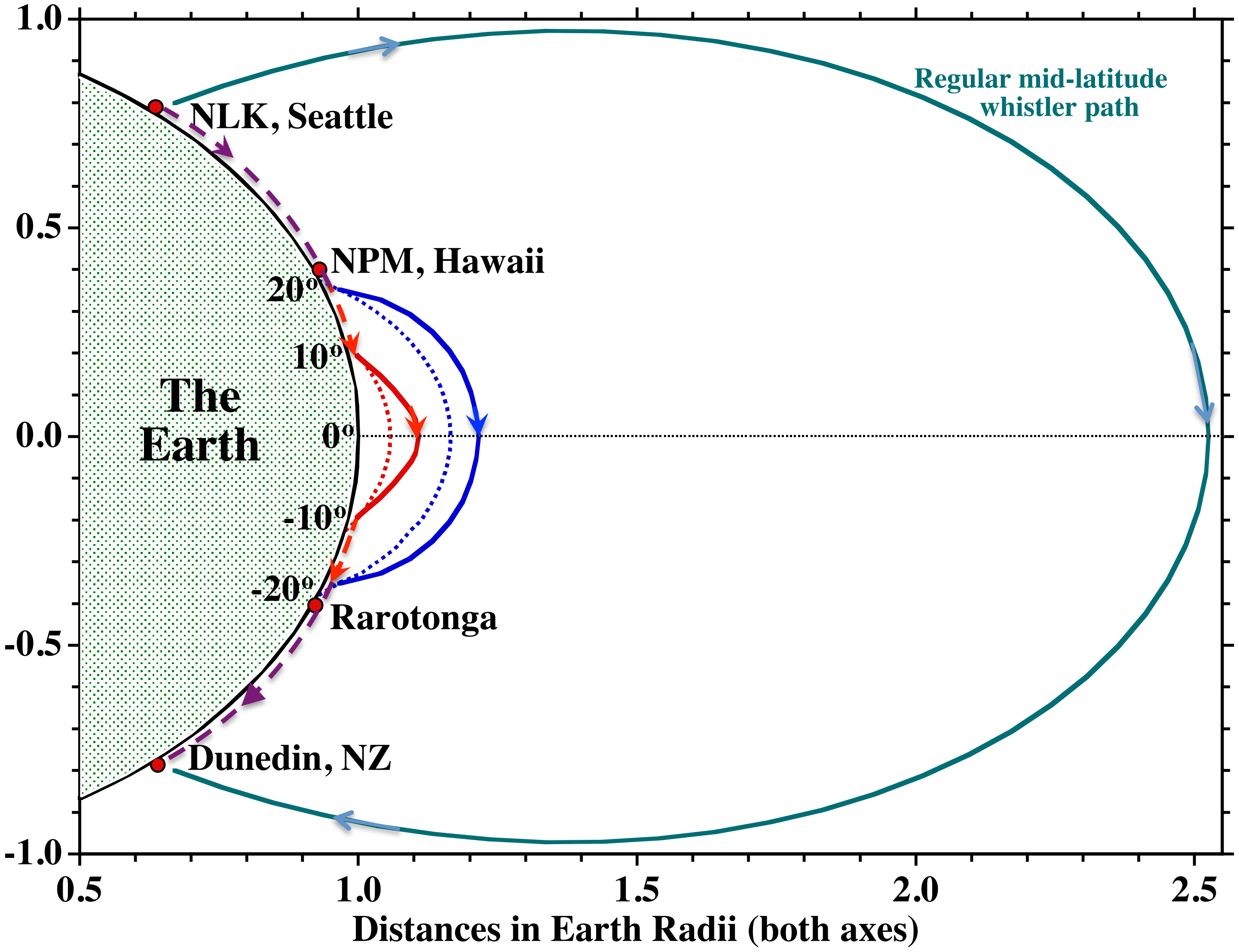

Regular mid-latitude whistler path
NLK, Seattle
NPM, Hawaii
Rarotonga
Dunedin, NZ
The Earth
20°
10°
0°
-10°
-20°
1.0
0.5
0.0
-0.5
-1.0
0.5
1.0
1.5
2.0
2.5
Distances in Earth Radii (both axes)

Figure 3.

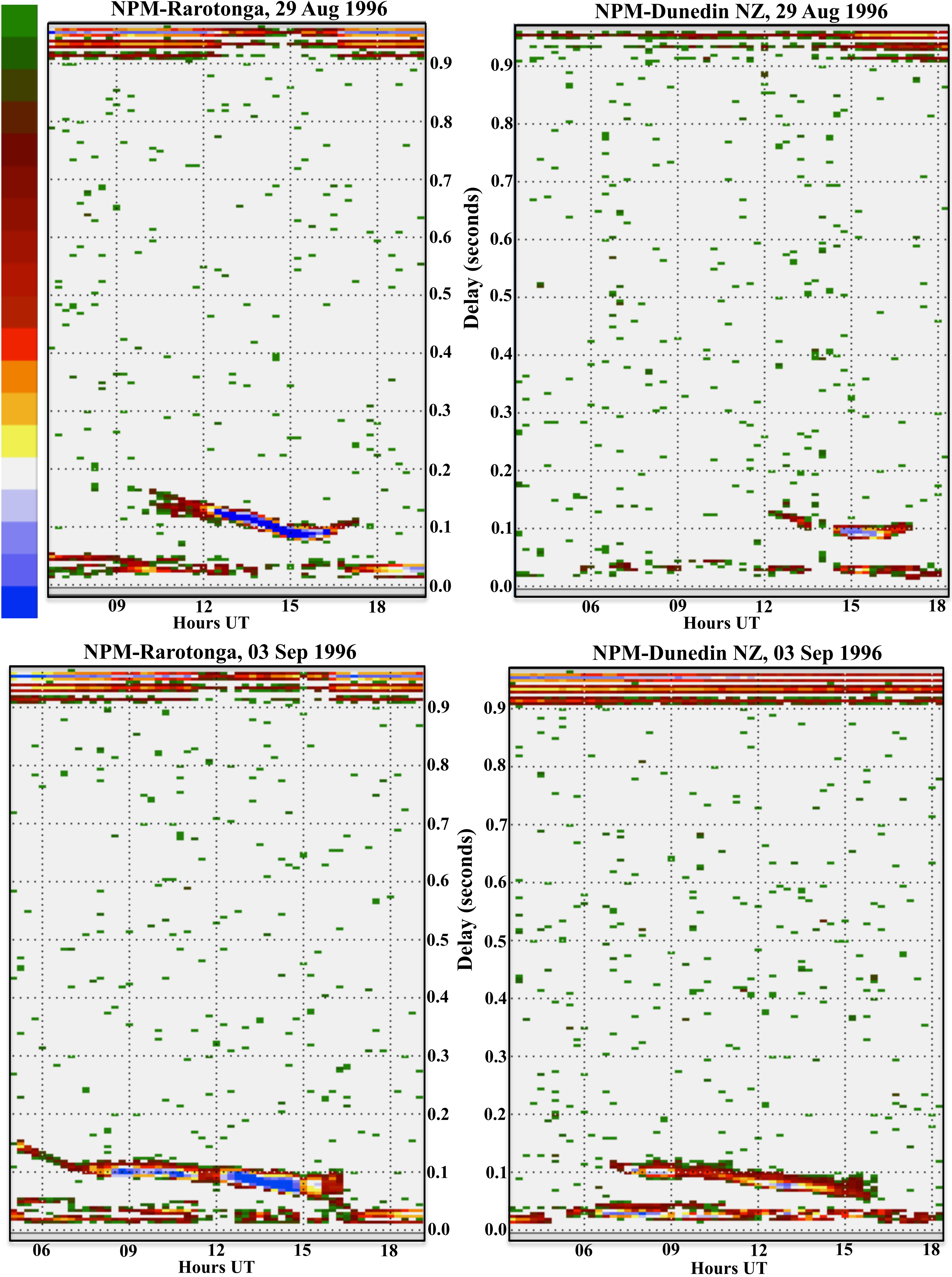
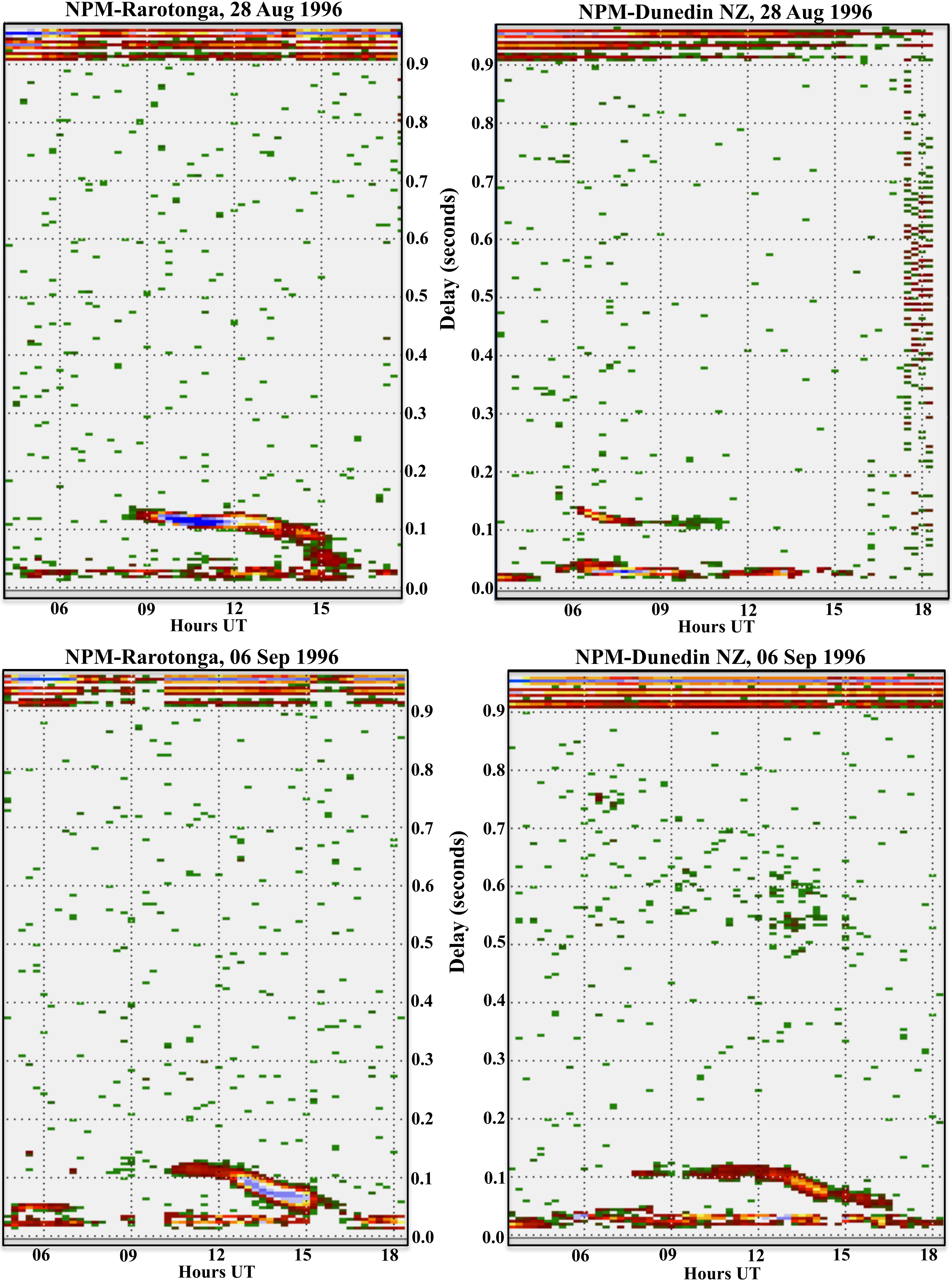
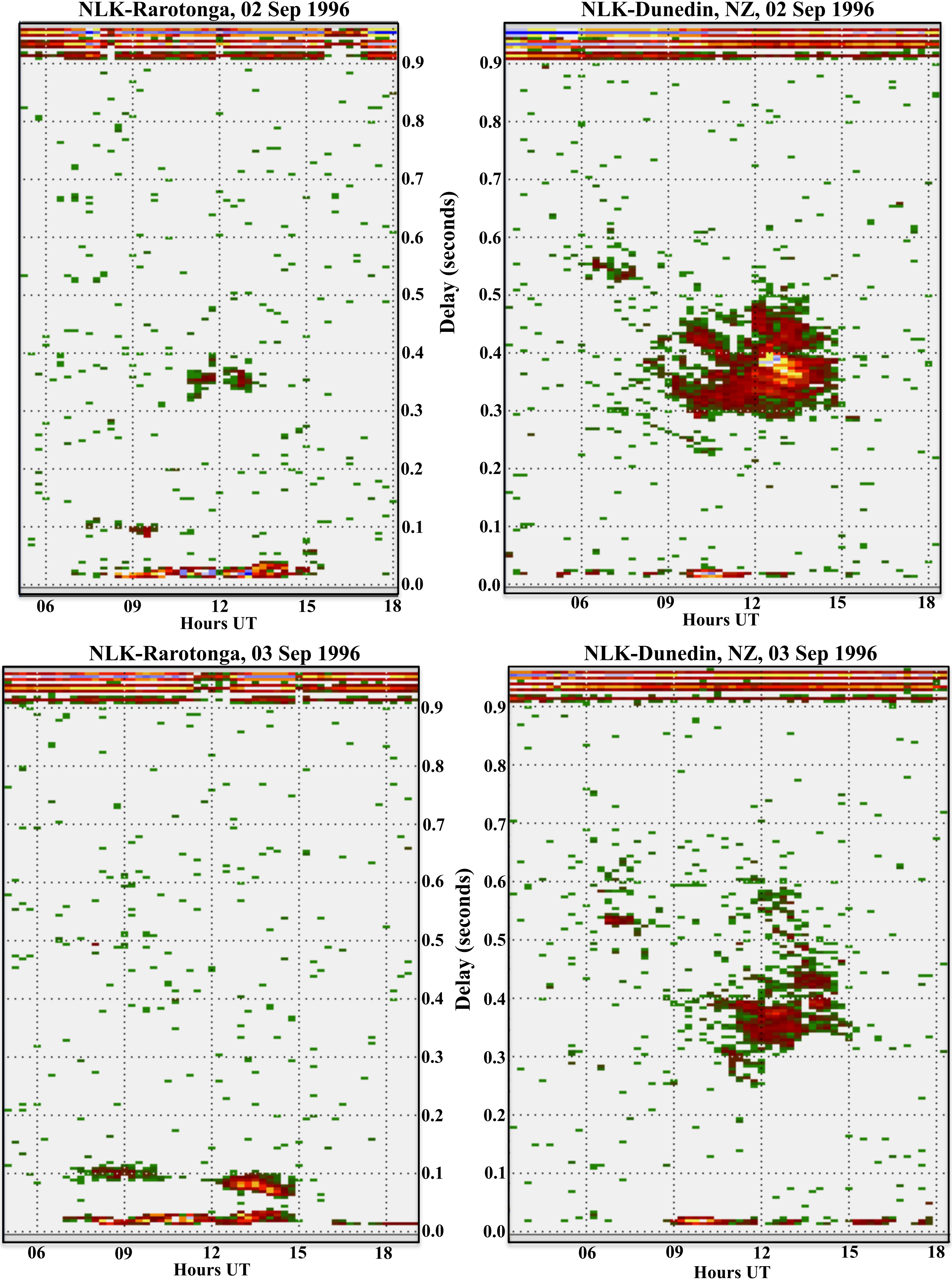

NPM-Rarotonga, 29 Aug 1996
NPM-Dunedin NZ, 29 Aug 1996
NPM-Rarotonga, 03 Sep 1996
NPM-Dunedin NZ, 03 Sep 1996
Delay (seconds)
Hours UT
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
06
09
12
15
18

Figure 4.



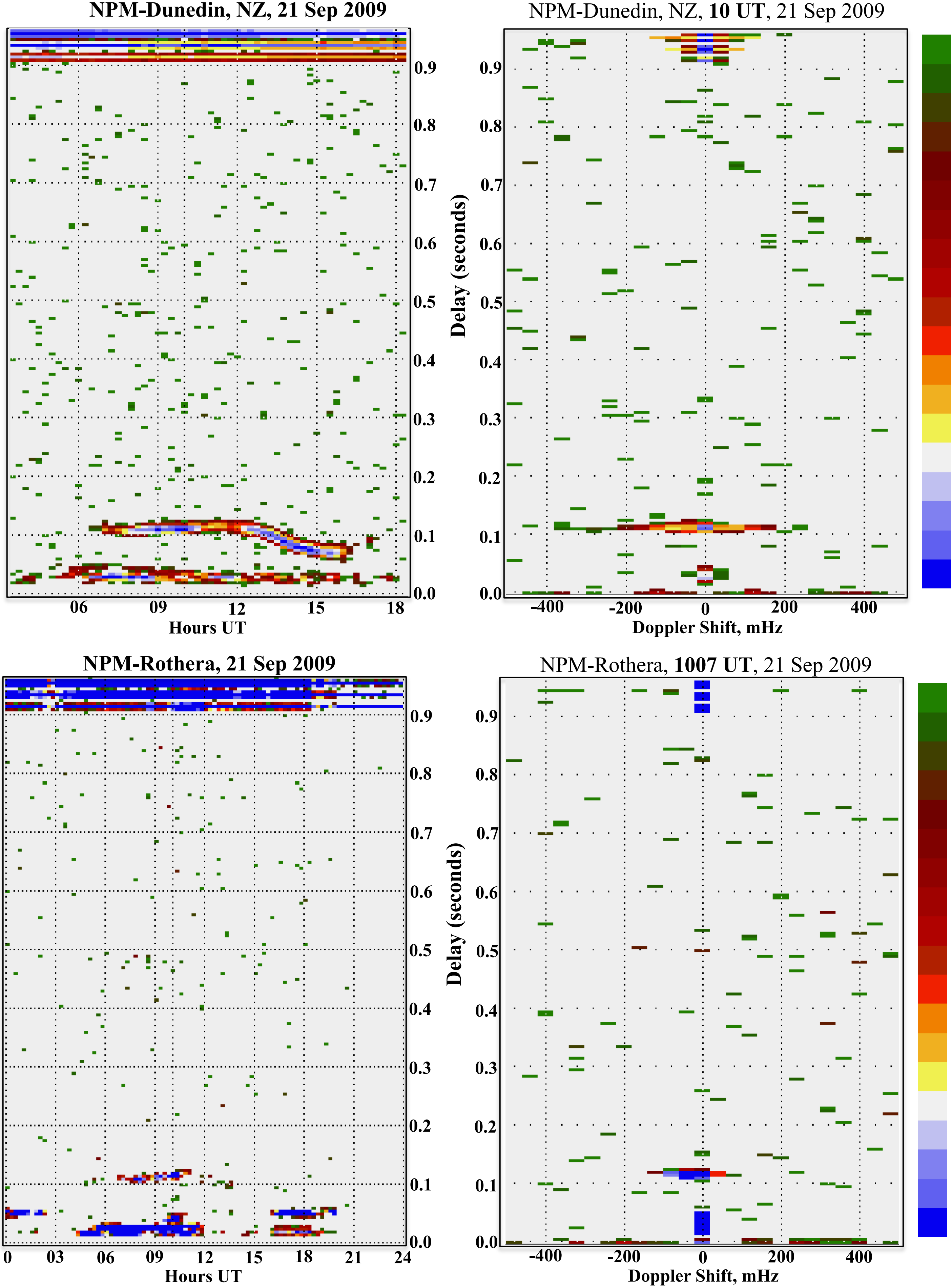
NPM-Rarotonga, 28 Aug 1996
NPM-Dunedin NZ, 28 Aug 1996
NPM-Rarotonga, 06 Sep 1996
NPM-Dunedin NZ, 06 Sep 1996
Delay (seconds)
Hours UT
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
06
09
12
15
18

Figure 5.



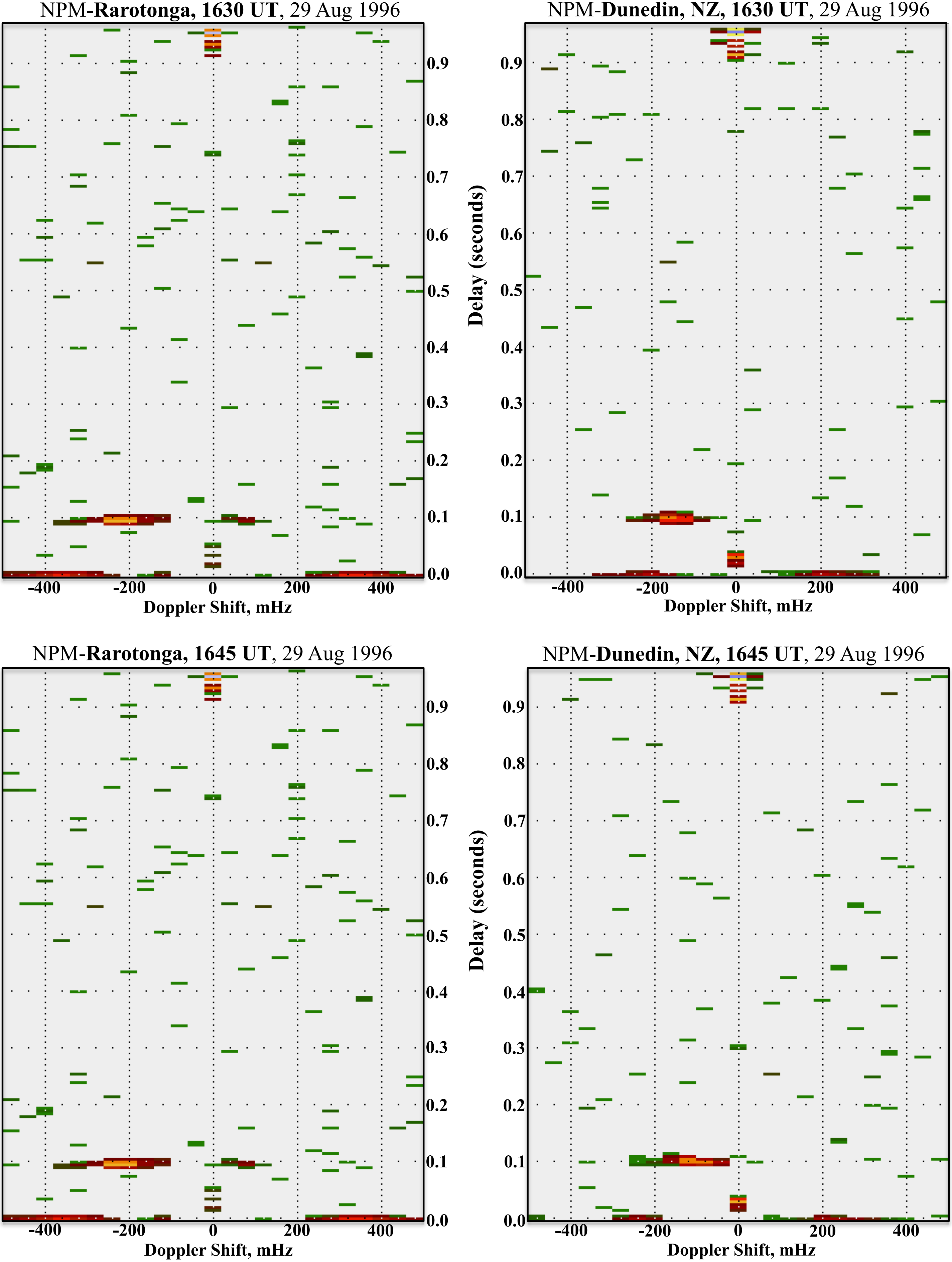
NLK-Rarotonga, 02 Sep 1996
NLK-Dunedin, NZ, 02 Sep 1996
NLK-Rarotonga, 03 Sep 1996
NLK-Dunedin, NZ, 03 Sep 1996
Delay (seconds)
Hours UT
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
06
09
12
15
18

Figure 6.



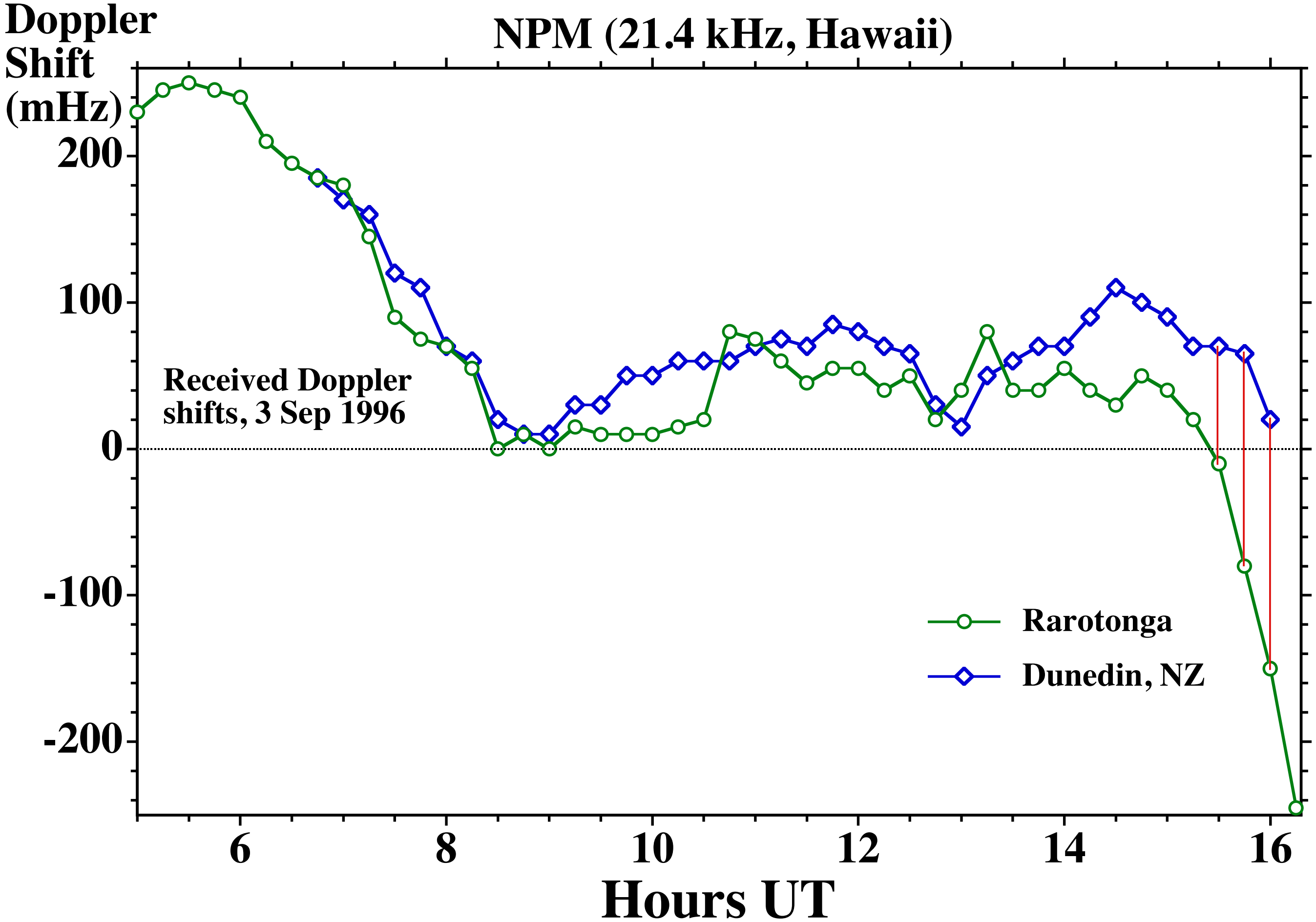
NPM-Dunedin, NZ, 21 Sep 2009
Hours UT
NPM-Dunedin, NZ, 10 UT, 21 Sep 2009
Delay (seconds)
Doppler Shift, mHz
NPM-Rothera, 21 Sep 2009
Hours UT
NPM-Rothera, 1007 UT, 21 Sep 2009
Delay (seconds)
Doppler Shift, mHz

Figure 7.



NPM-Rarotonga, 1630 UT, 29 Aug 1996
NPM-Dunedin, NZ, 1630 UT, 29 Aug 1996
NPM-Rarotonga, 1645 UT, 29 Aug 1996
NPM-Dunedin, NZ, 1645 UT, 29 Aug 1996
Delay (seconds)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
-400
-200
0
200
400
Doppler Shift, mHz

Figure 8.


Doppler
Shift
(mHz)
NPM (21.4 kHz, Hawaii)
200
100
0
-100
-200
Received Doppler
shifts, 3 Sep 1996
Rarotonga
Dunedin, NZ
6
8
10
12
14
16
Hours UT