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Arrival time difference lightning detection systems in the meteorological aids service in operation below 20 kHz

RS Series

Remote sensing systems

International Telecommunication Union

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REPORT ITU-R RS.2184

Arrival time difference lightning detection systems in the meteorological aids service in operation below 20 kHz

(2010)

TABLE OF CONTENTS

Page

1 Summary

This Report describes the general operational and technical characteristics of the arrival time difference (ATD) system of the meteorological aids services operating in the frequency range below 20 kHz.

2 Introduction

This ITU-R Report characterizes the technical properties and operational characteristics of the ATD system operating in the meteorological aids service in the frequency range below 20 kHz.

3 ATD network basics

The purpose of this section is to address the use by the meteorological aids services of frequencies below 20 kHz.

Long-range lightning detection using observations near 10 kHz has been performed since 1939, originally with a very manpower-intensive system measuring the direction from which signals were received, but since 1987 detection has been carried out with an automated Arrival time difference system (ATD) using the time differences of signals received to derive strike locations.

The ATD system utilizes a network of “detector” out-stations to monitor spectral emissions of cloud to ground lightning strikes centred between about 5 and 20 kHz. At these frequencies the sky waves, reflected off the ionosphere, propagate for very large distances with relatively little attenuation and are preceded by a ground wave at shorter ranges. Thus, it is possible to receive the emissions from the cloud to ground strokes at thousands of kilometres from the stroke location. A distributed network of ground based sensors can locate the origin of the lightning stroke, using the time differences between the arrivals of the lightning emission at the individual sensor sites.

At June 2010, the network comprised 11 sensors distributed across Europe from Iceland to Cyprus, operating in collaboration with Finland, France, Germany, Iceland, Ireland, Portugal and Switzerland.

The network configuration is shown in Fig. 1.

A further sensor has been placed in La Reunion (in the Indian Ocean to the east of Madagascar) to evaluate improvements in location for Africa, but this is not yet processed as part of the operational system. In the immediate future new sensors are to be installed in Croatia, at some sites in Africa, South America, the Middle East and in western Asia, and in the long term there should be opportunities to extend the system to provide global coverage.

This and other intended sensor locations are shown in Fig. 2.

FIGURE 1

The current ATD system sensor network

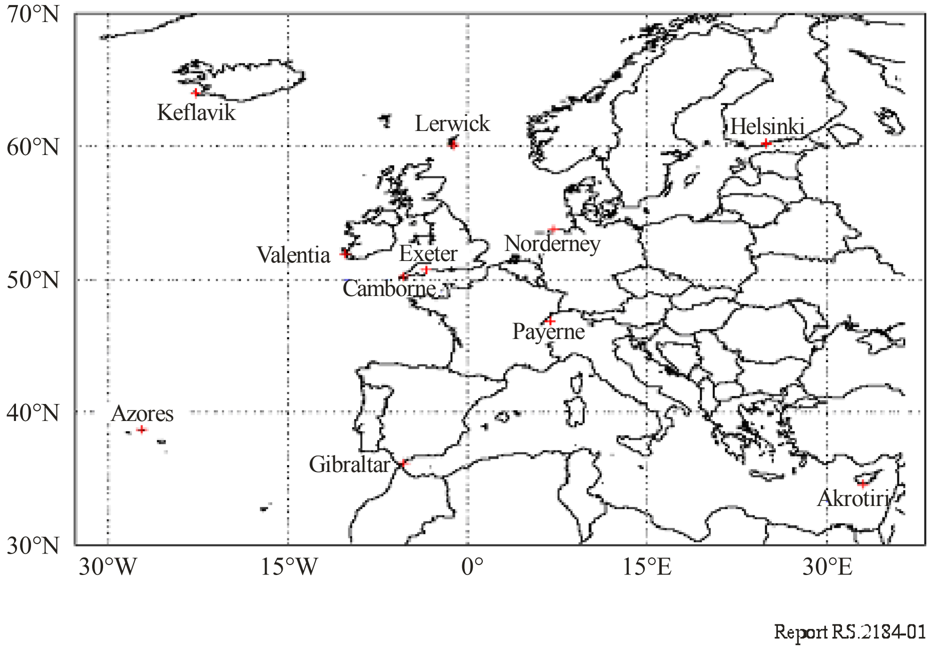
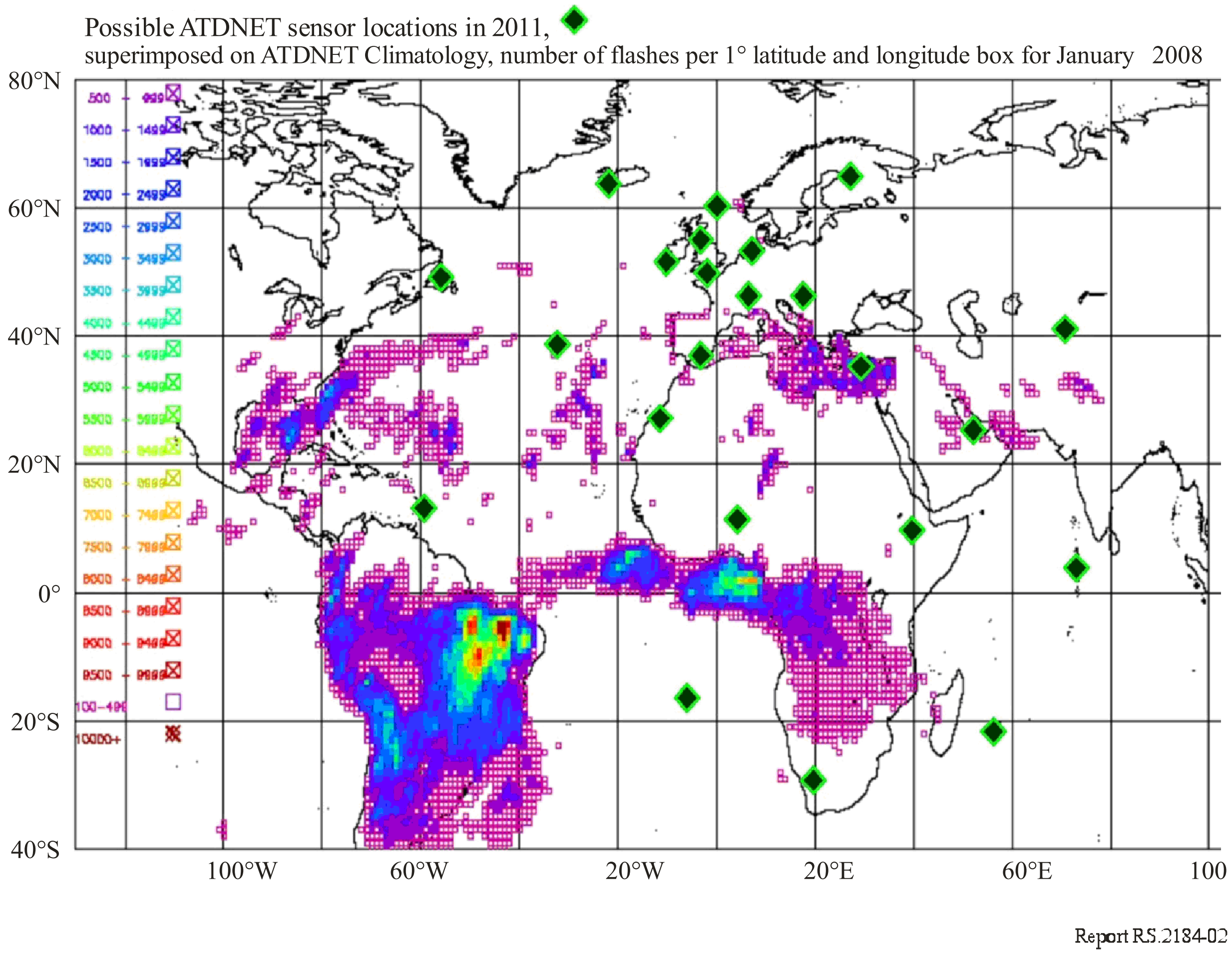


FIGURE 2

New and proposed locations of ATD system

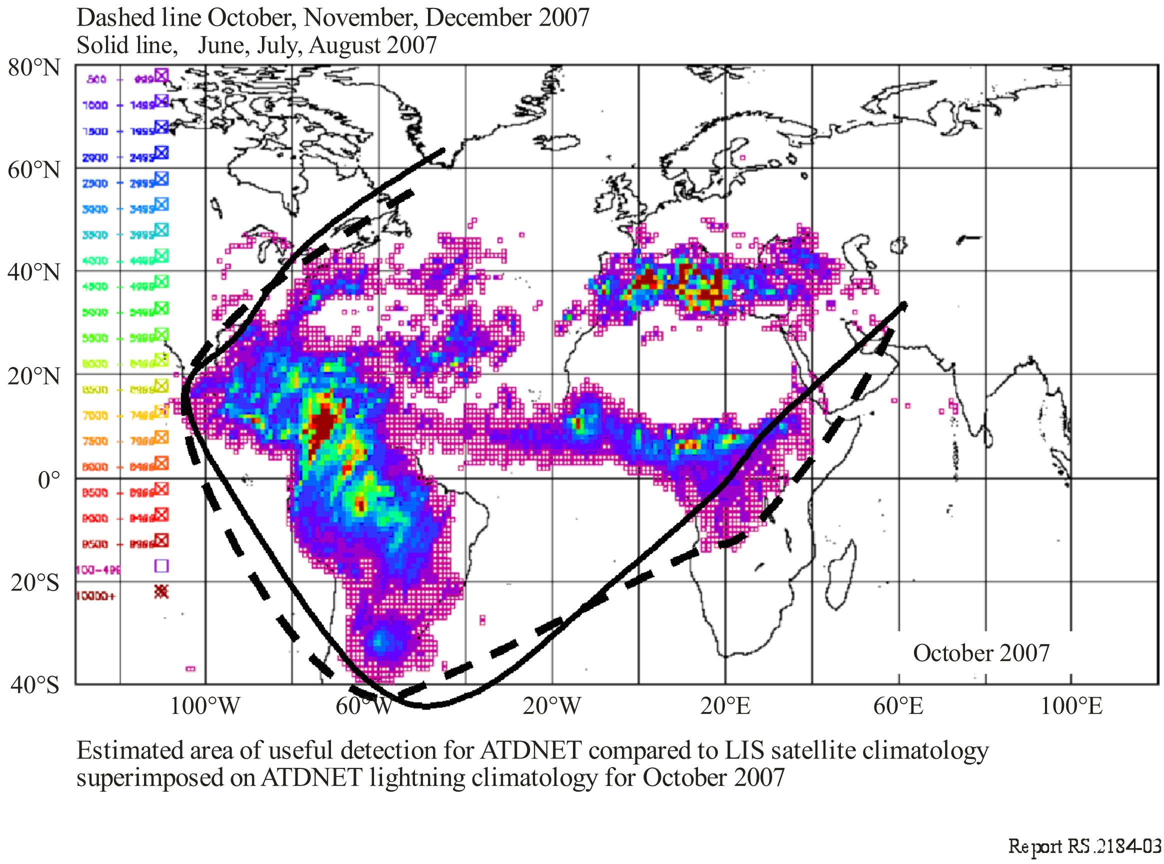


3.1 ATD network service area

The ATD network can provide a 24-hour thunderstorm detection service over the areas shown in Fig. 3. The area of coverage is governed by the properties of sferic[1] propagation, with least loss of sensitivity with distance travelled occurring along sea tracks. In South America, Central America the Caribbean and North and West Africa the system provides useful thunderstorm detection throughout the day. South Africa is well outside of the Service Area covered throughout the day, but work is under way in extending the ATD service area to cover the whole of Africa.

FIGURE 3

ATD system network coverage



3.2 ATD network detection output data

The typical output from the system is illustrated in Fig. 4, where the lightning locations have been detected at a time of year when there are few thunderstorms in Europe, with intense activity in Central Africa, the Caribbean and parts of South America.

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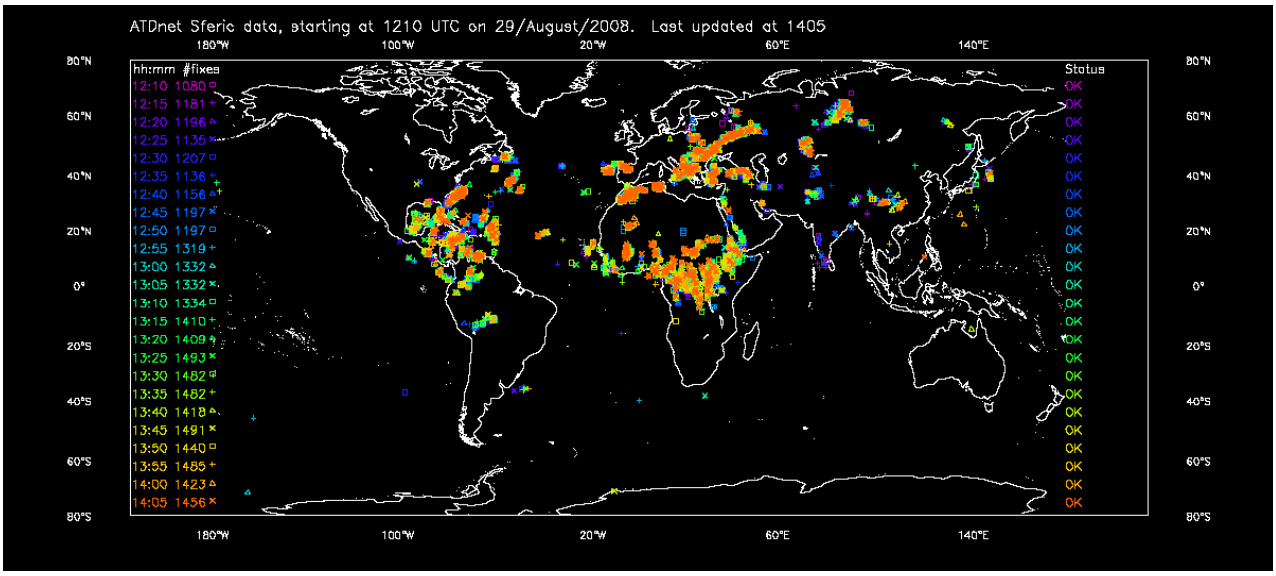
[1] Sferic: A lightning generated electromagnetic signal (abbreviation for radio-atmospheric).

FIGURE 4

Example of two hour's lightning detection output around the world from a long-range lightning detection system based in Europe, the numbers on the left show the number of lightning strokes detected in each 5 min, sensors operating at 13.733 kHz



Report RS.2184-04

Now, with modern sensor systems and communications it is possible to monitor the radio frequency received at the sensor in real time. The optimal frequency for ATD measurements is around 9.76 kHz. Recent monitoring (2004) showed that it was not practical to use this frequency at all the sensor sites (particularly at Gibraltar and at Reunion in the Indian Ocean), because of powerful transmissions near 10 kHz in some locations. This adversely impacted the performance and accuracy of the system. Due to this, the system now operates at 13.733 kHz as noted in Fig. 4. Note that, before this time, the lightning detection systems have coexisted with the existing services operating below 20 kHz without any problems.

The data provided by the ATD system is used by meteorological organizations worldwide and contributes towards safety of life, both in terms of forecasting for public safety and safety in forecasting aviation operations, especially over the oceans, and large areas of land, where national lightning detection systems do not exist. As well as the dangers of the lightning strike itself, thunderstorms can result in intense precipitation with consequent flooding, severe icing, wind shear, turbulence and gusting winds. Additionally it has the potential to give a service across Africa in support of disaster risk reduction initiatives.

3.3 Lightning detection method basics

The system uses arrival time difference techniques for lightning detection by measuring differences between sferic arrival times of VLF signals emitted by lightning strikes at network outstations. Spectral emissions from lightning strikes propagate within the VLF earth-ionosphere wave guide at ranges of up to many thousands of kilometres from the strike location.

The ATD system is entirely passive and measures the vertical component of the VLF signal, which enables lightning strikes to be fixed at ranges of thousands of km. The horizontal ground component could be used to fix strikes up to a few hundreds of km, up to maximum of about 400 km. There is not much of a seasonal or diurnal propagation effect. The long-range propagation of the vertical component is hardly affected, but detection capabilities at shorter ranges can be somewhat less at night because of interference between the various modes of the sky waves. Propagation characteristics of the VLF lightning emission mean that the best frequencies for long-range detection are below 20 kHz. This is the frequency range with highest emission from cloud to ground lightning strokes and where the propagation characteristics become increasingly favourable.

4 ATD outstations

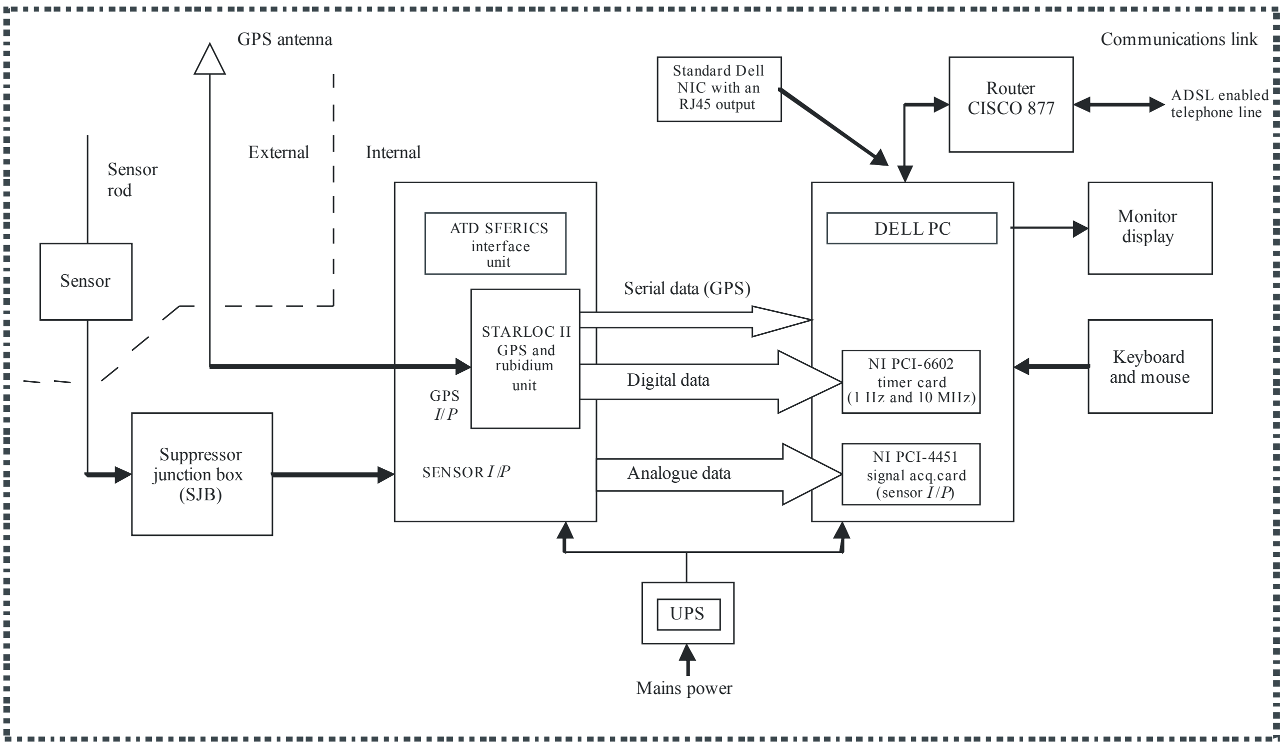
The purpose of this section is to address the characteristics and processes in use of outstations within the ATD Network.

4.1 Outstation configuration

The constituent items shown in Fig. 5 are described in §§ 4.2 to 4.2.3.

FIGURE 5

Outstation configuration



Report RS.2184-05

4.2 Sensor unit

An outdoor-mounted whip antenna receives radio waves over a wide frequency range, up to several hundred kHz. The electric field variations are capacitively coupled to the sensor unit and converted to a differential voltage. The sensor unit has a capacitively coupled essentially flat frequency response to signals over the frequency range 40 Hz-400 kHz.

4.2.1 Starloc II GPS and rubidium unit

The Starloc unit uses a high precision rubidium oscillator calibrated from GPS time pulses to provide one pulse per second (1 PPs) and also a phase coherent 10 MHz reference signal.

4.2.2 Signal acquisition card and counter/timing card

The signal acquisition card and counter/timing card includes the following features:

– simultaneous sampling on two channels;

– programmable gain, –20 to +60 dB;

– anti-alias protection;

– flat group delay.

At present two input channels are connected to the same ATD sensor. One channel is operated with a higher gain than the other in order to maximize the dynamic range of the system. The software normally selects data from the high gain channel, but switches to the low gain channel if the former is overloaded.

The sampling rate is set to 109.864 kHz. Each ADC channel has a 16-bit A to D converter. Given that a signal of only 6 bits will still yield an acceptable waveform, the dynamic range is 2^{10} in amplitude, or 60 dB. By running one channel at a gain level 10 or 20 dB higher than the other the effective dynamic range of the system can be increased to 70-80 dB. This should allow both near and distant flashes to be reported with no change in hardware gain settings. In practice, overlap of sferic waveforms could become a problem if there is intense local activity.

The channels have built-in overload protection. A hardware gain setting of 10 dB in the high-gain channel is recommended; this gives a maximum signal of ±3.2 V and allows the receiver to 'see' sensor noise adequately. 0 dB in the low-gain setting gives a maximum of ±10 V.

4.2.3 Summary of technical characteristics of ATD stations

Technical characteristics of ATD BBB is presented in Table 1.

TABLE 1

Technical characteristics of the ATD system

Receiver (sensor unit) amplifier gain	12 dB if switched on by control software (normally the case) otherwise zero
Centre frequency	13.733 kHz[(1)]
Measurement bandwidth	3 kHz
Total passband	6.87 to 20.6 kHz
Antenna type and directivity	V-pol, omnidirectional whip
Software filter	Broad-band high-pass filter (3 dB at 2.0 kHz), cascaded with low-pass filter (0.28 dB pass-band limit at 17.75 kHz)
Software narrow-band pass filter	3 dB bandwidth 2.5 kHz 10 dB bandwidth 4.3 kHz 20 dB bandwidth is 5.7 kHz
Typical receiver noise floor[(2)]	−70.4 dBm/5 kHz
Signal-to-noise ratio (*S*/*N*)	Values of < 15 dB are rejected as the phase accuracy would be degraded
Permissible interference-to-noise ratio (*I*/*N*)	−4 dB

(1) The centre frequency of 13.733 kHz is used for current ATD measurements due to current spectrum environment and a reduced possibility of harmful interference to ATD measurements at this frequency. The optimal frequency for ATD measurements is around 9.76 kHz.

(2) These values are relative to the input to the signal acquisition card, ignoring contribution from atmospheric noise.

4.3 Outstation functions

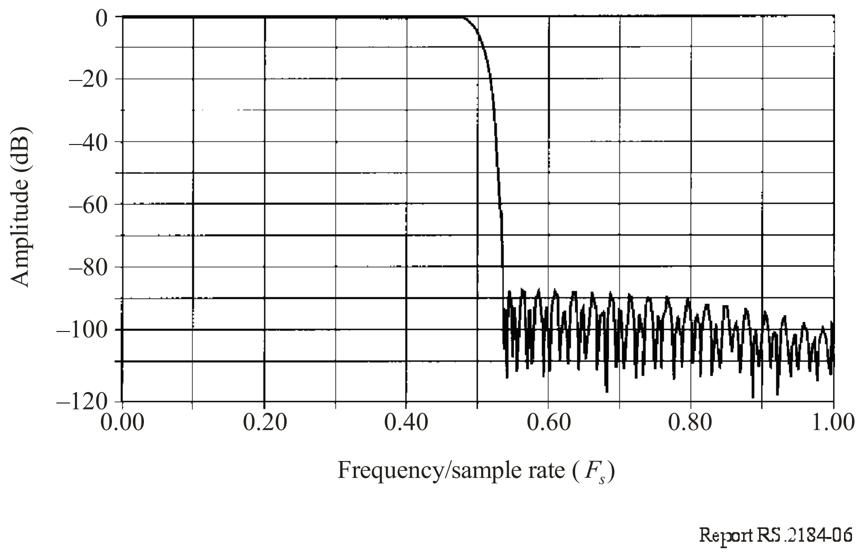
4.3.1 Signal processing

The interface unit is configured with a base clock of 20 MHz (using its internal clock). The sampling period in the ATD outstation is 9.1 µs with a Nyquist at 54.95 kHz. The frequency response curves (Fig. 6) shows that the response is flat and alias-free up to 0.464 × sampling frequency (0.892 × Nyquist).

This means that frequencies detected would be alias-free up to 49.01 kHz, well above the maximum frequency of interest.

FIGURE 6

NI-4451 digital filter characteristics



4.3.2 Digital processing

Note that the values indicated here assume a central detection frequency of 13.733 kHz.

Every 9.31 ms carry out the following operations for each channel:

1. Acquire a 512 point waveform from each channel, with samples every 9.1 µs. Pass the waveform to the host memory for short-term storage.
2. As each 3 584 points comes in, perform an FFT using the most recent 4 096 points. Frequency shift so that 13.733 kHz is shifted to DC. Select the 512 complex points centred on DC and low-pass filter by *multiplying* the frequency-domain signal by the required filter functions. These are digital versions of earlier model hardware filters, namely:
   – High pass Butterworth;
   – Low pass Chebychev;
   – Band pass Bessell.
3. Multiply by the required "notch filter" profile in order to remove the effect of any frequencies that are believed to be contaminated by man-made transmissions. Retain the original un-nulled spectrum for use in Step 5. The frequency resolution is 13.41 Hz.
4. Inverse FFT back to time domain, discard the 32 points at each end of the time sequence, and append the waveform to the previous waveform segment, together with the time stamps from the counter readings. The waveform samples are in complex representation at this stage, with 72.8 µs between samples.

5. Search for significant flash events by looking for periods in which the SNR (maximum amplitude divided by median, taken over 128 points) exceeds a pre-defined value and/or the maximum amplitude exceeds a pre-defined value. For such periods, the 128-point waveform centred on the maximum is Huffman encoded and stored ready for reporting to the control station.

4.3.3 Waveform reporting

Event files are compiled containing, for each event:

a) Packed (Huffman encoded) complex sferic waveforms.

b) Epoch (precise time to the nearest 0.1 µs) of the centre of the transmitted waveform.

c) Relative amplitude of the peak of the waveform.

These files are transmitted from all active outstations to the central flash location processor (at Exeter) at regular intervals, e.g. every 20 s.

5 Flash location processor functions

This section describes the functions of the flash location processor (FLP) based in Exeter.

5.1 Overview of wave form processing

The ATD flash location processor uses coherent waveform correlation techniques in order to measure the arrival time differences of the sferic waveforms to a precision of a few microseconds. Basically this process consists of the following:

– Waveforms (amplitude against time) with precise epochs are received from all the outstations.

– Groups of waveforms close together in time are collected for possible flash location.

– A reference station is selected for each group.

– Waveforms from each non-reference station are correlated with the reference station waveform to estimate time differences ΔT. This is necessary to work with the sky waves and waveguide propagation that are essential for long-range operation.

– Arrival time differences are then used to calculate lightning position by an iterative method.

5.2 Wave form extraction

Waveforms from the outstation are unpacked so that we have 256 amplitudes, which are defined to be the 128 real points, followed by 128 imaginary points, of a complex waveform. The waveform is a frequency-shifted and band-limited version of the original sferic waveform.

It covers the frequency range 6.87 kHz to 20.6 kHz. Samples are separated by 72.8 µs.

The original frequency domain spectrum (as determined in § 4.3.2 Step 4) is then restored by FFT.

There are various possible normalization conventions in defining FFT. The convention used is:

$$f_k = \frac{1}{N}\sum_{j=0}^{N-1} T_j \exp(-2\pi ijk/N) \qquad T_k = \sum_{j=0}^{N-1} f_j \exp(2\pi ijk/N)$$

where:

f: frequency spectrum

T: time domain waveform

N: number of points and $i^2 = -1$.

5.3 Selection of reference station

Two rules are used to weight selection of the reference station:

- Stations with short waveforms are preferred.
- Stations are preferred whose sferic arrival time is towards the median of those received, i.e. they are neither closest nor furthest away from the lightning location.

5.4 Spectral corrections

The sferic wave propagates in a waveguide system bounded by the Earth and the ionosphere. It can be shown that for a wave propagating in a waveguide the relationship between wave number ($k = 2\pi/\lambda$) and angular frequency ($\omega = 2\pi f$).

$$k = \frac{1}{c}\sqrt{\omega^2 - \omega_0^2}$$

here c is the velocity of light, ω_0 is the "cut-off frequency" for the waveguide. No energy can propagate freely at a frequency below the cut-off frequency. Consequently the phase velocity (v_p, propagation velocity of the wave fronts) and group velocity (v_g, propagation velocity of the energy) are not equal.

To allow for this, a phase correction is applied at all frequencies in the spectrum, which varies in proportion to the time difference and in proportion to the difference between the squares of the frequency and the central detection frequency 13.733 kHz. (The correction is zero at the central frequency itself.)

The phase correction is:

$$\pi f_0^2 (f^2 - f_1^2) / (f_1^2 f)\, \Delta t$$

where:

f_0: waveguide cutoff frequency (of the order 1 kHz)

f: frequency to be corrected

f_1: central detection frequency e.g. 13.733 kHz

Δt: time difference.

Thus the phase shifts are corrected by manipulating the waveform spectra of the non-reference stations and taking the reference station as "truth".

If ΔT exceeds about 4 000 µs (which is not uncommon for overseas stations) then uncorrected time differences are likely to be ~100 µs in error. Time differences can reach 10 000 µs for Cyprus.

Values of ΔT are computed on the basis of the timing of the largest peak in the 128 point waveform.

Visual superposition of waveforms shifted by time differences with and without spectral calibration have indicated the value of doing this. This is an indication of the importance of having good representation over the frequency range.

5.5 Time difference extraction

The waveform reconstruction process results in waveforms, T_i, of 1 024 complex samples, separated by 9.10 μs. The absolute epoch of each waveform is the time of the centre point.

To determine the time difference between two waveforms we compute the correlogram, *C*. This is defined as the convolution of the first waveform with the time-reverse of the second waveform. (So if the waveforms are identical the peak of the correlogram will be at element 0). Convolution in the time domain is equivalent to multiplication in the frequency domain, and time-reversal is equivalent to taking the complex conjugate in the frequency domain, so:

$$C = \text{FFT}^{-1}\left\{F_1 F_2^*\right\}$$

where F_i = FFT(T_i), FFT denotes the forward Fourier transform, FFT^{-1} denotes the inverse and * denotes complex conjugate. The correlogram is pure real.

Since the original time domain points are sampled every 9.10 μs then so will the correlogram points. To find the maximum of the correlogram to high precision we need to compute the differential of the correlogram. To differentiate in the time domain multiply by ω in the frequency domain (ω being 2π × frequency, and of course increases linearly from zero at the first element). Then inverse FFT back to time domain the differential appears in the imaginary component. So to obtain simultaneously both the original correlogram and its differential compute:

$$C' = \text{FFT}^{-1}\left\{F_1 F_2^* \times (1+\omega)\right\}$$

The real part of C' identifies the largest peak, while interpolation of the imaginary part of C' to find its zero crossing gives the true precision time difference.

Also the following is used to compute the correlation signal-to-noise ratios that are used in quality control.

– Absolute signal-to-noise ratio (ASNR) is a measure of how much the flash stands out above noise. Positive values are best.

$$ASNR = 10\log_{10}\left(\frac{C_{max}^2}{\overline{T_1^2}\,\overline{T_2^2} - C_{max}^2}\right)$$

where:

C_{max} = peak value of correlogram *C*

$\overline{T_1^2}$, $\overline{T_2^2}$ = mean values of waveform amplitudes in the two waveforms correlated.

This ASNR should not be confused with the signal to noise ratio of an individual waveform as determined at the outstation (§ 4.3.3 (5)).

– Relative signal-to-noise ratio (RSNR) is a measure of the probability of the time difference being 100 μs in error and is obtained from the value of *C* for the next highest correlogram peak. Always negative.

$$RNSR = ASNR_{next\ highest} - ASNR_{highest}$$

Time difference variances are set as follows:

Basic TDV = Epoch variance + (8 μs)^2

If RSNR > −2: TDV = Epoch variance + (100 μs)^2

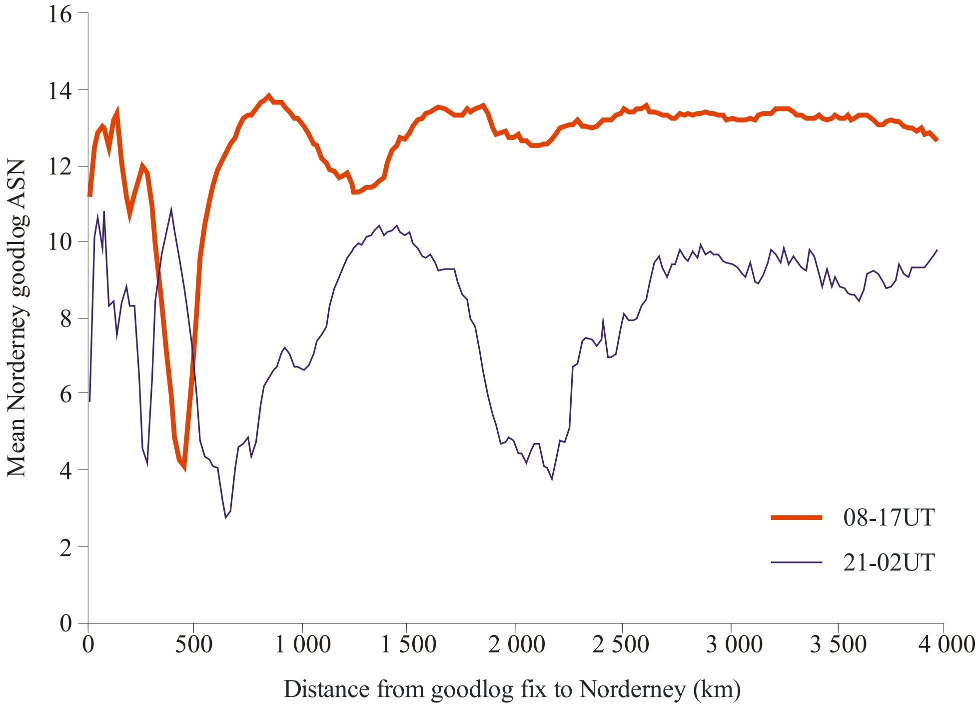
If ASNR < −5: TDV = TDV + (500 μs)^2

The 8 μs is supposed to represent the combination of encoding/digitization errors and propagation effects. The above replaces a rather complicated formula in the original ATD specification.

For illustration purposes a diagram showing the mean absolute signal-to-noise ratio (ASN) with distance from lightning fix location during the day and night is shown in Fig. 7.

FIGURE 7

Mean absolute signal-to-noise ratio (ASN) with distance from lightning fix location during the day and night for signals received at Norderney



Report RS.2184-07

5.6 Principles of flash location

A geometrical method is used first to get an approximate fix.

We need to find the flash location that finds the best fit between the theoretical time differences, ΔT_{th} and the measured time differences ΔT_m. In other words, minimize:

$$\sum_{i=1}^{M} \frac{(\Delta T_{th} - \Delta T_m)_i^2}{\sigma_i^2}$$

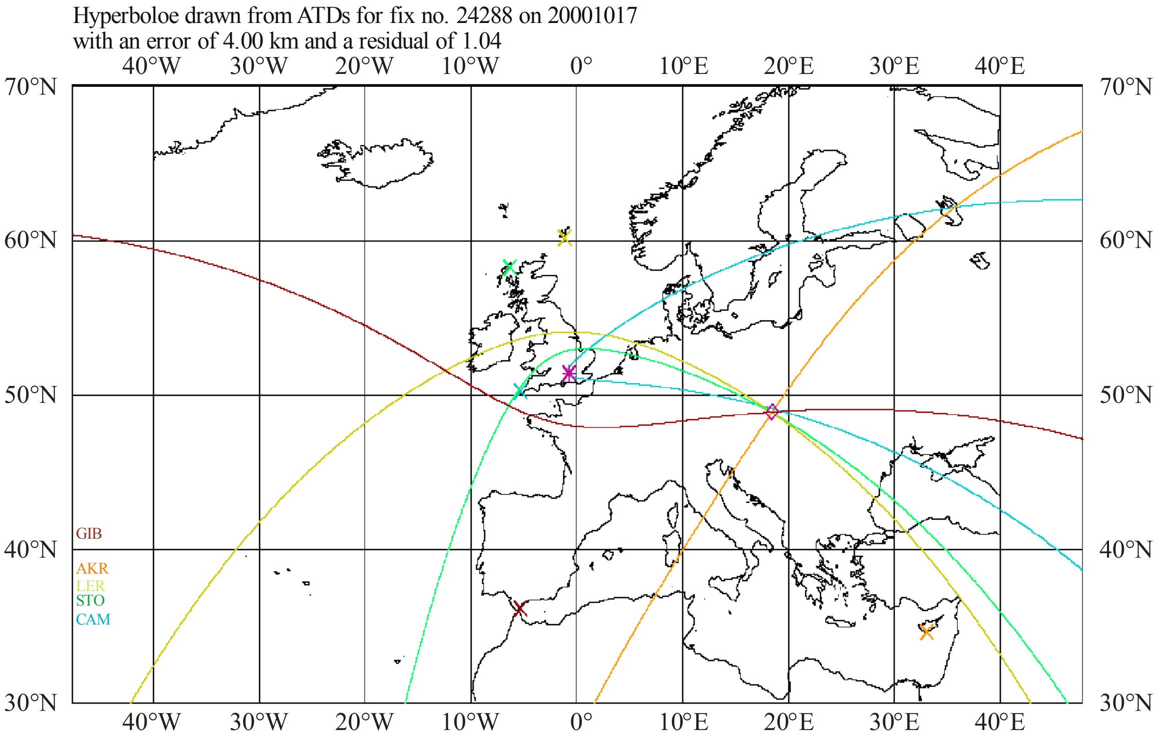
where there are M time differences, with variances σ_i^2. In theory this is a straightforward task: we use a suitable minimizer, combined with a routine for evaluating theoretical time differences, and expect that the final solution should not depend on the first guess position.

It is convenient to visualize the flash fixing process in terms of lines of constant time difference. For a pair of stations with a given time difference the locus of possible fix positions is a hyperbola (or rather its equivalent on the surface of a sphere) with foci at the station locations.

The best results from the network are achieved when waveforms are received at five or more sensor sites; this is shown in Fig. 8.

FIGURE 8

Hyperbola fixing from five outstations



Report RS.2184-08

6 Characterization of interference

The ATD lightning detection system relies on naturally occurring emissions from lightning strikes and can be badly compromised by interference from other man made sources. Therefore it is essential to identify when intermittent signals are interfering with sensor reception. Interfering signals are often transient, whilst others have specific repeat cycles. However because of long-range propagation of interfering signals, interference can affect many stations simultaneously and this does seriously degrade system performance.

There are two main sources of interference, high powered fixed systems and lower powered more mobile type applications.

A few relatively high powered fixed transmitters can adversely affect the performance of the system, limit the ability to be extended the current ATD network to provide wider coverage and in some cases can result in the total loss of data. The impact of such interference sources can have significant impact to more than one sensor site and impact whole or substantial parts of the ATD network

Lower power mobile interference sources can also lead to a significant, but more local, degradation of data quality within the ATD system.

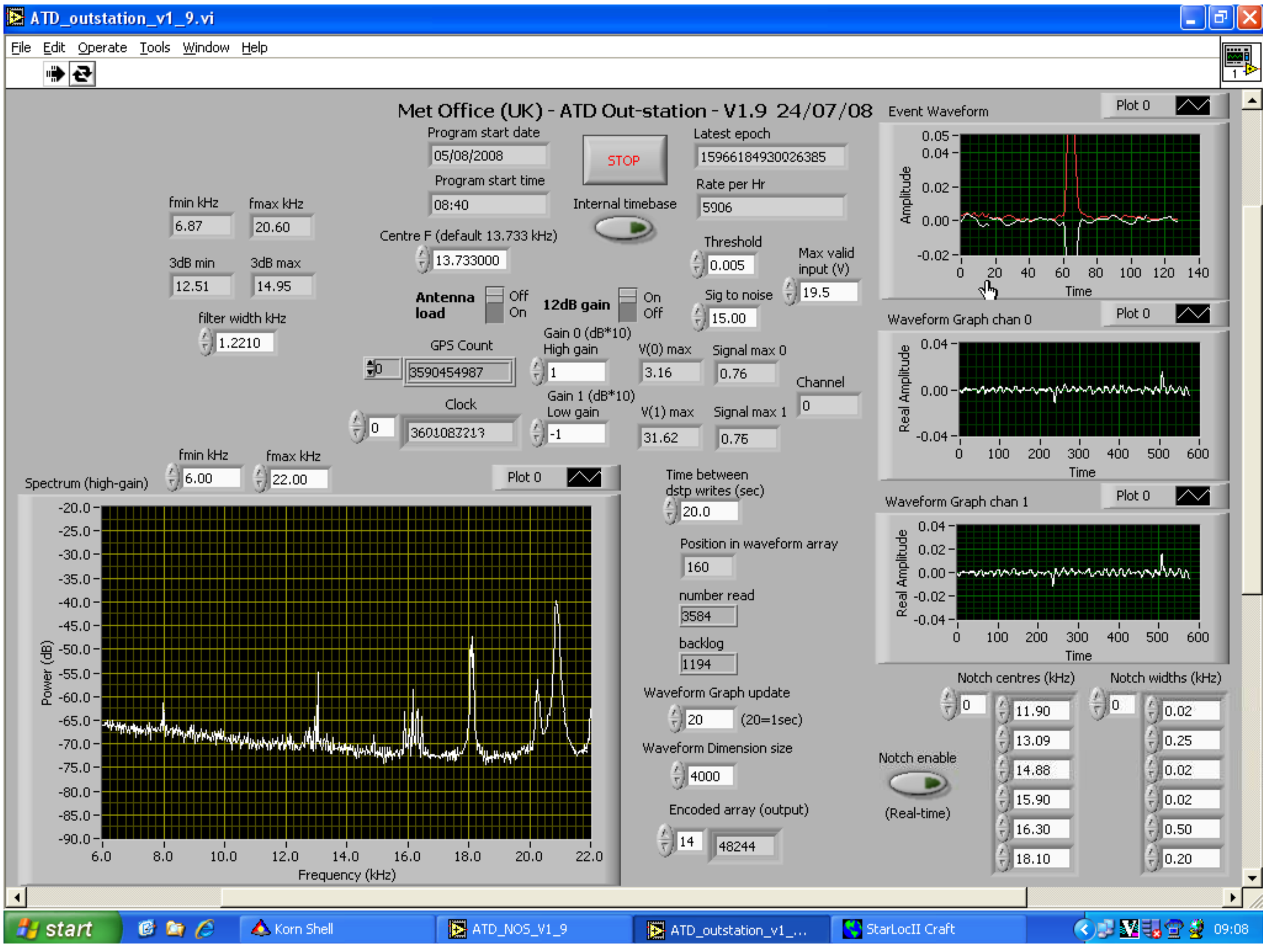
6.1 Impact of interference

Interference can reduce the number of events seen at one or more outstations and/or cause inaccuracy in measuring the time differences between one or more pairs of stations. The former case may reduce the number of fixes in an area, thus reducing the apparent severity of a storm. An example when the number of events was seriously reduced is described in § 6.3. Time difference inaccuracies may result in "spurious fixes" in the wrong locations. For example, in Fig. 8 if the Akrotiri hyperbola (orange) was incorrect it could result in a fix in the wrong position, particularly if the other hyperbolae were to intersect at even smaller angles than shown in that example, with little redundancy.

6.2 Examples of interference received at various ATD network outstations are shown in Figs 9 and 10

FIGURE 9

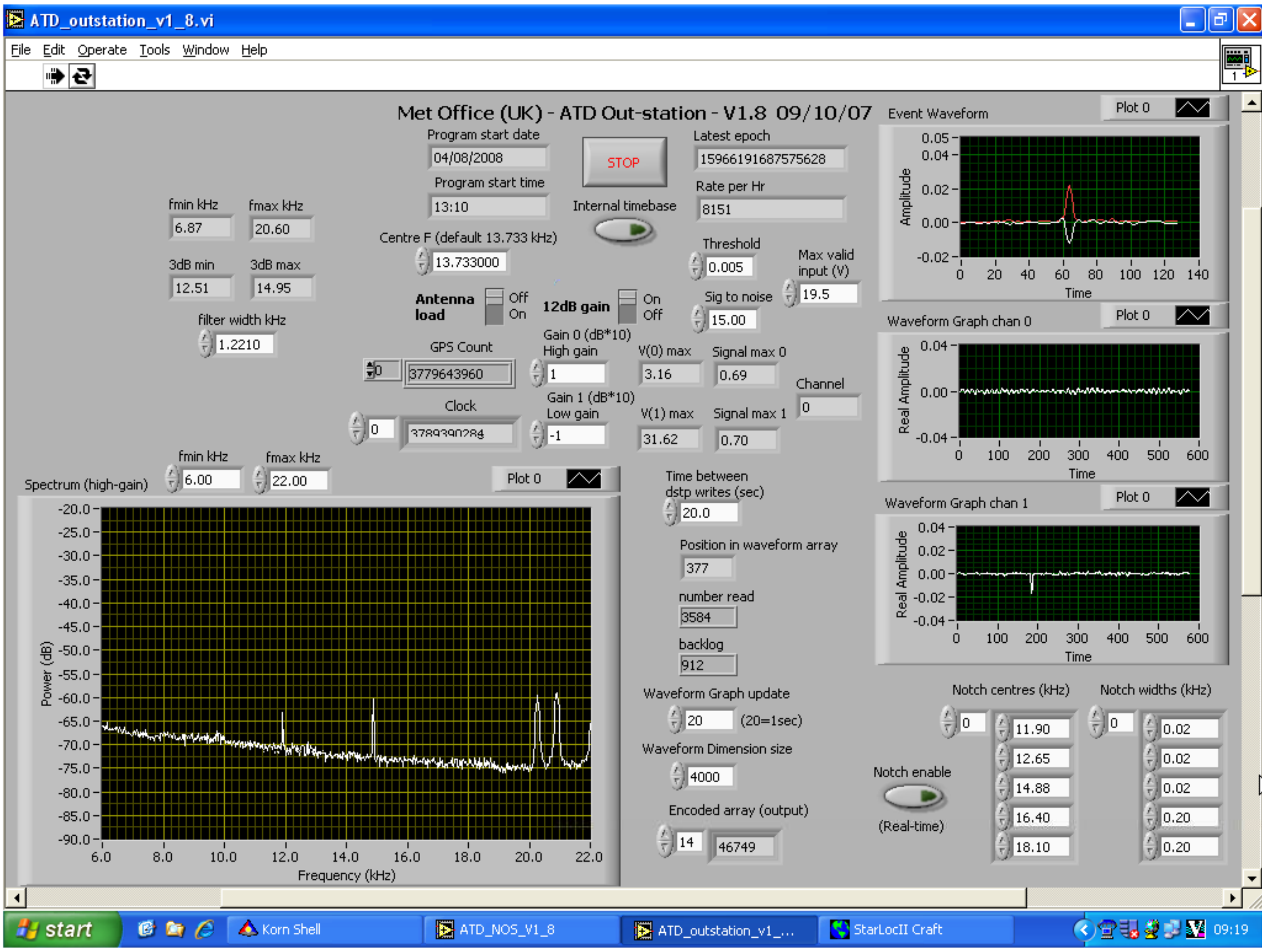
Interference received at Payerne outstation (see frequency spectrum plot at bottom left)



Report RS.2184-09

FIGURE 10

Interference received at the Helsinki outstation



Report RS.2184-10

Looking at these examples, which are typical, we can see that the transmitter sources are about 20 dB to 30 dB above the noise floor.

6.3 An example of intermittent interference emanating from Norway and received at Lerwick, Keflavik and Camborne

On 12 April 2007, a source of the problem which caused a much-reduced volume of fixes at the hours beginning 00, 04, 08, 12, 16, 20 GMT was identified. An intermittent source of interference at about 16.5 kHz was noticed with a maximum peak power about −49 dB at Lerwick, −50 dB at Keflavik, and −60 dB at Camborne.

This source of interference caused a reduction in output fix events per hour at Lerwick from between 64 to 71%. The transmission stopped at 1 355 GMT and the number of events restored to between 15 000 and 20 000 events per hour. Keflavik behaved similarly, and Exeter was also affected less significantly.

There is a 16.4 kHz transmitter at Helgoland in Norway which was identified as the source of the problem. A software notch filter (see § 7) has been installed at the above mentioned stations, and this is largely effective in mitigating problems cause by this transmitter (which still operates at times). However, the reduction in sferic events here illustrates the potential severity of an undetected new transmission, even if the interference frequency is well away from the central detection frequency. Currently there is no automatic method of detecting new sources of interference, and a significant degradation in performance could remain undetected for some days, or for longer if the degradation is not large enough to be noticed beyond natural variations in activity.

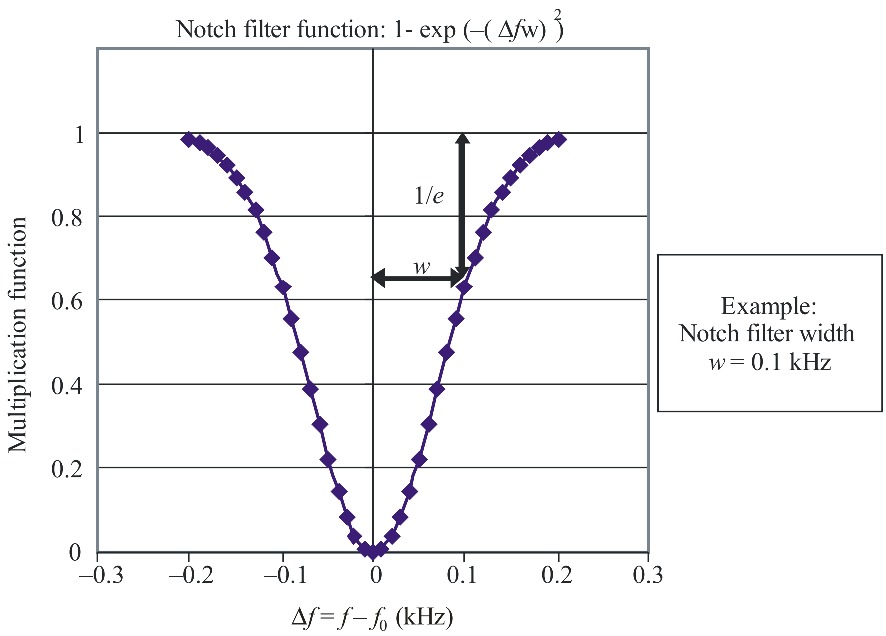
7 Interference mitigation

Notch filters are provided for removing the effects of interfering VLF radio transmissions, which could in principle be highly coherent between outstations and could give rise to errors. Although in earlier (obsolete) outstations they had been implemented as hardware band-stop filters, they are now implemented in the outstation software. These software notch filters do not suffer from group delay problems. However, there is a risk in any filtering of the energy blocked by a notch filter and the impact this has on system accuracy and performance.

The software notch filter function has the form $1 - \exp(-(\Delta f/w)^2)$, as indicated in Fig. 11. f_0 is the nominal frequency of the notch, Δf is the displacement of the frequency f from f_0, and w is its width. This function is the multiplier referred to in § 4.3.2, Step 3. At the notch filter nominal frequency the signal is zeroed, but the reduction in signal becomes negligible at twice the notch width.

FIGURE 11

Notch filter function



Report RS.2184-11

7.1 Limits to usefulness of notch filters

Notch filters tend to be useful in the following situations:

1. When the interfering source bandwidth (and hence notch filter width) is small (of the order of 0.1 kHz).
2. When the frequency is well away from the central detection frequency (now 13.733 kHz).
3. When the source of interference is known in advance (even if intermittent) so the filter can be implemented.

Notch filters are not very useful, if at all, when:

1. When the interfering source bandwidth is large (of the order of 1.0 kHz or more) and the frequency is close to the central detection frequency (now 13.733 kHz).
2. When a new source of interference occurs and has not been detected.