Accuracy of Virtual Height Measurements with Digisondes

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Abstract

We analyzed precision-ranging ionograms taken by the Digisonde Portable Sounder (DPS-4) and its successor, the Digisonde 4D, to reveal a previously unnoticed negative bias in the virtual height values determined by the ARTIST-4 software using the trace lowering algorithm. Signal processing in DPS and Digisonde 4D is discussed, pointing to the digital pulse compression technique as the reason for a code-induced pulse widening that manifests itself as forerunner range bins. The forerunner bin is then mistaken for the leading edge of the echo. The effect is visible in ionograms from stations with high signal-to-noise ratio, in which case the widened pulse side lobes exceeds the background noise level. We present recommendations for the DPS and Digisonde 4D ionogram processing and analysis. Use of the precision ranging mode for routine measurements is strongly encouraged. ARTIST-5 version disables the trace lowering algorithms when ionograms obtained with pulse compression are processed. No change to analysis of Digisonde 256 ionograms is suggested.

Terminology

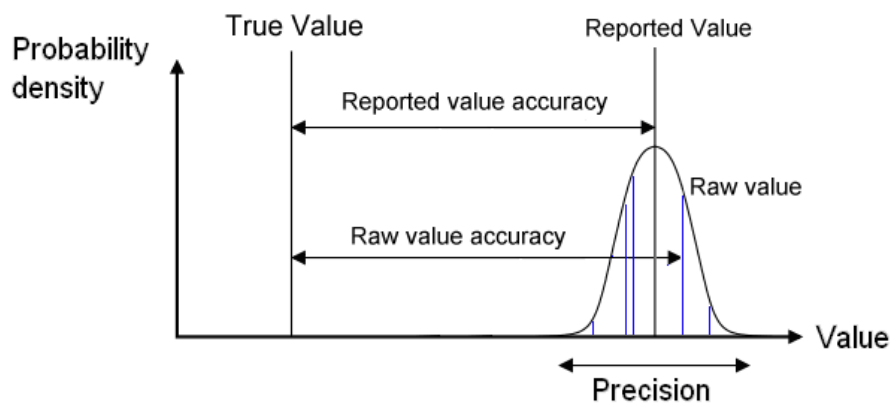|	
Raw Value	Single measurement of a physical quantity.
Reported Value	Value produced from a set of one or more raw values.
Error	Difference between a reported value and its true value known from an independent measurement.
Uncertainty	Estimated difference between a reported value and its true value when the true value is not known.
Bias	Systematic error in the reported value that persists over multiple observations of the same quantity.
Precision	Degree to which further measurements of the same quantity show the same result. Precision of the reported value is usually governed by the instrument precision, unless the physical quantity changes with time.
Imprecision	Degree to which further measurements of the same quantity show different result. Uncertainty of a single raw measurement includes bias and imprecision. Imprecision is sometimes referred to as *unbiased error*. By our convention, we do not use the term "error" unless the true value is known.
Accuracy	Agreement of a reported value with its true value. Figure 1 illustrates difference between accuracy and precision. A measurement can be accurate but not precise, precise but not accurate, both accurate and precise, or neither. Higher accuracy means lower bias.

Figure 1. Measurement accuracy (degree of closeness to the true value) and measurement precision (degree of repeatability of the value in subsequent measurements). Error of a single measurement includes bias and imprecision components.

Resolution	Smallest change in the true value that a measurement can detect. Resolution influences choice of the number of significant digits in presentation of the reported value. For single-valued measurements, resolution depends on the precision of the measurement. For multiple-valued measurements (e.g., arrival times of several echoes) it also reflects the ability of the instrument to resolve two closely spaced values obtained in one measurement.
Error Bar	An interval around the reported value that contains the true value at a pre-determined level of probability. Higher probability level results in wider error bar. Error bar is obtained by statistical evaluation of the errors obtained from a representative set of measurements for which true values are known from independent measurements.
Uncertainty Bounds	An interval around the reported value that is expected to contain the true value at a pre-determined level of probability. Higher probability level results in wider uncertainty bounds. The uncertainty bounds are provided for the measurement whose true value is not known. Common techniques for calculation of uncertainty bounds are (1) calculation of the measurement precision (e.g., standard deviation) from a set of available raw values, (2) attributing previously, independently evaluated error bars to the reported values (i.e., calibrating the instrument), and (3) use of the error bars obtained analytically under model assumptions about the noise affecting the measurement.

Background: Virtual Height Measurement in Ionosondes

Diagnostic capabilities of ionosondes vary depending on the instrument model; we will limit this discussion to evaluation of the ionospheric characteristics pertaining to the vertical profile of electron density. Measurement of such characteristics is based on the ability of the ionosonde to determine the virtual height h' of a particular electron density. In the classic "group path" approach to the task, the h' value is obtained from the signal travel time τ_{gr} between the leading edge of the transmitted pulse and the leading edge of the reflected signal. Use of the leading edge as the reference point on transmitted and received pulses is not optimal for waveforms without clearly defined edges, such as the Gaussian or half-sine shapes. However, multi-path propagation conditions in the ionosphere had influenced decision to emphasize the lower edge of the ionogram trace that corresponds to the shortest distance to the reflector and therefore closest to the vertical signal propagation [Piggot and Rawer, 1972].

Precision of a single h' measurement

Early studies of the classic τ_{gr} approach can be traced back to the 1950s; it was then noted that amplitude variations of the reflected signal inflict an uncertainty in τ_{gr} measurements [Lyon and Moorat, 1956]. Figure 2 illustrates measurement uncertainties associated with the use of the first echo point above the signal detector threshold, together with its suggested correction based on the measured pulse length w [Lyon and Moorat, 1956; Piggot and Rawer, 1972].

The measurement uncertainty of the signal time delay τ_{gr} has been formally studied in the radar community; the minimum *unbiased error*[1] of τ_{gr} for a single target was shown to be inversely proportional to the signal bandwidth Δf and the root of the signal-to-noise ratio μ [Woodward, 1953]. Adapted to the ionospheric sounding, the theoretical imprecision of the virtual height $\Delta h'$ is [Galkin, 1968]:

$$\Delta h' = \frac{c}{2}\Delta\tau_{gr} = \frac{c}{2}\frac{1}{\alpha\cdot\Delta f\cdot\sqrt{\mu}} \tag{1}$$

where α is the pulse shape constant, $\alpha \geq 2\pi$. Eq. (1) has been instrumental to the ionosonde system design, in particular, the choice of the h' resolution for digital ionograms. For example, in order for an

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[1] Unbiased error in our terminology is associated with the measurement precision rather than accuracy, so we refer to it as *imprecision*.

ionosonde measurement with a typical value of μ=6 to attain ±0.5 km precision in h' so that measured values can be presented to the nearest 1 km (i.e., with 1 km resolution), its signal bandwidth Δf would have to be at least 40 kHz. At such signal bandwidth, however, a theoretical bound can not be reached because of dispersion of the wideband signal in the ionosphere that causes additional widening of the signal, not accounted for in Eq.(1) which is only applicable to mirror reflectors like a metal sphere or airplane.
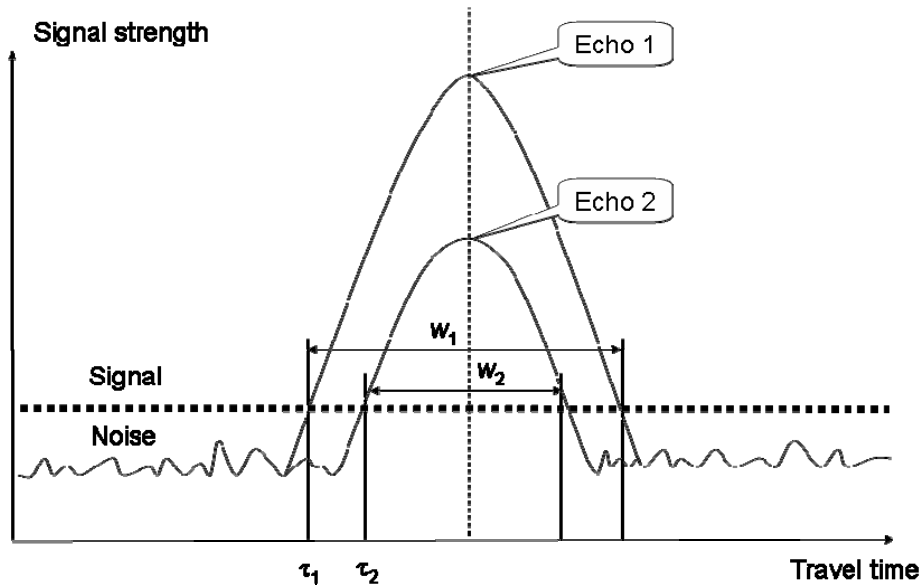

Figure 2. Signal amplitude variation introducing uncertainty of the travel time τ calculations by locating the first point of echo above the signal detection threshold. Travel time τ_2 of a weaker echo 2 is higher than travel time τ_1 of a stronger echo 1. Compensation of the error uses measured echo width w [Lyon and Moorat, 1956; Piggot and Rawer, 1972].

Precision of multiple h' measurements

When multiple measurements of h' can be made on the same operating frequency, for example, by processing individual transmitted pulses and antenna channels independently [Wright *et al.*, 1998], their standard deviation σ can be calculated over the assembly of raw h' values to characterize precision of the measurement. Under assumption of the normal distribution of the h' values, thus obtained σ can be used to attribute the uncertainty bounds at a particular probability level, e.g., 1σ = 68 %, to the reported mean h' value.

Bias of h' measurement

The h' measurements using the travel time method can also be *biased* because of the unknown and varying delays of the signal in the sounder circuitry and cables. The bias can be calibrated out by comparing h' of multi-hop reflections from a flat totally reflecting Es layer [Piggot and Rawer, 1972]. However, such "zero height gate reference" calibration has to be repeated periodically because of its drift with time in the ionosonde equipment.

Alternative techniques for h' measurement

In later years of ionosonde development, multiple techniques were implemented to approach or exceed Eq(1) constraints and compensate the h' bias. Of particular relevance to our topic are signal

processing techniques that were used in the Digisonde 256 sounder [Reinisch, 1996; Bibl and Reinisch, 1978].

Shape-Matching Filter and Trace Lowering for Digisonde 256

Artifacts of using the first echo point above the threshold as the leading edge (Figure 2) motivated a targeted study of alternative h' evaluation techniques for the Digisonde 256 in the 1970s. Instrumental to the study was the introduction of a time-domain matching filter tuned to the shape of the received pulse echo. In the method, maxima of the cross-correlation function between the received signal and a replica of the model pulse are treated as positions of the leading edges. Subsequent research indicated that the first local maximum (FLM) of the signal envelope represents the signal travel time with a similar accuracy.

While the FLM technique was free from the imprecision artifacts associated with the echo strength variations and multi-path propagation, thus obtained h' values of extracted traces appeared overestimated in comparison to the ionogram scaling convention (Figure 3a).
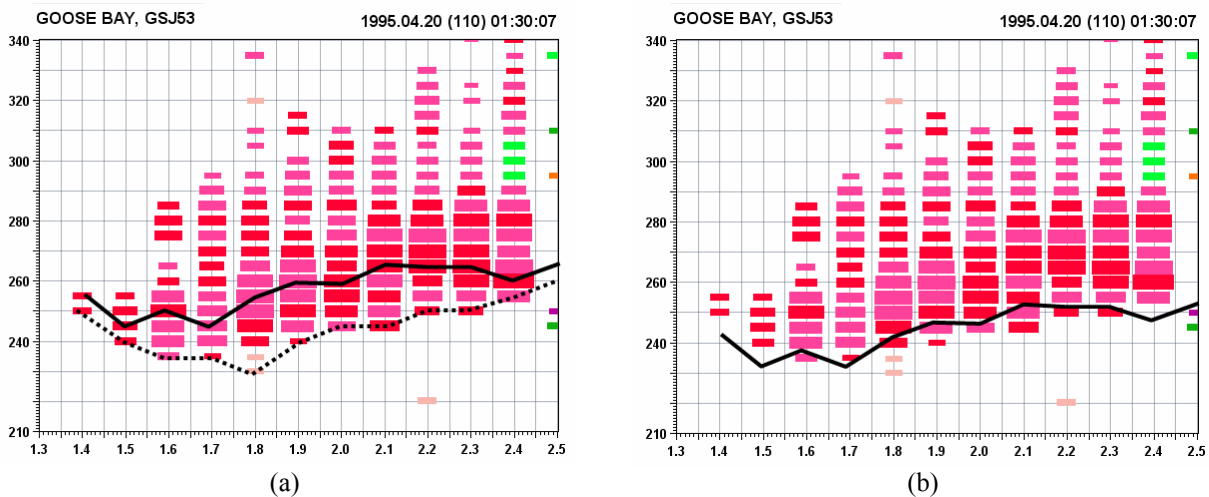

Figure 3. Leading edge detection in Digisonde 256. (a) Trace extracted using the first point of echo (dashed line) technique versus First Local Maximum (FLM) technique (solid line). (b) FLM-extracted trace lowered to the leading edge, algorithm implemented in ARTIST-4.

To remove this positive bias of h' values determined by the FLM method, the original ARTIST software [Reinisch and Huang, 1982] lowers the h' values of the extracted traces by the same adjustment value Δ_L to better match the leading edge of the echo trace (Figure 3b). The lowering value Δ_L is obtained individually for each ionogram by an algorithm that seeks the lowest trace position when it still overlays the ionogram echoes. Introduction of the "trace lowering" in ARTIST allowed the zero range reference in the Digisonde 256 to be set conventionally and calibrated using leading edges of multi-hop Es echoes.

Precision Ranging in Digisonde 256 and DPS

The *precision ranging* technique in digisondes uses phase difference between two signals of closely spaced frequencies, a well known technique for radar applications based on the principle of stationary phase [Whitehead and Malek, 1963], often referred to as the $d\phi(f)/df$ method, where $\phi(f)$ is the RF phase of the signal with frequency f. For a hard reflecting target, phase difference $d\phi(f)$ is linearly proportional to the target range, with $2n\pi$ ambiguity. Because of the $2n\pi$ ambiguity of the

$d\phi(f)/df$ method, it can be viewed as a Vernier scale between the main scale markers provided by the τ_{gr} method. It was not until a rigorous study by Reinisch *et al*. [2008] that the $d\phi(f)/df$ method was proven applicable to ionospheric sounding (inspite of the fact that the two signals reflect from different heights in the ionosphere) and commonly accepted for use in the digisonde analysis.

Precision ranging technique improves:

- **precision**, because the signal phase is used rather than the pulse shape for h' calculations; with typical 6-8º precision of the phase measurement and 10 kHz frequency separation, the $d\phi(f)/df$ technique can be precise to ~300 m;

- **accuracy**, because $d\phi(f)/df$ analysis does not rely on appropriate calibration of the absolute travel time, and signal phases at closely spaced frequencies are affected very similarly by the sounder circuitry, so that their difference is bias-free;

- **resolution** for a single echo because of improved precision.

Figure 4 shows an example of "P1=b" ionogram made by the Digisonde 256 in Dourbes, Belgium (courtesy J.-C. Jodogne). The arrows point to the leading edges of Es trace multiples. The first hop trace is at 100 km; however, the leading edges of the second and third order echoes from Es suggest a negative bias of the zero height reference in the Dourbes Digisonde 256 in February 1992.

Dourbes, DB049 **1992.02.18 (049) 20:44:05 _IE**

Data courtesy of Dr. Jean-Claude Jodogne, Institut Royal Météorologique, Belgium.   SAO Explorer, v 3.4.14b6
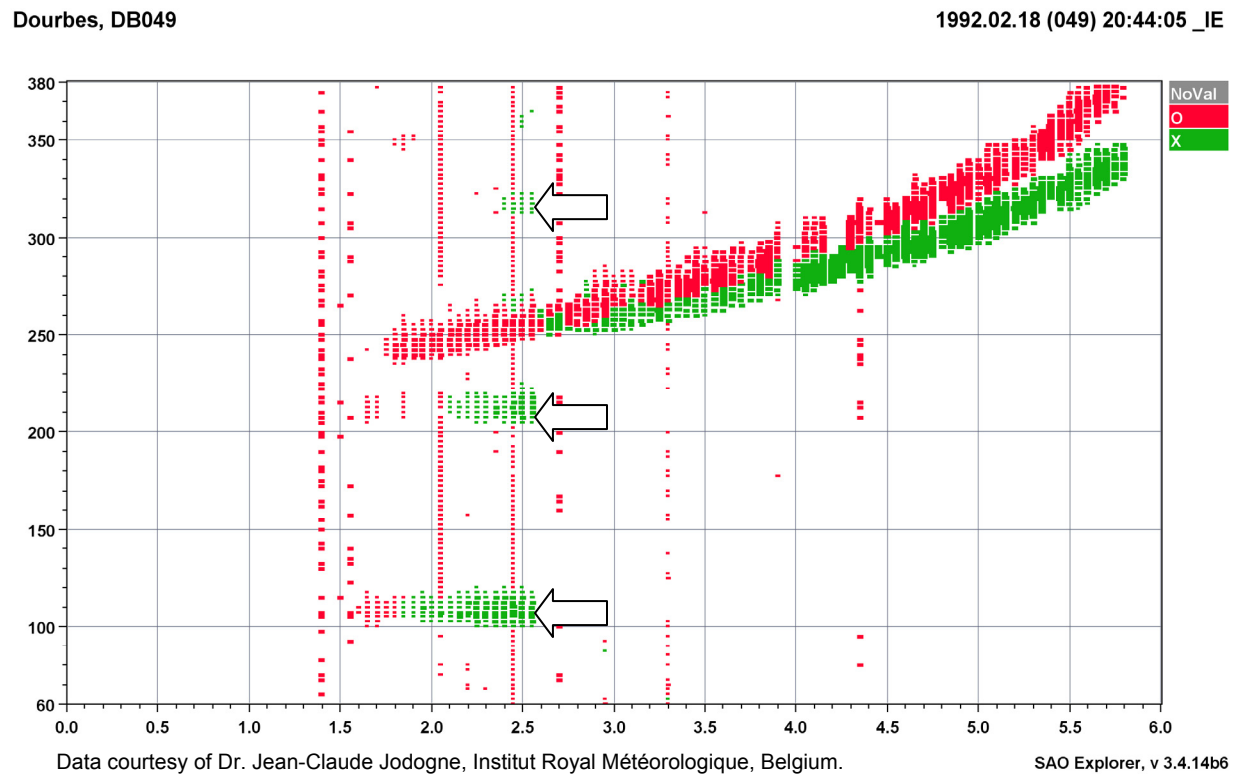
Figure 4. Precision ranging ionogram taken by Digisonde 256 in Dourbes, Belgium. The arrows point to the leading edges of Es trace multiples. The first hop trace is at 100 km; however, leading edges of the second and third order echoes from Es suggest negative bias of the height scale.

Figure 5 confirms the h' bias of the Dourbes digisonde by inspection of precision ranging heights of Es echoes at 2.5 MHz (precise ranges shown in km inside the echo pixels). The first Es hop echo is evaluated at 104.5 km, and the second hop echo comes out at 209 km.
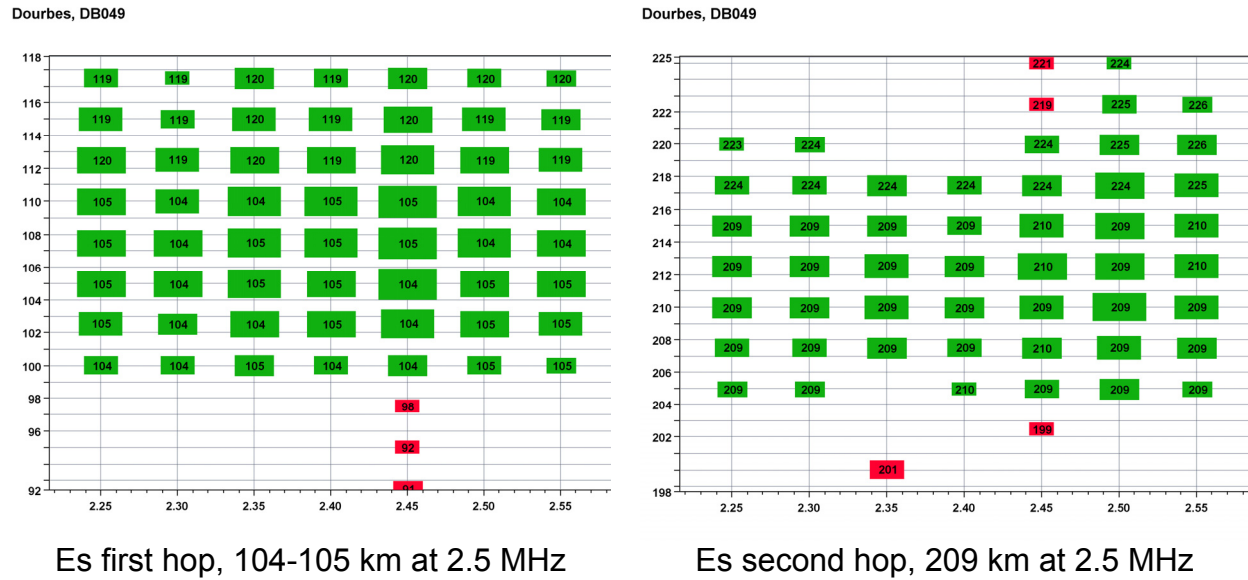

Es first hop, 104-105 km at 2.5 MHz

Es second hop, 209 km at 2.5 MHz

Figure 5. **Precision ranging ionogram taken by Digisonde 256 in Dourbes, Belgium. Precise virtual height of the first Es hop echo at 2.5 MHz comes out as 104.5 km, and the h' of the second hop Es echo is 209 km, thus confirming the height scale bias of –4.5 km.**

Precision ranging does not necessarily help the task of resolving two echoes arriving at almost the same time (close ranges). If the overlapping echoes cannot be separated by independent processing techniques, their summary phase cannot be used correctly for $d\phi(f)/df$ analysis. Separation of the echoes by their Doppler frequency and polarization [Reinisch, 1996a; Kim *et al.*, 1986] is commonly used to improve echo resolution and therefore precision ranging during multi-path conditions.

Pulse Compression in DPS-4 and Digisonde 4D

The Digisonde Portable Sounder (DPS) [Reinisch *et al.*, 1997] and its successor, the Digisonde 4D [Reinisch *et al.*, 2008], were results of a systematic effort to refine the digisonde technology to operate at lower transmission power and operating voltages. The possibility to reduce transmission power from 10 kW (Digisonde 256) to 300 W (DPS) was much due to the use of the phase modulation to code the signal, so that its digital compression yields additional 24 dB gain in comparison with the short pulse without modulation. Since 1996, digisonde models use 16-chip complementary codes [Haines et al., 1997; Reinisch, 1996b]] consisting of two parts compressed independently and then summed to cancel the code residuals as illustrated in Figure 6. To compress individual pulses, a cross-correlation function of the received signal with an exact copy of the code sequence is used:

$$A[signal_{compr}(\tau)] = \sum_{n=0}^{15} A[signal(\tau + n)] \cdot A[code(n)] \qquad (1)$$

Although the spread spectrum technology had proved most valuable for low-power ionospheric sounding, the pulse compression introduced an important side effect, an additional h' bias that remained unnoticed until recently.

Code 1

Code 2

(a) Uncompressed code sequences

(b) Individually compressed code sequences

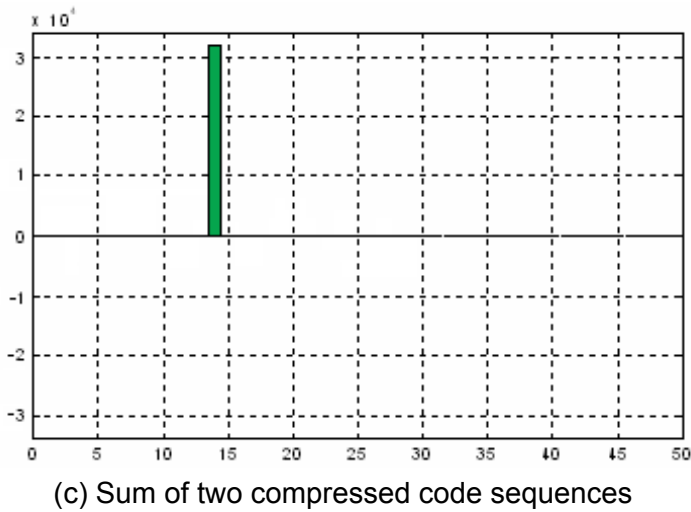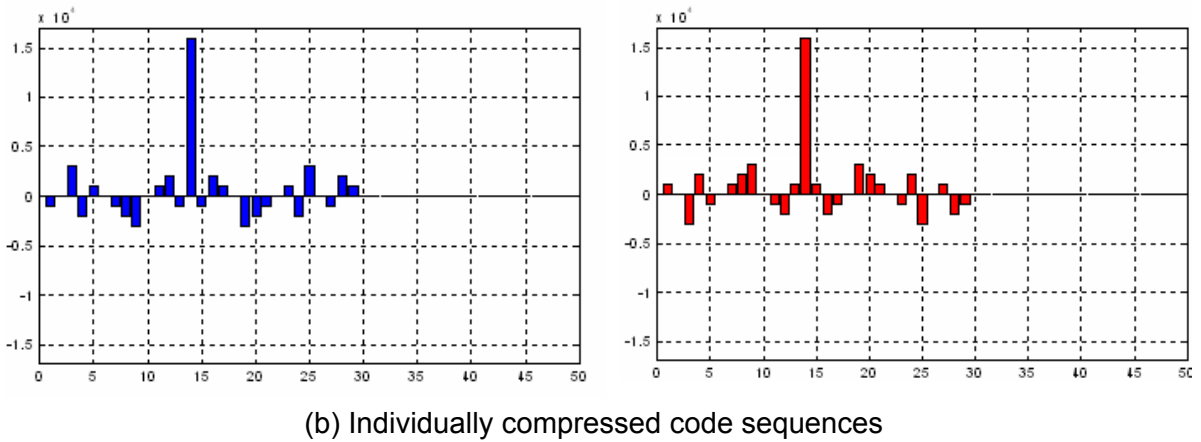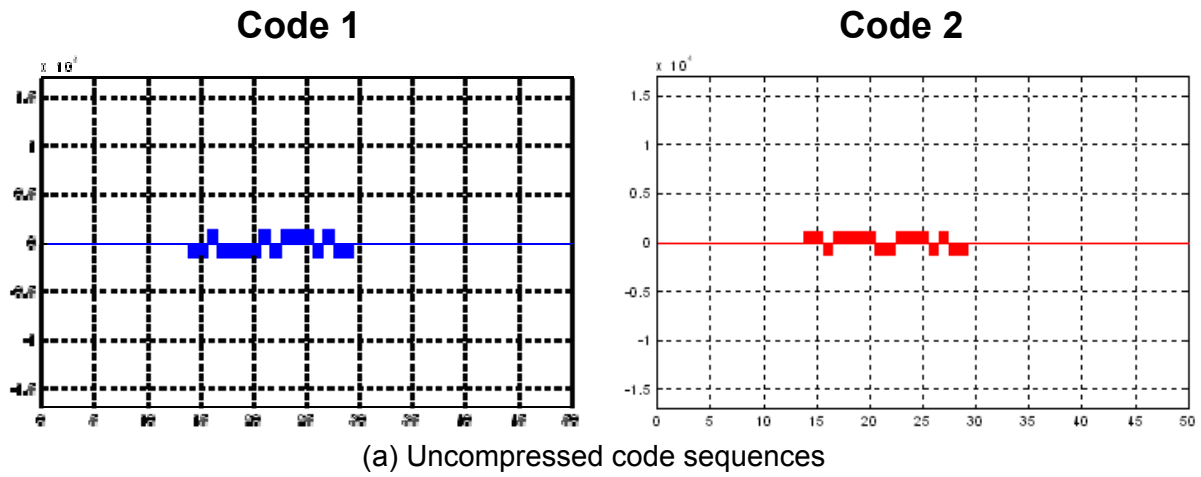(c) Sum of two compressed code sequences

Figure 6.   Pulse compression in the DPS. Two complementary codes are used to modulate a pair of pulses that are compressed individually and summed to cancel code residuals.

Bias of *h'* Value Due to Pulse Compression

The illustration of the pulse compression technique in Figure 6 is for the idealized case of signal processing in a noiseless environment that permits receiver operation with the bandwidth wide enough to capture most frequencies of the phase-modulated, spread-spectrum signal. More realistically, though, the receiver bandwidth is constrained to $\pm$ 15 kHz around the carrier frequency to reduce the in-band interference. Figure 7 shows three cases of the pulse compression performed on a digitally synthesized ideal signal (the upper panel), and a loopback calibration signal fed to the Digisonde 4D digital receiver whose bandwidth Δf_{Rx} was configured at 60 and 30 kHz (the middle and lower panels, respectively). In all cases, standard 2.5 km sampling resolution is used, so that two samples per code chip are acquired, thus resulting in 32 samples per 80 km pulse waveform. Odd and even samples (shown as two shades of gray in Figure 7) are compressed independently using the 16-chip code key.
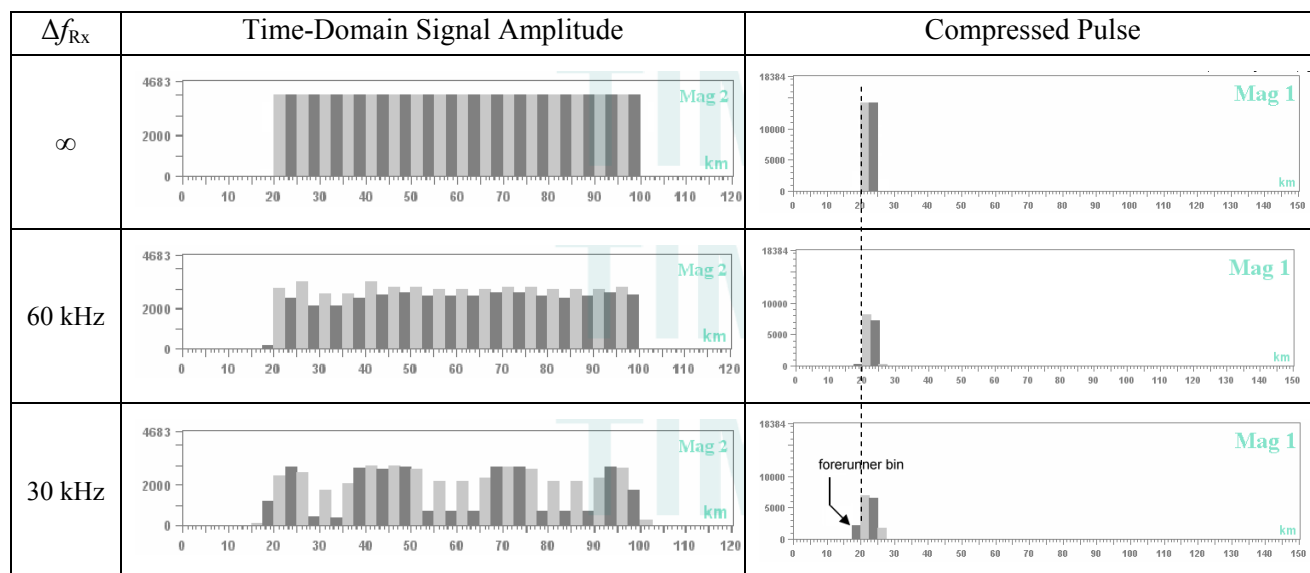
Δf_{Rx}	Time-Domain Signal Amplitude	Compressed Pulse
∞		
60 kHz		
30 kHz		

Figure 7. Effect of the narrow-band filtering in the receiver on pulse compression. Δf_{Rx} is the receiver bandwidth.

Clearly, all cases shall yield the same pulse travel time. However, the narrow bandwidth case (the lower panel of Figure 7) shows widening of the compressed pulse because of the narrow-band filtering in the receiver. The "code-induced pulse widening" causes the appearance of a "forerunner echo" in the compressed pulse, as a result of the limited receiver bandwidth. This forerunner should not be interpreted as a shorter actual travel time of the signal.

As refinements to the Digisonde technology allow for a better signal/noise ratio (SNR), the code widening seen in Figure 7 becomes visible in the ionograms. Figure 8 illustrates echo detection processing at low and high SNR. Once detection algorithm places the threshold at the lower noise level, artifacts of the narrowband filtering become visible, causing the echo to span more than the nominal 5 km. The presence of the additional range bin, tagged as an echo, triggers the ARTIST-4 algorithm to lower the trace towards apparent leading edge (see Figure 3), thus introducing a negative bias of 2.5 km or more.

Figure 9 shows a sample ionogram taken at Millstone Hill by the Digisonde 4D in the precise ranging mode. Precise ranging data support the negative bias observations with the loopback signal.
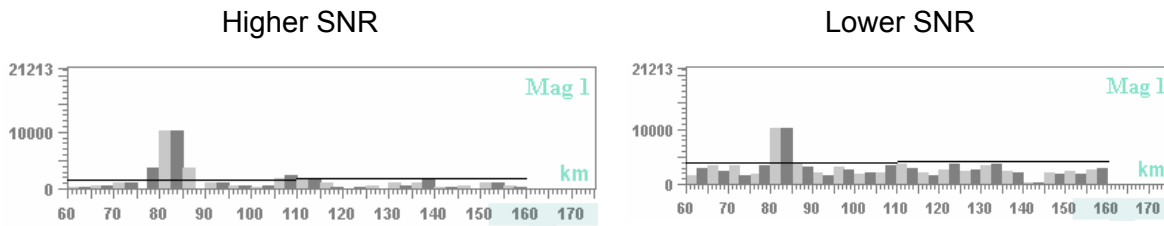
Figure 8. Improved SNR reveals code leakage of the pulse compression. Horizontal lines correspond to the echo detector thresholds determined dynamically from the most probable amplitude corresponding to the noise level. Data below the threshold are suppressed for post-processing and display. Echo width appears larger for the higher SNR case, with a forerunner range bin causing a bias of the h' values produced by ARTIST.

(a) Precision ranging data in km displayed for each echo bin

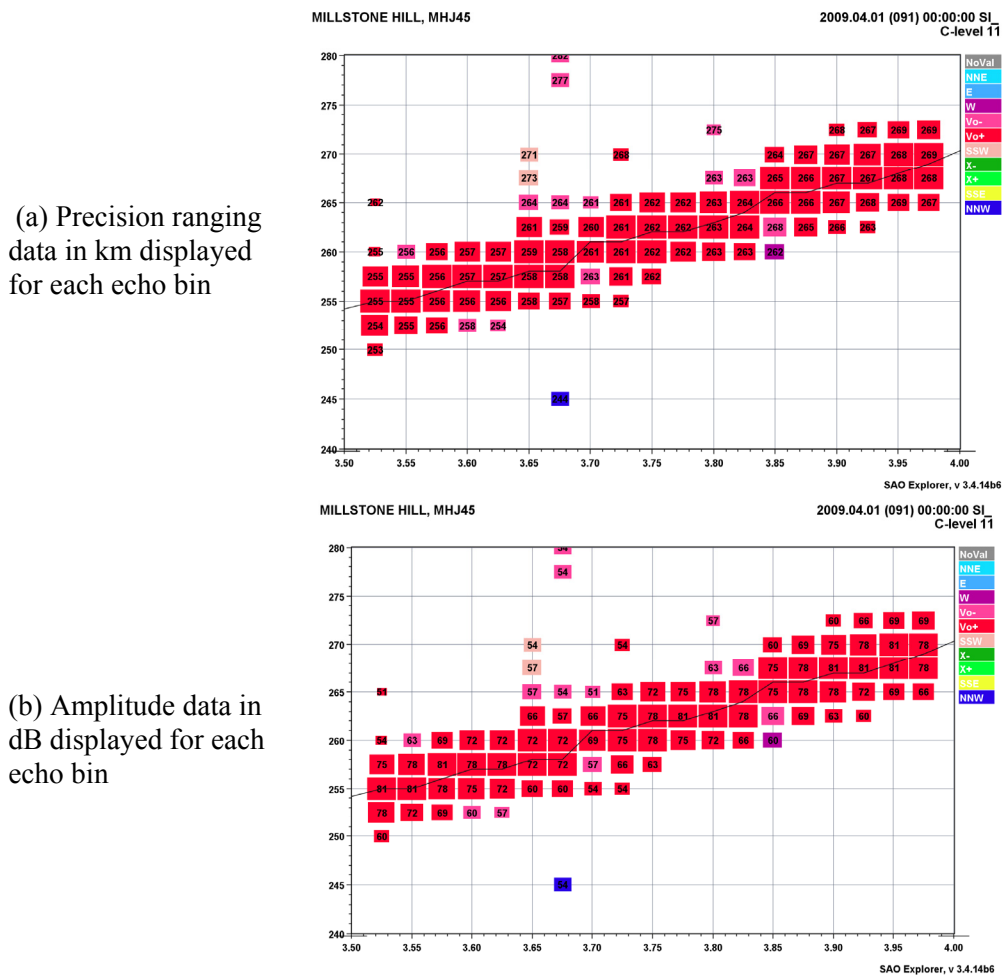(b) Amplitude data in dB displayed for each echo bin

Figure 9. DPS precision ranging data suggest using the first local maximum of the echo trace for evaluation of the travel time. Upper panel: precision range in km, lower panel: signal amplitude in dB. Black line: ARTIST-5 trace obtained using precise h' values.

Recommendations for Digisonde Users

Strong demand for accurate ionospheric specification should drive efforts of the ionosonde data providers to identify and eliminate sources of errors and uncertainties in the ionogram-derived data. We have determined that ARTIST autoscaler versions prior to V5 (May 2008) can introduce a negative bias in h' values of up to several km by lowering the extracted trace toward the leading edge of echoes in the Digisonde Portable Sounder (DPS) ionograms. The lowering technique is applicable to Digisonde 256 data only. The amount of trace lowering applied to any particular ionogram can be obtained from the list of reported ionospheric characteristics [SAO-4 format, 1998; SAO-XML format, 2008] as items *downE* and *downF* given in km.

The Digisonde Forum of 2008 made several recommendations aimed at improved accuracy of the Digisonde data in conjunction with the study of h' evaluation in the ARTIST.

1. Use of Precise Ranging in Digisondes

The digisonde operators are strongly encouraged to operate their sounders in the precise ranging mode to resolve the issues of h' bias due to zero-range gate miscalibration and trace lowering by ARTIST. Appendix A describes the configuration of the digisonde for precision ranging ionograms.

2. Ionogram Autoscaling with ARTIST-5

Version 5 of the ARTIST software [Galkin *et al*., 2008] does not lower the trace for ionograms taken by DPS-1, DPS-4, and Digisonde 4D, thus introducing no bias in the virtual height. Upgrading digisondes to the latest ARTIST-5 is strongly recommended, especially because the new version makes use of the precise ranging data when they are available in ionograms. However, data analysts shall carefully consider long-term effects on the retrospective ionogram-derived data acquired by the station that such ARTIST update incurs.

2.1. Ionogram Reprocessing for Climatological Studies

Upgrading the ARTIST software to version 5 introduces a noticeable change to the station h' data that will affect the climatology studies undertaken to detect long-term trends in ionospheric characteristics. Climatological studies based on the automatically scaled ionograms have to be handled with care, and certainly inconsistent use of different versions of ARTIST software must be avoided when such a study is considered. Reprocessing the archived ionogram data is strongly recommended, best arranged by ingestion of the retrospective ionogram data in the Lowell DIDBase repository, after which they can be reprocessed by a background ARTIST-5 task operating online with the DIDBase.

3. Recommendations for Manual Ionogram Scaling

Use of precision ranging information is the best way to avoid an h' bias in the scaled trace altogether. When precision ranging measurements are not available, follow the example in Figure 9 that suggests, for DPS ionograms, there is no need to place traces as close to the leading edge as possible. Digisonde 256 ionogram with precise ranging shown in Figure 10 confirms that no changes are needed in the manual scaling technique used for the Digisonde 256 data. The diamond symbols in Figure 10, placed at the precise range values, generally correspond to the leading edge of the visible pulse signals.

Data courtesy of Dr. David Altadill. Ebre Observatory, Spain
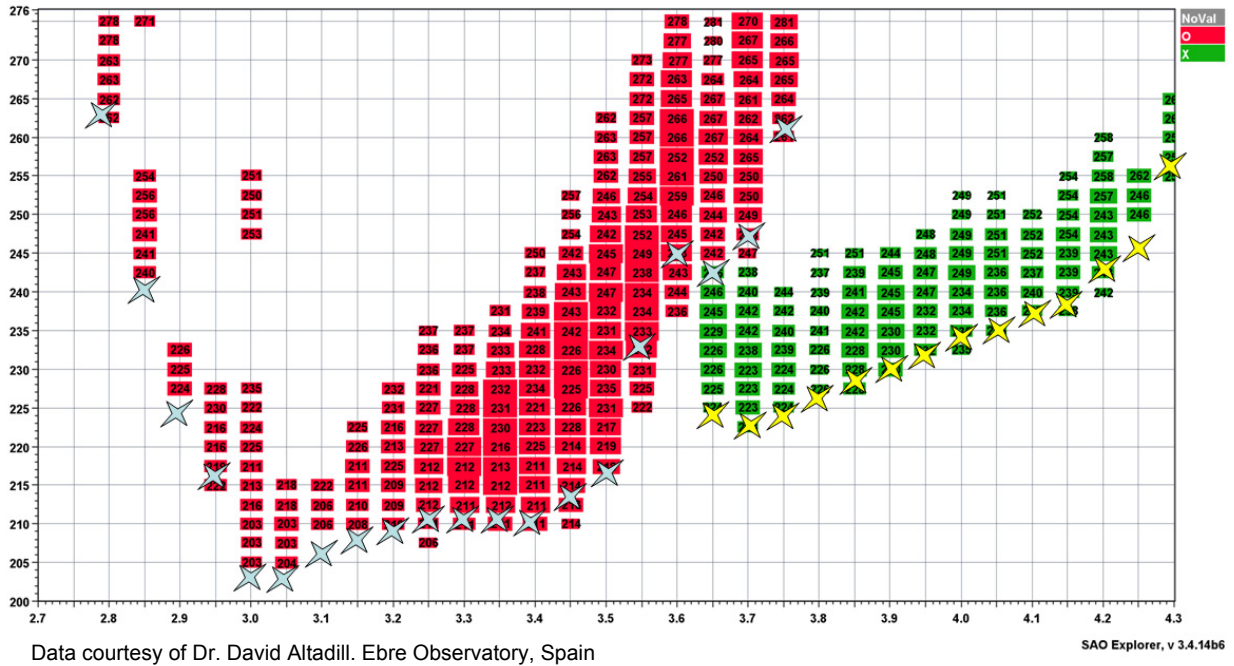
SAO Explorer, v 3.4.14b6

Figure 10. Digisonde 256 precision ranging data suggest use of the first visible echo point for evaluation of the travel time. Diamond shapes are placed at the precise range values. No modifications to the Digisonde 256 autoscaling and manual scaling techniques are suggested.

Pulse Compression in Digisonde 4D

Digisonde 4D implements 2.5 km range resolution, thus resulting in 32 samples collected within one 80 km coded pulse waveform (see Figure 7). Odd and even samples are compressed independently using the 16-chip code key, so that the compressed signal occupies two abutting range bins, corresponding to 5 km pulse width. The first bin of the two (odd samples) is very little different from the second bin (even samples collected within the same signal chips as the odd samples), thus causing an undesirable situation for the first local maximum (FLM) technique that determines the travel time τ_{gr}: the second bin can happen to have a slightly larger signal amplitude, causing +2.5 km error in h' (see the middle panel of Figure 11).

For Digisonde 4D ionograms without precise ranging data, we recommend an additional *forward averaging* processing that allows better evaluation of τ_{gr}:

$$A_i = \frac{A_i + A_{i+1}}{2} \tag{2}$$

The forward averaging operation helps to resolve the ambiguity of the odd/even bin selection using the FLM technique, as shown in the lower panel of Figure 11.
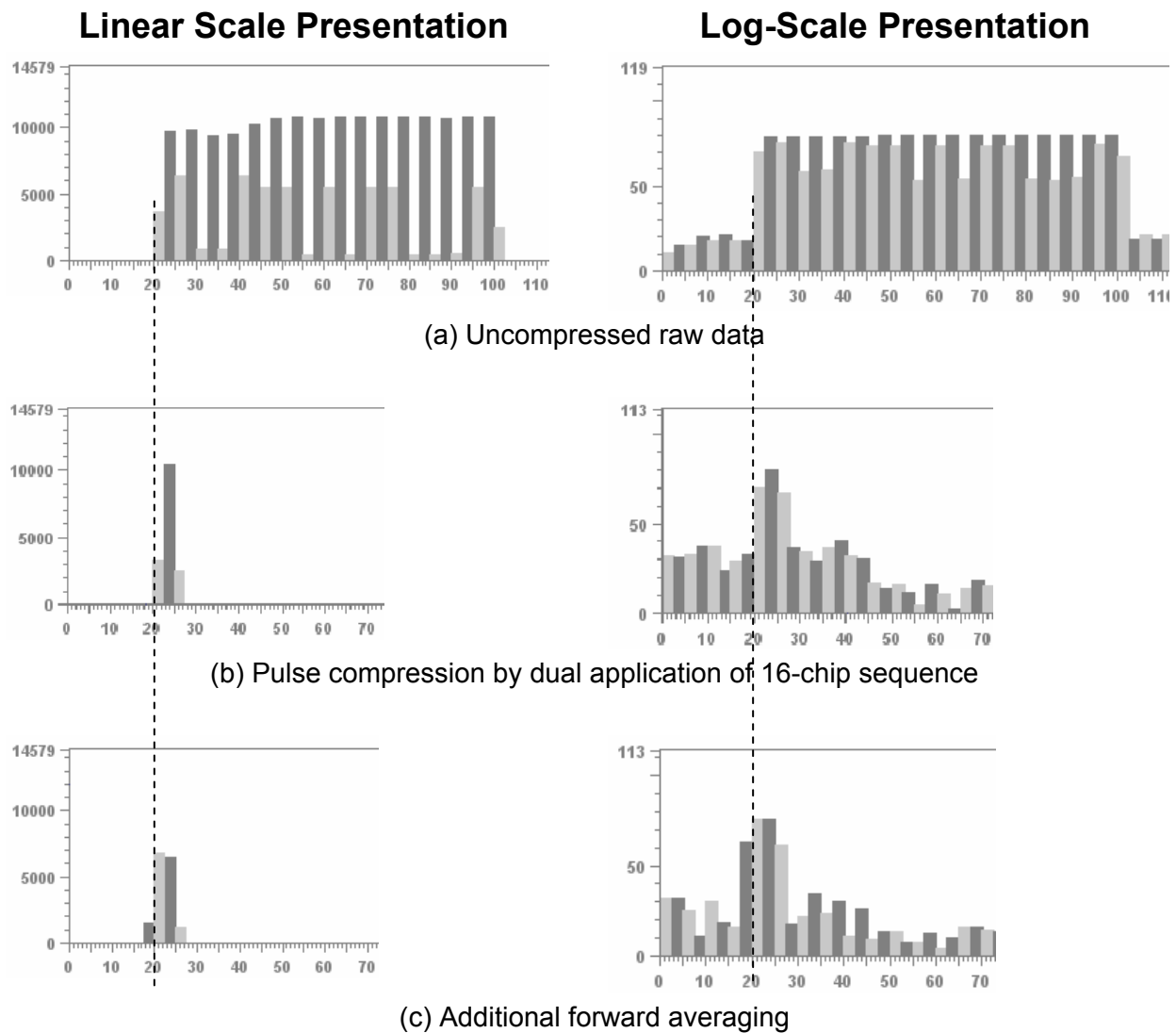
Linear Scale Presentation   **Log-Scale Presentation**

(a) Uncompressed raw data

(b) Pulse compression by dual application of 16-chip sequence

(c) Additional forward averaging

Figure 11. Use of forward averaging filter to improve evaluation of τ_{gr} in Digisonde 4D ionograms. (a) time domain representation of the raw signal, loopback calibration, 60 kHz bandwidth of the digital receiver; (b) 16-chip pulse compression applied to odd and even samples of the raw data; (c) forward averaging filter applied to pulse-compressed data. Dashed line shows correct τ_{gr} value. The FLM method produces error of one height bin using pulse-compressed data (b), and no error after averaging filter is applied (c).

Summary

Analysis of precision-ranging ionograms taken by the Digisonde Portable Sounder (DPS) and its successor, the Digisonde 4D, reveal a previously unnoticed bias in the virtual height values determined by the ARTIST-4 software using the trace lowering algorithm, while no such bias has been noted in Digisonde 256 ionograms. Analysis of the signal processing in DPS and Digisonde 4D points to the digital pulse compression technique as the reason for a code-induced pulse widening that manifests itself as a forerunner range bin. The forerunner bin is then mistaken for the leading edge of the echo by the trace lowering algorithm in ARTIST. The effect is especially visible in ionograms from stations with high signal-to-noise ratio, in which case the widened pulse side lobes exceeds the background noise level.

We strongly recommend configuring all digisondes to use of the precision ranging mode for routine measurements to resolve uncertainty of the zero range gate calibration in all digisondes. ARTIST-5 disables the trace lowering algorithms when ionograms obtained with pulse compression are processed. No change to the analysis of Digisonde 256 ionograms is required.

Acknowledgements

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Appendix A. Digisonde Program Definitions for Precise Ranging Mode

A1. Precise Ranging Mode in Digisonde 256

Pre-requisites:	Hardware modification to Digisonde 256 card 08, evidenced by wiring between U6, U10, and U14. For greater detail contact David Kitrosser, dkit@digisonde.com
Program parameters:	P1=0xB (precision ranging), P2=5 (use 128 statii mode for precise height in km), I=5 (10 kHz spacing), Z=0xD, T=2.
Usage implications:	No directional data reported in the output, 2x increase of ionogram running time unless N is reduced, 256 height mode not supported.
Known locations:	Dourbes (campaign in 1992)

A2. Precise Ranging Mode in DPS-1 and DPS-4

Pre-requisites:	Hardware Generation 5 (with C-40 DSP board), DPSCntl software 5.*
Program parameters:	Fine frequency step = 5 (5 kHz spacing), Number of small steps = 2, Disk = R (RSF ionograms)
Usage implications:	2x increase of ionogram running time unless N is reduced.
Known locations:	Fortaleza (default ionogram mode), Sao Luis (default ionogram mode), 21 more systems in campaign mode

A3. Precise Ranging Mode in Digisonde 4D

Program parameters:	Fine frequency step = 5 (5 kHz spacing), Number of fine steps = 2, RSF output file, note presence of the yellow status flag "2 frequency PGH (5 kHz)".
Usage implications:	2x increase of ionogram running time unless N is reduced.
Known locations:	All Digisonde 4D stations (default ionogram mode)