Confidence Score of ARTIST-5 Ionogram Autoscaling

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Table of Contents

Abstract 1
Background: ARTIST Autoscaling and its Quality Control 2
0/1 Autoscaling Confidence Level (ACL) and ADEP Merit Check 2
Two-digit C-Level 2
QUALSCAN 3
ARTIST-5 Confidence Score Evaluation 4
Concepts for Selecting Quality Criteria 4
Quality control of interim autoscaling steps 4
Use of NHPC per-point-error to detect unreasonable trace shapes 4
Automatic detection of disturbed ionospheric conditions 4
Separate analysis of O- and X-polarization data 4
No detection of outliers 4
Evaluation of ARTIST-5 Confidence Score 5
Access to Confidence Metrics 5
Acknowledgement 7
References 7

Abstract

Over the decades, INAG advisory functions have been shifting their focus from manual ionogram scaling to autoscaling and from consistency of interpreting the ionogram signatures to consistency of autoscaling quality. This transformation reflects the strengthening role of ionosonde as a fully autonomous 24/7 instrument for global, accurate, and prompt specification of the bottomside ionosphere. The ionogram autoscaling plays a critical part in enabling such change. In this article, we review motivation and concepts for calculating a quality metric of ionogram autoscaling by ARTIST 5 software, called Confidence Score (CS). We anticipate the CS flag to be used as an automatic total error qualifier for ruling out those records that are likely to be inaccurate, whether because of insufficient ionogram quality, disturbed geophysical conditions, or mistakes in automatic ionogram interpretation. The CS calculation is based on a system of quality criteria interspersed within the logic and algorithm of ionogram interpretation, as well as certain "sanity" checks applied to the autoscaling outcome. Without evaluation of a confidence metric, the autoscaled results would always be accepted at their face value into the next analysis stage, regardless of their quality. To aid research and applied usage of the ARTIST-5 records, the Confidence Score is now reported in the Digital Ionogram Database (DIDBase) of the Global Ionospheric Radio Observatory (GIRO) for all ionospheric characteristics.

Background: ARTIST Autoscaling and its Quality Control

Development of the automatic scaling software for Digisonde® ionograms, ARTIST, started in the late 1960s and continued through the next four decades [Reinisch and Huang, 1982, Reinisch *et al*., 2005, Galkin *et al*., 2008a]. Since 2007, further autoscaling development at UMLCAR has focused on continuing integration of the ARTIST into the operational environment of the space weather modeling [Galkin *et al*., 2008b]. With the data quality control objective in mind, the ARTIST-5 team developed concepts and algorithms for specifications of uncertainty and confidence of the autoscaled results.

0/1 Autoscaling Confidence Level (ACL) and ADEP Merit Check

The Autoscaling Confidence Level (ACL) was first introduced for digisondes in the late 1980s as a part of the Merit Check system in the Artist Data Editing and Printing (ADEP) software [Zhang, 1989]. The ACL is a quality flag computed automatically to one of the two possible values: 0 (fail) and 1(pass); in the 1990s, the ionograms that fail the examination (ACL is 0) were brought to the ADEP operator's attention for their manual editing.

The ADEP Merit Check introduced several concepts for validation of the ARTIST outcome that later were borrowed and enhanced in other confidence calculation schemes. It used 19 quality criteria of two types: *data integrity* performed by validating the autoscaled characteristics against low/high tolerance limits, and *data outlier* accomplished by contrasting the current measurement to previous and subsequent measurements. The cumulative result of the quality criteria checks (i.e., total error qualifier) was compared to a user-defined threshold to produce the ACL flag.

By validating the outcome of the electron density profile inversion, the ADEP Merit Check was able to easily detect most significant errors of ionogram autoscaling that result in an excessive error-per-point metric of the profile inversion. The error-per-point value was obtained by comparing the ARTIST-produced ionogram trace to the trace recomputed from the NHPC-calculated density profile. The "true height" inversion program NHPC [Huang and Reinisch, 2001] is part of ARTIST. The ADEP Merit Check also spawned an active discussion of the false positive ACL rulings in the ionogram scaler community of that time, leading to the eventual abandonment of the Merit Check approach in subsequent software tools used for manual analysis of Digisonde ionograms. However, automated quality control concepts were eventually adopted in the operational space weather environment.

Two-digit C-Level

Further development of the ARTIST confidence evaluation algorithms in the mid-1990s targeted deeper integration with the ARTIST interpretation logic in comparison with the predecessor Merit Check. Such integration was accomplished by including new criteria checks at those interim autoscaling steps whose outcome was not available in the ADEP environment. In particular, signal-to-noise conditions at relevant frequencies were evaluated to predict subsequent confidence of the ARTIST interpretation. In 1995, a two-digit Confidence Level ("C-Level") based on the new concepts was accepted network-wide for all Digisondes with the specifications described in Table 1:

Table 1. Calculation of 2-digit C-level in ARTIST-4

C-level	Tolerance Criteria	Evaluation Algorithm
Lower digit	A. Deviation of autoscaled foF2 from prediction B. Deviation of h'F from previous ionogram C. Error-per-point of the ionogram trace and re-inverted trace D. Ratio of trace points with insignificant amplitude E. Average signal-to-noise ratio	Output range: 1 (best) to 5 (worst) If any of the criteria A-E are strongly violated, return 5. Otherwise, compute weighted average of criteria scores A-E
Upper digit	1. Realistic scaling of F1 2. Gap width between foE and fminF 3. Presence of multi-hop Es at F-region heights	Output range: 1 (best) to 5 (worst) Computation uses scaled foE, fminF, foEs, and foF1 values, and predicted foEp and foF1p from IRI

An important part of the C-level development was addition of the 2-digit confidence level to the SAO-4 format [Reinisch, 1998] for the end users to reference in subsequent data analysis steps. Regretfully, the intricacy of the 2-digit C-level content has hindered its use outside the operational environment of the Jindalee radar in Australia. Actually, the 2digit C-level was originally developed for the digisonde network supporting the Jindalee radar.

QUALSCAN

The "QUALSCAN" quality control of autoscaled records [McNamara, 2001; 2006] has been in operation at the NOAA NGDC since the 1990s as a part of the ionosonde data service to the USAF Weather Agency (AFWA) Space Wx Analysis and Forecast System (SWAFS) that operates real-time assimilative models for ionospheric specification. QUALSCAN employed an elaborate scheme of data integrity verification of the autoscaling results based on a suite of checks that identify 17 conditions (Table 2) that result in the low-confidence ACL ruling [McNamara, 2007].

Table 2. Quality criteria of QUALSCAN triggering ACL

Code #	Description	Evaluation Algorithm
1	Low quality of the F-trace cusp	Acceptable ratio of the average amplitude over the last MHz of the trace and average non-zero amplitudes of the whole trace
2	F-trace scaling is incomplete	M(3000)F2 comes from the F2 trace tip rather than from ~0.9 below
3	Unreasonable true height inversion at fminF	True height should be sufficiently lower than virtual height at fminF
4	Incompatible POLAN and NHPC results	POLAN and NHPC profile inversion algorithm produce sufficiently different hmF2
5	Scaled F-trace is second-hop Es	F-trace is too flat
6	F-trace shape is unreasonable	Smoothed and original traces differ, pointing to bad height jitter/jumps
7	F-trace shape is unreasonable	Too many height jumps in the trace
8	Imprecise POLAN representation of peak	Standard deviations of the peak fit by POLAN are too large
9	NHPC inversion is unreasonable	hmF2 peak from NHPC is below 200 km
10	F1 trace shape is unreasonable	Smoothed and original traces differ, pointing to bad height jitter/jumps
11	F2 trace cusp pointing down	Slope of F2 layer decreases as it approaches the tip of the trace
12	Wide gap between E and F traces	Difference between fminF and foE is too large
13	Steep kink in F trace, possibly 2xEs trace transition to F trace	Check the trace slope for sudden step-like change
14	Restricted frequency affecting foF2 scaling	foF2 value is close to the lower band of restricted frequencies
15	foF2 cusp not definitive	Slope of F2 O-trace tip is not sufficient
16	F-trace too fragmentary for accurate inversion	fmin is too high for good inversion
17	Low trace quality	Too many blank amplitudes within the trace

ARTIST-5 Confidence Score Evaluation

The ARTIST-5 autoscaling system (2004-2013) [Galkin *et al*., 2008a] in the in the Digisonde-4D [Reinisch *et al*., 2009] bases its Confidence Score (CS) evaluation technique on the best solutions developed for the Merit Check, C- Level, and QUALSCAN.

Concepts for Selecting Quality Criteria

Quality control of interim autoscaling steps

To achieve higher fidelity of the confidence computations, quality checks have to be aware of particular strengths and weaknesses of autoscaling algorithms. Assessing success of the interim steps in the autoscaling logic allows closer monitoring the process for imperfections that, while benign on each accord, cumulatively may lead to erroneous final results. The ARTIST-5 confidence score calculation initializes a confidence score to the maximum value (100) in the beginning of interpretation, and each time a quality criterion fails during ionogram processing, the score is lowered by a particular decrement. If multiple problems are detected, the final score (i.e., total error qualifier) becomes sufficiently low to rule out the autoscaling outcome, and an ACL flag 0 is reported.

Use of NHPC per-point-error to detect unreasonable trace shapes

Instead of evaluating, through a system of sanity checks, the likelihood for the profile inversion to fail, ARTIST-5 always runs the NHPC profile inversion and then analyses, similar to ADEP Merit Check, the resulting per-point-error metric against a threshold value. If the extracted trace shape is physically unreasonable, the NHPC inversion will produce a “high per-point-error” value.

Automatic detection of disturbed ionospheric conditions

ARTIST-5 operates an automatic Spread F condition detector that classifies each ionogram to fall into one of four categories:

Q	Quiet ionospheric conditions
M	Moderate Spread F conditions
H	Heavy Spread F conditions
E	Excessively Heavy Spread F conditions

The confidence score is automatically reduced for M and H categories of ionograms in recognition of the known difficulties in interpreting data recorded during disturbed ionospheric conditions. Ionograms in the E category are not autoscaled (ACL is 0): no vertical profile can reliably be determined.

Separate analysis of O- and X-polarization data

ARTIST-5 uses a new interpretation scheme for scaling the O and X wave critical frequencies of the F2 layer (foF2 and fxF2), in which polarization channels are processed independently of each other and then extracted values of foF2 and fxF2 are tested for separation by half the gyrofrequency. Similarly to previous ARTIST versions, each critical frequency cusp is determined as the best-fit of the hyperbolas from a candidate pool, and the pool is built dynamically for each ionogram using the extracted F layer trace [Reinisch and Huang, 1983]. All of the process steps, including preparation of the candidate pool, cusp fittings, and fxF2-foF2 separation are quality-controlled in ARTIST-5, with several options to proceed in the event of imperfections, though at reduced confidence score.

No detection of outliers

The confidence calculation algorithm in ARTIST-5 does not compare the autoscaled values to previous/next measurements or their long-term predictions to identify potential outliers. For real time analysis, the next ionogram is not yet recorded when ARTIST runs, which makes an outlier detector task difficult during periods of high ionospheric activity (i.e., arguably most important times for space weather applications), when large deviations from previous measurement can be observed. Negligence in updating remote Digisonde observatories with the latest solar and geomagnetic activity predictors leads to low reliability of the long-term references. Given the practical difficulties of the process, the burden of detecting autoscaling outliers is placed at the ingesting or assimilation protocols of the system.

Evaluation of ARTIST-5 Confidence Score

Table 3 lists the status conditions that ARTIST can encounter while interpreting an ionogram, together with the score values that are subtracted from the original full score. If the final confidence score is above a predefined threshold value (usually 40), the autoscaling record is labeled as acceptable for further use (ACL is 1).

Table 3. Interpretation criteria causing lowering of the ARTIST-5 confidence score

Criterion	Point Reduction	Description
SF_MODERATE	10	Spread F detector determined that the ionogram was taken during moderately disturbed conditions
SF_SEVERE	20	Spread F detector determined that the ionogram was taken during heavily disturbed conditions
X_CUSP_NOT_UNIQUE	5	Multiple trace segments can be interpreted as F2 layer X cusp
O_CUSP_NOT_UNIQUE	5	Multiple trace segments can be interpreted as F2 layer O cusp
NO_X_CUSP	20	No cusp could be found among F2 layer X polarization traces
NO_O_CUSP	20	No cusp could be found among F2 layer O polarization traces
F2_MISMATCH_FIXED	10	Separately fitted foF2 and fxF2 were not ½ gyrofrequency apart, but could be refitted in post-analysis
F2_MISMATCH	30	Separately fitted foF2 and fxF2 were not ½ gyrofrequency apart, and could not be refitted in post-analysis
POL_SWAP	10	O- and X-wave F2 cusps were identified as swapped in polarization tagging and had to be relabeled (equator problem)
O_HYPER_MISFIT	20	Best fit model of foF2 cusp could not be attached to an O-trace
BASELINE_NOCNTR	25	F2 baseline trace was built even though the “center” of the F2 echo trace could not be detected reliably
NO_BASELINE	40	One or both foF2/fxF2 fits were successful, but F2 baseline could not be built
BASELINE_MISFIT	40	F2 baseline does not go through the center of F2 trace
BASELINE_OVERLAP	20	Conflicting overlapping traces found while building baseline
LEFT_ABOVE_FOF2	20	Residual O polarization trace segments were found above foF2
BASELINE_2XES	25	Baseline height matches double height of Es layer
STRONG_ES	25	Es layer blanketing is too strong
NO_PROFILE	100	NHPC could not obtain electron density profile within given per-point-error threshold

Access to Confidence Metrics

The ARTIST-5 confidence score is directly available in SAO.XML data files in the section for the autoscaler comments, for example:

```
<Comments>
AR.5002.47 Confidence: 60% PACIFIC flags: Moderate F-spread, Multiple candidates for F2x
cusp, Multiple candidates for F2o cusp, One of F2 cusps was derived from the other, Trace
overlaps while constructing baseline
</Comments>
```

Listing 1. Comments section of an SAO.XML file showing ARTIST-5 Confidence Score

The confidence score is included in the data provided through the DIDBase online access port at GIRO, http://giro.uml.edu/didbase/scaled.php, for example:

```
# Global Ionospheric Radio Observatory
# GIRO Tabulated Ionospheric Characteristics, Version 1.0 Revision B
# Generated by DIDBGetValues on 2013-11-25T16:30:47.752Z
#
# Location: GEO 69.6N 19.2E, URSI-Code TR169 TROMSO
# Instrument: Ionosonde, Model: DPS-4
#
# Query for measurement intervals of time:
# 2002-11-18T00:00:00.752Z - 2002-11-18T08:01:00.752Z
#
# Data Selection:
# CS is Autoscaling Confidence Score (from 0 to 100, 999 if manual scaling, -1 if unknown)
# foF2 [MHz] - F2 layer critical frequency
# foEa [MHz] - Critical frequency of auroral E-layer
#
#Time                     CS   foF2 QD  foEa QD
2002-11-18T00:01:00.000Z 999  8.550 UF  2.15 UA
2002-11-18T00:16:00.000Z 999  8.300 UF  5.00 /_
2002-11-18T00:31:00.000Z 999  8.150 UF  5.15 /_
2002-11-18T00:46:00.000Z 999  7.700 UF  5.10 /_
2002-11-18T01:00:59.000Z 999  6.500 UF  5.15 /_
2002-11-18T01:16:00.000Z 999  6.650 UF  5.15 /_
2002-11-18T01:30:59.000Z 999  5.500 /_  3.40 /_
2002-11-18T01:46:00.000Z 999  6.300 UF  3.40 /_
2002-11-18T02:00:59.000Z 999  6.700 UF  4.30 /_
2002-11-18T02:15:59.000Z 999  5.350 UF  4.40 /_
2002-11-18T02:30:59.000Z 999  4.950 UF  4.30 /_
2002-11-18T02:45:59.000Z 999  4.600 /_  3.80 /_
2002-11-18T03:00:59.000Z 999  4.900 UF  3.60 /_
2002-11-18T03:15:59.000Z   0  3.200 //   --- __
2002-11-18T03:30:59.000Z 999  5.750 UW  4.45 U_
2002-11-18T04:00:59.000Z   0  3.250 //   --- __
2002-11-18T04:30:59.000Z 100  3.225 //   --- __
2002-11-18T05:30:59.000Z 100  4.057 //   --- __
2002-11-18T05:45:59.000Z  75  2.025 //   --- __
2002-11-18T06:15:59.000Z 100  4.075 //   --- __
2002-11-18T06:30:59.000Z 100  2.725 //   --- __
2002-11-18T06:45:59.000Z 100  4.325 //   --- __
2002-11-18T07:00:59.000Z  75  4.875 //   --- __
2002-11-18T07:15:59.000Z 100  4.975 //   --- __
2002-11-18T07:30:59.000Z 100  5.175 //   --- __
2002-11-18T07:45:59.000Z  75  5.725 //   --- __
2002-11-18T08:00:59.000Z 100  5.975 //   --- __
```

Listing 2. Sample output of GIRO access portal to ionogram-derived characteristics showing ARTIST-5 confidence scores (http://giro.uml.edu/didbase/scaled.php)

To maintain compatibility with the ARTIST-4.5, the confidence score of ARTIST-5 is also converted to the 2-digit C-level representation using the following mapping:

CS: 81..100	→	C-level: 11
CS: 61..80	→	C-level: 22
CS: 41..60	→	C-level: 33
CS: 21..40	→	C-level: 44
CS: 0..20	→	C-level: 55

for storage as ARTIST flag #10 in SAO and SAO.XML data files and common display types of DIDBase and SAO Explorer.

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