THORPEX Pacific Asian Regional Campaign (TPARC) and Tropical Cyclone Structure 2008 (TCS08) ELDORA Data Quality Report

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I. Overview

The Electra Doppler Radar (ELDORA) is an airborne, dual beam, meteorological research radar developed jointly by NCAR and France's Centre de Recherches en Physique de L'Environnement Terrestre et Planetaire (CRPE.) ELDORA was originally mounted on the NCAR Electra in 1992. After the NCAR Electra retired in 2000, ELDORA has been mounted on the tail of a Lockheed P-3 aircraft, operated by the Naval Research Lab (NRL). The ELDORA radar operated during TPARC/TCS08 on the NRL-P3 aircraft for 23 research flights from 12 August to 04 October 2008. Data quality was generally very good and INS navigation errors appear to have been stable. The most significant quality degradation was in the Aft radar reflectivity late in the project as described in section 3.

The research flight speed of the P-3 aircraft is approximately 130 m s^{-1}. At this flight speed the scientific requirement for samples every 300-500 m dictates an antenna rotation rate of approximately 24 RPM. This resolution also dictates at least one integration period (dwell time) to be completed every degree of rotation which gives dwell times the order of 8 ms. Since the phenomena to be studied has a time to independence of 3-7 ms, only two or three independent samples can be taken in a dwell time with a simple radar pulse. To meet the velocity accuracy of 1 m s^{-1} requires about 10 independent samples per dwell time. As a result, a complex waveform is therefore necessary. The waveform is normally a 4-element stepped chirp. Physically, a complex waveform consists of a pulse of RF energy, within which are sub-pulses or chirps which are coded in some way. For ELDORA these chips are distinguished by discrete shifts in transmit frequency which enable the received signals to be processed individually, thus improving the sampling statistics of the radar measurements. Test flights in Colorado prior to the start of the project revealed poor Doppler velocity measurements due to problems with the receiver. Repairs resulted in excellent velocity quality but also the loss of the fourth transmit frequency, which required a slightly slower antenna rotation rate for this project. The details of the scanning strategy for the project are given in Table 1.

Number of Radars	2 (fore and aft)
Wavelength	3.2 cm
Transmit Frequency	9.7 GHz fore; 9.6 GHz aft
Beamwidth (H x V)	1.8° x 2.0°
Antenna gain	39.2 dB
Polarization (0° elevation)	Horizontal
First Sidelobe Power	-35 dB
Beam Tilt Angle	+15.6° fore; -16.5° aft
Antenna Rotation Rate	~78°/s
Dwell Time	18 ms
Peak Transmitted Power	40 kW
Receiver Bandwidth	1.0 MHz
Pulse Repetition Frequency	1600/2000 Hz
Minimum Detectable Signal (at 10km)	-12 dBZ
Unambiguous Range	75 km
Unambiguous Velocity (dual PRT)	+- 62 m/s
Number of Frequencies	3
Pulse Chip Length	1.00 us
Range Averaging	None
Total Cell Length	150 m
Along Track Sweep Spacing	~500 m

Table 1. ELDORA Characteristics during TPARC/TCS08

II. Navigation Corrections

Airborne weather Doppler radar data (Doppler velocity) contain both meteorological signals and aircraft motion. In order to accurately obtain multiple Doppler wind synthesis, the aircraft motion must be properly removed from the Doppler velocities. Errors in the aircraft inertial navigation system (INS) and the radar pointing angles can be corrected using various methodologies, outlined briefly here.

The corrections currently calculated and distributed by EOL use the "THL" (Testud-Hildebrand-Lee) methodology, described in A Procedure To Correct Airborne Doppler Radar Data For Navigation Errors, Using The Echo Returned From the Earth Surface (Testud, et al. 1995). These corrections are obtained primarily from calibration legs performed on each research flight, but in some cases are from other legs. The algorithm uses the fact that the ground echo return should be flat, and have zero residual velocity. Solving a system of equations iteratively computes the correction to the INS parameters and radar pointing angle needed for accurate radial velocities.

While several of the INS corrections remain stable throughout a research flight, the ground speed and drift corrections may vary from leg to leg during a flight. These corrections are tightly coupled with the tilt angle, and can be further refined on a leg-by-leg basis using the techniques defined in Procedures to Improve the Accuracy of Airborne Doppler Radar Data (Bosart, et al 2002). The "ETHL" (Extended THL) method works similarly to the original algorithm by iteratively reducing ground velocity residuals to zero. In cases where the ground velocity is not expected to be zero (ie. moving ocean surface), or over complex terrain, the "BLW" (Bosart-Lee-Wakimoto) method can be applied, which compares the in situ wind recorded on the aircraft with the near-aircraft Doppler winds, reducing the discrepancy between them to produce corrections.

For TPARC, the entire project was conducted over water, therefore making the assumption of zero surface velocity and use of the ETHL technique problematic. Reverse heading legs from the aircraft calibration flights (RF01 and RF20) were used to determine the ground speed and tilt angles. Assuming the ocean surface velocity is constant over the course of the legs results in oppositely signed errors in the ground speed that average to the 'true' error. This technique resulted in a stable ground speed error of ~0.9 m s^{-1} from 16 reverse heading legs. Fixing the ground speed error then allows for solution of the tilt error. This yielded stable tilt errors of 0.3 and -0.15 consistent with previous projects. The drift error was estimated by averaging the calibration legs, assuming that the ocean surface velocity was uncorrelated with the aircraft heading, yielding a small residual error of 0.2°. Since the ground speed and drift corrections vary throughout the project, these values are given as a project averages. It is strongly recommended that the user validate these corrections for the legs of interest by performing the BLW method when possible before performing multiple Doppler analysis.

A summary of the navigation correction statistics is provided in Tables 2 and 3, followed by individual corrections for each research flight in Table 4:

	Drift Corr	Ground Speed (Reverse Legs Only)	Tilt Aft (Reverse Legs Only)	Tilt Fore (Reverse Legs Only)
Maximum	-1.095	0.59	0.2	-0.21
Minimum	0.895	1.035	0.4	0.08
Mean	0.019565	0.88563	0.30053	-0.13158
Median	0.055	0.9275	0.3	-0.15
Std Deviation	0.49641	0.15072	0.060044	0.070179

Table 2. Average navigation corrections applied to all research flights

	Range Fore	Range Aft	Altitude Corr (km)	Pitch Corr	Rotation Aft	Rotation Fore
Maximum	38.15	84.66	-0.053	-1.66	-0.28	-0.53
Minimum	168.96	209.02	-0.013	-1.565	0.09	-0.11
Mean	102.51	153.58	-0.030652	-1.6207	-0.041304	-0.30739
Median	94.17	151.09	-0.029	-1.625	-0.03	-0.33
Std Deviation	42.167	35.907	0.010731	0.024602	0.10559	0.1103

Table 3. Average navigation corrections for per flight parameters

Research Flight	Date	Time	Range Fore	Range Aft	Altitude Corr	Pitch Corr	Rotation Aft	Rotation Fore
1	8/12/08	28:00.0	135.03	139	-0.036	-1.565	0.09	-0.17
2	8/16/08	08:00.0	122.28	120.38	-0.03	-1.575	0.03	-0.27
3	8/16/08	46:00.0	99.84	143.42	-0.053	-1.64	0.08	-0.22
4	8/18/08	49:00.0	84.26	175.26	-0.025	-1.605	0.02	-0.18
5	8/28/08	00:00.0	40	148.56	-0.013	-1.64	0.08	-0.11
6	8/29/08	43:00.0	41.29	156.29	-0.028	-1.585	0.05	-0.2
7	9/1/08	25:00.0	132.06	130.8	-0.039	-1.605	0.06	-0.18
8	9/8/08	12:00.0	125.63	202.43	-0.029	-1.625	0.09	-0.2
9	9/9/08	32:00.0	61.84	98.27	-0.031	-1.62	0.06	-0.23
10	9/11/08	00:00.0	165.28	151.09	-0.017	-1.63	-0.2	-0.47
11	9/13/08	20:00.0	126.73	146.37	-0.043	-1.645	-0.02	-0.34
12	9/14/08	20:00.0	88.62	84.66	-0.021	-1.63	-0.03	-0.32
13	9/17/08	40:00.0	38.15	171.38	-0.025	-1.635	-0.08	-0.33
14	9/18/08	10:00.0	134.1	163.38	-0.028	-1.645	-0.08	-0.38
15	9/19/08	30:00.0	159	145.24	-0.035	-1.61	-0.03	-0.37
16	9/20/08	16:00.0	66.5	196.3	-0.018	-1.64	-0.04	-0.33

17	9/22/08	15:00.0	168.96	156.46	-0.023	-1.645	-0.11	-0.39
18	9/23/08	06:00.0	79.65	209.02	-0.048	-1.615	-0.11	-0.32
19	9/24/08	15:00.0	89.18	120.33	-0.047	-1.625	-0.14	-0.33
20	9/25/08	27:00.0	94.17	90.62	-0.039	-1.58	-0.08	-0.36
21	9/27/08	12:00.0	46.47	192.2	-0.036	-1.62	-0.08	-0.33
22	10/2/08	27:00.0	164.69	184.85	-0.02	-1.63	-0.28	-0.51
23	10/4/08	35:00.0	94.07	205.96	-0.021	-1.66	-0.23	-0.53

Table 4. Individual correction factors for each research flight

III. Reflectivity errors

Due to the 3 cm wavelength of the ELDORA radar, attenuation can be significant in heavier precipitation. ELDORA data is not recommended for rigorous quantitative precipitation estimation without an attenuation correction. The maximum reflectivity observed by either the Fore or Aft radar is usually utilized for analysis, with typical differences on the order of a few dBZ. The rotary joint in the ELDORA rotodome broke during some turbulence in RF16 (09/20), resulting in reduced sensitivity for the Aft radar for the remainder of that mission and the following seven missions. This was repaired for the final two missions (RF22 & 23). While this does not affect the Doppler velocity accuracy, this reduced sensitivity yields discrepancies in reflectivity exceeding 10 dBZ between the two radars in some cases, and loss of velocity signal in weak echo regions. Wind fields should still be retrievable in precipitation, but may be problematic in cloudy or clear air where only the Fore velocity is available.

IV. Distribution

The radar data is distributed in DORADE (Doppler Radar Exchange) sweep files tarred into 10 minute chunks. The total dataset is ~165 GB. The sweep files can be viewed and edited using soloii software available from NCAR[1]. Additional packages are available for gridding and Doppler synthesis, with more detailed information on this process available on the ELDORA website[2]. Though the radar functioned reliably for the entire project, the distributed sweep files contain radar artifacts resulting from low power returns, sidelobes, ocean surface returns and reflections, variations in INS errors, and occasional signal processing errors or radio interference. These artifacts should be removed before analyzing or assimilating the

[1] ftp://ftp.eol.ucar.edu/pub/archive/rdpdist/README.soloii
[2] http://www.eol.ucar.edu/instrumentation/airborne-instruments/eldora

radar data. It is currently unfeasible to automatically remove these artifacts without also removing good weather echoes, although there is an ongoing research effort to improve this process. The ELDORA radar data is released 'as is' with the fields listed in Table 5, with the user responsible for removing non-weather echoes since this often involves scientific decision-making and may require significant time for manual editing. ELDORA data typically does not require dealiasing due to the high Nyquist velocity. New users are encouraged to visit the ELDORA website and contact the NCAR scientific staff for advice on editing and synthesis techniques. Additionally, though the data have been reviewed, some errors may not be apparent until the data have been sufficiently analyzed. Feedback from users on suspected problems is welcome.

Field Name	Description
DBZ	Radar Reflectivity
VG	Ground-relative, navigation corrected, Doppler velocity
NCP	Normalized Coherent Power
SW	Spectrum Width
VT	VG thresholded with NCP below 0.25
VS	Short-pulse Doppler velocity
VL	Long-pulse Doppler velocity
VR	Aircraft-relative Doppler velocity

Table 5. ELDORA data fields

V. Flight Specific Issues

Only persistent errors affecting a long time period will be mentioned here and this is not likely to be an exhaustive list. Care should be taken to closely examine any legs over which a detailed analysis is to be done to remove any data that are bad. Times when the radar was restarted are not included, unless it happened multiple times in close succession, and ferry segments were largely ignored. All times listed are in UTC.

RF01
This was a calibration flight and there were some tests that being done, resulting in some spurious sweeps.

RF02
0009 – 0023: Both radars have a number of incomplete sweeps.

0119 – 0132: Both radars are restarted twice and are down for most of this time.

RF03
No major problems identified.

RF04
0005 – 0015: Both radars are restarted twice and are down for most of this time.

RF05
0033 – 0035: Strong sidelobe reflections off the island of Rota are evident in both radars.

RF06
0042 – 0050: Many incomplete sweeps and downtime for both radars.
0257 – 0307: Either the radar or the transmitter was off for much of this time.
0336 – 0346: Many incomplete sweeps and much downtime for both radars.
0413 – 0422: Many incomplete sweeps and much downtime for both radars.
0215: Fore radar shows some high ground velocities around this time, possible drift error.

RF07
No major problems identified.

RF08
No major problems identified.

RF09
0341 – 0349: In both radars there are discontinuities in the velocity data that are suspect. In many cases they represent a boundary between inbound and outbound velocities with no "zero" line in between. The ELDORA technicians noted problems in the archiving computer at this time.
0337 – 0420: The discontinuities show up in the aft radar, very sporadically at first but increasing in number from 0405 – 0420. The radars were restarted at 0423.
0623 – 0626: Similar discontinuities appear in both radars again.

RF10
0019: In both radars the surface velocity increases around this time. Errors such as these are likely related to large values of drift angle, which usually occur in strong winds or sharp turns.

RF11
0237 – 0258: The transmitter is shut off and then both radars are down.

RF12
0001 – 0010: Random beam errors (higher magnitudes of reflectivity and velocity than surrounding beams) in various sweeps during this time in both radars. These

beams appear to have low NCP and high spectral width so they will be mostly erased with standard noise removal techniques.
0039 – 0050: Random beam errors evident in both radars.
0104 – 0107: Random beam errors evident in both radars. Transmitter is shut down at 0107.

RF13
0215 – 0238: Both radars have blocks of bad velocity. These are in the velocity data only. The reflectivity field appears to be fine.

RF14
2241 – 2301: Mountain sidelobe reflection and possible RF interference near coastal Japan. The radar is down from 2301 - 0000.
0021 – 0054: Bad velocity data in the fore radar.
0217 – 0224: Mountain sidelobe reflection and possible RF interference near coastal Japan.
0513 – 0558: Mountain sidelobe reflection and possible RF interference near coastal Japan.

RF15
0017 – 0100: Mountain sidelobe reflection and possible RF interference near coastal Japan.
0114 – 0115: Both radars have a few sweeps with anomalously large velocity.
0337 – 0532: Both radars have some incomplete sweeps, but the radar is never down during this time. This happens every 1-2 minutes on average.
0505 – 0520: Random beam errors in the aft radar.

RF16
0557 – 0619: The fore radar has anomalously large velocity values throughout this period.
0648 – 0730: The aft radar begins to show choppiness and weakness in the reflectivity data. This is documented further in Section 3 of the readme document and is due to the reduced sensitivity of the receiver. This problem persists until RF22.

RF17
The sensitivity is reduced in the aft radar.

RF18
The sensitivity is reduced in the aft radar.

RF19
The sensitivity is reduced in the aft radar.
2319 – 2322: Some velocity discontinuities are evident in both radars.

RF20
The sensitivity is reduced in the aft radar.
0008 – 0030: Some dropped beams.

RF21
The sensitivity is reduced in the aft radar.
0019 – 0022: The transmitter is shut off and the radar is restarted.
0030 – 0033: The transmitter is shut off and the radar is restarted.

RF22
No major problems identified.

RF23
0231 – 0256: The transmitter is shut off initially and then the radar is shut down until 0256.

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