14.4 **ON THE DEVELOPMENT OF A WEATHER RADAR DATA ASSIMILATION SYSTEM FOR THE US NAVY**

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1. INTRODUCTION

A meteorological radar data assimilation system has been developed at the Marine Meteorology Division of the Naval Research Laboratory (NRL) to enhance the safety of ship and aircraft operations. Radar observations are assimilated into the Navy's Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS®) to improve the 0-24 hour forecasts of hazardous weather and to provide decision makers with timely products to help exploit or mitigate those predictions. The system takes advantage of Navy vessels having weather processors for their tactical radars (e.g., SPS-48E/G: Hazardous Weather Detection and Display Capability (HWDDC); SPY-1 Tactical Environmental Processor (TEP)). The ships in the battle fleet having this capability will be able to digitally generate full-resolution, full-volume weather radar data, and archive those data in Universal Format (UF – Barnes (1980)) files approximately every 5 minutes. Several UF files will be transmitted in near-real-time per hour to Fleet Numerical Meteorology and Oceanography Center in Monterey, CA, where the data assimilation into COAMPS® is conducted. UF file sizes range from ~5 MB (SPS-48E) to ~13 MB (SPY-1), which would be too large a load on the operational bandwidth of the ships' communication systems. To overcome this obstacle, NRL has also developed a novel UF file compressor that typically reduces UF file sizes by a factor of forty, thus permitting their transmission from a ship to FNMOC.

The HWDDC is a weather radar processor and web-display server that passively taps into volume scan data from the SPS-48E radar onboard selected US Navy aircraft carriers and large-deck amphibious ships. The SPS-48E is an S-band, long range, air defense radar that operates with multiple pencil beams in a mechanically rotating phased-array antenna which scans electronically in elevation. The HWDDC digitally combines several consecutive SPS-48E volume scans into a single reference volume at a fixed position. Several nowcasting products are created every minute for the HWDDC display on-ship, whereas the UF files are created every five minutes. The UF files contain full-resolution (915 m in range; 1° in azimuth) reflectivity factor (DZ), raw radial velocity (VE), de-aliased radial velocity (VD), spectrum width (SW), signal to noise ratio (SN) and valid radial velocity indicator (VV) data. These data are available within PPI scans at 22 different elevation angles ranging from 0.2° to 24° out to 275 km range, except for VE, VD, SW and VV, which are only available from the first three elevation tilts (up to 1.6° elevation) out to 52 km range. The near-future SPS-48G/HWDDC and SPY-1/TEP will have fuller-volume, fuller-range Doppler data.

In January of 2006, a prototype HWDDC was successfully tested with a land-based SPS-48E at Navy facilities in Dam Neck, VA (Harasti et al. 2006; Maese et al. 2007). Later in February of 2006, the HWDDC was deployed onboard the USS PELELIU (NPEL) for a 6-month, at-sea demonstration. UF data were archived during the NPEL's encounter with hazardous weather near Hawaii on 22 February 2006. This paper presents a case study of this data to demonstrate both the UF file compressor capability and the forecast impact of UF data assimilation into COAMPS®. UF data quality control (QC) issues and solutions will also be discussed.

2. WEATHER SCENARIO AND UF DATA QC

On 22 February 2006, the NPEL encountered lines of showers and thunderstorms associated with a low pressure center and trough that traveled eastward just north of the Hawaiian Islands (Fig. 1). The commanding officer of the NPEL used the real-time HWDDC display of the SPS-48E weather radar data to steer the ship around non-flyable storm cells into clear areas so that the ship could resume flight operations. The HWDDC

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thus enhanced operational safety and efficiency and provided considerable time and resource savings.

Figure 2 shows a PPI image of the lowest elevation reflectivity taken from the HWDDC UF file created at 0544:30 UTC as the trough of low pressure advanced through the area from the west. The NPEL SPS-48E radar is located at the center of the image, and aft of the ship's mast. Thus, the mast obstructs the radar beam as the radar rotates past the ship's bow direction. Note the missing-echo notch in the precipitation echo in Fig. 2 caused by this obstruction. Also note the intense reflectivity caused by ground and sea clutter.

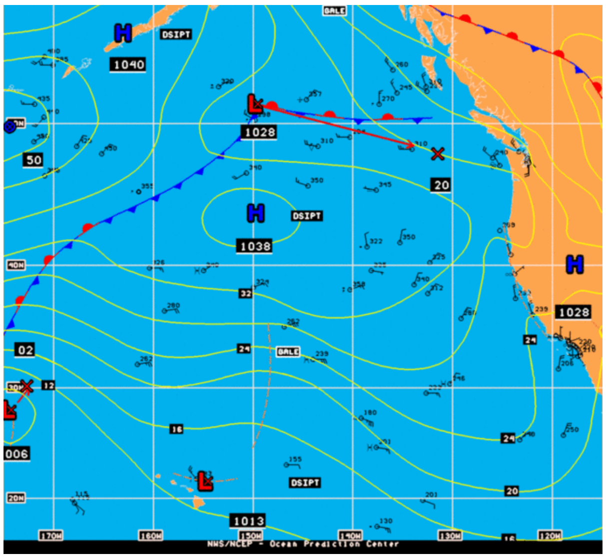

Fig. 1. Surface analysis and forecast chart for the Eastern Pacific Ocean at 18 UTC 22 Feb 2006. A low pressure center and trough were located just north of the Hawaiian Islands (courtesy of the NOAA/NESDIS/ NCDC /SRRS website).

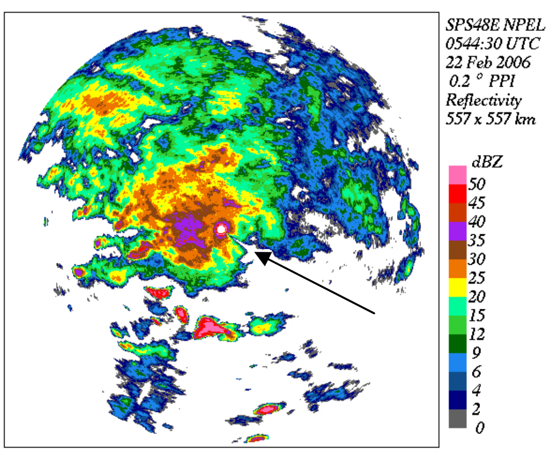

Fig. 2 PPI image of reflectivity taken from the SPS-48E 0.2° elevation scan for the time indicated. Note > 45 dBZ reflectivity in the southern quarter sector caused by ground clutter from the highlands of the Hawaiian Islands, and the > 30 dBZ concentric rings of reflectivity at the center of the image caused by sea clutter. The arrow points to the missing-echo notch described in the text.

PPI images are shown in Fig. 3 at a later time when a bow echo associated with the low pressure center moved east of the area. Further examples of quality control issues are also illustrated. The ship's mast not only obstructs the radar beam but it also reflects a portion of the beam at an obtuse angle towards reflectors within approximately ±20° azimuth of the mast, thus causing mast reflection artifact echoes as shown in the figure. Harasti et al. (2007) describe in detail the geometry behind mast reflection artifacts and show further examples.

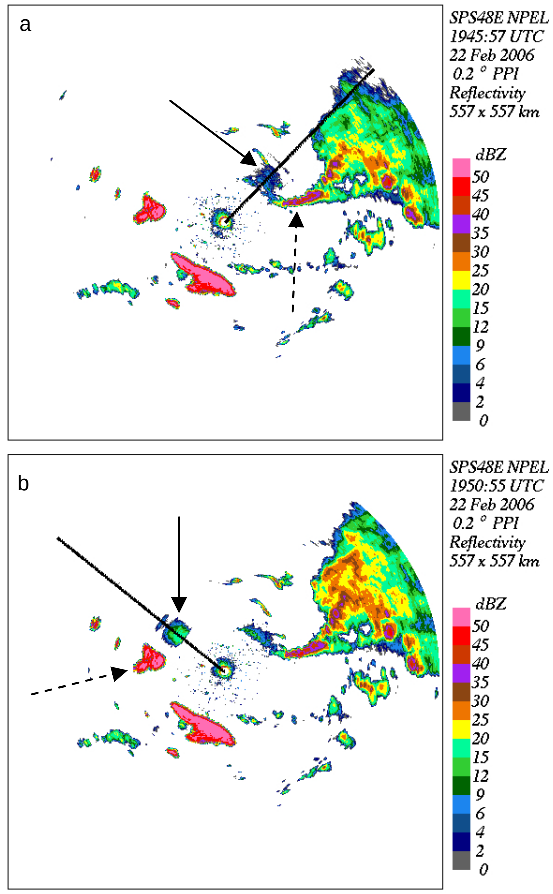

Fig. 3. Same as Fig. 2 but at the later times indicated, demonstrating mast obstructions and reflections. The images were created from two consecutive UF files as the ship changed heading from (a) 44° azimuth counter-clockwise through to (b) 309° azimuth. The solid black lines delineate the ship's instantaneous heading at each time. Note the attenuation of the weather echo in the vicinity of the ship's heading in (a) compared to the same echo shown 5 minutes later in (b), which was caused by the mast's obstruction to the radar beam. The precipitation echo intensity and pattern at 1940 UTC (not shown) was very similar to (b) thus confirming the mast's obstruction to the precipitation echo in (a). Solid arrows indicate mast refection artifacts caused by the obtuse reflection of the radar beam off the mast toward the echo source indicated by the dashed arrows. These echo sources are (a) precipitation in the bow echo, and (b) ground clutter from the highlands of Maui. In addition, all of the radar echo within ~50 km of the radar is sea clutter.

NRL-developed solutions to these demonstrated quality control issues are summarized as follows. Given the very complicated nuisance of the mast being both an obstruction to the radar beam and the source of mast reflection artifacts from both precipitation and non-meteorological echoes, for radar data assimilation purposes, all data within ±20° azimuth of the mast's direction relative to the radar are excluded from the radar data assimilation. In addition, the quality control software formerly developed at NRL (Harasti et al. 2005) and a modified version of the NCAR Radar Echo Classifier (Kessinger et al. 2005) will be combined to remove ground and sea clutter. Constant power function artifacts, such as sun strobes (not seen in the NPEL data set), will be removed using an algorithm that calculates the sun's azimuth and elevation angles at the time and location of the radar observations. And lastly, given the anomalous propagation due to surface and evaporation ducts that results in sea and ground clutter, atmospheric refractivity information obtained from COAMPS® data will be used to estimate the vertical coordinates of the UF data. Allowances for ship motion are discussed in section 4.

3. RESULTS FROM THE UF FILE COMPRESSOR

It was estimated that in order to permit UF file transmission from a US Navy ship to FNMOC, the compressed UF files would need to be reduced to below 1 MB. To achieve this goal, a three-step compression algorithm was developed: (i) The scaled UF data are unscaled back to their meteorological values, followed by their rounding to the nearest integers. The impact of rounding on COAMPS® forecasts are not expected to be statistically significant since the measurement uncertainty of the UF data are at least a factor of two larger than the round-off errors. (ii) Data reduction by removal of unutilized UF data types (VD, VV, SN), and optional/adjustable threshold operations applied to the retained data (DZ, VE, SW). The SN and VV data are used to quality control the retained data prior to their removal. In addition, a 5 dBZ threshold is applied to DZ and the spatially corresponding VE and SW data. This threshold was chosen to be consistent with reflectivity limits implied by the empirical reflectivity-liquid water content/ice content transformation operation used in the radar data assimilation system discussed in section 4. (iii) A intra-UF file compression software package based on the open-source *bzip2* algorithm, which achieves significant lossless compression on the UF file headers and the retained, thresholded data. Spatial correlations and significant header redundancies are exploited to maximize the compression. The algorithm is versatile enough to handle UF files of all possible sizes dynamically, and any variations to the two-character UF data type names encountered in the field. See Fig. 4 for a schematic summary of the method, and Pan et al. (2009) for more details.

The UF file compressor was tested on the NPEL SPS-48E UF data files created by the HWDDC on 22 February 2006. The data contained 255 volume scans executed at a frequency of 5 minutes for approximately 22 hours. Figure 5 gives a summary of the test. The original 5.4 MB UF files were compressed down to an average value of 130 KB, thus achieving better than 40:1 compression. As expected, there is a positive correlation between the amount data being blanked out due to the threshold applied to DZ and the compression achieved on the UF files. The maximum possible compressed UF file was estimated to be ~500 KB by assuming a worst case scenario of > 5 dBZ reflectivity (i.e., no thresholding by reflectivity) everywhere in the SPS-48E volume scan domain.

NRL has delivered the UF file compressor to Basic Commerce and Industries, Moorestown, NJ, who is the developer of the HWDDC under contract for SPAWAR Systems Center, San Diego, CA. From May to August 2009, BCI and SPAWAR conducted tests using the land-based SPS-48E at Navy facilities in Dam Neck, VA on version 2 of the HWDDC, which will soon be installed on ~10 Navy ships. One of these tests was the successful transfer of compressed UF files from the HWDDC to NRL in real-time.

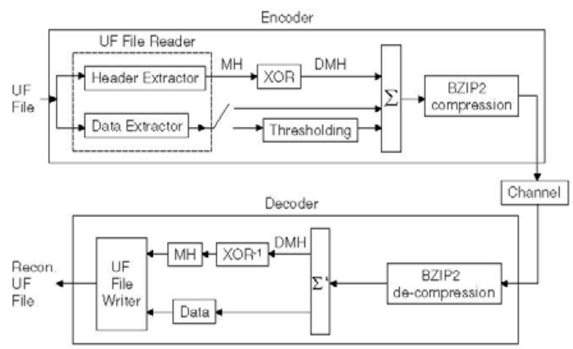

Fig. 4. Architecture of UF file encoder and decoder. MH and DMH denote macro-headers and differential macro-headers, respectively. Thresholding is an option at the encoder. XOR (Exclusive OR) is a bitwise operation that tends to be "safer" and faster than subtraction, to obtain the differences between neighboring MH. The encoder is located on the ship whereas the decoder is located at NRL/FNMOC. The channel is the secure data transfer mechanism from the ship to FNMOC.

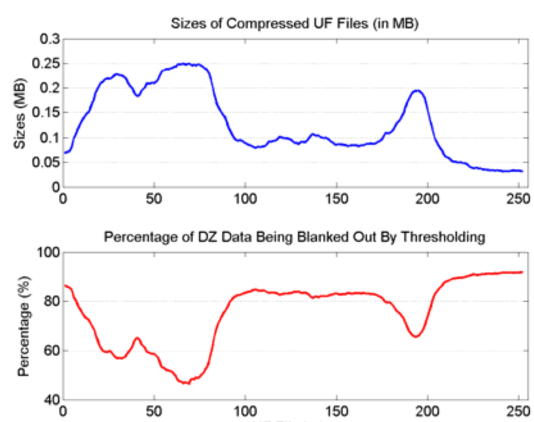

Fig. 5. Summary of the UF compressor test on the NPEL SPS-48E/HWDDC UF data: On average, the size of the compressed files was 130 KB. Thus the size of the original UF files (5.4 MB) was reduced and compressed by an average of 40 times.

4. COAMPS® ASSIMILATION OF NPEL UF DATA

The NRL multiple-radar data assimilation system (Zhao et al. 2006; 2008) includes two components: a 3d-Var reflectivity and a 3.5d-Var radial velocity assimilation system. The 3d-Var component retrieves rain water, snow and graupel mixing ratios from one time level (e.g., one UF file) of reflectivity observations, yielding one retrieval. The 3.5d-Var component has a simplified adjoint model that applies dynamical constraints to the 3D wind retrieval, modifies the temperature (or pressure) fields to keep initial dynamical balance, and uses three consecutive time levels of radial velocity data, yielding one retrieval. It was necessary to adapt the gridding component of the assimilation system to handle the moving radar coordinate system due to the ship's velocity. This was accomplished by creating a model grid domain large enough to handle the projected ship movement over 24 hours (arbitrary, adjustable time frame), then treat each of the assimilated UF data files from a single ship as if they were coming from a different radar located at its UF-file-specified latitude and longitude. The radial velocity VE data are automatically corrected for ship motion within the HWDDC before archival to the UF files. Radar observations are assimilated hourly after conventional and satellite observations are assimilated every six or twelve hours.

A hardware problem during the NPEL SPS-48E/HWDDC weather observations on 22 February 2006 caused invalid ship position data (latitude, longitude, speed, heading) to be stored in the UF files. It was therefore necessary to determine the position of the ship over the 22 hour period on this day by a separate method. The positions were determined by iteratively adjusting the latitude and longitude origin of a coastline geography overlay grid of the island of Molokai until the coastline enclosed the ground clutter echo seen in the UF-file reflectivity from the island. However, given the varying anomalous propagation of the radar beam and the ship's position over time, the ground clutter echo from Molokai varied significantly over the 22 hours of observation, which resulted in a ship position measurement uncertainty ranging from 2 to 5 km.

The UF-file radial velocity data were not assimilated in this case study because of the uncertain success of their correction for the ship's motion, given the hardware failure described above. However, the hourly reflectivity data over the 22 hour observation period of 22 February were assimilated into COAMPS® with the 3d-Var component after being quality controlled for sea and ground clutter, and mast artifacts (see section 3). The equitable threat scores of storm areas of different intensities shown in Fig. 6 indicate that the assimilation of this reflectivity data into COAMPS® had a marginal impact on the storm forecasts. The main reason for this is believed to be the exclusion of radial velocity assimilation in this case, since Zhao et al. (2006; 2008) clearly show the importance of radial velocity assimilation in resolving storm-scale predictions. Other possible reasons include inaccurate data registering to the grid due to the uncertainty in the ship's position, and also the height of the reflectivity data were not determined using actual radar beam trajectory calculations from COAMPS® refractivity data. The varying range limit (from 20 to 60 km) and intensity variations of the sea clutter echo over the 22 hour period suggest that the refraction of the radar beam due to varying anomalous propagation conditions need to be accounted for in the future. When fuller-volume, fuller range radial velocity data become available in the near future from the SPS-48G/HWDDC and SPY-1/TEP, having both reflectivity and radial velocity data correctly registered into the 3D model domain grid will be necessary to maximize their impact on forecasts. The importance of having fuller-volume, fuller-range radial velocity was also underscored in this case study with the observation of persistent sea clutter within 60 km range, rendering only the upper radial velocity elevation tilt (1.6°) relatively free from sea clutter contamination.

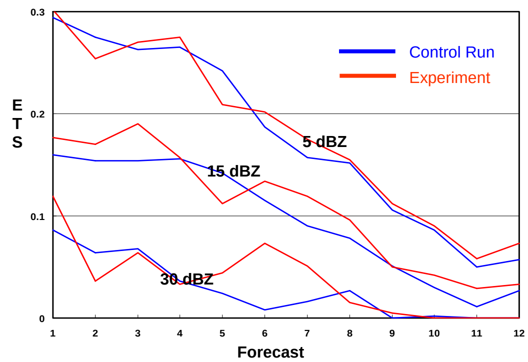

Fig. 6. COAMPS® forecast results for model runs commencing 00 UTC 22 February 2006. Equitable Threat Score (ETS) versus forecast hour for the three reflectivity levels shown. The Control Run was performed with only the assimilation of conventional and satellite data whereas the Experiment run assimilated these data along with radar reflectivity data.

5. SUMMARY AND FUTURE WORK

This paper summarizes the progress and tests of the components of the meteorological radar data assimilation system at NRL. When assimilation of full-resolution, volumetric radar data in Universal Format (UF) obtained from ship-board US Naval radars is involved (e.g. SPS-48E/HWDDC), there are three components: (i) quality control, reduction and compression of the UF data on the ship(s), (ii) transmission of compressed UF data from the ship(s) to FNMOC, and (iii) decompression and further quality control of the UF data, followed by their assimilation into COAMPS® at FNMOC.

A case study comprised of 22 hours of UF data archived by the SPS-48E/HWDDC onboard the USS PELELIU on 22 February 2006 is used to demonstrate quality control issues that have been addressed at NRL. In addition, these data are used to demonstrate the performance of a novel UF file compressor developed by NRL that more than meets the goal of compressing UF files to a size below 1 MB, which will thus permit their transmission to FNMOC in near real-time over the limited communication bandwidth. Quality controlled reflectivity data from the case study were also assimilated into the 3d-Var component of the assimilation system, demonstrating marginal impact of the COAMPS® forecasts. More significant impacts are expected when fuller-volume, fuller-range radial velocity data are assimilated using the SPS-48G/HWDDC and SPY-1/TEP data expected in the very near future. Furthermore, NRL is currently completing and testing its next-generation radar data assimilation system that has a flow-dependent background error covariance and will greatly improve COAMPS® forecasts of the future.

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