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Utility of tactical environmental processor (TEP) as a Doppler at-sea weather radar

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NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

UTILITY OF TACTICAL ENVIRONMENTAL PROCESSOR (TEP) AS A DOPPLER AT-SEA WEATHER RADAR

by

Sean D. Robinson

June 2002

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Tactical Environmental Processor (TEP) is a through-the-sensor technique that converts radar returns from the AN/SPY-1 into environmental information known as spectral moments. TEP was installed aboard the USS Normandy (CG 60) in May 2000 to support a Limited Objective Experiment during Joint Task Force Exercise (JTFEX) 00-2. On 15 May, TEP observed severe weather associated with a line of passing thunderstorms. These weather events proved serious enough to suspend mid-cycle flight operations for the USS George Washington (CVN 73) during its simulated wartime scenario. TEP is a significant benefit to nowcast weather forecasting and supports at-sea METOC and warfighters in two primary areas: improved situational awareness and optimization of sensors, weapons and tactics. Results from this case study demonstrate the importance of TEP as a Doppler at-sea weather radar in support of naval operations.

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UTILITY OF TACTICAL ENVIRONMENTAL PROCESSOR (TEP) AS A DOPPLER AT-SEA WEATHER RADAR

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ABSTRACT

Tactical Environmental Processor (TEP) is a through-the-sensor[1] technique that converts radar returns from the AN/SPY-1 into environmental information known as spectral moments. TEP was installed aboard the USS Normandy (CG 60) in May 2000 to support a Limited Objective Experiment during Joint Task Force Exercise (JTFEX) 00-2. On 15 May, TEP observed severe weather associated with a line of passing thunderstorms. These weather events proved serious enough to suspend mid-cycle flight operations for the USS George Washington (CVN 73) during its simulated wartime scenario. TEP is a significant benefit to nowcast weather forecasting and supports at-sea METOC and warfighters in two primary areas: improved situational awareness and optimization of sensors, weapons and tactics. Results from this case study demonstrate the importance of TEP as a Doppler at-sea weather radar in support of naval operations.

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[1] Through-the-sensor is a technique that extracts new information from existing sensor data, in this case; TEP converts the AN/SPY-1 radar returns into atmospheric measurements (spectral moments).

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TABLE OF CONTENTS

I. INTRODUCTION 1

II. TACTICAL ENVIRONMENTAL PROCESSOR 3
  A. SYSTEM DESCRIPTION 3
  B. TEP SCAN MODES 5
  C. TEP PRODUCTS 6
  D. AEGIS RADAR VS. NEXRAD 9

III. TEP DATA PROCESSING IN AT-SEA DEMONSTRATION (JTFEX 00-2) ... 15

IV. JTFEX 00-2: 15 MAY 2000 19
  A. OBSERVATIONAL DATA 20
  B. SYNOPTIC ANALYSIS 23
    1. Upper Levels 23
    2. 850mb and Surface 24
  C. MESOSCALE ANALYSIS 27
  D. TEP ANALYSIS 32
  E. DISCUSSION 45

V. SUMMARY AND CONCLUSIONS 47
  A. SURFACE WARFARE 47
  B. AVIATION 49
  C. METOC 50
  D. ISSUES TO OVERCOME 51

VI. RECOMMENDATIONS FOR FUTURE STUDIES 53
  A. TEP LIMITED AT-SEA EXPOSURE AND TESTING 53
  B. TEP DATA PROCESSING, DISTRIBUTION AND DISPLAY 53

APPENDIX. AEGIS RADAR OPERATING FUNDAMENTALS 55

LIST OF REFERENCES 61

INITIAL DISTRIBUTION LIST 63

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LIST OF FIGURES

Figure 2-1: TEP Block Diagram (from: TEP Final Report, 2000).. 4
Figure 2-2: Radial Velocity Plot; blue-green colors indicate scatters moving toward TEP, and brown colors for scatters moving away TEP. (from: TEP Final Report, 2000).. 7
Figure 2-3: Composite Reflectivity (from: TEP Final Report, 2000).................................... 7
Figure 2-4: Comparison of TEP Reflectivity (left) vs. NEXRAD (right) for a Developing Squall Line Off Jacksonville on 09/10/99 (from: TEP Final Report, 2000).. 11
Figure 2-5: TEP vs. NEXRAD Difference Plot (from: TEP Final Report, 2000) 12
Figure 4-1: GOES 8 VIS Satellite Image (1 km resolution) for 2245Z on 15 May 2000 (red circle represent the USS Normandy area of operation).......................... 21
Figure 4-2: 16/00 300mb Heights and Isotachs (red cross-hair represents center of JTFEX OPAREA).. 25
Figure 4-3: 16/00 500mb Heights and Absolute Vorticity (red cross-hair represents center of JTFEX OPAREA)... 25
Figure 4-4: 16/00 850mb Heights and 500mb Heights (red cross-hair represents center of JTFEX OPAREA)... 26
Figure 4-5: 16/00 850mb Heights and Equivalent Potential Temperature (red cross-hair represents center of JTFEX OPAREA)... 26
Figure 4-6: 16/00 Sea Level Pressure and IR Satellite Image (red cross-hair represents center of JTFEX OPAREA)... 27
Figure 4-7: Comparison of 300 mb Heights for 15/12 (green) at Model Time +12 hours and 16/00 (blue) Initialization (red cross-hair represents center of JTFEX OPAREA)... 29
Figure 4-8: Comparison of 500 mb Heights for 15/12 (green) at Model Time +12 hours and 16/00 (blue) Initialization (red cross-hair represents center of JTFEX OPAREA)... 30
Figure 4-9: Comparison of 850 mb Heights for 15/12 (green) at Model Time +12 Hours and 16/00 (blue) Initialization (red cross-hair represents center of JTFEX OPAREA)... 30
Figure 4-10: Comparison of Sea Level Pressure for 15/12 (green) at Model Time +15 Hours and 16/00 (blue) at Model Time +3 Hours (red cross-hair represents center of JTFEX OPAREA)... 31
Figure 4-11: Comparison of 850 mb Equivalent Potential Temperature for 15/12 (green) at Model Time +12 Hours and 16/00 (blue) Initialization (red cross-hair represents center of JTFEX OPAREA)... 31
Figure 4-12: Plot of TEP Reflectivity for 00:57Z on 15 May 2000...................................... 34
Figure 4-13: Zoomed Plot of TEP Reflectivity for 2340Z on 15 May 2000 35
Figure 4-14: TEP Reflectivity Plot for 22:43Z on 15 May 2000 (Strom of interest occurred at 23:00Z, previous TEP data was at 22:05) 38
Figure 4-15: TEP Reflectivity Plot (9.1^0 elevation) for 22:43Z on 15 May 2000 (notice upper level of intense storm at 315^0, body of storm within first range gate).. 39

Figure 4-16: TEP Reflectivity Plot for 22:53Z on 15 May 2000 39
Figure 4-17: TEP Reflectivity Plot for 23:10Z on 15 May 2000 40
Figure 4-18: TEP Reflectivity Plot for 23:20Z on 15 May 2000 40
Figure 4-19: TEP Reflectivity Plot for 23:30Z on 15 May 2000 (distinct SPY-1 waveform or power change between 240^0 and 280^0) 41
Figure 4-20: TEP Reflectivity Plot for 23:40Z on 15 May 2000 (SPY-1 waveform between 240^0 and 280^0 is still de-sensitized) 41
Figure 4-21: TEP Reflectivity Plot for 23:50Z on 15 May 2000 (SPY-1 waveform between 240^0 and 280^0 is still de-sensitized, second thunder cell bearing 040 @ 27nm) 42
Figure 4-22: TEP Reflectivity Plot for 00:00Z on 16 May 2000 (SPY-1 waveform between 240^0 and 280^0 is still de-sensitized) 42
Figure 4-23: TEP Reflectivity Plot for 00:37Z on 16 May 2000 (SPY-1 waveform between 240^0 and 280^0 has been restored to a more robust search pattern, lightning directly corresponds with significant intensities from both thunderstorm cells) 43
Figure 4-24: Zoomed TEP Reflectivity Plot for 00:37Z on 16 May 2000 (lightning corresponds with strong reflectivity for a significant storm) 43
Figure 4-25: Zoomed TEP Reflectivity Plot (9.1^0 elevation) for 00:37Z on 16 May 2000 (snapshot of intense convection within upper portions of the thunderstorm cell) 44
Figure 4-26: TEP Reflectivity Plot for 00:47Z on 16 May 2000 44
Figure 4-27: Independent Severe Storm Verification - GOES IR Channel 5 Imagery (23:35Z) Overlaid with TEP Reflectivity (23:40Z) and Archived Lightning Data 45
Figure 5-1: Plot Demonstrating the Method and Importance of Real-Time Sensor Optimization (from: Easton, 2000) 48
Figure A-1: TEP Reflectivity Overlaid with Clutter Track Initiations, reflectivity color bar not included (from: TEP Final Report, 2000) 57
Figure A-2: Overlay of Real vs. Clutter Tracks (from: TEP Final Report, 2000) 58
Figure A-3: TEP Radial Velocity with SPY-1 Auto MTI (from: TEP Final Report, 2000). 59

LIST OF TABLES

Table 2-1: TEP Modes and SPY-1 Responses 5
Table 4-1: TEP Reflectivity Data Used for 15 May 2000 Case Study 33
Table A-1: SPY-1 Scheduling Order 56

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LIST OF ACRONYMS

AD	Air Defense
AESP	Auxiliary Environmental Signal Processor
CIDD	Configurable, Interactive Data Display
CO	Commanding Officer
COAMPS	Coupled Ocean Atmosphere Prediction System
CONUS	Continental United States
COTS	Commercial Off The Shelf
CSSQT	Combat System Ship Qualification Trial
CVN	Nuclear Aircraft Carrier
DCS	Display & Control Subsystem
DOD	Department of Defense
EMCON	Emission Control
GCCS-M	Global Command and Control System – Maritime
GW	USS George Washington (CVN 73)
I/Q Data	Radar In-Phase and Quadrature Data
JTFEX	Joint Task Force Exercise
LOE	Limited Objective Experiment
LHD	Amphibious Assault Ship
MDV	Meteorological Data Volume
METOC	Meteorology and Oceanography
MTI	Moving Target Indicator
MVOI	Multivariate Optimum Interpolation

NCAR	National Center for Atmospheric Research
NEXRAD	Next Generation Weather Radar
NIPRNET	Unclassified but Sensitive Internet Protocol Router Network
NLMOC	Navy Atlantic Meteorology and Oceanography Center
NOGAPS	Navy Operational Global Atmospheric Prediction System
NPS	Naval Postgraduate School
NRL	Naval Research Laboratory
NTDS	Naval Tactical Data System
NWS	National Weather Service
OOD	Officer of the Deck
PD	Pulse Doppler
PPI	Planned Position Indicator
REA	Rapid Environmental Assessment
RHI	Range Height Indicator
RFC	Refractivity From Clutter
SIPRNET	Secret Internet Protocol Router Network
SPAWAR	Space and Naval Warfare Systems Center
TEP	Tactical Environmental Processor
TIP	Track Initiation Processor
UF	Universal Format
VAD	Velocity Azimuth Display

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EXECUTIVE SUMMARY

Tactical Environmental Processor (TEP) is a through-the-sensor technique that converts radar returns from the AN/SPY-1 into environmental information known as spectral moments. TEP was installed aboard the USS Normandy (CG 60) in May 2000 to support a Limited Objective Experiment during Joint Task Force Exercise (JTFEX) 00-2. On 15 May, TEP captured a severe weather cell associated with a line of passing thunderstorms. Observers on the USS George Washington (CVN 73) witnessed a waterspout, intense lightning storm and apparent microburst. These weather events proved serious enough to suspend mid-cycle flight operations for the USS George Washington during its simulated wartime scenario.

This thesis is one of the first public reports to exhibit the TEP program. Focusing on the significant weather events from 15 May 2000, this case study contains a synoptic, mesoscale and Doppler at-sea weather radar (TEP) analysis. The goal of analyzing the severe weather events from different perspectives is not to determine why the events occurred, but to emphasize the distinction between traditional at-sea forecasting and nowcasting[2] with TEP. The objective of this thesis is to provide an evaluation of TEP's utility to the Navy, especially the warfighters.

As weather radar, TEP directly supports the warfighter while providing METOC with an at-sea nowcast of the atmosphere. The JTFEX synoptic and mesoscale analysis indicated thunderstorm activity in an area of operations, but TEP revealed individual storm cell locations. Additionally, TEP provided a measure of the relative storm strength, which could be used for safety of flight and strike planning. By fusing the TEP environmental nowcast with model forecasts and satellite interpretations, at-sea METOC can provide superior atmospheric knowledge to support the warfighter in a real-time fashion. TEP is an environmental window that helps the surface warrior optimize his air defense radar while providing the carrier an excellent tool for operational planning. The utility of the TEP atmospheric nowcast allows the Navy, especially the warfighters, to take advantage of the environment!

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[2] Nowcast is a real-time rapid environmental assessment (REA) in the short (0-2 hours) and small horizontal scale (0-100 nautical miles).

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I. INTRODUCTION

In this era of increasing global conflict, our naval forces are frequently called upon to operate in remote and confined locations. Environmental conditions affecting operations have become more complex and dynamic with the shift from open ocean to the littoral region. In the littoral arena, naval forces are stationed in close proximity to hostile forces ashore and must operate in an environment defined by greater temporal and spatial atmospheric variability. This complex battlespace combined with advanced naval systems mandates aggressive characterization of the tactical battlespace in order to determine the impact on aircraft, ships and sensors. Without an accurate and timely characterization of the continually changing atmosphere, the warfighter is left to react to the constraints the environments places on the battlespace. However, with a nowcast of the atmosphere, the warfighter is able to adjust sensors, weapons and tactics to exploit the environment surrounding the battlegroup in real-time.

Littoral operations have greatly confined the space available for ship and air operations. With less room to maneuver, there is an increased demand to identify potential severe weather cells before they influence naval operations. The ability to directly observe and quantitatively measure properties of convective storm cells and predict their movement can benefit air and radar operations, especially those conducted outside the CONUS weather network. Current operational Meteorology and Oceanography (METOC) products do not have the spatial or temporal resolution needed to capture real-time littoral varying environmental conditions nor can they nowcast specific weather events. Tactical Environmental Processor (TEP) provides the critical atmospheric nowcast needed to configure weapons systems and ensure the safety of continuous air operations in the dynamically changing atmospheric conditions associated with the littorals.

TEP is a thru-the-sensor technique that converts radar returns from the AN/SPY-1 into environmental measurements known as spectral moments. Unlike other environmental sensing techniques, TEP can perform these measurements simultaneously with normal radar operations. On request from U.S. Second Fleet, TEP was engaged to support a METOC Limited Objective Experiment (LOE) conducted during Joint Task Force Exercise (JTFEX) 00-2. The purpose of this LOE was to evaluate the benefits and usefulness of TEP environmental sensing in support of the Navy. This thesis is focused on a significant weather event that occurred during JTFEX 00-2. On 15 May 2000, TEP observed an apparent microburst associated with a line of passing thunderstorms. This weather event proved serious enough to suspend mid-cycle flight operations on the USS George Washington (CVN 73) during the simulated wartime scenario.

Since 1995, the U.S. Navy and Lockheed Martin have been developing new and more efficient methods of characterizing the environment by utilizing through-the-sensor techniques. These studies culminated in an at-sea demonstration of TEP aboard USS O'Kane (DDG 77) and the LOE aboard USS Normandy (CG 60). Both of these at-sea trials are detailed in the TEP Final Report (prepared by Lockheed Martin for the Office of Naval Research with limited distribution). This thesis is the first in-depth analysis of the SPY-1/TEP system in an operational environment. Since the TEP Final Report is the single source of TEP information, this thesis makes repeated reference to its content, especially when describing the TEP system and associated at-sea demonstration results.

The objective of this thesis is to provide an evaluation of the utility of TEP for the Navy, especially the warfighters. The thesis includes background material (Chapter II) - a description of the TEP system, TEP products and a comparison of the SPY-1 to the ground truth weather radar, NEXRAD. Chapter III details the TEP data collection and processing. Chapter IV contains two meteorological accounts, a synoptic/mesoscale[3] description and a TEP analysis (nowcast) of the weather events that took place during JTFEX 00-2. A discussion of the synoptic/mesoscale analysis and the TEP nowcast ability concludes the JTFEX 00-2 section. Chapter V is an evaluation of the TEP operational and environmental performance from a surface warfare, aviation and METOC perspective. Recommendations for future TEP studies and research are found in Chapter V. The Appendix provides a background discussion about AN/SPY-1 radar operations, giving non-AEGIS TEP users an understanding of SPY-1 dynamics from a radar operator perspective.

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[3] Synoptic scale is atmospheric motion on a range of thousands of miles; where Mesoscale is defined on horizontal scales of few to several hundred miles.

II. TACTICAL ENVIRONMENTAL PROCESSOR

The primary focus of the TEP program has been to optimize Air Defense (AD) radar performance by using TEP to detect changing atmospheric conditions in near real-time. However, the utility of TEP as a tactical weather radar also provides critical nowcast information to non-AEGIS personnel. To fully exploit the utility of TEP, potential users need to have a general understanding of the AN/SPY-1 radar system and its environmental influences from a warfighter perspective. However, results of thesis can be presented outside of this AEGIS understanding. For this reason, a background discussion about AN/SPY-1 radar operations is provided in the Appendix

TEP performs its function with a combination of Commercial Off-The-Shelf (COTS) processors and specialized algorithms that convert radar returns from the AN/SPY-1 radars into environmental measurements known as spectral moments. Spectral moments (reflectivity, radial velocity and spectrum width) are basic radar meteorological measurements that could be used to support safe and effective at-sea operations. The following section contains a description of the TEP system, TEP modes, TEP products and a comparison of TEP to another Doppler weather radar, NEXRAD.

A. SYSTEM DESCRIPTION

TEP is a COTS-based signal processor that generates environmental spectral moments from SPY-1 radar in-phase and quadrature (I & Q)[4] data. TEP consists of two major sub-systems: Auxiliary Environmental Signal Processor (AESP) and Display & Control Subsystem (DCS). The AESP is responsible for capturing radar I/Q data and processing this data into spectral moments. The DCS provides an operator interface and display for the processed spectral moment data. The TEP system obtains radar I/Q data through a passive data tap and receives ship motion data from the Gyro Data Converter (GDC, an AEGIS subsystem). Figure 2-1 provides the TEP system architecture. The passive tap in the SPY-1 signal processor provides digitized I/Q data to TEP. It is

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[4] In-phase is the component of a complex signal along the real axis in the complex plane, and Quadrature is the component of the complex signal perpendicular to the real axis.

important to note that the data tap installed in the SPY-1 signal processor does not alter the functionality of the radar but merely extracts existing signals. A TEP patch set for the SPY-1 radar control program was installed and operated in all modes of the SPY-1 with the exception of weapons engagement. Since the TEP operation aboard Normandy was only approved for demonstration during the JTFEX, TEP active patches were removed during weapons release, including gun and missile firings. However, the TEP passive data tap remained resident in the SPY-1 signal processor.

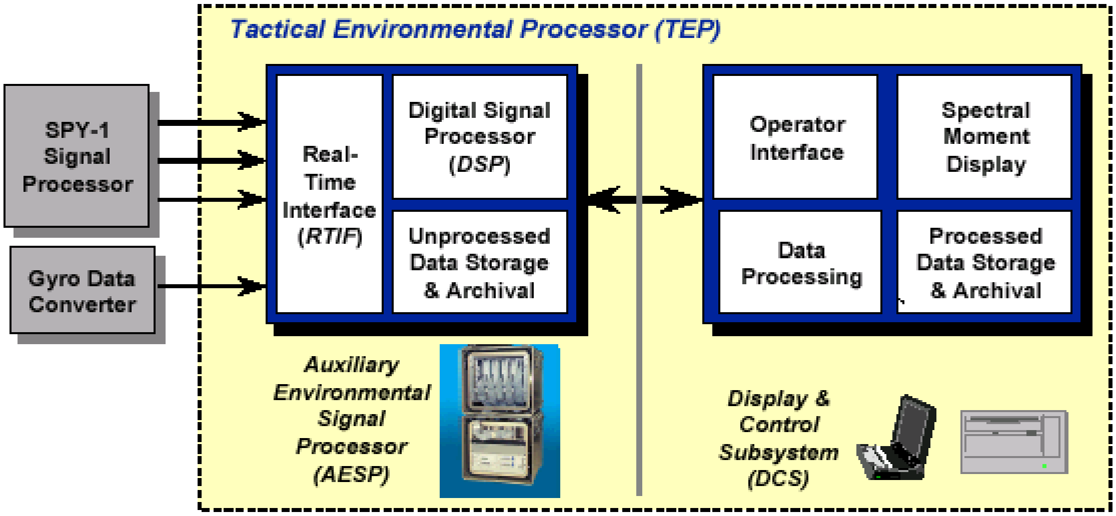

Figure 2-1: TEP Block Diagram (from: TEP Final Report, 2000)

The AESP subsystem performs two basic functions: collect SPY-1 I/Q and stimulus data, and process the data into spectral moments. After collection, the data is passed to a TEP signal processor where special algorithms convert raw I/Q data into spectral moments. NTDS interface cards receive and decode ship motion data tapped from the Gyro Data Converter interface. Ship motion data is used to remove the effects of a moving radar platform from the spectral moment data. The AESP subsystem has a high-density 8 mm tape drive for archiving raw I/Q data streams for future data analysis.

Once the SPY-1 returns are processed by the ASEP, the spectral moment data are transferred to the DCS where it is written into Universal Format (UF) data files. The DCS serves as the operator interface and controller for the TEP system. It is hosted on a portable UNIX-based workstation, which includes an external hard disk drive for processing data storage and an 8-mm tape drive for data archiving. From the DCS, operators choose which TEP scan mode to use for environment characterization. Processed UF files can be displayed using a NCAR RDI (National Center for Atmospheric Research, Radar Data Interface) display package. The DCS operator has the ability to view available TEP products, displayed by elevation (PPI radar format) or along a particular radial from the radar (RHI display).

B. TEP SCAN MODES

TEP is an adjunct signal processor that performs remote sensing of environmental measurements known as spectral moments. In a passive role, TEP performs these atmospheric measurements simultaneously with normal SPY-1 operations. Using standard SPY-1 search waveforms, TEP passively extracts high-resolution environmental data from normally scheduled radar scans. TEP can also be used in an active role, where special 16- and 32-pulse Doppler (PD) SPY-1 waveforms achieve higher sensitivity to profile specific atmospheric conditions. Each scan of the active TEP system requires a minimal amount of available SPY-1 resources (see Appendix for a description of AEGIS time allocation and the importance of radar resources). Table 2-1 is a listing of the four TEP scan modes and their subsequent SPY-1 response.

TEP Mode	SPY-1 Usage	SPY-1 Waveform	Comments
Tactical	Passive	Clear	1-Pulse = Reflectivity Only
Tactical	Passive	MTI	3 or 4- Pulse = 3 Spectral Moments
Non-Tactical	Active	PD-16	Special Refractivity Measure (RFC)
Wind Profile	Active	Sparse PD-32	Radial Velocity and VAD used
Clear Air	Active	PD-32	High Sensitivity Scan

Table 2-1: TEP Modes and SPY-1 Responses

The TEP tactical mode passively uses normally scheduled SPY-1 clear and Moving Target Indicator (MTI) search waveforms to provide up to three spectral moments. TEP only extracts reflectivity from the 1-pulse clear waveform, but generates all three spectral moments from the 3 or 4-pulse MTI waveform. Therefore, depending on SPY-1 radar settings, the TEP tactical mode data may contain any combination of reflectivity-only or reflectivity and velocity-based measurements for each dwell. Since SPY-1 typically schedules MTI waveforms in regions where clutter exists, TEP tactical mode will usually provide data for all three spectral moments wherever significant surface clutter or precipitation is present. In both cases (clear and MTI), refractivity and radio frequency propagation loss are provided via the SPAWAR Refractivity From Clutter (RFC) technique.

The non-tactical PD-16 mode uses 16 coherent pulses at each beam position for the first two elevation angles in the SPY-1 search pattern. This yields an improved level of sensitivity for the purpose of detailed refractivity estimation and increased spectral characterization for enhanced clutter filtering.

To further increase radar sensitivity, the wind profiling and clear air modes use PD-32 waveforms (32 coherently integrated pulses). Clear air mode uses waveforms that provide enough sensitivity to measure clear air winds, and turbulence found in the marine boundary layer or non-precipitating clouds. The wind-profiling mode is a subset of the clear air mode, using a sparse PD-32 scan (every 4 beam positions) between 20^0 and 30^0 in elevation.

C. TEP PRODUCTS

TEP uses up to three spectral moments to monitor the changing atmospheric state. Reflectivity is a measure of the strength of the radar echo (in dBZ) and is indicative of the density associated with the scatterer. This product is used to detect precipitation, evaluate storm structure, estimate storm intensity and locate storm boundaries. Radial velocity is a measure of the relative movement of the scatterer versus the radar. Figure 2-2 is a plot of the radial component of the wind, either toward or away from the radar. Radial velocity is used to estimate wind speed and direction, identify storm boundaries, locate severe weather signatures and observe suspected areas of turbulence. Spectrum width is an estimate of velocity dispersion within the sampled radar volume. The primary use of this variance product is to estimate turbulence in the radar volumes associated with a variety of phenomena, including wind shear, turbulence, mesoscale circulations and general storm-generated turbulence

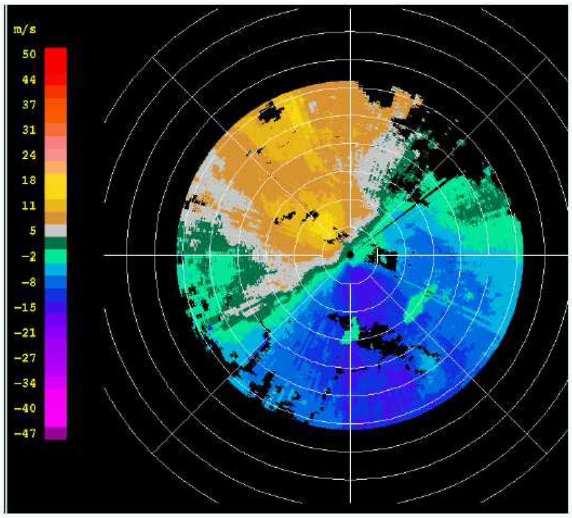

Figure 2-2: Radial Velocity Plot; blue-green colors indicate scatters moving toward TEP, and brown colors for scatters moving away TEP. (from: TEP Final Report, 2000)

TEP can convert the three base meteorological radar measurements into a diverse set of products via computer processing and the use of tactical and special SPY-1 waveforms. The following describes some of the current TEP products. This summary is more of a starting point than an all-inclusive list, as TEP is an evolving system for the at-sea warfighter and METOC forecaster.

Among the various TEP products available, composite reflectivity was the feature chosen for automated display and dissemination during JTFEX 00-2. Figure 2-3 is plot

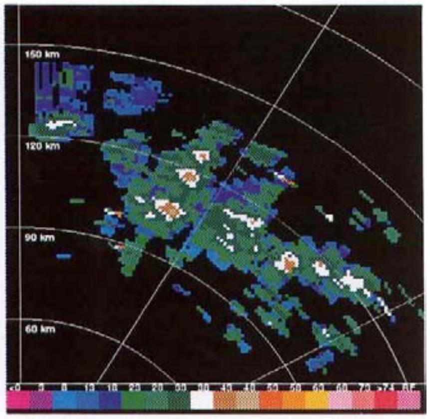

Figure 2-3: Composite Reflectivity (from: TEP Final Report, 2000)

of composite reflectivity. This two-dimensional map depicts the maximum reflectivity (i.e. storm's precipitation intensity) for the total volume within the range of the radar. Composite reflectivity describes reflectivity data from all the elevations projected down to the first elevation tier. Further, the maximum reflectivity value for each projection was chosen for display. Although not optimal for meteorology, this "quick look" product provides an overview of the storm structure within the radar volume.

TEP makes spectral measurements of the clutter environment and timely volumetric estimations of radar propagation conditions using the RFC algorithm (Gerstoft, et al., 2001). TEP supplies high-resolution surface clutter maps from which RFC performs real-time assessments of propagation and ducting conditions surrounding the resident TEP platform. Point measurement devices (i.e. rawinsondes) used with traditional radio frequency propagation assessment approach (i.e. Advanced Refractive Effects Prediction System) lack the three-dimensional refractivity assessments possible with TEP and RFC. A single temperature-humidity profile relies on the simplified assumption of atmospheric homogeneity to derive refractivity for the entire battlespace. In contrast, RFC uses radar clutter returns to derive a sector-by-sector assessment of ducting and propagation surrounding the ship. This propagation data can be used to position battlegroup assets to take advantage of spatial varying anomalous propagation conditions, or to compensate for deteriorating conditions. Eckardt (2002) has evaluated the effect of model errors with the RFC approach.

When local atmospheric conditions are clear (no precipitation, heavy clouds or scatterers), TEP can utilize special high-sensitivity waveforms to characterize the environment. These dedicated PD waveforms measure the weaker signals produced by phenomena that cause a change in the index of refraction. TEP uses these active waveforms to perform cloud detection, wind profiling, and marine boundary layer characterization. Wind profiling transmits a high-sensitivity PD-32 waveform in a sparse lattice to generate data for Velocity Azimuth Display (VAD) processing. This data supports the generation of three-dimensional wind fields that could be used to nowcast carrier positioning for aircraft launch and recovery cycles. Clear air conditions require the PD-32 waveform at all beam positions to collect data on a non-precipitating atmosphere such as cloud profiles and boundary layer information.

TEP can also provide a two-hour history loop and storm track forecast. These movie-like views allow the at-sea warfighter and forecaster to witness how the environment evolves and reveal a glimpse of how it may progress into the immediate future. Additionally, TEP could provide critical mesoscale model verification data and eventually be adapted to support mesoscale model data assimilation. Derived TEP products allow the at-sea forecaster to exploit the variability of atmospheric weather conditions and provide the critical ingredient for any potential nowcast weather system.

D. AEGIS RADAR VS. NEXRAD

In previous reports describing the TEP system, many comparisons of TEP and NEXRAD were made. The two systems are similar; however, there are distinct differences that define TEP as a ”tactical” weather radar. The first distinction is the difference in Doppler waveforms used by the two radars. Another difference is location; NEXRAD is geographically fixed where TEP is resident on a moving platform. Finally, the two radars vary in mission, NEXRAD is a stand-alone weather radar; whereas TEP is an external subset of the AN/SPY-1 radar and AEGIS Combat System. Despite all these differences, it is still important to compare TEP and NEXRAD data sampled from the same time and point in space.

TEP products are dependent on the SPY-1 tactical radar, which has a coded signal and compressed pulse to improve sensitivity and range resolution. Pulse compression produces range sidelobes that produce ambiguous information when applied to weather events. Recent radar technology has made significant inroads to this barrier through the use of Doppler tolerant sidelobe suppression techniques. TEP’s ability to use pulse compression waveforms results in three major benefits: 1) increased sensitivity to detect weaker weather phenomena; 2) reduced data collection time scales; and 3) higher quality data points through averaging over more independent samples. SPY-1 enhanced sensitivity provides enhanced examination of weak weather signals, such as vertical and horizontal wind shear, low altitude turbulence, and clear air turbulence. Additionally, phased array radars with tactical waveforms can collect data for the same sample volume in a matter of seconds compared to several minutes for rotating radars such as NEXRAD.

Since TEP is deployed at-sea, it is not fixed with regard to location and its performance is subject to sea clutter. Ship motion contributes to errors in the estimation of mean radial velocity (and the estimation of spectral width) and can degrade the performance of Doppler-tolerant processing. TEP receives and decodes ship motion data that removes the effects of a moving radar platform from the spectral moment data and allows the use of phase compensation in TEP Doppler-tolerant processing techniques. Since most weather radars operate in fixed positions over land, low-pass filtering can be used to remove ground clutter contamination from the spectral moments. However, sea clutter varies dramatically in intensity and velocity. TEP uses a sophisticated matrix clutter filter to estimate sea clutter characteristics, and then remove the clutter signal without degrading the meteorological signal.

Since TEP is a moving weather radar, TEP products must be referenced with respect to the user's location (e.g. the carrier) and not necessarily with respect to the ship possessing TEP. For example, NEXRAD systems are geographically fixed and therefore, their displays are viewed with a familiar geographic boundary such as shorelines, state or country boundaries. Interpretation of detected features occurs with the user positioning themselves with respect to a familiar feature and immediately referencing the storm location and probable impact. However, in naval operations, the ship based TEP data, ship-borne TEP user and radar observed storm feature could all be moving independently. There may be not physical boundaries to reference besides man-made latitude and longitude parallels.

The most notable difference between TEP and NEXRAD seems to be related to their respective mission foci. NEXRAD operations are focused only on characterizing the environment using various waveforms to produce a multitude of displays and products that help the weather forecaster describe the atmosphere. The AEGIS Combat System and the AN/SPY-1 radar operations are focused on fleet air defense, not weather description. Air Defense (AD) requires maximum radar ranges and rapid search times with minimal radar loading. As a tactical weather radar, TEP uses passive and active modes of operation to characterize a constantly evolving environment. Used passively (i.e. with SPY-1 tactical waveforms), TEP can support faster SPY-1 search times through clutter recognition without additional radar loading. However, nowcasting may require the use of active TEP/SPY-1 waveforms to characterize small-scale events. This places a minimal, but additional resource load on the already stressed tactical air radar. TEP and SPY-1 must have balanced operations, allowing all interested parties to utilize the benefits that TEP has to offer, but not at the expense of excessive SPY-1 search times. The advantages of an at-sea NEXRAD quality weather radar are too great to be overshadowed by minimal increases in radar loading.

One goal of the TEP at-sea demonstrations was to validate the accuracy of the TEP spectral moment measurements by comparison to WSR-88D (NEXRAD) radar. A direct comparison of NEXRAD and TEP spectral moment values does not prove that TEP measurements are exact. However, it is generally accepted by the operational meteorological community that TEP environmental measurements within a few dB of NEXRAD, are within the margin of error for the two radars and would be considered more than adequate for most operational applications. The TEP Final Report contains a direct comparison of TEP reflectivity to the Jacksonville, Florida WSR-88D radar. Figure 2-4 shows the NEXRAD site compared with TEP data acquired from the USS

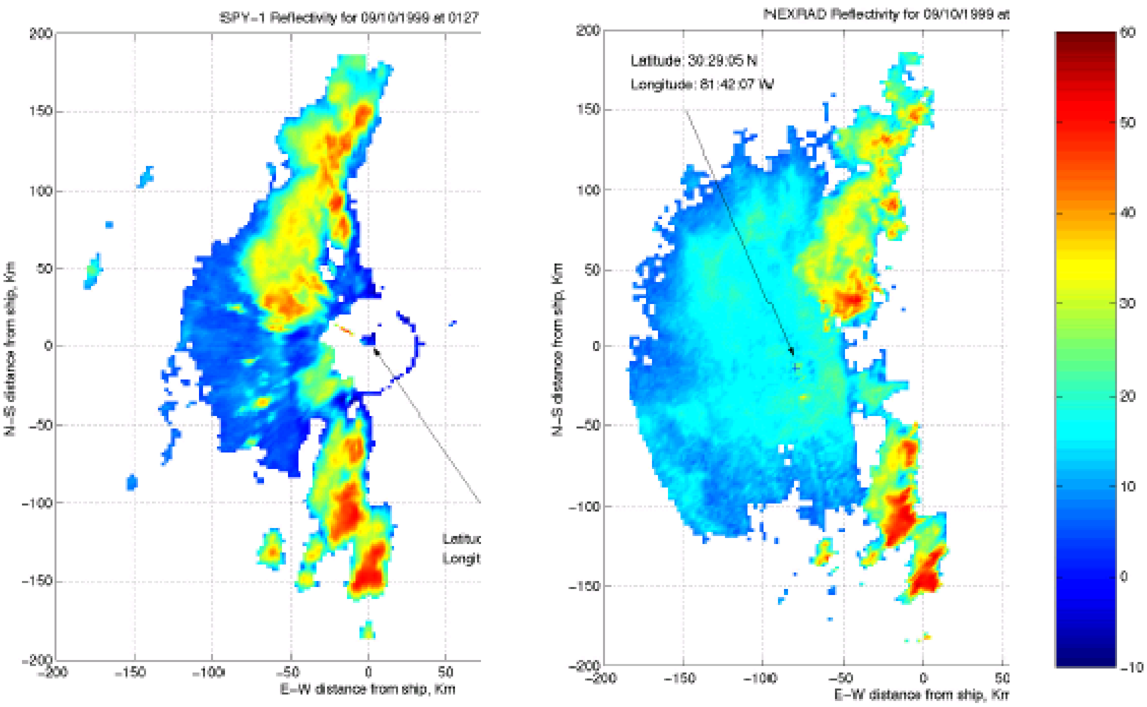

Figure 2-4: Comparison of TEP Reflectivity (left) vs. NEXRAD (right) for a Developing Squall Line Off Jacksonville on 09/10/99 (from: TEP Final Report, 2000)

O'Kane that was positioned about 30 nm offshore. Both reflectivity plots are a representation of the first elevation plot from their respective radars. The scans were within 5 minutes of each other and represent the same convective storm. The scans did not occur at the exact same time, due to the different time periods required for the two radars to obtain a full volume scan.

To compare the accuracy of TEP measured reflectivity values, the difference between NEXRAD and TEP first elevation reflectivity plots were calculated. Figure 2-5 represents the difference between 0028Z TEP and 0024Z NEXRAD scans. Additionally, the median difference was calculated for all overlapping 1x1 nm range cells in which both radars reported valid reflectivity measurements. Results show a mean reflectivity difference of only 5 dBZ or less, well within the limits of measurement accuracy for both radars. Considering that some minor differences can be attributed to variations in radar locations and thresholding of the SPY-1 data, TEP detected storm boundaries, structures and changes in storm intensity with similar accuracy to the NEXRAD system. Assuming that NEXRAD measured reflectivity is accurate, this example shows that TEP measured

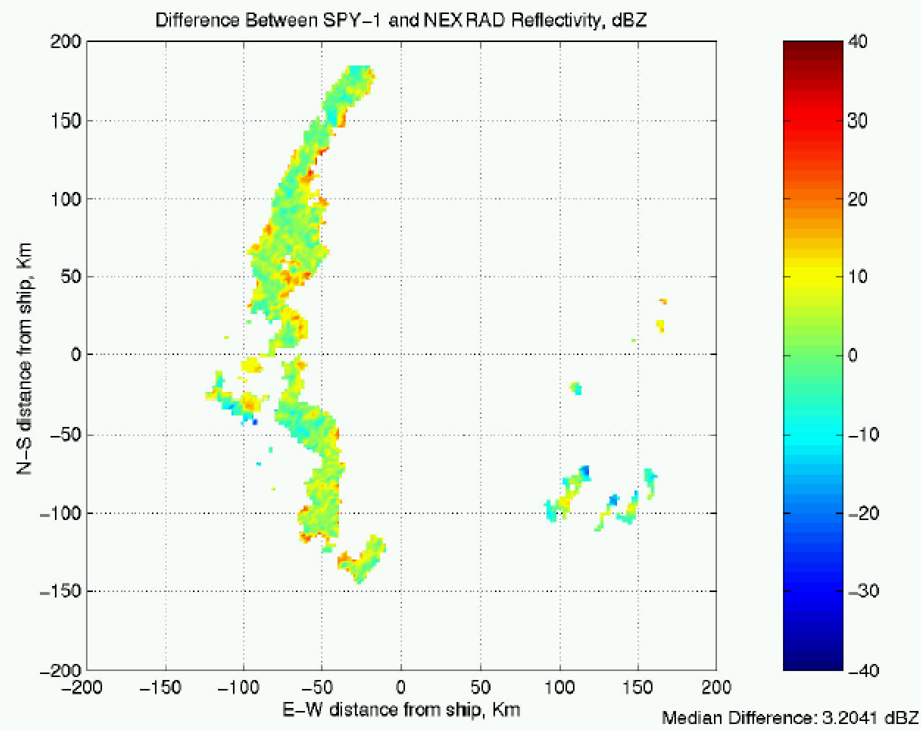

Figure 2-5: TEP vs. NEXRAD Difference Plot (from: TEP Final Report, 2000)

reflectivity is comparable to NEXRAD reflectivity accuracy. This allows for the practical benefits of NEXRAD-like operations in forward-deployed regions that have no other *in situ* meteorological radar resources.

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III. TEP DATA PROCESSING IN AT-SEA DEMONSTRATION (JTFEX 00-2)

On request from U.S. Second Fleet, TEP was deployed to support a METOC Limited Objective Experiment conducted during JTFEX 00-2. Beginning in February 2000, TEP was configured for autonomous operations aboard USS Normandy (CG 60). Since JTFEX is a simulated high-threat environment, TEP was only operated in the passive (tactical) mode. Data extracted from normal SPY-1 search waveforms during this demonstration supplied three spectral moments (reflectivity, radial velocity and spectrum width). No high sensitivity waveforms were available.

After operator initiation during the JTFEX 00-2 demonstration, TEP automatically sampled and processed a new volume scan approximately every ten minutes for the entire JTFEX. A complete SPY-1 volume scan takes 20-30 seconds; however, ten-minutes was the approximate interval required to allow the Refractivity From Clutter (RFC, see Chapter II for further description) sub-system to conduct its environmental calculations. TEP operated in an autonomous mode during most volume scans, but was manually terminated to support JTFEX scripted SIPRNET attacks and for periodic maintenance. This explains the irregular (greater than ten-minute) data gaps associated with the JTFEX 00-2 data. Since TEP is dependent on SPY-1 resources for environmental measurements, during non-radiating maintenance, Emission Control (EMCON) periods, or the establishment of flight quarters, there were occasional but sector specific TEP data outages.

Once the Auxiliary Environmental Signal Processor (ASEP) processed the spectral moments, the data were transferred over a TEP ethernet to the Display and Control Subsystem (DCS). The DCS converted the spectral moment into Universal Format (UF) data files and transferred the UF files to 8-mm tapes for data archiving. During processing, the JTFEX radial velocity spectral moments were corrupted. Lockheed Martin engineers believe these spectral moments are correctable, but the data were unavailable at the time of this thesis (personal communication).

Throughout the TEP LOE, composite reflectivity was derived from the reflectivity data and made available for viewing in the Combat Information Center (CIC) onboard Normandy. Plots of composite reflectivity were then transferred via an internal ship-network to the Global Command and Control System – Maritime (GCCS-M) system, where a separate server at Navy Atlantic Meteorology and Oceanography Center (NLMOC, located at Norfolk, VA) pulled the composite reflectivity image every 30 minutes via the SIPRNET. Once at NLMOC, the composite reflectivity image was made available to the George Washington Battle Group via a JTFEX web site.

At the conclusion of JTFEX 00-2, the TEP system and 8mm data tapes were removed from Normandy. Lockheed Martin released a copy of the TEP data tapes to the Naval Research Laboratory (NRL) Monterey, CA for research purposes. In the raw UF, TEP data are classified secret to protect the sensitivity of the AN/SPY-1 radar system. To comply with security declassification procedures, the TEP data included in this thesis have been thresholded at the 3-dBZ reflectivity level by an approved Lockheed Martin algorithm, and are thus declassified. This prevents the disclosure of SPY-1 sensitivity and allows the TEP data to be processed, displayed and disseminated on unclassified media sources. Additionally, during the declassification process the distance associated with the first range gate was modified to protect this classified part of the operation of the SPY-1 radar. The unclassified value for the distance to the first range gate presented in this thesis is 4.26 nm (7.89 km).

Development of processing procedures that were performed after declassification was done with the assistance of NRL and NCAR programs and personal. First, the thresholded TEP data were hand corrected to properly increment the individual scan numbers into a sequential format. TEP is a unique Doppler weather radar that is dependent on the collection of spectral moment data from the SPY-1, a tactical phased array radar. All of the existing weather radar display programs are designed to support NEXRAD. Since NEXRAD uses a rotating beam to observe weather events, it has different time sequencing properties than the SPY-1 radar. Subsequently, the TEP processors wrote the mandatory UF header data (Barnes, 1980) based on rotating radar technology. The corrected TEP UF data were converted to DORADE (SWP, also called “sweep”) and meteorological data volume (MDV) files to be displayed on two existing NCAR visualization software packages (both designed to visualize NEXRAD).

The first NCAR data display and manipulation system is called SOLO II. SOLO II only accepts DORADE (SWP) files, but allows the user to view and edit the individual sweep volumes. This tool was used to investigate the individual TEP files, but not as an editor. All the TEP reflectivity data used in this thesis were left in their raw declassified format. This allows the reader to witness any range or velocity aliasing errors and the sea clutter returns associated with TEP.

The second NCAR visualization tool was the Configurable, Interactive Data Display (CIDD) software. CIDD was developed to display real-time meteorological data but can be used for archived case studies. Converting the raw or SOLO II processed UF TEP files into MDV format allows CIDD to display TEP reflectivities from the Normandy. CIDD allows the user to integrate and display (in real-time), meteorological data from disparate and distributed sources (Hage, 2002). It combines visualizations of gridded data, symbolic data and text overlaid with maps and geographical symbols. Data from grids of differing sources, resolutions or positions can be viewed simultaneously, being automatically registered onto the same image. Displays are automatically updated as new data arrives, and movie loops shift forward as time progresses. Its client-server design allows a wide variety of distributed storage topologies and access modes. By using an intelligent server, temporal and spatial clips are rendered to support the user, vice requesting entire data files. This processes makes CIDD an ideal display system for low bandwidth applications. CIDD was the display tool used in this thesis to visualize and investigate the TEP data associated with the 15 May 2000 case study.

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IV. JTFEX 00-2: 15 MAY 2000

TEP was included in a Limited Objective Experiment (LOE) during JTFEX 00-2. JTFEX is a simulated high-threat environment that involves naval, air and ground components, incorporating surveillance, reconnaissance and other operations that may include maritime interdiction, embassy support, and non-combatant evacuation. The realistic scenario incorporates many of the challenges a carrier battle group and possible amphibious ready group may encounter during their upcoming deployment. The METOC Limited Objective Experiment (LOE) conducted during JTFEX was designed to evaluate the benefits and usefulness of TEP environmental sensing in support of the operational fleet. TEP was installed aboard USS Normandy (CG 60) and interfaced with the ship GCCS-M network, which provided SIPRNET connectivity to the George Washington Battle Group via Naval Atlantic Meteorology and Oceanography Center (NLMOC) ashore at Norfolk, VA.

JTFEX 00-2 took place during a time and in a location where mesoscale convective systems were almost a daily occurrence. The JTFEX operating environment, off the North Carolina coast, ranged from benign to prohibitive depending on thunderstorm location, a situation common in spring when cold frontal activity interacts with warm Gulf Stream waters. The difference between environmental extremes could span a few nautical miles or an hour in storm evolution. Thunderstorm events during the JTFEX provide a good illustration of the sensitivity of carrier operations to mesoscale weather events and the drastic need for an at-sea weather radar.

On Monday, May 15, a line of severe thunderstorms formed to the south of the George Washington Battle Group. Satellite imagery provided limited data; owing to the time delay to receive satellite updates and the inability of the satellite to penetrate cirrus cloud cover that was produced by and overlay the thunderstorm system. Doppler weather radar, NEXRAD via the NIPRNET, was the primary tool used by forecasters aboard the USS George Washington (CVN 73) to track and observe storm conditions.

At 19:28 (EST, 23:38 UTC) the USS George Washington (GW) turned into the storm front in an attempt to create enough headwind for a scheduled launch/recovery cycle. Severe storm conditions were observed, including heavy rain, intense lightning and an observed waterspout that was reported just 7 nm from the carrier. As the GW passed under the downdraft of the storm, the winds suddenly increased and became radially outbound. With no options available to maintain the required headwind, all flight operations for the simulated war were suspended until the carrier could reposition.

The TEP Final Report recounts the events from the shooter on duty who had to quickly react to changing wind conditions for the last F/A 18 that was launched in the storm. The flight was dialed-in at 28 kts, but during the pre-launch scan the winds suddenly increased to an estimated 50 kts. This forced a quick and unexpected change of the launch settings. Immediately following the aircraft launch, the shooter lost sight of the bow safety in the heavy rain and flight operations were suspended until the carrier could clear the storm area.

The following chapter is a description of the events that occurred on 15 May 2000. The goal of approaching the severe weather events from different perspectives is not to determine why the events occurred from a purely scientific perspective, but to detail the differences between traditional at-sea forecasting and nowcasting with TEP. Section A contains two detailed accounts from meteorologists onboard the GW participating in the TEP LOE. Sections B and C are a synoptic and mesoscale analysis. The next section is a description of the thunderstorm by the at-sea Doppler weather radar, TEP. Finally, a brief summary of the analysis methods is included to demonstrate the value a nowcast system has on operational events.

A. OBSERVATIONAL DATA

During the JTFEX, sets of observers were stationed aboard the USS Mount Whitney (LCC 20, Command and Control Ship for Commander, 2nd Fleet), USS George Washington, and the USS Normandy. These observers, Lockheed Martin engineers and scientific personnel, provided TEP support to the GW Battle Group as well as a first-hand account of how TEP products and services were received and utilized. The following is an account of the activities that occurred on 15 May as witnessed by the meteorology observers aboard the GW. The following observational weather summary is compiled from the detailed trip reports of Dr. George Young (Penn State University) and Dr. John McCarthy (Naval Research Laboratory).

Dr. Young witnessed a thunderstorm cluster to the south of GW which was proceeding NE with arcus on the SE side. TEP and NEXRAD data (from Wilmington, N.C. NWS station) showed Normandy penetrating the NW edge of anvil precipitation. The thunderstorm cluster had not been forecasted, nor was the continued triggering of new convection along the gust front that formed its perimeter. Satellite imagery was rarely able to penetrate the cirrus cloud deck located over the center of this mesobeta system of thunderstorms (Figure 4-1, red circle represents the USS Normandy position at the time of analysis). Therefore, the gust front and new thunderstorm triggering were often obscured from remote sensors.

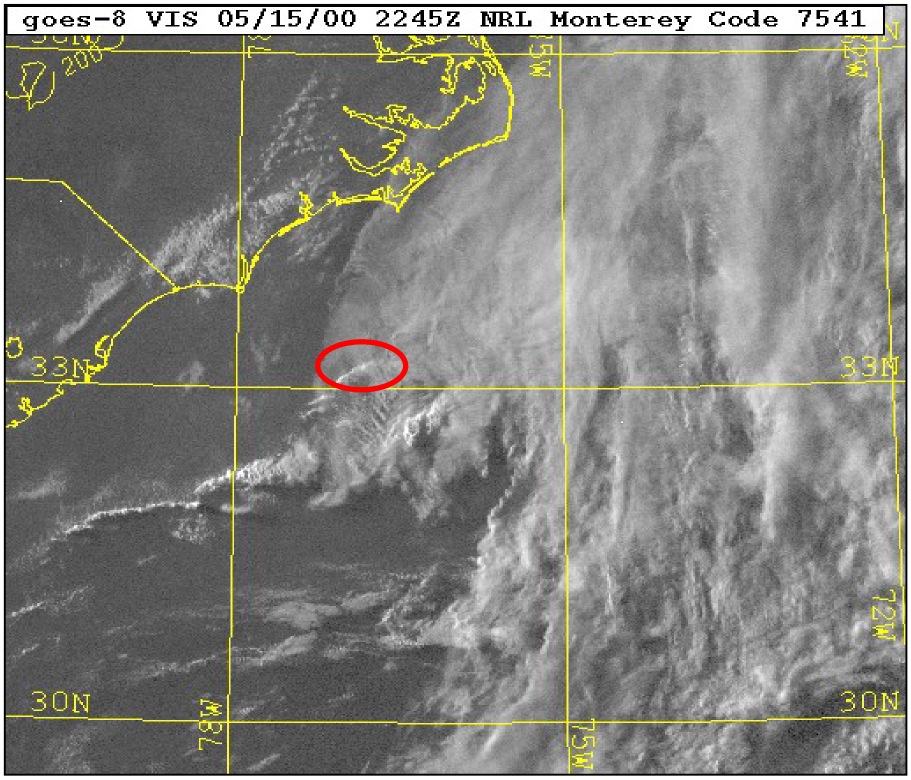

Figure 4-1: GOES 8 VIS Satellite Image (1 km resolution) for 2245Z on 15 May 2000 (red circle represent the USS Normandy area of operation)

At 0900(EST, 1300 UTC) lightning, rain and arcus was observed along the gust front boundary, located NW of the GW. Thunderstorm condition 2 (thunderstorm development within 25 nm or expected within 6 hours) was declared. At 1247, an IR satellite image showed arcus around the boundary on the NE/SW batch of anvil that extended from Jacksonville, FL to Cape Hatteras. The GW was located under the anvil, inside the ring of arcus. TEP radar showed the same two cumulus congestus lines under the cirrus at the NW edge of the anvil and surface cold pool. At 1450, GW was under a line of highly sheared cumulus-congestus. The sky was overcast cirrus to the east and to the west it had scattered cumulus and cumulus congestus, some with lowering bases suggesting rainsqualls. At 1533, the congestus line overhead GW dropped a "surprise" shower.

At 1850, after watching the cumulus congestus line for 30 minutes, Dr. Young spotted a waterspout about 7 nm off the starboard beam of the GW. A spray ring with a height and width of about 100 feet was visible under the funnel. This storm was a mesogamma segment of the mesobeta gust front that circled the cold pool. At 1856 the waterspout terminated as the rain and lightning became more intense; Dr. McCarthy stated that the cloud-to-sea/ground lightning was perhaps the most intense he had ever witnessed.

At 1928, GW turned towards the storm to achieve enough headwind to support a launch/recovery cycle. The storm was displayed as a line of 45 dB convective cores, within the range that TEP detects sea clutter, and one core at 50 dB. After driving into the storm, GW had to terminate the launch due to increasing tailwinds under the downdraft. GW set thunderstorm condition 1 (thunderstorm development within 5 nm or within 1 hour).

Dr. McCarthy states that a major gust front/microburst associated with an intense thunderstorm appeared to form directly over the carrier and had a major impact on flight operations for the GW, although there was no sensor verification besides observation. It was almost 1900 when a line of congestus formed into cumulonimbus, and a waterspout formed off of the starboard bow of the carrier. This preceded the formation of an apparent microburst/downburst directly over GW. There was heavy rain and intense lightning in all directions from the carrier. GW was sailing northward into strong headwinds at the start of the event. Aircraft were being launched into the face of the storm, with wind speed intensity as high as 50 knots. As the intensity of rain increased and visibility decreased, the flight deck crew and Airboss felt that the weather was becoming too severe to support air operations. Soon the winds shifted and became southerly, indicating a tailwind flow on the backside of the microburst. These winds made the flight deck unsuitable for continued air operations without a turn back toward the storm.

B. SYNOPTIC ANALYSIS

The following synoptic description is based on model initialization analysis from 0000Z (16 May). This date and time is referenced as 16/00, with 2300 on 15 May being the approximate time of the waterspout and apparent microburst events. This analysis is from the Navy Operational Global Atmospheric Prediction System (NOGAPS). NOGAPS is a primitive equation, with hydrostatic approximation, model that uses the Multivariate Optimum Interpolation (MVOI) scheme to assimilate observations, model forecasts and climatology. Even so, the NOGAPS analyses describe synoptic features of the atmosphere well. Each NOGAPS model graphic displays a red “cross-hair” to represent the center of the JTFEX operating area (approximately 15 nm radius). The model was used to provide an indication of the general conditions pertinent to the TEP case study, but should not be construed to be an exhaustive model analysis.

1. Upper Levels

A negative tilted trough is located over the eastern seaboard of the United States (Figure 4-2). The trough extends north from the JTFEX operating area into the Hudson Bay. Over the past 12 hours, the 300 mb long wave trough has developed more of a negative tilt and is slowly deepening. A relatively weak vorticity max associated with the 500 mb long wave trough is centered over Vermont (Figure 4-3). Downstream of the trough, a short wave ridge is building over the western Atlantic near 35N 60W. A low pressure system, centered at 37N 50W, is almost vertically stacked between the 300 mb and 850 mb height fields. The east coast is dominated by meridional flow associated with the deepening continental trough and building offshore ridge (located at eastern edge of the model field). The 300 mb and 500 mb troughs axes appear to be forward stacked, with 300 mb trough slightly ahead of 500 mb axis (not shown).

At 300 mb, two jet streaks are evident in the meridional flow (Figure 4-2). A 100 kt NW-SE oriented jet streak is crossing the southern U.S. before terminating at the base of the upper level trough. The northern jet streak consists of two separate meridional jets. First streak is just north of the 100 kt southern jet, while the second northern jet streak is found along the eastern seaboard. This downstream jet streak has intensified and become more aligned with the coast during the past 12 hours. The 100 kt core of downstream jet streak is positioned just off the coast of Maine. Of particular interest is the location of the jets' divergent regions in relation to area of interest. The southern jet streak is positioned such that the left exit region is just south of the JTFEX operating area, while the downstream northern jet streak has its right entrance region near the area of operations.

2. 850mb and Surface

A strong ridge extending from southern Illinois into northern Minnesota is found over the continental U.S. (Figure 4-4). A trough with a strong positive tilt is located off the eastern seaboard over the Gulf Stream. This deepening trough almost extends to the pre-existing trough associated with the 850 mb cyclone over northern Canada. The 500 mb and 850 mb troughs appear to be out-of-phase, but the short wave ridge found in the upper levels over the western Atlantic is evident at 850 mb between the two merging troughs. Upper level closed low appears at 850 mb near 37N 53W. A distinct frontal boundary is found in the equivalent potential temperature field, located directly over the area of interest (Figure 4-5). This frontal boundary has intensified and slowly propagating through the JTFEX operating area during the past 12 hours.

At sea level, the eastern half of the U.S. is dominated by a 1021 mb anticyclone positioned over Ohio, while the western Atlantic is under the influence of a weak 1010 mb low pressure center (Figure 4-6). The JTFEX area of operations is loosely bound between the high and low pressure systems.

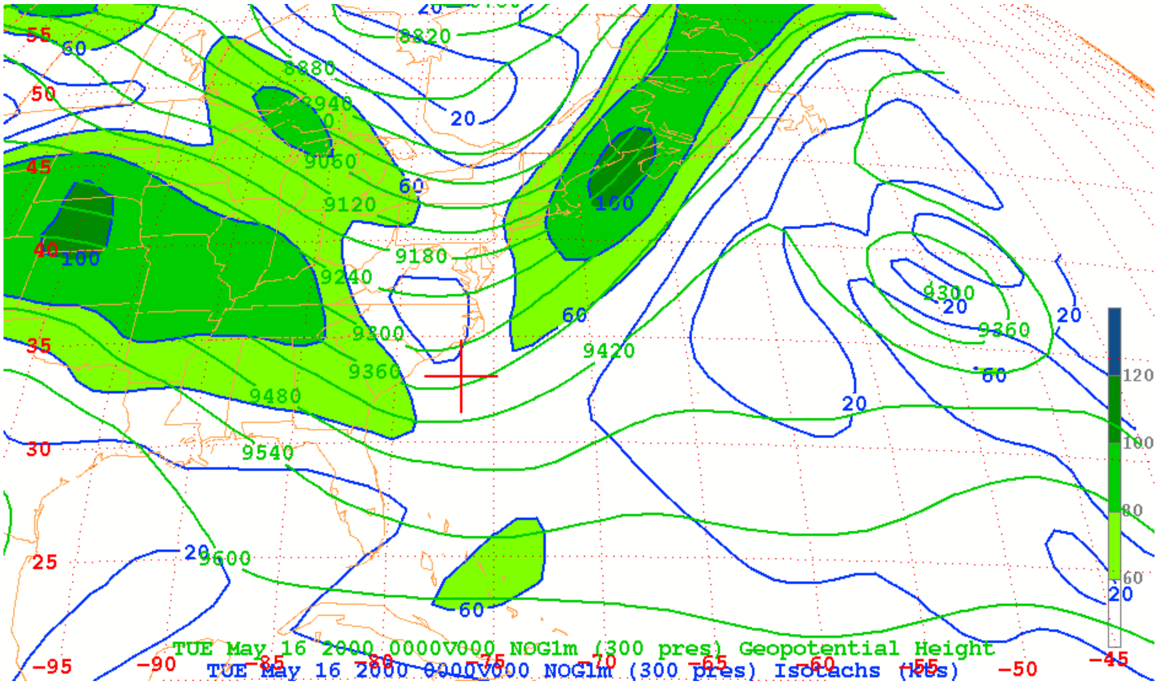

Figure 4-2: 16/00 300mb Heights and Isotachs (red cross-hair represents center of JTFEX OPAREA)

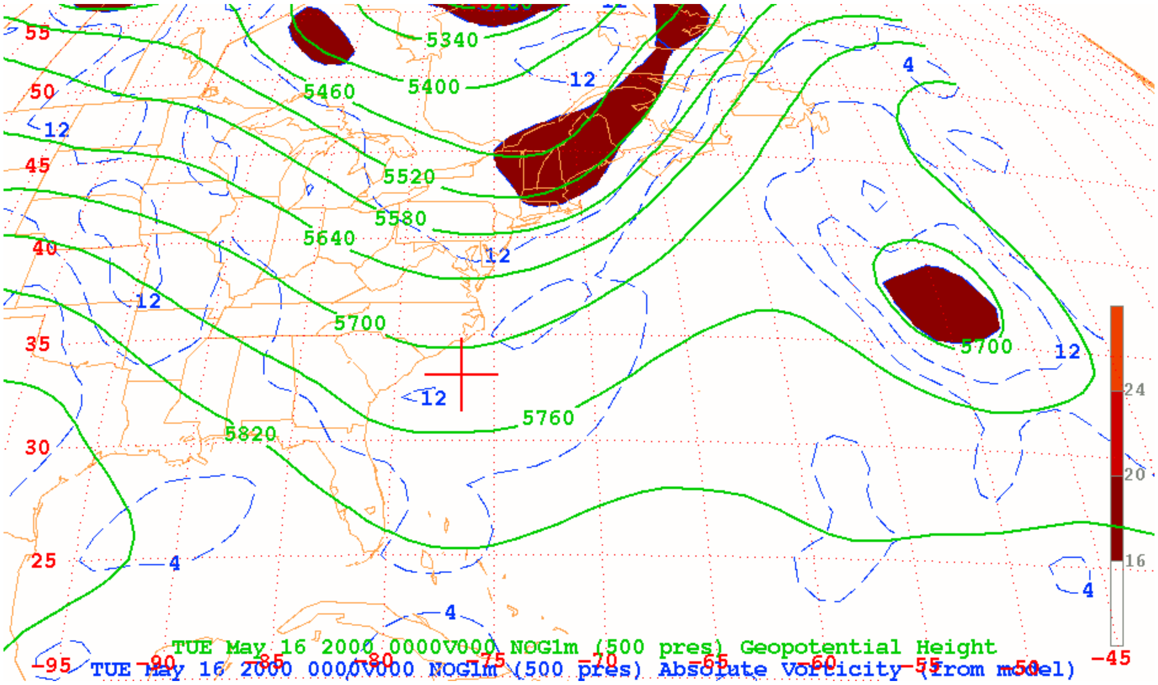

Figure 4-3: 16/00 500mb Heights and Absolute Vorticity (red cross-hair represents center of JTFEX OPAREA)

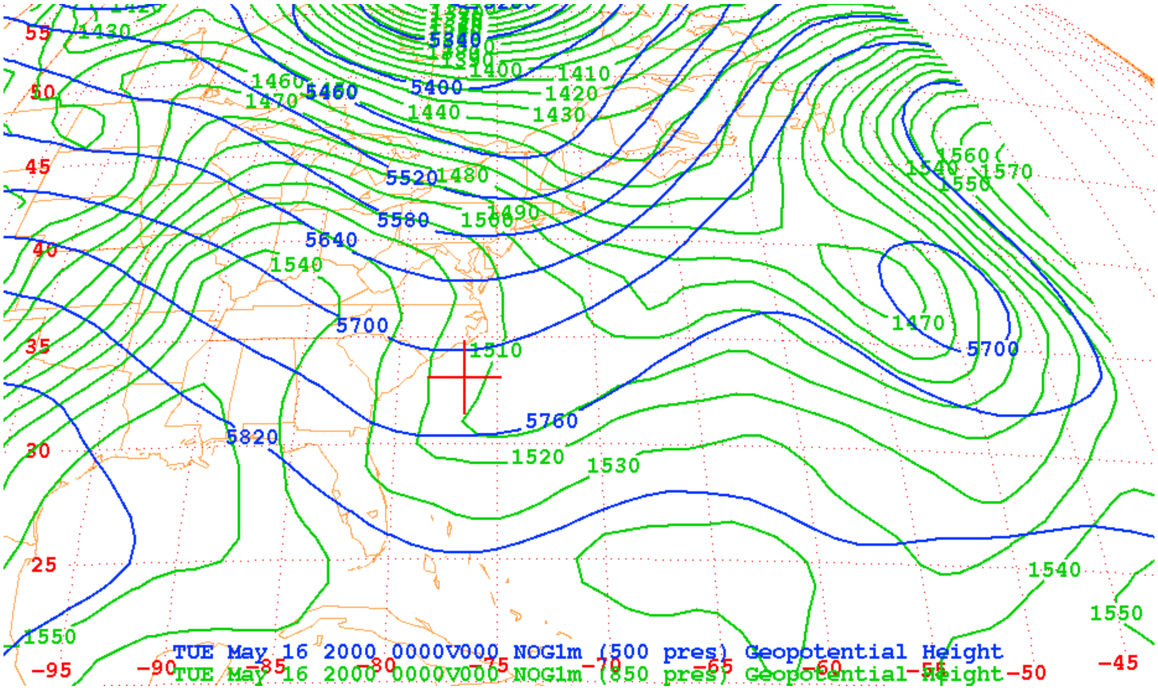

Figure 4-4: 16/00 850mb Heights and 500mb Heights (red cross-hair represents center of JTFEX OPAREA)

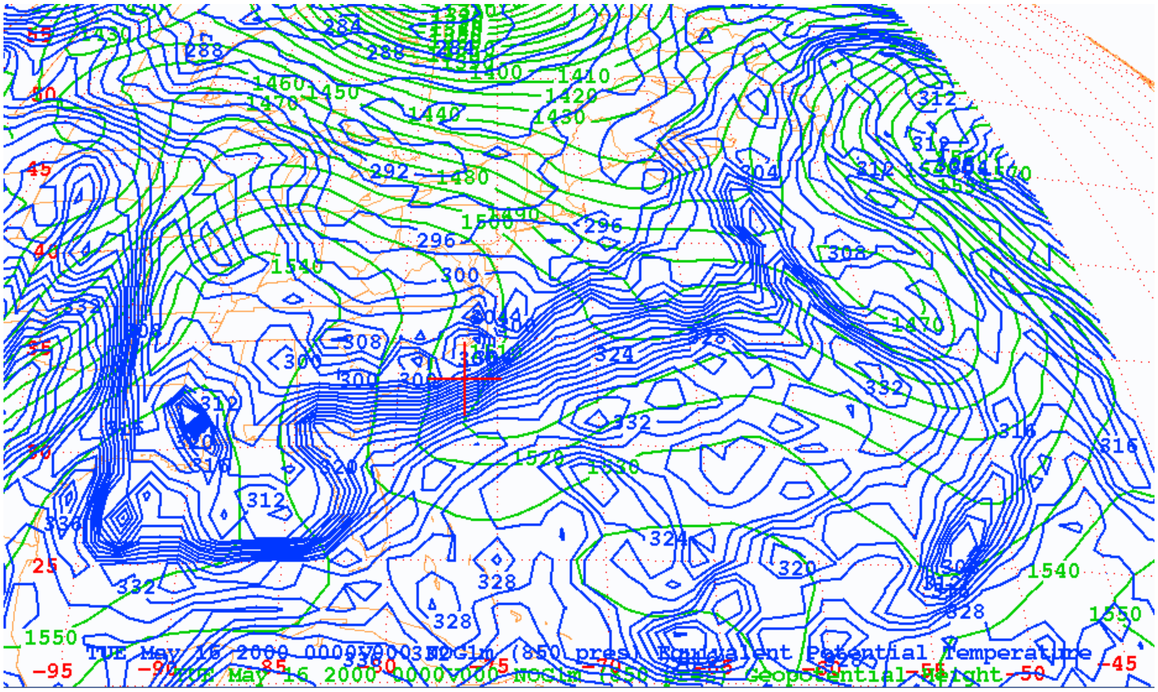

Figure 4-5: 16/00 850mb Heights and Equivalent Potential Temperature (red cross-hair represents center of JTFEX OPAREA)

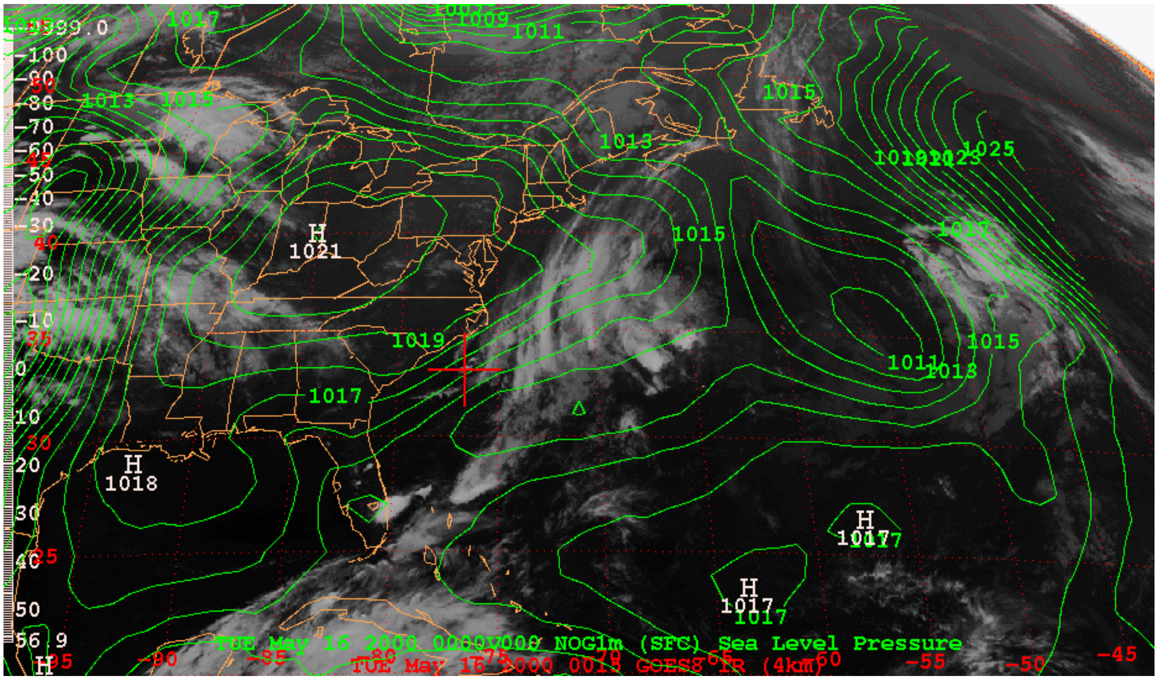

Figure 4-6: 16/00 Sea Level Pressure and IR Satellite Image (red cross-hair represents center of JTFEX OPAREA)

C. MESOSCALE ANALYSIS

Similar to the synoptic analysis, the following is a description of the atmosphere from a mesoscale perspective. These analyses are from the mesoscale Coupled Ocean Atmosphere Prediction System (COAMPS) model. COAMPS uses a nested grid scheme to achieve finer horizontal resolution. Three nested grids result in horizontal output domains of 81 x 27 x 9 km. The outer grid (81 km resolution) was defined to represent the U.S. East Coast and initialized from NOGAPS analysis fields. Vertical levels were resolved with 10 levels on sigma z coordinates. COAMPS ran for two 24-hour periods, one initialized at 1200Z (15 May) and the other at 0000Z (16 May). These dates and times are referenced as 15/12 and 16/00, with 16/00 being the approximate time of the waterspout and apparent microburst events. Again, a red "cross-hair" in the COAMPS model display represents the center (approximate 15 nm radius) of the JTFEX operating area for this limited 15 May 2000 case study. As in the NOGAPS analysis, use of COAMPS is considered instructional regarding the general mesoscale situation, but should not be considered an in depth scientific analysis.

Similar to the synoptic NOGAPS analysis, COAMPS displays the 300 mb trough/jet streaks (Figure 4-7, jet streaks not shown) and 500 mb trough/absolute vorticity (Figure 4-8, absolute vorticity not shown) throughout the two model runs. Since the significant weather events occur near the initialization of the 16/00 COAMPS model, Figure 4-7 and Figure 4-8 overlay the 15/12 +12 hour and 16/00 initialization model runs. Note the similar structure used by the two different COAMPS model runs to define the 300 mb and 500 mb long wave troughs located over the region of interest. Both 300 mb COAMPS troughs display the similar negative slope found in the synoptic analysis. The 300 mb southern and seaboard meridional jet streaks described by NOGAPS have similar placements and strengths in the COAMPS model. At 500 mb, synoptic and mesoscale models views are again similar. The 500 mb trough displays an almost neutral slope over the focused JTFEX area for both COAMPS and NOGAPS. Similarly, no appreciable vorticity is associated with either model's mesoscale 500 mb trough.

The 850 mb comparison of 15/12 +12 hour and 16/00 initialization models (Figure 4-9) shows a good resemblance to the NOGAPS 850 mb height analysis (Figure 4-4). A timing difference between the two COAMPS model runs is evident in Figure 4-9, but each run displays the positively tilted long wave trough in similar locations. However, there is a discrepancy in the comparison of sea level pressure between NOGAPS and COAMPS. COAMPS 15/12 +12 hour model representation of sea level pressure is similarly to the 16/00 NOGAPS analysis (Figure 4-6), but the 16/00 COAMPS initialization is distinctly different (comparison of COAMPS 15/12 +12 hour and 16/00 initialization models are not shown). Believing the difference to be related to COAMPS model initialization, Figure 4-10 is a comparison of 15/12 +15 hour to 16/00 +3 hour sea level pressure fields. Figure 4-10 show a similar structure between the two COAMPS model runs, with a small variation in intensity over the area of interest.

The synoptic and mesoscale model similarity found in the upper level features is not found in the comparison of 850 mb equivalent potential temperature. The well defined frontal feature found over the JTFEX area in the NOGAPS analysis (Figure 4-5) is not seen in the COAMPS model, in terms of phase. The COAMPS frontal feature appears to be about 100 nm to the west of the NOGAPS analysis, nevertheless, there are certainly similarities except for the phase shift. The 15/12 +12 hour equivalent potential temperature analysis (Figure 4-11) shows a strong coastal baroclinic zone, but does not reveal a frontal feature over the JTFEX operating area. The 16/00 initialization analysis is not displayed because COAMPS was originally initialized without NOGAPS moisture fields. Therefore, the 16/00 initialization requires 6-8 hours to generate an equivalent potential temperature structure. Of particular interest, the COAMPS 500-1000 mb thickness fields are comparable to the NOGAPS model, but neither model thickness fields represents the well defined frontal boundary like the equivalent potential temperature profile (thickness plots for NOGAPS and COAMPS are not shown).

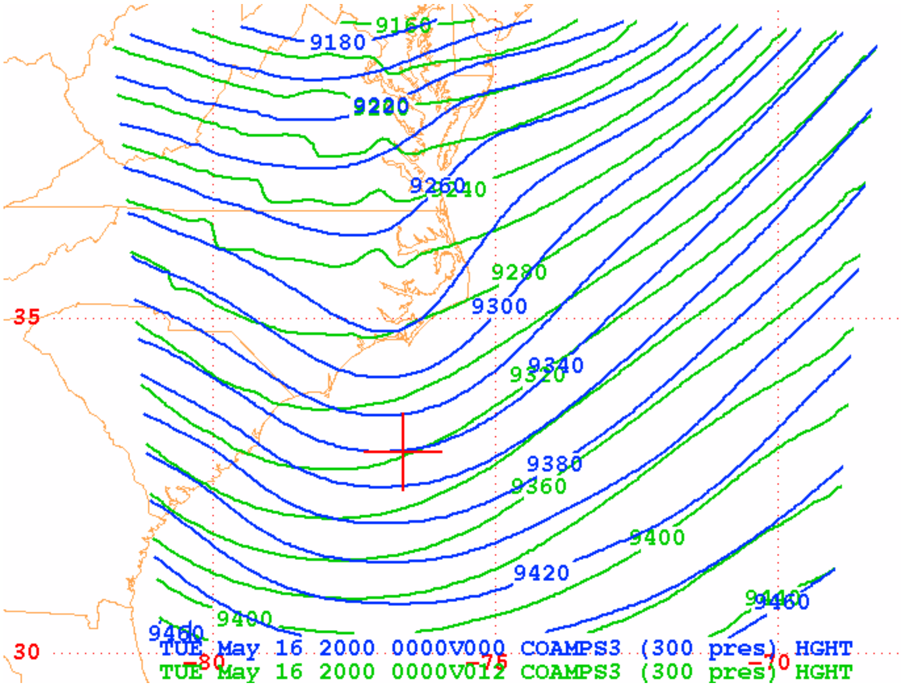

Figure 4-7: Comparison of 300 mb Heights for 15/12 (green) at Model Time +12 hours and 16/00 (blue) Initialization (red cross-hair represents center of JTFEX OPAREA)

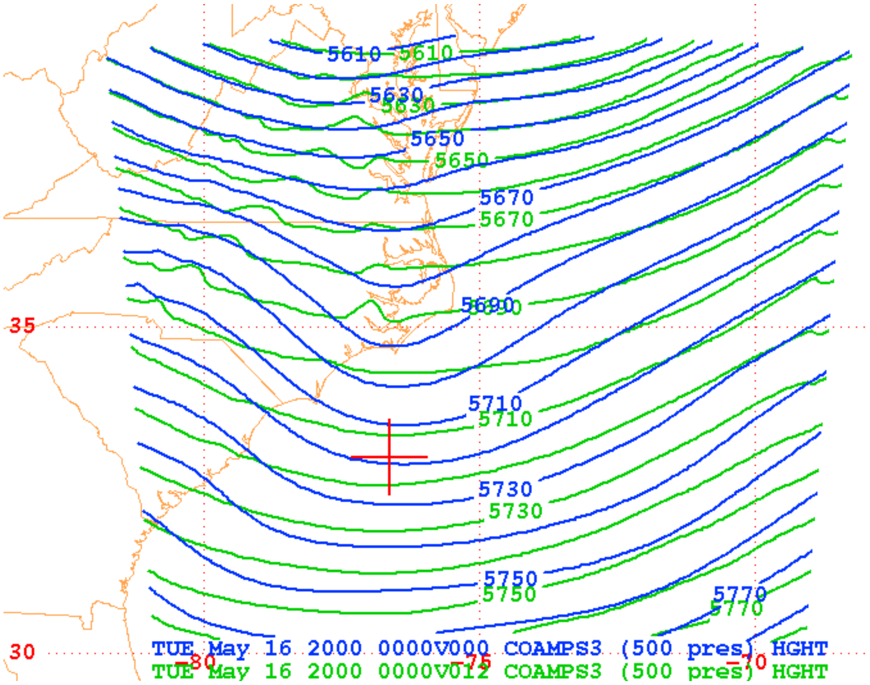

Figure 4-8: Comparison of 500 mb Heights for 15/12 (green) at Model Time +12 hours and 16/00 (blue) Initialization (red cross-hair represents center of JTFEX OPAREA)

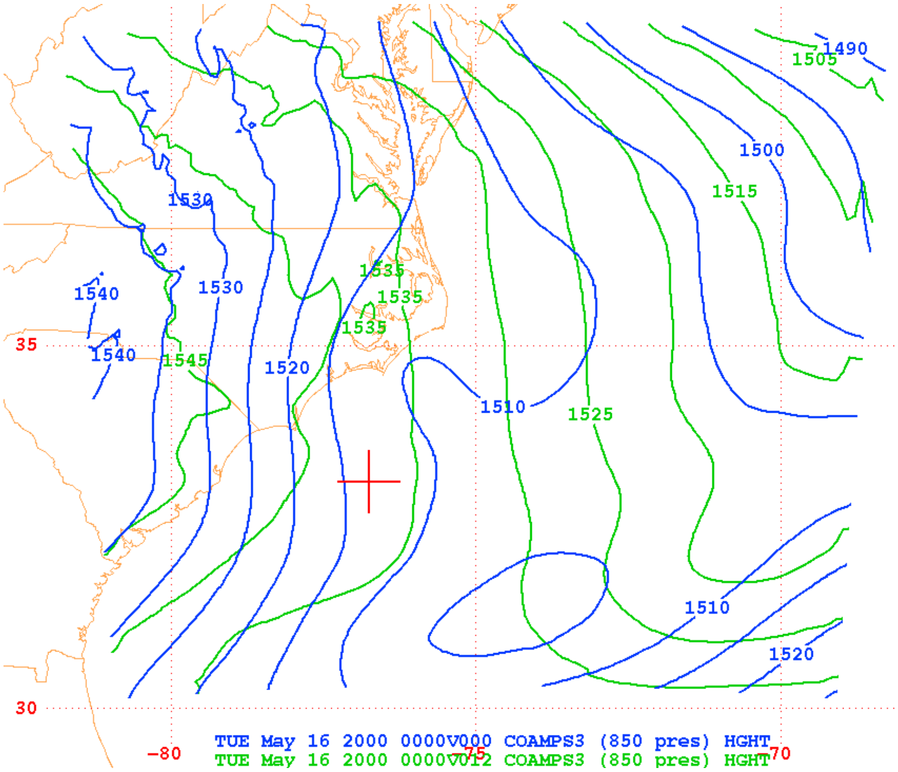

Figure 4-9: Comparison of 850 mb Heights for 15/12 (green) at Model Time +12 Hours and 16/00 (blue) Initialization (red cross-hair represents center of JTFEX OPAREA)

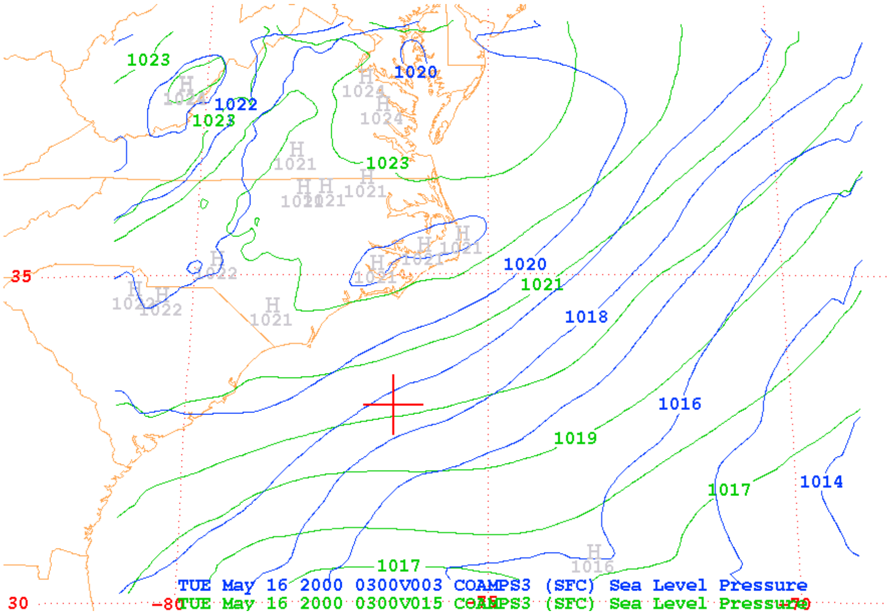

Figure 4-10: Comparison of Sea Level Pressure for 15/12 (green) at Model Time +15 Hours and 16/00 (blue) at Model Time +3 Hours (red cross-hair represents center of JTFEX OPAREA)

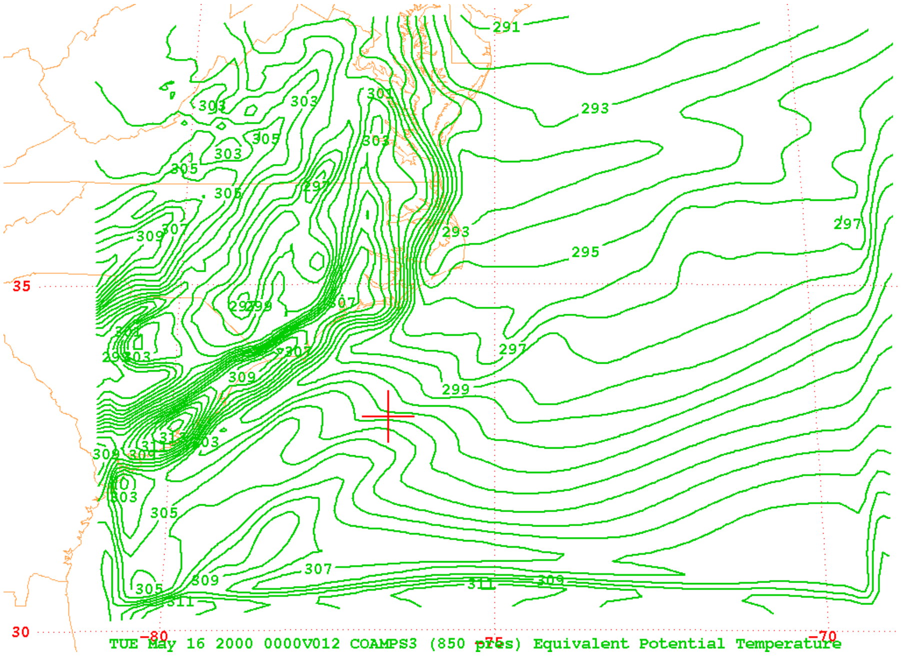

Figure 4-11: Comparison of 850 mb Equivalent Potential Temperature for 15/12 (green) at Model Time +12 Hours and 16/00 (blue) Initialization (red cross-hair represents center of JTFEX OPAREA)

D. TEP ANALYSIS

TEP was placed aboard the USS Normandy to characterize the JTFEX atmosphere. During this simulated high-threat environment, no active pulse Doppler waveforms were permitted due to the experimental nature of the TEP installation. TEP was only exercised in a passive role and collected spectral moment data from normal SPY-1 operations. The TEP data were simultaneously archived to 8mm tape. During processing, the radial velocity spectral moments were corrupted. For the purpose of this limited case study, only TEP reflectivity data will be presented.

After the TEP data were collected, SPY-1 volume scans were displayed as plots of composite reflectivity in the Combat Information Center (CIC) onboard Normandy. This processed TEP product was then pulled by NLMOC at Norfolk, VA every thirty minutes. The composite reflectivity plots were made available to the George Washington Battle Group, mainly the METOC Team aboard GW, via a SIPRNET connection to the JTFEX 00-2 website. Like most new experiments, there were connectivity issues associated with the transfer of data. NLMOC had difficulty pulling the processed TEP data from Normandy. Additionally, the GW METOC Team experienced long delays in downloading the TEP composite reflectivity plots from the JTFEX website. These difficulties were compounded significantly by simulated SIPRNET attacks that were scripted into the JTFEX scenario. The end result was that most TEP images were far too late to be of value to the METOC Team or GW Battle Group.

Drs. Young and McCarthy observed the severe weather events from the GW beginning at 1900 (EST) or 2300 (UTC). Table 4-1 is a complete listing of the available TEP volume scans that display the suspected thunderstorm cell. Of the 17 scans listed, only volume scan #9 (00:24:51 UTC) was incomplete and contained no usable data. Table 4-1 also shows an inconsistent time interval between each volume scan. A ten-minute interval is the approximate time required to allow the Reflectivity From Clutter (RFC, see Chapter III for further description) program to conduct its environmental calculations. During some volume scans, TEP was operated in an autonomous mode (ten

Scan Number	Time (UTC)	Scan Time (sec)	Latitude (W)	Longitude (N)
1	22:43:48	23	33^0 06’ 41.4”	076^0 50’ 26.2”
2	22:53:36	33	33^0 08’ 05.3”	076^0 49’ 13.1”
3	23:10:00	30	33^0 08’ 59.6”	076^0 47’ 11.0”
4	23:20:24	28	33^0 09’ 29.2”	076^0 46’ 04.4”
5	23:30:00	24	33^0 08’ 39.8”	076^0 44’ 54.2”
6	23:40:45	12	33^0 07’ 10.6”	076^0 44’ 50.3”
7	23:50:57	34	33^0 04’ 42.2”	076^0 46’ 38.6”
8	00:00:26	24	33^0 02’ 04.2”	076^0 48’ 22.0”
9	00:24:51	No Data	32^0 56’ 33.4”	076^0 53’ 48.1”
10	00:37:29	25	32^0 57’ 13.0”	076^0 54’ 51.5”
11	00:47:16	24	32^0 58’ 46.6”	076^0 52’ 44.0”
12	00:57:15	30	33^0 00’ 35.3”	076^0 52’ 14.9”
13	01:07:14	30	33^0 01’ 39.7”	076^0 51’ 48.6”
14	01:17:12	28	33^0 02’ 19.3”	076^0 50’ 49.6”
15	01:26:56	22	33^0 03’ 28.1”	076^0 50’ 00.6”
16	01:37:15	30	33^0 04’ 13.1”	076^0 49’ 02.3”
17	01:46:51	31	33^0 05’ 07.4”	076^0 48’ 37.8”

Table 4-1: TEP Reflectivity Data Used for 15 May 2000 Case Study

minute intervals) and during other scans TEP was manually terminated to allow for experimentation with the RFC program. This explains the irregular data gaps associated with the case study presented here. The ending scan time is used to name and reference each volume scan file. Additionally, Table 4-1 contains the actual SPY-1 radar time required to conduct each volume scan. Every scan was sampled from regions where the SPY-1 radar was actively radiating, nominally defined as a full 360° in azimuth and 19°

in elevation. The positioning of the Normandy is included, but the relative spacing between the Normandy and GW is not available.

The following TEP reflectivity plots are snapshots taken from the Configurable, Interactive Data Display (CIDD, NCAR display system) system that was described in the TEP data processing section (Chapter IV). Figure 4-12 shows a TEP reflectivity plot. Most of the CIDD plots presented are volume scans from the lowest elevation angle, 0.7^0 (note pink elevation bar located on the right-hand-side of Figure 4-12). The CIDD plot includes a reflectivity color bar (dBZ units), plot title, range rings and azimuth markers (not displayed on Figure 4-12). Figure 4-12 shows a full volume scan of TEP reflectivity out to 100 nm (display limit of all TEP products during the LOE). Overlaid on the reflectivity plot is archived lightning data (an archived National Convective Weather Forecasting (NCWF) product provided by NCAR, specifically Research Applications Program Division).[5] The lightning is symbolized by a small orange "+" symbol (only over the ocean) and remains resident on the reflectivity plot for thirty minutes. This long-range plot of TEP reflectivity also displays the North Carolina coast and corresponding

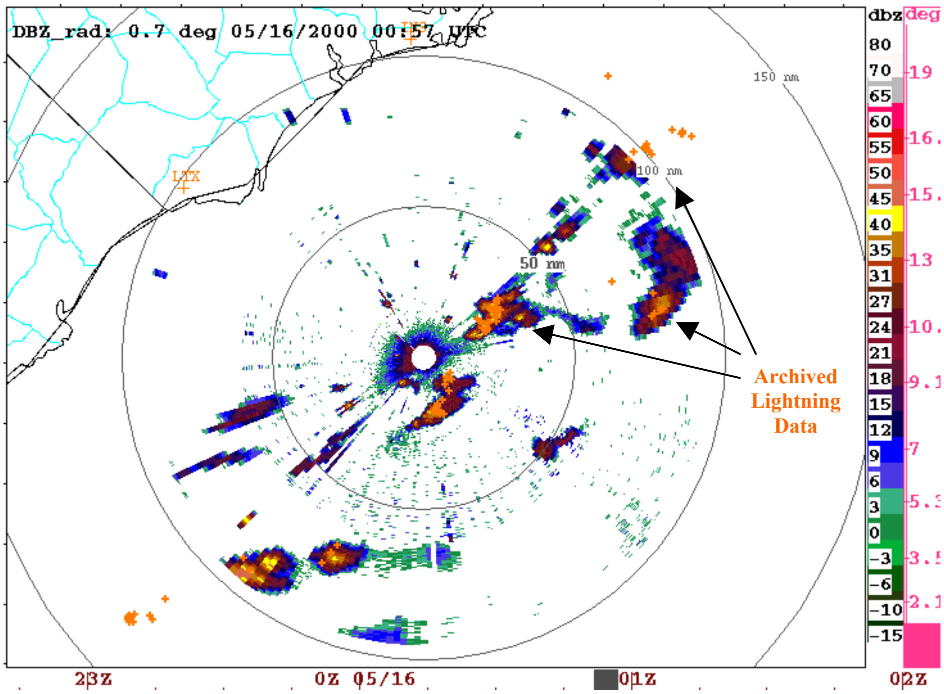

Figure 4-12: Plot of TEP Reflectivity for 00:57Z on 15 May 2000

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[5] Original lightning data was from Global Atmospherics Inc. (via NCAR)

National Weather Service (NWS) NEXRAD locations (LTX = NWS Wilmington and INS = NWS Morehead City). All the reflectivity displays used in this TEP analysis will be close-in snapshots of this same operating area.

Figure 4-13 is a zoomed plot of TEP reflectivity. Of particular interest is the blank region located between 345^0 and 085^0. This non-radiating ("blanked") region for the SPY-1 radar could be the result of common maintenance procedures or something as routine as the setting of flight quarters for helicopter launch/recovery. Since the SPY-1 radar is not radiating in this sector, there were no TEP data collected. This same condition applies for the inner blind zone associated with the non-radiating region before the first range gate (range to the first range gate is 4.26 nm). A closer examination of the reflectivity plot demonstrates how different SPY-1 waveforms or sensitivities sample the environment. Notice the distinct SPY-1 waveform/sensitivity alteration at 095^0 and 275^0 that reveal a noticeable change in the sea-clutter return. These changes could be the result of high power versus low power sectors or an alteration in the actual waveform generated to analyze the battlespace. Figure 4-13 also shows the level of detail obtained

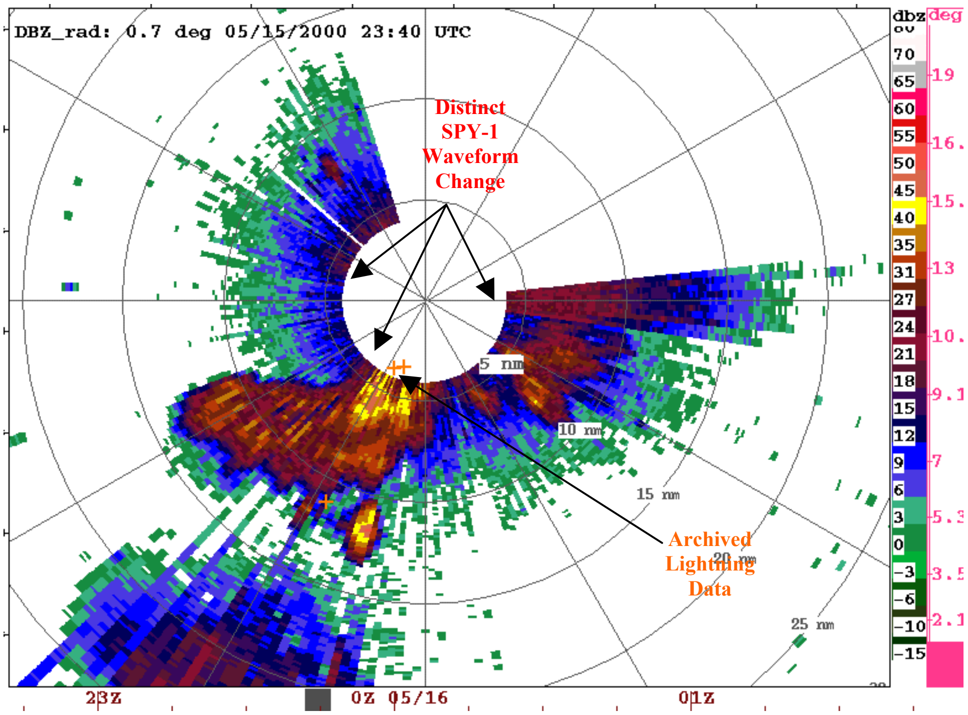

Figure 4-13: Zoomed Plot of TEP Reflectivity for 2340Z on 15 May 2000

with the TEP environmental characterization. The NCAR CIDD software measured pixel values of 49 dBZ at 5 nm on a bearing of 210^0 and 52 dBZ at 12 nm on a bearing of 195^0. Note the relative placement of archived lightning data in relation to the reflectivity centers and within the first range gate. This archived product provided an independent account of the storm location within the non-illuminated region of the TEP sensor. Accounting for storm motion, it is clear to see that the reflectivity and lightning data directly correspond with the convective weather.

The following reflectivity analysis is a chronological account of the TEP data gathered during the time of significant weather. It is assumed that the thunderstorm of interest was located within the Normandy reflectivity display. This assumption is justified by the fact that the focus of this case study is to show the value added by the TEP nowcast ability and not to determine the exact cause of the severe weather present on 15 May 2000. It should be emphasized that the discussion and plots of TEP reflectivity are a description of the environment from the perspective of tactical weather radar. Any direct comparison to the NEXRAD characterization of the storm would be made out of context and are beyond the scope of this case study. Additionally, this thesis describes captured CIDD plots of TEP reflectivity; however, a long-range movie projection of the seventeen TEP scans listed in Table 4-1 can be viewed at the following web page: [ftp://ftp.nrlmry.navy.mil/receive/7500/7503/Robinson/TEP Movie.ppt].

Figure 4-14 shows a zoomed plot of the TEP reflectivity data collected at 22:43Z. Prior to this analysis, there was a 38-minute data gap. At 22:43Z, there are no significant reflectivity returns in the 0.7^0 reflectivity plot that would support the severe weather observed from the GW. However, when the elevation was increased to 9.1^0 (Figure 4-15) there was evidence of a severe storm just inside the first range gate. The 55+ dBZ reflectivities found at 315^0 represent strong convection within the top[6] of the storm cell. The next TEP analysis, Figure 4-16 (22:53 displayed at 0.7^0) reveals no signature of the storm cell. In fact, it was not until 23:20 that CIDD overlays lightning data with

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[6] The phased array and rapid scan of the SPY-1 radar allows TEP to analyze a storm that is essentially located over the USS Normandy. Conventionally scanning weather radars, like NEXRAD, would not be able to observe an overhead storm (directly overhead is within their no-radiating region, cone-of-silence).

relatively high reflectivity returns (+40 dBZ). The main thunderstorm cell was located within the TEP blind zone, inside the first range gate.

At 23:30 (Figure 4-19), there was a drastic change in the SPY-1 waveform between 240^0 and 280^0. The radar operator was reacting to the environment by adjusting the SPY-1 settings to minimize the clutter return associated with the storm. This clutter region will be searched by the de-sensitized waveform for the next 30 minutes to an hour. Unfortunately, the incomplete TEP data scan (00:24Z) occurs in middle of when the waveform was returned to its original state. Therefore, it is hard to exactly determine the time when the radar operator was able to re-sensitize the region with a more robust waveform. However, these regions of sensitivity adjustment are important for the conservation of SPY-1 resources and become tactically significant when they are co-located within or near a designated threat bearing. Without a nowcast of the atmosphere, the radar operator is left to guess when the environment can support increased SPY-1 sensitivity. This is one of the main areas where TEP is an outstanding utility for the surface warfare community.

From the first TEP reflectivity plot (Figure 4-14, 22:43) until time 23:40 (Figure 4-20), the CIDD plot remained centered on the Normandy initial position. This provides a “viewer referenced display” where the sequential TEP reflectivity plots reveals Normandy’s movement throughout the storm period. This movie-like display is useful to TEP users who are not onboard the TEP platform and want to visualize storm motion. Between times 22:43 and 23:40, Normandy traveled NE and returned to the SW. At time 23:40, Normandy was displaced by 4.69 nm (bearing 267^0) from the original position. The movement pattern of the Normandy helps to explain why the thunderstorm remains within the SPY-1 blind zone for such an extended time period.

After 23:40, the lightning activity began to increase but the storm cell was still confined to the blind zone within the first range gate. Finally, at time 00:37 (Figure 4-23) the thunder cell are characterized by TEP and clearly evident between 090^0 and 150^0. The archived lightning data corresponds with the strong TEP reflectivity returns and the observed reports of an intense lightning storm. Figure 4-24 is a zoomed picture of the same thunderstorm cell. Strong convective weather was represented by the reflectivity values near 50 dBZ throughout the cell. A zoomed display of the same storm cell (still at time 00:37) from a 9.1^0 elevation shows a snapshot of intense convection within upper portions of the cell. This elevated plot strongly resembles the elevated snapshot of reflectivity from initial time of 22:43 (Figure 4-15), two hours prior.

There was a second storm cell in Figure 4-23 (time 00:37) bearing 050^0 at 25 nm from Normandy. Similar to the storm of interest, strong reflectivities and intense lightning also define this second cell. In the last reflectivity plot shown for this case study, Figure 4-26 (time 00:47), the two storms are clearly evident and show regions of strong convective weather. For the next hour, both storms are characterized and tracked by TEP as they head due south.

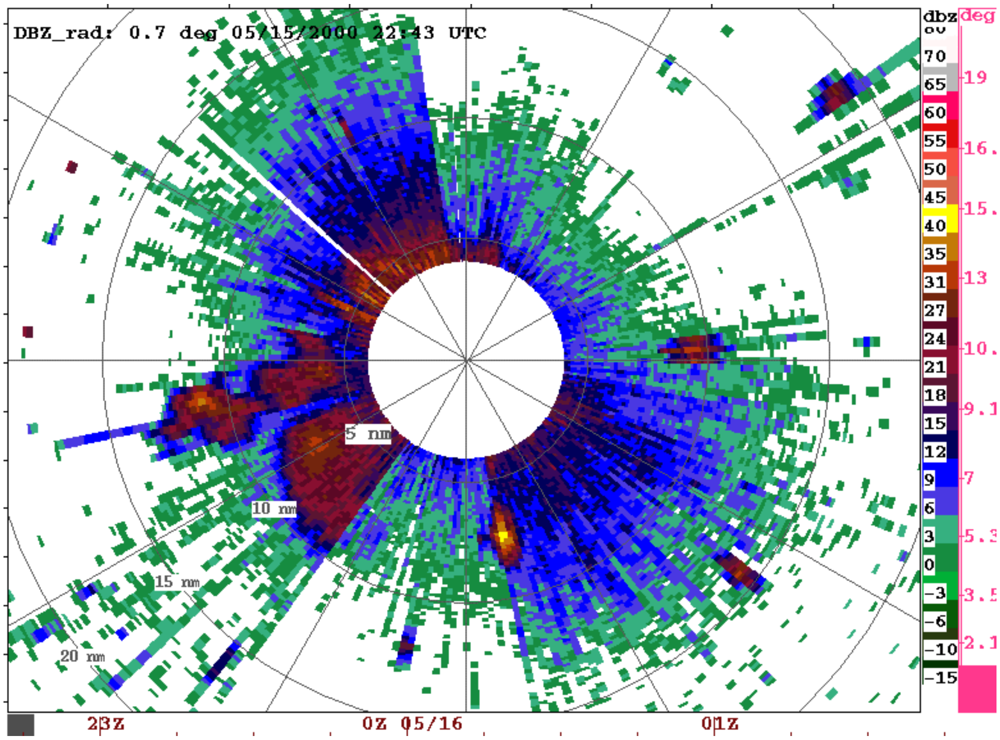


Figure 4-14: TEP Reflectivity Plot for 22:43Z on 15 May 2000 (Strom of interest occurred at 23:00Z, previous TEP data was at 22:05)

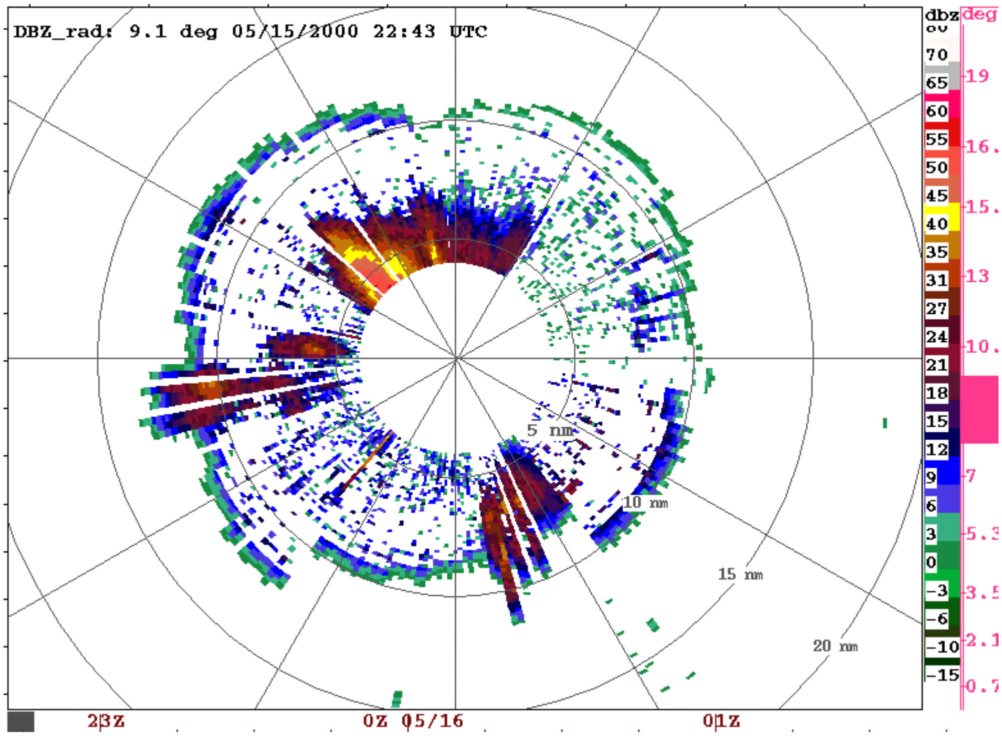


Figure 4-15: TEP Reflectivity Plot (9.1^0 elevation) for 22:43Z on 15 May 2000 (notice upper level of intense storm at 315^0, body of storm within first range gate)

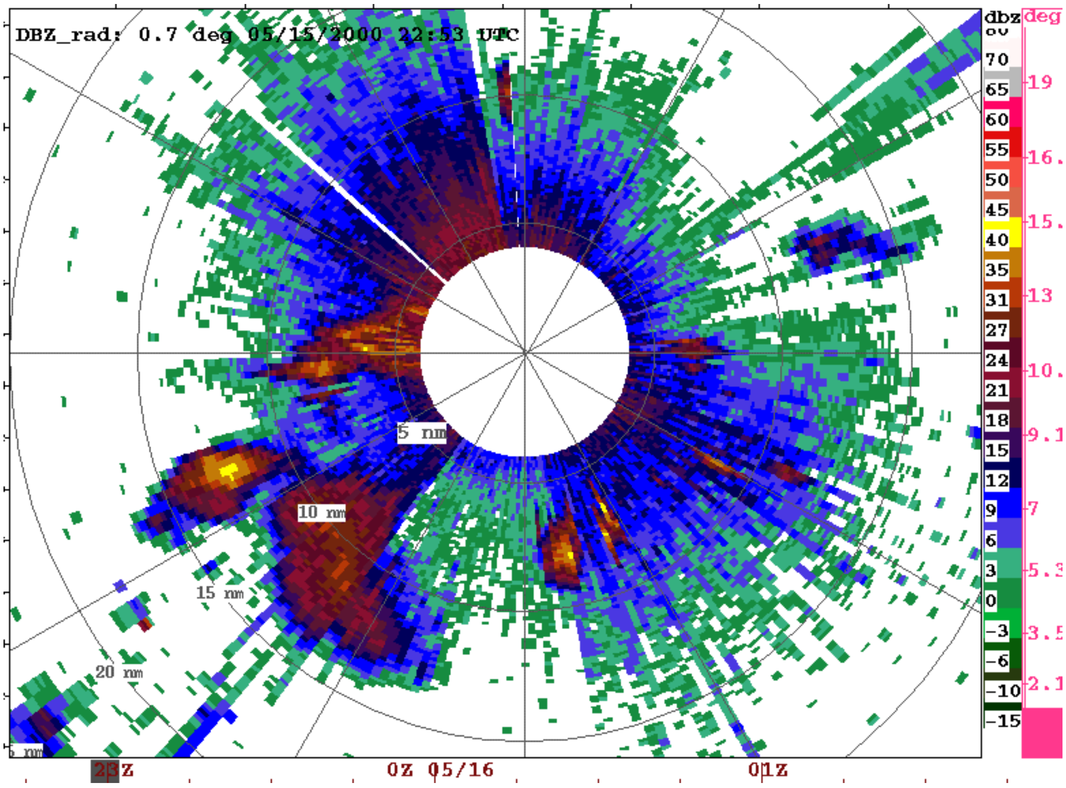


Figure 4-16: TEP Reflectivity Plot for 22:53Z on 15 May 2000

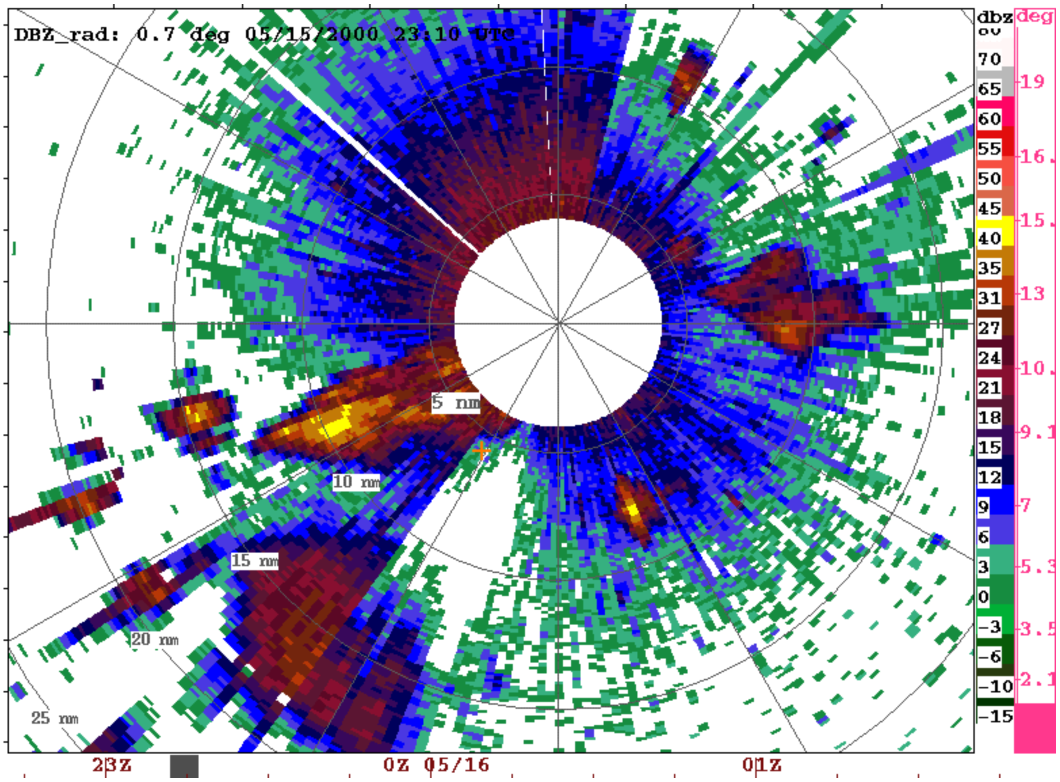


Figure 4-17: TEP Reflectivity Plot for 23:10Z on 15 May 2000

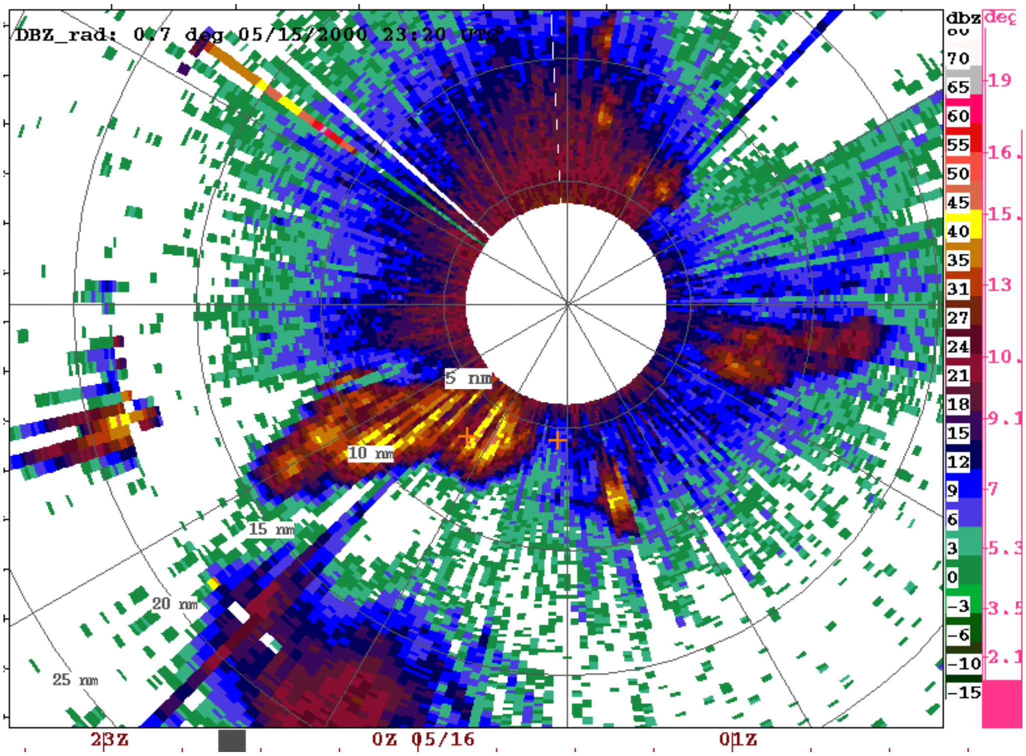


Figure 4-18: TEP Reflectivity Plot for 23:20Z on 15 May 2000

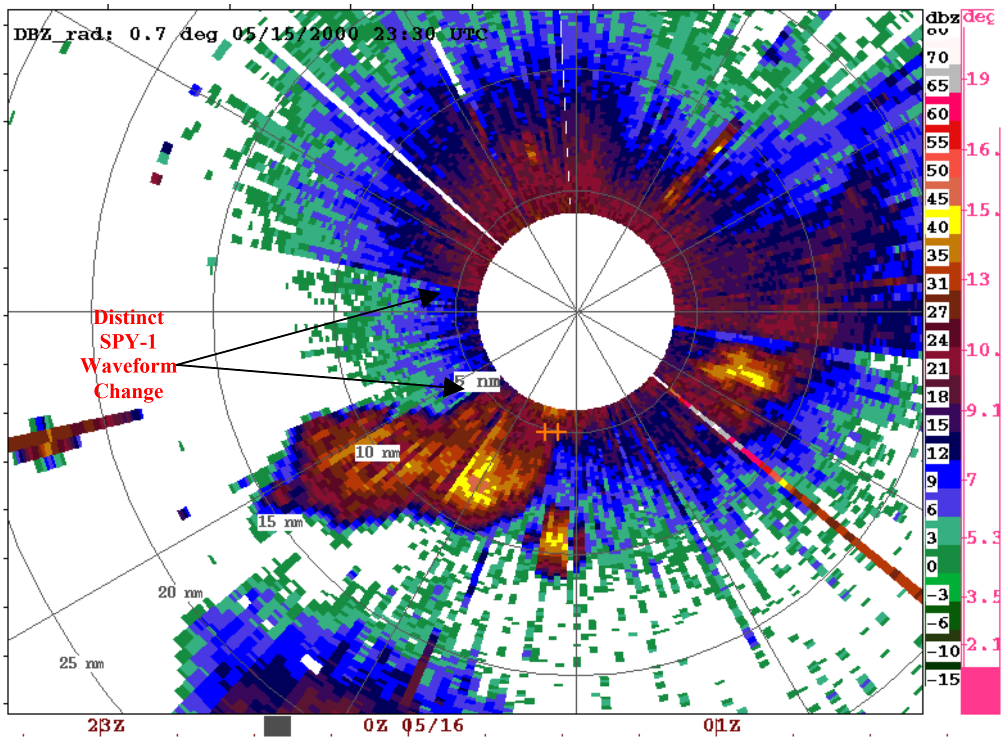


Figure 4-19: TEP Reflectivity Plot for 23:30Z on 15 May 2000 (distinct SPY-1 waveform or power change between 240^0 and 280^0)

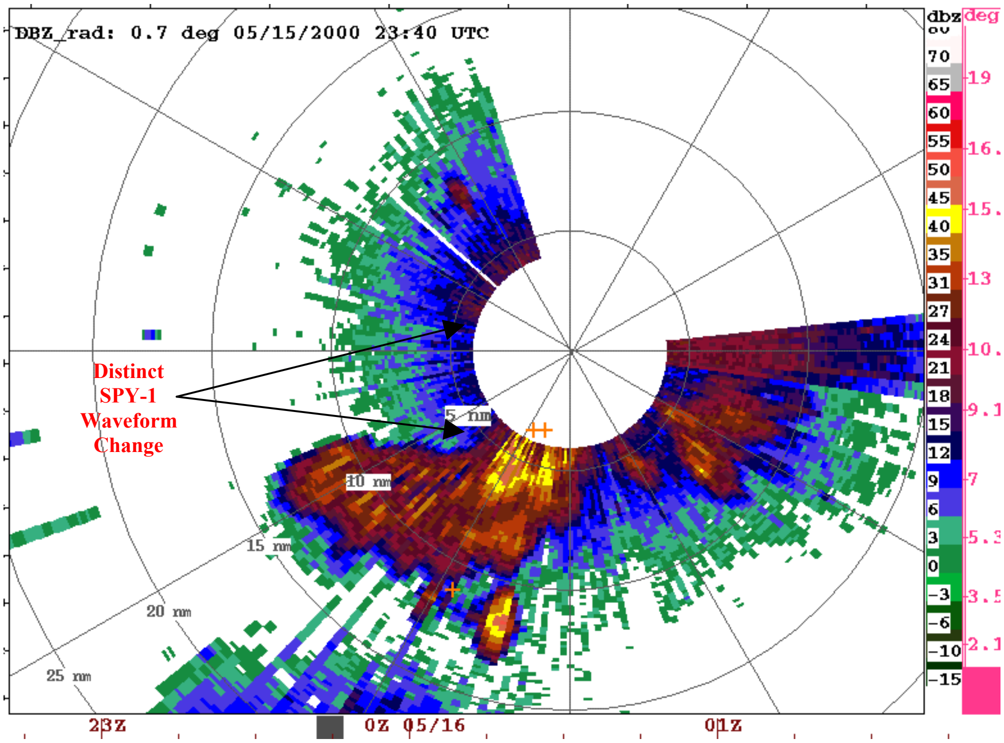
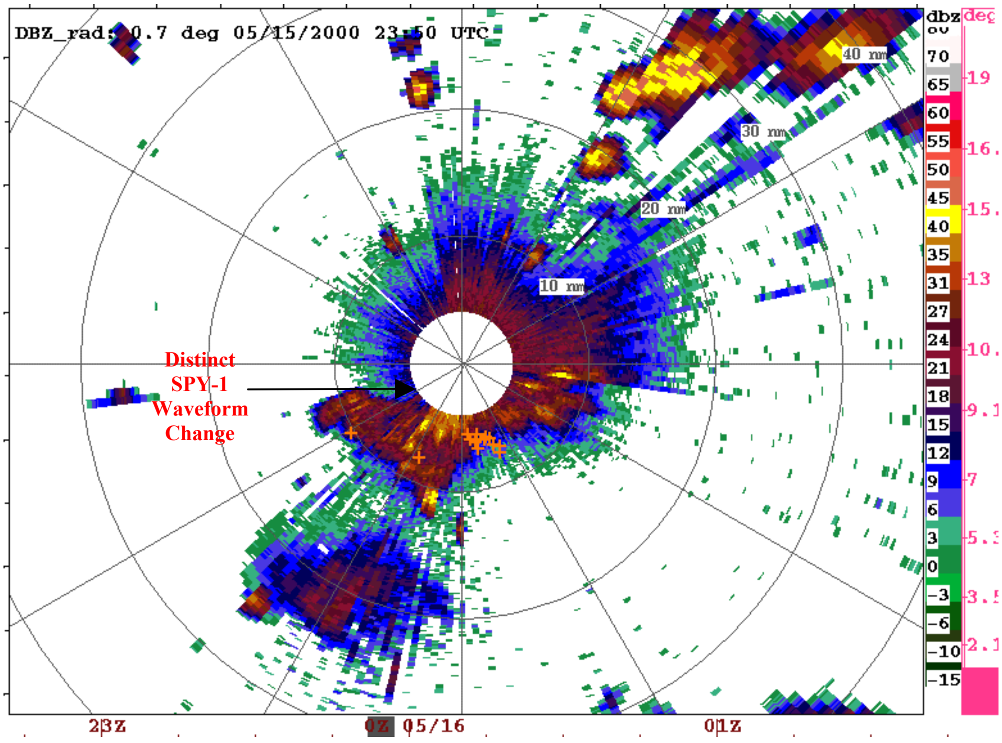
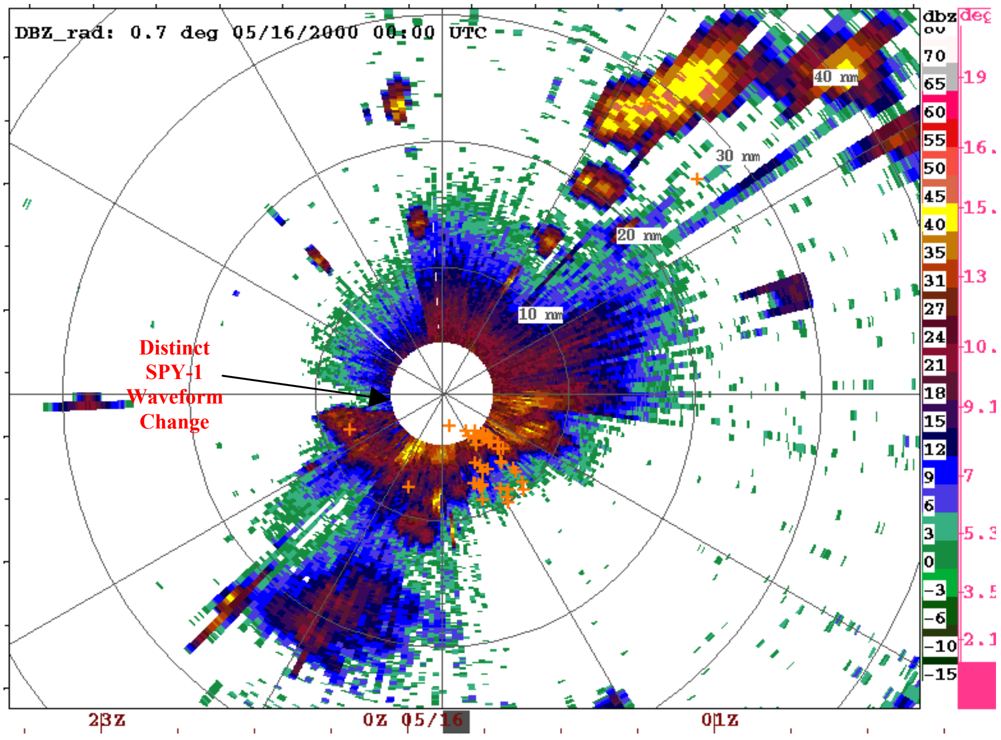


Figure 4-20: TEP Reflectivity Plot for 23:40Z on 15 May 2000 (SPY-1 waveform between 240^0 and 280^0 is still de-sensitized)



Distinct SPY-1 Waveform Change

Figure 4-21: TEP Reflectivity Plot for 23:50Z on 15 May 2000 (SPY-1 waveform between 240^0 and 280^0 is still de-sensitized, second thunder cell bearing 040 @ 27nm)



Distinct SPY-1 Waveform Change

Figure 4-22: TEP Reflectivity Plot for 00:00Z on 16 May 2000 (SPY-1 waveform between 240^0 and 280^0 is still de-sensitized)

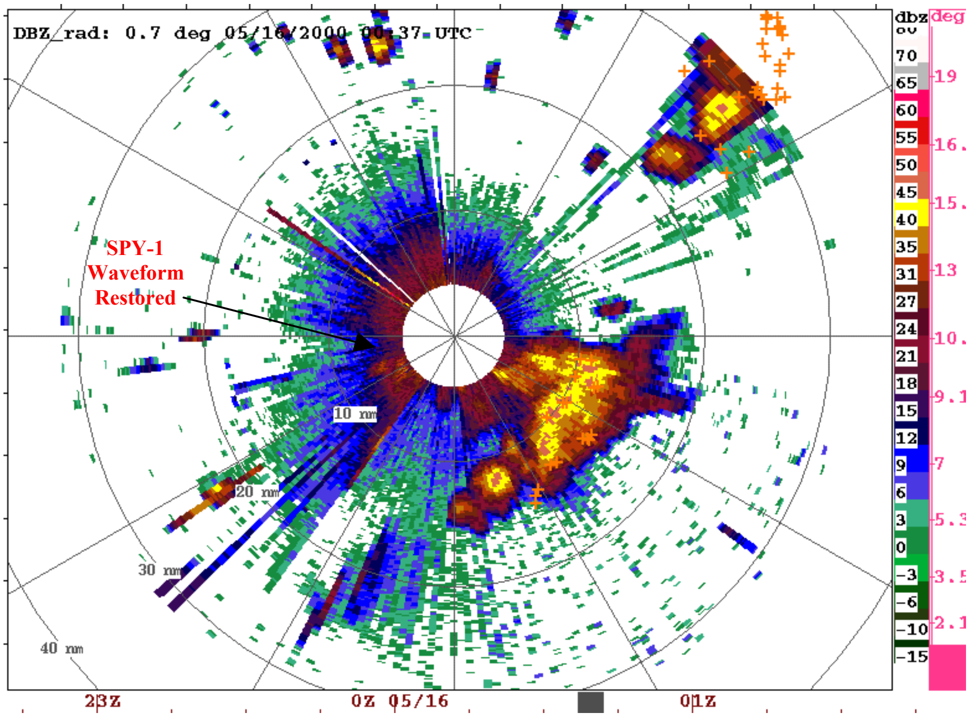


Figure 4-23: TEP Reflectivity Plot for 00:37Z on 16 May 2000 (SPY-1 waveform between 240^0 and 280^0 has been restored to a more robust search pattern, lightning directly corresponds with significant intensities from both thunderstorm cells)

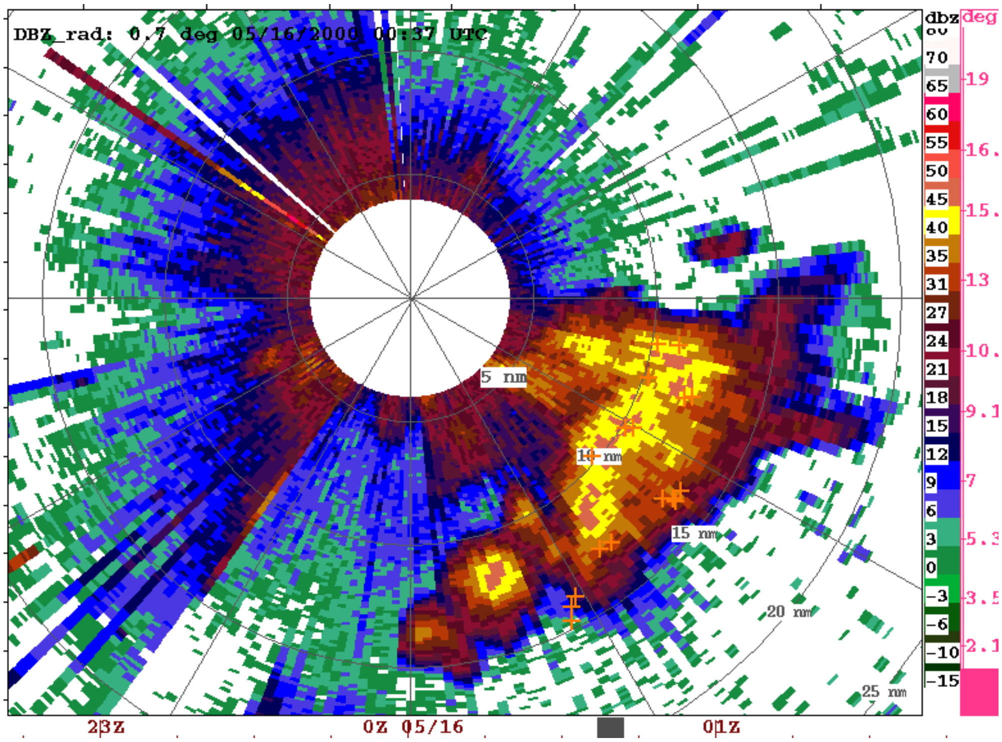


Figure 4-24: Zoomed TEP Reflectivity Plot for 00:37Z on 16 May 2000 (lightning corresponds with strong reflectivity for a significant storm)

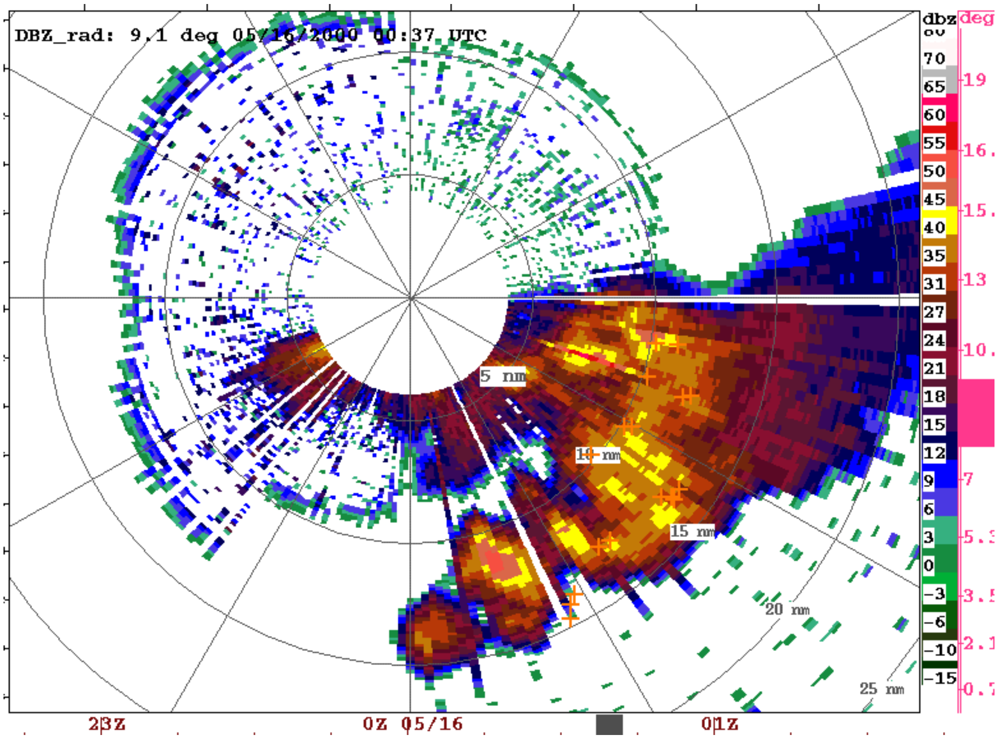


Figure 4-25: Zoomed TEP Reflectivity Plot (9.1^0 elevation) for 00:37Z on 16 May 2000 (snapshot of intense convection within upper portions of the thunderstorm cell)

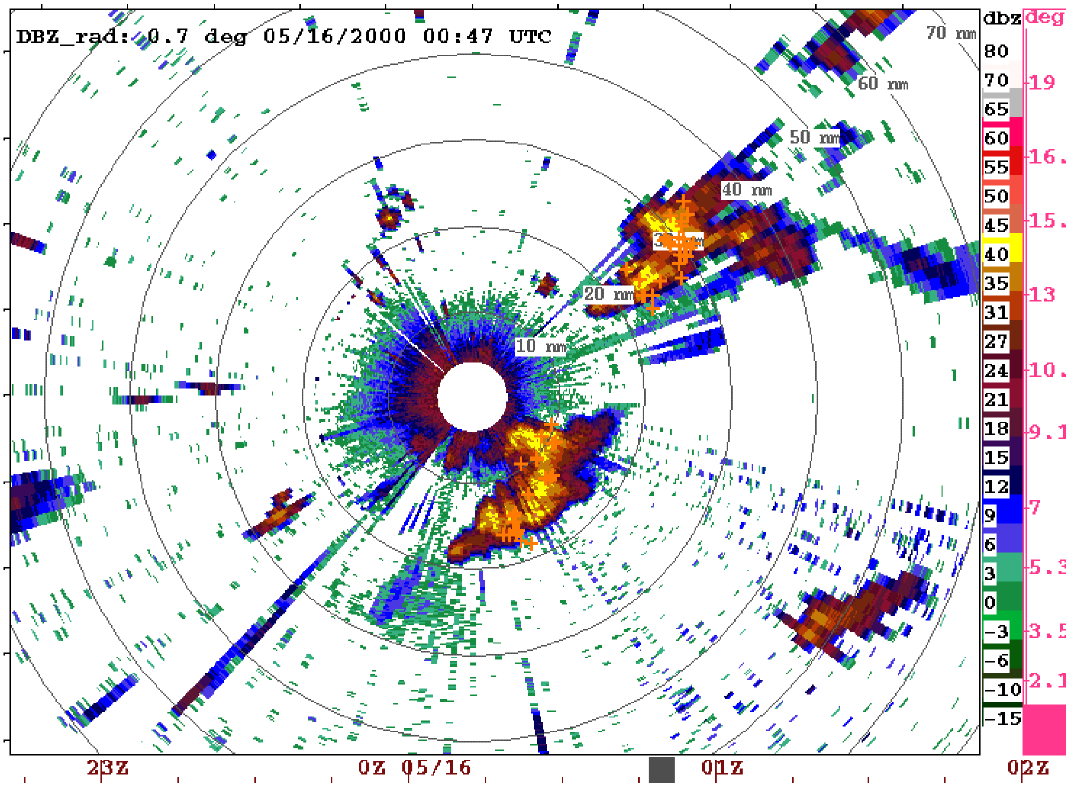


Figure 4-26: TEP Reflectivity Plot for 00:47Z on 16 May 2000

E. DISCUSSION

The goal of this chapter was not to evaluate TEP during the JTFEX, but to demonstrate the TEP utility as an at-sea Doppler weather radar. Analyzing this severe and operational important weather event was accomplished by two distinct weather characterization methods. The synoptic/mesoscale analysis provided a forecast for thunderstorm activity, while the TEP nowcast revealed individual cell detection and relative storm intensities. In comparison to the environment, these two techniques could have provided the GW METOC Team with the tools necessary to support the warfighter. However, connectivity issues and experimental data gaps constrained the TEP operational debut. Had this information been made available to the GW Battle Group in a real-time manner, the weather conditions that suspended flight operations on 15 May could have been avoided if the METOC office had the conduit necessary to inform the decision-makers on the bridge of the hazardous weather situation.

From an analysis perspective, TEP provided critical weather information to the JTFEX warfighters and METOC. Figure 4-27 contains a background display of IR

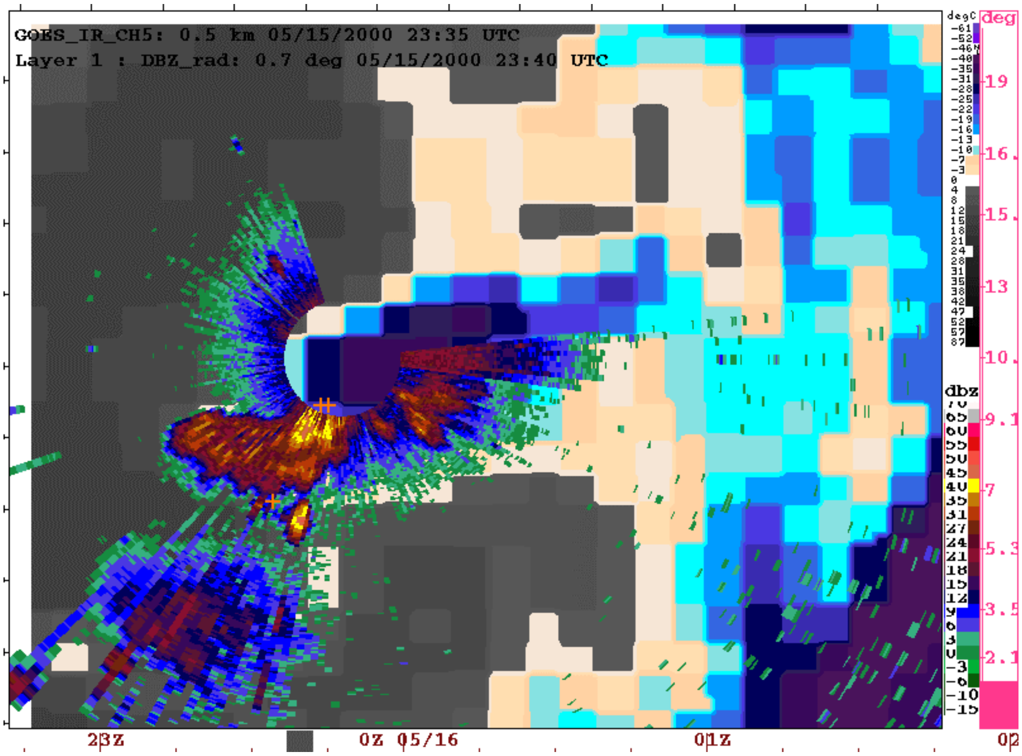


Figure 4-27: Independent Severe Storm Verification - GOES IR Channel 5 Imagery (23:35Z) Overlaid with TEP Reflectivity (23:40Z) and Archived Lightning Data

satellite (channel five) imagery overlaid with TEP reflectivity (0.7^0 elevation) and archived lightning data. The TEP reflectivity (23:40Z) and the satellite data (23:35Z) are within five minutes. The data fusion plot reveals the storm cell location and relative intensity from three independent sources. This composite plot collaborates the TEP analysis and is an independent verification of the severe weather that occurred on 15 May 2000. It is important to note the value-added by incorporating all the weather sensors into a common operating picture or data fusion system.

V. SUMMARY AND CONCLUSIONS

Diverse battlespace challenges and advanced naval systems have increased the importance of accurate and timely atmospheric characterization. A deployed naval battlegroup faces diverse and often challenging environments. Clutter and anomalous propagation impact sensor and weapon performance while clouds and severe weather effect fleet operations. At-sea warfighters and weather forecasters require current, relevant information about the ever-changing environment surrounding the battlegroup. This requirement is enhanced in littoral regions, where restricted space and volatile environmental conditions combine to amplify the dramatic meteorological variability. TEP provides this critical weather information to the warfighter and METOC in a nowcast format.

The objective of this thesis was to demonstrate TEP utility to the Navy, especially to the warfighter. The results from the JTFEX 00-2 TEP analysis clearly show that TEP provides a significant at-sea capability for the Navy. TEP demonstrates this capability via a case study that could be considered a worst-case scenario for the nowcast of the JTFEX storm. There was no history of the thunderstorm prior to 22:43Z and for the next two hours the TEP characterization was masked by the non-radiating sector within the first range gate. Even with all these difficulties, it is evident from the JTFEX severe weather analysis that TEP offers a significant advantage to any at-sea naval operation. TEP nowcast weather information could be used to make measurable impacts on the operational capabilities for any battle group or deployed naval unit. The utility of the TEP atmospheric nowcast allows the Navy, especially the warfighters, to take advantage of the environment!

A. SURFACE WARFARE

Tactical engagements are inseparable from the environment in which they are fought. Therefore, to fully exploit the METOC aspects of the battlespace is to gain the tactical advantage over an adversary. The AEGIS weapon system, the premiere air defense system in the U.S. Navy, does not have the environmental support to continuously optimize system parameters and adapt to evolving atmospheric conditions. The TEP environmental nowcast combined with the RFC ducting estimates provide the temporal and spatial sampling that can help to detect and subsequently control difficult SPY-1 clutter events. TEP and RFC provide the radar operator an environmental window to control radar resources. Radar operators can become proactive vice reactive in their response to a constantly changing atmosphere. Figure 5-1 demonstrates how the TEP environmental nowcast could be used to balance available radar resources against constantly changing environmental conditions. Goal is to match the blue-dashed line (radar sensitivity) with the solid-red line (environmental conditions). TEP can specifically help the radar operator in two critical areas: 1) de-sensitizing the radar when the environment degrades (darker green shading) and; 2) re-sensitizing the radar when battlespace characterization is less than what is permitted by the atmosphere (light yellow shading). De-sensitizing the sensor is instinctive; minimize radar resources when search times exceed operational levels. However, increasing radar sensitivity is counter-intuitive and difficult to predict without an atmospheric nowcast tool. To alter a satisfactory radar picture, even though the current sensitivity setting is sub-optimizing the radar's

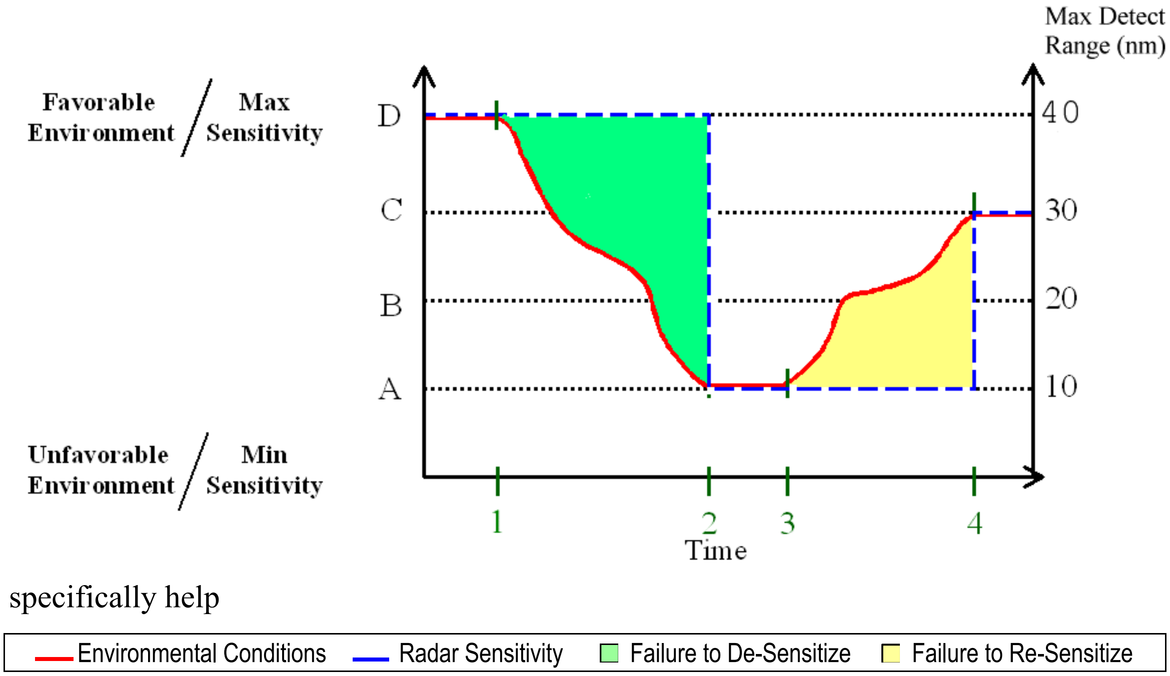


Figure 5-1: Plot Demonstrating the Method and Importance of Real-Time Sensor Optimization (from: Easton, 2000)

capability, is not an obvious conclusion for even the most experienced radar operator. TEP provides the tools to help tailor sensor configuration with changing atmospheric conditions, thereby maximizing sensor capabilities and optimizing radar coverage. Another use of weather radar at sea would be to exploit stormy conditions against the enemy. By placing critical assets within a storm, to avoid surface or airborne detection or attacks, could be a temporary but significant advantage on the battlefield.

Operationally, TEP supports the SPY-1 radar by providing an environmental characterization, but TEP can detract tactically from available SPY-1 resources if the active TEP load is too great. Potential TEP users must have an understanding of SPY-1 operations and the significance of over-scheduling active TEP waveforms. To preserve the tactical importance of SPY-1 resources, a balance needs to be established between the operational significance of available SPY-1 resources and the atmospheric sensitivity required. This balance should not be a constant, but a flux that favors the tactical importance of SPY-1 resources based on operational threats and the significance of the environmental characterization requested.

B. AVIATION

Almost 160 NEXRAD radars are located throughout CONUS and also in Alaska, Guam, Puerto Rico, and South Korea. These radars provide continuous atmospheric information with an invaluable focus on severe weather warnings. In contrast, current carrier and amphibious air operations are conducted without the protection of an at-sea weather radar. The ability to nowcast atmospheric conditions at-sea is critical to daily aviation operations.

From FY90-98, weather related mishaps to the aviation community were found to have caused $69 million in damage and produced 11 fatalities per year (Cantu, 2001).[7] From a safety of flight stand-point, an at-sea weather radar is long overdue; without it, the Navy lags further behind CONUS and other landbase weather safety capabilities. TEP could be used to identify aviation hazards like approaching storms or severe wind

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[7] It is important to note that the Navy Safety Center does not permit weather to be causal in mishaps, but only a factor (by their definition).

shifts. This would allow for smoother operational transitions between launch/recovery cycles and provide the CVN or LHD CO/OOD with an excellent planning tool. Additionally, TEP would prove useful as an aid in flight planning, not to mention the potential TEP offers for strike planning. A relatively simple display of weather radar for naval aviation operations, particularly the carrier or large deck amphibious platforms (i.e. ready rooms, bridge, combat) would have major advantages to flight planning and operations. Air traffic controllers could use the weather information for aircraft routing and in the establishment of marshalling stacks and CAP stations.

C. METOC

TEP provides an at-sea nowcast tool. TEP reflectivity and radial velocity plots provide the weather data necessary for real-time forecasts and storm tracking. This nowcast ability fills a gap that currently exists in the METOC arsenal. At-sea weather forecaster are very good at synoptic and mesoscale analysis, but they simply cannot forecast accurately on the temporal and spatial scales required for daily at-sea operations. TEP environmental radar data is invaluable to the METOC community, especially in forward-deployed locations away from the CONUS weather network.

TEP supports the METOC role at-sea. Without a forecast, radar observers will often miss the first events of an at-sea weather episode. Regardless of the quality of the radar data, a forecast is necessary to alert the radar operator of a potential severe weather situation. With a forecast, the TEP operator will be anticipating severe weather and will use radar data to identify particular severe weather storms as they develop in, or move into, the area operations. With the marriage of current model forecasts and a nowcast tool, the at-sea METOC is able to provide relevant, real-time environmental knowledge to better support the warfighter.

TEP links the warfighter and METOC closer together. With all the advances in naval weapon and sensor technology, the largest wartime variable is still the environment. The ability to assess and predict the effect of the environment on both force and threat sensors is a key facet in mission planning. By linking synoptic/mesoscale model forecasts and satellite interpretation to present weather, TEP becomes a meteorological component in any system that would fuse data from a myriad of sources (*in situ* and remote sensors, models, etc.). A temporal-based weather plot would provide an invaluable wartime advantage over the enemy and allow for safer peacetime operations. TEP exploits the battlespace to leverage a tactical advantage and provides the Navy a nowcasting tool that affects both forces and sensors.

D. ISSUES TO OVERCOME

Through-the-sensor technology allows TEP to utilize the SPY-1 radar to characterize the atmosphere. Like the SPY-1 air defense umbrella, TEP is an environmental cloak that supports the warfighter. This provides a positive impact on a range of naval operations and an asymmetrical battlespace advantage. However, before TEP is implemented into common fleet use, there are a few areas of interest that need to be addressed:

- TEP is a time critical product. Since TEP and its data are resident on the CG or DDG, there must be enough bandwidth to provide the CVN/LHD the raw TEP data, and allow these larger platforms to distribute the requested TEP products to the Carrier Battle Group (CBG) or Amphibious Ready Group (ARG).
- TEP may be an organic sensor for the CBG or ARG, but who will have access to the generation of active TEP waveforms? TEP is resident onboard the AEGIS platform, but best operated by the CVN/LHD embarked METOC Teams.
- A threshold for too many active TEP waveforms[8] needs to be defined. This allows all the interested TEP parties a boundary to work within. Potential model use for TEP products could require significant active PD SPY-1 environmental characterization, which could distract valuable radar resources.

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[8] Note: Lockheed Martin estimates a 1% SPY-1 load for auto scheduling of high sensitivity TEP waveforms to cover the radar volume once every 10 minutes (personal communication).

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VI. RECOMMENDATIONS FOR FUTURE STUDIES

A. TEP LIMITED AT-SEA EXPOSURE AND TESTING

At the time of this thesis, TEP has only been included in two at-sea demonstrations: 1) Maiden voyage and initial CSSQT for USS O'Kane (DDG 77); and 2) METOC LOE conducted during JTFEX 00-2, TEP aboard the USS Normandy (CG 60). This limited at-sea exposure and testing needs to be expanded to explore additional advantages and disadvantages offered by an at-sea Doppler weather radar. For example:

- One or more battle group assets could incorporate TEP into their deployment training and work-up cycle.
- TEP should be evaluated in Amphibious Ready Group (ARG) operations.
- Further RFC testing and development which could eventually lead to some form of automated SPY-1 optimization.
- TEP has the potential to characterize the environment to support a variety of DOD, Home Land Defense and Naval Warfare specialties (i.e. wind analysis for WMD fallout, strike/land attack planning, etc.).

B. TEP DATA PROCESSING, DISTRIBUTION AND DISPLAY

There are many potential uses of TEP data and products. However, for each TEP product desired, the data must be collected, processed and delivered in a timely manner and usable format. In most cases, the user is not interested in the actual origin or myriad of data that emanates from TEP, but rather in the graphical end-user product. This product needs to present the TEP data in a framework that makes the environment easier to understand for operational decision makers.

Significant research needs to be dedicated into the processing, distribution and display of TEP data. Fast and reliable data transfer methods need to be investigated to ensure that the time sensitivity of TEP products are a benefit to the warfighter and not a barrier. Additionally, CIDD or a similar data fusion display system must become part of the TEP package. Relatedly, TEP could readily become part of other larger data fusion program such as Nowcast for the Next Generation Navy, currently an ONR effort being funded to the Naval Research Laboratory, Monterey. Such steps would allow an integrated weather database, fusion display and the distribution of user specified weather products to the entire battle group. Together, the TEP products and associated battle group architecture could be used as a valuable decision-making tool that will have significant impact on operations.

APPENDIX. AEGIS RADAR OPERATING FUNDAMENTALS

Tactical Environmental Processor (TEP) is a technique that converts radar returns from the AN/SPY-1 radar into environmental measurements known as spectral moments. These spectral moments provide critical nowcast-weather information to AEGIS and non-AEGIS personnel. TEP generally operates in a passive role, extracting weather data from tactically scheduled SPY-1 returns. When designated, TEP can be used in an active scan mode, where TEP requests the SPY-1 radar to generate specialized waveforms to characterized small-scale features in the atmosphere. However subtle the differences between the two TEP scan modes seem, their scheduling of SPY-1 resources is an important concept. To exploit the utility of TEP, potential users need to have a general understanding of the AN/SPY-1 radar system and its environmental influences from a warfighter perspective. This Appendix is a generic, unclassified discussion about the interactions between the SPY-1 radar and TEP.

The AEGIS Combat System, resident on Ticonderoga Cruisers (CG) and Arleigh Burke Destroyers (DDG), was designed as a total weapon package. At the heart of the AEGIS system is an advanced, automatic detect and track radar, the AN/SPY-1. This multi-function radar is electronically scanned and operates in the S-Band with an output of several megawatts. The SPY-1 radar has no moving parts and utilizes four fixed transmit and receive arrays. Each phased-array covers 90+ degrees of azimuth. Every radar element is computer controlled to produce multiple energy pulses (dwells) that are able to radiate at any azimuth, at any elevation, at any time. SPY-1 can simultaneously search, detect, classify, and track targets of interest. However, the radar resources required to perform these basic radar functions varies. Searching the battlespace for unknown point targets and tracking objects of interest carry a minimal radar resource cost. While transitioning tracks to a “tracking” mode (i.e. detecting and classifying potential targets) is resource intensive, as the radar has to develop a track history prior to “tracking” the target. Since the AEGIS Combat System tries to maximize the tactical use every available SPY-1 radar resource, events that place a heavy load on SPY-1 radar resource are significant.

SPY-1 is focused on fleet air defense, not weather description. Air Defense (AD) requires maximum radar ranges and rapid search times with minimal radar loading. Considering that each AEGIS cruiser or destroyer can simultaneously track 100+ targets, atmospheric events that slow search times become tactically significant. Airborne debris, birds and atmospheric effects can cause SPY-1 to initiate a significant number of "clutter" tracks. To appreciate why clutter tracks are a burden and to gain a basic understanding of SPY-1 operations, an explanation of SPY-1 radar time allocations is necessary. The AEGIS Combat System and SPY-1 are designed to maximize the tactical use of all available radar resources. On a millisecond time interval, SPY-1 must generate a series of dwells to support the immediate tactical mission. To accomplish this, SPY-1 uses a pre-established order that gives priority to dwells of higher tactical significance. The list would be similar to the following table:

Tracking
Horizon Search
Volume Search
House Keeping

Table A-1: SPY-1 Scheduling Order

Dwells are scheduled similar to the order listed. If tracking, including transition-to-track, consumes too many resources then House Keeping is delayed in scheduling. Eventually the load can become too great and the search functions are delayed. If a significant number of clutter cells are detected and subsequently transitioned to track, this can have a serious effect on SPY-1 search times. Since clutter cells are generally associated with weather, these SPY-1 nuisance events are significantly important to TEP.

SPY-1 uses many schemes to help eliminate clutter tracks. Moving Target Indicator (MTI) is one of the primary means. MTI uses a sequence of three or four pulses to determine which targets are stationary (i.e. clutter) and which are moving (i.e. targets). The goal of SPY is to only allow moving targets to transition to track, whereas weather radars wants to remove point targets and observe stationary weather events. In addition to MTI, Track Initiation Processor (TIP) is used in the SPY horizon search volume to prevent non-moving targets and clutter detections from transitioning to track. MTI is used in all beam positions where clutter is mapped or can be manually ordered in any search sector by the radar operator. MTI is a special SPY waveform that is used to reduce clutter, but still supports the TEP environmental characterization and produce three spectral moments.

At ranges beyond the extent of horizon search, neither TIP nor MTI processing is available. Additionally, it is at ranges beyond horizon search, that large numbers of clutter tracks are encountered. Supplemental techniques are used to help eliminate these long-range clutter tracks. In spite of all these clutter suppression techniques, the SPY-1 radar can still be burdened with clutter detections. The most stressing cases for SPY-1 operators are those that cause search frame times to exceed acceptable levels. This is often caused by excessive clutter, particularly long-range clutter that cannot be eliminated by MTI or TIP. Operation in the littoral environment and the presence of ducting can contribute to this severe clutter load.

Figure A-1 is an example of a reflectivity map generated by TEP onboard the USS O'Kane (DDG 77). The USS O'Kane was positioned off the coast of Jacksonville,

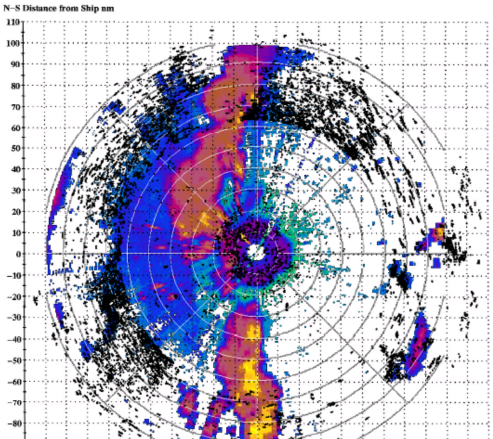

Figure A-1: TEP Reflectivity Overlaid with Clutter Track Initiations, reflectivity color bar not included (from: TEP Final Report, 2000)

Florida when a severe squall line moved through the area. The reflectivity map represents the TEP radar volume (azimuth: 0^0 to 360^0 and elevation: 0^0 to 3^0) and is thresholded to prevent disclosure of SPY-1 sensitivity. Overlaid on this reflectivity map are clutter tracks seen by the SPY-1 radar. For the purpose of this analysis, clutter tracks are defined as those tracks that were in existence less than time required to successfully transition-to-track. Colored areas represent reflectivity intensities and SPY-1 clutter tracks are denoted by black dots. The reflectivity map gives an indication of the storms magnitude and shows the presence of long-range clutter tracks that are subject to costly transient dwells. Since transient dwells are scheduled at a higher rate to ensure that potential targets are smoothly transitioned-to-track with quantified metrics, it is easy to witness how long-range clutter can put a heavy load on SPY-1 resources. This figure also represents the delicate balance between nuisance SPY-1 clutter tracks and important weather radar environment characterization.

Figure A-2 shows real targets in track by the SPY-1 radar overlaid on clutter tracks for the same period. Real targets are defined as those tracks that remain in track long enough to transition-to-track. Each long line is a single point target under track by SPY-1, and represents objects of tactical interest (i.e. aircraft) or nuisance tracks (i.e. birds). After targets have transitioned-to-track, they are typically tracked at a slower rate; therefore, putting little load on SPY-1 resources. In Figure A-2 it is clear to see that there are significantly fewer real tracks than clutter tracks. This is a problem for SPY-1 resource management, as clutter tracks that are transitioning are more expensive than real

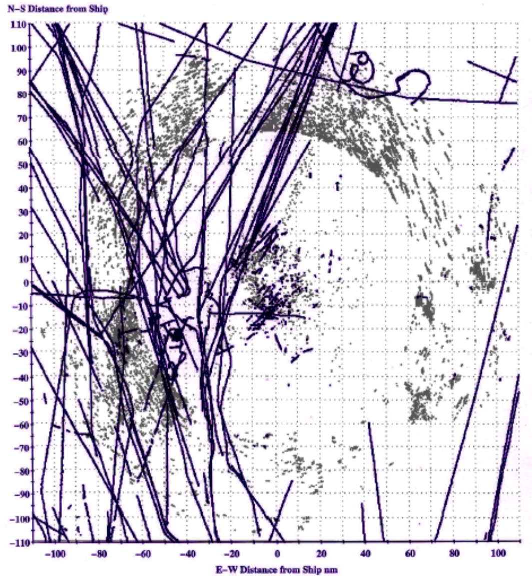

Figure A-2: Overlay of Real vs. Clutter Tracks (from: TEP Final Report, 2000) targets in terms of SPY-1 radar allocations. Without continuous sampling techniques, the radar operator is only left to guess the present atmospheric conditions by their impact on radar resources. To reduce the long-range clutter content, the radar operator is generally forced to desensitize the radar. Desensitizing the radar reduces its ability to see targets, and may allow hostile aircraft or missiles to go undetected long enough to prevent the ship from defending itself or others in the battle group. It is the detection and elimination of clutter tracks that allows SPY-1 to maintain its fast search frame times and thus achieve its primary goal of defense of the fleet. In the situation of clutter detection, TEP can provide both help and hindrance. Used passively, TEP can only help to define the environment, especially ducting situations that can lead to increased clutter detection. However, active TEP waveforms must be used conservatively so as to not over allocate necessary SPY-1 resources needed to survey and protect the battlespace.

It needs to be emphasized that TEP/SPY-1 are not and will never be NEXRAD weather radars. The differences between a dedicated weather radar and tactical air defense radar are too drastic. Since TEP is dependent on a tactical radar, it is subject to periodic data gaps and unannounced waveform alterations. The TEP data gaps may be sector orientated (i.e. non-radiating sectors for flight quarters, underway replenishment, etc.) or subject to the full radar volume (i.e. EMCON restrictions or maintenance periods). Additionally, TEP velocity measurements are only available in beam positions where SPY-1 doctrine selects the MTI waveform (active TEP scan modes also support velocity measurements). Figure A-3 is a good example of the lack of velocity data

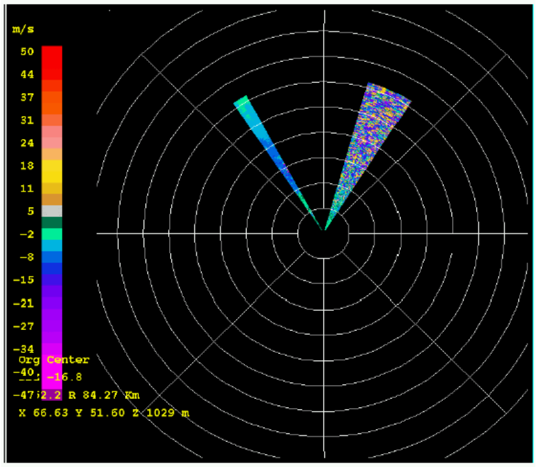

Figure A-3: TEP Radial Velocity with SPY-1 Auto MTI (from: TEP Final Report, 2000) available from an auto-MTI[9] SPY-1 radar function. The figure shows two small sectors where radial velocity was measured. However, even with all these distinctions from NEXRAD, TEP is a significant asset to the at-sea METOC and warfighter.

TEP does not need to be of the same quality as NEXRAD to support the warfighter. TEP has proven to be operationally equivalent to NEXRAD, but the paragraph above demonstrates some of the quality differences. This is an important distinction in the at-sea operational environment. Plots showing accurate storm boundaries and areas of high reflectivity are more useful to the warfighter than having highly accurate absolute reflectivity measurements. The benefit to aviation that TEP provides is it allows the carrier CO/OOD to relocate the airfield in the event of potentially severe weather. Because the airfield is mobile, there is a lesser requirement of detailed atmospheric characterization. However, as naval weapons and sensors evolve, the requirement to describe the environment will become more stringent. TEP could evolve to meet these challenges, but for now the benefit of the TEP environmental nowcast and weather composite plots is an order of magnitude improvement in at-sea METOC forecasting.

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[9] Auto-MTI is a SPY-1 operator initiated function that automatically schedules MTI search dwells in the horizon wherever clutter is mapped.

LIST OF REFERENCES

Barnes, S. L., 1980; Report on a Meeting to Establish a Common Doppler Radar Data Exchange Format. *Bulletin American Meteorological Society*, **61**, No. 11, 1401-1404.

Cantu, R.A., 2001; The Role of Weather in Class A Naval Aviation Mishaps FY 90-98, MS Thesis, Naval Postgraduate School, Monterey, CA.

Collier, C.G., 1996; *Applications of Weather Radar Systems, A Guide to Uses of Radar Data in Meteorology and Hydrology*, Second Edition. John Wiley & Sons Ltd, Chichester, West Sussex, England.

Doviak, R.J., and Zrnic, D.S., 1993; *Doppler Radar and Weather Observations*, Second Edition. Academy Press, San Diego, California.

Easton, R.C. and Sanabia, E.R., "Exploiting the Environment to Win in the 21st Century," paper presented at the U.S. Navy METOC Support to the Surface (AEGIS) Warfighter Conference, Pearl Harbor, Hawaii, 14 December 2000.

Eckardt, M.C., 2002; Assessing the Effects of Model Error on Radar Inferred Evaporative Ducts, MS Thesis, Naval Postgraduate School, Monterey, CA.

Gerstoft, P., Rogers, L.T., Krolik, J.L., and Hodgkiss, W.S., 2001; Inversion of refractivity Parameters from Radar Sea Clutter. Submitted to *Radio Scienc*e.

Hage, Frank, "Configurable, Interactive Data Display (CIDD) Introduction and Overview." [http://www.rap.ucar.edu/CIDD/doc/cidd_intro.html]. March 2002.

Lockheed Martin, 2000; Tactical Environmental Processor (TEP) Final Report and Addendum (Agreement Number N00014-98-2-0001), Lockheed Martin, Naval Electronic and Surveillance Systems, Moorestown, NJ.

National Weather Service, “National Convective Weather Forecast.” [http://cdm.aviationweather.noaa.gov/ncwf]. March 2002.

Naval Atlantic Meteorology and Oceanography Center Instruction 3140.2C, *Local Area Forecaster’s Handbook for Naval Air Station, Norfolk, Virginia*, 1994.

Office of the Federal Coordinator for Meteorological Services and Supporting Research, 1990. Federal Meteorological Handbook No. 11, Doppler Radar Meteorological Observations-Part B, Doppler Radar Theory and Meteorology. Report FCH-H11B-1990, Interim Version One. Rockville, Maryland. Department of Commerce, NOAA. Washington, D.C.

Rinehart, R.E., 1991; *Radar for Meteorologists*, Second Edition. Knight Printing Company, Fargo, North Dakota.

Rogers, L.T., Hattan, C.P., and Stapleton, J.K., 2000; Estimating Evaporation Duct Heights from Radar Sea Echo. *Radio Scienc*e, **35**, No. 4, 955-966.

USS Port Royal Naval Message, Subject: Modernizing METOC Support to the Surface (AEGIS) Warfighter Conference, 020400Z Mar 01.

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