TECHNICAL DOCUMENT 3326
August 2018

Advanced Refractive Effects Prediction System (AREPS) Radar Threshold Model (RTM)

Amalia E. Barrios
Rick Navarro
SSC Pacific

Katherine Horgan
Naval Surface Warfare Center Dahlgren Division (NSWC DD)

Paul Frederickson
Naval Postgraduate School (NPS)

SSC Pacific
San Diego, CA 92152-5001

SSC Pacific
San Diego, California 92152-5001

M. K. Yokoyama, CAPT, USN
Commanding Officer

W. R. Bonwit
Executive Director

ADMINISTRATIVE INFORMATION

The work described in this report was performed for PEO C4I/PMW-120 by the Office of Sponsor by the Atmospheric Propagation Branch (Code 55280) of Networks Division (Code 55200), Space and Naval Warfare Systems Center Pacific (SSC Pacific), San Diego, CA. Further support was provided by Naval Surface Warfare Center Dahlgren Division, and Naval Postgraduate School .

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ACRONYMS

A2AD	Anti-access and Area Denial
APAR	Active Phased Array Radar
APM	Advanced Propagation Model
AREPS	Advanced Refractive Effects Prediction System
CMS	Combat Management System
COAMPS	Coupled Ocean/Atmosphere Mesoscale Prediction System
CWP	Coalition Warfare Program
ECMWF	European Centre For Medium-Range Weather Forecasting Model
EDH	Evaporation Duct Height
EM	Electromagnetic
EMW	Electromagnetic Warfare
EMSPPA	Electro Magnetic Spectrum Performance Products Ashore
METOC	Navy Meteorology and Oceanography
MoE	Measures-Of-Effectiveness
N2N6E	Oceanography, Space and Maritime Domain Awareness Directorate
NAVSLaM	Naval Atmospheric Vertical Surface Layer Model
NITES	Naval Integrated Tactical Environmental Subsystem
NPS	Naval Postgraduate School
NSWC DD	Naval Surface Warfare Center, Dahlgren Division
NWP	Numerical Weather Prediction
ONR	Office Of Naval Research
OPNAV	Office of the Chief of Naval Operations
PAR	Phased Array Radar
PoD	Probability Of Detection
RDT&E	Research Development Test and Evaluation
RF	Radio Frequency
RMSE	Root Mean Square Error
RNLN	Royal Netherlands Navy
RTM	Radar Threshold Model
RTP	Rapid Transition Project
SST	Sea Surface Temperature
TDA	Tactical Decision Aid
US-NL	U.S.-Netherlands

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1. INTRODUCTION

1.1 OVERVIEW

This technical document is an end-of-year report for Space and Naval Systems Center Pacific (SSC Pacific), Office of Naval Research (ONR) 32 funded Advanced Refractive Effects prediction Systems (AREPS) Radar Threshold Model (RTM) testing effort.

The methodology discussed in the document includes a greatly improved algorithm that increases the overall efficiency of determining a Phased Array Radar (PAR)'s performance when compared to current algorithms employed within the AREPS.

1.2 LONG TERM GOALS

Improve and validate the radar propagation/threshold modeling capability in AREPS. The AREPS is a tactical decision aid containing models and algorithms which are being considered for transition to Office of the Chief of naval Operations (OPNAV) Oceanography, Space and Maritime Domain Awareness Directorate (N2N6E)'s/PMW-120's Naval Integrated Tactical Environmental Subsystem (NITES)-NEXT program of record. NITES-NEXT is the primary Navy Enterprise software tool being fielded afloat and ashore for Navy operators to produce and disseminate assessments and planning forecasts based on Navy Meteorology and Oceanography (METOC) conditions to support Fleet warfighters.

1.3 OBJECTIVES

This was a one-year follow-up effort of the AREPS radar threshold model enhancement project, that took place under the U.S. Netherland (US-NL) Coalition Warfare Program (CWP) in FY14. The specific objectives for this performance period were:

1. Supported the Royal Netherlands Navy (RNLN) in integration of the Advanced Propagation Model (APM), within the RNLN's Combat Management System (CMS) or prototype application specifically for use by the RNLN.
2. In collaboration with the RNLN, obtained and completed analysis of METOC and Radio Frequency (RF) propagation data collected during the Joint Warrior 15–2 trial that occured October 2015, hereafter called Phase 2.
3. Improved the Naval Atmospheric Vertical Surface Layer Model (NAVSLaM) for coastal areas.
4. Investigated compression techniques for numerical weather prediction (NWP) forecasts. The typical data volume of NWP makes it hard to distribute through satcom. With the use of lossy compression, NWP data was scaled down to acceptable proportions. Performed follow-up research (the goal was to focus on a tradeoff between data volume, data quality, and computation time for (de)compression).

2. APPROACH

SSC Pacific provided technical support to the RNLN for integration of the APM into their CMS. Technical support also supported a prototype software application for providing RF performance. products. This support included performing software modifications for unforeseen bugs or manipulation of NWP data not originating from the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS).

The RNLN shared RF and METOC data collected during the Phase 2 trial. U.S. participants analyzed and documented the results.

The focus of the Naval Postgraduate School's (NPS) work as part of this collaborative effort was to improve the performance of the Navy Atmospheric Vertical Surface Layer Model (NAVSLaM) in characterizing the evaporation duct in coastal areas. The ultimate goal was to improve radar and electromagnetic (EM) system performance predictions for U.S. Navy warfighters when operating in littoral regions. In collaboration with the RNLN, NPS investigated techniques to better characterize the evaporation duct and its development near coastal areas. Much of this work was based on data collected during the US-NL CWP Phase 1 campaign.

The RNLN was already investigating the problem of providing NWP fields in a timely manner, and with sufficient resolution, to shipboard personnel. SSC Pacific and the Naval Surface Warfare Center, Dahlgren Division (NSWC DD) collaborated with the RNLN to investigate data compression techniques to provide similar capabilities to the USN.

3. WORK COMPLETED

Considerations: Partial funding for the AREPS RTM project arrived to all performers during Q1 and Q2. Due to delays in receiving the remaining funds, all performers continued their respective efforts through the end of CY17, coinciding with the end of the period of performance.

3.1 APM SUPPORT

The APM v5.3 executable library was delivered to the RNLN in July 2017. The RNLN provided their prime contractor, TNO, the APM library for integration into the Computer-Aided Radar Performance Evaluation Tool (CARPET). TNO is the developer of CARPET and is the RNLN's primary RF tactical decision aid (TDA). As mentioned in Section 2, SSC Pacific provided technical support and assistance, as needed, for the integration through the end of the expiration date of the US-NL AREPS Project Agreement on 10 Sep 2017.

The measures-of-effectiveness (MoE) algorithm developed for improved radar threshold modeling techniques was incorporated into our regular process for radar detection. This was tested and finalized within SSC Pacific's in-house research tool. The model description and results are documented in a SSC Pacific's technical report 3079 (Barrios, 2017).

3.2 PHASE 2 ANALYSIS

Analysis was completed on the Phase 2 sea surface temperature (SST) data collection.

Three sources of SST were logged during the three-week operating period of the Phase 2 exercise:

1. Shipboard seawater intake temperature
2. Infrared (IR) gun readings
3. Hull-temperature sensor readings.

Intake temperature was manually logged by the ship's crew on the hour and was used to feed the CARPET radar performance tool within the RNLN's CMS. Handheld IR readings were collected as the most-accurate available measurements. The hull SST sensor was chosen to ensure that a passive SST reading was recorded even at times when it was unsafe or disallowed to take manual readings topside on deck. Time windows were chosen to subset the data and SST values. Values were compared for each region.

CONOPS for Phase 2 involved constant generation of performance predictions using the AREPS application. Generation of these performance predictions required a combination of regular NWP forecasts provided by NSWCDD, correct radar system parameters, and the current ship position to feed into the AREPS. Comparing these predictions to the recorded tracks on the shipboard CMS system, It was possible to test the efficacy of the RTM in predicting the performance of the Active Phased Array Radar (APAR) and similar advanced phased-array radar systems.

During the exercise two complications prevented the real-time performance analysis of the models:

- The ship's position was not readily available
- The onboard laptop used to test was not populated with the correct radar parameters.

Despite these issues useful data was collected including:

- In-situ data collected manually and through ship systems, surface layer parameters, radiosonde measurements.
- SST RF propagation factor and loss recorded from the ships CMS, sanitized to 20 confirmed tracks (6 with complete data) on scheduled exercise target events and targets of opportunity.

3.3 NAVSLaM ENHANCEMENTS FOR COASTAL AREAS

Two factors impacted the spatial variation of the evaporation duct across a coastal region with onshore winds. Additionally, there was shallowing of the water from the open ocean to the beach, and enhanced sea spray in the surf zone. These issues lead to enhanced sensible and latent heat fluxes due to the evaporation of spray droplets and heat and moisture transfer at the surface of the spray droplets. The shallowing water lead to increased surface roughness, as parameterized by the Charnock parameter, which says it is more difficult for the wind and wave fields to come into equilibrium with each other in shallower water. Experiments using the NAVSLaM model with increasing Charnock parameter values to reflect the shallowing water from the open ocean to the beach did not demonstrate a significant enough impact on the evaporation duct height (EDH) to justify continued testing in this area.

To examine the potential impact of sea spray on the evaporation duct, the NPS used the bulk flux model developed by Edgar Andreas, Mahrt, and Vickers (2012), which includes the Andreas sea spray model described in Andreas Persson, and Hare (2008). Enhanced sea spray in the surface layer was expected in surf zones near the ocean-land interface, as well as in high wind conditions in the open ocean. The adoption of a sea spray model into NAVSLaM therefore had the potential to improve the model for both high-wind, open-ocean conditions, and coastal applications.

Andreas stated in his notes provided with the model code that his sea spray model is linked to and must be used in conjunction with his bulk flux algorithm. Taking this into consideration, it was determined that it could not be easily attached to different bulk flux models for testing being conducted. For this reason, the NPS although they initially decided to use the Andreas model, later use of the model was questioned whether using it was worth the effort to carefully incorporate the Andreas sea spray model into NAVSLaM. The Andreas bulk model only computes air-sea fluxes, and not the required vertical profiles of temperature, humidity and pressure needed to evaluate data tested for this report. It was determined that the NPS needed to fuse the vertical modified refractivity profile and EDH determination portions of NAVSLaM (but not the actual surface flux portion) from the Andreas bulk flux and sea spray model.

3.4 NWP MODEL COMPARISONS

A comparison of COAMPS and the European Centre for Medium-Range Weather Forecasting Model (ECMWF) predictions were performed using radiosonde measurements as truth data. Both exploratory data analysis techniques as well as quantitative statistical techniques were employed to assess the performance of the two models. The analysis revealed over-prediction, under-prediction and overall error trends in the models. Evaluating COAMPS and ECMWF is imperative for radio frequency prediction, because the environmental information from these numerical weather prediction (NWP) models is an essential factor in determining radio frequency propagation.

4. DATA COLLECTION AND ANALYSIS METHODS

4.1 CONSIDERATIONS

In order to obtain truth data to evaluate the models, radiosonde measurements were taken from a boat traveling in the North Sea during the Joint Warrior 15 – 2 NATO exercise. The radiosondes analyzed in this report were released on eight different days in the beginning of October 2015. Numerical weather prediction forecasts from COAMPS and ECMWF were obtained for a grid of latitudes and longitudes that encompassed the area in which the radiosondes were launched.The nearest neighbor numerical weather prediction grid location from the radiosonde location was used for comparisons.

Single profiles at these coordinates of the following variables were plotted as a function of geometric height using data from both models and the radiosondes these included:

- Water Vapor Mixing Ratio
- Potential Temperature
- Modified Refractivity

For further analysis, the heights from COAMPS and ECMWF within 5 meters of the radiosonde measured heights were selected in order to perform the statistical comparison. The water vapor mixing ratio, potential temperature, and modified refractivity at the selected heights were compared to the corresponding parameters from the radiosonde measurements. Residuals of these chosen parameters were calculated for each model with the following equation.

$$residual = parameter_{radiosonde} - parameter_{model}$$

The residuals from data taken over eight different days were plotted versus height. The residuals were averaged over time and plotted with height as was the average root mean square error.

5. RESULTS

5.1 IMPROVED RTM

A methodology to improve radar performance prediction for a phased array radar (PAR) were completed and documented (Barrios, 2017). This method maximizes re-use of propagation modeling results from the APM and incorporates multiple waveforms and scan parameters from a PAR. The method discussed in (Barrios, 2017) establishes a fundamental baseline upon which more sophisticated waveforms and operational scan modes can be applied. One of the obstacles in realizing this scheme is obtaining the information regarding a PAR's configuration. The methodology discussed in the report is a greatly improved algorithm that increases the overall efficiency of determining a PAR's radar performance when compared to current algorithms employed within the AREPS.

An example of a 90% probability of detection (PoD) area coverage for a PAR with two operational scan modes, using coherent processing is shown in Figure 1. The environment is a COAMPS-generated forecast. The target height is 6 meters and its mean RCS is 10 dBsm. The methodology developed employs all applicable fluctuation models, or Swerling cases, to determine the final area coverage. For a coherent processing PAR, only Swerling cases 1 and 3 are applicable. The detection ranges illustrated in red and green indicate the detection coverage using both Swerling cases (red) and one Swerling case (red and green).

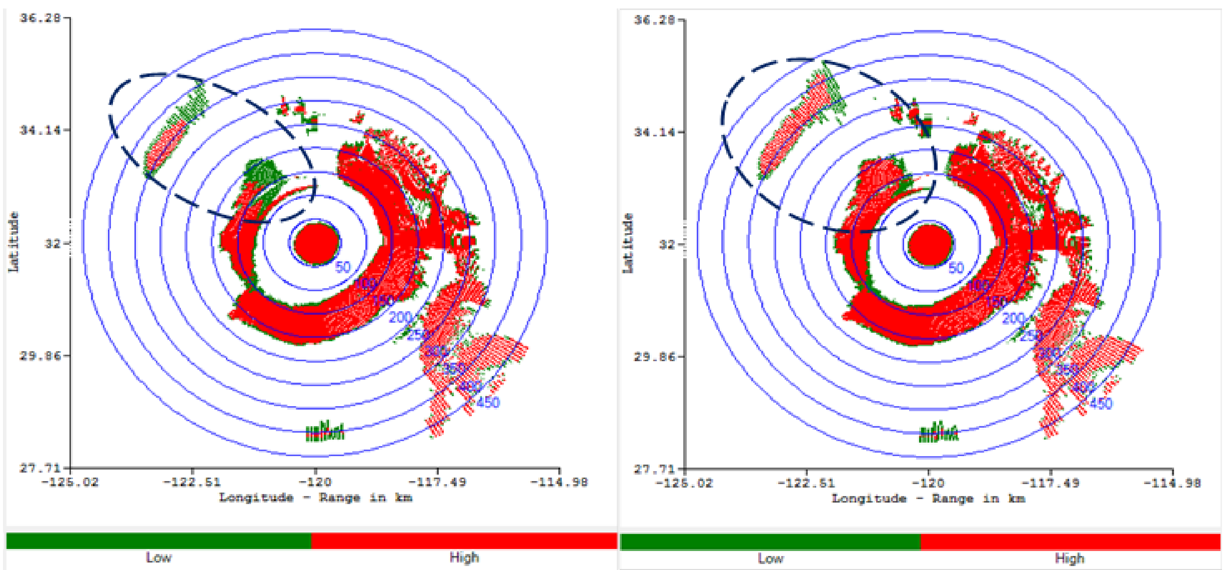

Figure 1. 90% PoD area coverage for Mode 1 (left) and Mode 2 (right) at a target height of 6 meters (19.7 feet).

An example for a PAR using non-coherent processing is shown in Figure 2, where all other parameters are identical as in the coherent processor case. For this example, all four Swerling cases are employed and the resulting area coverage is depicted with low/medium/high indicating common detection ranges by the various fluctuation models.

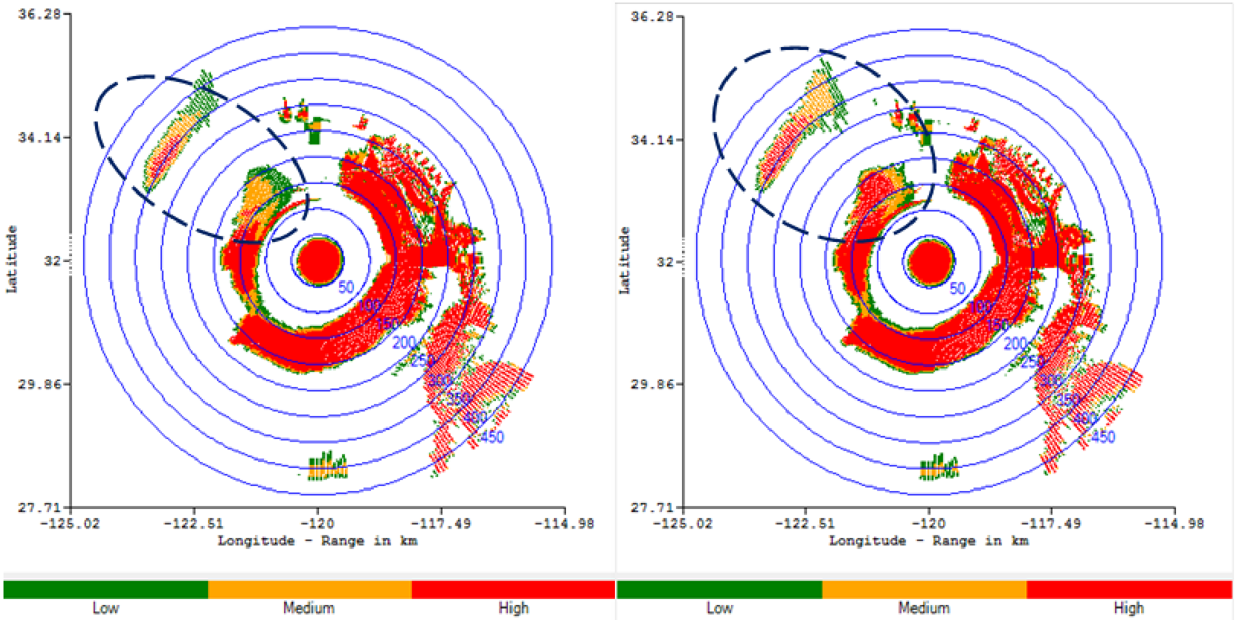

Figure 2. 90% PoD area coverage for Mode 1 (left) and Mode 2 (right) at a target height of 6 meters (19.7 feet) for a non-coherent PAR.

5.2 PHASE 2 ANALYSIS

Figure 3 shows SST collected, as a function of time, from the various sources for the three-week measurement period.

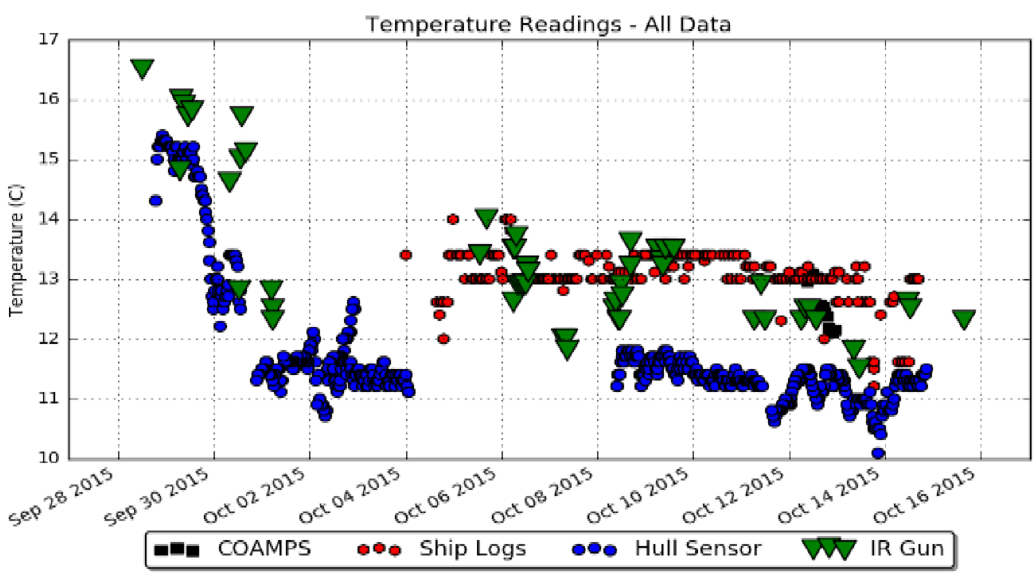

Figure 3. SST data collected during Joint Warrior 2015-2 (total readings/time interval). Handheld infrared readings (59, intermittent), seawater Intake (226, 1 hour), in-hull sensor (661, .5 hours).

Figure 4 shows a subset of the SST data. In Figure 4, a strong correlation suggests a strong linear relationship corresponding to a local temperature bias of ~1.07 degrees C. This bias value appears almost uniformly across all calculated regions for these data where both IR and hull SST data exist.

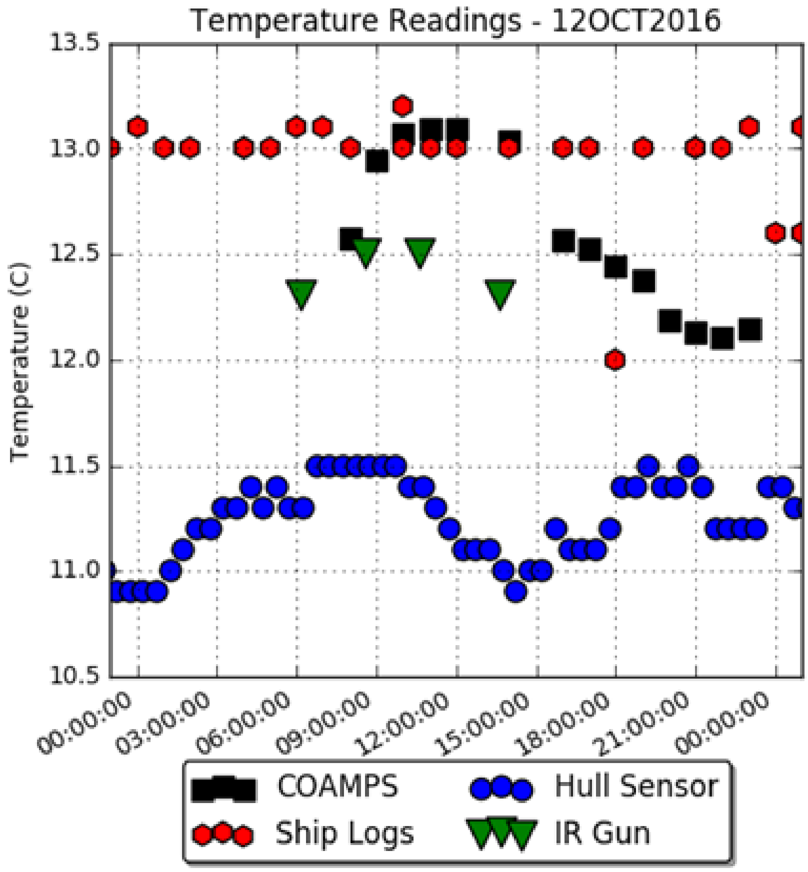

Figure 4. SST data for 12OCT2015. Low variation in ship logs (seawater intake). Hull sensor reading and COAMPS predictions follow IR trend. Correlation coefficient 0.822, Temperature Bias 1.0701 degrees.

Although the initial results are promising, the through-hull method of SST capture required further testing. It is recommended that future tests incorporate regular automated IR SST measurements recorded over longer periods of time. To further test this dataset, the results of this analysis were used to complete the Phase 2 RF analysis. Preliminary results were presented at 2017 National Radio Science Meeting.

This Phase 2 post-analysis was conducted a live exercise to produce a validation scorecard for all available radar tracks provided by the RNLN. Performance predictions were generated using available COAMPS NWP forecasts and estimated ship position to determine radar detection ranges for each of the recorded radar tracks. An example track is shown in Figure 5, with predicted detection range shown in Figure 6. Similar performance predictions were generated using in-situ measurements easily obtained on ship to estimate RTM performance in operational environments that are bandwidth-limited.

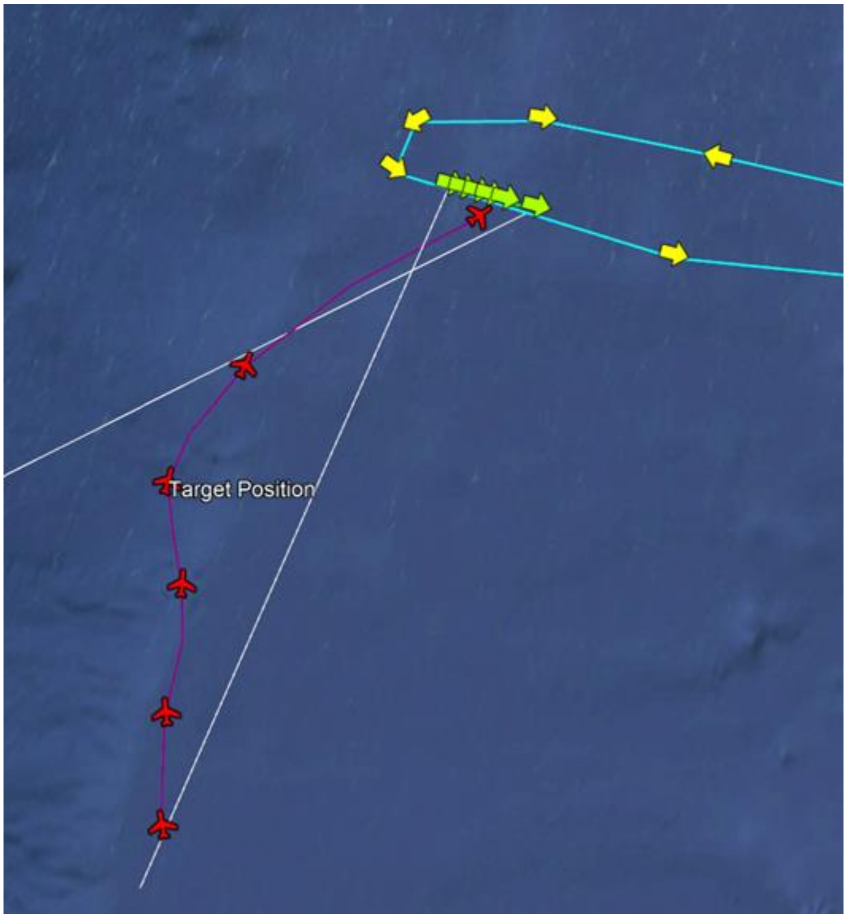

Figure 5. Track 100 - recorded closing radar track on sensor platform HNLMS De Zeven Provincien (yellow/green arrows) corresponding to recorded closing run of a Hawk T1 Training Jet. This target was detected at 74 kilometers with an elevation of 100 meters.

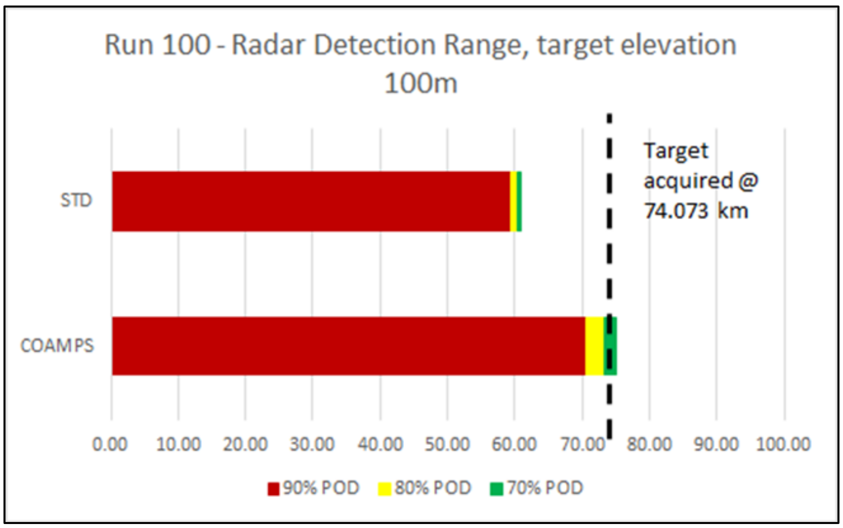

Figure 6. Radar detection range calculated for a small jet closing at an altitude of 100 meters, geometry shown in Figure 5.

5.3 NAVSLAM ENHANCEMENTS FOR COASTAL AREAS

Multiple runs with different wind speed and relative humidity values were performed with the fused Andreas-NAVSLaM model to compare EDH results when the combined model was run both with and without the sea-spray model activated. The results of these model runs are shown in Figure 7.

These results show that for wind speeds below about 15 m/s, the inclusion of the sea-spray model had a small impact on the resulting EDH estimates. Above 15 m/s the sea-spray model had an increasingly large impact on the EDH estimates, especially with lower values of the relative humidity. The inclusion of sea spray impacts with a wind speed of 30 m/s increased the modeled EDH by about a factor of two for both the low and high humidity cases examined. For the lower relative humidity case (70%), the EDH increased from 13.3 meters to 27.8 meters, and for the high humidity case (90%) the EDH increased from 6.5 meters to 14.2 meters. These changes due to including sea spray effects had a highly significant impact on radar performance predictions. These results indicate that enhanced sea-spray impacts are indeed significant with high winds and consideration should be made to incorporating the Andreas sea spray model into NAVSLaM. Note that this made the model much more complicated and slowed its execution.

Application in a coastal zone, a mechanism will need to be developed to translate the modeling of enhanced sea spray in high winds to enhanced sea spray in a surf zone, regardless of wind speed. Different methods to do this are being evaluated.

Work on this project for the work completion date of 31 December 2017 included validating the combined Andreas-NAVSLaM model with actual observations. Data collected during CASPER-EAST was examined, and the concurrent in situ meteorological and propagation data was evaluated that was collected during an at-sea experiment off the coast of Den Helder, The Netherlands, in September 2014. The impact of employing the combined Andreas-NAVSLaM model with NWP model forecasts, such as from the NRL's COAMPS, was evaluated in a coastal area.

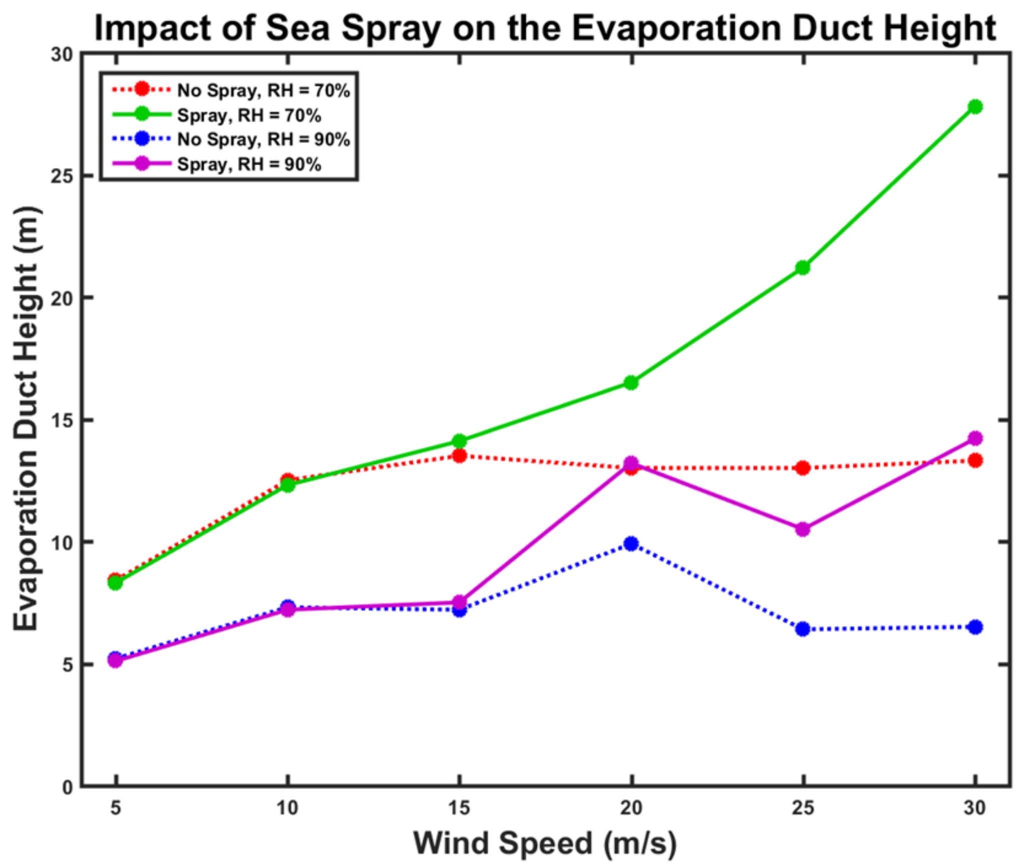

Figure 7. Evaporation duct height, computed by the combined Andreas-NAVSLaM model, versus the wind speed, for no-spray and spray model options and different values of the relative humidity (70% and 90%), as indicated.

5.4 NWP MODEL COMPARISONS

A visual inspection of the modified refractivity, potential temperature, and water vapor mixing ratio profile plots allowed for an initial comparison of COAMPS and ECMWF. Both ECMWF and COAMPS did not always capture the features of the modified refractivity profile, failing to capture ducting features at times. The potential temperature calculated from ECMWF data, however, appeared closer to the radiosonde's potential temperature than was the potential temperature determined from COAMPS data. Examining the water vapor mixing ratio plots did not provide a definitive answer as to the greater accuracy of the models.

Plots of the residuals and the root mean square error (RMSE) revealed prediction trends in the models. For instance, graphs of the residuals vs. height in Figures 8 and 9 show that COAMPS modified refractivity and water vapor mixing ratio residuals form vertical bands around zero, displaying equal variance in error. Figures 8 and 10 indicate that the modified refractivity and the potential temperature calculated from the ECMWF data became increasingly inaccurate with increasing height. The same trend was seen in the COAMPS modified refractivity and potential temperature residuals, but COAMPS potential temperature exhibits larger errors at the initial heights. Hence, the thermodynamics used to determine the potential temperature were examined. The pressure data were seen to have the same relationship of increasing inaccuracy with increasing height. Further examination will have to be made of the ECMWF equations used to model the pressure and height in order to identify the underlying issue.

The number of residuals greater and less than zero were determined and exhibited over-prediction and under-prediction trends in the models. Table 1 presents the prediction results. Overall, modified refractivity, water vapor mixing ratio, pressure, and temperature from ECMWF data tended to be over-predicted. When COAMPS data was used, potential temperature and temperature tended to be over-predicted while a greater percent of the pressure predictions tended to be under-predicted.

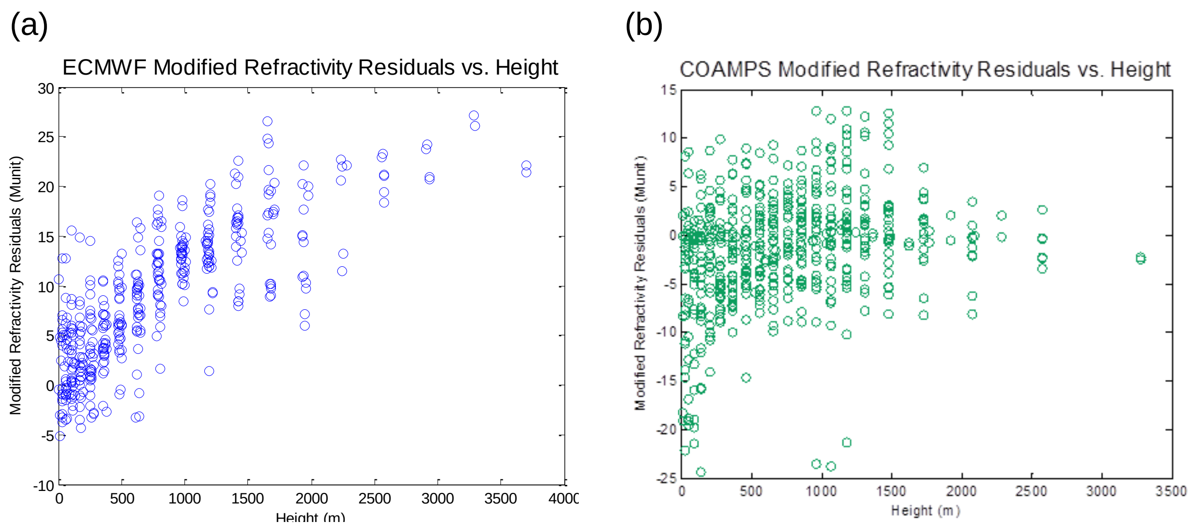

Figure 8. From left to right: (a) ECMWF Modified Refractivity Residuals, (b) COAMPS Modified Refractivity Residuals.

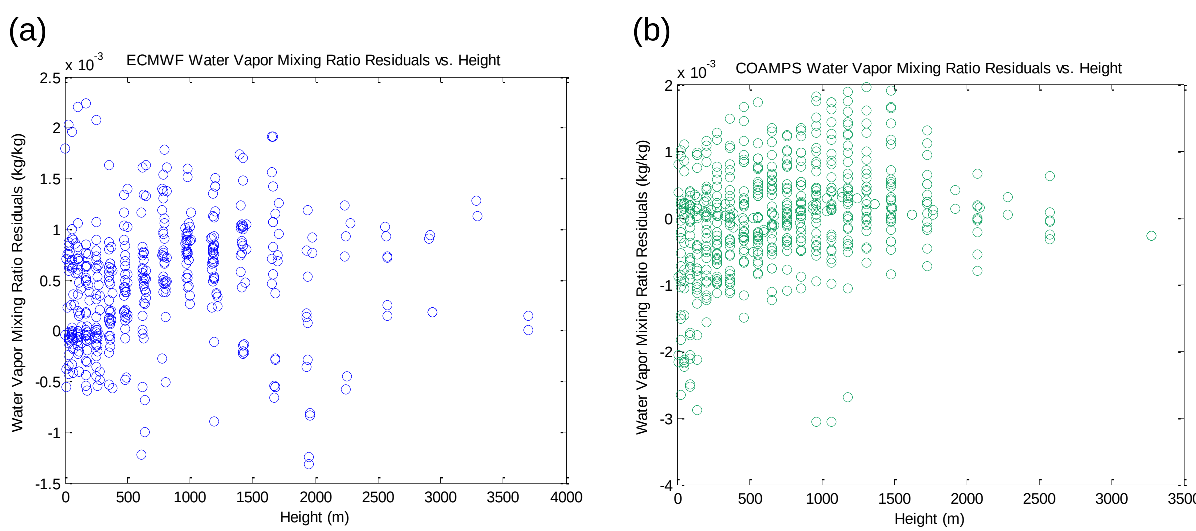

Figure 9. From left to right: (a) ECMWF Water Vapor Mixing Ratio Residuals, (b) COAMPS Water Vapor Mixing Ratio Residuals.

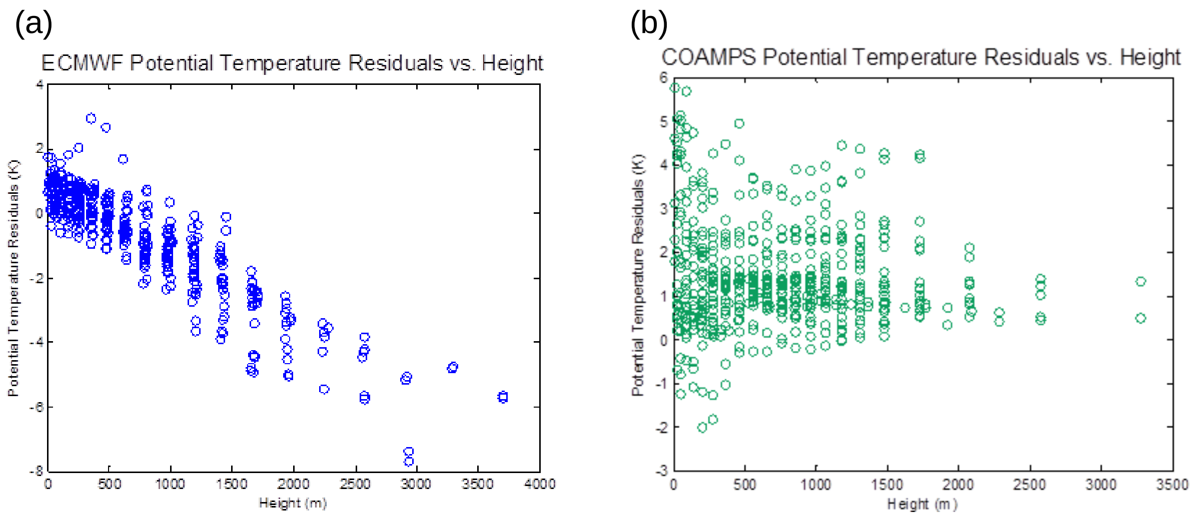

Figure 10. From left to right: (a) ECMWF Potential Temperature Residuals, (b) COAMPS Potential Temperature Residuals.

The RMSE of the modified refractivity and water vapor mixing ratio are shown in Figures 11 and 12, respectively. The mean bias of the modified refractivity for both COAMPS and the ECMWF models are shown in Figure 13.

Comparing the data from COAMPS and ECMWF to each other using the radiosonde measurements as truth data provided insight into the limits of both NWP models. The ECMWF modified refractivity and potential temperature was seen to become increasingly inaccurate with increasing geometric height. COAMPS potential temperature, however, had larger residuals than ECMWF. Both models failed to predict some of the features of modified refractivity profiles. Assessments of how these errors in modified refractivity affect the resulting RF propagation output were assessed.

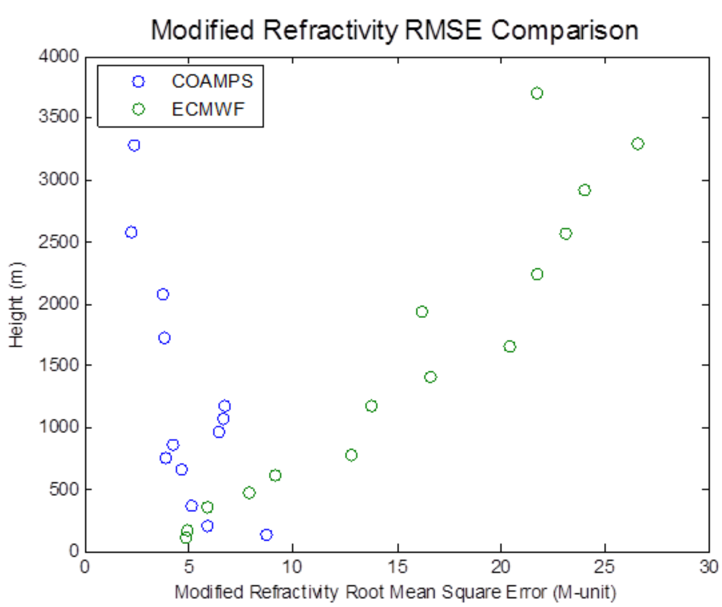

Figure 11. Modified refractivity RMSE.

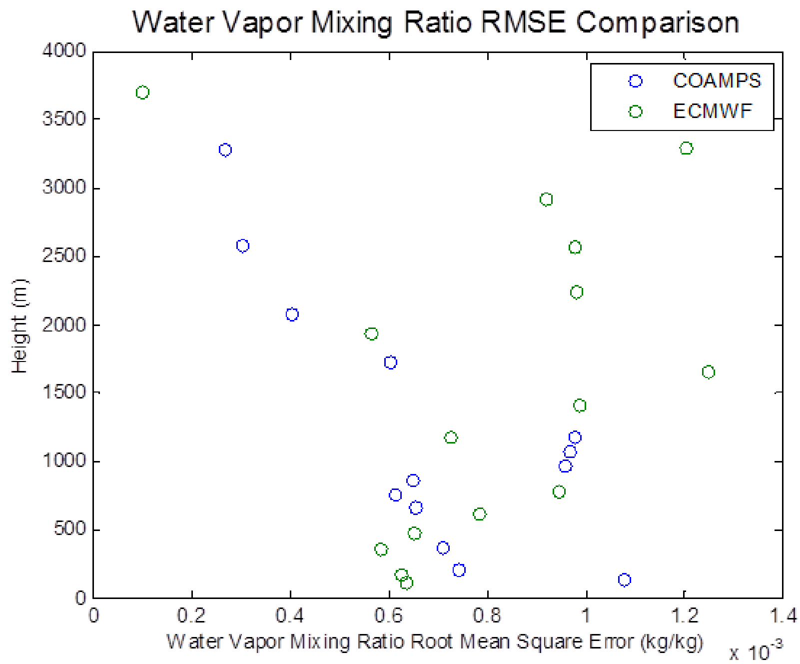

Figure 12. Water vapor mixing ratio RMSE.

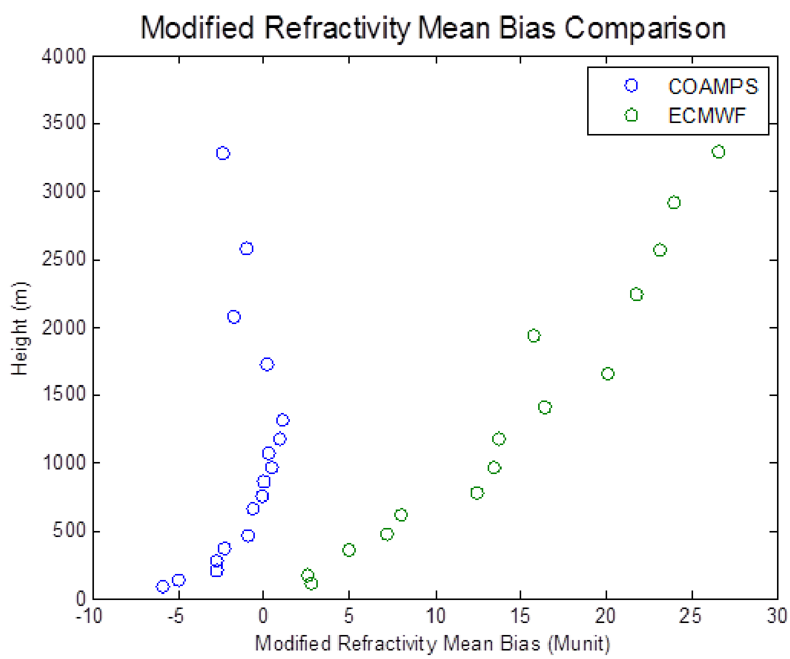

Figure 13. Modified refractivity mean bias.

COAMPS and ECMWF residuals comparison is shown on Table 1.

Table 1. COAMPS and ECMWF residuals comparison.

	ECMWF		COAMPS	
Parameter	Percent of Residuals > 0 (%)	Percent of Residuals < 0 (%)	Percent of Residuals > 0 (%)	Percent of Residuals < 0 (%)
Potential Temperature	38.4798	61.5202	95.5197	4.4803
Modified Refractivity	88.5986	11.4014	41.5771	58.4229
Water Vapor Mixing Ratio	75.0594	24.9406	54.6595	45.3405
Temperature	97.6247	2.3753	94.8029	5.1971
Pressure	96.9121	3.0879	32.4373	67.5627
Relative Humidity	60.095	39.905	30.4659	69.5341

6. IMPACT APPLICATIONS

The primary payoff of this task was the evaluation of the ability to automate the detection and counter-detection performance predictions with an improved radar threshold model, specifically for phased array radars. The improved RTM, along with the APM, should be used for maximum efficiency.

7. RECOMMENDATIONS

Specific research and development areas addressed in our testing are (from the FY17 N26E Research Development Test and Evaluation (RDT&E) Priorities Letter):

- Collaborate across the Navy Information Warfare Community to develop techniques to fuse the predicted environment with organic CSG/ARG and theater or national assets to improve operational situational awareness and to enable the Fleet's current capacity to deliver Electro magnetic Warfare (EMW) decision superiority in permissive and Russia's anti-access areal denial (A2AD) environments.
- Accelerate development of EM models that deliver an operational (vs. point-to-point) assessment of realistic sensor or weapon seeker performance due to daily changing atmospheric conditions.

8. RELATED PROJECTS

Algorithms, applications and TDA products developed under this task and intended for operational use are earmarked for transition into the Naval Integrated Tactical Environmental Subsystem NITES-Next EM module, PE 0603207N, and should transition into other propagation assessment systems. It is also recommended that propagation models and algorithms developed under this task and intended for operational use should transition to the EM Spectrum Performance Products Ashore (EMSPPA) Rapid Transition Project (RTP).

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-01-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
August 2018	Final	

4. TITLE AND SUBTITLE

Advanced Refractive Effects Prediction System (AREPS)
Radar Threshold Model (RTM)

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHORS

Amalia E. Barrios
Rick Navarro
SSC Pacific

Katherine Horgan
Naval Surface Warfare Center Dahlgren Division (NSWC DD)

Paul Frederickson
Naval Postgraduate School (NPS)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

SSC Pacific
53560 Hull Street
San Diego, CA 92152–5001

8. PERFORMING ORGANIZATION REPORT NUMBER

TD 3326

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

PEO C4I / PMW-120
4301 Pacific Highway OT-01
San Diego, CA 92110-3127

10. SPONSOR/MONITOR'S ACRONYM(S)

PMW-120

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This technical document is an end-of-year report for Space and Naval Systems Center Pacific (SSC Pacific) by the Office of Naval Research (ONR) 32 funded Advanced Refractive Effects prediction Systems (AREPS) Radar Threshold Model (RTM) testing effort.

The methodology discussed in the report includes a greatly improved algorithm that increases the overall efficiency of determining a PAR's radar performance when compared to current algorithms employed within the AREPS.

15. SUBJECT TERMS

Active phased array radar; advanced propagation model; combat management system; COAMPS; coalition warfare program; electromagnetic warfare; NITES

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Rick Navarro
					19B. TELEPHONE NUMBER *(Include area code)*
U	U	U	U	25	(619)-553-1422

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SSC Pacific
San Diego, CA 92152-5001