Passive Microwave Data Exploitation via the NRL Tropical Cyclone Webpage

A proposal submitted to the:
National Oceanic and Atmospheric Administration (NOAA)
Joint Hurricane Testbed (JHT)
Funding Opportunity Number: NOAA-OAR-OWAQ-2015-2004200

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Submitted: December 5, 2014

Year 1 Requested Funds: $89,800
Year 2 Requested Funds: $90,344
Total Requested Funds: $180,144

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Abstract

Near-realtime information from polar orbiting satellite passive microwave imagers and sounders critically enhances the operational monitoring of tropical cyclone (TC) structure and the surrounding environment. Observations by microwave frequencies interrogate the internal microphysical structure of the TC that cannot be seen with conventional (visible and infrared) imagery. The Naval Research Laboratory's (NRL) TC webpage has demonstrated the ability to provide essential TC passive microwave data through near-realtime web distribution since 1997. Since many of the NRL TC web products were first developed, the goals and needs of the operational TC community has evolved.

The following proposal provides for these upgraded needs by suggesting multiple upgrades to the passive microwave imagery products on the NRL TC webpage. There are four related projects that are proposed:

1. Enhancement of the near-realtime 37 and 85/89/91 GHz H/V/PCT/color imagery products for all global TCs is proposed. This includes recalibration of the ice scattering channels to 89 GHz to reduce bias between sensors, Backus-Gilbert remapping of SSM/I and SSMIS data (the sensors with the coarsest spatial resolution), and ARCHER recentering. A streamlined and cleaner python based processing and plotting will be used.
2. To complement the above upgrades, this section aims to populate an archive of historical passive microwave data since 1987. Using a similar methodology as in the near-realtime upgrades, a standardized database of both digital data and image products will be generated and made available to the TC community to compliment the near-realtime data.
3. Parallax of the storm based on feature heights and sensor scan angle can misrepresent the TC position. A study and application of a more sophisticated parallax correction scheme is proposed to provide increased confidence in the initialization of the TC center.
4. The color tables used to visualize the TC were subjectively developed based on a small sample of cases observed by the SSM/I. Resolution and frequency changes since that time necessitate an expanded and quantitative revisiting of this visualization.

Multiple forecast priorities from the funding opportunity announcement are identified:

- NHC-2/JTWC-2. Improved capability to observe the tropical cyclone and its environment to support forecaster analysis and model initialization.
- NHC-4/JTWC-9. Enhancements to the operational environment (e.g., ATCF, AWIPS-II) to increase forecaster efficiency, by expediting analysis, forecast, coordination, and/or communication activities.
- NHC-15/JTWC-3. Techniques to improve the utility of microwave satellite and radar data for tropical cyclone intensity and location analysis (e.g. develop a "Dvorak-like" technique using microwave imagery).

STATEMENT OF WORK

1. Project Duration

This proposal requests two years of funding to provide enhancements to the real-time tropical cyclone (TC) satellite products on the Naval Research Laboratory (NRL) TC webpage, which provides global monitoring of all active TCs and "invests" covering all tropical basins and seasons throughout the calendar year.

2. Project Description/Prior Research Results

The Naval Research Laboratory's (NRL) Tropical Cyclone (TC) webpage (http://www.nrlmry.navy.mil/TC.html; (Hawkins et al. 2001) provides global access to products derived from passive microwave imagers and sounders among other information. By incorporating near-realtime data from operational (i.e., SSM/I and SSMIS) and research (i.e., AMSR-E, AMSR2, GMI, TMI, WINDSAT) instruments, operational users are able to better interrogate the structure and intensity of TCs globally. In particular, such imagery displays storm structural evolution of hydrometeor and surface features, providing enhanced ability to diagnose structures that are not seen in visible and infrared channels due to upper-level cloud obscuration. Microwave imagery mitigates this inherent spectral limitation and identifies the presence of the low level circulation, single or concentric eye/eyewalls, and spiral rainband organization. The utility of this data is frequently noted in storm discussions by hurricane specialists at the National Hurricane Center (NHC), typhoon duty officers (TDO) at the Joint Typhoon Warning Center (JTWC) and by the Regional Meteorological Specialized Centers (RMSC) and Tropical Cyclone Warning Centers (TCWC) sponsored by the World Meteorological Organization (WMO).

Archival and climatological calibration of microwave data and improvements in data processing allow for the NRL TC suite of microwave products to be updated, thereby enhancing interpretation and analysis. Cossuth et al. (2015) created an archive of TCs as observed by passive microwave imagery using several standardization steps: 1) The ice scattering channels (i.e., 85, 89, 91 GHz) were recalibrated following Yang et al. (2014) to 89 GHz, reducing error in brightness temperature (T_B) comparisons and matching the planned observing frequency of current and future missions. 2) Sensors with coarser resolution (i.e., SSM/I and SSMIS) were optimally remapped using the Backus-Gilbert technique (Poe 1990) to provide enhanced spatial resolution and a smoother field. 3) The images are centered on the TC using the interpolated best track and refined by ARCHER (Wimmers and Velden 2010) at 89 GHz and 37 GHz.

While inquiries were made to transition these products to the Satellite Services Division of the NOAA National Environmental Satellite, Data, and Information Service (NESDIS), 24/7 upkeep of this data could not be guaranteed. Thus, the following project suggests augmenting the utility of the current NRL TC webpage to the operational TC community by applying the standardization of Cossuth et al. (2015) to the real-time products. Furthermore, several additional improvements are proposed which aim to reduce bias, enhance ease and accuracy of analysis, and facilitate training and climatological analysis of TC position, intensity, and structure.

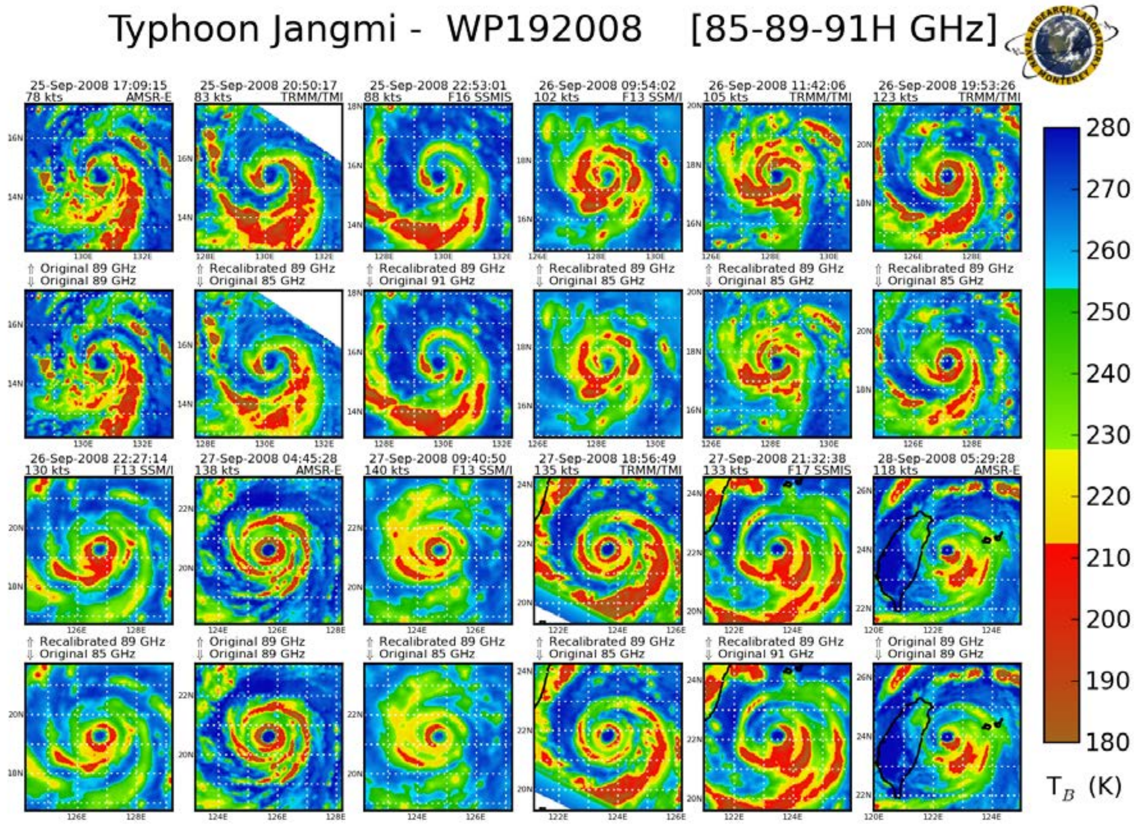

Figure 1: Multi-panel time series of Typhoon Jangmi as imaged by various passive microwave imagers. Note that the $1^{st}/3^{rd}$ rows depict 89 GHz horizontal polarization (with recalibration applied to SSM/I, TMI, and SSMIS data), while the $2^{nd}/4^{th}$ rows show the original frequencies.

a. Enhancement of the NRL TC microwave products suite

The processing and display of passive microwave imagery on the NRL TC webpage will be improved in several ways. Firstly, standardization of the passive microwave imagery – recalibration of the ice scattering channels to 89 GHz, remapping of SSM/I and SSMIS data by Backus-Gilbert optimal interpolation, and recentering using ARCHER – will be applied as post-processing steps as the data are received in near-realtime. Figure 1 shows an example of how this will improve meteorological analysis. The recalibrated images (1^{st} and 3^{rd} rows) mitigate a large portion of brightness temperature (T_B) variation due to frequency differences (2^{nd} and 4^{th} rows). T_B differences can be as large as 7-10 K between frequencies, representing a significant issue for subjective intensity change inferences or via automated objective algorithms attempting to capture intensity variations. After applying these standardization steps, variations in the T_B presentation of the TC will be better correlated to convective strength and microphysical changes rather than changes in observing frequency.

Furthermore, much of the processing code will be incrementally updated from the current proprietary systems (Terascan) to the free Python programming language, thereby reducing complexity and code maintenance and facilitating more efficient updates as new sensors become available. A comparison of the proposed imagery format and the current images is shown in Figure 2. These new images will be produced as PNG files near-realtime display and analysis, as well as netCDF digital data for ingest and quantitative analysis into other systems.

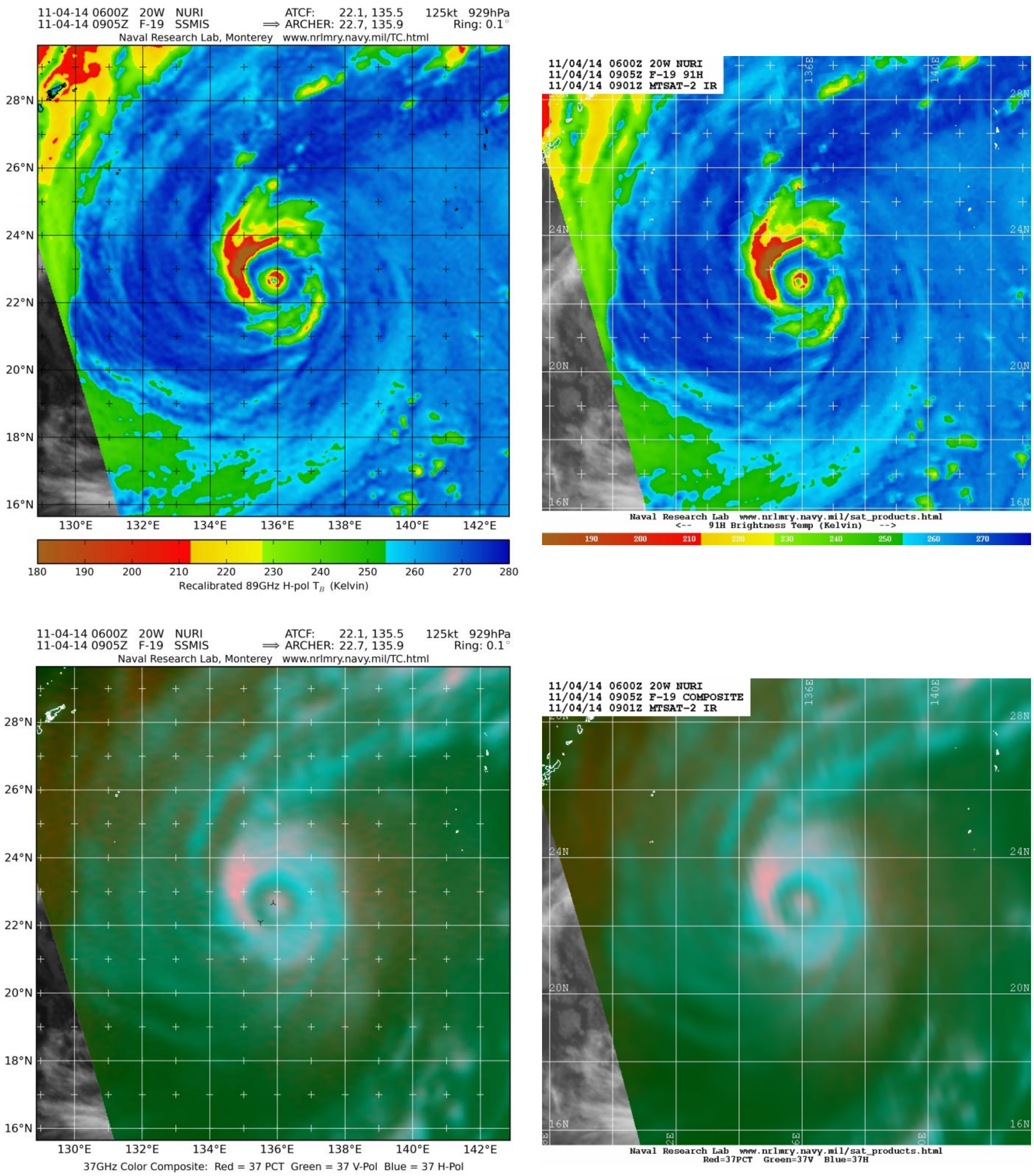

Figure 2: Typhoon Nuri on November 14, 2014 at 0905z from the F19 SSMIS. Images show comparisons of the proposed python figures using the recalibrated, remapped, and recentered data (left column) and the currently available terascan figures (right column). Top row shows the horizontal polarization for the recalibrated 89 GHz (left)/91 GHz (right), while the bottom row displays the 37 GHz color product.

This section proposes to upgrade the 37 and 89 GHz H/V/PCT/color imagery products for all global TCs, given operational forecaster feedback on their utility. Also, a separate text product of ARCHER positioning data can be made available if requested. However, additional information such as rain, wind, vapor, and separate IR and visible channel data may also be provided, depending on interest and need. Additionally, the delivery system is flexible enough to leverage feedback from the JHT committee and POCs to implement further customization (such as zoomed-in multi-panel plots, loops, etc.).

b. Archive of TC-centered upgraded passive microwave digital data and images

NRL TC microwave images are frequently referenced to analyze structure of historical cases. This includes use in best track, TC reports, case study analysis, and model verification. To make the use of microwave data easier and to facilitate quantitative meteorological analysis, this section proposes to make available the climatology of global TCs observed by passive microwave imagery since 1987. Individual netCDF files of digital data for each overpass and reprocessed images for the 37 and 89 GHz H/V/PCT/color imagery products as shown in Figure 2 will be made available via an online ftp archive hosted at NRL.

Such a project can facilitate multiple operational goals. Primarily, the expanded and standardized climatology can help training by providing the entire range of observed cases in an easily comparable format. The extension backward in time of cases can moreover help best track reanalysis efforts, particularly during and prior to the late 1990s when microwave data was not available in real time to all but JTWC. Finally, the availability of digital data allows direct quantitative inter-comparisons to further TC research goals, such as fostering comparisons with NWP case-study output and providing a climatological database and training set for improvements in intensity and structure forecasting. This effort would encompass rapid intensification, weakening events, and eyewall replacement cycles (ERC), a growing topic of interest and study by both the operational and research communities.

c. Development and application of a sophisticated parallax correction scheme

Passive microwave frequencies shown on the NRL TC webpage depict vertically integrated microphysical attributes of the storm structure, specifically ice scattering and liquid water and water vapor emissions. Although these processes occur throughout the troposphere, the positional information is assumed to be at the surface. As shown in Figure 3, the geometric difference between the observed atmospheric signal and the surface location results in a location offset of the TC. The resulting differences can lead to position offsets on the order of 10-20 km. ARCHER (Wimmers and Velden 2010) provides for a simple parallax correction for the TC center based on the subjectively estimated height of the observed atmospheric features in a given frequency, however this is not based on a rigorous analysis.

This section of the project aims to provide a more sophisticated scheme to correct for parallax throughout the image scene. Using a similar methodology to Yang et al. (2014), output from a high resolution TC simulation will be run through a radiative transfer model to allow a comparison of microwave frequency T_B and the heights of TC microphysical structures. A multiple linear regression will be created to correct for the heights of each pixel in a satellite microwave overpass based on the total surface and atmospheric information found in multiple frequencies. Thus, positions of pixels will be individual adjusted based on their radiative profile.

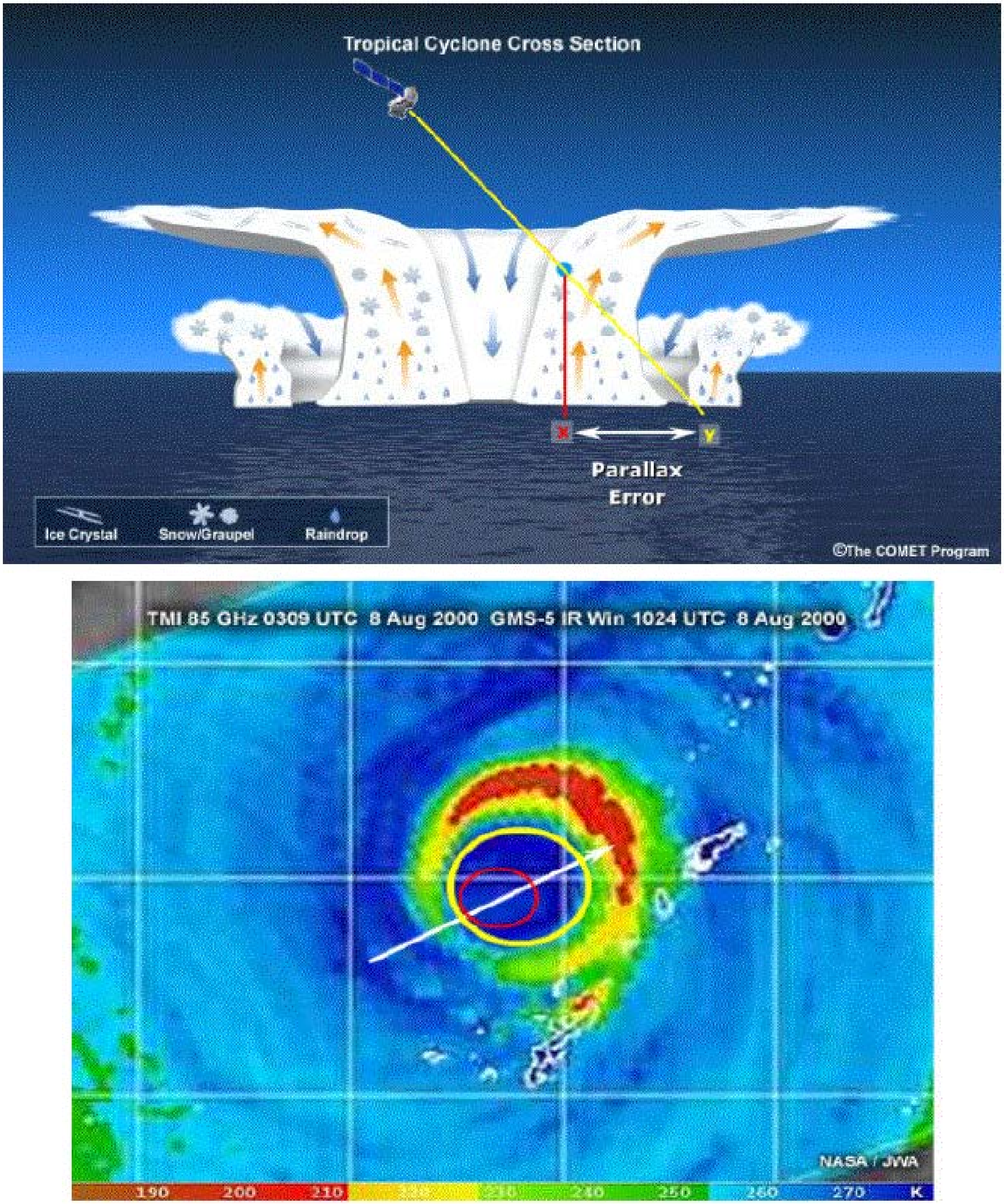

Figure 3: Illustration of parallax error from Lee et al. (2006). In the top figure, the feature imaged above point x (blue dot) is displaced to point y on images. Parallax errors using images from different microwave frequencies are shown in the bottom figure. The red circle represents the eye location from a 37 GHz image (not shown); the yellow circle represents the eye location from the image shown at 85 GHz. The difference in location is based on parallax.

d. Modification of microwave products color tables and break points

The last part of this proposal aims to improve subjective interpretation of TC structure and intensity by producing a rigorous analysis of T_B occurrences in the climatological data from Cossuth et al. (2015). The original NRL color table (Hawkins et al. 2001) was created by subjective analysis of TC features using SSM/I data. However, as seen in Figures 1 and 4, there can be large differences in T_B presentation between SSM/I and newer instruments such as AMSR2. Not only does SSM/I have the coarsest spatial resolution of available near-realtime passive microwave imagers (thus resulting in a higher average T_B signal), but 85 GHz provides a smaller signal for ice scattering than 89 and 91 GHz. As it relates to observation of TC convective strength, lower T_B signals are observed in newer sensors, pushing the limits of the original color table range.

To better relate the image presentation to the observed physical structures, a probability density function of archived, recalibrated T_B data will be created and analyzed for naturally occurring maxima and minima. Using these historically seen values, the break points between colors will be refined to more physically meaningful values. This can help facilitate identification of convective development and decay. Furthermore, an evaluation of the T_B range will be performed to determine if extension of the color table range is necessary, particularly on the lower end of the T_B range. The sensors with the highest spatial resolution, AMSR-2 and TMI, illustrate that 5-6 km spatial resolution can capture T_B values as low as 165K (due to large ice scattering from very heavy convection and the presence of frozen hydrometeors). This is below the 180K used as the "low" point via SSM/I interrogation. The sum of these efforts will allow a better opportunity to interrogate TC structure and streamline the ability for operational forecasters to quickly and accurate assess the TC state.

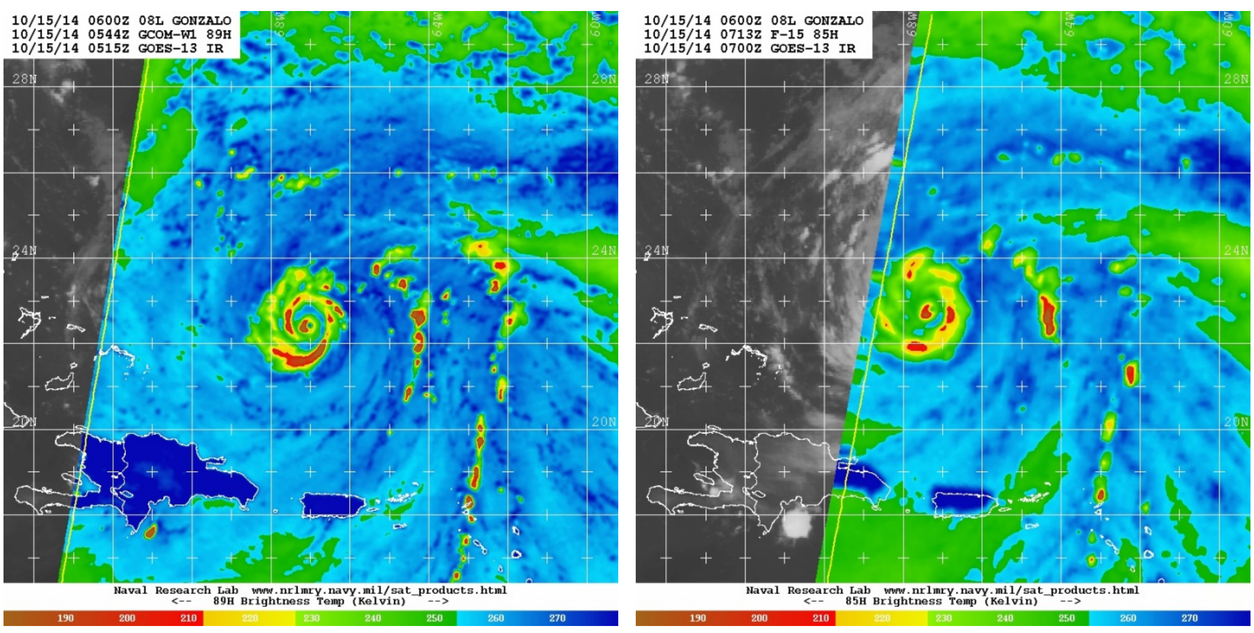

Figure 4: Comparison of two temporally proximate passive microwave images of Hurricane Gonzalo on October 15, 2014. Left image shows an AMSR2 89 GHz horizontal polarization overpass at 0544Z, while the right image shows an F15 SSM/I 85 GHz horizontal polarization overpass at 0713Z. Both images use the same color table and scale. Note the higher spatial resolution and broader use of the color table range (especially at the lowest T_B) in the left image.

References:

Cossuth, J. H., J. D. Hawkins, S. Yang, K. Richardson, J. Solbrig, M. Surratt, A. Wimmers, and C. S. Velden, 2015: Creating a standardized digital climatology of tropical cyclones as observed by passive microwave satellite sensors, in revision for new journal submission.

Hawkins, J. D., T. F. Lee, F. J. Turk, C. Sampson, J. Kent, and K. Richardson, 2001: Real–Time Internet Distribution of Satellite Products for Tropical Cyclone Reconnaissance. *Bull. Amer. Meteor. Soc.*, **82**, 567–578.

Lee, T. F., S. D. Miller, F. J. Turk, J. D. Hawkins, P. Dills, and S. Wang, 2006: Tropical Cyclone Satellite Tutorial Online Through the COMET Program. Preprints, 27th Conf. Hurr. Trop. Meteor., Orlando, FL, Amer. Meteor. Soc., 9A.2

Poe, G.A., 1990: Optimum interpolation of imaging microwave radiometer data. *Geoscience and Remote Sensing, IEEE Transactions on* , **28**, 800-810.

Wimmers, Anthony J. and Christopher S. Velden, 2010: Objectively Determining the Rotational Center of Tropical Cyclones in Passive Microwave Satellite Imagery. *J. Appl. Meteor. Climatol.*, **49**, 2013–2034.

Yang, S., J. Hawkins, and K. Richardson, 2014: The Improved NRL Tropical Cyclone Monitoring System with a Unified Microwave Brightness Temperature Recalibration Scheme. *Remote Sens.*, **6**, 4563-4581.

3. Work Plan

The proposed project consists of multiple operational aid possibilities toward using passive microwave imagery to better analyze TC structure. Depending on perceived need and feedback, different aspects of work and cost for this proposal can be augmented or scaled back. The following work plan assumes the above four proposals are accepted as outlined.

In Year 1, work will begin with the generation of code to process climatological images as outlined in task b and development of climatological statistics for color table analysis and parallax correction and in tasks c and d. An estimated 1 million images will be generated. During the image processing, interaction with the POCs will occur to align the project goals and operational needs. Based on feedback, the climatological images will be evaluated and reprocessed while the code will be modified for real-time application. Additional feedback will be gathered at IHC and AMS conferences and implemented into our procedure. During the summer, the climatological archive will be populated and made available online. Soon after, tests of the data standardization will be made on real-time cases during the northern hemisphere TC peak season. While the ftp archive and real time tests are being evaluated, statistics will be performed on the distribution of T_B occurrence for color table changes.

Year 2 will largely be concerned with tests and evaluations of real-time products and research into parallax correction. While testing of the standardized data will be occurring on the NRL TC webpage, the analysis on statistical T_B occurrence will be applied to different visualization options for amending the color table and range. High resolution case study runs will be performed towards parallax analysis. These results will be discussed with the POCs and their feedback will be implemented and presented at IHC. As the new color table and range is being transitioned to real-time products, statistics will be performed on the parallax case study output. Finally, real-time tests of the color table and parallax applications will occur.

4. Timeline

- Sep 2015: Funding begins
- Sep-Dec: (Tasks a and b) Process historical images and T_B statistics
- Nov: Interact with POCs at NOAA/NHC to assess operational needs
- Jan-Apr 2016: (Tasks a and b) Quality control historical images and test standardization process for transition to realtime datasets.
- March: Present Mid-Year 1 results and collaborate at IHC
- April: Present and collaborate at AMS Tropical Conference
- May: (Task b) Populate ftp archive with climatological netCDFs, images
- Jul-Sep: (Task d) Perform statistical analysis on historical T_B distributions and formulate revised color table and ranges
- Aug-Oct: (Task a) Real-time tests of standardized data on NRL TC webpage
- Sep-Dec: (Task c) Run high resolution TC simulation and process through radiative transfer model
- Nov: Interact with POCs at NOAA/NHC to evaluate updated goals
- Feb-Apr 2017: (Task d) Finalize color table, ranges based on POC/IHC feedback
- March: Present Mid-Year 2 results and collaborate at IHC
- March-May: (Task c) Develop statistics on simulated T_B, feature height parallax
- July-Sep: (Task c and d) Real-time tests of new color tables and parallax correction scheme on real-time NRL TC page images.

5. Schedule and Needs for Expected Travel

- Nov. 2015: Travel to NOAA/NHC to meet with POCs
- March 2016: Travel to the Interdepartmental Hurricane Conference
- April 2016: Travel to the AMS Conference on Hurricanes and Tropical Met.
- Nov. 2016: Travel to NOAA/NHC to meet with POCs
- March 2017: Travel to the Interdepartmental Hurricane Conference

6. Estimates of JHT Staff Requirements

Since this project aims to sustain and expand the currently available NRL TC webpage framework, no new JHT staffing requirements are needed. Efforts will be made to help make the coding package portable should NOAA develop the interest and capability to transition and maintain these products in real-time.

Project Budget

Project Budget Summary	**2015-2016**	**2016-2017**	**Total**
Bankert (0.1 work year)	*17,400*	*17,922*	*35,322*
Cossuth (0.25 work year)	*25,000*	*25,750*	*50,750*
Richardson (0.1 work year)	*17,400*	*17,922*	*35,322*
Total Salaries/Wages/Fringe	59,800	61,594	121,394
Overhead	25,000	25,750	50,750
Travel (NHC, IHC, AMS Trop 2016)	5,000	3,000	8,000
JHT facility funding requirements	0	0	0
Total Costs	**89,800**	**90,344**	**180,144**

Notes:

- NRL is a working capital fund activity governed by the legal requirements of 10 USC Section 2208. NRL is required to fully recover all costs of such work and services on a reimbursable basis. This includes the costs of civilian and military personnel, overhead operating expenses, and other direct reimbursable costs.
- Salaries and Overhead incorporate a 3% increase in year 2.
- Should only a portion of the above proposed tasks be funded, the following is an estimated break down of the tasks by work year:

Project Time Summary	**2015-2016**	**2016-2017**	**Total**
Task A (real time upgrades)	*0.15*	*0.05*	*0.2*
Task B (archive creation)	*0.15*	*0.05*	*0.2*
Task C (parallax correction)	*0.1*	*0.2*	*0.3*
Task D (color table upgrade)	*0.05*	*0.15*	*0.2*
Total Costs	**0.45**	**0.45**	**0.9**

Abbreviated Curriculum Vita (R. Bankert, PI)

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EDUCATION

1988: M.S., Meteorology
The Pennsylvania State University

1983: B.S., Meteorology
The Pennsylvania State University

PROFESSIONAL EXPERIENCE

1990-Present:

Meteorologist, Naval Research Laboratory (NRL), Marine Meteorology Division, Monterey, CA (1990-1992: known as Navy Oceanographic and Atmospheric Research Laboratory before incorporation into NRL)

RESEARCH INTERESTS

Research, development, and application of machine learning and pattern recognition techniques to the complex problems related to the interpretation of meteorological satellite data and other atmospheric science data.

RECENT/RELEVANT JOURNAL PUBLICATIONS AND BOOK CHAPTERS

Miller, S.D., J.M. Forsythe, P.T. Partain, J.M. Haynes, R.L. Bankert, M. Sengupta, C. Mitrescu, J.D. Hawkins, and T.H. Vonder Haar, 2014: Estimating three-dimensional cloud structure via statistically blended satellite observations. *J. Appl. Meteor. Clim.*, **53**, 437-455.

Kuciauskas, A., J. Solbrig, T. Lee, J. Hawkins, S. Miller, M. Surratt, K. Richardson, R. Bankert, and J. Kent, 2013: Next generation satellite meteorology technology unveiled. *Bull. Amer. Meteor. Soc.*, 94, 1824-1825.

Lee, T.F., R. L. Bankert, and C. Mitrescu, 2012: Meteorological education and training using A-Train profiles. *Bull. Amer. Meteor. Soc.*, 93, 687-696.

Bankert, R.L., J.E Solbrig, T.F. Lee, and S.D. Miller, 2011: Automated lightning flash detection in nighttime visible satellite data, *Weather and Forecasting*, **26**, 399-408

Donovan, M.F., E. R. Williams, C. Kessinger, G. Blackburn, P. H. Herzegh, R. L. Bankert, et al, 2008: The identification and verification of hazardous convective cells over oceans using visible and infrared satellite observations, *J. Appl. Meteor. and Clim.*, **47,** 164-184.

Bankert, R.L., M. Hadjimichael, A.P. Kuciauskas, K.A. Richardson, F.J. Turk, and J.D. Hawkins, 2003: Automating the estimation of various meteorological parameters using satellite data and machine learning techniques. *Frontiers of Remote Sensing Information Processing*, C.H. Chen, Editor. World Scientific Publishing Co., 227-252.

Bankert, R.L. and P.M. Tag, 2002: An automated method to estimate tropical cyclone intensity using SSM/I imagery. *J. Appl. Meteor.*, **41,** 461-472.

Current and Pending Federal Support

Richard Bankert

1. Project Title: DASH
   Supporting Agency: NRL
   Grant Number: 6618-0-3-5
   Investigator Months: 2
   Award Amount: $215K
   Duration: Oct 2013 – Sep 2016

2. Project Title: Remote Sensing Tropical Cyclone
   Supporting Agency: ONR
   Grant Number: 7838-A-3-5
   Investigator Months: 2
   Award Amount: $210K
   Duration: Oct 2014 – Sep 2015

3. Project Title: Ship Routing
   Supporting Agency: SPAWAR
   Grant Number: 1A85-0-5-5
   Investigator Months: 3
   Award Amount: $79K
   Duration: Oct 2014 – Sep 2015

4. Project Title: Sat METOC
   Supporting Agency: SPAWAR
   Grant Number: 5161-A-3-5
   Investigator Months: 3
   Award Amount: $162K
   Duration: Oct 2014 – Sep 2015

Joshua Cossuth

None.

Kim Richardson

1. Project Title: DASH
   Supporting Agency: NRL
   Grant Number: 6618-0-3-5
   Investigator Months: 2
   Award Amount: $215K
   Duration: Oct 2013 – Sep 2016

2. Project Title: TC MultiSensor
   Supporting Agency: SPAWAR
   Grant Number: 5657-A-3-5
   Investigator Months: 3
   Award Amount: $181K
   Duration: Oct 2014 – Sep 2015

3. Project Title: OM&N TC
   Supporting Agency: SPAWAR
   Grant Number: 5657
   Investigator Months: 3
   Award Amount: $200K
   Duration: Oct 2014 – Sep 2015

4. Project Title: VIIRS Cal/Val
   Supporting Agency: NOAA
   Grant Number: 8630-0-2-5
   Investigator Months: 2
   Award Amount: $105K
   Duration: Oct 2014 – Sep 2015