Assessing HF Radar Data in the New York Harbor: Comparisons with Wind, Stream Gauge and Ocean Model Data Sources

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Abstract— **The Physical Oceanographic Real-Time System (PORTS) is operated in 26 regions of the United States including New York/New Jersey Harbor. This system provides observations and predictions of water level, currents, salinity and meteorological parameters that are used by mariners to safely navigate the coastal waters. HF radar surface current measurements are a new data product available in three of the regions. A study was conducted to analyze this new data stream to ensure that is suitable for PORTS. The NOAA Center for Operational Oceanographic Products and Services (CO-OPS) using data from the U.S. Integrated Ocean Observing System (IOOS) has recently released a new HF Radar Surface Currents web product which provides near real time surface current observations and tidal current predictions in estuarine and coastal locations. Two High Frequency radar systems are providing surface current measurements over Lower Bay, just outside New York Harbor. A year long record of surface currents was used to generate tidal harmonics for the region. These harmonics are used to generate surface tidal current predictions along the 1 km grid in Lower Bay. The tidal harmonics were calculated for 37 constituents and analyzed in detail the five major constituents for the region (M2, S2, N2, K1 and O1). The tidal components matched those of previous studies. HF radar is now available in NOAA PORTS and surface current predictions cover approximately 50% of the bay. The use of HF radar in NY/NJ PORTS as well as other IOOS assets will improve navigation in NY Harbor and lead to economic growth for the region.**

Keywords—HF radar, remote sensing, ocean models

I. INTRODUCTION

The Mid-Atlantic Regional Association Coastal Ocean Observing System (MARACOOS) is operated as part of the Integrated Ocean Observing System (IOOS). A major component of MARACOOS is a High Frequency Radar Network. It is comprised of a total of 45 radars, 17 being long-range sites (5MHz), 7 standard-range sites (13 MHz), and 21 high resolution sites (25 MHz). This network has been in operation since 2007 and has expanded to have consistent coverage from Cape Cod to Cape Hatteras. The surface current data obtained from this radar network has a variety of important uses, including Coast Guard search and rescue, response to hazardous material spills, water quality monitoring, coastal inundation, and fisheries support [1].

This study assessed the HF radar network in New York Harbor and looked for correlations between the surface current measurements, other environmental measurements and an ocean model. Specifically, our study area (Figure 1) was Lower Bay, which will be referred to as New York Harbor in this manuscript. The 25 MHz radars in the New York Harbor were the focus of this study.

Seventeen High Frequency radars were damaged within MARACOOS when Hurricane Sandy passed through the region in October 2012 [2]. The radar at Staten Island (SILD) was damaged and the radar at Port Monmouth, NJ was submerged in salt water. We have been working to repair and harden the observing system assets that were damaged or lost during Hurricane Sandy. The aim of this study is to ensure accurate measurements by the repaired radar stations for use by NOAA PORTS and others.

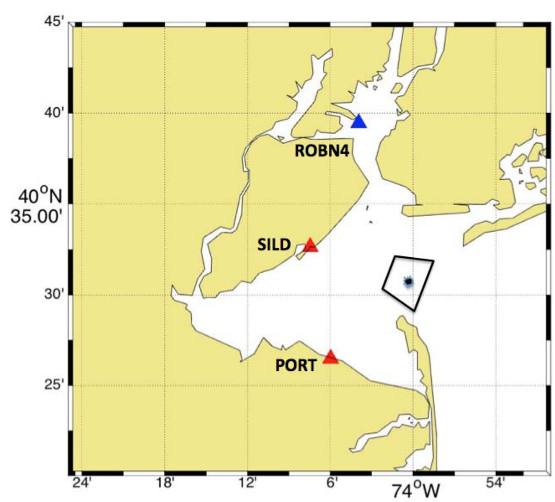

Figure 1- Map of the New York Harbor where Red triangles are HF radar sites SILD and PORT and blue triangle is NDBC Station ROBN4. Current measurements from SILD located inside the black polygon were averaged to create a radial velocity time series. The surface current data from ESPreSSO was located at the black star.

HF radar data was compared against wind measurements from the National Data Buoy Center (NDBC), river discharge measurements from the United

States Geological Survey's (USGS) stream gauges and Rutgers University's Experimental System for Predicting Shelf and Slope Optics Model (ESPreSSO).

NDBC, operated as a part of the National Weather Service, is an online portal where data from buoys from all over the world are logged and made available to the public and scientists alike. This data consists of wind direction, speed, and gusts, atmospheric pressure, air temperature, and water level among other measurements, which assist in meteorological predictions.

The USGS's stream gauges provided information on the discharge from the two main rivers that feed the New York Harbor, the Raritan River and the Hudson River. These two data sources served as comparison points for the HF radar measurements in the New York Harbor.

The HF radar data is now available through the National Oceanic and Atmospheric Administration's Physical Oceanographic Real-Time System (NOAA PORTS). NOAA PORTS is part of NOAA's Tides and Currents program where historical and real-time observations and predictions of water levels, coastal currents and other meteorological and oceanographic data for a dozen US estuaries is provided to the public and maritime industry [3]. This program utilized one year (July 14, 2013 to July 14, 2014) of measurements to perform a harmonic analysis of the surface current data in New York Harbor to generate the tidal predictions for the area. Currently, HF radar tidal predictions are available over approximately 50% of the bay. We examined the HF radar data to ensure the highest quality and most accurate data was being passed to NOAA PORTS.

Rutgers University's ESPreSSO model uses the Regional Ocean Modeling System (ROMS) [4] and spans the entire Mid-Atlantic Bight. The coverage of the ESPreSSO model is similar to that of the Mid Atlantic HF radar network. ESPreSSO also assimilates the 5 MHz HF radar measurements into its model.

Correlation of the radar data with several of the data sources was expected. This is due to the fact the ESPreSSO model assimilates the long-range HF radar data to make its forecast. The highest expectations for correlations with radar data were with the USGS's stream gauges and NDBC's wind measurements. Measurements from these data sources had the potential to provide information about discrepancies or important features of the radar data. By addressing the accuracy of the HF radar network, navigation in the region will improve and economic growth will be stimulated, along with a variety of other important uses for the network.

II. Methodology

This study utilized measurements from each data source from January 1, 2015 to June 1, 2015. The main radar used in this study was located in Staten Island, New York (SILD). There is also another radar in the New York Harbor in Port Monmouth, New Jersey (PORT) that, when combined with SILD, produces a total plot for the harbor. HF radars use a vertically polarized signal, which travels along the electrically conductive ocean water surface. These signals travel from the radar, reflect off of an ocean wave and travel back to the radar. These radars first measure signal range, then velocity, and finally the bearing of the scattering ocean waves. After subtracting the theoretical speed of the ocean waves from the received Bragg Scatter, the signal received at the radar can be used to determine a radial velocity measurement of surface current. The radar network reports data every hour at a resolution dependent on the frequency of the radar. The hourly radial map of surface currents measured at SILD can bee seen in Figure 2. The total map for New York Harbor can be seen in Figure 3.

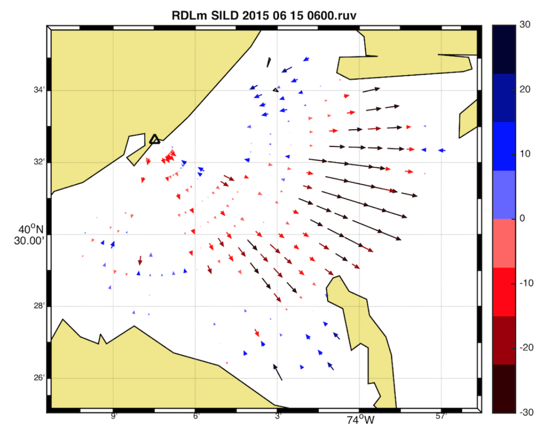

Figure 2- Radial map from HF radar station SILD. Red indicates currents moving away from the radar (negative) and blue indicates currents moving towards the radar (positive).

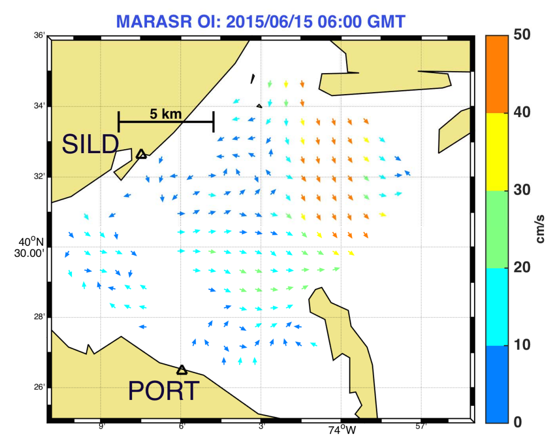

Figure 3- Map of total surface currents in the New York Harbor from HF radar stations SILD and PORT(black triangles). The colorbar on the right signifies current magnitude (0-50 cm/s).

Plots of radial surface current velocities at specific points in the New York Harbor were made from the SILD radar. The radial resolution of the radar was set to 1 km and the bearing resolution was set to 5 degrees. The radial measurements between bearing angles 97 and 113 degrees in range cells 10, 11 and 12 (a total of 9 radial vectors) were averaged to make a single surface current measurement in the vicinity of the harbor entrance. This averaging area is depicted as the black polygon in Figure 1 and an example of a surface current time series is shown as the blue line in Figure 7. A plot like the one in Figure 7 was generated for each month of the study, five in total. Positive flow is directed into the harbor and negative flow is out of the harbor. The radar surface current measurement is aligned parallel to the Ambrose channel and the entrance to the harbor. The M2 and K1 tidal constituents were calculated over each month to create the tidal component of the flow. Lastly, the surface currents were filtered with a Lancocz (low pass) filter with a cut-off period of 32 hours to remove the tidal variability. The low pass filtered data is shown as the green line. This low pass filtered record was utilized to compare the radar measurements with the wind and stream gauge measurements.

Stream gauges from the USGS record measurements consisting of discharge, gauge height, temperature, specific conductance, and turbidity among other parameters every 15 minutes. Gauge data from the Raritan and Hudson Rivers was compared against HF radar data. The stream gauge used from the Raritan River was located in Bound Brook, NJ (40°33'04", 74°32'54") while the stream gauge used from the Hudson River was located in Poughkeepsie, NY (41°39'03", 73°56'42"). One complication that arose was the proximity of the most downstream gauge in the Hudson River to the harbor. The furthest downstream gauge is 120 km north of the radar measurements. Therefore, in order to account for the full discharge from the Hudson river the data from Poughkeepsie were multiplied by a factor of 1.12 [5]. This factor was derived from the estimated additional discharge from the remaining watershed. This new value became the Hudson River discharge estimate. Another complication that arose was the strong tidal signature shown in the discharge data for the Hudson River. This signature was removed with a low pass (32-hour) filter in order to obtain a more representative, general description of how the water was moving. The results of the low pass filter can be seen as the green line in Figure 4. The stream gauge record from the Raritan was not modified as it was only 20 km from the radar measurements and did not exhibit the large tidal oscillations as seen in the Hudson.

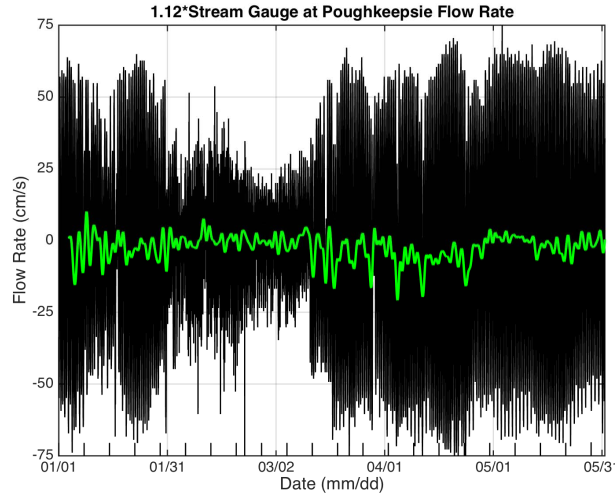

Figure 4: Graph of the raw (black) and low pass (green) Hudson River flow rate from January 1, 2015 to May 31, 2015. Positive flow is towards the north. General flow (green line) of the river downstream is indicated by the negative flow rate values.

Lastly, the discharge data from these stream gauges were converted to flow rate to be in comparable format of the radar surface current measurement. This conversion was done by dividing the rate of discharge by the average cross-sectional area of the river [6]. The final result of this alteration can be seen in Figure 4 for the Hudson and Figure 5 for the Raritan. From these modifications, signals seen in the stream gauge data could be compared to the low pass record of the HF radar.

NOAA's National Data Buoy Center also contributed significant data to this comparison. In particular, wind speed and direction measurements were utilized in order to make comparisons. A 5-month plot of wind data from buoy station ROBN4 (40°39'26" N 74°3'55" W) in Bayonne, New Jersey can be seen in Figure 6.

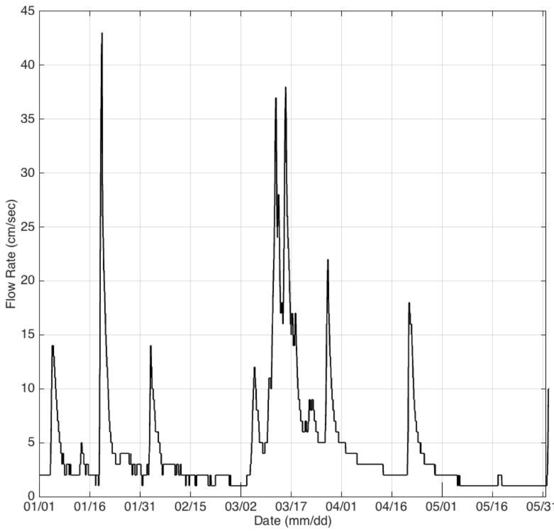

Figure 5: Graph of the flow rate from the Raritan River at Bound Brook from January 1 to May 31, 2015. Large flow rate events are attributed to large rainfall events.

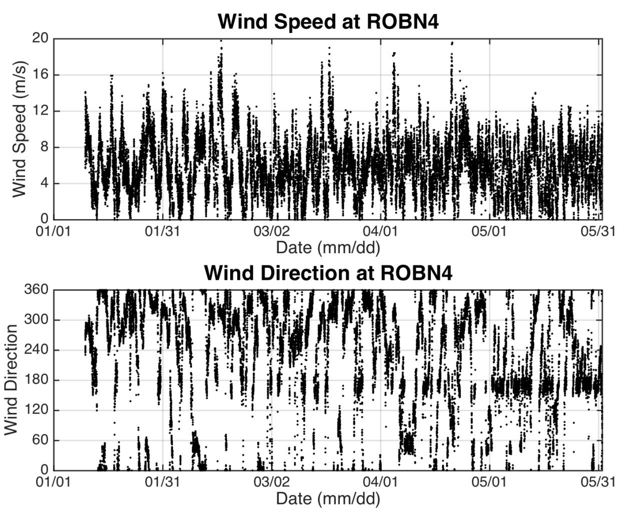

Figure 6: Graph of wind speed (top) and direction (bottom) from NDBC station ROBN4 from January 1, 2015 to May 31, 2015.

HF Radar data from NOAA's Physical Oceanographic Real-Time System is different from our other data sources because it provides a prediction for future oceanic conditions. This system produces an hourly harmonic prediction of oceanic conditions based on historical HF radar data. Therefore, any deviation of the radar data from the predictions suggested that other environmental data should be examined to explain the difference.

The last comparison point of this study was with an ocean model, Rutgers University's ESPreSSO model. ESPreSSO's goal is to develop an understanding of the coupled bio-optical and physical processes in the coastal zone [7]. Time-series plots and spatial coverage maps will enable this study to compare model's results with radar data and analyze inconsistencies. Through this comparison, the models' uncertainties were analyzed and the need for further assimilation with radar data was shown.

III. RESULTS

An interesting correlation was determined through comparisons of the HF radar data with wind data from ROBN4. This comparison analyzed the HF radar's ability to show the effects of wind on the currents in the New York Harbor. Utilizing the low pass filtered HF radar data, it was determined that any positive flow (into the harbor) or flow more negative than -20 cm/s (out of the harbor) would be considered a large event in terms of surface currents. In order to make this comparison, time-series plots of wind measurements from NDBC station ROBN4 were created for each of the large surface current events noticed on the HF radar record. As can be seen in Figure 1, this station is only 14 km from the HF radar surface current measurements so we assumed that the wind field was isotropic over this distance.

From January 1, 2015 to June 1, 2015 there were 7 large surface currents events in New York Harbor that were compared with wind data in this study. The results of this comparison can be seen in Table 1. From this comparison, the correlation between changing surface currents in the harbor and wind direction and speed was very obvious. An increased flow in or out of the New York Harbor consistently aligned with an increase in wind speed from the East/Northeast or West/Northwest respectively. The large surface current events occurred when speeds were above 12 m/s. This was further evidence for wind being the cause of this increased flow because the average wind speed over the 5-month study period was 6 m/s.

One particular instance when the radar and wind records lined up particularly well occurred from March 14-17, 2015 as seen in Figures 7 and 8. During this event, the winds were blowing at about 17 m/s from the West/Northwest for about a day. This wind event can be seen on the radar record on 3/15. Increased flows out of New York Harbor were not only attributed to large wind events but also large rainfall events, as seen in the USGS stream gauge record.

NDBC ROBN4 Wind Data vs HF Radar Data						
Event Date	**General Wind Direction**	**Max Wind Speed (m/s)**	**Flow in or out of harbor on radar?**	**Event Low Pass Magnitude**	**Consistent with wind?**	**Comments**
1/15/15-1/18/15	West/Northwest	16 m/s	Out	~ -30 cm/s	✓	Highest winds on 1/17
2/12/15-2/15/15	Northwest	16 m/s	Out	~ -30 cm/s	✓	Highest winds on 2/13
2/19/15-2/22/15	Northwest	16 m/s	Out	~ -30 cm/s	✓	Winds strong from 2/19-2/20 → visible on radar
3/14/15-3/17/15	West/Northwest	17 m/s	Out	~ -33 cm/s	✓	Highest winds on 3/15
4/10/15-4/13/15	West/Northwest	14 m/s	Out	~ -32 cm/s	✓	Highest winds on 4/11
4/18/15-4/21/15	East	20 m/s	In	~ 10 cm/s	✓	Highest winds on 4/20
4/22/15-4/25/15	West/Northwest	12 m/s	Out	~ -35 cm/s	✓	Highest winds on 4/23

Table 1: Large surface current events in NY Harbor and the corresponding wind measurements at ROBN4.

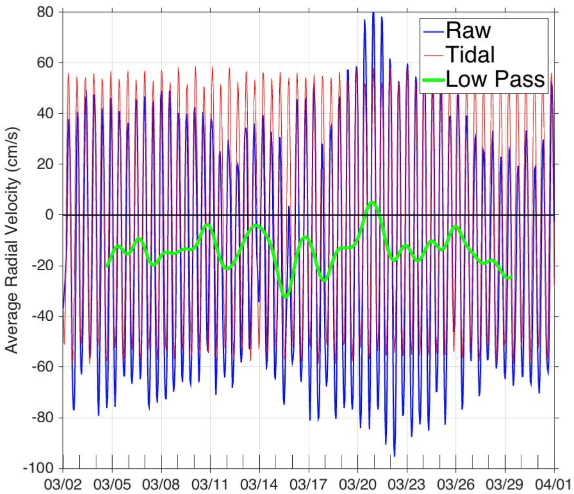

Figure 7- Graph of average radial velocity (blue) from HF radar station SILD for March 2015. The tidal component of the flow is in red and the low pass filtred flow is in green. Large flows out of harbor are indicated by values in green less than -20 cm/s while large flow events into the harbor are indicated by values greater than zero.

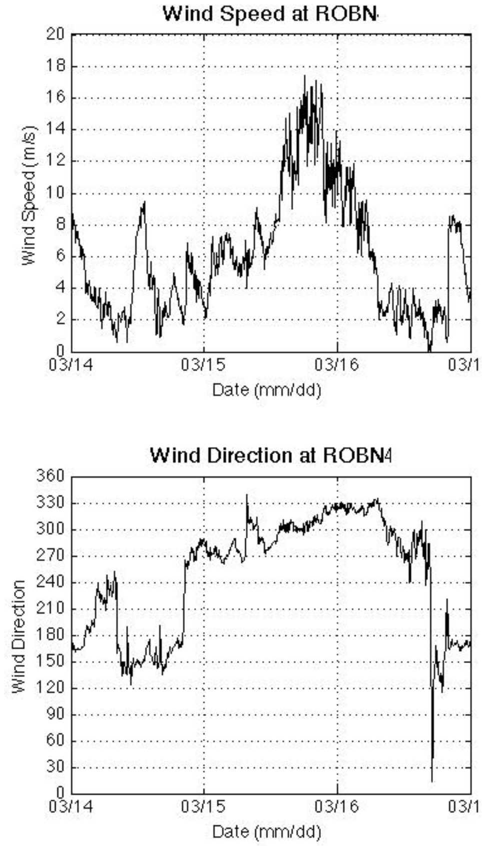

Figure 8: Graphs of wind speed (top) direction (bottom) from NDBC station ROBN4 from a large wind event from March 14-17, 2015.

Comparisons with the USGS stream gauges also showed a noteworthy relationship. For this analysis, we looked for large flow events in the stream gauge data and then examined the corresponding time period in the surface current data. There were four instances that stood out in the discharge record that were deemed worthy of comparison. The results of this comparison can be seen in Table 2. During these large rainfall events, the flow rate increased by about 5 to 10 times the average flow rate for each river. One particular instance when the radar and flow rate records lined up particularly well occurred from March 11-17, 2015. During this time there were two large rainfall events on March 12th and 15th in the Raritan River where the max flow rate increased to 40 cm/s from the average of 5 cm/s. This increased flow rate was visible on the radar record three days later on March 15th and 17th. There was about a three-day span between rainfall events, which is visible on the radar as well, as seen in Figures 7 and 9.

Table 2: Table of USGS stream gauge data from large rainfall events seen on HF radar record

Rainfall Event Data USGS Stream Gauges vs HF Radar Data						
Event Date	**Location**	**Max flow rate**	**Mean flow rate for location**	**When visible on radar?**	**Event Low Pass Magnitude**	**Time-lag**
1/19/15-1/22/15	Raritan River	44 cm/s	4.66 cm/s	1/25/15	~ -23 cm/s	Two day time-lag
3/11/15-3/14/15 & 3/15/15 3/17/15	Raritan River	40 cm/s	4.66 cm/s	3/15/15-3/18/15	~ -33 & -25 cm/s	One day time-lag and gap because of two storms
4/21/15-4/22/15	Raritan River	18 cm/s	4.66 cm/s	4/23/15	~ -35 cm/s	One-two day time-lag
4/4/15-4/6/15	Hudson River	21 cm/s	2.04 cm/s	4/11/15	~ -32 cm/s	Five day time-lag

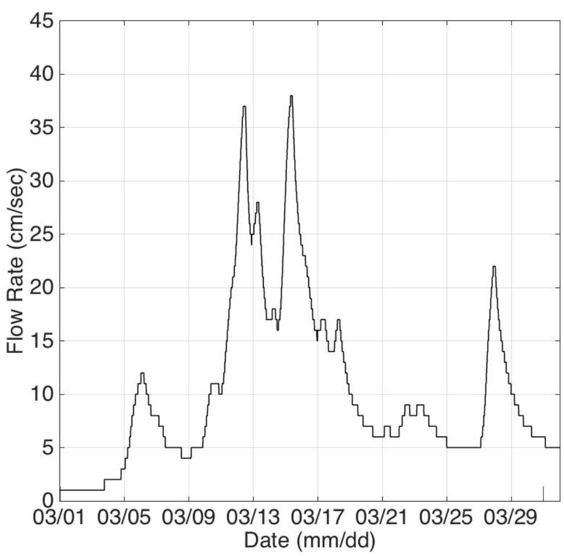

Figure 9: Graph of flow rate from the Raritan River for the month of March. Two large rainfall events on 3/12 and 3/15 were noticeable on HF radar record with a timelag.

These external wind and rain factors influencing the surface currents in the New York Harbor could very well be the key characteristics affecting surface current plots in NOAA PORTS. The NOAA PORTS HF radar product utilizes HF radar observations to calculate tidal current predictions. By performing a harmonic analysis of the observations, tidal constituents like the M2 (principal lunar semidiurnal; Figure 10) are calculated and enable indefinite predictions of tidal currents.

Tidal current predictions can be quite accurate for locations and time periods when tidal currents are the dominant forcing mechanism. However, in some cases tidal currents may be relatively weak or there may be strong non-tidal influences like wind and river flow, at which point tidal current predictions can be inaccurate since it is no longer a majority of the current energy. For example high non-tidal residual was found in the western extent of the harbor when performing the harmonic analysis (Figure 11).

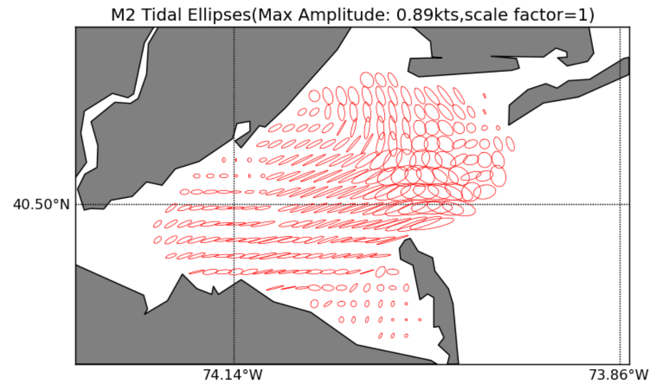

Figure 10: The M2 tidal ellipses resulting from the harmonic analysis of HF radar observations.

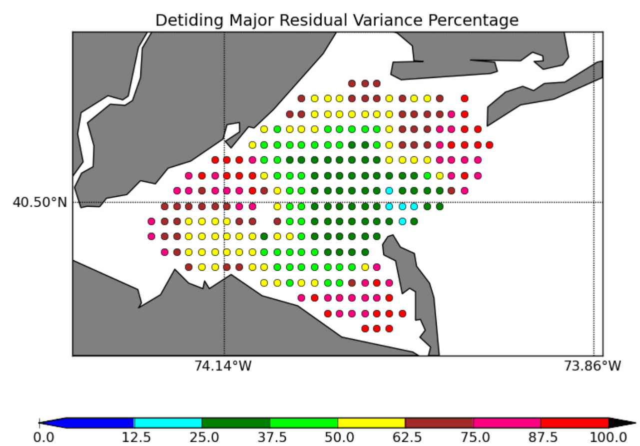

Figure 11: The percent of non-tidal residual variance observed at each point in the HF Radar domain. Note the high (> 50%) residual variance observed for many of the data points.

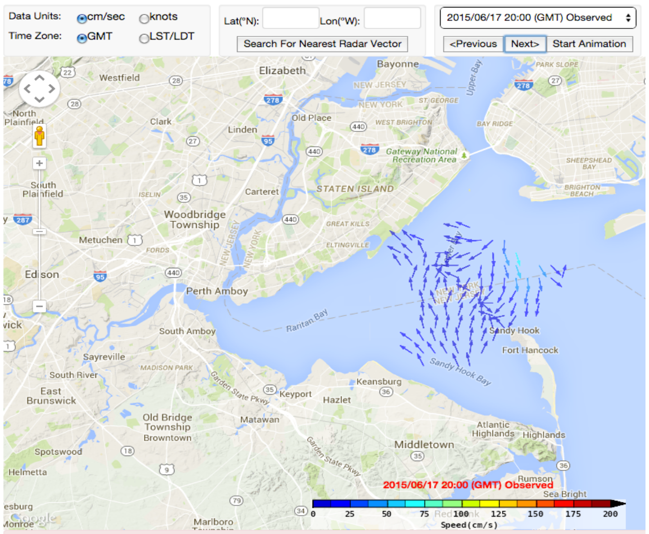

Figure 12- Map of NOAA PORTS HF radar data in the New York Harbor. The spatial coverage of the surface currents in NOAA PORTS is noticeably smaller when compared with the HF radar map in *Figure 13*.

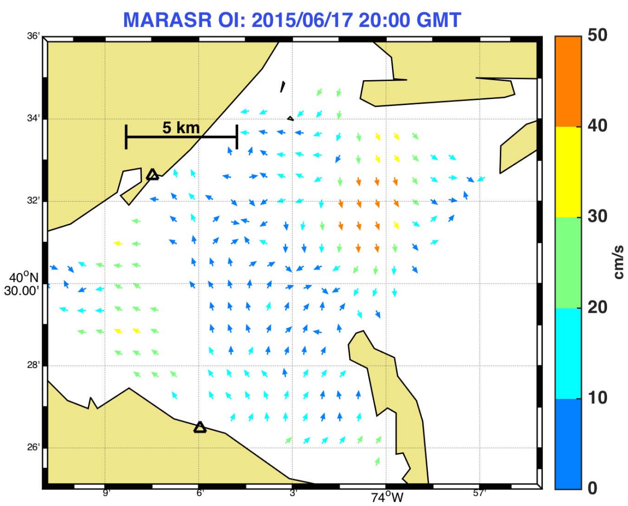

Figure 13: Map of total radials in the New York Harbor

These locations of high non-tidal residual were not utilized in the NOAA PORTS product (Figure 12), and because of this there is a significant spatial limitation when compared to the HF Radar observations (Figure 13). Part of the reason for the high non-tidal residual observed in the western extent of the harbor may be due to HF Radar data quality in these locations. Radar measurements are currently excluded along the baseline between SILD and PORT, as the system is unable to make an accurate measurement perpendicular to the baseline. Rutgers is experimenting with adding a third radar in the New York Harbor located near the mouth of the Raritan River in order to increase the quality and coverage of the radar measurements in the harbor.

Another interesting comparison with the HF radar record was through oceanographic models, and in particular, the Rutgers University's ESPreSSO model. We chose the closest ESPreSSO grid point to compare with the HF radar measurements (black star in Figure 1). The u and v components of ESPreSSO were combined and rotated to match the radial bearing line from SILD. A one-month plot of this time series for March 2015 is shown in Figure 14. The HF radar surface current velocities ranged between ±80 cm/s while the range for ESPreSSO was ±40 cm/s, half that of the radar. The low pass signature of ESPreSSO better matched the HF radar at approximately -20 cm/s, however ESPreSSO estimated two large flow events into the harbor while the radar measured one large event. These two factors are key points highlighting ESPreSSO's need to assimilate the high resolution HF radar data into its model for better estimation of New York Harbor currents.

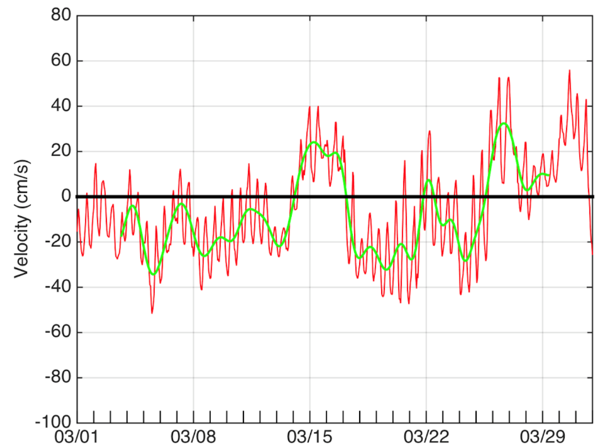

Figure 14: Graph of ESPreSSO surface velocity north of Sandy Hook, positive is into the harbor. When compared with the HF radar surface current velocity graph, ESPreSSO's range of surface currents is an underestimate.

IV. CONCLUSIONS

The results of this study indicate that the HF radar network in the New York Harbor has a variety of correlations with other oceanographic data sources. Furthermore, HF radar data can certainly be used to increase the accuracy of ocean models. As for comparison with other oceanographic data sources, the most striking correlation with HF radar data that this study discovered was with wind data from NDBC. Wind direction and speed proved to be a correlation with increased flows in the New York Harbor. In addition, discharge data from the USGS's stream gauges also proved to show interesting correlations. Mainly, when a large rainfall event was noticed by a stream gauge, more often that not, it was also noticed with a time lag by the HF radars in the harbor. Lastly, this comparison showed how ocean models, such as ESPreSSO, could benefit from the assimilation of HF radar data from the New York Harbor because of this regions complicated nature. Details from this study will be presented to the creators of ESPreSSO in order to increase the models accuracy in the New York Harbor as well as NOAA in order to increase their PORTS program's accuracy.

V. Acknowledgments

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