Remote Sensing of the Ocean

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The Need for Environmental Observations

Just by looking at images of the Earth from space, it's clear that the ocean is a significant piece of the Earth's story. In fact, the global oceans represent more than 70 percent of the Earth's surface, and are the primary driver of weather and climate.

When you open the daily newspaper or a weekly news magazine, you can frequently witness the harmful impact of the physical forces of Earth's oceans and atmosphere, and their profound economic and societal implications. The more societies become dependent on resources and products from widely separated regions, the more an event that produces local devastation, such as Hurricane Katrina, most recently, also leads to disruptions across the globe. There is never enough predictive ability and sufficient advance notice, or governmental capabilities, to protect all individuals and property from harm. The catastrophic hurricane season of 2005 demonstrates the value of spaceborne sensors that observe atmospheric and oceanic processes to predict natural disasters. This demonstration indicates the urgency to both extend these capabilities and to improve management of our land-based facilities. Although scientific consensus indicates that these current events are part of a climatic cycle, this unusual hurricane season accentuates concerns regarding the impending effects of human activities that are causing environmental changes at an accelerating rate.

Transitioning From Sensor Development to Scientific Analysis

For the purpose of defense and environmental applications, I have been actively involved in radar remote sensing of the ocean for more than three decades. In the early 1970s, I joined what became a group of pioneers who were developing the field of microwave radar sensing of the ocean from aircraft and spacecraft. For young engineers and scientists such as ourselves, trained in the rigorous and precise disciplines of electrical engineering and physics, the transition to geophysical observations was a bit of a cultural transformation. We would concentrate on producing instruments that had very carefully defined specifications and physical capabilities, but then realized that what we were observing was so complicated that it defied complete characterization. Additionally, we realized that what little characterization information had been measured, changed with location and time. This is because, when you are observing the oceans and the atmosphere, you are dealing with processes that have substantial variability over a wide range of spatial scales, time variations and interactions (heat and momentum exchange). The best one can accomplish is to pursue descriptions with statistical and probabilistic terminology. For example, this means that one must contrast the satellite estimate of the wind as an average over a 25-by-35 km area (footprint), with the measurement taken by an instrument on the ocean (buoy) that provides the measurement at a single point. When discussing its calibration (accuracy), the conventional terminology uses the mean and standard deviations between these ocean "point" estimates and the satellite footprint estimates. Weather forecasters can benefit from satellite estimates that cover an area up to a thousand miles from shore, collected during a single overpass.

Figure 1: An artist's rendition of the QuikSCAT satellite, which was launched in June 1999. The dish-like object at the bottom is the SeaWinds Scatterometer.

However, oceanographers need a full global view of winds, which can take the satellite about two days to collect. Because the satellite cannot observe the complete globe at every instant, analysts need to qualify their findings with an appropriate list of assumptions and geographic boundaries. One then creates programs and investigations that can reduce the uncertainty in the measurement of selected parameters, and that can improve predictive abilities. People who must predict weather and ocean events usually add a "confidence" statistical parameter, based on the number of days ahead one is trying to estimate.

Our initial efforts were to create, explore and evaluate possible technologies using aircraft-based experiments to assess what might be valuable as satellite-based sensors, which would ultimately be used to observe as many sea surface and air-sea interaction quantities as possible. These would include wave heights, wave lengths and wind speed (including the stress on the sea surface).

In the recent decade, I have concentrated on developing a system for measuring wind stress on ocean surfaces using satellite radar from space. This method of measurement has the ability to measure sea surface wind stress, or the force on the seas's surface created by wind, and also to "correct" these wind measurements when rain interferes with the radar across the areas we would like to observe. Since rain can, at any given time, exist over about 5 percent of the world's oceans, the removal of the interference it causes is a high priority to scientists and meteorologists using these wind measurements for interpreting ocean phenomena. Unfortunately, the erroneous wind data is commonly found in the vicinity of synoptic scale (covering many hundreds of miles) and dynamic atmospheric systems, such as cyclones and frontal boundaries, where measurements of surface winds are most important for scientific and operational (weather prediction) investigations.

Origins of Satellite Remote Sensing

Radar, the "Invention that Changed the World" [Buderi, 1996], was invented in the 1930s and played a decisive role during World War II. Many scientific leaders at the time stated that, considering the broad scope of its usage on land, sea and air, radar contributed more to the United States' World War II victory than the atomic bomb. Radar quickly became indispensable for all military and civilian aviation. During the wartime years, radar was a critical factor in combat operations from aircraft and Navy vessels. Its potential for meteorology, to precisely locate and measure atmospheric events, was also recognized and exploited for forecasting weather changes to guide mission decisions.

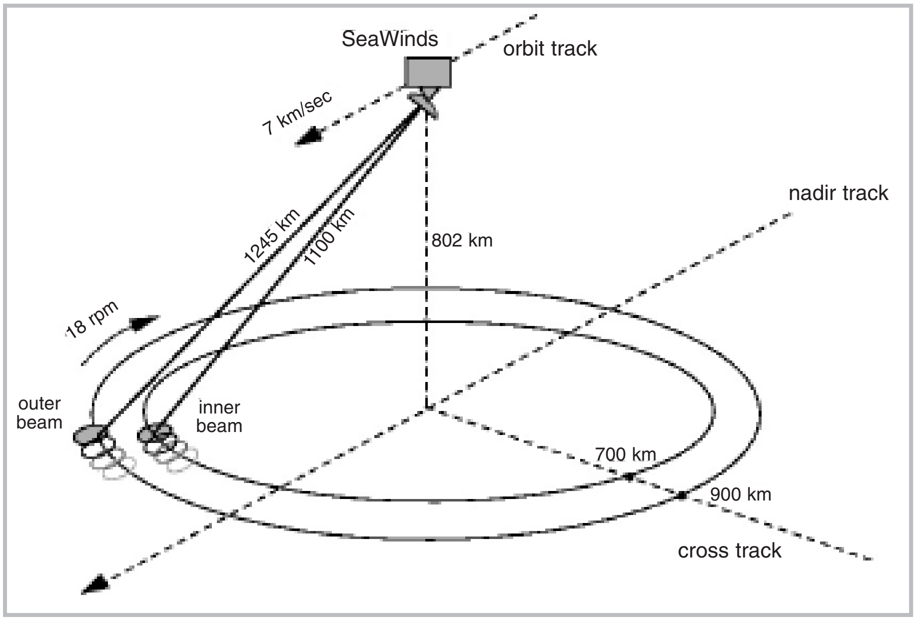

Figure 2: SeaWinds measurement geometry illustrating the antenna beam locations for the different polarizations. Inner beam is horizontal polarization; outer beam is vertical polarization.

The field of Radar Meteorology thus began with World War II. Radar is also known as an "active" sensor because it generates and transmits its own electromagnetic energy. These waves are reflected by whatever medium or surface they encounter, and are then returned to the source where they are stored, measured and interpreted. This capability enables the study of the atmosphere in three dimensions, and the study of land and ocean surfaces under all conditions and circumstances. The data can be made available immediately for urgent applications or later for extended scientific investigations. Our current television-based weather forecasters show us the color-coded images of rain locations, intensities and their motions.

The field of satellite remote sensing for earth observations began in April 1960 with TIROS-1, the first meteorological observer weighing all of about 200 pounds, whose launch was spurred on by the Soviet Union's Sputnik in 1957. TIROS stands for Television and Infrared Observation Satellite. Congress delegated to the then U.S. Weather Bureau the responsibility for managing and maintaining these satellites. While TIROS-1 consisted of only a TV camera to observe cloud formations, seven months later it was joined by TIROS-2, whose instruments operated in both the visible and infrared portions of the electromagnetic spectrum. Both TIROS-1 and TIROS-2 are designated as "passive" instruments, which only receive the radiation produced by thermal emission from the atmosphere or the Earth's surface, or their reflected sunlight. The invention of these instruments was followed by the invention of dozens of bigger and better passive instruments, but still using the same "physics," that is, visible and infrared frequencies. However, in the early 1970s, another innovation was made; microwave instruments operating at much lower frequencies were able to demonstrate their ability to "see through" clouds and often through rain, greatly improving weather forecasting skills and advancing scientific knowledge. By that time, the National Oceanic and Atmospheric Administration (NOAA) was formed and charged by Congress with advancing this field. However, since the 1970s, the prime agency for developing and testing new microwave Earth sensors has been the National Aeronautics and Space Administration (NASA), because of its vast resource of scientific and engineering manpower, which was created by the manned space exploration effort. The first Earth observations from space, for scientific investigations, were from the NASA Skylab launched by the Space Shuttle in 1974, for a one-week orbital mission.

The research community and the project Science Teams associated with each satellite instrument consist of a broad variety of specialists. The current population consists of engineers, physicists, oceanographers, meteorologists and atmospheric scientists. We concentrate on specific investigations and applications: some groups focus on testing the accuracy of the instrument data, while others develop specific algorithms (mathematical formulas and instructions) to convert the radar data into wind vector and stress estimates and data products, while still other scientists use these data to investigate oceanic processes and events. There is both interdependence and independence among these highly talented and motivated investigative subgroups. Often our studies involve a combination of two or more instruments (some may be surface-based), possibly on the same or different satellite platforms. Results and accomplishments promptly sent to scientific publications rapidly find their way into the larger international community of scientists, educators and policy makers who will make decisions about the lifetime of current sensors and their successors.

NASA's Ocean Remote Sensing Program

Part of NASA's mission is to develop an understanding of the total Earth-Sun system and the effects of natural and human-induced changes on the global environment. Our oceans play a major role in influencing changes in the world's climate and weather, because of the continuous exchange of heat, moisture, momentum and gases. Collecting and analyzing long-term ocean data from satellites is a relatively new field of exploration. The analysis of remotely sensed ocean data makes it possible to understand the ocean in new and exciting ways. Exploration is discovery through disciplined, diverse observations and the recording of findings. Prior to satellite data, most of what we have learned about the oceans had come from infrequent measurements collected from ships, buoys and drifters. Ship-based oceanographers are limited to sampling the ocean in a relatively small area with often a great deal of difficulty, or to sampling in a large area with remarkably poor temporal sampling. Data from ships, buoys and drifters is not sufficient to characterize the conditions of the spatially and temporally diverse ocean.

The agency has been observing the oceans from space for more than 25 years. NASA launched SEASAT, the first civilian oceanographic satellite, on June 28, 1978. The satellite carried five complementary sensors designed to monitor the oceans from space. These sensors included: 1) a radar altimeter (looking straight down) to measure wave heights across the ocean surface; 2) a microwave radar scatterometer (looking across a 700 km swath) to measure wind speed and direction; 3) a scanning multichannel microwave radiometer to measure sea surface temperature; 4) a visible and infrared radiometer to identify cloud, land and water features; and 5) a synthetic aperture radar (very high resolution) to monitor the global surface wave field and polar sea ice conditions.

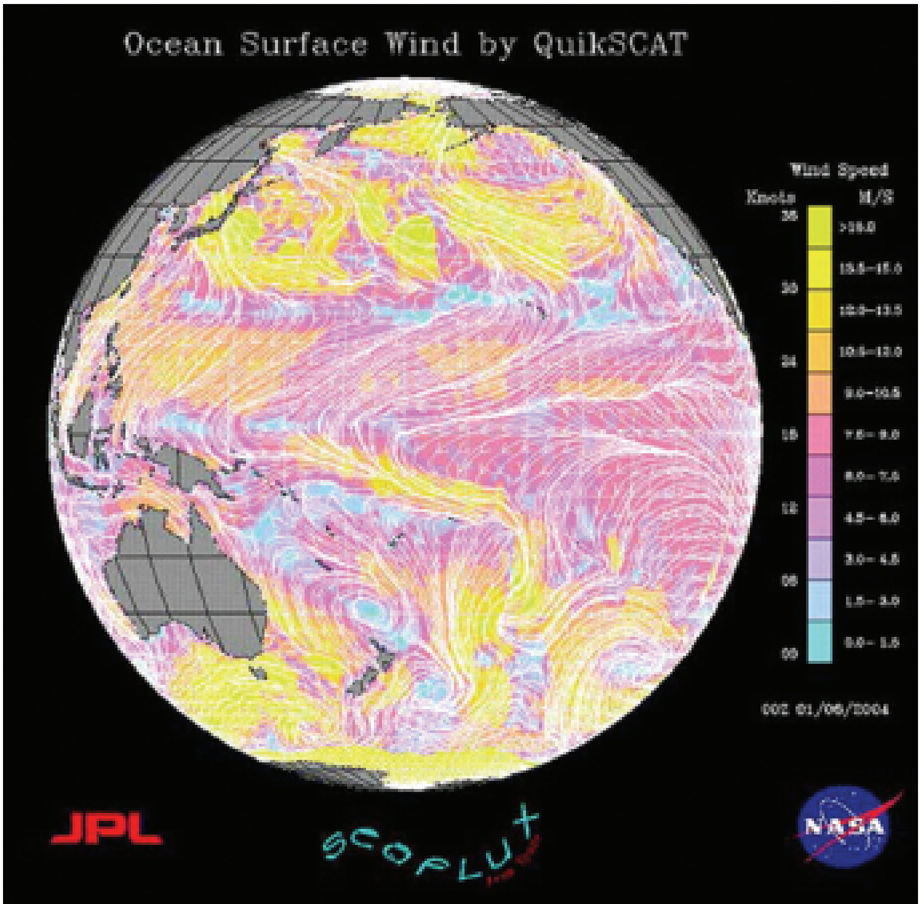

Figure 3: QuikSCAT image of winds on the surface of the Pacific Ocean on January 8, 2004.

Although a massive short-circuit in its power system ended all data-taking operations after only 105 days, the SEASAT instruments provided as much oceanographic data as had been acquired by ships in the previous 100 years! The variables that SEASAT measured in its short lifetime are some of the most important for understanding the ocean and its role in climate.

After successive NASA missions, in collaboration with the Japanese Space Development Agency, led to some limited successes and disappointments, a U.S. satellite dedicated to ocean wind vector measurements alone was quickly developed and tested within two years; hence, QuikSCAT was launched in June 1999. The radar instrument it carried was referred to as the SeaWinds Scatterometer (see Figure 1). It scans the sea surface with a narrow "flashlight" shaped beam, rotating its 30 km "footprint" in a full circle, with 18 revolutions per minute (see Figure 2). Its name, *Scatterometer,* is derived from the reflection or "back*scattering*" effect of microwaves that are returned from the small sea surface waves that are closely coupled ("connected") to the wind vector. One can observe a similar effect from a ship on a windy day, when your back is directed to the setting sun and you see the "twinkles" of sunlight from the short wavelets. Figure 2 shows two separate radar beams, one for each of the two polarizations (orientation directions) of the electromagnetic waves.

Samples of the global wind vectors derived from the Scatterometer over a two-day period can be seen in Figure 3. The swirls here indicate the wind directions, and the color code displays the wind magnitude. This is typical of the data needed by oceanographers, meteorologists and related scientists to study air-sea interaction, ocean circulation and their effects on short-term and long-term weather patterns and climate. However, necessary data can be lost when rain exists within the radar beam. The microwave frequency used by this radar is such that it is very sensitive to precipitation along the path of the narrow radar beam. The radar beams represented by the solid lines in Figure 2 are subject to weakening (attenuation) and reflection by the rain back to the satellite (backscattering).

One-time, but important, events such as storms or hurricanes will affect maritime commerce and coastal regions. These can be incisively observed by the QuikSCAT scatterometer. This is seen in the Hurricane Rita image of Figure 4. At the time this image was recorded, the hurricane had 195 kilometers per hour (120 mph) sustained winds. The images depict wind magnitude in color and wind direction with small "barbs."

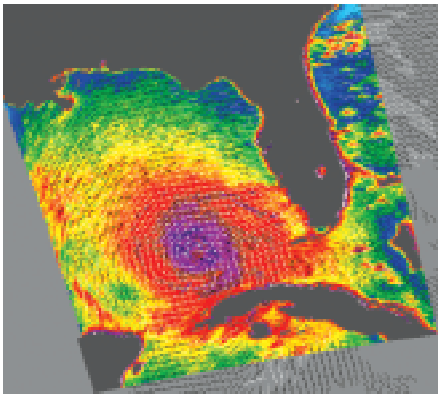

Figure 4: Hurricane Rita observed by NASA's QuikSCAT satellite on September 20, 2005, at 10:29 UTC (6:29 a.m. EST). The swirls represent the wind vectors at the sea surface. The color code indicates wind magnitude. Missing arrows indicate areas where rain prevents the sensing of winds at the surface.

Heavy rain occurred in the northern areas, and this prevented the estimation of wind directions, as can be seen in this image, where there are many areas without the direction barbs. Within the next 24 hours, Rita would surge in power, packing winds near 280 kilometers per hour, becoming the fourth most powerful storm ever recorded. Accurate surface winds are also crucial for the forecast of storm surge and coastal temperature change related to the upwelling of cold sub-surface waters. The storm surge is the excess sea level that inundates coastal communities; its prediction is used in decisions about population evacuations.

Hofstra's Recent Contribution – Combining NASA and National Weather Service (NWS) Resources

It is possible to make specialized space-based instruments for the measurement of rain. However, because these instruments are so far away, they have poor spatial resolution (they only observe areas larger than individual rain cells). Therefore, they cannot resolve the highly variable, smaller scale 3-D precipitation structure within the larger beam of the sensor. The optimum instrument for measuring rain intensity is the ground-based National Weather Service (NWS) next generation radar (NEXRAD). Many of these are stationed near the coasts, and can observe both the horizontal and vertical structure of the rain within each Scatterometer beam. Their radar reflectivity measurements can be converted into the desired rainrate parameters. These are then used to calculate the attenuation and backscattering, which can then be used to correct the data measured at the satellite.

Since 1999, Hofstra, in collaboration with colleagues at Florida State University and the New York City office of the National Weather Service, has been in involved in a research project to determine the locations and magnitudes of errors caused by rain within the beam [Weissman et al., 2002]. Scientists working on this project have been developing methods for correcting these errors, using independent measurements of the rain from which computation of the attenuation and backscattering amounts can be made, resulting in more accurate wind estimates. This will expand the spatial areas across which accurate, useable winds are available to scientists using the data for near-term predictions of ocean and weather events, and for long-duration climate studies.

The NWS routinely acquires all the NEXRAD data from the entire national network of stations, and stores it in the National Climatic Data Center (NCDC) in Asheville, North Carolina. However, the use of this data for the purposes of this research involves complex logistical and algorithmic operations. This capability was developed, starting in 1999, with financial and scientific contributions from the New York City office of the NWS. This facility is located in Upton, New York, on the property of the Brookhaven National Laboratory. Scientific Operations Officer Jeff Tongue has been an active collaborator in the acquisition, processing and application of the NEXRAD data to the scatterometer studies. Additional support was provided by the NWS Office of Science and Technology, at its headquarters in Silver Spring, Maryland.

This research project, with the New York City NWS office, was the key facilitator in having numerous NWS offices located along the Atlantic and Gulf coastlines (including Puerto Rico) incorporate the Scatterometer ocean wind measurements into their daily analysis of weather conditions for their local areas of responsibility and forecasts. This was facilitated through my longtime collaboration with the Florida State University Center for Ocean Atmospheric Prediction Studies, specifically with Drs. Mark Bourassa and James O'Brien (the director). Their extensive resources and expertise have created the mechanism by which each coastal NWS office could use this NASA satellite-derived near real-time wind information. The success of this work led to the Navy and National Oceanic and Atmospheric Administration (NOAA) developing their own pathways for bringing these data into use for their forecasting and analysis. Considering the bureaucratic maze and variety of government agencies and project offices, this partnership is a notable accomplishment. The value of this data is heightened during the hurricane season when the NWS offices and the National Hurricane Center in Miami are straining to acquire every possible piece of information about these savage storms.

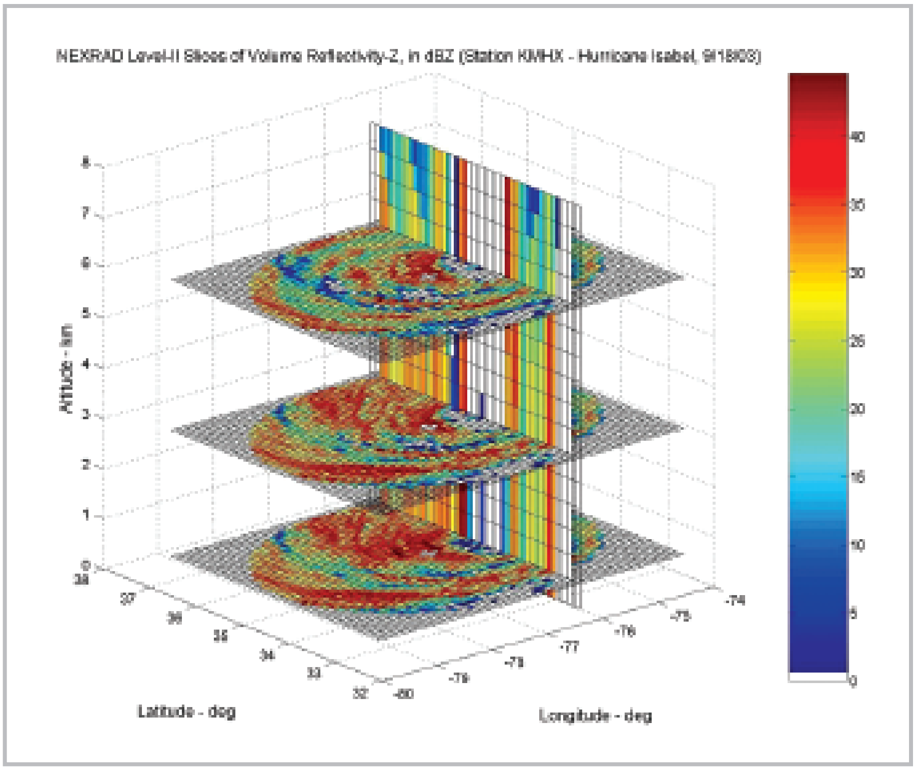

Figure 5: NEXRAD measurements of the volumetric radar reflectivity (from Morehead City, North Carolina, on September 18, 2003) within Hurricane Isabel. This was collocated with a SeaWinds Scatterometer overpass of Hurricane Isabel. The three horizontal slices were made at altitudes of 0.5, 3.0 and 6.0 km. The elevation plane shows quantized vertical steps of 0.5 km. The eye of Isabel was located at approximately 35°N, 76°W. The reflectivity scale is logarithmic, in dBZ, and indicated in the colorbar.

Hurricane Isabel

One of our ("Hofstra") research investigations focused on Hurricane Isabel, at the time it crossed onto the North Carolina coastline on September 18, 2003 [Weissman et al., 2005]. This fortuitous observation by the scatterometer occurred at about 1600 Greenwich Mean Time (GMT). The storm was centered in the swath of the satellite sensor, providing a rich source of scatterometer data, in addition to the NEXRAD data that was gathered. The conversion of the data files acquired from NCDC into 3-D arrays of reflectivity has been a very demanding task, but handled very effectively by my undergraduate research assistant, Greg Apgar, one of our Electrical Engineering majors at Hofstra. A sample of the NEXRAD 3-D reflectivity (we use a logarithmic amplitude unit, called dBZ) for a six-minute NEXRAD total scan for this event, is illustrated in Figure 5. This representation only shows planar slices at the indicated elevations and positions.

As this work progressed, we used the rain volume measurement to perform corrections to the Scatterometer measurements and thereby produce corrected wind speed measurements. The critical assumptions underlying these steps, namely the formulas for converting the NEXRAD measurements into scatterometer beam parameters, are in the process of being evaluated. This work is in close collaboration with Mark Bourassa of Florida State University. These test cases will continue to extend our understanding of the physical processes inherent in these circumstances. We will also share our results and methodology with NASA's lead institution for this satellite project, the Jet Propulsion Laboratory in Pasadena, California, to enable them to produce improved global wind vector products.

The ultimate solution for the rain problem will be found when NASA, in collaboration with the Japanese Aerospace Exploration Agency (JAXA) and our National Oceanic and Atmospheric Administration (NOAA), launches a new satellite carrying both a scatterometer and passive microwave radiometer whose main function is to measure atmospheric properties, including rain-rate [Yueh et al., 2003]. This radiometer scans the same atmospheric region as the Scatterometer. Its complete designation is the Advanced Microwave Scanning Radiometer (AMSR). The knowledge base and techniques developed for the NEXRAD precipitation measurements, in this Hofstra project, will be needed to evaluate the AMSR's ability to correct the Scatterometer. In effect, this methodology will be the calibration instrument that will define the limits of rain corrections for global wind studies.

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David E. Weissman began teaching at Hofstra University in 1968, shortly after earning a doctorate in electrical engineering at Stanford University, where he was also actively engaged in leading research on radar remote sensing. He received an undergraduate degree in electrical engineering from New York University. Upon arriving at Hofstra, his education in electrical engineering, combined with his previous industrial experience, provided Professor Weissman with an excellent background for offering new leadership to Hofstra's Electrical Engineering program. Hofstra University's program rapidly earned a reputation as the best electrical engineering program on Long Island for evening students.

Professor Weissman is a professor of engineering at Hofstra, and teaches intermediate and advanced courses in electronics, electromagnetics and communications. He has not only taught a wide range of courses, but has also created courses for the department. Additionally, he serves as coordinator of the Electrical Engineering program, whenever such service is requested.

Professor Weissman has a longstanding history of working with and receiving support from NASA. At the beginning of his career at Hofstra, summer recess breaks quickly became opportunities to conduct research-in-residence at NASA Research Centers such as the Electronics Research Center, Cambridge, Massachusetts, and the Langley Research Center (LaRC), Hampton, Virginia. Professor Weissman's research at NASA was a catalyst for his continued work with that agency, and for his receipt of annual research grants from the LaRC and NASA Headquarters to develop and evaluate radar measurements of ocean surface waves and air-sea interaction from aircraft and satellites. In 1975 Professor Weissman was awarded a National Research Council Senior Postdoctoral Fellowship, and spent the next year at the NASA Jet Propulsion Laboratory in Pasadena, California.

Professor Weissman has received NASA research grants during almost all of his 37 years at Hofstra. Invariably, these have involved close collaborations with engineers and scientists at research centers or other universities. During a sabbatical in 1990, he was a visiting scientist at the Woods Hole Oceanographic Institution (WHOI), where he began an additional long-term, ocean remote sensing research program under the auspices of the U.S. Navy, Office of Naval Research. There, he collaborated with scientists at WHOI and the University of Washington. In 1999 he began receiving support and collaborating with the New York City office of the National Weather Service, which led to some of the work discussed in this article. He has authored or co-authored more than 40 articles in archival journals and edited proceedings, and has presented more than 100 conference papers. In 1990 he was elected a Fellow of the Institute of Electrical and Electronic Engineers (IEEE). In 1977 he received the Best Journal Paper Award from the IEEE Transactions on Antennas and Propagation. Additionally, he has received other awards from NASA and the IEEE. He currently serves on the Executive Committees of the IEEE Oceanic Engineering Society (since 1975), and the Geoscience and Remote Sensing Society (since 1999).