RADARSAT-1 Hurricane Watch program contribution to wind field model development

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Abstract - Is has been well established that Synthetic Aperture Radar images over oceans can provide wind information over small spatial scales. Since 1999 the Canadian Space Agency has undertaken a joint project, called Hurricane Watch, with the U.S. National Oceanic and Atmospheric Administration / Atlantic Oceanographic and Meteorological Laboratory (NOAA/AOML), the Canadian Department of Fisheries and Oceans (DFO), and more recently with the Center for Southeastern Tropical Advanced Remote Sensing (CSTARS) of the University of Miami (UM). Over the years, this project has evolved from archival data searches to storm monitoring and dedicated planning. Program focus in recent years has been an effort to support research activities to define the capabilities of RADARSAT-1 as related to hurricane monitoring activities especially regarding extraction of vector wind field information. This paper will describe the overall management of issues related to data acquisition for the program as well as statistics and wind field model results obtained during the 2004 season to illustrate the contribution of RADARSAT-1 data in the study of hurricanes.

Keywords – RADARSAT-1, SAR, Hurricane, Windfield

1. HISTORY

Launched in November 1995 and designed for a five years lifetime period, RADARSAT-1 still continue acquiring high quality images. The satellite, into a dawn-dusk, sun-synchronous orbit offers a 24-day repeat cycle that could be reduced by selecting the multiple modes when available. One of the prime objectives of the mission was to be able to provide an operationally responsive system capable of providing data to the synthetic aperture radar (SAR) user community both in terms of data quality and turn-around time [1]. With the experience gained over the last 10 years, operability of the system and delivery structure is now well known and allows quick response to the end users. In parallel to fast delivery of data, RADARSAT-1 provides the distinct advantage of day/night and all-weather capabilities, allowing it to penetrate clouds and provide ocean surface views from above.

In 1998 attempts were made to acquire RADARSAT-1 imagery over hurricanes as part of the Canadian Space Agency (CSA) "Disaster Watch" program. The program was initiated to provide archival data of catastrophic events such as tropical storms, earthquakes, flooding, volcanic eruptions and others. This first experience gave the opportunity to acquire four images over hurricanes Bonnie, Danielle, Georges and Mitch. The data were subsequently ordered from archive by researchers at the Canada Centre for Remote Sensing (CCRS) to investigate the potential for identifying tropical storm related phenomena using RADARSAT-1 data [2].

Early in the mission it was found that RADARSAT-1 images could provide details about a storm's structure when it is out of range of coastal radars [3]. It was also seen there was the potential to recognize roll vortices in the region between the rain bands of hurricanes. In fact, the large spatial extent of boundary layer rolls was first recognized in RADARSAT-1 imagery [4].

With this in mind and the positive feedback provided by CCRS, efforts were initiated to develop an official CSA Hurricane Watch (HW) program.

Prior to the start of the 1999 hurricane season meetings were held between CSA and the partners of the program to identify roles and develop data acquisition strategies for the HW program. For 1999 and 2000 seasons, CCRS was responsible for monitoring storms and identifying the best-fit RADARSAT-1 acquisitions and plotting potential acquisition swaths, based on preferred beam, geographic location and date. Once the potential acquisitions were identified, the file containing information about the swaths was sent to CSA mission planners (MP) to assess the feasibility of acquisition. An evaluation based on system constraints, existing data requests and pre-defined priorities was made. Requests were submitted with a low priority to be planned on a resource available basis.

As a result of the review at the start of the 2001 season it became clear the process could be streamlined to provide more efficient planning, more effective timing to relevant requests and better status reporting. CSA became the focal point for all planning activities to expedite submission of requests. Additionally, a restricted access web site was developed to provide timely planning information and acquisition result to program partners [5] [6].

For the 2004 season, University of Miami's CSTARS joined the program with two roles. First by providing reception facility for RADARSAT-1 downlinks that improve the range of reception over Atlantic Ocean and the Caribbean Basin (figure 1) and second by processing in near real-time (NRT) the data received to extract the wind speed and directions from the SAR data.

Figure 1: Miami (CSTARS) reception facility coverage

2. OPERATIONAL STREAMLINE

Image planning is performed on a moving 14-day timeline. Within each day there are four sections, referred to as the *Second Half*, *First Half*, *SuperChill* and *Freeze* that are planned according to standard procedures and guidelines. The timeline of these sections is described in table 1.

The minimum time required between request submission and acquisition is 29 hours. This is critical to note when considering the storm forecast is provided for a 3-day (72 hours) or 5-day (120 hour) period. Submissions for HW are based on forecasts that fall within the Superchill timeframe, so two to three days in advance. Any change to the forecast may force changes to submissions, although it may be too late to respond to the new forecast.

Second Half	Starts at 1900 UTC on day 9 and ends at 1900 UTC on day 14
First Half	Starts at 1900 UTC on day 4 and ends at 1900 UTCon day 9
Superchill	Starts at 2100 UTC on day 2 and ends at 2100 UTC on day 3 (today + 2)
Freeze	Starts at 2100 UTC on day 1 and ends at 2100 UTC on day 2 (today + 1)

Table 1.

By using the Canadian Hurricane Center (CHC), the US National Hurricane Center (NHC) and other sources of track predictions, the MP extrapolates the storm trajectory for the Superchill dates. Even if hurricanes trajectory can be rather unpredictable MP focus to hit the eye of the storm multiple times when plotting RADARSAT-1 swaths.

However, getting these eyes is quite a challenge. In some cases, there are potential for RADARSAT-1 acquisition, but the requests either conflict with other higher priority requests, the forecast time is out of range of the Superchill, or the predicted location is outside the coverage swath. In other cases, some storms appear with limited warning and dissipate as quickly.

In several instances storms were monitored and acquisition requests submitted yet the storm dissipated before the acquisition. The limitations of available geographic coverage, lower priority of request and limitation of the On Board Recorder (OBR) resources sometimes makes it near to impossible to submit suitable requests. These facts coupled with the uncertainty of storm activity can keep the overall success rate at a fairly low level as indicated in table 2.

Year	Storms Tracked	Submissions	Eye Hits	Success %
1999	11	33	4	**12.12%**
2000	6	19	2	**10.53%**
2001	26	117	21	**17.95%**
2002	33	124	30	**24.19%**
2003	26	55	19	**34.5%**
2004	23	46	12	**26.1%**

Table 2.

The change in operations between the 2000 and 2001 seasons, when a dedicated planner was assigned to the program, is seen in the increase in the number of submissions, as well as the success rate. During the 2003 season additional changes were made to operations when a team of 4 planners was assigned to the Hurricane Watch task. As seen in table 2, the total number of submissions decreased, but the success rate was higher. The decrease in submissions can be attributed to efficiency of the planning team coupled with fewer number of storms tracked in 2003-2004 than 2002.

3. CSTARS WIND RETRIEVAL MODEL

Even if great progress were made in the last decade to predict more efficiently the track of large intensive storms, it's still difficult to define where it will make precisely landfall. Intensity, size, complexity of hurricanes and the multitude of factors that influence their tracks continue to vex forecasters. In order to improve their predictions, satellite data become essential to improve computer models allowing a better understanding of the internal dynamics of hurricanes, the winds and the other forces that steer them. Researchers are however faced with the difficulty of obtaining data to improve these models. In order to resolve this issue, CSA, with the agreement of Radarsat International (RSI), allowed CSTARS reception facility to process NRT RADARSAT-1 data and provide the products directly to UM during the 2004 season.

CSTARS developed jointly with GKSS Research Center an improved algorithm, which has shown to give good results under low and moderate wind conditions. The algorithm extracts wind directions from wind-induced streaks imaged by the SAR at scales above 200m. Wind speeds are derived from the SAR measured normalized radar cross section (NRCS) utilizing the geophysical model function CMOD5, which describes the dependency of the NRCS on wind. Applications to the RADARSAT-1 data demonstrated that the algorithm is capable to determine wind directions as well as wind speeds of over 50 ms-1.

Wind retrieval from C-band SAR images is accomplished in two steps. The first step extracts wind directions from wind induced streaks visible in SAR images at scales >200m and are needed as input for determining the wind speed. Wind speeds are retrieved from the normalized radar backscatter intensity of the ocean surface employing a model function, which relates the radar backscatter to the wind speed for different radar imaging geometry.

3.1 SAR Wind Direction Retrieval

The most popular methods for SAR wind direction retrieval are based on the imaging of linear features. Most of these features are associated to wind streaks [7] and marine atmospheric boundary layer (MABL) rolls [8], which are visible in SAR images. Studies of [9] utilizing high resolution real aperture radar imagery have shown that wind induced streaks at scales above 100 m are aligned within ~14° of the mean surface wind direction. Here we assume that linear features visible in the SAR images are always aligned with the mean surface wind direction. Applying SAR wind direction retrieval to features with scales > 3 km are often related to MABL rolls, which can significantly differ from the mean surface wind direction [8].

The orientation of the linear features visible in SAR images are derived with the Local Gradient Method (LG-Method) ([10]; [11]), which is applied in the spatial domain. The LG-Method is based on the retrieval of the local directions, defined by the normal to the local gradient. The directions are retrieved from SAR images by smoothing and reducing the resolution to 100, 200 and 400 m. An additional step is applied to all pixels that are affected by non-wind induced features (e.g. land, surface slicks). These pixels are masked and excluded from further analysis by utilizing high resolution land masks and SAR image filters ([11]). From all of the resulting directions only the most frequent directions in a predefined grid cell are selected. The 180° ambiguity can be removed if wind shadowing is present, which is often visible in the lee of coastlines. If such features are not present in the image other sources, e.g., weather charts, have to be taken into account.

3.2 SAR Wind Speed Retrieval

For wind speed retrieval, an empirical model function relating the NRCS of the ocean surface δ_o to the local near-surface wind speed u, wind direction versus antenna look direction Φ, and incidence angle θ is used. The general form of these functions is:

$$\delta_0 = A(\theta)u^{\gamma(\theta)}\left(1 + B(u,\theta)\cos\Phi + C(u,\theta)\cos 2\Phi\right)$$

where A, B, C, and γ are coefficients that in general depend on radar frequency and polarization. The resulting empirical C-band models CMOD4 ([12]) and CMOD5 ([13]) are only applicable for wind speed retrieval from C-band images acquired at vertical (VV) polarization, e.g. [14], [15], and [16]. For wind speed retrieval from RADARSAT-1 SAR images, which are acquired at HH polarization, a C-band polarization ratio (PR) must be applied. While several studies have been carried out to determine a suitable PR ([17]; [18], [19]; [10]; [20]), no definitive conclusions have been reached on the correct ratio to be applied. Because the CMOD4 model is limited to wind speeds less than 30 ms^{-1}, this model function was not apply for retrieving SAR winds. For the CMOD5 model a straight forward inversion does not work because at high wind speeds and small incidence angles the model is ambiguous. To take into account the ambiguities as well as other problems arising with the inversion approach, a neural network (NN) was trained. The resulting NN retrieves from the radar backscatter, incidence angle and wind direction two wind speeds of which one has to be selected. In most cases the lower wind speed is the correct solution.

4. RESULTS

During the 2004 hurricane season ten RADARSAT-1 SAR images of tropical storms and hurricanes were collected at CSTARS. Vector wind fields were produced for all RADARSAT-1 SAR images depicting partial or full hurricane eyes. Fig. 2 shows the resulting wind field of hurricane Ivan as it passed Jamaica on 10 September 2004. The wind directions were retrieved from wind induced streaks using the Local Gradient method and the wind speeds utilizing the CMOD5 model which utilizes the local SAR retrieved wind direction, radar backscatter and incidence angles as well as an incidence dependent polarization ratio.

The CMOD5 model as well as the SAR image data (Fig. 3) shows that at high wind speeds (> 30 ms-1) there is only a very small change in radar backscatter, which is significantly different to the predictions given by the CMOD4 model. The sheltering effect of the mountainous region of Jamaica is clearly visible in both figures showing reduced winds in the western part of the island and as well as darker backscatter values in the SAR image. The strong decrease of the wind speeds in the near range (left side of image) are due to power loss, a calibration issue of the RADARSAT-1 SAR system, which can be partially removed by additional SAR processing steps that were not implemented in the 2004 season.

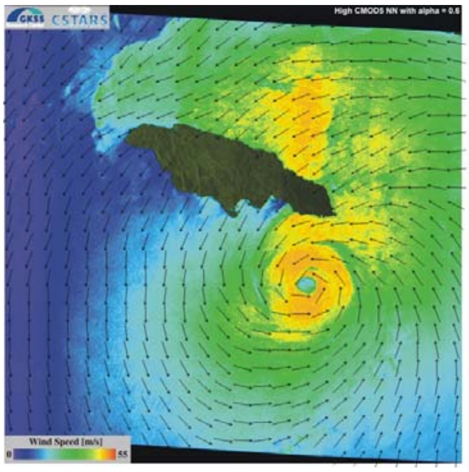

Figure 2: Wind field of hurricane Ivan using the NN inverted CMOD5 model for wind speed retrieval. Wind directions were retrieved on a 15 km resolution and wind speeds with a 200 m resolution. © CSTARS 2005

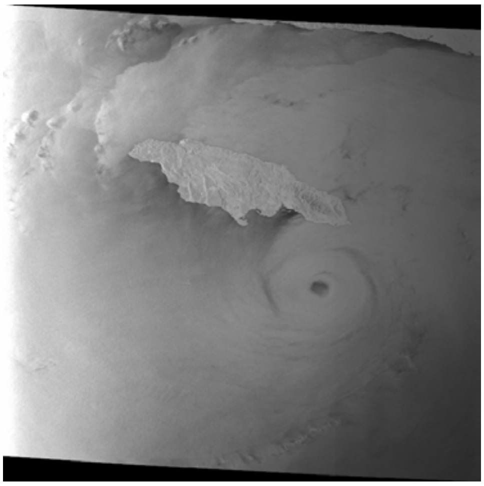

Figure 3: RADARSAT-1 Scan-SAR B image of Hurricane Ivan captured on 10 September 2004 at 2307 UTC as it approached Jamaica from the south. © Canadian Space Agency 2005

For comparing the SAR retrieved wind fields we used winds from a high-resolution tropical cyclone prediction model. The numerical model is initialize by considering hurricane analyses generated by using the AOML's Hurricane Research Division Real-time Hurricane Wind Analysis System (H*WIND). H*WIND ingests real-time tropical cyclone observations measured by land, sea, space and airborne platforms into an object relational database and generates high- resolution snapshots of hurricane wind analysis [21].

The use of these snapshots is the basis for the tropical boundary layer model (TC96) wind analysis system. The interactive objective kinematic analysis (IOKA) methodology [22 is capable to evolve in space and time the sub and mesoscale features in a developing cyclone such as surface wind jet streaks. Currently ingestion occurs at times when the H*WIND analyses were available. These snapshots can be incorporated at arbitrary times and on arbitrary grid spacing. A moving features time interpolation routine is used to preserve the system's circulation and prevent smearing of the interpolated wind fields. These snapshots are then blended into a background wind field using the IOKA objective analysis routine.

Performing the comparison we averaged the SAR retrieved wind vectors to the same resolution of the tropical cyclone prediction model which corresponds to a grid cell size of 15 km x 15 km. The numerical model results were available every 30 minutes. In order to represent the actual time of the RADARSAT-1 pass, the model wind fields were interpolated to the exact SAR image acquisition time. In Figure 4 the scatter plots of the comparison between the SAR retrieved winds and the model results are presented.

The comparison of wind directions gives a correlation coefficient of 0.95 with a bias of -1.2° and a root mean square error (RMS) of 19°. The comparison of SAR-retrieved wind speeds using the CMOD5 model function yields a correlation coefficient of 0.72 with a bias of -0.27 ms^{-1} and a RMS error of 3.75 ms^{-1}

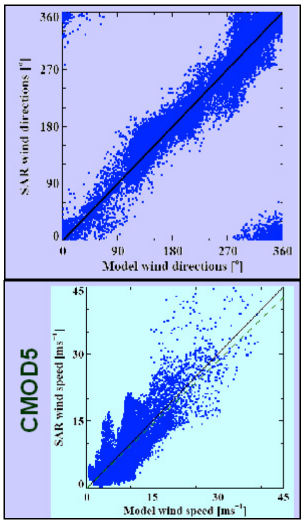

Figure 4: Scatter plot of SAR retrieved winds using the CMOD5 model function with winds from a tropical cyclone model. Top: Wind direction. Bottom: Wind speeds.

5. CONCLUSIONS

While RADARSAT-1 data at this time has not yet played a critical operational role relative to hurricane forecasting, we are able to monitor storms and provide data and wind fields in near real time that can be used to further research into tropical storm characteristics and development.

In the last 6 years CSA have built a program that is used to successfully monitor storms, identify and submit best-fit acquisitions and provide timely planning information to the HW partners. CSA have been able to take a certain level of serendipity out of the observations by creating a focused hurricane watch team responsible for storm monitoring and request submission [23].

A new algorithm for SAR wind field retrieval has been utilized to retrieve wind fields from SAR images of tropical storms and hurricanes. The algorithm computes the wind directions from wind-induced streaks using a methodology based on the local gradients. The SAR derived wind directions agree very well with model directions predicted by a tropical cyclone prediction model. The newly implemented CMOD5 model enables retrieval of significantly higher wind speeds especially for ones above ~20ms^{-1}. Investigation of the backscatter around the hurricane eye showed that the CMOD5 model describes the dependency of the normalized radar cross-section (NRCS) on wind speed and wind direction significantly better, especially for wind speeds stronger than tropical storm force (~17 ms^{-1}).

The collaboration between CSA and CSTARS in the Hurricane Watch program clearly demonstrated that it is feasible to provide operationally high-resolution wind field vectors within

45 minutes of reception to the National Hurricane Center (NHC). The SAR images and wind fields provide unprecedented details of tropical cyclones especially near the eye that is not available from other satellite remote sensed fields such as scatterometers and passive microwave radiometers.

These results provide incentive to continue the program and provide the SAR wind fields in near real time to the NHC during the 2005 hurricane season. Through the support from our partners the continued collection of RADARSAT-1 data of hurricanes and tropical storms will allow further improvement of our knowledge on hurricane characteristics and timely delivery of products which would help in disaster preparation and ultimately save lives.

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