## **CHAPTER 10**

### RADAR OBSERVATIONS OF HURRICANE WAVE DIRECTIONS

by

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#### ABSTRACT

This paper presents an analysis of data collected in a hurricane wave research program. The data were collected with a synthetic aperture radar (SAR) during five aircraft flights into hurricanes in August and September, 1976. These data are the first collected on the directional distributions of waves throughout the region of active generation.

The wave patterns in all of the storms are similar and show a marked radially asymmetry. The dominant waves propagate ahead of the storm in a broad arc that has an apparent center in a region of confused sea to the right and rear of the hurricane eye. The asymmetry in the wave patterns is attributed to the forward motion of the storms. The wave directions throughout the storms do not show a sensitive dependence on the forward speed of the storms or on their maximum wavespeeds. However, there is an increase in peak wavelength with increasing windspeed and forward velocity.

### Introduction

Hurricane waves play a controlling factor in the design of permanent structures along the Gulf and East Coasts of the United States and in other parts of the world. In spite of their importance, they are poorly understood and often not acequately predicted. This lack of understanding is due partially to the difficulty of data collection and partially to the fact that the wave generation process is not completely understood, even for the case of simple windfields.

Some of the first research on hurricane waves was conducted by Tannehill (1936). He, along with Arakawa (1954) and Pore (1957) compiled information on hurricane wave heights and directions collected from shipboard observations. This technique has not been followed up by other researchers because the frequency and the nature of the observations rendered them inadequate for an understanding of the processes involved.

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Few other measurements were collected until recently, when two large programs were initiated. The first, in the late 60's and early 70's, involved the instrumentation of offshore oil platforms in the Gulf of Mexico (See Ward (1974)). The second is a continuing project by the NOAA Data Buoy Office in which deep water environmental buoys have been moored at various offshore locations along the U.S. coasts. These buoys have recently encountered several hurricanes (See Withee and Johnson (1975), Johnson and Speer (1978) and Johnson and Renwick (1978)). Most of the reported wave height measurements are in the form of time histories of significant wave heights and dominant periods showing variations during periods when storms pass by or over the measurement sites. More recently, data revealing the directional nature of waves were analyzed and directional wave height spectra were reported (See Forristall et al (1978)). However, these results are restricted to only one site. The data do not reveal the directional distributions of wave fields over the entire region of hurricane influence.

### The Aircraft Hurricane Program

In August and September 1976, and again in October 1977, the Jet Propulsion Laboratory (JPL) participated in a hurricane research program with a number of other NASA research centers and with the NOAA — National Hurricane and Environmental Meteorological Laboratory. JPL collected information on the directional properties of hurricane waves using a Synthetic Aperture Radar (SAR) onboard a NASA CV-990 research aircraft. The 1976 flights were made into Tropical Storm Emmy on August 24 (designated as Emmy 1 in this paper), Hurricane Emmy on August 25 (Emmy 2), Hurricane Frances on August 31 (Frances), Tropical Storm Gloria on September 28 (Gloria 1), and Hurricane Gloria on September 30 (Gloria 2). These storms were all in the western Atlantic. The flight tracks and storm paths are shown in Figure 1. Approximately 700 minutes of data was collected in these five storms. Table 1 lists the important parameters associated with each storm.

On October 5, 1977, the JPL-SAR collected data in Typhoon Heather in the eastern Pacific. Images have also been obtained with the Seasat-1 SAR from Typhoon Fico on July 15, 1978. Data from these two storms are not included in this paper but preliminary analysis shows that their wave patterns are in good agreement with the data presented here.

### The Synthetic Aperture Radar (SAR)

The data presented in this paper represent the first extensive collection of directional wave data throughout the region of hurricane influence. The data were obtained with the SAR, a sensor that provides all weather images of the sea surface topography during day or night. The images are similar in appearance to photographs of the sea surface. The SAR transmits a microwave pulse in the L-band region (23.0 cm wavelength) and records the intensity and phase history of the signal returned from the sea surface. This information is then converted



Table 1. Important hurricane parameters associated with hurricanes Emmy 1 and 2, Frances and Gloria 1 and 2. The parameters are representative for the periods from 18 hours before SAR data collection to 6 hours after SAR data collection.

Hurricane	Emmy 1	Emmy 2	Frances	Gloria l	Gloria 2
Date	Aug. 24	Aug. 25	Aug. 31	Sept. 28	Sept. 30
Time of Collection (GMT)	15:34- 19:23	15:20- 16:48	15:13- 18:24	16:46- 17:45	15:58- 20:14
Max Winds (kn)	60	65-70	75-85	60-65	85-95
Min Pressure (mb)	995	990	975-963	992-988	980
Forward Speed (kph)	14-20	24-27	20-22	10-12	27-28
Heading	Turn NW-NE	Е	N	NW	NE
Radius of Gale Force Winds (nm)	225	225	225	175	250

through the use of an optical correlator to an image of the sea surface. Figure 2(a) is an example of an image showing surface waves.

The SAR has many advantages over optical photography. Operating at L-Band it can penetrate cloud cover and, being an active system, it is independent of solar illumination. The image can be further processed to yield the wave phase-speed and to resolve the  $180^{\circ}$ ambiguity in the direction of wave propagation. The imaging characteristics of the SAR and its application to oceanography has been the subject of intensive investigations recently (See for example Shemdin et al (1978)).

A two-dimensional spectral transform of the SAR image provides a convenient representation of the wavelengths and corresponding directions that appear in a wave image. The Fourier transform of the image shown in Figure 2(a) is given in Figure 2(b). The center of the transform represents an infinite wave length (or zero wave number). The wave direction is determined by the azimuthal angle of the two spectral peaks which are symmetrically aligned with respect to the origin.

## Observed Directional Wave Patterns in Hurricanes

Figure 3 shows processed SAR wave imagery at selected locations throughout Gloria 2. Each wave image is enlarged ten times relative to the hurricane scale. The direction of hurricane forward motion is to the top of the figure. For comparison, all the hurricane flights were oriented in this manner, regardless of the direction of true north. These images are placed in their proper location relative to the moving eye of the hurricane. Fourier transforms of each of the wave images in Figure 3 are shown in Figure 4. The transform scale is shown in the lower right hand corner of Figure 4. The innermost circle designates 300 meter waves, the next innermost designates 250 meter waves, then 200, 150, and 100 meter waves. The outside edges of the transforms are at 75 meter waves.

The striking feature of Figures 3 and 4 is the pronounced asymmetry in the wave field. There is an arc of waves which extends from the right front quadrant through the left front and into the left rear quadrant. The waves along the arc are propagating outward from the storm center. The hurricane winds are blowing in a counterclockwise spiral and thus the dominant waves in much of the storm are traveling at  $90^{\circ}$  or more with respect to the local wind direction. This is shown in Figure 5. The arc appears to have its center in the right rear quadrant but there is no distinct origin. Instead, the wave patterns in this area suggest a confused sea. The Fourier transforms show multiple dominant peaks which are traveling in different directions.

The pronounced asymmetry in the wave field is caused primarily by the forward motion of the hurricane. The counter-clockwise winds (for northern hemisphere storms) blow faster on the right hand side of a



# DIGITALLY CORRECTED SAR WAVE IMAGERY



HURRICANE SCALE

RELATIVE TO HURBICANE SIZE

Figure 3. SAR wave patterns in hurricane Gloria 2.

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# HURRICANE GLORIA 30 September 1976 DIRECTIONAL SPECTRAL WAVE TRANSFORMATIONS



Figure 4. Fourier transforms of Gloria 2 wave images shown in Figure 3.





moving hurricane than on the left due to the added speed of the storm. This causes larger waves to be generated in this area. However, more importantly, these waves tend to travel with the storm and so stay in the generation region much longer. These dominant waves then propagate throughout most of the storm depending on the group velocities and directions of propagation.

In comparing the wave patterns in different storms, it is necessary to know how the meteorological parameters vary in different storms. A comparison of wind speeds, central pressures, forward speeds, headings and radii of gale force winds are given in Table 1 for the five 1976 flights. The maximum wind speeds and hurricane forward speeds are likely to play important roles in the wave generation processes. A spread in these two parameters for the hurricanes shown would have been desirable. Unfortunately, this was not the case. All of the storms were of weak to moderate intensity (max winds of 60 to 90 knots) and of a moderate to medium forward speed (11 to 28 kph). Also, the slower storms had lower windspeeds and the faster storms had higher windspeeds, making it impossible to determine the relative importance of these two parameters. However, the wavefields show variations which can be related to these two parameters. Gloria 1 was the slowest moving storm. The next slowest was Emmy 1 whose wave pattern was complicated by the fact that she was in a 90° right turn during the time of data collection. Then in ascending order were Frances, Emmy 2 and Gloria 2. The maximum wind speed follows the same ascending order with the exception of Frances and Emmy 1 which are reversed.

Figures 6, 7, and 8 show spectral transforms from the five flights taken in the left-front, the right-front, and the right-rear quadrants, respectively. The transforms were taken in areas that appeared interesting and in which data from most of the storms were in close proximity. Table 2 summarizes the information in Figures 6, 7 and 8.

The left-front quadrant (Figure 6 and Table 2) is a typical example of the waves that propagate outward ahead of the storms. The directions of wave propagation in all of the transforms are in close agreement and within the uncertainty limit of determining the true heading of each storm. The peak wavelengths vary in close agreement with variations in intensity and forward speed of storms, the more intense and faster moving storms have longer wavelengths. The one anomalous point is Emmy 1, which may be due to the fact that Emmy 1 was in a turn.

The transforms in the right-front quadrant (Figure 7 and Table 2) exhibit the longest dominant waves compared to other regions of the storm. In this quadrant the wave propagation directions are in good agreement. Some variation is observed but is attributed to the spatial separations of the areas analyzed. As in the left front quadrant, the peak wavelengths again vary with the forward speed of the hurricane and its maximum wind speed.





Figure 7. Fourier transforms of waves in the right-front quadrant in five hurricanes.



Figure 8. Fourier transforms of waves in the right-rear quadrant in five hurricanes.

Table 2. Dominant wave lengths and wave directions measured for five hurricanes in left-front, right-front, and right-rear quadrants.

	Peak Wavelength (in meters)	Direction ( <u>+</u> 20 <sup>0</sup> )
LEFT FRONT QUADRANT		
Near 100 km, $315^{\circ}$ from storm center		
Emmy 1	275	300 <sup>0</sup>
Emmy 2	190	3200
Frances	230	3100
Gloria 1	160*	3150
Gloria 2	275	320 <sup>0</sup>
RIGHT FRONT QUADRANT		
Near 40 km, 80 <sup>0</sup> from storm center		
Emmy 1	250	50
Frances	300 275	3450 3200
Gloria 1	125*	3250
Gloria 2	275	350 <sup>0</sup>
RIGHT REAR QUADRANT		
Near 60 km, 140 <sup>0</sup> from storm center		
Emmy 1	160	335 <sup>0</sup>
Frances	250 210	50 1200
Gloria l	100	10 <sup>0</sup>
Gloria 2	280 120	800 300

\*Poor quality images; wave lengths inferred.

The right-rear quadrant (Figure 8 and Table 2) has different properties because it shows little agreement among different hurricanes in wave direction, in contrast to the other two regions examined. It is difficult to determine the causes of the diversity observed. However, it is reasonable to conclude that this region deserves special attention in future modeling efforts and in future data collection missions. Nevertheless, in spite of the apparent confusion in the wave directions in this quadrant, the dominant wavelengths tend to vary with the maximum wind speed and forward speed parameters.

Thus based on dominant wavelengths in three different quadrants the hurricanes under study fall into the following ascending order: Gloria 1, Emmy 1, Frances, Emmy 2, and Gloria 2. There are two exceptions. Emmy 1 is out of this order in the left-front quadrant and Frances and Gloria 2 are reversed in the right-front quadrant.

The correlation between increasing wind speed and dominant wavelength is straightforward and in agreement with known wave generation theories. The argument for an observed correlation between increasing forward storm speed and wave length is more subtle. As waves are generated in the right-hand side of the storm, those that are correctly aligned will travel in the same direction as the storm. These waves are generated over a spectrum of wavelengths and, as such, have a spectrum of group velocities, some slower and some faster than the storm. The generated waves will either lag the storm forward motion and increase in height to saturation through breaking or travel faster than the storm and appear as waves ahead of the storm. The dominant waves, however, are likely to be those waves which extract maximum energy from the wind through elongated residency in the region of intense wave generation. The latter is determined by the difference between the wave group velocity and forward speed of the hurricane. Also, nonlinear interaction plays an important role in affecting energy transfers across a wave spectrum. In an active generation region the frequency of the spectral peak shifts continuously to lower frequencies. The processes of atmospheric transfer, dissipation and nonlinear transfer must all be correctly simulated in a moving circular storm pattern in order to predict the observed directional wave pat-It is clear that this type of analysis must now follow. Howterns. ever, it is possible to infer that the dominant waves are likely to have wave lengths longer than those which are resonant with the hurricane forward speed. Such inference is consistent with Figure 9 and Table 2 which indicate that the dominant waves are considerably longer than those which are resonant with the hurricane forward motion.

### Summary and Conclusions

In summary, this paper presents a unique data set on the directional distribution of wave fields in hurricanes, and as such it provides an insight into the configurations associated with such wind fields. However, it also opens the question of why these wave fields are as they appear. The paper introduces in a qualitative manner certain hypotheses on the generation processes in hurricanes. It also



Figure 9. Comparison of hurricane forward speeds amd equivalent wave lengths having equal group velocities.

lay the ground for a logical follow-on analytical effort, namely that of modeling the generation processes through the use of numerical techniques.

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