TRACKING ANALYSIS OF HURRICANE GONZALO USING AIRBORNE MICROWAVE RADIOMETER

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ABSTRACT

There is a huge consideration in the use of microwave airborne radiometry for remote sensing instead of satellite, the important role of airborne way is how to provide high accuracy real time data. The airborne hurricane tracking is an important method compared with the space borne method, which is developed by NASA Marshall Space Flight center to provide high resolution measurements. By flying special aircraft equipment using synthetic thinned array radiometry technology and included all critical measurements such as hurricane eye location, speed of wind and the pressure. This paper describes the data analysis of best track positions for Hurricane Gonzalo based on the date collected by airborne microwave radiometry. Significant analysis comes from comparing the airborne data with the surface observations from ship reports. The vast majority is to estimate peak intensity and minimum central pressure of Gonzalo from 12 to 19 October 2014, based on blend of SFMR flight-level winds and pressure retrievals from observing brightness temperatures. SFMR: Stepped-Frequency Microwave Radiometer is a highly developed tool developed by the Langley Research Center that is designed to measure the wind speed at the ocean's surface, and the rain fall rates within the storm accurately and continuously. The work also addresses the realistic details of the locations and the valuable information about the pressure and wind speed, which is very critical to predict the growth and movement to get the idea for future monitoring of the hurricane disasters. Also presents a conceptual of step frequency microwave radiometer in airborne side. The objective of this research is tracking analysis techniques based on comparing the satellite, ship and airborne reports to get higher accuracy. The system operates at four spaced frequencies in the range between 4 GHz and 7 GHz provides wide measurements between ± 45 incidence angle. Gonzalo 2014 is an example; the best results of retrieved wind speed, locations and pressure are presented. There are several national projects have been developed for earth observation, such as fire, hurricane and border surveillance. In this work, the efficient high resolution techniques of C-band, four-frequency, the work also addresses a valuable information comes from the airborne system and the prediction way of the growth and movement of hurricanes. In passive microwave remote sensing from space at C band has the penetrating advantages of atmosphere. Airborne system is able to work in full Polari-metric in four bands, C, X, S, L and P-band, which cover the wavelengths from 3 to 85 cm. The modes of measurement contain single channel operation wavelength and polarization.

KEYWORDS

Passive microwave radiometer, airborne instrument, remote sensing, SFMR and Hurricane tracking

1. INTRODUCTION

The airborne hurricane tracking and surveillance is a very significant method compared with space borne method which is developed by NASA and improved the accuracy by about 50% since last decade greatly by using special remote sensing techniques. Because it provides a real time data by flying special aircraft equipment included all critical measurements such as hurricane eye location, wind speed, directions and the pressure value. These reports are done by (NOAA) National Oceanic and Atmospheric Administration, Hurricane research Division.

According to the NOAA National Hurricane Center, Hurricanes caused more destruction in the US than any other kind of natural disaster. The accomplishment is to minimize the social and economic impact of hurricanes is over a variety of measurement techniques, such as using airborne and space borne. This is the best way to predict the growth and movement of hurricane as they develop and make landfall. In 2014 airborne devices are effectively taken all the details observations of Hurricane Gonzalo over three consecutive days. At that time satellite observations specify that Hurricane Gonzalo underwent two complete eyewall replacement cycles. These observations verify past observations of secondary, the second secondary eyewall developed a similar circulation as seen on the day before but with weaker winds. Airborne radar measured valuable information in Gonzalo area about the actual precipitation, wind speed and pressure, thus reducing the spin-up problem that usually impacts the beginning of the forecast period. Figure 1 shows the hurricane airborne radiometer. [1]

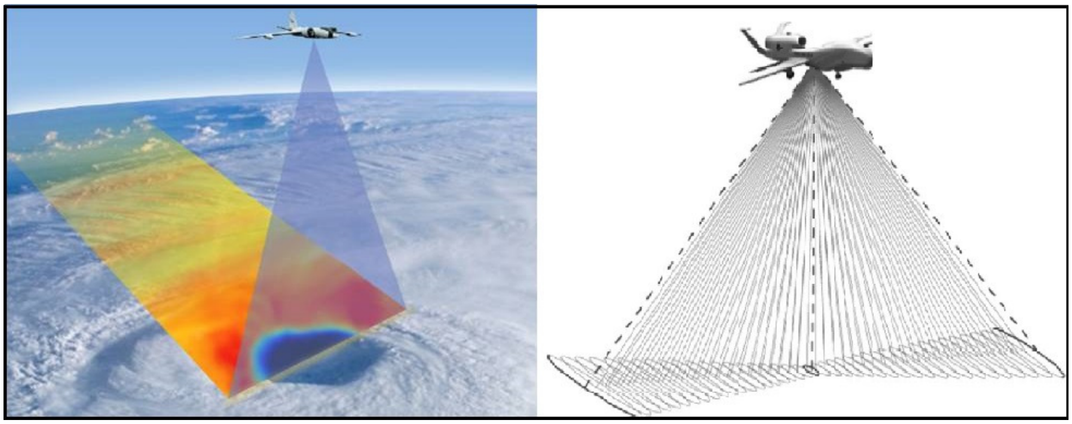

Figure 1, the airborne microwave radiometer.

In the U.S, the weather events, such as hurricane location is very important natural threats to coastal areas and maritime interests. There are several tropical storms formed and some of them became hurricanes, which are developed to category three or higher up to five, monitoring and tracking at high resolution are critically needed for research on hurricane and for improvement in intensity forecasting. The airborne radiometer is one of the dominant methods because the space borne cannot fully overcome the difficulty. Although the WindSat and QuikSCAT instruments are provide wind speed measurements on a global scale, but they are partially limited to ocean surface wind measurements. The big challenge in the implementation of Doppler wind is the retrieval algorithms for space borne radars. Also the space borne measurements has a low spatial resolution compared with the airborne method. Due to these limitations of spaceborne which are not covered in this paper, now the attentions of most researchers over the past decade on either an airborne system which is great interest or an orbit satellite. A large number of radiometer systems have been developed and work in various aircraft to provide the full wind vector, pressure and cloud regions. Such as NOAA and NASA operate several aircraft to sample and observe the hurricanes. [2] The airborne techniques works at C-band microwave frequency range at 4-6 discrete C band frequencies as shown in figure 2. The passive remote sensing approach is to measure the emissivity, or the temperature that emitted from surface of the water foam coverage which is a parameter for wind and the rain. These physical characteristics permit to be derived from emissivity measurements, wind speed and rain retrievals are derived from empirical correlation of measured emissivity at working incidence angles. The value of the measured wind is approximately invariant with frequency while at the same time rainfall emissivity is a strong function of frequency. Which is accepted functional relations for the attenuation of frequency vs rain and wind emissivity. [3]

There are measurements available at specific times in the Atlantic basin from sensors attached on research aircraft, but not in other hurricane basins have ability of aircraft exploration. Even the hurricanes in the Atlantic are out of range of the aircraft for most of their lifetimes.

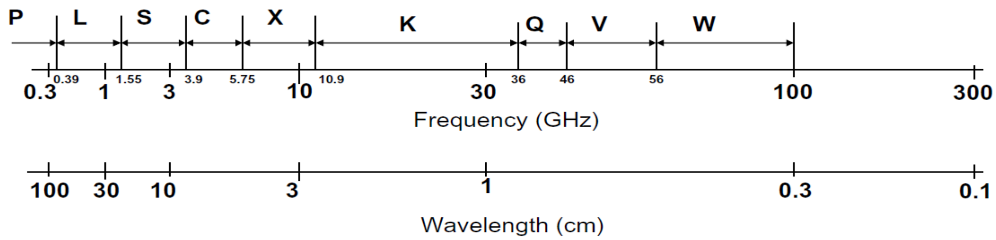

Figure 2, Microwave region of the electromagnetic spectrum

Currently the measurements of the surface wind and pressure with high resolution, wide swath would strongly improve model initialization and result analysis. The goal is daily mapping of the surface wind field from the center of the storm in the distance of maximum winds located in the eyewall. This will be the most key contribution that could be made from airborne microwave remote sensing. [4] For the past two decades, the only way of remote sensing that can provide a real time continuous measurement is Airborne Stepped Frequency Microwave Radiometer, which is providing wind speed and rain rates in hurricanes including category 5 conditions. But the narrow measurement swath below the aircraft is present disadvantage of SFMR. Hurricane Research Division of NOAA uses the Stepped Frequency Microwave Radiometer, to provide measurements of the maximum one minute sustain wind. This is the dominant factor in hurricane category. Currently SFMR is the most reliable surface wind speed measuring instrument in hurricane surveillance. That makes NASA developed several airborne and spaceborne projects for that target such as HiRAD. SFMR will be allowed to measure wind speeds up to 85 m/s (category 5 hurricane and utilizes six different frequencies in the C-band region to perform its measurements as shown in figure 3. Which is presents the all parameters.

Freq. (GHz)	4.0	5.0	6.0	6.6
Antenna spacings (in units of λ)	.305	.381	.457	.503
IF Bandwidth	62.5 MHz			
IF Subbands	16			
# Array Elements	10			
# Antenna Pairs	45			
# Unique Baselines	36			
Sampling Frequency	150 MS/s			

Figure 3, NASA - Parameters of the airborne system [5].

The collaboration with NOAA's, Atlantic Meteorological Laboratory leds The NASA aircraft instrument has been developed over the past years under Marshall Space Flight Center. This work deals with the data analysis of remotely sensed wind speed and pressure, which is second object in hurricanes, based on data given by MSFC. This project is an airborne passive microwave synthetic aperture radiometer designed to provide wide swath images of ocean surface wind speed under heavy precipitation.

This aircraft flew on high-altitude aircraft over hurricanes Gonzalo Dec 2014, the instrument operates at C band 4, 5, 6 and 6.6 GHz and uses the interferometric signal processing with no mechanical scanning. There is a planar antenna is composed of linear arrays of multi-resonant radiators, And can provide four-frequency images of brightness temperature about 60 km swath width with 3 km spatial resolution. Each linear array viewed as an individual element of beam antenna. After each beam element there is an individual receiver contain internal calibration for both hot and cold loads. Also, it distributed a single noise diode to all receivers for correlation and to calibrate the interferometric measurements. [5], [6]

2. PASSIVE VERSUS ACTIVE MICROWAVE SENSING

The microwave sensing can be divided into two major types: passive, known as radiometers, and active, known as radars, see Figure 4. Both classes of sensors have been used on aircraft and spacecraft to study the Earth and the other planets.

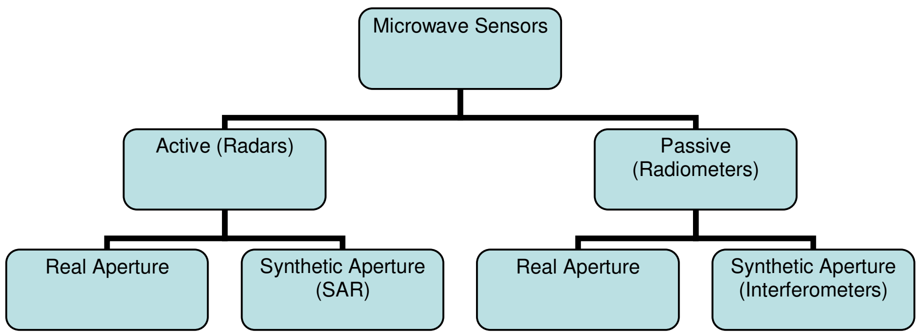

Figure 4, major classes of microwave remote sensors.

First of the active (radar) is divided into two general types the first one is the real aperture which is divided in to; scatterometers altimeters, and weather radars. The second synthetic aperture radar (SAR) systems SAR systems are radars designed to make high resolution radar images. They operate by transmitting modulated pulses and using Doppler/range processing to construct backscatter images. Typically, they are not as well calibrated as scatterometers. Scatterometers are designed to measure radar backscatter very precisely, but typically have lower resolution than SARs. They tend to be less complicated than SARs. Altimeters are radars designed to measure height or distance, though other information such as radar backscatter is extracted from the echo. Weather radars are specially designed scatterometers which have ranged capability.
They are designed to measure rainfall and other meteorological phenomena. On the other hand, for the Passive radiometers, it deals with the thermal emission which produced by the microwave signals comes from objects. The emission is comes from the electrical properties, physical temperature that is sensed from the surface. In addition the passive sensors cost less power since it does not contain transmitter [7], [8].

3. AIRBORNE VERSUS SPACEBORNE SENSING

There are many operational differences between airborne and spaceborne platforms. Each type of platform has important strengths and weaknesses which must be considered when designing a remote sensing-base solution to a particular problem The first microwave sensors were ground-based, but aircraft-based applications quickly followed. Microwave radar systems were first deployed on aircraft in World War II and microwave sensors flew aboard spacecraft early in the space age. Ground-based microwave sensors have been widely used in astronomy and weather. Currently, some of the most important Earth sensing microwave instruments is based on spacecraft.

Spacecraft basing offers a number of advantages over aircraft-basing, including much broader spatial (often global) and temporal coverage. Airborne platforms can respond easily to changes in weather and cloud cover. On a day-by-day basis, flight planners can modify flight plans to accommodate these changing, uncontrollable conditions. Multiple aircraft can easily work on a single project, ensuring that over large contiguous areas, the size of counties and even states, remotely sensed data can be acquired in a matter of days or weeks. Acquired data can be reviewed on a near-real-time basis by crews in the field; areas requiring reflight can be discovered before the platform leaves the project area. Finally, any problems that may occur with the sensor, or upgrades that may become available from the sensor manufacturer during the lifetime of the sensor can be easily implemented during downtime between projects. This ensures that consumers of remotely sensed data always have access to the most current technological advancements. Satellite-based remote sensing was initiated during the 1950's and was originally proposed for military and defense-related applications. Scientific instruments, such as Landsat and Modis, developed and maintained by civilian government agencies, collect low to medium resolution imagery for a myriad of research and operational applications, including environmental, resource management, planning, and disaster response. Commercial high-resolution satellite-borne systems, such as SPOT, IKONOS and QuickBird, now contribute panchromatic and multi-spectral imagery at up to .60 cm GSD to the broad remote sensing community. One could jump to the conclusion that the future of airborne remote sensing is limited, and that satellites are the dominant sensor platform of the day. That, in fact, has not been the case, and a basic understanding of the operational mechanics of satellite platforms will reveal the reason [9]. Figure 5, shows the main difference between the airborne and the spacebourne.

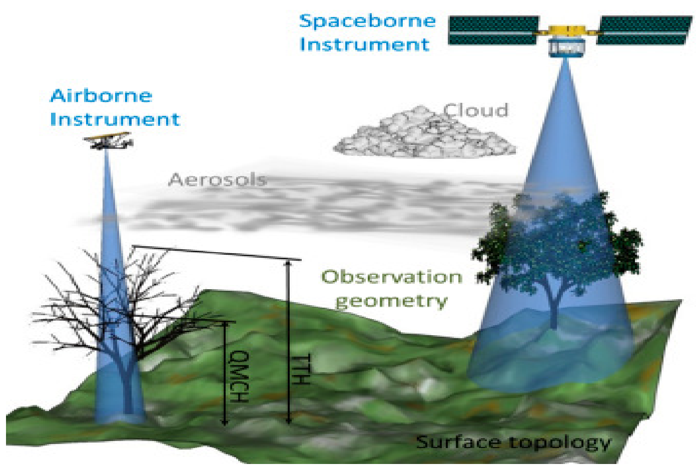

Figure 5, airborne and the spacebourne instrument.

4. PASSIVE MICROWAVE SENSING RADIOMETRY

The passive Microwave radiometers measure the thermal emission, sometimes called the Plank radiation, radiating from natural objects see figure 6. As passive sensors they require no transmitter, but are receive-only. As a result, radiometers require less power to operate than radars. The passive radiometry is related more to the IR sensors and classical optical more than to radar, it is also called radiometers which can be divided into three categories such as, surface feature profiles, imagers of surface features, and sounders of atmospheric profiles of temperature, The energy detected by a radiometer at microwave frequencies comes from two source the first one is emission of the target in addition to that, thermal emission that arrives at the radiometer is the reflection of the target after it goes through the sky. The main difference between the thermal emission and microwave frequencies, the first one depends on the product of the target emissivity and its absolute temperature. On the other hand, the microwave frequencies depend on is the changing in emissivity but not the change in temperature [7].

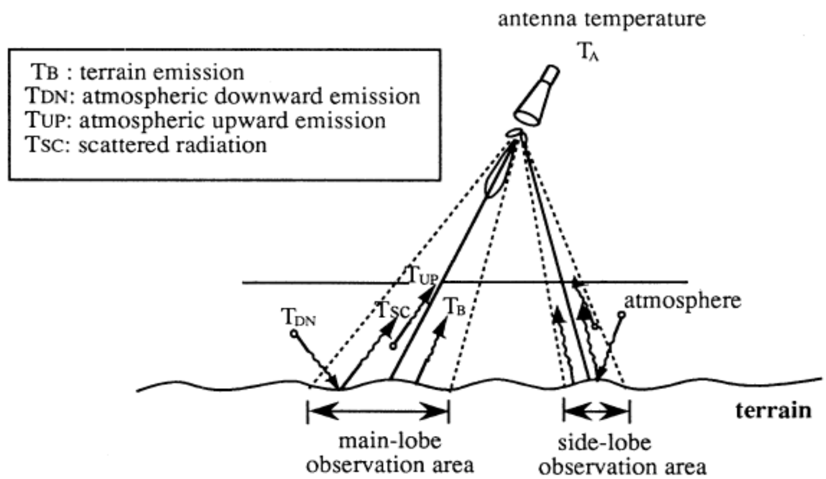

Figure 6, basics of passive microwave radiometry.

4.1 Brightness temperature

The brightness temperature or it can be called radiometric temperature of the source is the most important parameter to be measured in passive radiometry. The brightness temperature of an object is the temperature of a blackbody with the same brightness as the object sensed.
In order to explain the emissions from the earth, it is important to describe the main reflected temperatures through the earth and the atmosphere. Figure 7, shows the main reflected temperatures. The temperature, which is seen by a microwave radiometer apparent brightness temperature T_{app} is a result of the following temperatures

1. T_{sur}: is the sea surface brightness temperature.
2. T_{refl}: is the sum of the cosmic background (T_{cos}) contribution, the reflection from the sea surface and the down welling brightness temperature (T_{DOWN}).
3. T_{UP}: the upwelling atmospheric brightness temperature

While at the radiometer antenna the T_b components represent the combination of the non-coherent (powers add).

$$T_{app} = T_{UP} + e^{-\tau}(T_{sur} + T_{refl}), Kelvin$$

Where, $e^{-\tau}$ represent the total one-way atmospheric transmissivity. Figure (7) shows the three components of brightness temperatures described above.

$$T_{SKY} = e^{-\tau} * T_{\cos} + T_{DOWN}$$

$$T_{refl} = (1-\varepsilon) * T_{SKY}$$

$$T_{sur} = \varepsilon * SST$$

Where *SST* represents the sea surface temperature, which calculated in Kelvin, T_{cos} = 2.7 K is the cosmic microwave background and ε is the sea surface emissivity [11][12].

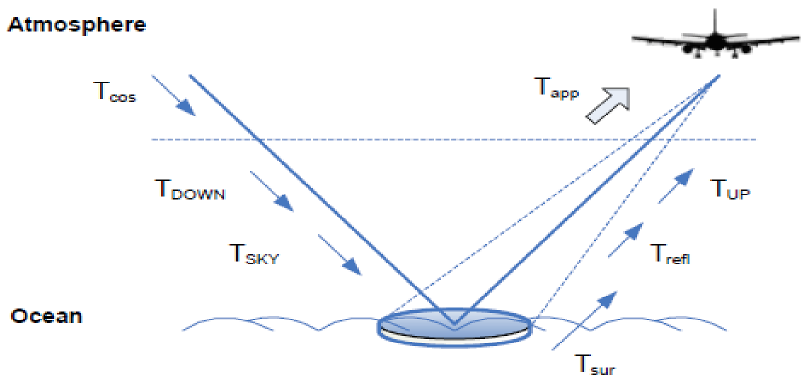

Figure 7, Brightness temperature reaches airborne radiometer.

4.2 Polarization

Polarization is an inherent characteristic of microwave sensors. This is convenient, since the emissivity is also strongly dependent on polarization. Polarization for microwave sensing is generally described as vertical or horizontal (rather than parallel or perpendicular). As illustrated in Figure 8. Vertical polarization is essentially equivalent to parallel polarization (the electric vector is in the plane of the incident radiation and the normal to the target surface) and horizontal polarization is basically equivalent to perpendicular polarization

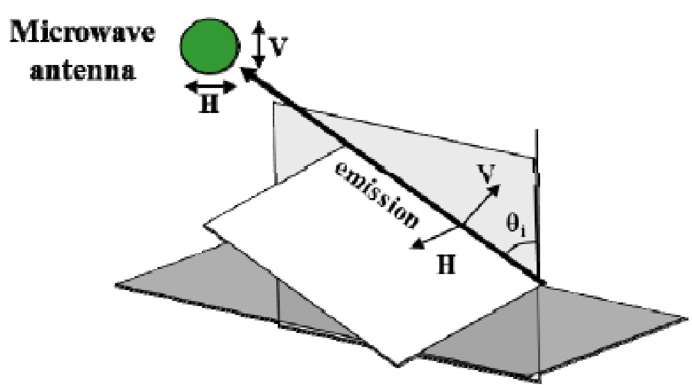

Figure 8, the orientation of polarization for microwave sensing.

The Emissivity varies with polarization. This is particularly true when moisture content is a consideration, but is also an issue even in dry a condition. As is illustrated in Figure 9, emissivity varies both with polarization and frequency. It also varies with look angle, further complicating the problem [12], [13].

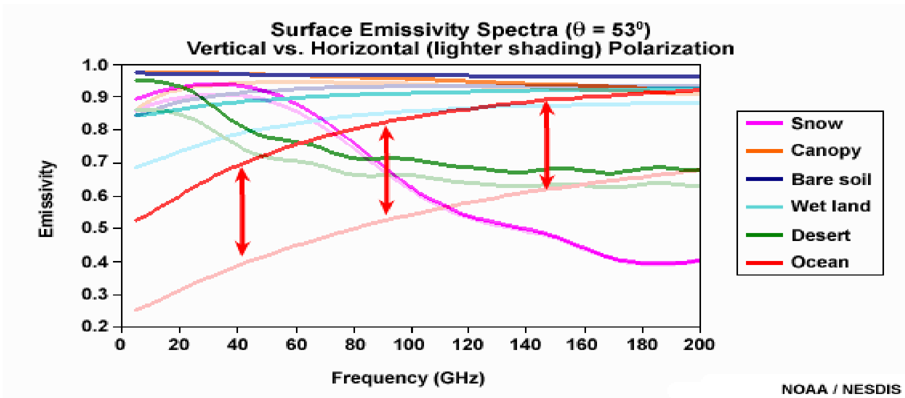

Figure 9, Sensitivity of emissivity to polarization

5. Stepped-Frequency Microwave Radiometer

The Stepped-Frequency Microwave Radiometer is a highly developed tool developed by the Langley Research Center that is designed to measure the wind speed at the ocean’s surface, and the rain fall rates within the storm accurately and continuously. When the plane flies through a storm, has a downward pointing antenna, this antenna will read the microwave radiation which is coming from the ocean surface. Assumptions will be made about the vertical structure of the atmosphere together with sea surface temperature measurements by a downward-looking airborne infrared radiometer in order to find accurate measurements. Then the computers will be able to determine wind speeds according to the levels of microwave radiation which is detected by the SFMR. Figure 10, shows an example of the SFMR.

Figure 10, Stepped Frequency Microwave Radiometry

SFMR used to measure microwave brightness temperature, Tb as a nadir-viewing instrument, at six C-band frequencies (4.7 – 7.1 GHz). The surface wind speed and columnar rain rate are well recorded from these data by using a statistical regression algorithm. Estimation of the rainfall rate below the aircraft also can be calculated, because the attenuation of some frequencies of the rainfall is more than the other [11], [13].

6. HURRICANE GONZALO

Hurricane Gonzalo is a tropical storm that hits the Leeward Islands and Bermuda in October 2014. Then it quickly turned into a hurricane which was a very strong hurricane in the Atlantic since Igor in 2010, When Hurricane Gonzalo hit Bermuda on Friday, it was still a Category 3 hurricane with 115 mph winds. But by the time the eye of the storm passed over the island, it had been downgraded to a Category 2 with 110 mph winds. According to catastrophe modelling firm AIR worldwide, the eye passed over Bermuda at 8:30 p.m. AST, and the eye was twice the size the length of the island. It caused a huge damage and left a landfall on the island, table 1, shows the scale categories of the hurricanes and the difference between them in the damage they cause

Table 1, scale categories of the hurricanes

Scale Number (Category)	Damage
1	Minimal: Unanchored mobile homes, vegetation and signs.
2	Moderate: All mobile homes, roofs, small crafts, flooding.
3	Extensive: Small buildings, low-lying roads cut off.
4	Extreme: Roofs destroyed, trees down, roads cut off, mobile homes destroyed. Beach homes flooded.
5	Catastrophic: Most buildings destroyed. Vegetation destroyed. Major roads cut off. Homes flooded.

On Oct. 15 an aircraft named WB-57 flew over Hurricane Gonzalo. This aircraft was carrying two HS3 mission instruments. The aircraft microwave images and data showed concentric eyewalls in addition to the inner radius of maximum winds which is about 4-5 nautical miles from the centre. Later in the Oct. 15, Gonzalo's the wind increased to 130 mph. The aircraft reported that the peak intensity of Gonzalo based on SFMP 125 kt at 1200 and 1800 UTC and the level of wind that is measured 1200 UTC 16 October. Also the aircraft estimate an SFMR wind of 135 kt, and the peak 700 mb for the flight-level wind of 127 kt. The last scouting for the aircraft mission for Gonzalo done about 4-6 hours before the hurricane cause the landfall in Bermuda, and with limited sampling reported peak 700 mb flight-level winds of 124 kt and based on these data, Gonzalo's intensity is analysed to have been 105 kt in 17 October. After that the hurricane became weaker that afternoon and its intensity become 95 kt, category 2 Hurricane Wind Scale at landfall on Bermuda Hurricane Wind Scale. On the other hand the estimated amounts of Rainfall which relate to Gonzalo also reported. Where the highest rainfall recorded was in the Leeward Islands which is 5.70 inches at St. Martin, while in Antigua the amount of rainfall was 1.28 inches. Also Gonzalo had 2 to 3 inches of the amount of rainfall in Bermuda in addition to Canada and over portions of southeastern Newfoundland. Figure (11) shows the exact trucking positions for Hurricane Gonzalo [14].

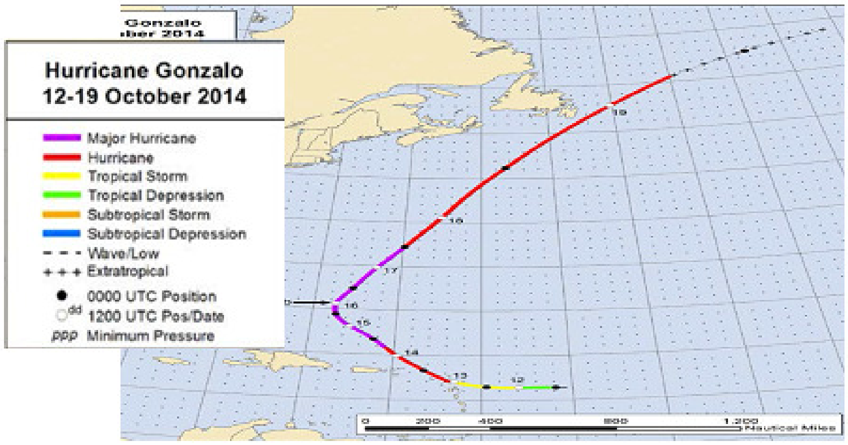

Figure 11, Path categories of Hurricane Gonzalo, 12-19 October, 2014. [Source:NASA]

7. Results and Discussions

In this section included the results of the main two factors of hurricane Gonzalo 2014, which are the wind speed and the pressure based on the data collected by airborne instrument. As shown in the previous section about the growing, map and some general information about Gonzalo, the wind speed and pressure in 16 October was the important time to track the hurricane. According to the analysis of all data collected in 3 consecutive days for several hours we have found the best track time based on pressure and wind speed with respect to longitude and latitude as shown in the figure 12 below:

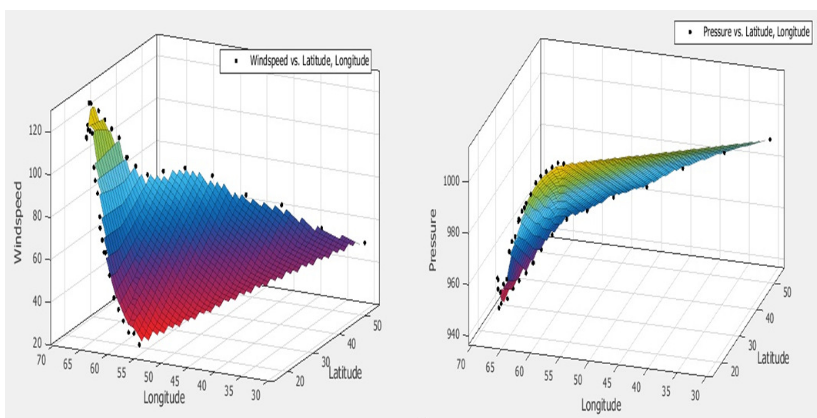

Figure 12, Wind speed and Pressure verses longitude and latitude.

This figure shows clearly the maximum wind speed related to the position to estimate the peak intensity based on SFMR and this occurred about 4-6 hours before the hurricane end arrival in Bermuda, also Gonzalo was absorbed over the North Atlantic after it became an extratropical cyclone, this cause a fierce wind gusts over portions of Europe and specifically in the UK on 21 October, now clearly the figure shows a continuous decrease in the magnitude of the pressure versus increasing in the wind speed both entering and exiting the eye-wall. Before going into more details it's important to know the categories of any hurricane, for future tracking models, which give an exact idea about how much the hurricane, could cause a damage base on the speed of wind as shown in the figure below:

Tropical depression	≤38 mph	≤62 km/h	Category 3	111–129 mph	178–208 km/h
Tropical storm	39–73 mph	63–118 km/h	Category 4	130–156 mph	209–251 km/h
Category 1	74–95 mph	119–153 km/h	Category 5	≥157 mph	≥252 km/h
Category 2	96–110 mph	154–177 km/h	Unknown		

Figure 12, Hurricane categories 1,2,3,4 and 5 based on wind speed.

This section will give a scheduling to apply our experience of studies in the North Atlantic, to the early detection of tropical hurricanes based on airborne data instrument. Below in figure 13, is the result of deep analysis of Gonzalo hurricane that shows the linear model of the best time track with respect to pressure and wind speed. That gives a better scene with respect to location and how the movement of hurricane is behaves. The future desired target is to calculate the error in the pressure consider as a function of spatial resolution on each side of the eye wall,

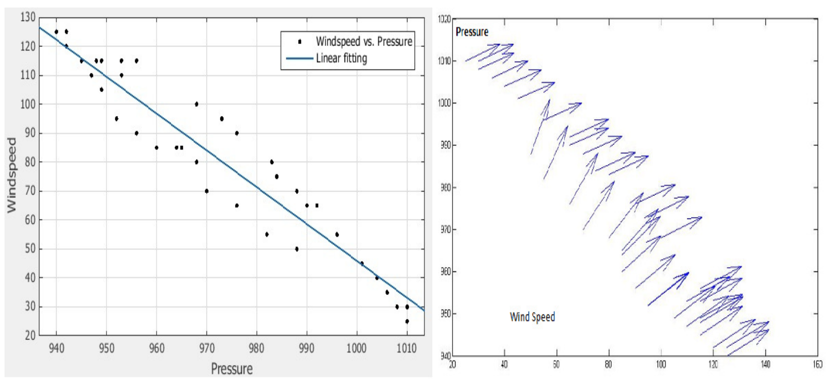

Figure 13, linear trajectories of hurricane Gonzalo.

Our study is to use the data of airborne remote sensing compare with satellite and ship reports, for detecting the start point of hurricanes based on statistical and imperial models seems to be good. This result will extend for future models and simulations based on location, pressure and wind speed. This information is much related so it should be collected as soon as possible with higher resolution in all steps and adjacent locations to the eyewall of the hurricane. Figure 14, shows the Gonzalo 2014 case for best tracking data location based on three flight days.

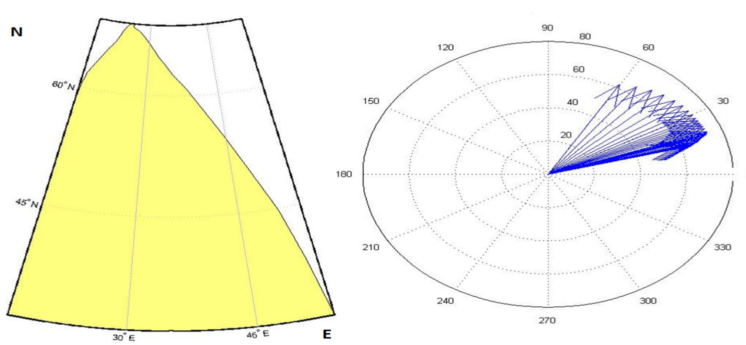

Figure 14, Directional and map positions (E+N) of hurricane Gonzalo.

Basically Gonzalo accelerated toward the waters of the North Atlantic as we have shown the map in the previous section; Hurricane Gonzalo was a powerful Atlantic tropical cyclone that shaped in Bermuda. To do right monitoring of hurricane or any other natural disaster, deep study should apply to all previous ones to build perfect data sets. This one goal of this work to avoid surprising attack or avoiding delay time for hurricane detection like in Katrina case were 31 hour delay of detection. Gonzalo 2014 tracked as category 4 hurricane, which is the first season in history to feature two hurricane landfalls. But as shown in our airborne results it peaked with maximum sustained wind speed about 140 mph. The airborne hurricane tracking is an important method compared with the space borne method, which is developed by NASA Marshall Space Flight center to provide high resolution measurements. By flying special aircraft equipment using synthetic thinned array radiometry technology and included all critical measurements such as hurricane eye location, speed of wind and the pressure. This airborne system designed to measure pressure and wind by collecting doppler profiles with better resolution and the fastest continuous real time data.

8. CONCLUSION

There is a massive attention in the use of microwave airborne radiometry for remote sensing instead of satellite, the recent trend of hurricane tracking techniques is described in this paper. We have presented the best track analysis of hurricane Gonzalo 2014 based on data collected by airborne microwave radiometer, using the stepped frequency. The important role of airborne way is how to provide high accuracy real time data, to track the natural disasters such as hurricane. There is no doubt that the existing techniques which are the spaceborne and ship reports are so limited. A hurricane is a severe tropical cyclone that forms in the Atlantic Ocean, which is starting to form in the atmosphere when the vapour water plus heat are being released at the ocean surface. Last decade, airborne microwave radiometry is an integral part of NASA's Earth Observations. In this work two empirical hurricane factors pressure and wind speed have been used to get best tracking locations for Gonzalo 2014. These data collected in three consecutive flight days, which is developed by NASA. Also we have described the physical characteristics of hurricanes. This paper also presented the design details and analysed the data of airborne microwave radiometer of Gonzalo, Also we have showed a good result of the best track 12-19 Oct 2014. In the future we hope to improve the accuracy of retrieval wind and pressure.

Data from Hurricane Gonzalo 2014 are available for further study, modelling and analysis. This chance will give the best way for future tracking of hurricanes or any other natural disasters. The airborne techniques have successfully demonstrated the capability for more robustness in remote sensing with respect to satellite and ship reports. Finally, the airborne techniques have successfully demonstrated the capability for more robustness in remote sensing with respect to satellite and ship reports. The airborne hurricane tracking is to provide high resolution measurements by flying special aircraft equipment using synthetic thinned array radiometry technology and included all critical measurements such as hurricane eye location, speed of wind and the pressure. Last decade, airborne microwave radiometry is an integral part of NASA's Earth Observations. As a future work the determination of the thermal controller is very significant for long stability measurement and to build a prediction models and correction mechanism.

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