USE OF HDSS SONDES TO CALCULATE ZERO WIND CENTERS, VORTEX STRUCTURE, AND STORM-RELATIVE WINDS*

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OBJECTIVES

- Provide an example of why analysis of high density soundings across Hurricane Joaquin also require highly accurate center positions

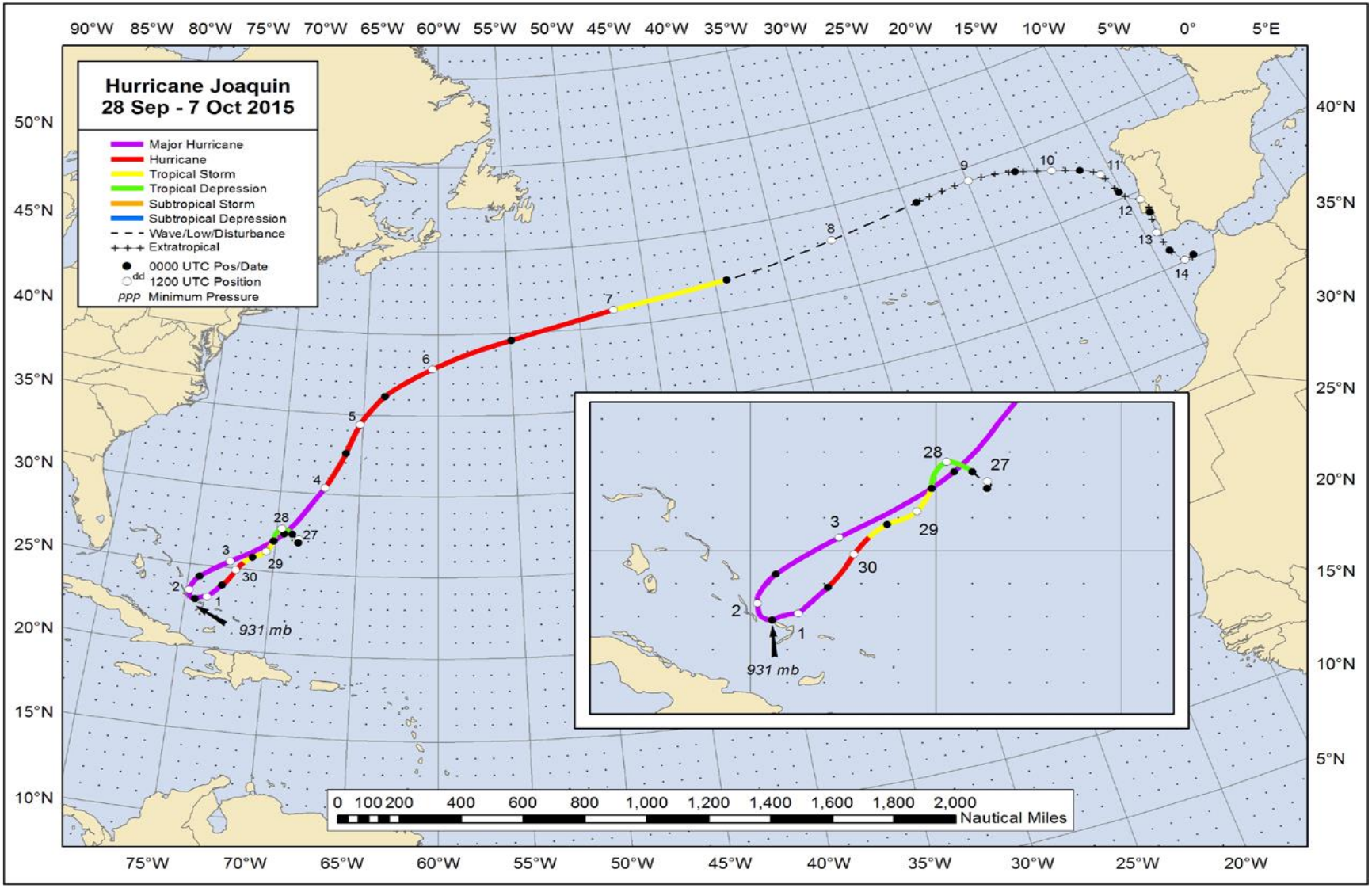
- Describe technique for calculating 3-D zero-wind center positions from the highly accurate GPS positions of sequences of High-Density Sounding System (HDSS) soundings as they fall from 10 km to the ocean surface

- Illustrate the vertical tilt of the vortex above 4-5 km during two center passes through Hurricane Joaquin on 4 October 2015; Vortex tilts on 2-3 October

- Illustrate storm-relative winds at 1830 UTC 4 October with ZWC-based storm translation speed and direction

BEST-TRACK FOR HURRICANE JOAQUIN (2015)

- Primary focus is on WB-57 mission on 4 October (~ 18 UTC)



NHC BEST-TRACK FILE FOR HURRICANE JOAQUIN, 3-7 October 2015

- Values in red are near center times of three WB-57 missions

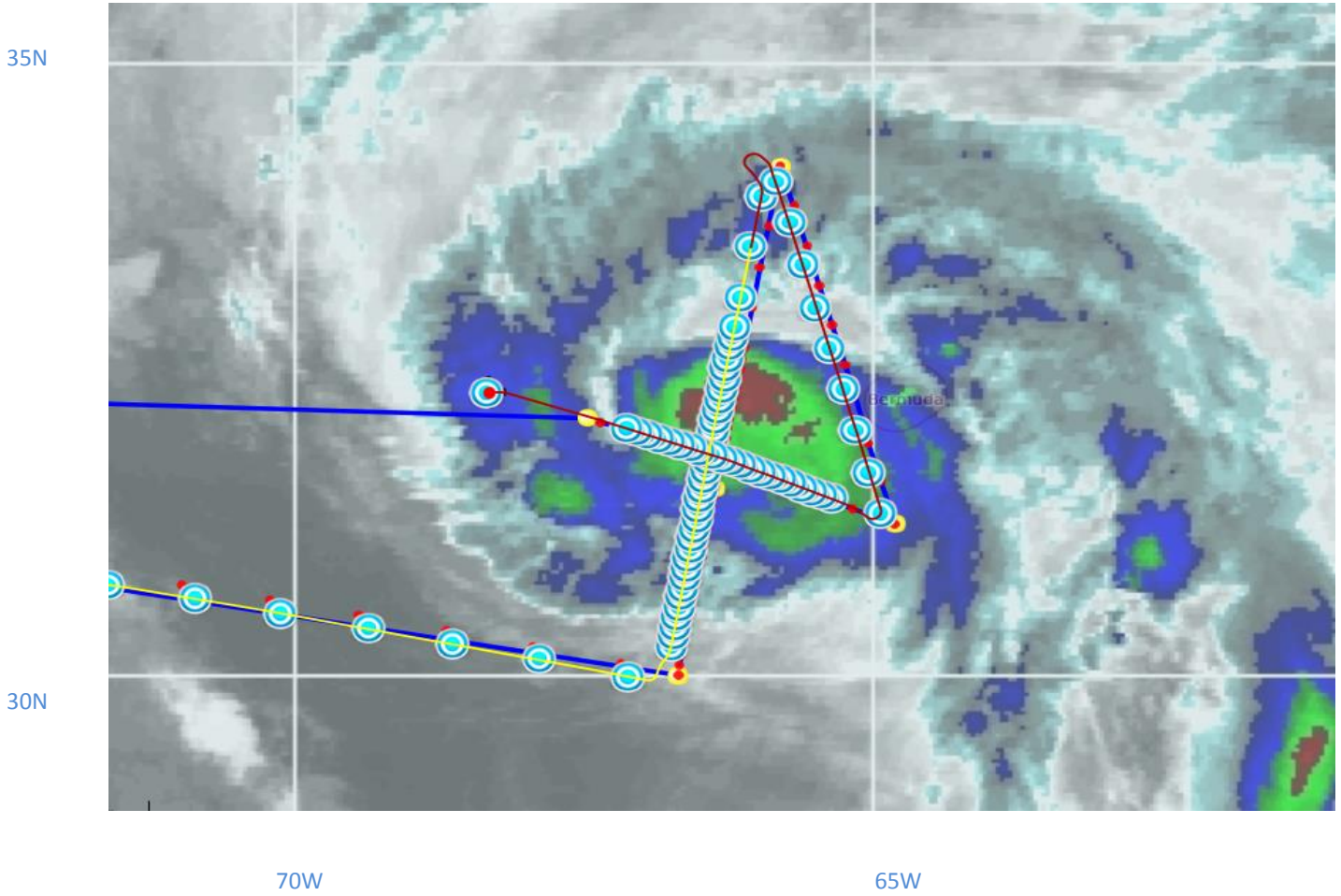
Date/Time (UTC)	Latitude (◦N)	Longitude (◦W)	Pressure (mb)	Wind Speed (kt)	Translation Heading/ Speed (kt)
03/0000	24.3	74.3	943	115	51.7◦ / 8.1
03/0600	24.8	73.6	945	120	56.3◦ / 10.9
03/1200	25.4	72.6	934	135	57.6◦ / 17.0
03/1800	**26.3**	**71.0**	**934**	**130**	**50.2◦ / 17.3**
04/0000	27.4	69.5	941	115	34.9◦ / 18.4
04/0600	28.9	68.3	949	105	32.2◦ / 17.8
04/1200	30.4	67.2	956	95	26.4◦ / 13.4
04/1800	**31.6**	**66.5**	**958**	**85**	**22.8◦ / 10.9**
05/0000	32.6	66.0	961	75	18.4◦ / 10.6
05/0600	33.6	65.6	964	75	22.4◦ / 8.6
05/1200	34.4	65.2	964	75	32.3◦ / 10.7
05/1800	**35.3**	**64.5**	**964**	**75**	**38.8◦ / 11.6**
06/0000	36.2	63.6	967	75	52.1◦ / 13.1
06/0600	37.0	62.3	970	75	58.6◦ / 17.5
06/1200	37.9	60.4	974	70	63.7◦ / 20.9
06/1800	38.8	58.0	974	70	70.6◦ / 25.3
07/0000	39.6	54.9	974	70	

HDSS SONDE DROPS in HURRICANE JOAQUIN 4 October 2015*

Center crossings: South-to-North ~ 1800 UTC; East-to-West ~ 1900 UTC

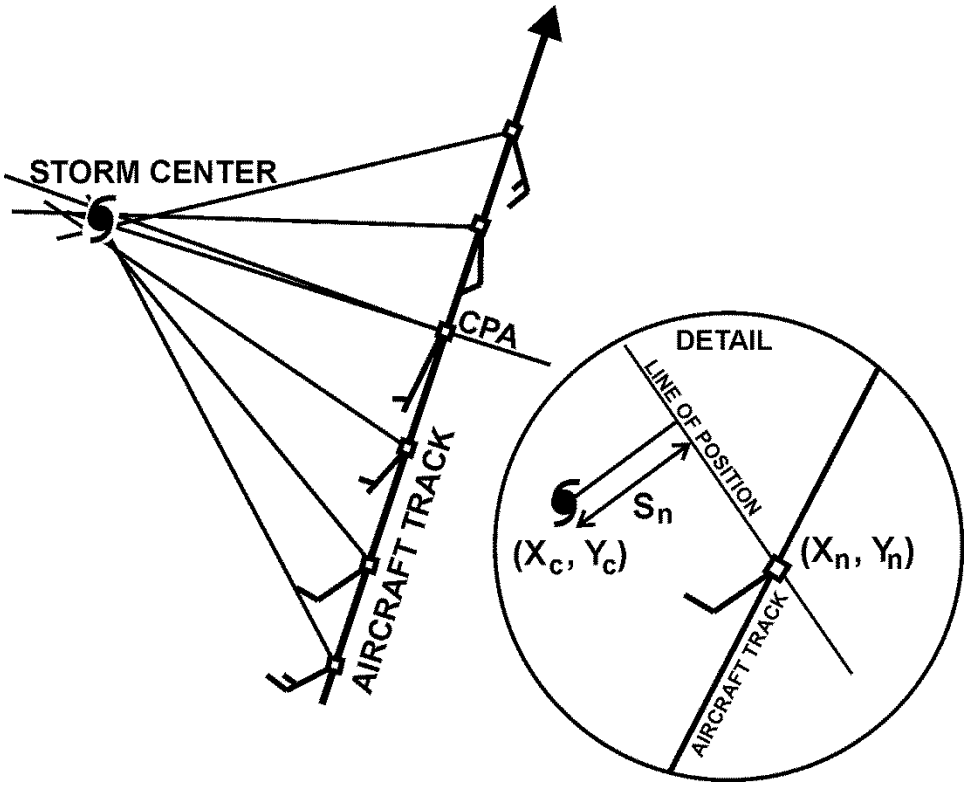
Sondes deployed ~ 42 sec (~ 4.67 miles) during two center crossings

Require accurate center positions for storm-relative positions of HDSS observations



* GOES IR image is at 1915 UTC

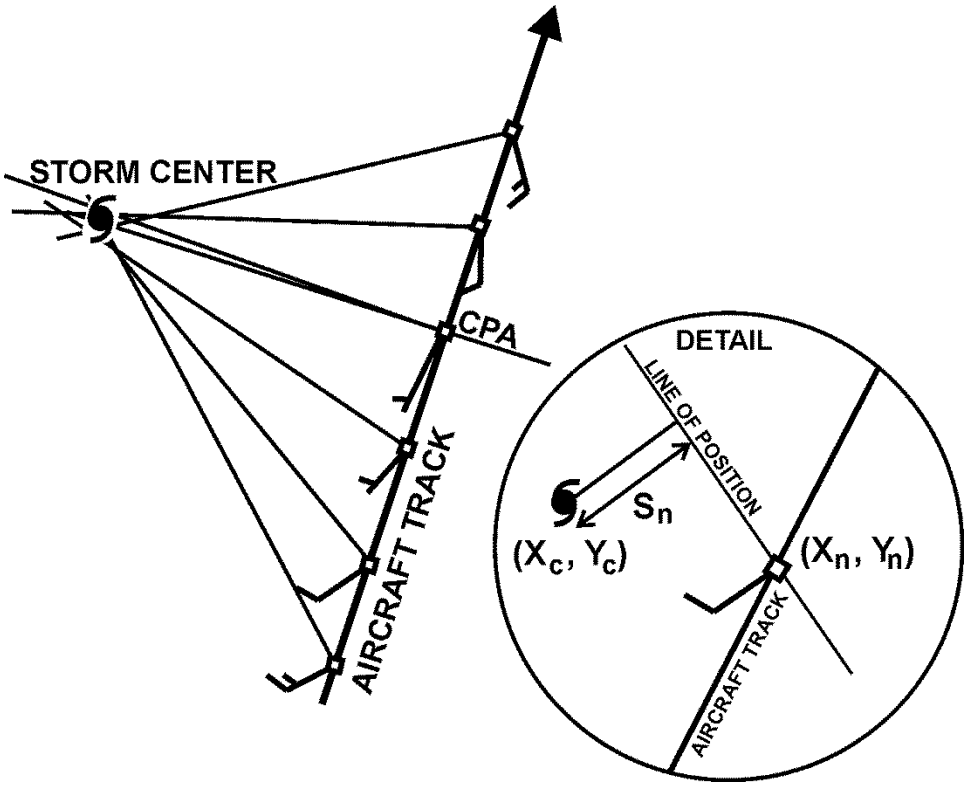
WILLOUGHBY AND CHELMOW (1982)
CENTER LOCATION TECHNIQUE - AIRCRAFT



- Utilize flight-level wind directions at maximum temporal resolution (~ 1 sec; approximately 100 m) while the aircraft passes through the eye
- Lines of positions (or bearings) perpendicular to wind directions intersect to accurately locate the zero-wind center position

- Dynamic center (zero wind speed versus minimum pressure height or visual satellite center) must exist in any closed vortex
- Assumes gradient wind balance and neglects divergent component of the wind relative to the rotational component

FACTORS TO BE CONSIDERED IN USING HDSS SONDES WITH WILLOUGHBY AND CHELMOW (1982) TECHNIQUE FOR HIGHLY ACCURATE STORM CENTER POSITIONS



Consider these seven vector wind directions are to be extracted at specific elevations from seven HDSS soundings deployed from the NASA WB57 aircraft overflying the tropical cyclone center at 60,000 ft at a speed of 400 mph

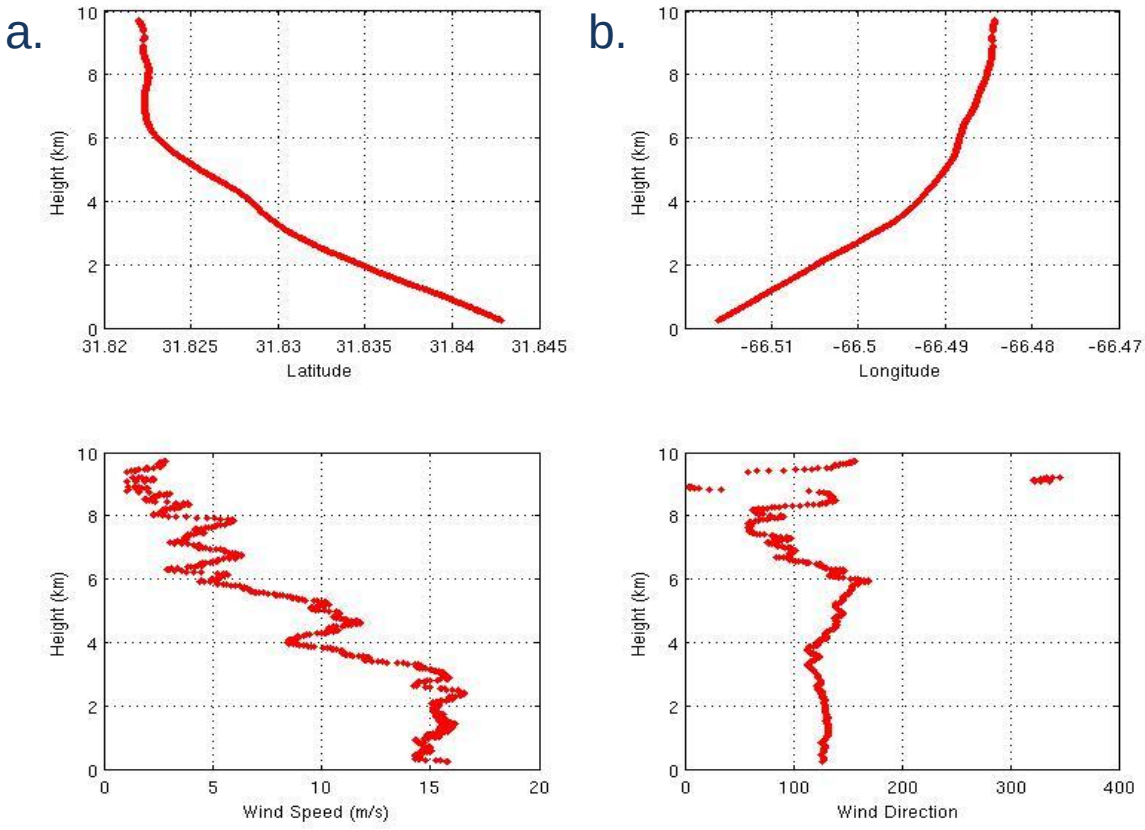
HDSS sondes are deployed at ~42 sec intervals (~ 4.67 miles) and fall to the ocean surface in ~700 sec (11.67 minutes). However, the sondes drift with the local winds at each elevation so their lat./long. positions are not directly below the deployment positions along WB57 aircraft track

- In addition to capability for high frequency drops, HDSS provides highly accurate GPS lat./long. positions at each elevation for these wind direction determinations
- During this sequence of seven sonde deployments over 294 sec and the sondes taking ~ 700 sec to fall to the surface, the TC center will have moved as well

CRITICAL REQUIREMENTS FOR HIGHLY ACCURATE GPS LAT/LONG WITH HDSS

HDSS sonde deployed at 1800 UTC 4 October during first overpass of Hurricane Joaquin eye

Northward (panel a) and westward (panel b) drift off of vertical profile

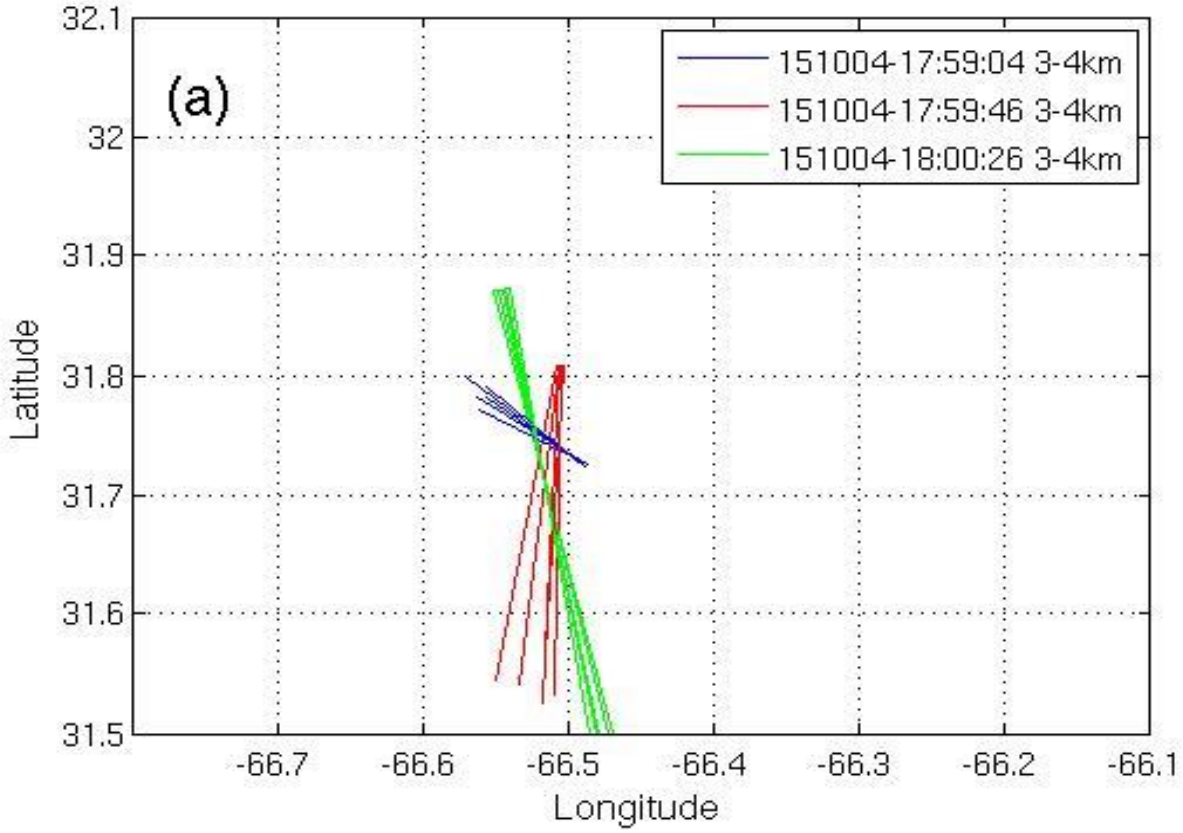


- **Wind speeds every second are small above 6 km within the eye, but increase in outer region of eye**
- **Wind directions (and thus bearings) constant at 120 deg below 4 km indicate ZWC is to west-southwest**

INTERSECTIONS OF BEARINGS FROM PAIRS OF HDSS AVERAGE WIND DIRECTIONS OVER 1 KM BASED ON GPS LAT/LONG POSITIONS

OVERPASS 1 WITH ZWC IN 3-4 KM LAYER

- Bearings from 1 km layer-average wind directions overlapping at 200 m in the vertical
- Lengths of bearing lines are proportional to wind speed

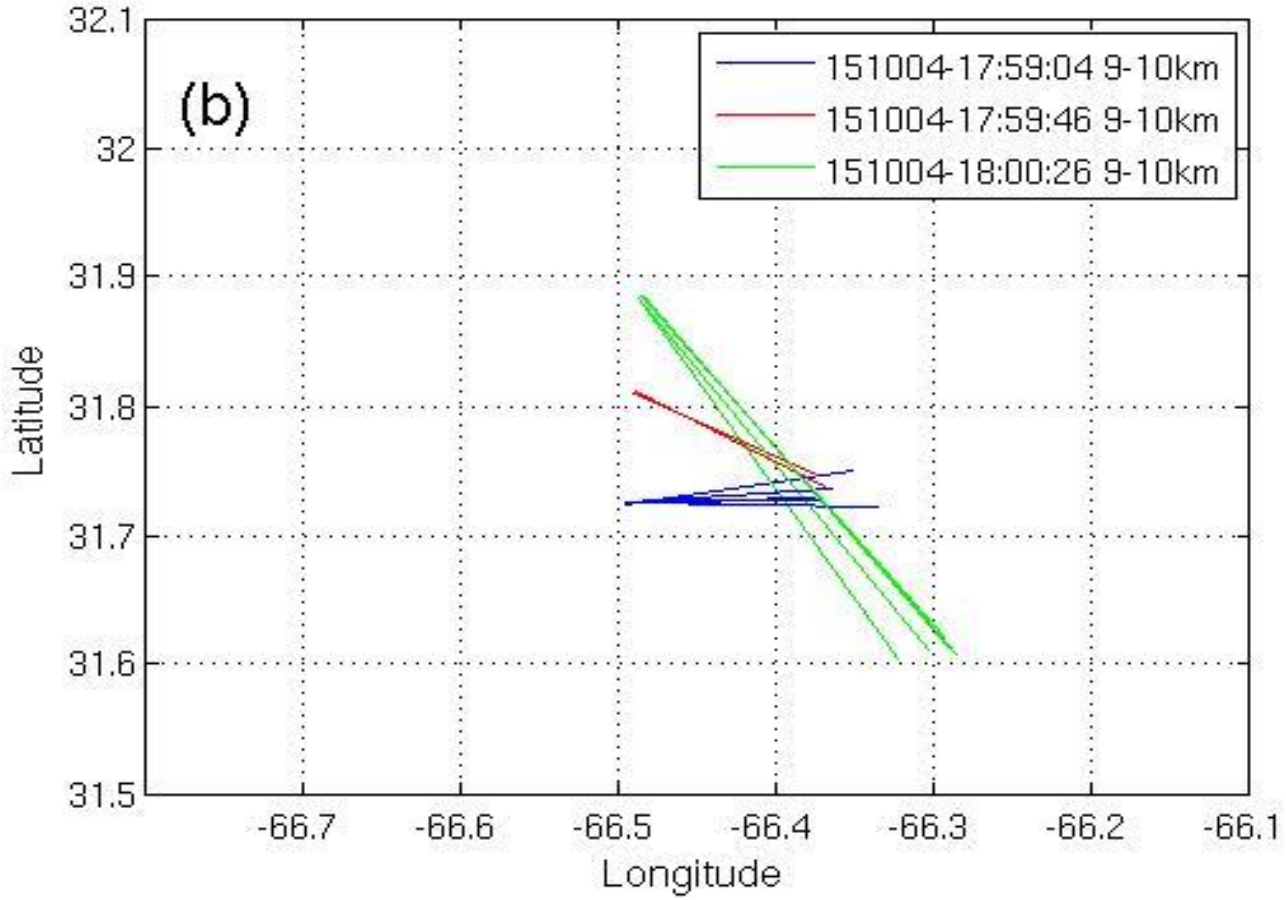


3.5 km ZWC at 31.75°N, 66.52°W vs HIRAD surface center 31.69°N, 66.58°W

INTERSECTIONS OF BEARINGS FROM PAIRS OF HDSS AVERAGE WIND DIRECTIONS OVER 1 KM BASED ON GPS LAT/LONG POSITIONS

OVERPASS 1 WITH ZWC IN 9-10 KM LAYER

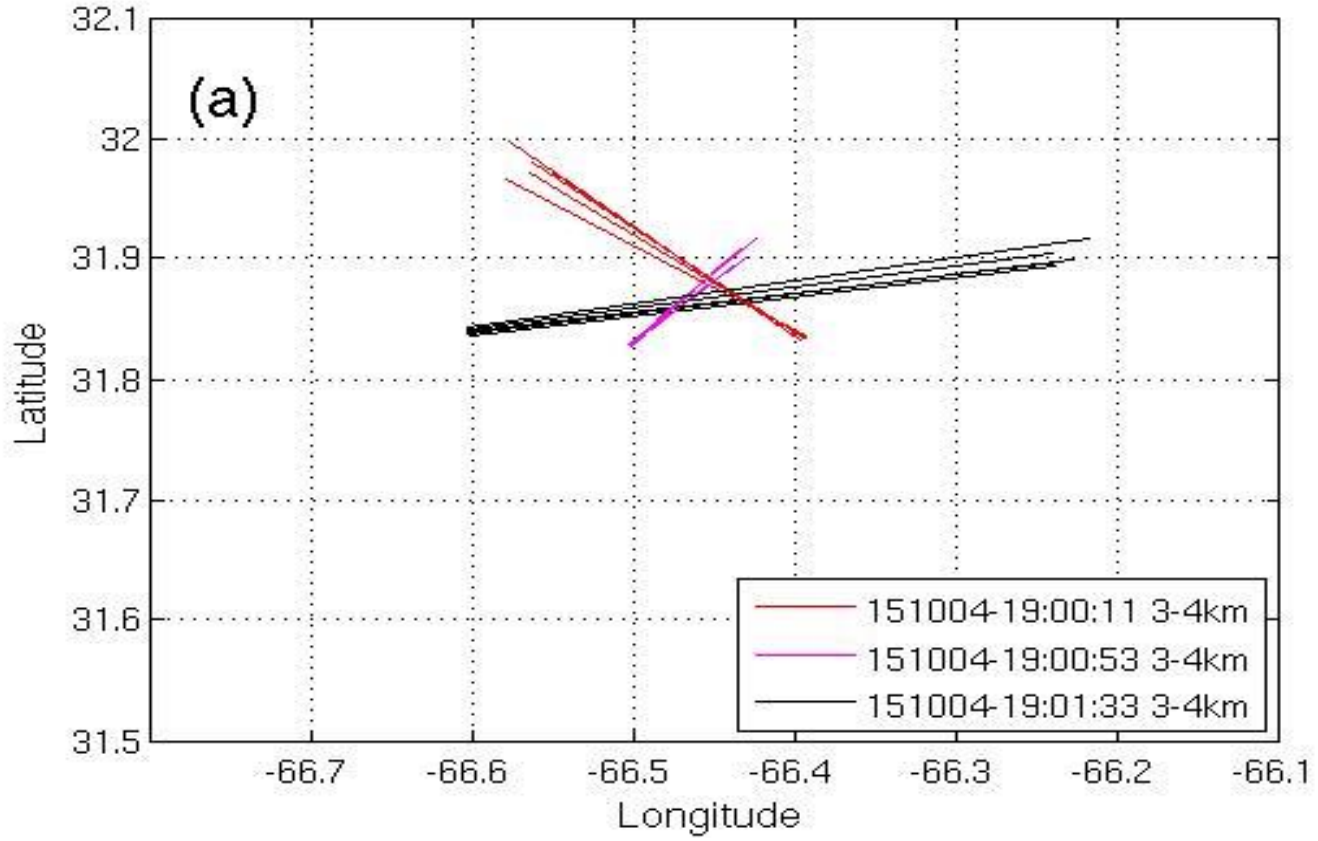
- Bearings from 1 km layer-average wind directions overlapping at 200 m in the vertical
- Lengths of bearing lines are proportional to wind speed



INTERSECTIONS OF BEARINGS FROM PAIRS OF HDSS AVERAGE WIND DIRECTIONS OVER 1 KM BASED ON GPS LAT/LONG POSITIONS

OVERPASS 2 WITH ZWC IN 3-4 KM LAYER

- Bearings from 1 km layer-average wind directions overlapping at 200 m in the vertical
- Lengths of bearing lines are proportional to wind speed

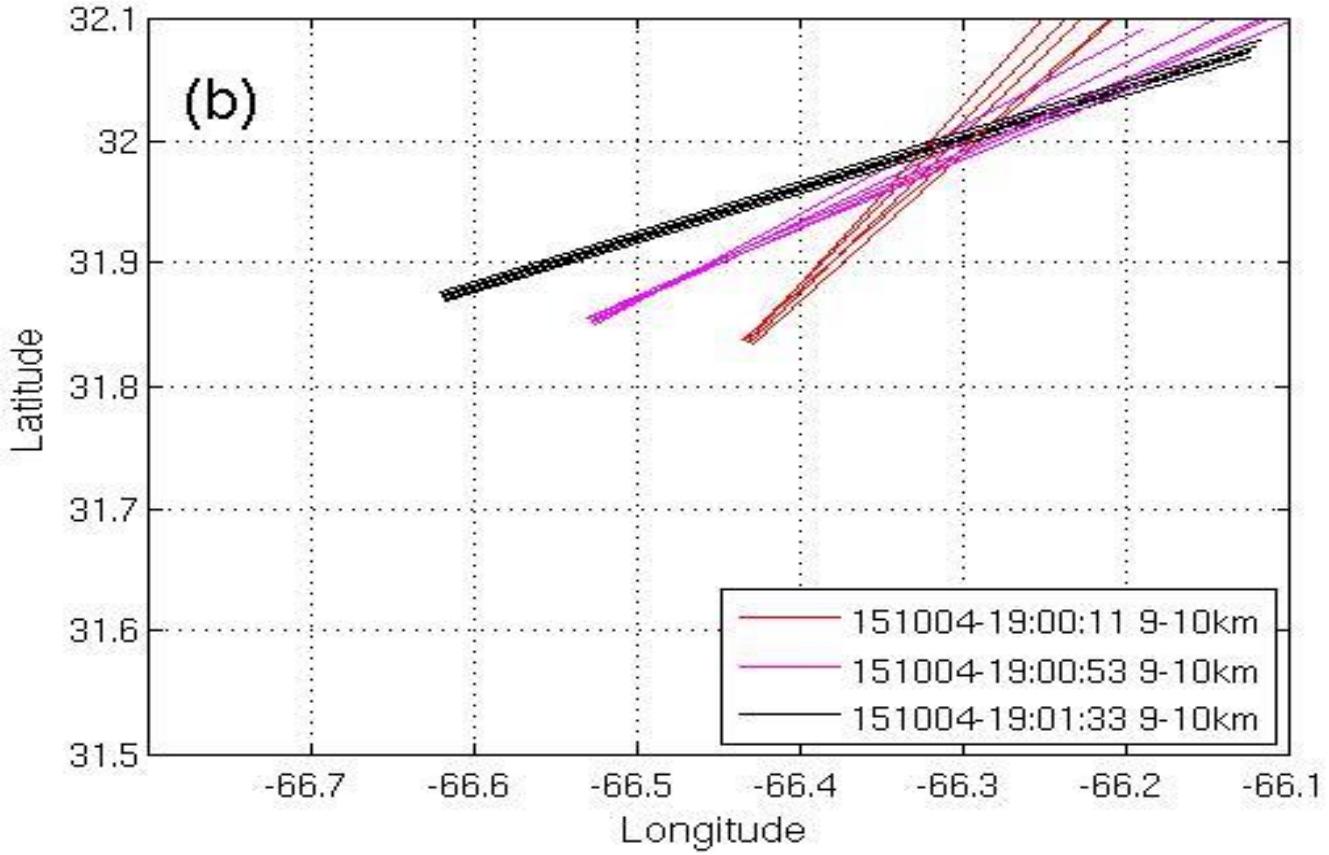


3.5 km ZWC at 31.87°N, 66.46°W vs HIRAD surface center 31.87°N, 66.53°W

INTERSECTIONS OF BEARINGS FROM PAIRS OF HDSS AVERAGE WIND DIRECTIONS OVER 1 KM BASED ON GPS LAT/LONG POSITIONS

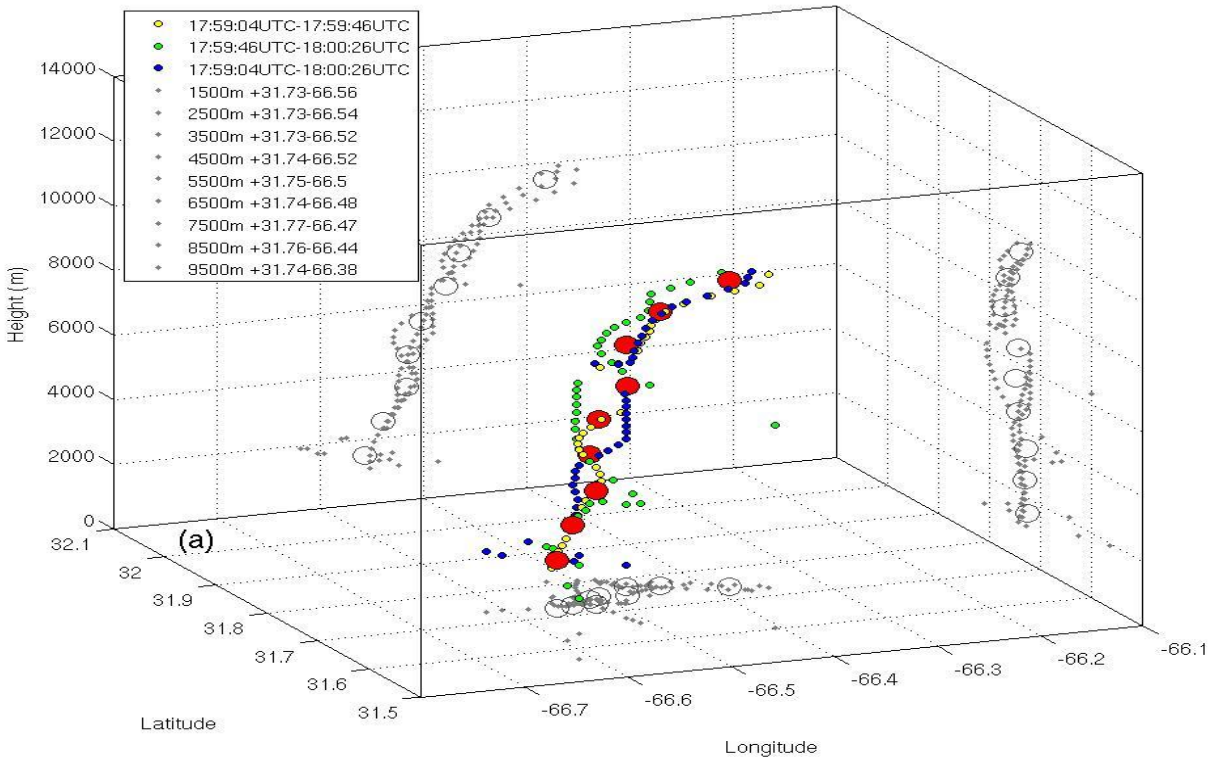
OVERPASS 2 WITH ZWC IN 9-10 KM LAYER

- Bearings from 1 km layer-average wind directions overlapping at 200 m in the vertical
- Lengths of bearing lines are proportional to wind speed



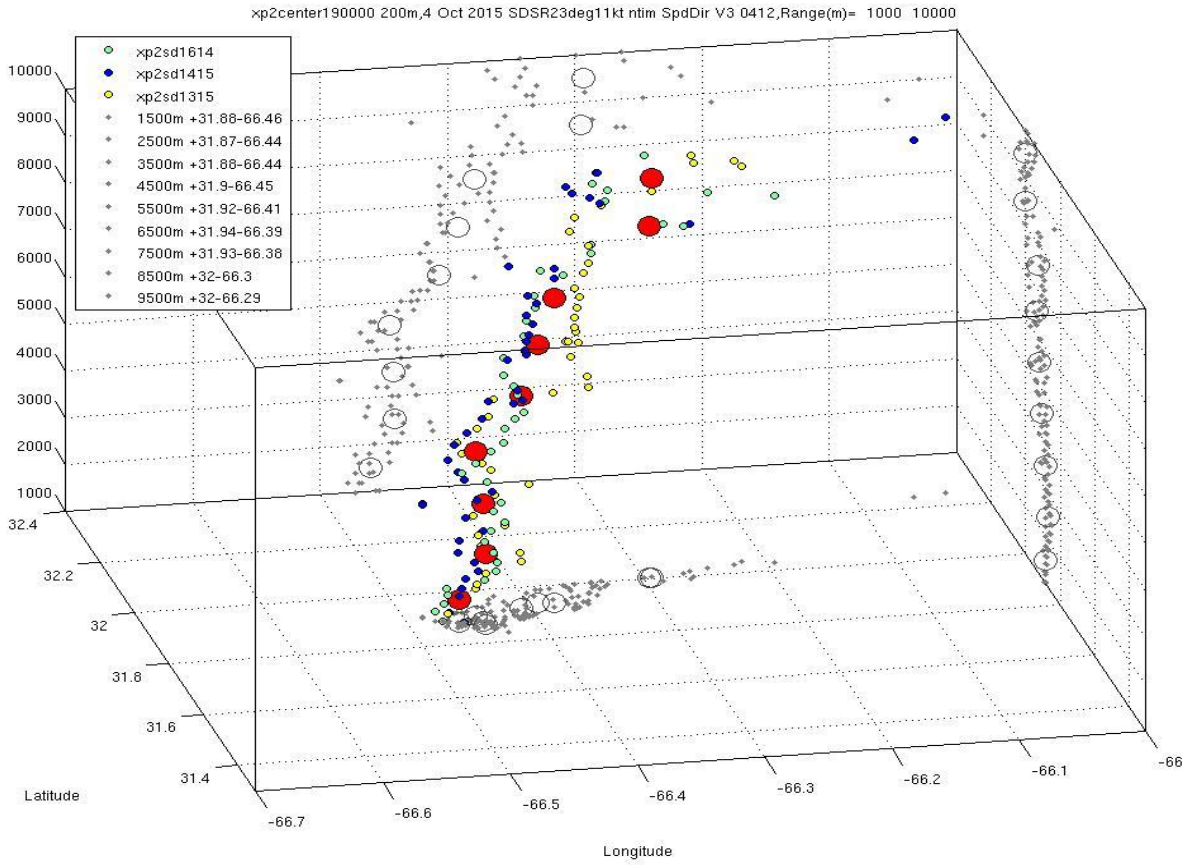
VORTEX TILT BETWEEN 1.5 KM AND 9.5 KM FROM OVERPASS 1 HDDS WIND DIRECTIONS OVER 1 KM BASED ON GPS LAT/LONG POSITIONS

- Large red circles indicate ZWCs at one kilometer spacing based on consensus of 3 pairings of HDSS sondes (small colored circles) at 200 m spacing
- Tilt from 1.5 km to 6.5 km is 62 degrees and between 7.5 km and 9.5 km is 80 degrees



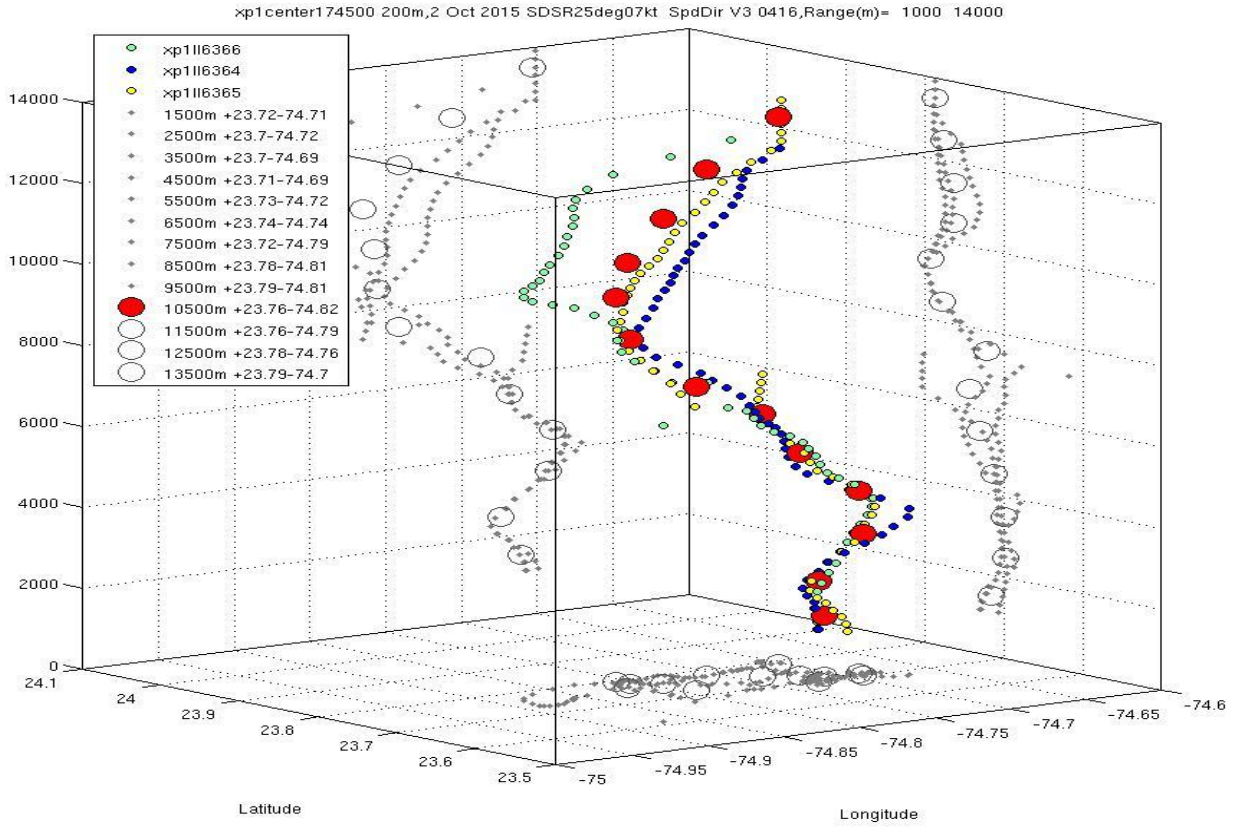
VORTEX TILT BETWEEN 1.5 KM AND 9.5 KM FROM OVERPASS 2 HDSS WIND DIRECTIONS OVER 1 KM BASED ON GPS LAT/LONG POSITIONS

- Large red circles indicate ZWCs at one kilometer spacing based on consensus of 3 pairings of HDSS sondes (small colored circles) at 200 m spacing
- Tilt from 1.5 km to 6.5 km is 52 degrees and between 7.5 km and 9.5 km is 80 degrees



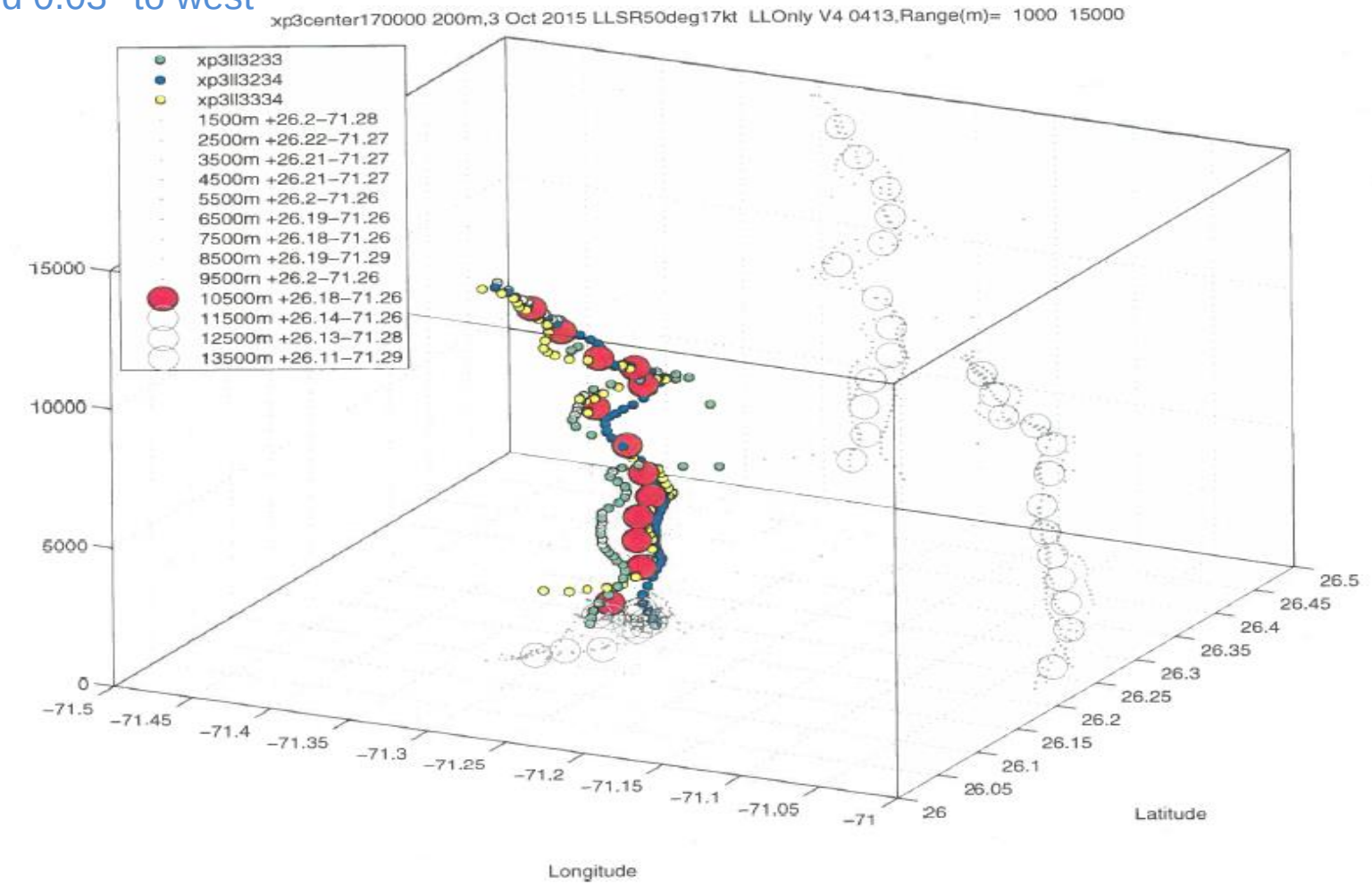
VORTEX TILT BETWEEN 1.5 KM AND 13.5 KM FROM HDDS WIND DIRECTIONS AT 1745 UTC 2 OCTOBER (VMAX = 110 kt; previously 125 kt)

- Large red circles indicate ZWCs at one km spacing based on consensus of 3 pairings of HDSS sondes (small colored circles) at 200 m spacing
- Except for small longitude deviation at 3.5 and 4.5 km, center is vertical between 1.5 km and 5.5 km, then tilts 0.05° to the north and 0.10°to the west from 5.5 km to 10.5 km, and then tilts 0.12° back to the east at 13.5 km



VORTEX TILT BETWEEN 1.5 KM AND 13.5 KM FROM HDDS WIND DIRECTIONS AT 1700 UTC 3 OCTOBER (VMAX = 130 kt)

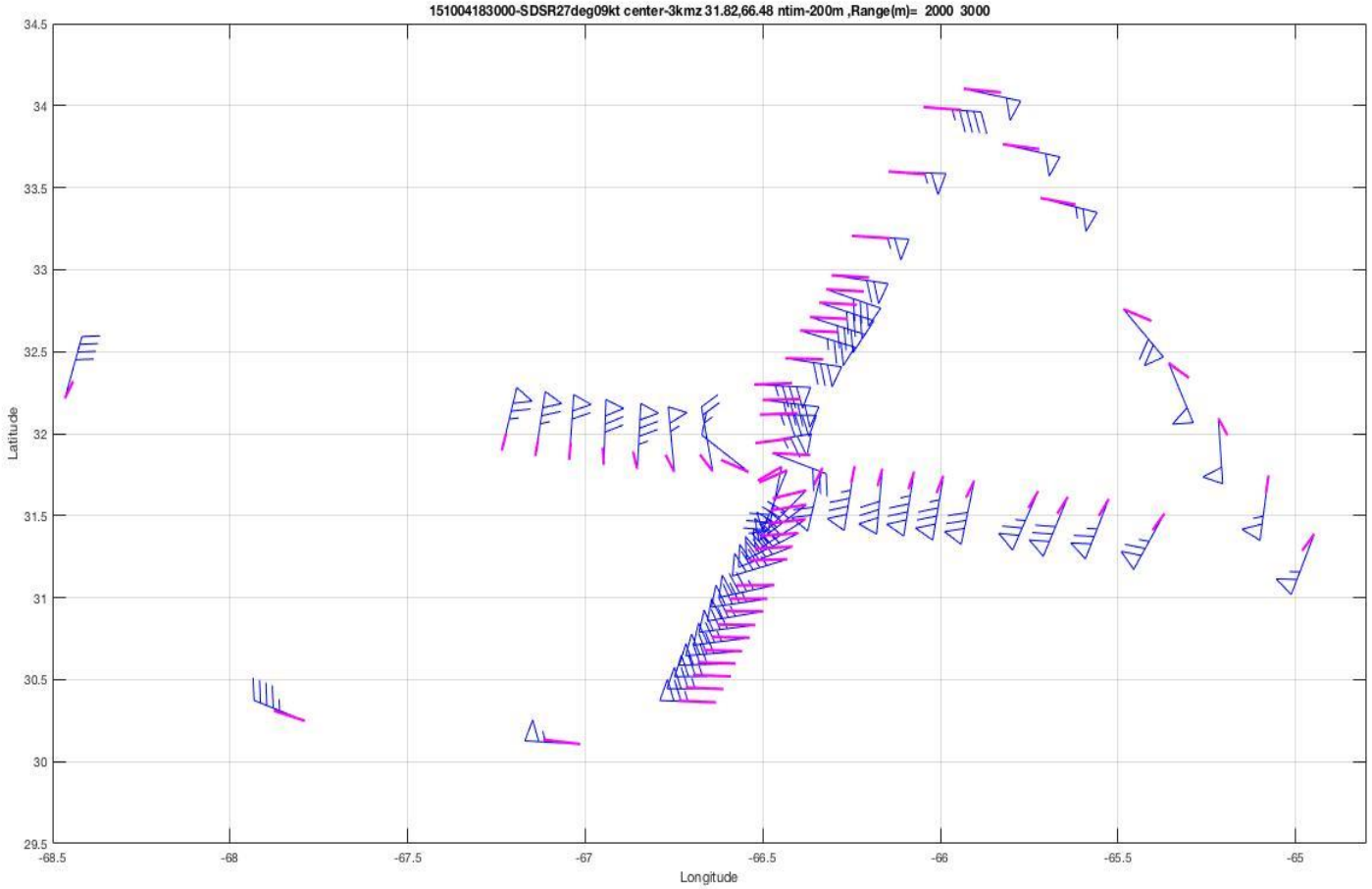
- Large red circles indicate ZWCs at one km spacing based on consensus of 3 pairings of HDSS sondes (small colored circles) at 200 m spacing
- No tilt from 1.5 km to 5.5 km and then tilt between 5.5 km and 13.5 km is 0.09° to south and 0.03° to west



HURRICANE JOAQUIN STORM-RELATIVE WINDS
1830 UTC 4 OCTOBER

ELEVATION: 2.5 KM **RELATIVE WIND: Blue** **AZIMUTH: Magenta**

- Multiple center crossings allow iterative adjustments of the ZWC positions to fine-tune the storm translation speed and direction at the time between the center crossings
- For 1830 4 October, the translation is 9 kt toward 27 deg., which can be compared with the NHC best-track translation between 18 UTC 4 October and 00 UTC 5 October of 10.7 kt toward 23 deg.



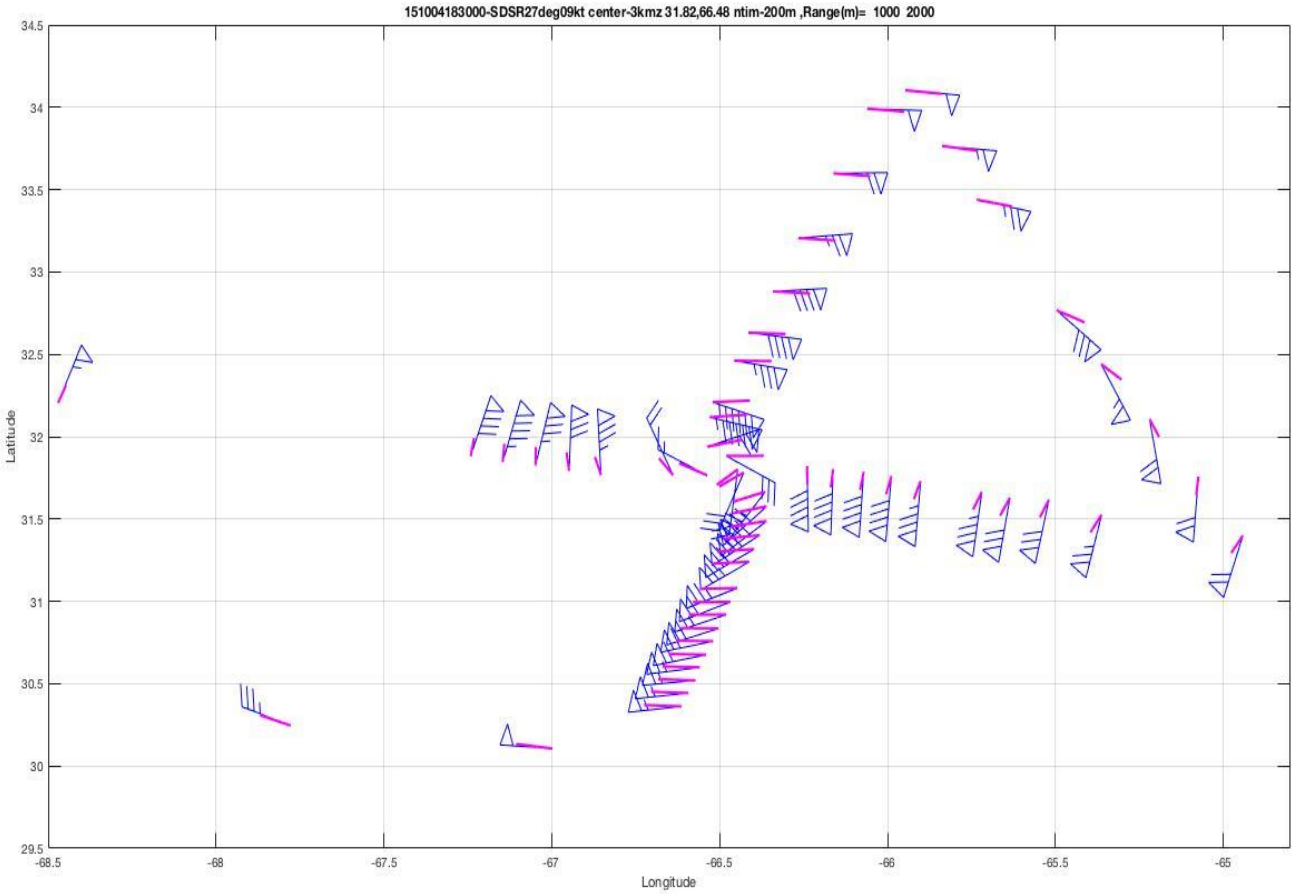
- Note changes in relative wind directions of high density HDSS winds near center

SUMMARY

- High accuracy ZWC positions may be derived from HDSS sondes deployed from 60,000 ft as in Willoughby and Chelmow (1982) due to
  - GPS lat./long. positions accounting for HDSS drift as sonde falls
  - GPS lat./long. position differences to define an average wind direction over 1 km layers
- Vortex tilts (and rotation?) between 1 km and 10 km of Hurricane Joaquin on 4 October 2015 demonstrate new capability of the HDSS to observe tropical cyclone structure
- High accuracy storm translation speeds and directions from HDSS/ZWC are essential for storm-relative wind field plots

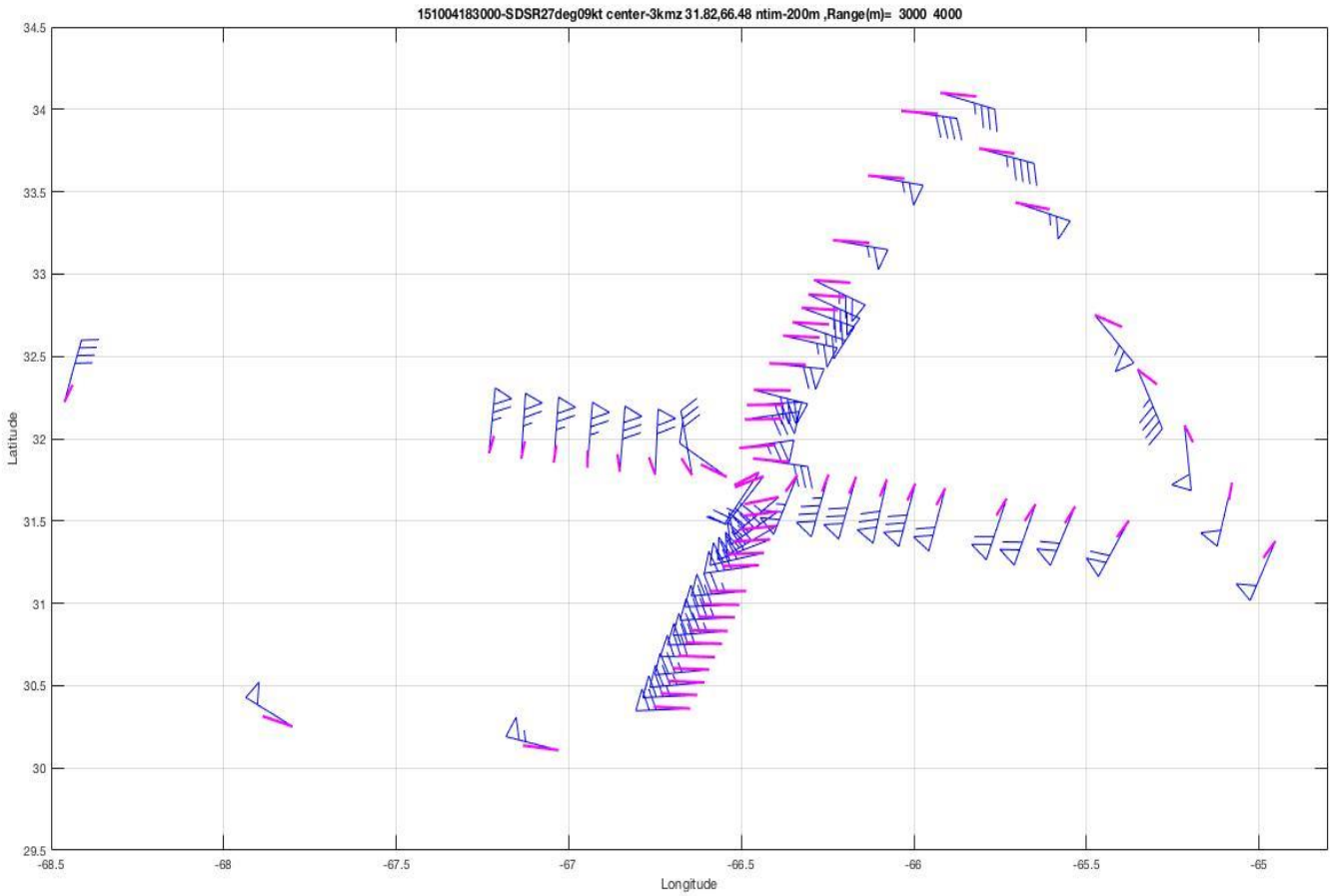
HURRICANE JOAQUIN STORM-RELATIVE WINDS
1830 UTC 4 OCTOBER

ELEVATION: 1.5 KM RELATIVE WIND: Blue AZIMUTH: Magenta



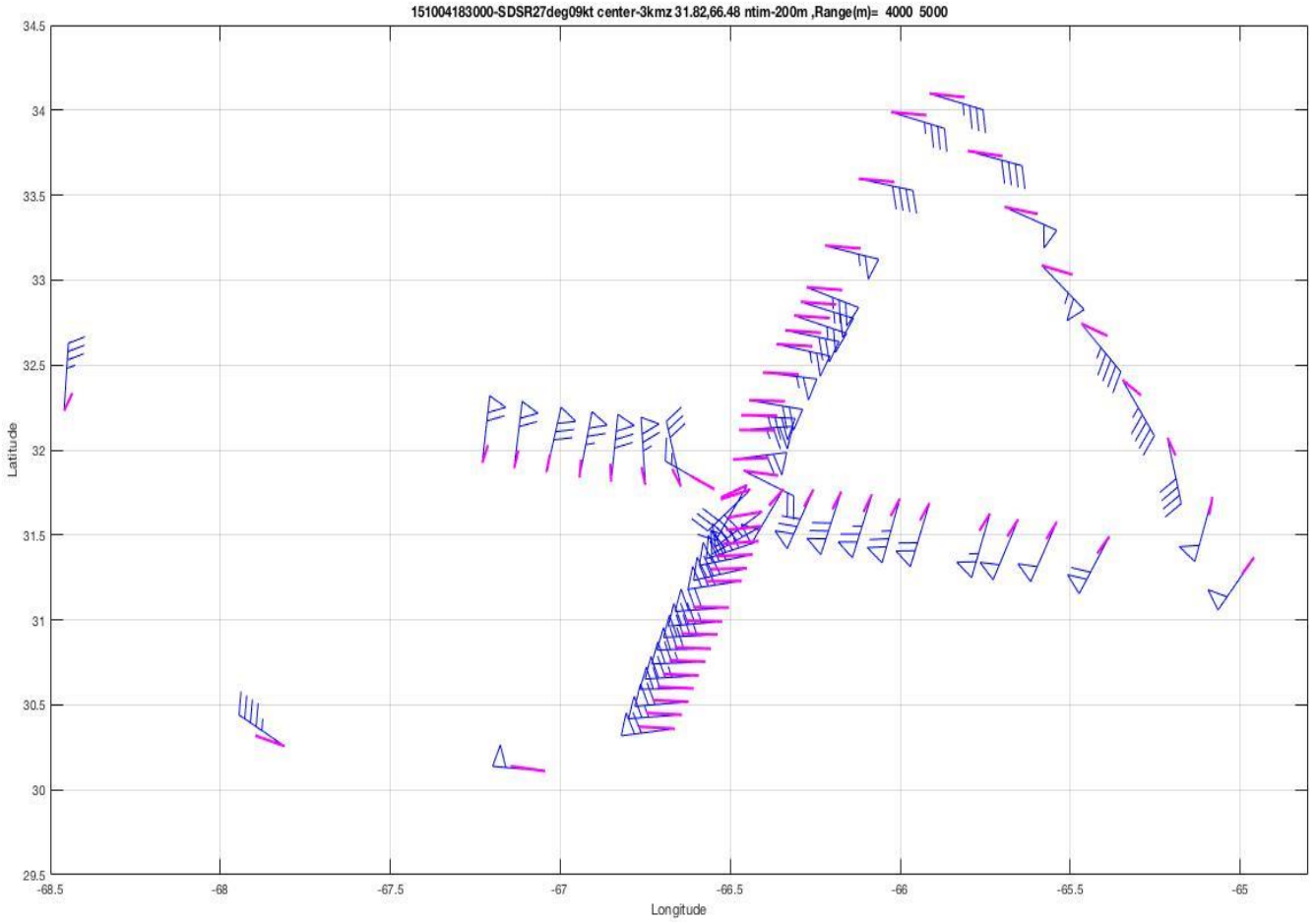
HURRICANE JOAQUIN STORM-RELATIVE WINDS
1830 UTC 4 OCTOBER

ELEVATION: 3.5 KM RELATIVE WIND: Blue AZIMUTH: Magenta



HURRICANE JOAQUIN STORM-RELATIVE WINDS
1830 UTC 4 OCTOBER

ELEVATION: 4.5 KM RELATIVE WIND: Blue AZIMUTH: Magenta



HURRICANE JOAQUIN STORM-RELATIVE WINDS
1830 UTC 4 OCTOBER

ELEVATION: 5.5 KM RELATIVE WIND: Blue AZIMUTH: Magenta