NATIONAL TRANSPORTATION SAFETY BOARD
Office of Research and Engineering
Washington, DC

Ship Dynamics from VDR Data Study

El Faro

DCA16MM001

January 29, 2017

Crider Dennis

Contents

Figures

1. ACCIDENT INFORMATION

Vessel:	*El Faro*
Accident Number:	DCA16MM001
Date:	10/1/2015
Time:	0739 eastern daylight time (EDT)
Location:	North Atlantic Ocean, 40 nautical miles northeast of Acklins and Crooked Islands, Bahamas 23.3925˚ N, 73.9029˚ W
Accident type:	Sinking
Complement:	27 crew, 6 supernumeraries

2. GROUP

No group was formed for this activity.

3. SUMMARY

On Thursday, October 1, 2015, about 0715 EDT, the US Coast Guard received distress alerts from the 790-foot roll-on/roll-off container (Ro/Con) ship *El Faro*. The US-flagged ship, owned by TOTE Maritime Puerto Rico (formerly Sea Star Line, LLC[1]) and operated by TOTE Services, Inc. (TOTE), was 40 nautical miles northeast of Acklins and Crooked Islands, Bahamas, and close to the eye of Hurricane Joaquin. The ship was en route from Jacksonville, Florida, to San Juan, Puerto Rico, with a cargo of containers and vehicles. Just minutes before the distress alerts were received, the *El Faro* master had called TOTE's designated person ashore and reported that a scuttle had popped open on deck two and that there was free communication of water into the No. 3 hold. He said the crew had controlled the ingress of water but that the ship was listing 15° and had lost propulsion. The Coast Guard and TOTE were unable to reestablish communication with the ship. Twenty-eight US crewmembers, including an off-duty engineering officer sailing as a supernumerary, and five Polish workers were on board. The vessel sank in 15,400 feet of water.

The Coast Guard, US Navy, and US Air Force dispatched multiple assets to the ship's last known position, but the search was hampered by hurricane-force conditions on scene. On Sunday, October 4, a damaged lifeboat and two damaged life rafts were located. The same day, the Coast Guard found a deceased crewmember wearing an immersion suit. A Coast Guard rescue swimmer tagged the body in

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[1] On September 17, 2015, the parent company, TOTE, Inc., announced that Sea Star Line had been renamed TOTE Maritime Puerto Rico.

the immersion suit and left to investigate reported signs of life elsewhere but then could not relocate the tagged suit. No signs of life were found, and on Monday, October 5, a debris field and oil slick were discovered. The Coast Guard determined that *El Faro* was lost and declared the event a major marine casualty. The Coast Guard suspended the unsuccessful search for survivors at sundown on Wednesday, October 7.

4. DETAILS OF INVESTIGATION

4.1. Purpose of Study.

The *El Faro* Voyage Data Recorder (VDR) recorded GPS antenna altitude. It was desired to determine if this altitude parameter provided information on the ship's sinking.

4.2. VDR data

Recorded GPS antenna altitude is plotted with heading in figure 1. A closer view of the antenna altitude dip at 16:00 September 30th and the peak altitude at 12:30 AM October 1st are shown in figures 2 and 3 respectively.

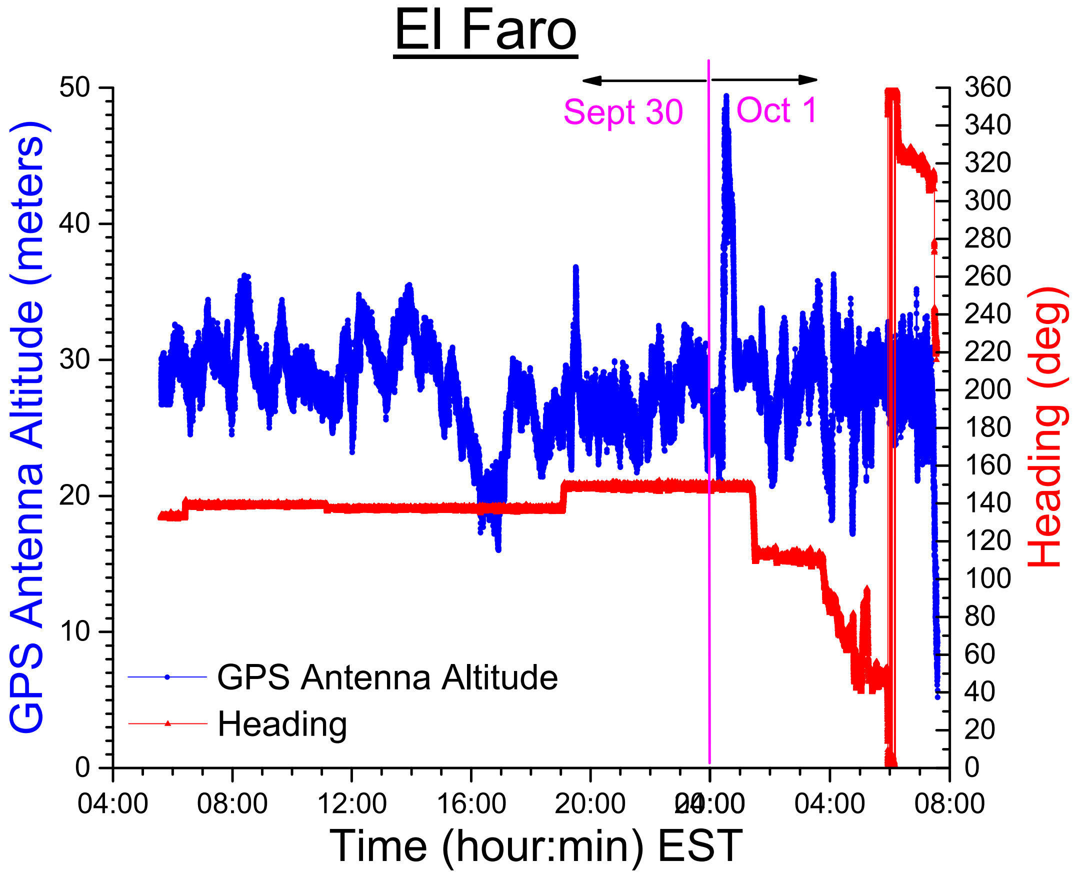

Figure 1 GPS altitude and heading

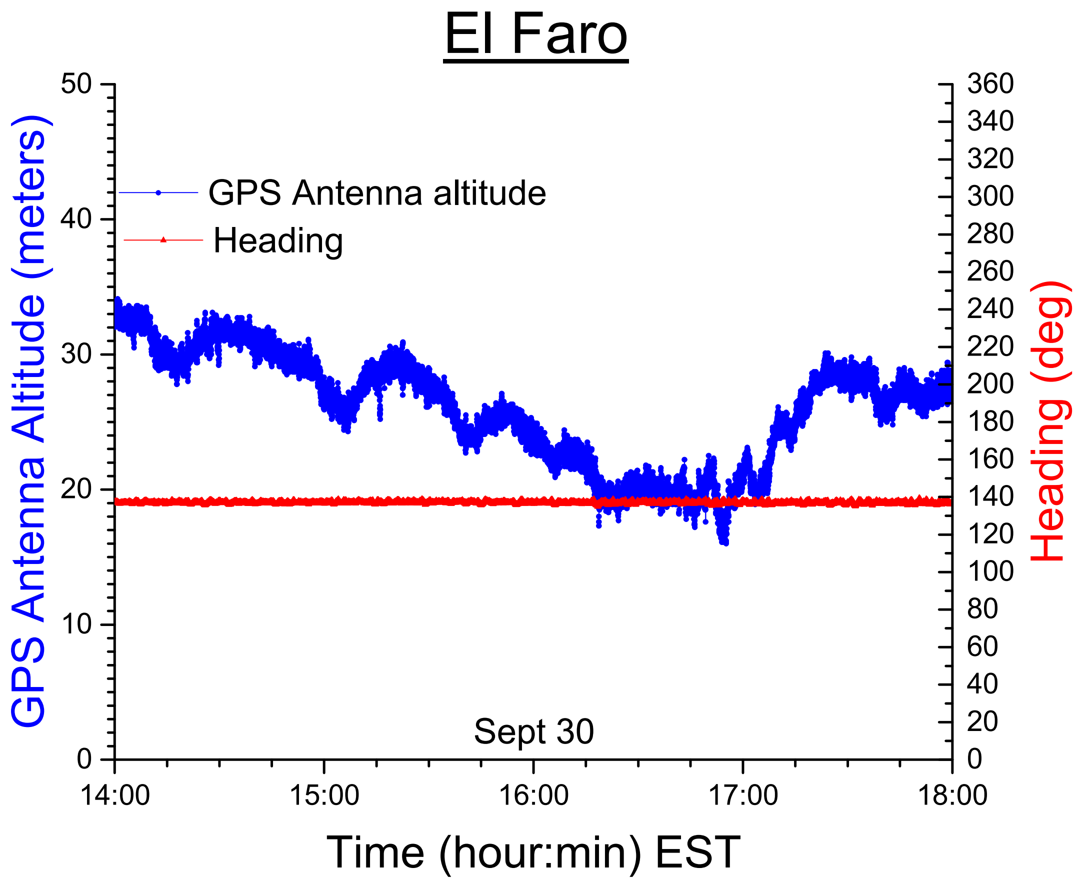

Figure 2 GPS Altitude and Heading (September 30, 14:00 hr)

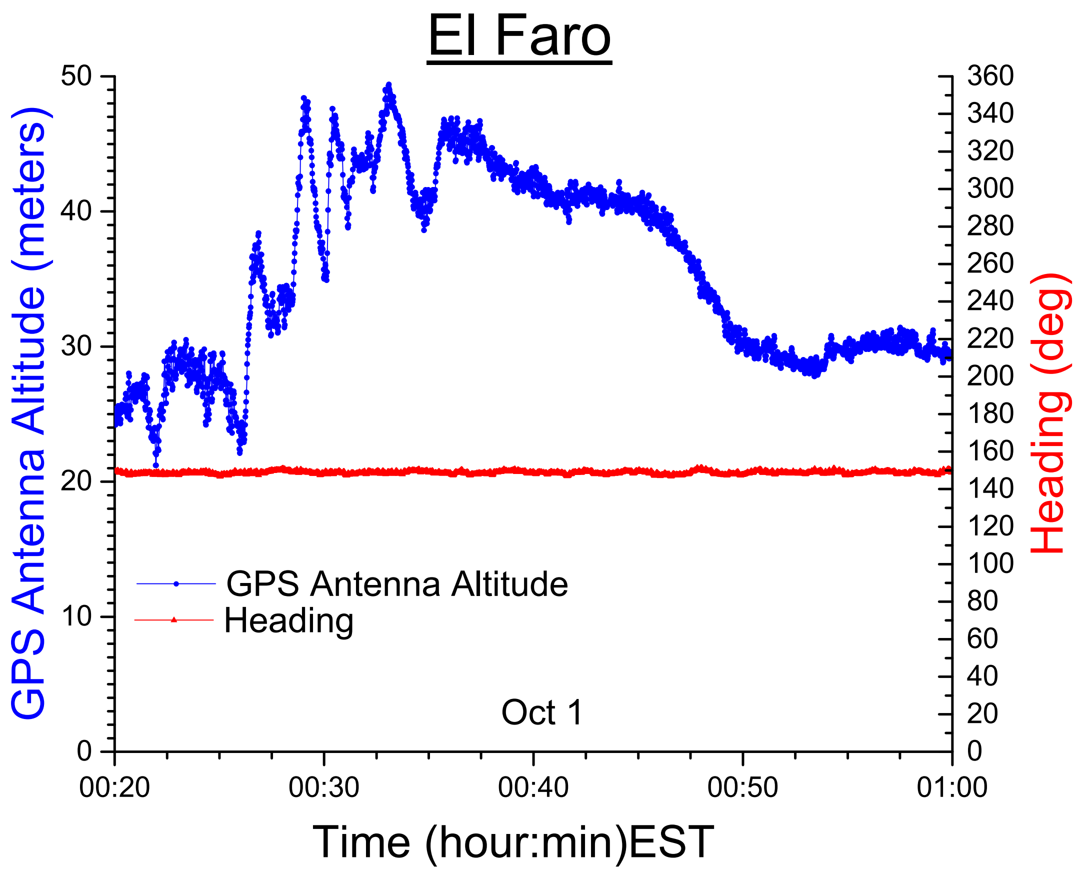

Figure 3 GPS Altitude and Heading (October 1st, 0:20 hr)

The 10+ meter reduction in GPS altitude shown in figure 2 is about an order of magnitude greater than the expected tidal variation in sea level relative to the geophysical datum. Similarly, according to NOAA, the sea level rise at the center of the storm would be about 0.64 meters. Classically GPS altitude is not as accurate as GPS position with significant errors accumulating over long periods of time but can be expected to be good over short time periods point to point. The long term altitude changes in figures 2 and 3 are consistent with accuracy limitations in long term GPS altitude data.

Selected crew comments from the VDR transcript are shown with altitude and heading in figures 4, 5, 6 and 7. Figure 7 in particular shows the crews comment on the loss of propulsion and the subsequent 40 degrees west heading change followed by the beginning of rapid sinking at about 7:25 EST followed by an almost 100 degree south change in heading.

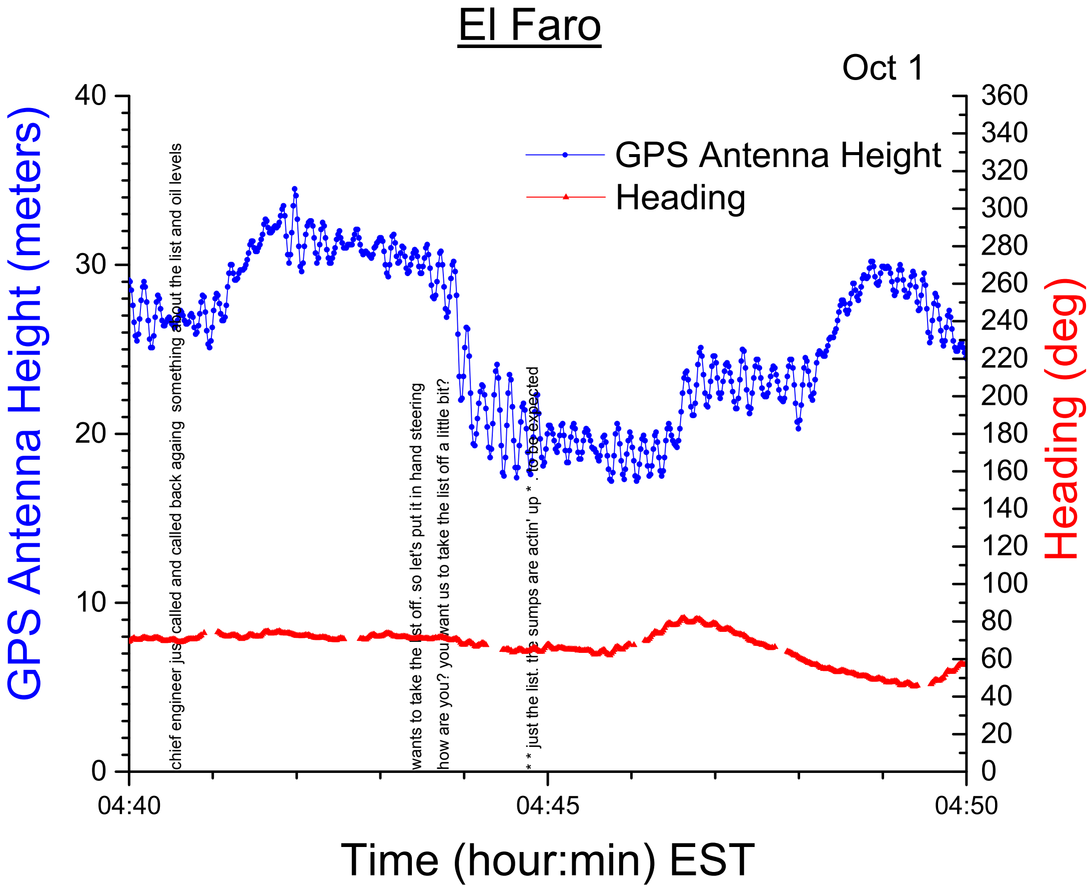

Figure 4 Selected comments with altitude 4:40 to 4:50 EST

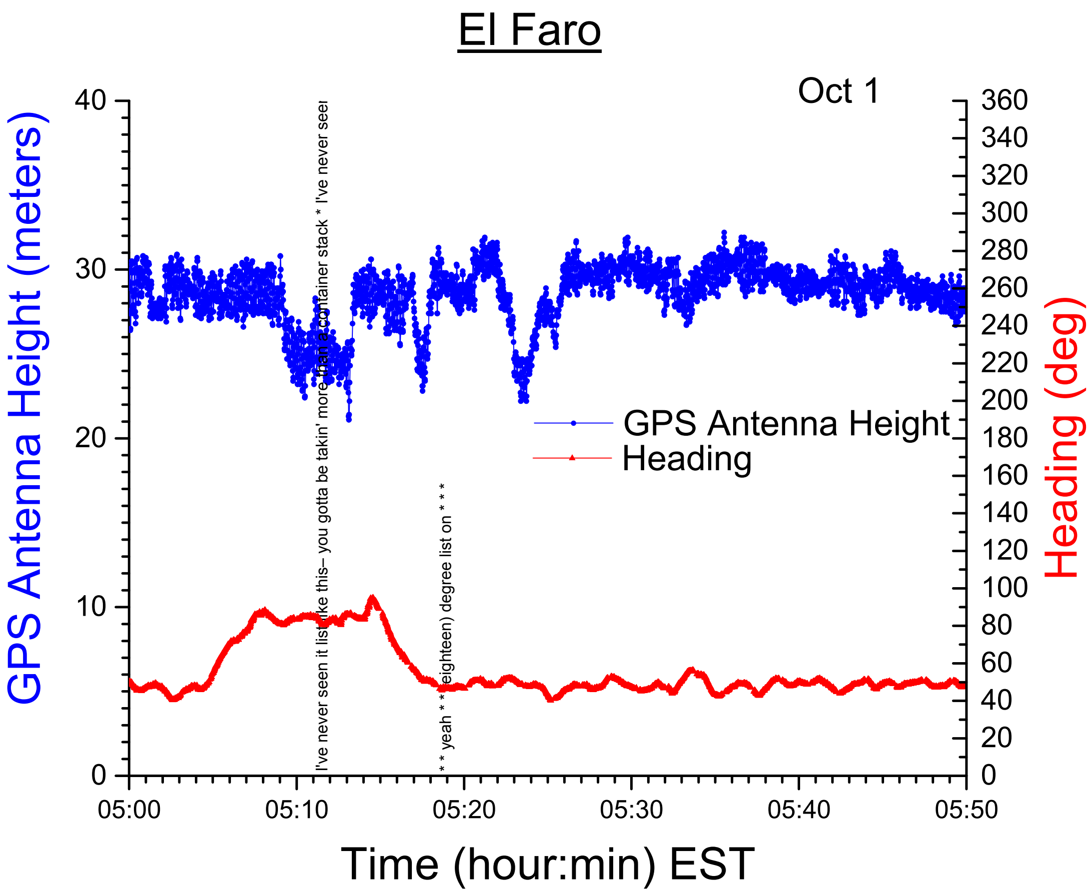

Figure 5 Selected comments with altitude 5:00 to 5:50 EST

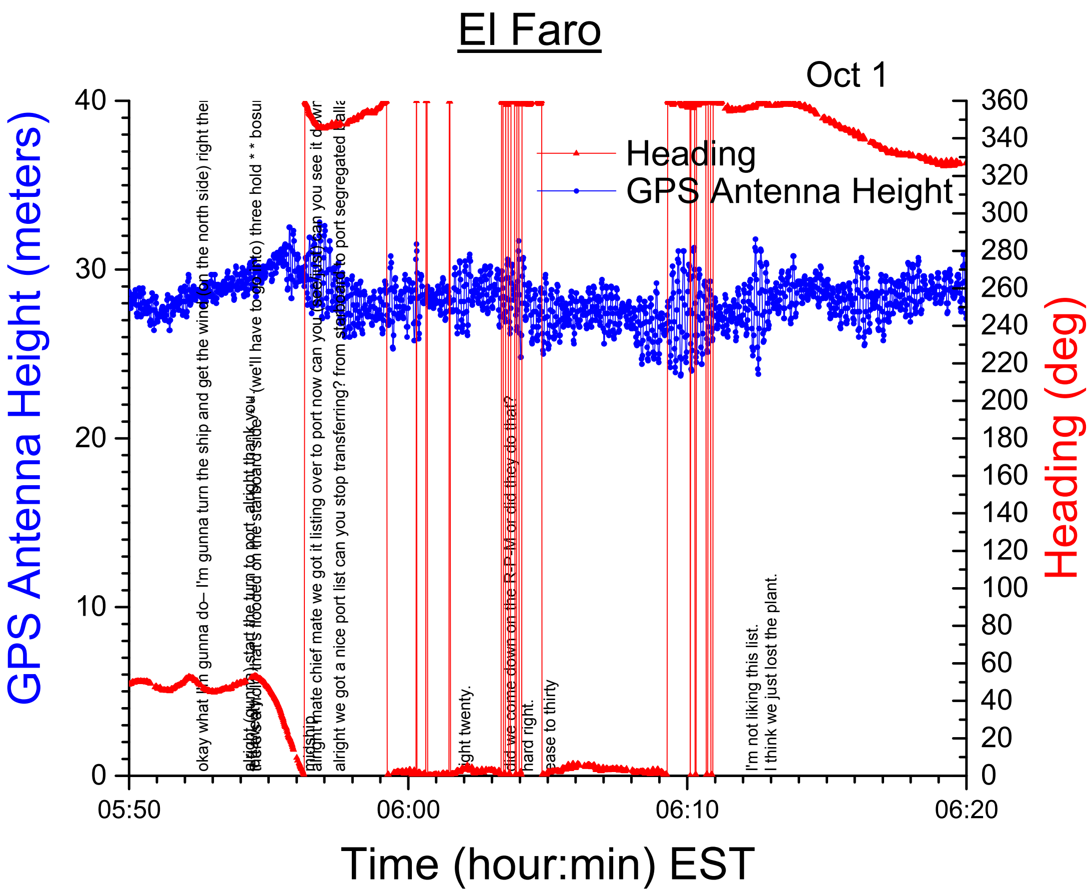

Figure 6 Selected comments with altitude 5:50 to 6:20 EST

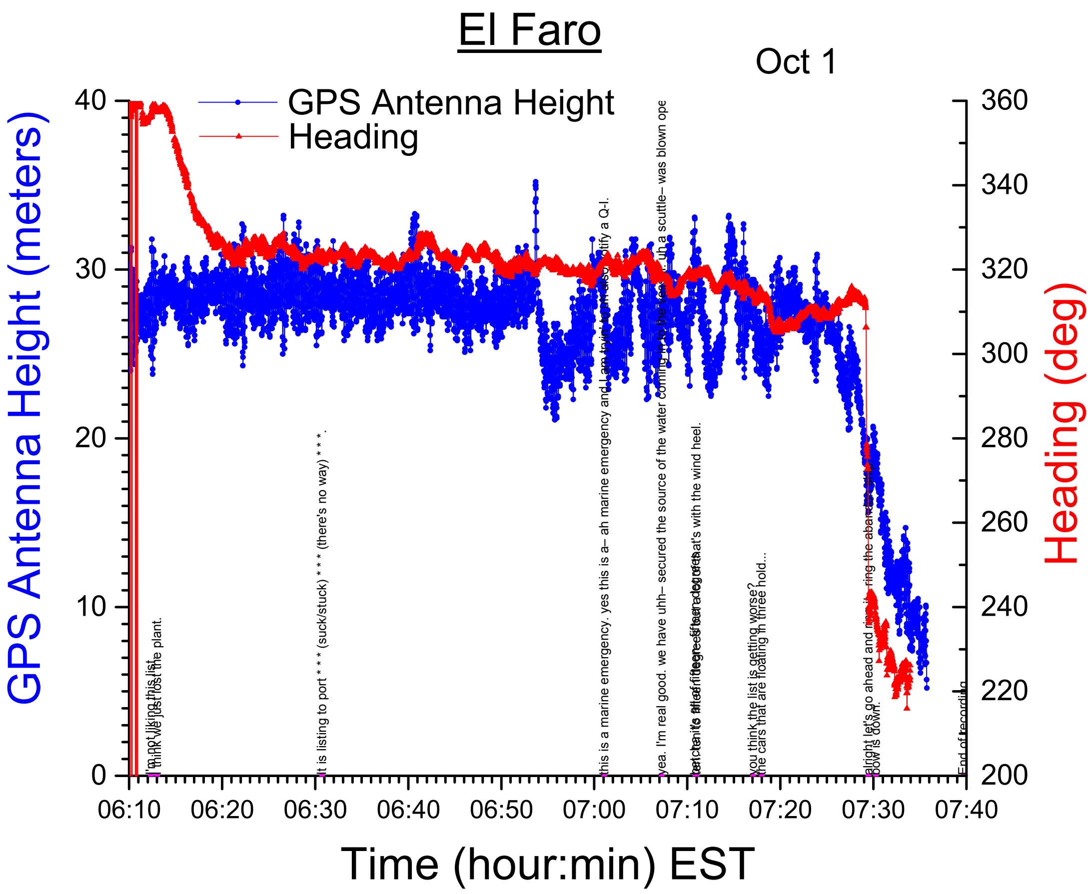

Figure 7 Selected comments with altitude 6:10 EST to end of VDR data

Selected transcript comments are presented in map view in figure 8.

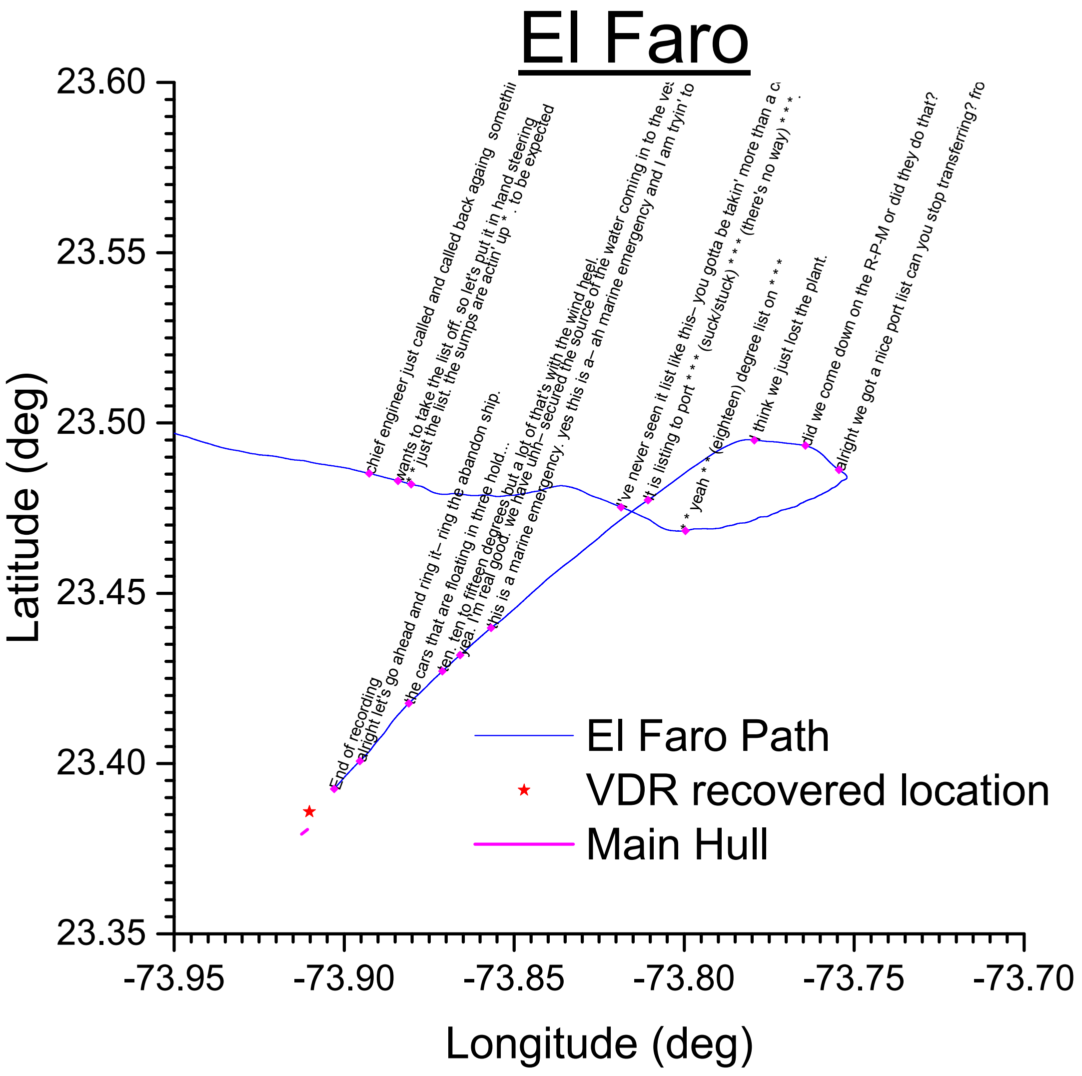

Figure 8 Selected transcript comments on the ships path

4.3. High frequency altitude component

To examine the high frequency altitude component, a low frequency altitude signal was first obtained by filtering out the high frequency data. This was done with a Savitzky-Golay 2nd order smooth with n = 101. The smoothed signal is compared to the unfiltered signal in figure 9 for the entire dataset and in figures 10 and 11 for shorter time intervals to illustrate the effect of the filter more clearly. This filtered signal was then subtracted from the unfiltered signal to obtain the high frequency component shown in figures 12, 13 and 14. The increased amplitude at the later time (closer to the storm center) is readily apparent.

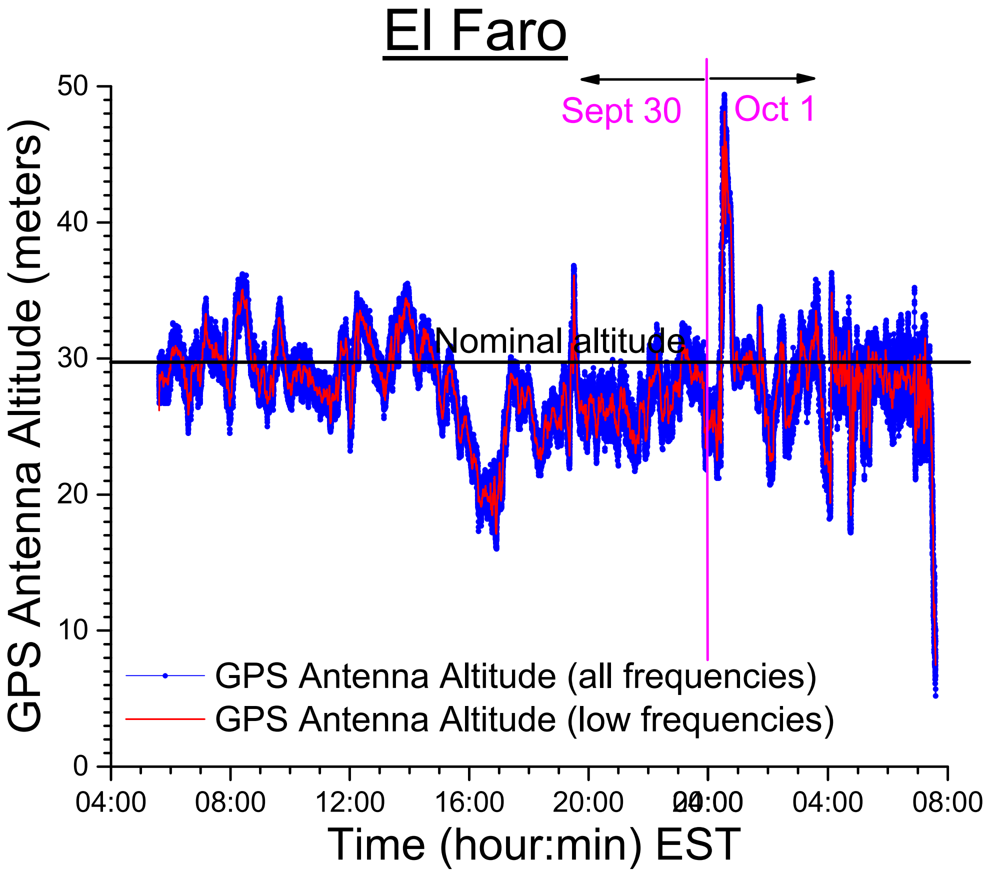

Figure 9 Filtered altitude

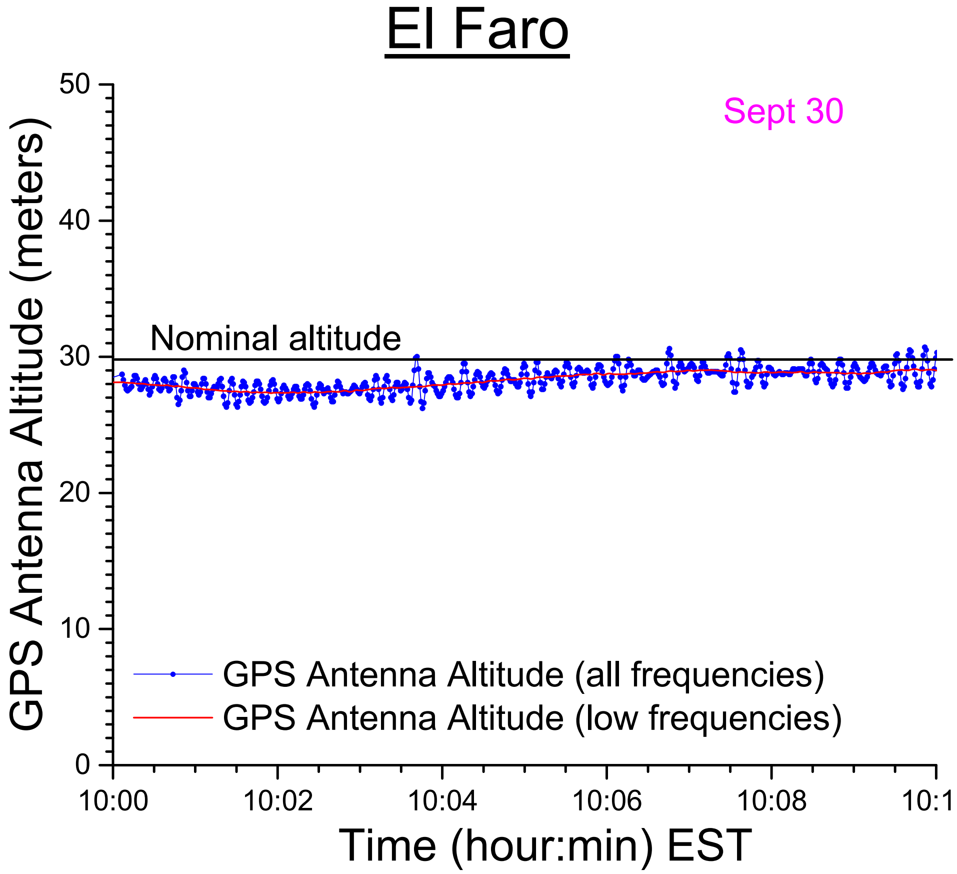

Figure 10 Filtered altitude (10:00 EST Sept 30)

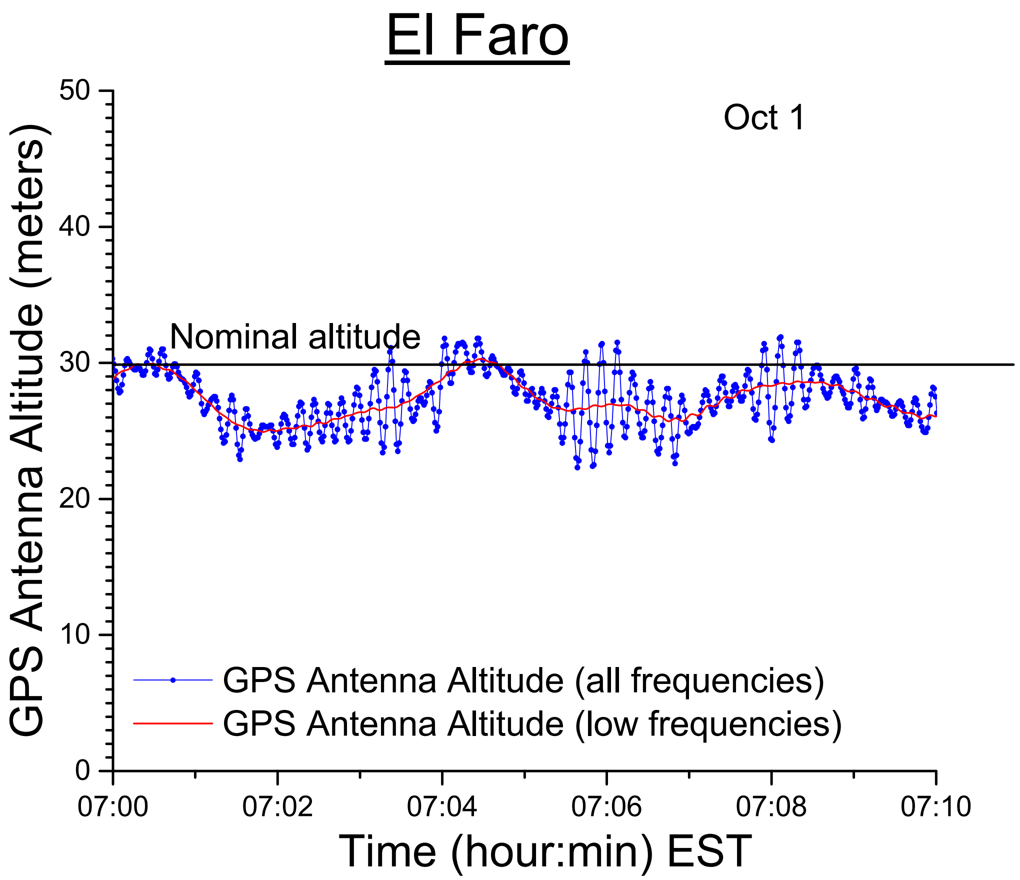

Figure 11 Filtered altitude (7:00 AM EST Oct 1)

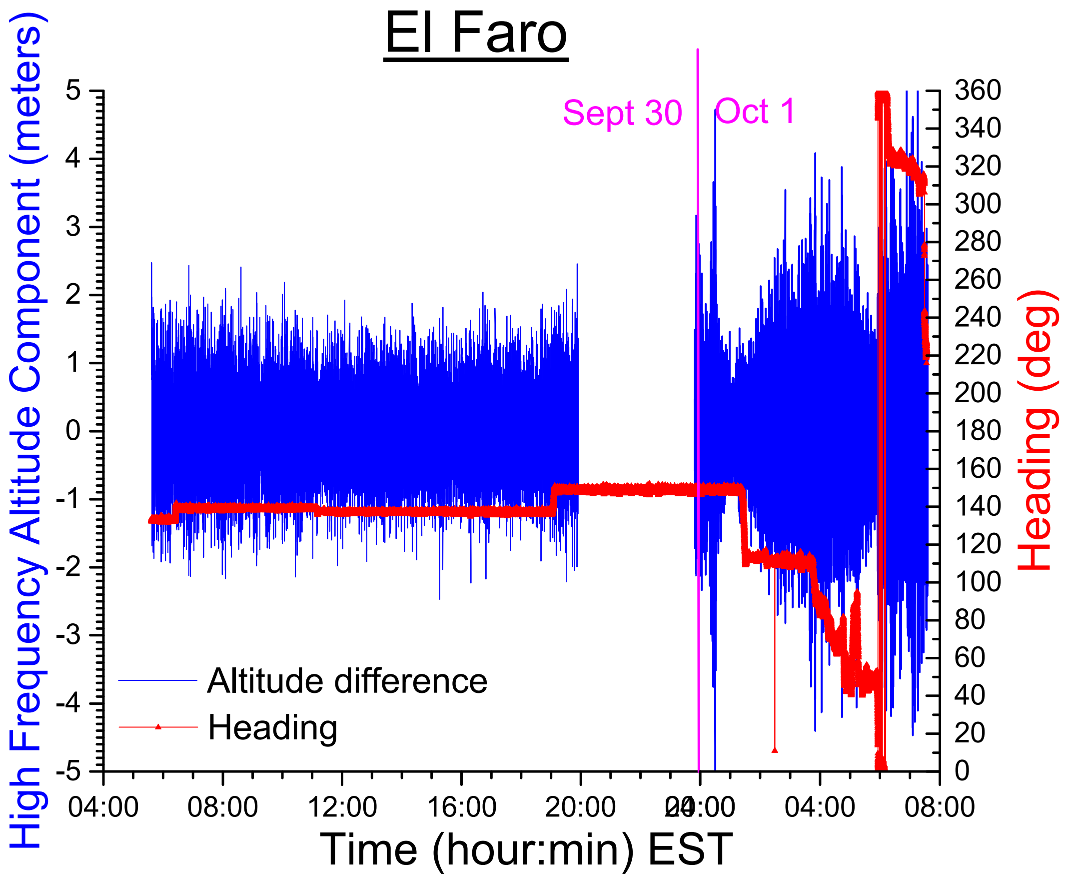

Figure 12 High frequency altitude component

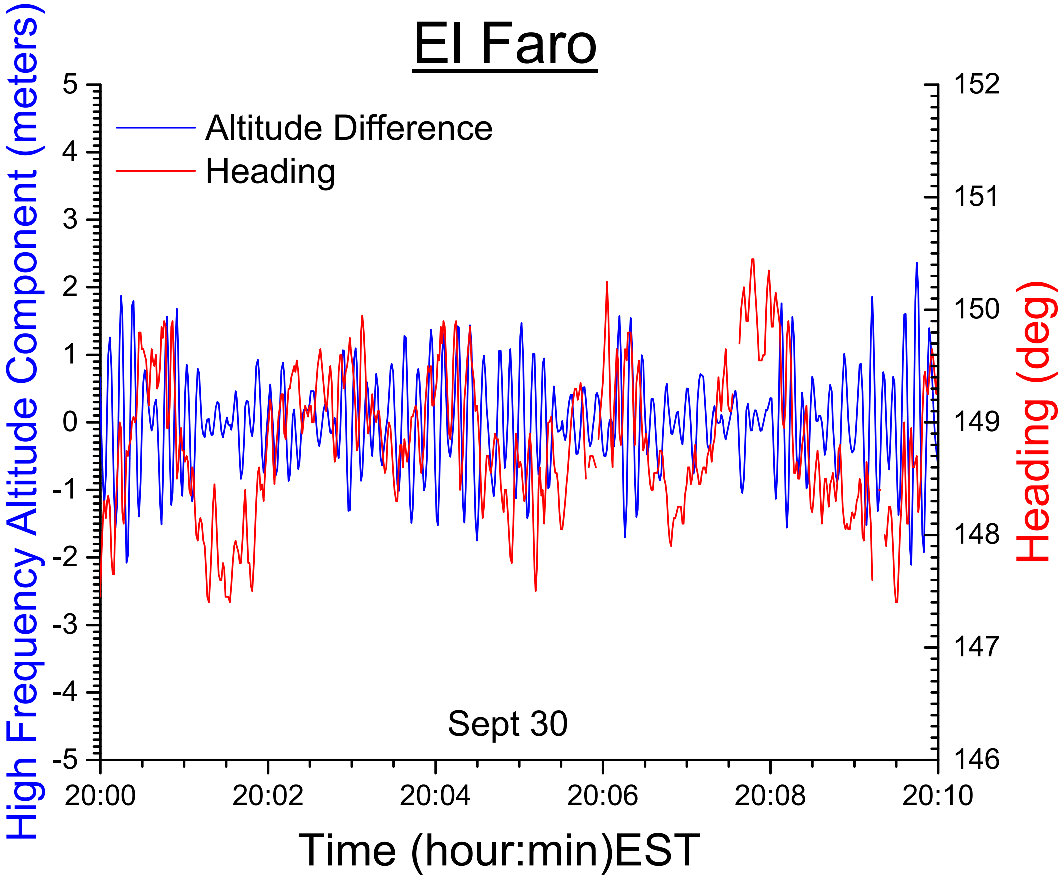

Figure 13 High frequency altitude component (20:00 EST Sept 30)

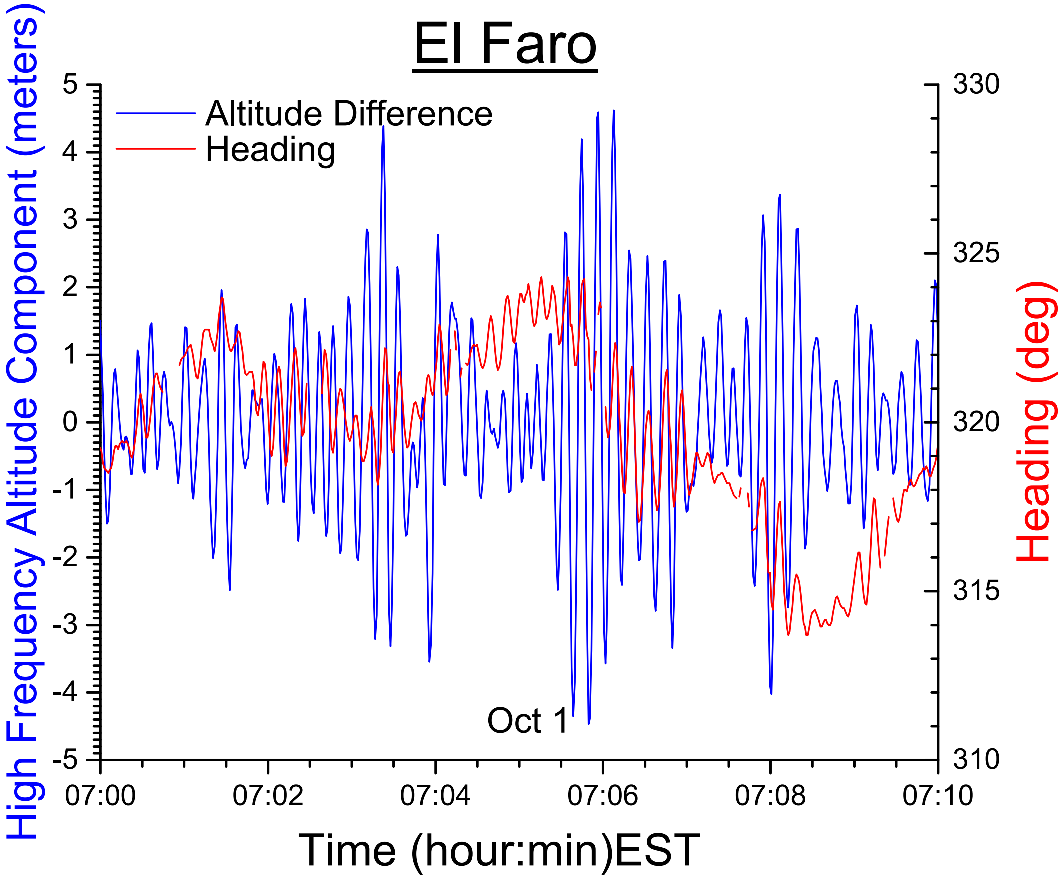

Figure 14 High frequency altitude component (7:00 AM EST Oct 1)

As can be seen in figures 13 and 14, heading and altitude both oscillate with approximately a 12-second period. The magnitude of these oscillations grew with time.

4.3.1. Equivalent List Angle

As the GPS antenna was located above the wheelhouse, oscillations in GPS antenna altitude could be due to a combination of vertical motion of the ship's center of rotation (heave), motion resulting from the ships pitch and the longitudinal arm between the ship's center and the wheelhouse and oscillatory rolling motion.

With the long term GPS drift, and the need for precise antenna altitude as well as waterline position as a function of roll (list) angle due to the high sensitivity of the calculations it is not possible to calculate a meaningful list angle from antenna altitude directly. The magnitude of any roll oscillations can be bracketed however by assuming a list angle and using the high frequency altitude component (shown in figures and 12, 13 and 14) as a perturbation. The maximum roll dynamics from mapping <u>the entire</u> high frequency altitude component into roll[1] is given in figures 15, 16 and 17. Note these plots describe the maximum roll dynamics as it is likely that at least some of the GPS altitude dynamics is due to heave or pitch motion.

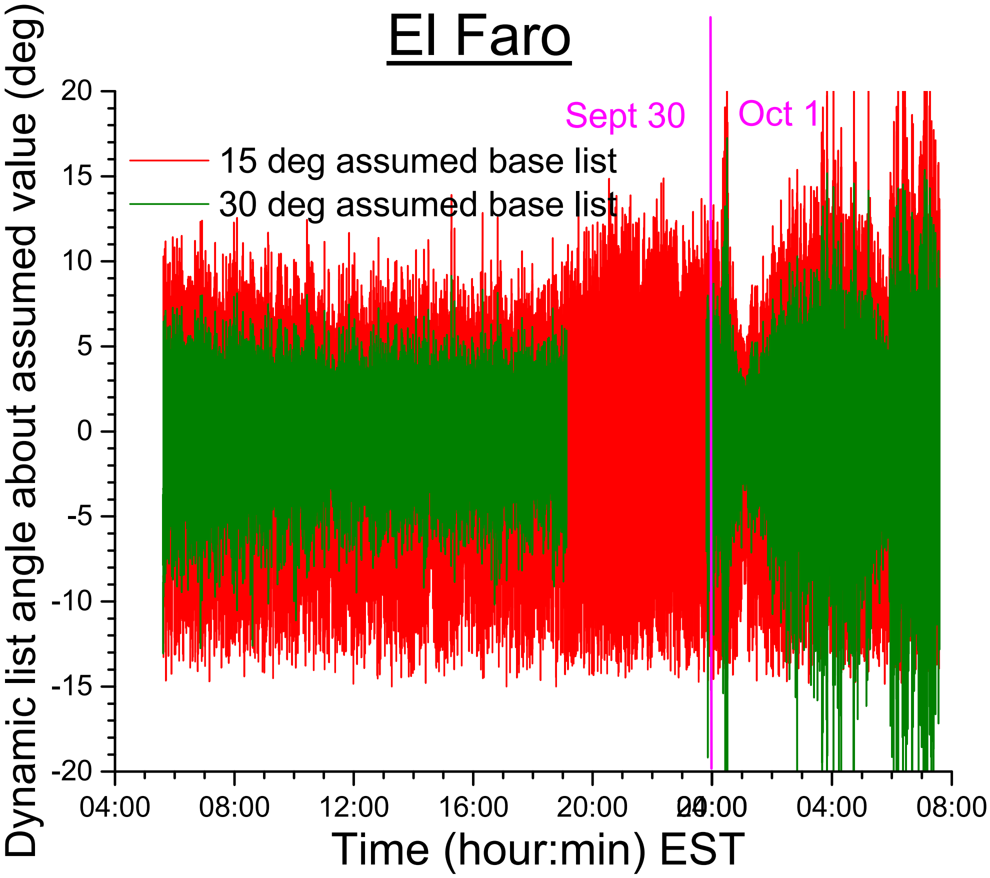

Figure 15 Maximum roll dynamic component from assumed base list

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[1] The method is outlined in Appendix A.

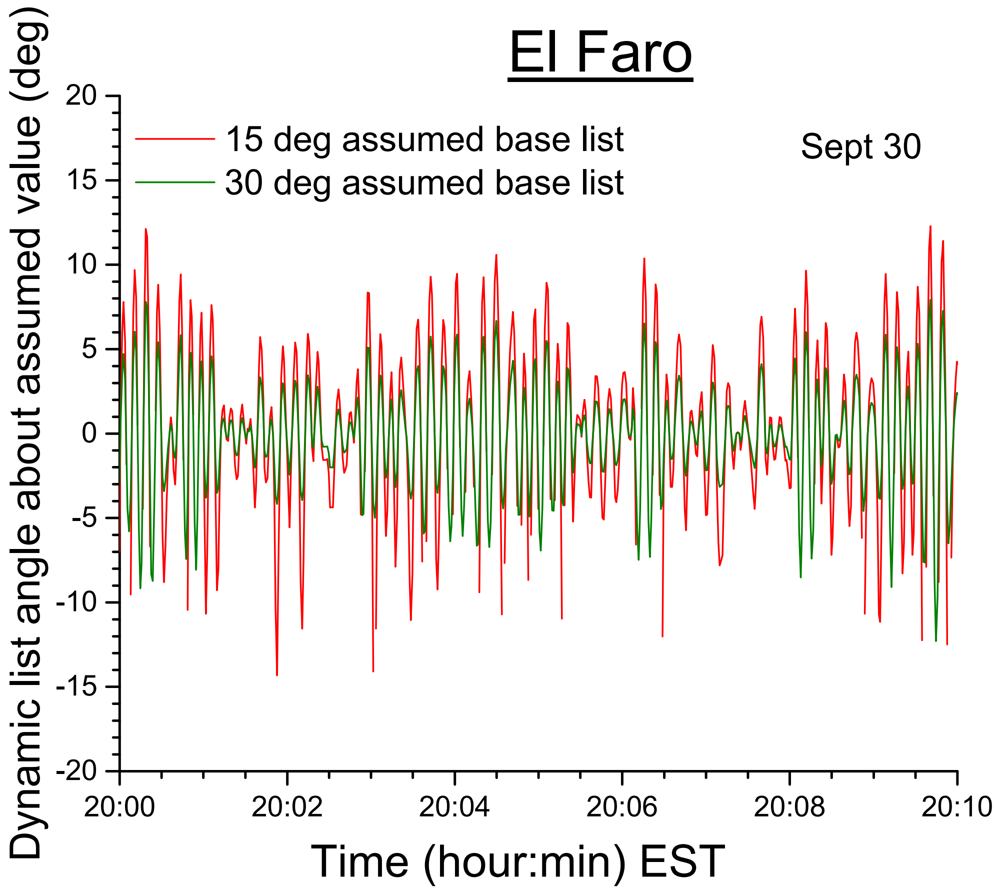

Figure 16 Maximum roll dynamic component from assumed base list (20:00 EST Sept 30)

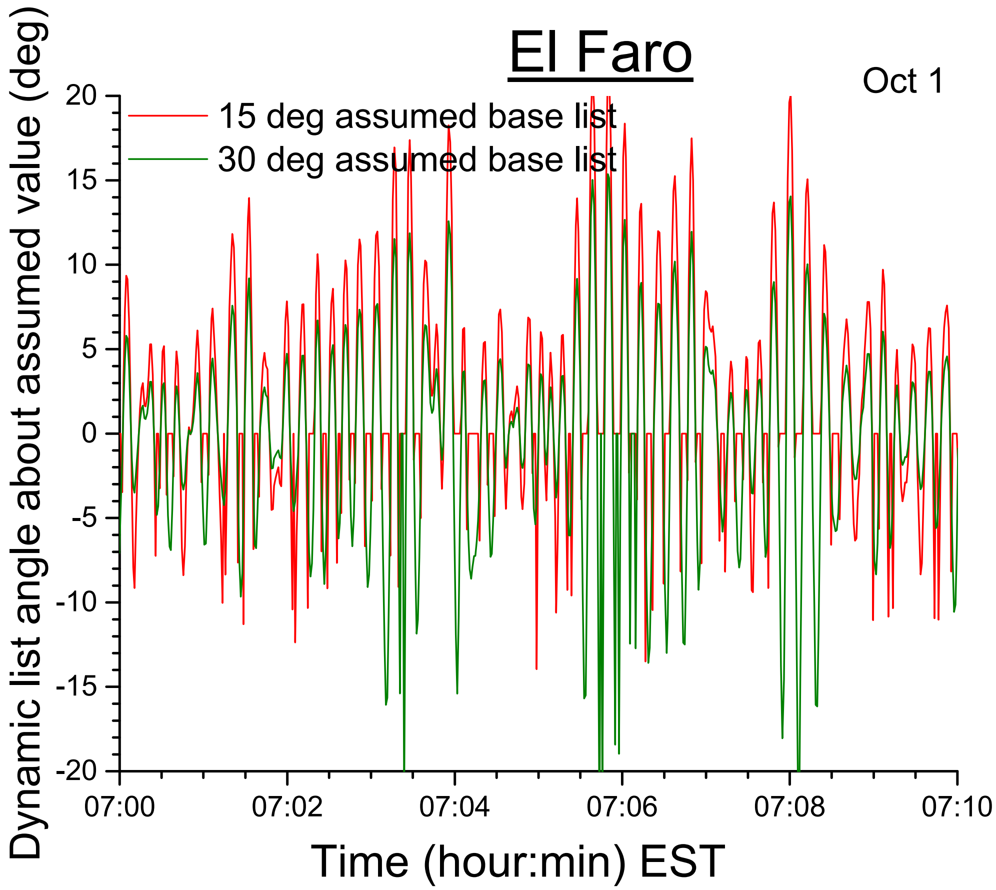

Figure 17 Maximum roll dynamic component from assumed base list (7:00 AM EST Oct 1)

In evaluating how much of the altitude dynamics reflect roll and how much reflect heave and pitch the following points were considered.

- The altitude oscillations are evident from the beginning of the VDR data record at 9:36 AM UTC September 30, long before the first crew mention of a list at 8:40 AM UTC October 1st.
- If the altitude dynamics reflected a roll motion that passed through zero, the altitude would reach maximum with a rate resulting in a sharp maximum rather than a characteristic sine wave maximum. Unfortunately, the sample rate was insufficient to determine the shape of the wave at this frequency.
- A pure roll motion would result in a common maximum altitude for each oscillation. The data does not show this, thus the altitude dynamics cannot be purely in roll and must contain heave and/or pitch motion.

- A roll through zero heel would produce a left and right minimum altitude with two maximum altitudes through zero heel. If the ship was not rolling through zero heel there should be only one maximum and minimum altitude. Thus, for a given roll period, the altitude period will be ½ the roll period when rolling through zero heel but equal to the roll period if not rolling through zero heel. The period of the altitude remains approximately 12 seconds throughout the recorded time period. There is no change in period, though the crew reported 15 degree heel (where several roll oscillations would not have passed through zero) near the end.
- The heading oscillation align with the GPS altitude oscillations suggesting coupling for these motions. The high frequency heading oscillations ranged from about +/-½ deg early on to +/-1½ degrees in the storm. Assuming that the roll to sideslip ratio for the *El Faro* is similar to the *Crown Princess*' -3 roll to sideslip ratio[2] and that the magnitude of sideslip at that frequency would be close to the magnitude of the heading oscillation, the corresponding roll oscillation would be approximately +/-1½ degrees early on and +/-4½ degrees in the storm.

4.3.2. Results and Conclusions

The VDR recorded GPS altitude that contained an approximately 12 second period oscillation that grew in magnitude as the ship got closer to the center of the storm ranging to approximately +/-4½ meters. This was coupled with a heading oscillation at the same 12 second period with an amplitude that grew to approximately +/- 1 ½ degrees as the ship got closer to the storm center. The altitude oscillation could represent a combination of heave, pitch acting on the distance between the ship's rotational center and the antenna, and roll. All three motions will raise and, more importantly, lower any openings in the ship and affect ship's flooding.

The GPS altitude oscillation was at least partially the result of pitch and/or heave motion. It was not possible to rule out or completely quantify any contribution of roll motion to the recorded altitude dynamics. However, the contribution was likely small as; if the roll was oscillating +/- 5 degrees (per the max heading oscillation) the altitude variation list would be +/- 0.104 meters with zero base list and +/- 0.717 meters with 15 degrees base list.

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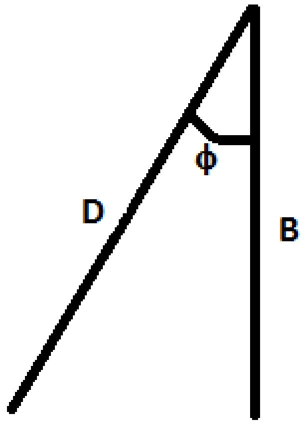
[2] NTSB "Crown Princess Vessel Kinematics Study", December 1, 2007

Appendix A, Roll Calculation Method



Defining D as the distance from the center of rotation to the GPS mask and B as the vertical component of that distance at an angle ϕ, B can be calculated as:

$$B = D \cos \phi$$

We define a perturbed vertical component by adding the high frequency altitude component as:

$$B' = D \cos \phi + \Delta h_{dynamic}$$

The dynamic roll component for an assumed ϕ can be calculated as

$$\phi' = \cos^{-1} (B'/D) - \phi$$