ABSTRACT
Installed 160 miles South of New Orleans in 1300 m of water, the Marco Polo Tension Leg Platform is subjected to an extensive monitoring campaign to benchmark design data and methods. The purpose of the full scale monitoring campaign is to evaluate the design in operation exposed to hurricane and loop-current conditions. Interests comprise the high and low frequency modes of motion, the fatigue loading of the platform and the dynamic behavior of the tendons and risers with focus on vortex induced vibrations. To evaluate these results wind, wave and current conditions are closely monitored.

INTRODUCTION
The Marco Polo field is located in Green Canyon block 608, 160 miles south of New Orleans. It is fully owned by Enterprise and Helix and operated by Anadarko Petroleum. The field was discovered in April 2000 and lies in water 1300 m (4,300 ft) deep. It produced its first oil in March 2004. With even deeper prospects at the horizon, the owners of the Marco Polo TLP awarded the instrumentation contract to Marin Trials & Monitoring and initiated a Joint Industry Project to share knowledge and experience in the deepwater industry. This ongoing JIP is currently supported by Anadarko, ABS, BHPB, BP, Enterprise, Hess, Modec, MMS, Sea Engineering and MARIN. The initial phase of the JIP consisted of design and installation of a measurement system and was completed mid 2004. The second phase consists of a three-year measurement campaign and associated analysis of the data, which started June 2004 and is scheduled to end November 2007. The aim of this JIP is to verify the design methods of deep water TLPs by evaluating loads and motions of the platform in combination with the encountered wind, wave and current conditions. Apart from the long term interest in the measured data, the measurement system also serves as an operational tool, allowing real time assessment of platform response and environmental loads, even in Hurricane conditions, when the platform is evacuated.

During the measurement campaign the Marco Polo TLP already encountered three major Hurricanes; Ivan (in Sep 2004 passed within 120 nm), Katrina (in Aug 2005 passed within 45 nm) and Rita (in Sep 2005 passed within 60 nm), see Figure 2. Measurements on other platforms during hurricane Ivan have been described by Perego (2005), Cox (2005) and Cooper (2005). In this paper the instrumentation of the Marco Polo
 platform will be described and characteristic results of the ongoing monitoring campaign will be presented.

![Image](39x592 to 292x684)

![Image](88x100 to 258x308)

![Image](378x89 to 535x205)

**Figure 2: MP relative to major hurricanes 2004 & 2005**

**INSTRUMENTATION AND MONITORING SYSTEM**

The Marco Polo Measurement System (MPMS) consists of an extensive set of sensors, a data acquisition and logging system and data transfer by satellite to enable near real-time access to the data by the operator of the platform on-shore and MARIN. The sensors on board the Marco Polo TLP consist of:

- Wave sensors (3 wave radars)
- Wind sensors (2 ultrasonic anemometers)
- Current sensors (top and bottom ADCPs)
- DGPS for low frequency motions
- 6 d.o.f. wave frequency motion sensor (MQK)
- Riser tensions (Danfoss)
- Riser vibrations (vertical accelerometers)
- Tendon tensions (TTMS)
- Stresses in gussets (strain gauges)

The location of these sensors is schematically shown in Figure 3. The sensors and measurement system are described in more detail in van den Boom et al. (2005).

All sensors are connected to the data acquisition system, using an appropriate interface. The data acquisition system stores the logged data in 30-minute data files. The data is displayed on board of the Marco Polo TLP for operational use by the crew and sent to shore for more detailed analysis of environmental conditions and platform response. Originally the stored data was sent to shore once a month on a back-up tape, with daily emails from the platform to shore to monitor the performance of the system. This approach required human intervention to obtain the data on the engineer's desk and a severe drawback was the delay between data acquisition and actual access to the data by experts who perform the analysis. Since December 2005 the data transfer from TLP to shore is done by satellite link. Proprietary software is installed at the offshore servers and at the onshore processing center. This software is designed to transfer large volumes of data in conditions of poor or intermittent communications, see also Mitchell et al. (2006).

A web-based delivery system is used to present the most relevant data on a secure web-page. This system involves storing the data in such a way as to be able to deliver samples and summaries of data very rapidly to the user, from storage typically in 10’s of gigabytes. The web service enables users to view latest values, and also to trend events as they happen. As this system is fully automated data transfer and presentation on the web continuous even when the platform is unmanned, such as in a hurricane event. This means that even in the most extreme conditions the environment and loads on the platform can be assessed and detailed post-hurricane analysis can be performed even before the crew has returned to the platform.

**MEASUREMENTS**

The measurements on board Marco Polo started in June 2004 and have been ongoing continuously since then. The MPMS has a current uptime of more than 98% and even the three major hurricanes of 2004 and 2005 have been recorded without interruption.

The recorded hurricane data reveals some very interesting phenomena, especially with respect to maximum wave heights and directionality of the waves. The wave height on board of Marco Polo is measured using three wave radars. The approximate location of these three wave radars is shown in Figure 3 and Figure 4.

![Image](36x38)
Some examples of actual wave and wind measurements are shown in the figures below. Figure 5 shows the significant wave height and wave peak period during hurricane Rita, based on 30-minute intervals. The lower figure shows the measured wind speed (30-min. mean and 1 sec. maximum) and wind direction. The maximum wave height occurs a few hours before the platform experiences the maximum wind speed.

Figure 5: Wave and wind measurements during Rita

Zooming in on the extreme waves measured during the hurricanes, Figure 6 shows the (uncorrected) time trace of an extreme wave measured during the peak of hurricane Rita. The top plot shows the full 30-minute record and the bottom plot shows a detail around the maximum wave height. This extreme wave is only measured on one of the three wave radars.

Figure 6: Extreme wave measured during Rita

A large number of similar events have been recorded in all three hurricanes, although hurricane Rita showed significant higher differences between the three wave radars than hurricanes Ivan and Katrina. This indicates more short crested seas, which can be explained by the fact that in hurricane Rita the platform was on the right hand side of the hurricane track. In hurricanes Ivan and Katrina Marco Polo was on the left hand side and the seas were in general more long crested.

Another observation in the measurements is that some extreme waves lead to impact loads on the platform. This phenomenon is also described in more detail by Forristall (2006), Johannessen et al. (2006) and Buchner et al. (2006 & 2007). These impact loads can be observed by the measured accelerations on the topsides. An example of an extreme impact is shown in Figure 7 below. The shape of the wave crest measured on the south side of the platform is very different from the normal wave profile and suggests a breaking wave or heavy spray.

Figure 7: TLP response on wave impact

The response of the platform due to this wave impact is very pronounced. The spectral densities of the three linear accelerations is shown in Figure 8 (note the different scales).

Figure 8: Spectral density of TLP response
The top figures show the wave frequency response (0 ≤ ω ≤ 1.5 rad/s), the middle figures show TLP resonant response (1 ≤ ω ≤ 6 rad/s) and the lower figures show high frequency response (6 rad/s ≤ ω ≤ Nyquist freq). The surge, sway and heave accelerations all show resonance near the natural period for heave, roll and pitch of the platform (3.9 sec, ω = 1.6 rad/s). The same resonance frequency is observed in the measured roll and pitch velocities (not shown). For surge and yaw (not shown) a second peak in the response is observed for a period of 1.25 seconds (5 rad/s). For heave a high frequency oscillation can clearly be observed in the time trace of Figure 7. This response is at 0.45 seconds (14 rad/s).

DATA ANALYSIS

As part of the JIP all measured data is processed. Long-term statistics are used to evaluate the measured and derived channels on a monthly basis. Based on the long-term statistics, certain -more interesting- events are selected for a more detailed short-term analysis. These events include hurricanes, loop current events as well as any other event that might be of interest for operation and design of the TLP. The results of these long term analysis and short term analysis are discussed twice a year in the JIP meetings and feedback is obtained from all JIP participants for further detailed analysis. In this section some highlights of the detailed short term analysis are shown.

An important question is of course: how reliable are the measured wave heights on board the Marco Polo TLP? The quality of the wave height measurement is affected by the following factors:

- The beam width of the radar
- Set down of the platform due to LF offset
- The motions of the TLP due to the waves
- The presence of radiated and diffracted waves
- The presence of wave spray

The results shown in Figure 6 are uncorrected, i.e. including all the above effects. The finite beam width of a wave radar has a limited effect on the measurement of the wave elevation. Given a beam angle of 15° the beam width at mean water level is approximately 6 m. Therefore waves with a short wave length will be measured less accurately. For hurricane waves the beam width is in the order of 2-3% of the wave length. Furthermore, wave crests of extreme waves are close to the wave radar and will be measured accurately due to the smaller beam width at this level. Measurement of wave troughs is less accurate as the wave radar measures the distance to the closest wave surface within the beam width. Therefore, the measured wave trough will be not as deep as the actual wave trough. It can be shown that in general the overall effect of the beam width of the wave radar on the wave measurements is very limited.

The LF set-down of the TLP results in a low frequency varying offset of the mean wave height, which can easily be identified as mean offset in the measured wave height and does not affect the measured wave height (i.e. ζ2-values).

The effect of the wave frequency platform motions can be assessed by taking into account the measured 6 d.o.f. motions. As the wave frequency motions of the platform are measured by MQK, the motions at the locations of the three wave radars can be calculated. By adding the instantaneous vertical motion to the measured wave height the corrected wave height can be obtained. Figure 9 (top figure) shows the vertical motions at the three different wave radars, as well as the measured heave at the MQK location. The bottom figure shows the original measured wave height (dotted line) and the wave height corrected for heave of the wave radars (solid line). Although the effect is in general small, for this extreme wave the maximum weight height reduces from 28.1 m to 26.9 m (i.e. a 4% reduction).

Figure 9 shows that the platform heave motions are in anti-phase with the wave height, which explains the reduction in maximum wave height. Further analysis of the platform motions shows that the platform heave motions are mainly in the wave frequency range. Figure 10 shows the low frequency and wave frequency surge and sway behavior of the TLP for the selected time trace, including 30-minute mean wave and wind direction.
Due to the low frequency and wave frequency offset variations of the platform the set down of the platform will change too. For the quasi-static situation the set down can be calculated as: 

\[ SD = \sqrt{(L_{Tendon}^2 - \text{offset}^2)} - L_{Tendon} \]

This formula assumes the tendon to be a straight line between tendon porch and piles. For dynamic behavior of the TLP this may not be entirely accurate, as tendon dynamics are involved. Figure 11 shows the correlation between the wave frequency heave and the wave frequency TLP surge and sway. In this plot the mean offset and mean set down have also been included. This plot shows that the mean set down due to the TLP offset is in the order of 1.5 m and that there is a strong correlation between the WF surge and sway motions of the TLP and heave. If a large wave passes the wave forces will move the platform with the wave, away from its mean position. Due to this increased offset the set down increases too. This effect is much larger than the upward movement of the TLP due to the temporarily increase in buoyancy.

The effect of radiated waves and diffracted waves on the measured wave elevation is assumed to be small for a TLP in severe waves, as the floating structure is relative small and the wave radars are some distance from the columns. The effect of the radiated and diffracted waves on the measured wave height as well as the calculated wave spreading is still being investigated as part of the JIP.

**Wave spreading**

As the platform has three wave radars, it is possible to estimate the directional wave spectrum. Different techniques are available for estimation of directional wave spectra, e.g. the Maximum Likelihood Method (MLM) or Maximum Entropy Method (MEM), as described in Isobe et. al. (1984) and Benoit et. al. (1997). For this project the MLM-approach has been selected as it is relatively fast and robust. In the MLM wave spreading analysis the wave direction is estimated for each wave frequency based on the measurements (amplitude and phase) on the three wave probes, assuming linear wave dispersion. For an accurate assessment of the wave spreading the distance between the individual wave measurements should be between 0.03\(\times\lambda_{wave}\) and 0.3\(\times\lambda_{wave}\) in order to avoid aliasing. For the Marco Polo TLP the wave radars are approximately 50 m apart. This translates to wave periods between 10 and 30 seconds. Wave spreading analysis on waves with periods outside this range will be less accurate. An example of an MLM wave spreading analysis result during hurricane Rita is shown in Figure 13 below.

The polar plot to the right shows the actual wave spreading analysis results. The peak of the wave spectrum is marked red. For comparison the mean wind speed and direction of that 30-minute time trace is shown in the same plot as red arrow. In this example the mean wave direction is approximately (waves coming from) 130-135° and the wave spreading is considerable, i.e. the wave spreading covers nearly 180°.
degrees. In the top left figure the wave spectrum is shown and a vertical red dotted line indicates the time of the current wave spreading analysis. In the bottom left figure the wind speed and direction are shown. The vertical red dotted line indicates the time of the wave spreading analysis shown in the polar plot.

By generating such a figure for each 30-minute time trace an animated movie can be made. Such a movie clearly shows how the wave direction and wave spreading changes as the hurricanes approaches and passes the platform. By comparing the wave spreading analysis of different hurricanes a good assessment of the wave development over the duration of hurricane can be made, as well as the relation between wind direction and wave direction can be assessed. The results show that for hurricane Ivan and Katrina (where Marco Polo was on the left side of the track) the waves were in general more or less long crested. For hurricane Rita (where Marco Polo was on the right side of the track) the waves were significantly more short crested.

Wave frequency motions: DGPS versus MQK

The motions of the TLP are measured by means of a DGPS and a six degree-of-freedom motion box (MARINs ‘Marine Quality Kit’, or MQK). The DGPS is primarily meant for measurement of low frequency surge, sway and yaw motions, whereas the MQK measures 6 d.o.f. wave frequency motions. However, detailed analysis of the measured signals reveals that the DGPS is also capable of measuring the wave frequency motions to some extent. Figure 14 shows a comparison of the measured wave frequency motions of the DGPS and the MQK. Note that the DGPS surge and sway are high pass filtered for this comparison (ω > 0.2 rad/s) to eliminate the low frequency motions. The MQK only measures wave frequency motions.

From top to bottom the surge and sway motions are shown for increasing sea states. Based on this comparison it is concluded that the DGPS measures the wave frequency surge and sway motions of the TLP with an accuracy of better than 10 cm. The comparison for WF yaw motions is not as good and differences up to 1 degree are observed.

DISCUSSION

In order to assess if the observed extreme waves on board Marco Polo can really occur, a comparison is made between one of the measured extreme waves on Marco Polo and an extreme basin wave. This extreme basin wave was measured by coincidence (i.e. it was originally not generated on purpose) and is discussed in more detail in Buchner et. al. (2007). This basin wave was measured using resistance type wave probes. As no floating structure was present in the basin during the wave measurement the wave time trace has little error. The comparison is shown in Figure 15.

The wave condition in the basin is a long crested wave with Hs = 11.9 m, Tp = 15.3 s (γ = 2.6), generated under an angle of 15° with a current of 1.9 m/s. This basin wave condition is close to the sea state measured on Marco Polo when the extreme wave occurred. The top figure shows the 30-minute time trace of the basin wave and the bottom figure shows the comparison between the extreme waves in the basin and the corrected wave as measured on Marco Polo on a time scale relative to the time of maximum wave elevation. The agreement between the two extreme wave crests is quite remarkable. This comparison shows that the extreme wave as observed on Marco Polo is not unrealistically steep and can indeed occur in such a severe sea state.

CONCLUSIONS

As part of a Joint Industry Project measurements on board of the Marco Polo TLP have been ongoing for nearly three years without interruptions. The TLP proves to be a stable platform for measurements of waves, wind and current.
Although the motions of the platform have some effect on the measured wave elevation, in general these effects are small. For detailed analysis of extreme waves these factors can be taken into account.

Three major hurricanes of the previous three years, Ivan, Katrina and Rita, all passed Marco Polo at close distance. Although Marco Polo was extremely close to the center of these severe hurricanes, no significant damage was inflicted to the platform and valuable data has been recorded.

The significant wave heights in these three hurricanes as observed on board Marco Polo ranged from typical 10-year return condition to 100-yr return conditions (i.e. Hs ~ 8.5 to 12 m, Tp in range of 12 to 15 s). However, the measured extreme wave heights exceeded the expected extreme values. In hurricane Rita a maximum wave height of 26.9 m was observed (including the correction for platform motions) with an associated crest height of 17.4 m.

Using the data of all three wave radars the wave spreading during the three hurricanes has been assessed. Significant differences in wave spreading have been observed between hurricanes Ivan and Katrina (with Marco Polo on left side of track) and Rita (with Marco Polo on right side of track). Detailed analysis of the environmental data is still ongoing.

In some of the extreme waves that were observed on Marco Polo high frequency vibrations were observed on the topsides, which indicate impact loads of these extreme waves on the columns, although no structural damage was observed. The detailed analysis of the structural response of the platform in these extreme conditions and a comparison to the original design is part of the deliverables of the JIP.

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REFERENCES


