UNCERTAINTY: second report

Espina, Pedro I. to: Ira Leifer, Juan Lasheras , Alberto Aliseda, Franklin Shaffer, Ömer Savas , Wereley, Steven T., James J Riley, Poojitha Yapa — 06/03/2010 03:16 PM

Cc: "mark_sogge@usgs.gov", "Chris.Barker@noaa.gov" , "Kathryn_Moran@ostp.eop.gov", Marcia McNutt, Bill Lehr , "pmbommer@mail.utexas.edu"

Dear Plume Team Members,

Many of you are working on the PIV analysis of the leak at the end of the drilling riser. In order for NIST to provide NOAA with an uncertainty analysis on this estimate, we need your help. Could you please answer these questions for your current work.

1. Do you think that the enclosed analysis (used during the first report) describes, in principle, what you are doing using the video footage of the leak at the end of the drilling riser? If not, could you tell me why?
2. Do you think that you can determine length scales in the video to about ±5%? If not, to what level?
3. Do you think that you can determine time between video frames to about ±3.8%? If not, to what level?
4. Do you think that you can determine the diameter of the plume (where you are making the PIV determinations) to about ±5%? If not, to what level?
5. What value of average volume fraction of oil in the jet (i.e., oil/total flow) are you using?
6. What uncertainty are you willing to assign to that value of average volume fraction of oil in the jet?

I know you are loosing sleep at the moment, so I thank you in advance for supporting the NIST work with your answers.

Pedro

Pedro I. Espina, Ph.D.
Program Analyst
Program Office, Office of the Director

Tel: +1 301 975 5444 NIST Uncertainty Estimate v3.pdf

Deepwater Horizon Leak Estimation

On April 20, 2010, the Deepwater Horizon offshore oil drilling platform exploded and two days later, it sunk 40 miles (64.4 km) southeast of the Louisiana coast. As a consequence of this incident, an underwater oil leak resulted, originating from a number of sites at a depth of about 5,000 feet (1,524 m). Numerous estimates have been made for the amount of oil being discharged, ranging from over 1,000 barrels (42,000 US gallons; 158,987 liters) to more than 100,000 barrels (4,200,000 US gallons; 15,898,729 liters) of sweet, light crude oil per day. A more accurate determination of the magnitude of the oil spill is of interest. This note discusses how various parameters affect the estimation of the oil spill and attempts to bound the uncertainty in this estimation.

It is believed that oil is leaking from a number of sites at the bottom of the ocean including the end of the drilling riser. However, this note focuses on the estimation of the flow leaking from a fissure on top of the drilling riser (i.e., the bent pipe just above of the blowout preventer, BOP).

Video from remotely operated underwater vehicles (ROVs) shows a turbulent gas/liquid jet rushing out of a fissure on the central portion of the drilling riser bent above the BOP (see Figure 1). In this jet, the fluid is believed to be a mixture of crude oil and gas/hydrates (the gas being mostly methane). From the three leaks at the location viewed in the video, this analysis focuses on the leak in the center of the drilling riser, as it is believed to the most significant based on visual inspection of the video.

Figure 1. Video image of oil leak coming from the bent drilling riser just above the BOP. Three leaks are observed – this analysis focuses on the jet rushing out of the fissure next to the lettering at the center of the pipe.

If a number of parameters are measured and others approximated, an estimate of the flow of that jet can be performed using particle image velocimetry (PIV). In this method, a flow event in the leaking oil plume (e.g., an eddy in the flow) is observed in two consecutive video frames and its traveling velocity is estimated by dividing the distance traveled by the event, by the time between the two video frames. If this analysis is performed in a sufficiently large number of spatially- and time-distributed events, an average velocity of the leak jet can be adequately estimated. This note examines this methodology for the estimation of the oil leak and tries to assess it measurement uncertainty.

The average oil leak at this location, $\overline{Q}_{oil}$, can be estimated using the following expression,

$$\overline{Q}_{oil} = \overline{\overline{V}_{PIV} A_{PIV}}\,\overline{X}_{oil} \pm U_{\overline{Q}_{oil}} \tag{1}$$

where, $\overline{V}_{PIV}$ is the average velocity of the oil jet estimated using PIV, A_{PIV} is the average cross-sectional area of the jet at the location where the velocity of the jet was measured using PIV, and $\overline{X}_{oil}$ is the average volume fraction of oil in the jet (i.e., the fraction of the jet that is not gas and/or hydrates). Equation (1) will yield an estimate of the oil leak at the selected location (e.g., in barrels of oil per day, BPD) with an uncertainty, $\pm U_{\overline{Q}_{oil}}$, also expressed in BPD. It is worth noting than in (1), the product $\overline{\overline{V}_{PIV} A_{PIV}}$ is averaged over the ensemble of PIV observations made (more on this later in this note).

If a flow feature in the jet exiting from the fissure on top of the bent drilling riser is selected from the video, it will be observed to travel a distance L'_{12} in the time between two consecutive video frames, Δt_{12}. But unless the travel path of the event is viewed from an orthogonal plane, the true distance travelled by the flow event, L_{12}, will be larger than the observed distance L'_{12}. The relation between the observation and the reality will be given by,

$$L_{12} = \frac{L'_{12}}{\cos\alpha_{12}} \tag{2}$$

where, α_{12} is the angle by which the video camera is off a perfectly orthogonal view of the jet. Using the above, the velocity of an observed event, i, will be given by,

$$\left(V_{12}\right)_i = \frac{\left(L_{12}\right)_i}{\left(\Delta t_{12}\right)_i} = \left(\frac{L'_{12}}{\Delta t_{12}\cos\alpha_{12}}\right)_i \tag{3}$$

It is the opinion of the expert team that $\alpha_{12} \le 5^{\circ}$, making this error insignificant in this analysis (further details in the uncertainty section below). But it is worth noting that if the video camera view is assumed to be perfectly orthogonal, that is to say $\alpha_{12} = 0$ (i.e., best case scenario), the flow of oil coming out of the jet is likely to be underestimated. In addition, there are instances when the ROV changes location as it is filming the jet or when the operator of the video camera zooms in or out in the view and/or changes focus. These changes cause two problems in the interpretation of the PIV results. First, these filming disruptions might add an apparent velocity to the PIV measurements, and second, they might change the coordinate system in the images relative to the jet (i.e., will change α_{12}). Fortunately, the error due to these effects can be minimized by selecting portions of video where no ROV drift and/or changes in the viewing parameters of the video camera appear to be present.

The observed travel distance of a flow event, L'_{12}, is determine by inspection in the video frames. For physical scaling in the video images, BP provided the exterior diameters of a number of pipes in the video field of view:

- that of the black pipe entering the frame from the bottom left hand side = 1.22 inches (30.48 mm), and

- that of the grey pipe entering the frame from the bottom right = 3.5 inches (88.90 mm).

Using these numbers and interrogating the video at an equivalent depth of field to the apparent axis of the jet (i.e., the diameter of the pipes near the center of the video window), we find that the black pipe is about 18.4 pixels in diameter and the grey pipe is about 44.4 pixels in diameter. As a result, each pixel is likely to represent a distance between 0.0665 inches (1.69 mm) and 0.0788 inches (2.00 mm). Thus, under the best of cases, the distance traveled by a flow feature could at best be estimated to ±1 pixel or with an uncertainty, $U_{L'_{12}} = \pm 0.0725$ inches (1.84 mm). However, due to the turbulent nature of the jet, the main source of uncertainty in the determination of L'_{12} is likely to be the visual inspection made by the evaluator, which for the purposes of this analysis we assume to be $U_{L'_{12}} / L'_{12} = \pm 5\%$.

The time between video frames, $(\Delta t_{12})_i$, can be obtained from the framing rate of the video, FR_i. The video acquired by the ROV is analog and it has been digitized for the purposes of this study. Inspection of the video reveals that the framing rate of the digital video is not constant,[1] with framing rates in the range from 14 to 48 frames/second (fps). However, members of the expert team determined that the true framing rate of the analog video is 25 fps. Thus, for the purposes of the PIV analysis, $(\Delta t_{12})_i$ can be estimated with a measure of confidence to ±1 frame in that interval. That is to say,

$$(\Delta t_{12})_i = \frac{1}{FR_i \pm 1} \tag{4}$$

There are computer programs that can interrogate the available video for hundreds of such flow events, thus providing the ability for hundreds of observations in an adjacent pairs of video images. As a result, the space-averaged velocity of the jet in the observation window of the video for any two consecutive frames will be given by,

$$\overline{V}_{12} = \frac{1}{n} \sum_{i-1}^{n} (V_{12})_i \tag{5}$$

where n is the number of flow events considered in the averaging (i.e., this is a spatial average of the observed phenomena).

Because, the spatial and temporal distributions of the selected flow events could greatly influence the average yielded by **(5)**, care should be taken to ensure that the ensemble of events considered is representative. In addition, the procedure described above does not constitute PIV in the traditional sense, where small particles that faithfully follow the flow are tracked. Rather, the procedure described above tracks flow features in the shear layer of the jet that might move at lower speeds. This effect is likely to lead to an <u>underestimation</u> of the oil flow in this leak.

---

[1] BP provided video in file name "H14 BOP Plume May 15 1920-1945.asf" depicting the flow on top of the BOP. The video appears to have been recorded on 15/05/2010 between 19:20 and 19:45. The original analog video was acquired by the ROV NSV Skandi Neptune at a reported depth of about 4924 ft below sea level.

Because oil is opaque, the video camera can only see events occurring in the outer edge of the jet (i.e., its shear layer) where the velocity is less than in the core of the jet. The relationship between the observed velocity in the jet shear layer and the jet average velocity can be estimated using correlations for turbulent jets in the literature. However, if $\overline{V}_{12}$ is taken to be the average velocity of the jet at the observation site (i.e., $\overline{V}_{12} = \overline{V}_{PIV}$), the flow in the oil jet is likely to be underestimated.

The average cross-sectional area of the jet at the location where its velocity was measured, A_{PIV}, can be determine from a direct interrogation of the video frames used during the $\overline{V}_{PIV}$ estimation. This area has to independently evaluated for each $\overline{V}_{PIV}$, thus the average of their product is given by,

$$\overline{\overline{V}_{PIV} A_{PIV}} = \frac{\pi}{4m}\sum_{j=1}^{m}\left(\overline{V}_{PIV}\right)_j\left(d_{PIV}^{2}\right)_j \qquad (6)$$

where $\left(d_{PIV}\right)_j$ is the observed diameter of the jet at each of the m instances when $\overline{V}_{PIV}$ was evaluated (i.e., this is a temporal average of the observed phenomena). As it was the case for L_{12}, the relation between the observation and the reality will be given by,

$$d_{PIV} = \frac{d'_{PIV}}{\cos\alpha_{12}} \qquad (7)$$

where, α_{12} is the angle by which the video camera is off a perfectly orthogonal view of the jet. As with L'_{12}, d'_{PIV} could be estimated to no better than ±1 pixel or ±0.0725 inches. However, due to the turbulent nature of the jet shear layer, the main source of uncertainty in the determination of d'_{PIV} is likely to be the visual inspection made by the evaluator, which for the purposes of this analysis we assume to be $U_{d'_{PIV}} / d'_{PIV} = 5\%$.

The jet spilling from the fissure at the top of the drilling riser above the BOP is believe to be a mixture of gas and oil, that is to say, the brown plume view in the video is composed of oil with bubbles of gas and/or hydrates entrained in it. The concentration of entrained gas in the oil can be expressed in terms of a gas to oil ratio, $\mathcal{V}_{gas}/\mathcal{V}_{oil}$, where $\mathcal{V}_g$ is the volume of gas/hydrates entrained in the volume of liquid oil, $\mathcal{V}_l$. The gas to oil ratio could be estimated from sampling measurements or by other means, and it fact, it has been estimated twice:

- reported by BP (during the May 22, 2010 expert group conference call) – 3000 standard cubic feet of gas per barrel of oil [scf/bbl], based on their collection of recovered spill at the surface, and
- reported by the Coast Guard (on May 23, 2010) – 3000 scf/bbl, based on their recovery of spill oil from the riser insertion tube (RIT, i.e., the siphon sucking at the end of the broken drilling riser).

During the expert conference call on May 22, 2010, BP claimed that their estimate of gas to oil ratio was "pretty good" and when pressed for a number, "no worst than ±10 %"; the Coast Guard made no uncertainty claims in their gas to oil ratio estimate. These values are equivalent and both were provided at ocean surface conditions. For these values to be useful to this analysis, they have to be converted to values at the leak site. Using the ROV reported depth (approximately 5000 ft under sea level) and the BP reported ocean temperature at the leak site (1° C), the average volume fraction of oil in the jet, $\overline{X}_{oil}$, is given by

$$\overline{X}_{oil} = \frac{V_{oil}}{V_{oil} + V_{gas}} = \frac{1}{1 + \left(V_{gas} / V_{oil}\right)} \tag{8}$$

or 0.29 [2] with a relative uncertainty of ±10 % based on the reported values above. However, members of the expert team, estimated by other means the average volume fraction of oil in the jet to be 0.25 – the value use in this analysis. This value not only accounts for the distribution of gas/hydrates in the leaking jet but also for its temporal fluctuations over long periods of time. Given the critical nature of this value to this calculation and the poor sources of data used to arrive at it, we are giving it a conservative uncertainty value, $U_{\overline{X}_{oil}} / \overline{X}_{oil} = 40\%$.

It is worth noting that if the jet flow is assumed to have no entrained gas/hydrates (i.e., $\overline{X}_{oil} = 1$), the flow of oil coming out of the leak over the bent riser on top of the BOV will be overestimated.

Using the above analysis, the estimates of the average oil leak from a fissure on top of the drilling riser, $\overline{Q}_{oil}$, can be bounded by an uncertainty of $\pm U_{\overline{Q}_{oil}}$. What follows are two limiting examples for the results from the expert team.

Uncertainty Analysis

For the purposes of the uncertainty analysis, can be simplified as,

$$\overline{Q}_{oil} = \overline{\overline{V}_{PIV} A_{PIV}}\, \overline{X}_{oil} \approx \overline{V}_{PIV} A_{PIV} \overline{X}_{oil} = \frac{L'_{12}}{\Delta t_{12} \cos\alpha_{12}} \frac{\pi}{4} \left(\frac{d'_{PIV}}{\cos\alpha_{12}}\right)^2 \overline{X}_{oil} \tag{9}$$

Thus the relative uncertainty in $\overline{Q}_{oil}$ can be expressed as

$$\left(\frac{U_{\overline{Q}_{oil}}}{\overline{Q}_{oil}}\right)^2 = \left(\frac{L'_{12}}{Q}\frac{\partial \overline{Q}_{oil}}{\partial L'_{12}}\right)^2 \left(\frac{U_{L'_{12}}}{L'_{12}}\right)^2 + \left(\frac{\Delta t_{12}}{Q}\frac{\partial \overline{Q}_{oil}}{\partial \Delta t_{12}}\right)^2 \left(\frac{U_{\Delta t_{12}}}{\Delta t_{12}}\right)^2 + \left(\frac{\alpha_{12}}{Q}\frac{\partial \overline{Q}_{oil}}{\partial \alpha_{12}}\right)^2 \left(\frac{U_{\alpha_{12}}}{\alpha_{12}}\right)^2 + \left(\frac{d'_{PIV}}{Q}\frac{\partial \overline{Q}_{oil}}{\partial d'_{PIV}}\right)^2 \left(\frac{U_{d'_{PIV}}}{d'_{PIV}}\right)^2 + \left(\frac{\overline{X}_{oil}}{Q}\frac{\partial \overline{Q}_{oil}}{\partial \overline{X}_{oil}}\right)^2 \left(\frac{U_{\overline{X}_{oil}}}{\overline{X}_{oil}}\right)^2 \tag{10}$$

where the sensitivity coefficients are given by

$$\left(\frac{L'_{12}}{Q}\frac{\partial \overline{Q}_{oil}}{\partial L'_{12}}\right) = 1 \tag{11}$$

$$\left(\frac{\Delta t_{12}}{Q}\frac{\partial \overline{Q}_{oil}}{\partial \Delta t_{12}}\right) = -1$$

---

[2] NIST REFPROP

$$\left(\frac{\alpha_{12}}{Q}\frac{\partial \overline{Q}_{oil}}{\partial \alpha_{12}}\right) = -3\alpha \tan\alpha$$

$$\left(\frac{d_{PIV}^2}{Q}\frac{\partial \overline{Q}_{oil}}{\partial d_{PIV}^2}\right) = 2$$

$$\left(\frac{\overline{X}_{oil}}{Q}\frac{\partial \overline{Q}_{oil}}{\partial \overline{X}_{oil}}\right) = 1$$

and the relative uncertainties of each of the components are summarized in the text above and are given by,

$$\left(\frac{U_{L'_{12}}}{L'_{12}}\right) = \pm 0.05$$

$$\left(\frac{U_{\Delta t_{12}}}{\Delta t_{12}}\right) = \pm\frac{1}{25+1} = \pm 0.038 \tag{12}$$

$$\left(\frac{U_{d'_{PIV}}}{d'_{PIV}}\right) = \pm 0.05$$

$$\left(\frac{U_{\overline{X}_{oil}}}{\overline{X}_{oil}}\right) = \pm 0.4$$

Therefore the relative uncertainty of $\overline{Q}_{oil}$ is

$$\left(\frac{U_{\overline{Q}_{oil}}}{\overline{Q}_{oil}}\right)^2 = (1)^2(0.05)^2 + (-1)^2(.038)^2 + (-3\alpha\tan\alpha)^2\left(\frac{U_{\alpha_{12}}}{\alpha_{12}}\right)^2 + (2)^2(0.05)^2 + (1)^2(0.4)^2 \tag{13}$$

For $\alpha_{12} \le 5^{\circ}$, the uncertainty related to this angle becomes insignificant (less than 5 % of the total uncertainty) and thus can be ignored. As a result the relative uncertainty in the estimation of the flow from the leak on top of the BOV is no larger than,

$$\left(\frac{U_{\overline{Q}_{oil}}}{\overline{Q}_{oil}}\right)^2 = \pm 41\% \tag{14}$$

And this value is dominated, in a disproportional way, by the gas to oil ratio estimate. If the gas to oil ratio was know better, e.g., ± 20 %, the oil leak uncertainty would drop to ±22 %.