# Oil & Natural Gas Technology

**DOE Award No.: DE-FE0010144**

# Quarterly Research Performance Progress Report (Period ending 03/31/2016)

# Mapping Permafrost and Gas Hydrate using Marine CSEM Methods

**Project Period (10/1/2012 – 09/30/16)**


Submitted by:
Project PI Steven Constable
Scripps Institution of Oceanography
University of California San Diego
DUNS #:175104595.
9500 Gilman Drive
La Jolla, CA 92093-0210
e-mail: sconstable@ucsd.edu
Phone number: (858) 534-2409


Prepared for:
United States Department of Energy
National Energy Technology Laboratory

Steven Constable

Digitally signed by Steven Constable
DN: cn=Steven Constable, o=UCSD, ou=SIO, email=sconstable@ucsd.edu, c=US
Date: 2016.05.03 14:02:13 -07'00'

**Office of Fossil Energy**

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## EXECUTIVE SUMMARY

Last quarter we started to prepare the CSEM data collected in 2014 and 2015 for inversion. This quarter we have carried out preliminary inversions of all the lines collected in 2015, and are preparing a manuscript for submission to *Geophysical Research Letters*.

## ACCOMPLISHMENTS

### Major goals of project

Permafrost underlies an estimated 20% of the land area in the northern hemisphere and often has associated methane hydrate. Numerous studies have indicated that permafrost and hydrate are actively thawing in many high-latitude and high-elevation areas in response to warming climate and rising sea level. Such thawing has clear consequences for the integrity of energy infrastructure in the Arctic, can lead to profound changes in arctic hydrology and ecology, and can increase emissions of methane as microbial processes access organic carbon that has been trapped in permafrost or methane hydrate dissociates. There has, however, been significant debate over the offshore extent of subsea permafrost.

Our knowledge of sub-seafloor geology relies largely on seismic data and cores/well-logs obtained from vertical boreholes. Borehole data are immensely valuable (both in terms of dollar cost and scientific worth), but provide information only about discrete locations in close to one (vertical) dimension. Seismic data are inherently biased towards impedance contrasts, rather than bulk sediment properties. In the context of mapping offshore permafrost and shallow hydrate, seismic methods can identify the top of frozen sediment through the identification of high amplitude reflections and high-velocity refractors but simple 2D seismic surveys do little to elucidate the bulk properties of the frozen layers, particularly the thickness. However, permafrost and gas hydrate are both electrically resistive, making electromagnetic (EM) methods a complementary geophysical approach to seismic methods for studying these geological features. Deep ocean EM methods for mapping gas hydrate have been developed by both academia and industry, but the deep-ocean techniques and equipment are not directly applicable to the shallow-water, near-shore permafrost environment. This project addresses this problem by designing, building, and testing an EM system designed for very shallow water use, and using it to not only contribute to the understanding of the extent of offshore permafrost, but also to collect baseline data that will be invaluable for future studies of permafrost degradation.

We will use the new equipment to carry out a pilot project to map the contemporary state of subsea permafrost on part of the U.S. Beaufort inner shelf, reoccupying seismic lines acquired in 2010 to 2012. We will combine the interpretation of EM data with seismic data through a no-cost collaboration with Carolyn Ruppel of the USGS. Modeling suggests that a 500 m long EM array will be adequate to sense the top of permafrost in many of the areas where the USGS has completed mapping, although our receiver array is now 1,000 m long. The towed array will be supplemented by the deployment of 2 to 4 seafloor recorders that will be retrieved after the cruise so that nothing remains in the area. The use of a small number of seafloor recorders will allow us to collect data at larger offsets, providing insight into deeper structure.

We are exploiting the close association of hydrate and permafrost at high latitudes, and in particular their common response to changing climate. By using a second geophysical method to supplement seismic data, we will be able to better map the current extent of permafrost and so better understand the impact of past sea level rise on the hydrate stability field, and provide a critical baseline for studies which target the effects of current climate change.

Our work will not only expand our geophysical tool-kit but also expand our understanding of the geological and hydrological systems associated with gas hydrate. Instrumentation and analytical methods developed for this project can be easily applied for future permafrost and hydrate mapping elsewhere, and also other applications such as groundwater exploration and engineering studies associated with near-shore infrastructure development, and most recently offshore geothermal exploration.

## Work accomplished during the project period

The pseudosections we presented in the last quarterly report were frequency pseudosections, generated by taking apparent resistivities from a single receiver instrument and then using the skin depths at each frequency for the pseudo-depth scale. However, we noticed that there is more variation or apparent resistivity with source–receiver offset (i.e. instrument number) than with frequency, so we have generated the more conventional offset pseudo sections, shown in Figures 1 and 2. This also more closely represents the data as inverted, since to reduce the computational burden we invert only three of the 19 frequencies processed. (Studies and experience suggests that little is gained by including more than a small number of widely spaced frequencies.)

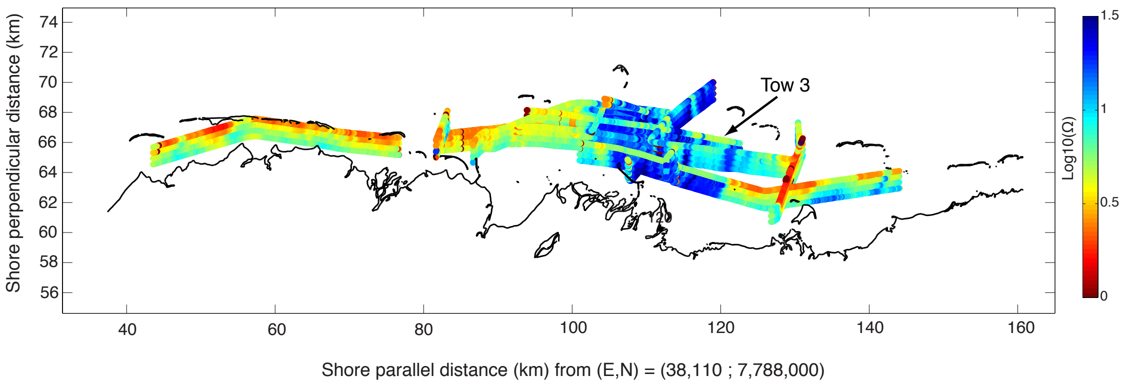


Figure 1. Apparent resistivity offset pseudosections for both years' data at a fixed frequency of 3 Hz, for the region west of Prudhoe Bay to the outflow of the Sag River. The increased resistivity (blue) associated with the river outflow is evident.

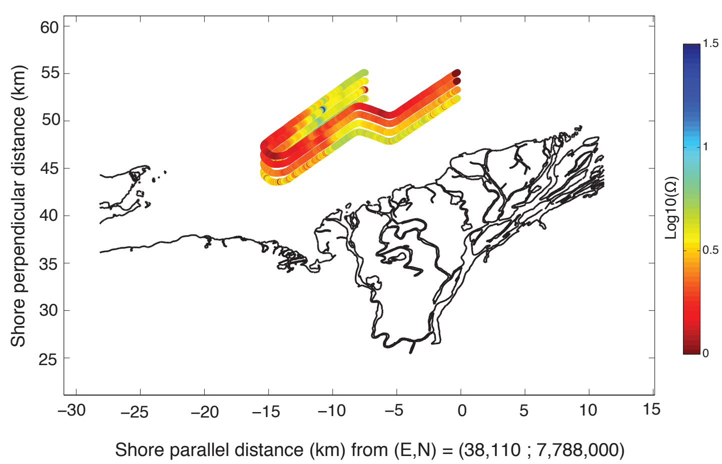


Figure 2. Apparent resistivity offset pseudosections for 2015 data at a fixed frequency of 3 Hz, for the Harrison Bay area. The seismically determined edge of permafrost is located at about the middle of these tows.

As we noted in the last report, there is a great deal of lateral variability in the apparent resistivities, with the highest resistivities in the region of the Sag River outflow (Figure 1). This is in keeping with models that suggest fresh groundwater discharge can stabilize permafrost from melting. Note that we measured surface water conductivity continuously along all the tow lines and included these data in the apparent resistivity calculations, so the higher apparent resistivities are NOT associated with freshwater outflow in the ocean.

In both years, sea ice restricted our operations close to shore and within the seismically predicted region of permafrost offshore Prudhoe Bay. However, in 2015 we opportunistically took advantage of a weather and ice window to collect a day of data in Harrison Bay, 100 km west of Prudhoe Bay (Figure 2) . Here we were able to cross the seismically determined edge of permafrost three times, but there is no signal evident in the apparent resistivities that we could easily associate with permafrost. Clearly, the seismic and resistivity signatures of permafrost are very different, and it will be very interesting when we get to the point of comparing resistivity inversions directly with seismic data, something we hope to do in the next quarter.

We have now carried out preliminary inversions of all the amplitude data collected in 2015. The inversions use the MARE2DEM code of Kerry Key (http://mare2dem.ucsd.edu/), which uses adaptive refinement of an unstructured finite element mesh to ensure that the forward model calculations are accurate. Even by modern standards, such inversions are computationally demanding, running for significant fractions of a day on 100-core clusters, and many runs are required to ensure that (a) the data errors are appropriately scaled, (b) the data are free of outliers, (c) the model domain is large enough, (d) and the model domain is adequately discretized. For these reasons, along with the fact that we have not yet included phase data in the inversions, we are presenting only an inversion of tow 3, and which should be considered a preliminary result (Figure 3). However, this inversion does illustrate two things: (i) to first order, the lateral changes in the apparent resistivity pseudosections reflect real variations in resistivity, especially in the upper 200 m, and (ii) inversion is required to recover deeper structure and variations with depth.

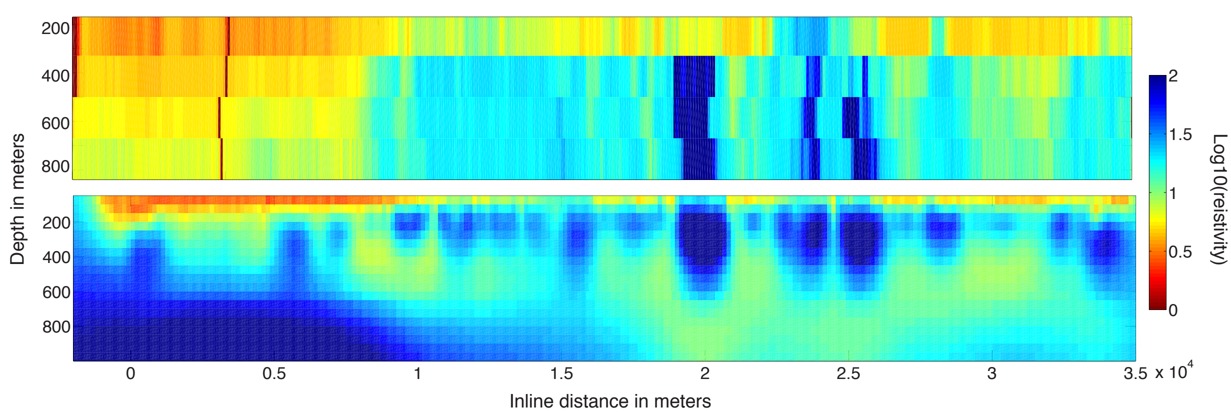


Figure 3. Offset pseudo section (top) and 2D inversion (bottom) of data from tow 3.

Figure 4 shows a comparison of the model response and actual data. Amplitudes vary greatly with source–receiver offset for CSEM studies, so we have normalized these plots by the median data amplitude for each receiver. That is, for a single receiver the three frequencies have been normalized the same way, illustrating the frequency dependence of the data, and the data and model response are normalized the same way in order to make direct comparisons. In some respects, a plot of residuals is a better way to demonstrate that our inversion is fitting the data, but the value of this plot is that it illustrates the clear signal associated with the more resistive parts of the shallow section near the Sag River outflow. Unfortunately our closest receiver, P1, saturated on the higher amplitude signals associated with these resistors. At the farthest receiver, P4, the signals fell below the noise floor over the more conductive parts of the section where the signals are smaller.

**Training and professional development.**

Dallas Sherman, PhD student, is now the student working on this project. She is current working on writing the first journal submission from this project.

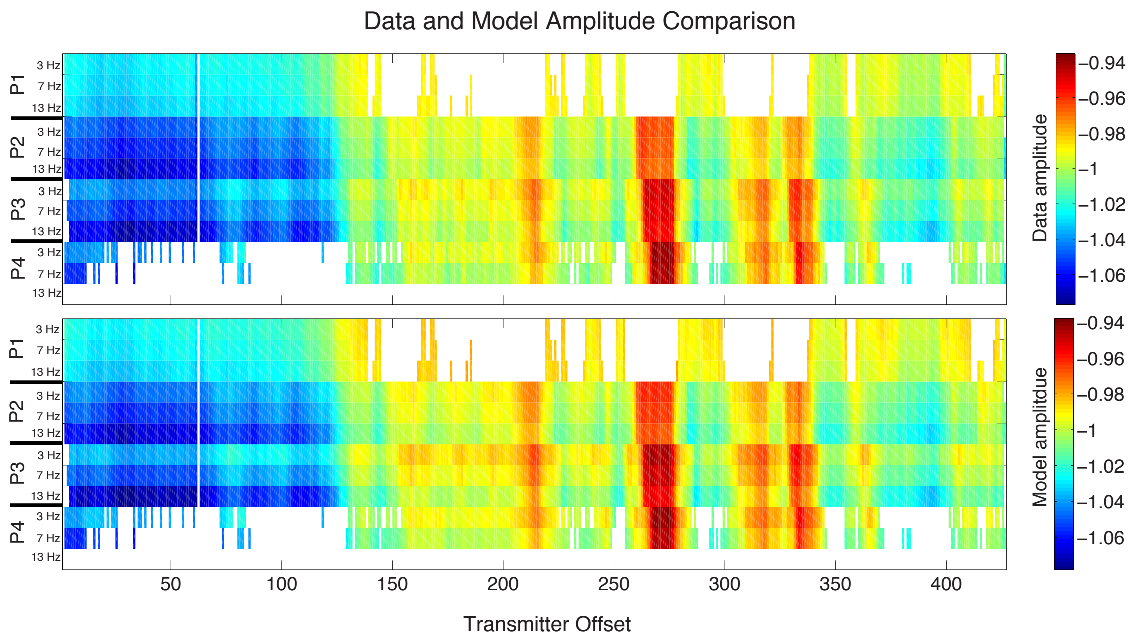


Figure 4. Data (top) and model (bottom) responses for the inversion showed in Figure 3 for the four receiver instruments (P1 – P4) at the three frequencies (3, 7, and 13 Hz) included in the inversion. The median data amplitude for each receiver has been subtracted from the data and model in order to plot all responses using a single color scale. Blank areas reflect data below the noise floor (P4) or which have saturated (P1). The sense is that red colors are large amplitudes.

**Plans for next project period.**

During the next project period we will continue to invert the 2014 and 2015 data sets, and submit our first paper for publication, thereby meeting the next milestone. We also hope to meet with USGS scientists and compare the inversion results to seismic refraction data collected by them.

Milestone status report.

| Milestone Title | Planned Completion Date | Actual Completion Date | Verification Method | Comments on progress |
|---|---|---|---|---|
| Equipment design approved | 5/1/2013 | 5/1/2013 | Internal review | |
| Equipment passes tests | 12/6/2013 | 12/1/2013 | Internal review | delayed one quarter |
| Y2 data collection | 9/1/2014 | 7/22/2014 | Internal review | |
| Y2 data processing | 9/30/2014 | 9/30/2014 | Internal review | |
| Y3 data collection | 9/1/2015 | 7/7/2015 | Internal review | |
| Y3 data processing | 9/30/2015 | 9/1/2015 | Internal review | |
| Publications(s) submitted | 4/1/2016 | | | imminent |
| Publications(s) accepted | 9/30/2016 | | | |

## PRODUCTS

*Project Management Plan.* The revised Project Management Plan was accepted on 19 November 2012.

The following abstracts are relevant to this and past DoE funded research:

*Gordon Conference Abstract, 2016: Surveying hydrates in the California Borderlands using electromagnetic methods.* Presented at the Natural Gas Hydrate Systems Gordon Research Conference. Galveston, Texas. Peter Kannberg and Steven Constable.

*AGU 2015 Fall Meeting: Resistivity structure of the Del Mar methane seep*, Peter Kannberg and Steven Constable.

*AGU 2015 Fall Meeting: Surface towed CSEM systems for shallow water mapping*, Joanna Sherman, Steven Constable, and Peter Kannberg.

*AGU 2015 Fall Meeting: Water and electricity do mix: Studying plates, petroleum, and permafrost using marine electromagnetism*, Steven Constable (invited Bullard Lecture).

*AGU 2014 Fall Meeting: Hydrates in the California Borderlands revisited: Results from a controlled-source electromagnetic survey of the Santa Cruz Basin*, Peter Kannberg and Steven Constable.

*Gordon Conference Abstract, 2014: Hydrates in the California Borderlands: Results from controlled-source electromagnetic surveys*, Peter Kannberg, Steven Constable, and Kerry Key.

*AGU 2013 Fall Meeting: Hydrates in the California Borderlands: 2D inversion results from CSEM towed and seafloor arrays*, Peter Kannberg, Steven Constable, and Kerry Key.

*AGU 2012 Fall Meeting: Mapping methane hydrate with a towed marine transmitter-receiver array*, Peter K. Kannberg; Steven Constable, presented in *GP33A. Advances in Electromagnetic Induction: From the Near Surface to the Deep Mantle III Posters.*

*AGU 2012 Fall Meeting: Mapping marine gas hydrate systems using electromagnetic sounding*, Steven Constable; Karen A. Weitemeyer; Peter K. Kannberg; Kerry W. Key, presented in *OS34A. Marine and Permafrost Gas Hydrate Systems III.*

*AGU 2012 Fall Meeting: Electrical conductivity of lab-formed methane hydrate + sand mixtures; technical developments and new results*, Laura Stern; Wyatt L. Du Frane; Karen A. Weitemeyer; Steven Constable; Jeffery J. Roberts, presented in *OS43B. Marine and Permafrost Gas Hydrate Systems IV Posters.*

The following papers acknowledge this or past DoE funded research:

Constable, S., P. K. Kannberg, and K. Weitemeyer, 2016. Vulcan: A deeptowed CSEM receiver. *Geochemistry, Geophysics, Geosystems*, **17**, doi:10.1002/ 2015GC006174.

Du Frane, W., L.A. Stern, S. Constable, K.A. Weitemeyer, M.M. Smith, and J.J. Roberts, 2015. Electrical properties of methane hydrate + sediment mixtures. *Journal of Geophysical Research*, **120**, 4773–4787, doi:10.1002/2015JB011940.

Weitemeyer, K., and S. Constable, 2014. Navigating marine electromagnetic transmitters using dipole field geometry. *Geophysical Prospecting*, **62**, 573–593, doi: 10.1111/1365-2478.12092.

Du Frane, W.L., L.A. Stern, K.A. Weitemeyer, S. Constable, J.C. Pinkston, J.J. Roberts, 2011. Electrical properties of polycrystalline methane hydrate. *Geophysical Research Letters*, **38**, doi:10.1029/2011GL047243.

Weitemeyer, K.A., S. Constable, S. and A.M. Trehu, 2011. A marine electromagnetic survey to detect gas hydrate at Hydrate Ridge, Oregon. *Geophysical Journal International* , **187**, 45-62.

Weitemeyer, K., G. Gao, S. Constable, and D. Alumbaugh, 2010. The practical application of 2D inversion to marine controlled-source electromagnetic sounding. *Geophysics*, **75**, F199–F211.

Weitemeyer, K., and S. Constable, 2010. Mapping shallow geology and gas hydrate with marine CSEM surveys. *First Break*, **28**, 97–102.

## PARTICIPANTS AND OTHER COLLABORATING ORGANIZATIONS

| | |
|---|---|
| Name: | Steven Constable |
| Project Role: | PI |
| Nearest person month worked: | 1 |
| Contribution to project: | Management, scientific direction |
| Funding support: | Institutional matching funds |
| Foreign collaboration: | Yes |
| Country: | United Kingdom |
| Travelled: | No |

| | |
|---|---|
| Name: | Dallas Sherman |
| Project Role: | PhD student |
| Nearest person month worked: | 3 |
| Contribution to project: | Processing 2014 data |
| Funding support: | This project, federal plus matching funds |
| Foreign collaboration: | No |

## CHANGES/PROBLEMS

No changes or problems to report at this time.

**BUDGETARY INFORMATION**

Table 2a: Spend profile

| | Budget Period 1 | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| baseline | 10/1/12 – 12/31/12 | | 1/1/13 – 3/31/13 | | 4/1/13 – 6/30/13 | | 7/1/13 – 9/30/13 | |
| | Q4 | | Q1 | | Q2 | | Q3 | |
| | Q4 | Cum. Total | Q1 | Cum. Total | Q2 | Cum. Total | Q3 | Cum. Total |
| **Baseline cost:** | | | | | | | | |
| Federal | $49,969 | $49,969 | $33,192 | $83,161 | $19,810 | $102,971 | $18,771 | $121,742 |
| Non-federal | $9,897 | $9,897 | $9,897 | $19,794 | $9,897 | $29,692 | $29,897 | $59,589 |
| Total | $59,866 | $59,866 | $43,089 | $102,955 | $29,707 | $132,663 | $48,668 | $181,331 |
| **Actual cost:** | | | | | | | | |
| Federal | $19,027 | $19,027 | $8,160 | $27,187 | $17,444 | $44,631 | $43,370 | $88,001 |
| Non-federal | $10,874 | $10,874 | $9,514 | $20,388 | $3,500 | $23,888 | $24,215 | $48,103 |
| Total | $29,901 | $29,901 | $17,674 | $47,575 | $20,944 | $68,519 | $67,585 | $136,104 |
| **Variance:** | | | | | | | | |
| Federal | -$30,942 | -$30,942 | -$25,032 | -$55,974 | -$2,366 | -$58,340 | $24,599 | -$33,741 |
| Non-federal | $977 | $977 | -$383 | $594 | -$6,379 | -$5,804 | -$5,682 | -$11,486 |
| Total | -$29,964 | -$29,964 | -$25,415 | -$55,380 | -$8,763 | -$64,144 | $18,917 | -$45,227 |

Table 2b: Spend profile

| | Budget Period 1 | | Budget Period 2 | | | | | |
|---|---|---|---|---|---|---|---|---|
| baseline | 10/1/13 – 12/31/13 | | 1/1/14 – 3/31/14 | | 4/1/14 – 6/30/14 | | 7/1/14 – 9/30/14 | |
| | Q4 | | Q1 | | Q2 | | Q3 | |
| | Q4 | Cum. Total | Q1 | Cum. Total | Q2 | Cum. Total | Q3 | Cum. Total |
| **Baseline cost:** | | | | | | | | |
| Federal | $0 | $121,742 | $10,588 | $132,330 | $160,134 | $292,464 | $16,705 | $309,169 |
| Non-federal | $0 | $59,589 | $9,899 | $69,488 | $14,854 | $84,341 | $14,854 | $99,196 |
| Total | $0 | $181,331 | $20,487 | $201,818 | $174,988 | $372,360 | $31,559 | $408,365 |
| **Actual cost:** | | | | | | | | |
| Federal | $18,959 | $106,960 | $12,002 | $118,962 | $144,084* | $263,046* | $35,382 | $298,428 |
| Non-federal | $11,486 | $59,589 | $3,247 | $62,836 | $36,360 | $99,196 | $0 | $99,196 |
| Total | $30,445 | $166,549 | $15,249 | $181,798 | $180,444* | $362,242* | $35,382 | $397,624 |
| **Variance:** | | | | | | | | |
| Federal | $18,959 | -$14,782 | $1,414 | -$13,368 | -$16,050 | -$29,418 | $18,677 | -$10,741 |
| Non-federal | $11,486 | $0 | -$6,652 | -$6,652 | $21,506 | $19,300 | -$14,854 | $0 |
| Total | $30,445 | -$14,782 | -$5,238 | -$20,020 | $5,456 | -$14,563 | $3,823 | -$10,741 |

* = estimate, includes ship time liened for 2014 field work.

Table 2c: Spend profile

| | Budget Period 3 | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| baseline | 10/1/14 – 12/31/14 | | 1/1/15 – 3/31/15 | | 4/1/15 – 6/30/15 | | 7/1/15 – 9/30/15 | |
| | Q4 | | Q1 | | Q2 | | Q3 | |
| | Q4 | Cum. Total | Q1 | Cum. Total | Q2 | Cum. Total | Q3 | Cum. Total |
| **Baseline cost:** | | | | | | | | |
| Federal | $18,842 | $328,011 | $18,842 | $346,853 | $48,842 | $395,695 | $111,322 | $507,017 |
| Non-federal | $9,900 | $109,096 | $9,900 | $118,996 | $9,900 | $128,896 | $9,900 | $138,796 |
| Total | $28,742 | $437,107 | $28,742 | $465,849 | $58,742 | $524,591 | $121,222 | $645,813 |
| **Actual cost:** | | | | | | | | |
| Federal | $6,397 | $ 304,825 | $35,075 | $339,900 | $72,796 | $412,696 | $104,030 | $516,726 |
| Non-federal | $9,900 | $109,096 | $9,900 | $118,996 | $9,900 | $128,896 | $9,900 | $138,796 |
| Total | $16,297 | $413,921 | $44,975 | $458,896 | $82,696 | $541,592 | $113,930 | $655,522 |
| **Variance:** | | | | | | | | |
| Federal | -$10,741 | -$23,186 | $16,233 | -$6,953 | $23,954 | $17,001 | -$7,292 | $9,709 |
| Non-federal | $0 | $0 | $0 | $ 0 | $0 | $0 | $0 | $0 |
| Total | -$10,741 | -$23,186 | $16,233 | -$6,953 | $ 23,954 | $17,001 | -$7,292 | $9,709 |

Table 2d: Spend profile

| | Budget Period 4 | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| baseline | 10/1/15 – 12/31/15 | | 1/1/16 – 3/31/16 | | 4/1/16 – 6/30/16 | | 7/1/16 – 9/30/16 | |
| | Q4 | | Q1 | | Q2 | | Q3 | |
| | Q4 | Cum. Total | Q1 | Cum. Total | Q2 | Cum. Total | Q3 | Cum. Total |
| **Baseline cost:** | | | | | | | | |
| Federal | $18482 | $525,499 | $24,596 | $550,095 | | | | |
| Non-federal | $9,900 | $148,696 | $10,719 | $159,415 | | | | |
| Total | $28,382 | $674,195 | $35,315 | $709,510 | | | | |
| **Actual cost:** | | | | | | | | |
| Federal | $8,810 | $525,536 | $4,338 | $529,874 | | | | |
| Non-federal | $9,900 | $148,696 | $10,719 | $159,415 | | | | |
| Total | $18,710 | $674,232 | $15,057 | $689,289 | | | | |
| **Variance:** | | | | | | | | |
| Federal | -$9,672 | $37 | $-20,258 | $-20,221 | | | | |
| Non-federal | $0 | $0 | $0 | $0 | | | | |
| Total | -$9,672 | $37 | $-20,258 | $-20,221 | | | | |