Development of real time geophysical data acquisition and processing toolbox to monitor flood performance

Quarterly Progress Report

Principal Investigators:
Len Pasion and Laurens Beran
Sky Research, Vancouver, B.C.

Technical lead:
Eldad Haber
University of British Columbia

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Chandra Nautiyal, DOE Project Manager

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Disclaimer

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Executive Summary

Sky Research , Inc. is engaged in a project funded by the National Energy Technology Laboratory, Strategic Center for Natural Gas and Oil in the U.S. Department of Energy to develop and validate novel non-invasive methods to monitor and quantify CO_2 EOR flood performance.

The project is divided into three research phases corresponding to the three budget periods. The emphasis in Phase I (Budget Period: February 1, 2011 through February 1, 2012) is on site selection, numerical modeling of CO_2 EOR flooring and associated expected geophysical signatures for a number of different geophysical sensing modalities for selected sites, and on sensing modality selection. The emphasis in Phase II (Budget period: February 1, 2012 through February 1, 2013) will be on sensing system assembly and testing and on inverse method development. The emphasis in Phase III (Budget period: February 1, 2013 through February 1, 2014) will be on the system field deployment on a selected site and on the interpretation of the field data. This report covers the second quarter of Phase II

A literature review comparing the potential approaches for in situ geophysical monitoring was completed in Phase I of this project. This review will be thoroughly updated by December 15, 2012 to provide detailed technical justification for the choice of an EM monitoring system.

A conference call with DOE in mid December 2012, will be initiated by SKY, to discuss completion of 2 Decision Points and the updated literature review findings as discussed above. There are two decision points at the end of Phase 2 that will be successfully completed before proceeding with Phase 3 proposed work. These decision points will ensure that the project team has demonstrated the technical readiness to proceed to Phase 3 monitoring and evaluating of CO_2 flood performance at Yates field in Texas. The two decision points are:

- ***Decision point 1***: This is a decision point at which SKY will decide whether the SKY acquisition hardware provides sufficient data quality and whether they can process this data. If they conclude this is not the case, they shall confer with the DOE program manager on how to re-scope their effort or whether to terminate the project.
    - **Status: Go/No Go:** In Jan 2013 the prototype instrument construction and testing will be completed.
- ***Decision point 2:*** This is a decision point at which point SKY will decide whether they can process and interpret any useable field data at the sites available to us. Based on this decision they may postpone or cancel field efforts until a better candidate site comes along.
    - **Status: Go/No Go:** Numerical studies of the Yates site indicate that they will be able to interpret borehole-borehole data for reservoir imaging. Flow modeling and EM imaging have produced good results.

This quarterly report details our efforts for the period July-October 2012, with emphasis on system construction efforts to meet decision point 1.

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1 Introduction

1.1 Background

Sky Research, Inc. is engaged in a project funded by the National Energy Technology Laboratory, Strategic Center for Natural Gas and Oil in the U.S. Department of Energy to develop and validate novel non invasive methods to monitor and quantify CO2 EOR flood performance.

The motivation for this project is the need for next generation imaging capabilities of CO2 EOR floods. Specifically, such imaging capabilities should allow companies involved in CO2 EOR the capability to obtain timely and actionable information about CO2 EOR floods which would allow for the optimization of such floods through injection parameter tuning. The ability to optimize floods is expected to increase the number of sites at which CO2 EOR can be economically applied, and thus result in increases in (and reduction in the cost of) tertiary oil production.

1.2 Scope of Work

The scope of the project is the design, development and validation of a CO2 mapping and monitoring system consisting of a geophysical sensing system and a suite of advanced data analysis algorithms. Specifically, Sky will deliver:

- **A field-tested, cross-borehole, time-domain electromagnetic system employing vector component receivers to measure all components of induced secondary magnetic fields.** The additional vector components produce more informative data that allow for more advanced data interpretation techniques, resulting in more accurate mapping and imaging.
- **Advanced EM data interpretation and imaging techniques.** SKY will test algorithms that directly couple the estimation of three-dimensional electrical conductivity and CO2 saturation

This EM system will map and monitor the injection of CO_2 in a reservoir during enhanced oil recovery (EOR). The output of the data processing (changes in physical properties estimated via the geophysical inversion) will be coupled to multi-phase flow models to provide for estimates of CO_2 flooding performance.

There are three phases of research in this project: Phase 1 (system design), Phase 2 (system construction) and Phase 3 (system field testing). These phases generally correspond to the three years of the project. The project started on February 1, 2011, and this report covers the third quarter of phase 2.

2 Progress of work

The main emphasis of our work this quarter has been construction of a downhole EM system. The following section details the design of the system.

2.1 Sensor system design and layout

Electromagnetic systems transmit a time-varying primary magnetic field that illuminates conductive targets in the earth. The variation of this primary field induces currents in the ground that, in turn, radiate a secondary magnetic field that can be measured by receivers deployed at the surface, or in boreholes. In the time-domain mode of operation, the transmitter field is terminated and the decay of induced secondary fields is measured during the off-time.

During the last quarter, we have worked on construction of a cross borehole EM system designed for geophysical monitoring of subterranean changes in conductivity. Utilizing a frequency domain transmitter in one borehole and a receiver system in another borehole will provide a method of monitoring any geophysical changes occurring directly between the two boreholes and also below the two boreholes. The goal is to have a large transmitted dipole moment at approximately 1 KHz and a very sensitive receiver system. One difficulty in a cross-borehole system is the size restriction on the diameter of the array; most boreholes are less than six inches in diameter. This small size creates a challenge when designing EM coils because the transmitted magnetic dipole moment and induced receiver coil voltage are directly proportional to coil area (A), as shown below;

$$\text{Induced Coplanar Receiver Coil Voltage} = \frac{[(\omega)(\mu 0)(\mathrm{NIATX})(\mathrm{NARX})]}{(4\pi)(\mathrm{d}3)}$$

Where
$\omega = 2\pi f$ and f = operating frequency (~1KHz)
$\mu_0 = 4\pi \times 10^{-7}$
NIA_{TX} = transmitter dipole moment, number of turns on Tx coil, current thru coil and average area of one turn
NA_{RX} = number of turns on Rx coil and average area of one turn
d = distance (meters) between the Transmitter and Receiver coils

Transmitter: The transmitter design (shown in Fig. 1) will implement a series resonance inductor capacitor circuit utilizing the transmitter coil as the inductor. This series resonant circuit will be driven by an H-Bridge. The H-Bridge will provide the current polarity reversal and the series resonant circuit with its high Q-Factor will filter out the fundamental frequency of the H-Bridge switching waveform. The switching waveform will be produced by the transmitter control electronics at the resonant frequency. This inherent filtering will yield a very low distortion sinusoidal transmitter primary current at the resonant frequency.

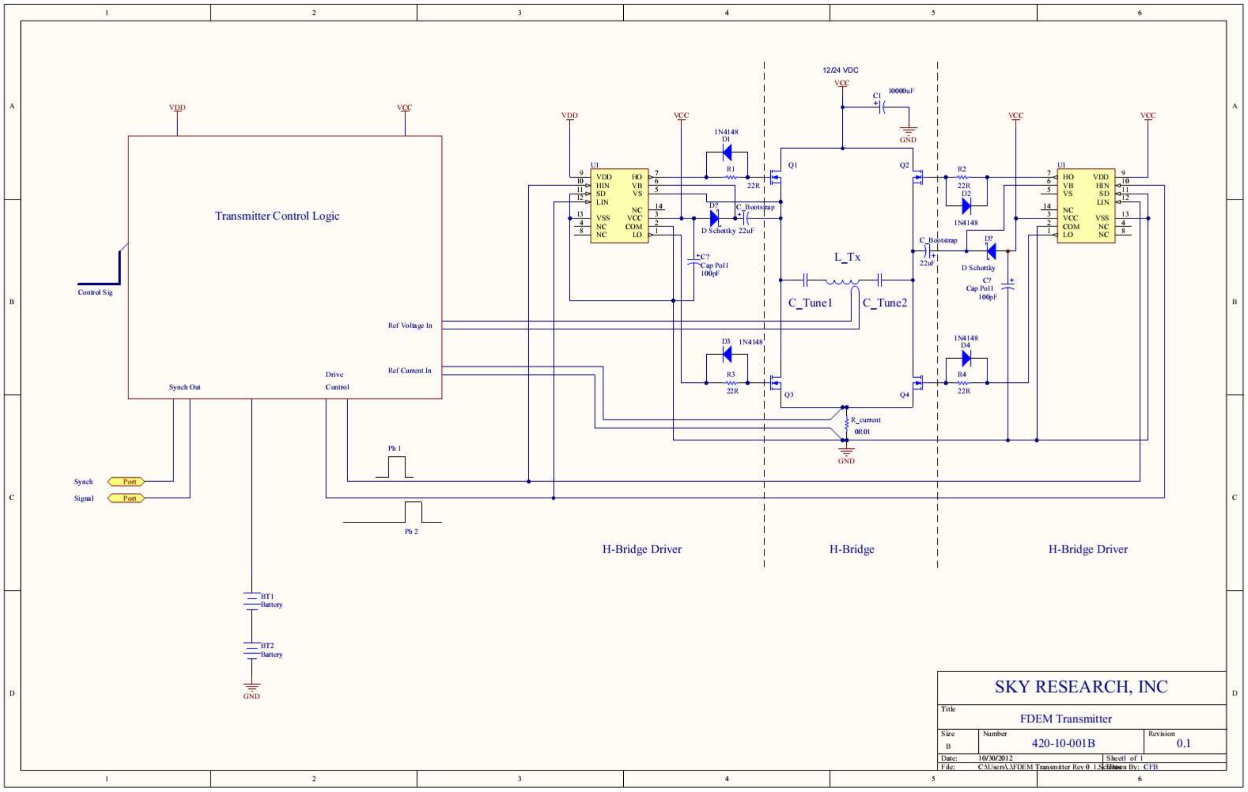

Figure 1. FDEM Transmitter Design Schematic

The resonant frequency of a series resonant circuit is determined by the formula:

$$f = 1 / 2\pi\sqrt{(LC)}$$

Where f = resonant frequency
L = transmitter coil inductance
C = series capacitance

When the series resonant circuit is driven at its resonant frequency, the inductive reactance cancels the capacitive reactance and the net load (presented to the H-Bridge) is strictly resistive. This resistance is the AC resistance of the inductor. The voltage developed across the inductor will equal the total voltage across the capacitors and having two capacitors will reduce each capacitor's applied voltage to 50%, thus lowering the voltage rating of each capacitor. The capacitors chosen are 0.1 microFarad/2500VDC capacitors which have an AC voltage corona limit of 850 VRMS at 1 KHz. The design will need to limit each capacitor's applied voltage to less than 850 VRMS. The effective capacitance value of the two series capacitors is 0.05 microFarads. Using the above resonant frequency formula and selecting 945 Hz as our operating frequency we calculate an inductor of 567 mH.

Transmitter Coil: The transmitter coil area can be effectively increased by using a very high permeable core instead of an air core. The ferrite core utilized in our transmitter coil design has a relative permeability (μ_r) of 2000. These high permeable cores will effectively increase our transmitted magnetic dipole moment and induced receiver coil voltage by 2000 times each, providing an overall increase of 4,000,000. A core's ability to sustain the magnetic flux change vs applied magnetic field is determined from its B-H curve, shown in Fig.2. When the magnetic flux change is not able to keep up with the applied magnetic field, the core enters a saturation region. When this happens, the coil's inductance starts to collapse and the coil appears as a resistive load (without the inductive reactance.) This produces unwanted effects and is very detrimental to the transmitter drive electronics. The saturation region is in the upper right quadrant where the curve becomes more horizontal.

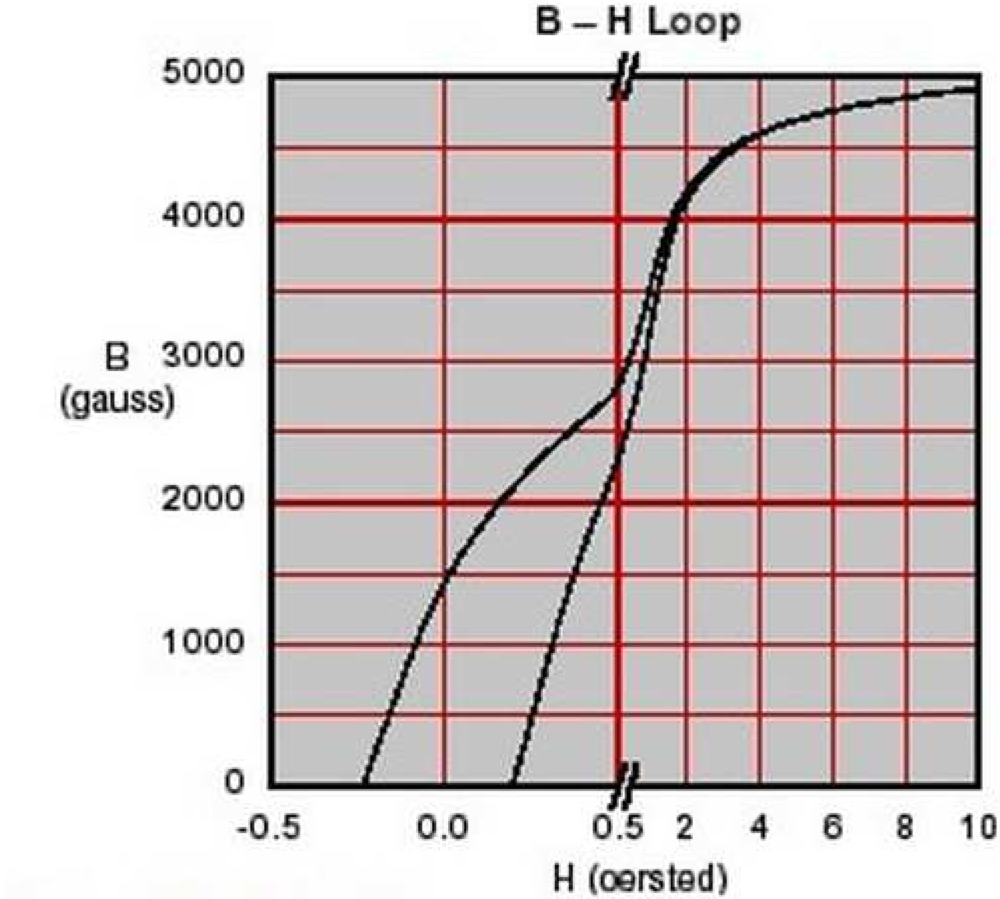

Figure 2. Ferrite 2000 B-H Curve

The transmitter ferrite rod is 24 inches long, 0.845 inch diameter with a plastic protective sleeve yielding an overall diameter of 1.0 inch and overall length of 25 inches. The inductance factor (A_L) was determined empirically by winding multiple selections of a specific number of turns on the ferrite core and noting the inductance values. The transmitter coil design started with a required inductance of 567 mH. Using the inductance factor we determined the number of turns to be 1950. The final number of turns on our transmitter coil is 2000. The wire gauge was selected to provide an AC resistance compatible with direct drive from the H-Bridge (without transformer step down) and still be able to dissipate any heat developed. Number 28 AWG wire gauge was calculated to provide ~ 34Ω DC resistance. The transmitter coil was wound and is shown below in Fig.3.

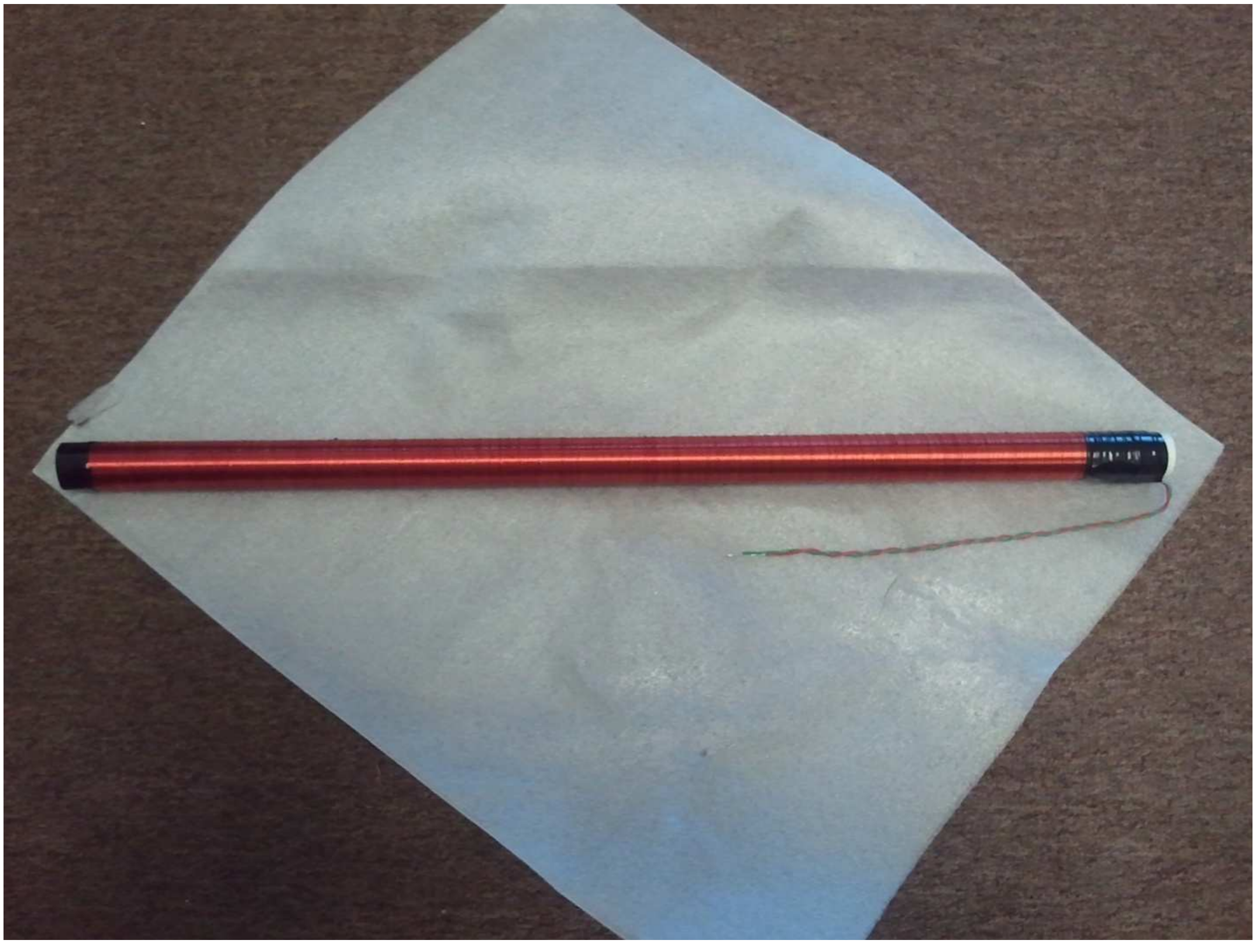

Figure 3. Completed Transmitter Coil Winding

The transmitter coil parameters measured by an LCR Bridge are:

DC resistance = 40Ω, AC resistance at 1 KHz = 47Ω, Inductance L = 556 mH at 1 KHz

The transmitter coil current is then calculated,
Coil current = applied voltage / AC resistance
if we use 24V across our H-Bridge we then have;
24V / 47Ω = 0.510 Amps Pk = 0.361 Amps RMS
Inductor voltage(V_L) = Inductor Current x Inductor Reactance (X_L);
$X_L = 2\pi fL = 2\pi(945)(556mH) = 3301\Omega$
V_L = 0.361 Amps RMS x 3301Ω = 1192 V_{RMS},
Therefore each capacitor will have 1192 / 2 = 596 V_{RMS} which is below our capacitor rated voltage of 850 V_{RMS}. Confirmation is now required to ensure we do not saturate our ferrite core with our developed magnetic field. Rearranging the standard formula of ferrite magnetizing forces, the magnetic field (B) is calculated as:

$$B = \frac{\mathrm{VRMS}}{[(4.44 \times 10 - 8)(N)(A)(f)]}$$

Where B = magnetic field (in gauss)

V_{RMS} = voltage across coil
N = number of turns on ferrite core
A = area of one turn

Substituting in our calculated parameters the magnetic field B = 2802 gauss. The magnetic field strength (H) is related to B by the following formula:

$H = B / \mu$

Where μ is the relative permeability of our ferrite rod (2000)

Substituting in B = 2802, H is calculated as 1.401. Looking at our B-H Curve in Figure 2 with B = 2802 and H = 1.4 we can see that we are still conservatively in our linear region, thus saturating our core is no concern. The maximum theoretical magnetic dipole moment produced by our 24V supplied transmitter system is thus 734 Am^2.

Receiver: The receiver design will utilize a lock-in amplifier method. This lock-in amplifier basically produces a very narrow, high-Q bandpass filter with its center frequency equal to our transmitter operating frequency. The signal voltage from our transmitter will be induced into our receiver coil (Rx). The receiver coil will be part of a resonant circuit, parallel resonant as opposed to series resonant (which was used in our transmitter.) This parallel resonance will provide a number of advantages; 1) it will offer front end tuning determined by the overall damped Q of the parallel circuit and 2) it provides inherent signal amplification that is proportional to the damped circuit Q. The receiver coil design is:

Rx turns = 4100 of #30 AWG
Coil length = 4 inches
Ferrite core = 22 inch length x 0.845 inch diameter
Ferrite core relative permeability = 2000
Inductance = 1.9841 H
DC resistance = 77.7Ω
AC resistance (1KHz) = 78.4Ω

The complete receiver coil is shown in Figure 4 below.

Figure 4. FDEM Receiver Coil

The impedance frequency response and phase shift are shown in Figure 5 below.

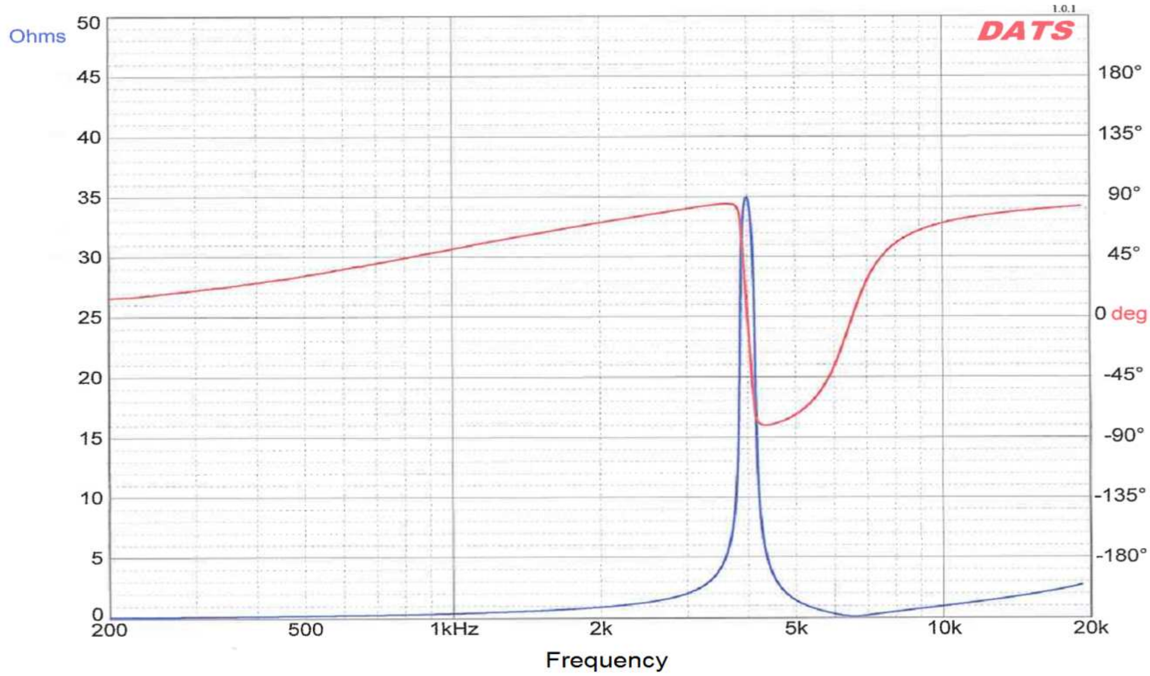

Figure 5. Receiver Coil Impedance and Phase Responses

It shows an undamped, untuned frequency response indicating a self-resonance of 4KHz. This frequency will be tuned to our transmitter operating frequency of 945 Hz with external tuning capacitors. Using the same series resonance formula shown earlier the external tuning capacitance is determined to be 14.3 nanoFarads. The Q-factor will be damped for an initial Q = 10. The external capacitors and damping resistors are shown in Figure 6, FDEM Preamplifier as C_Tune, R1 and R2 respectively.

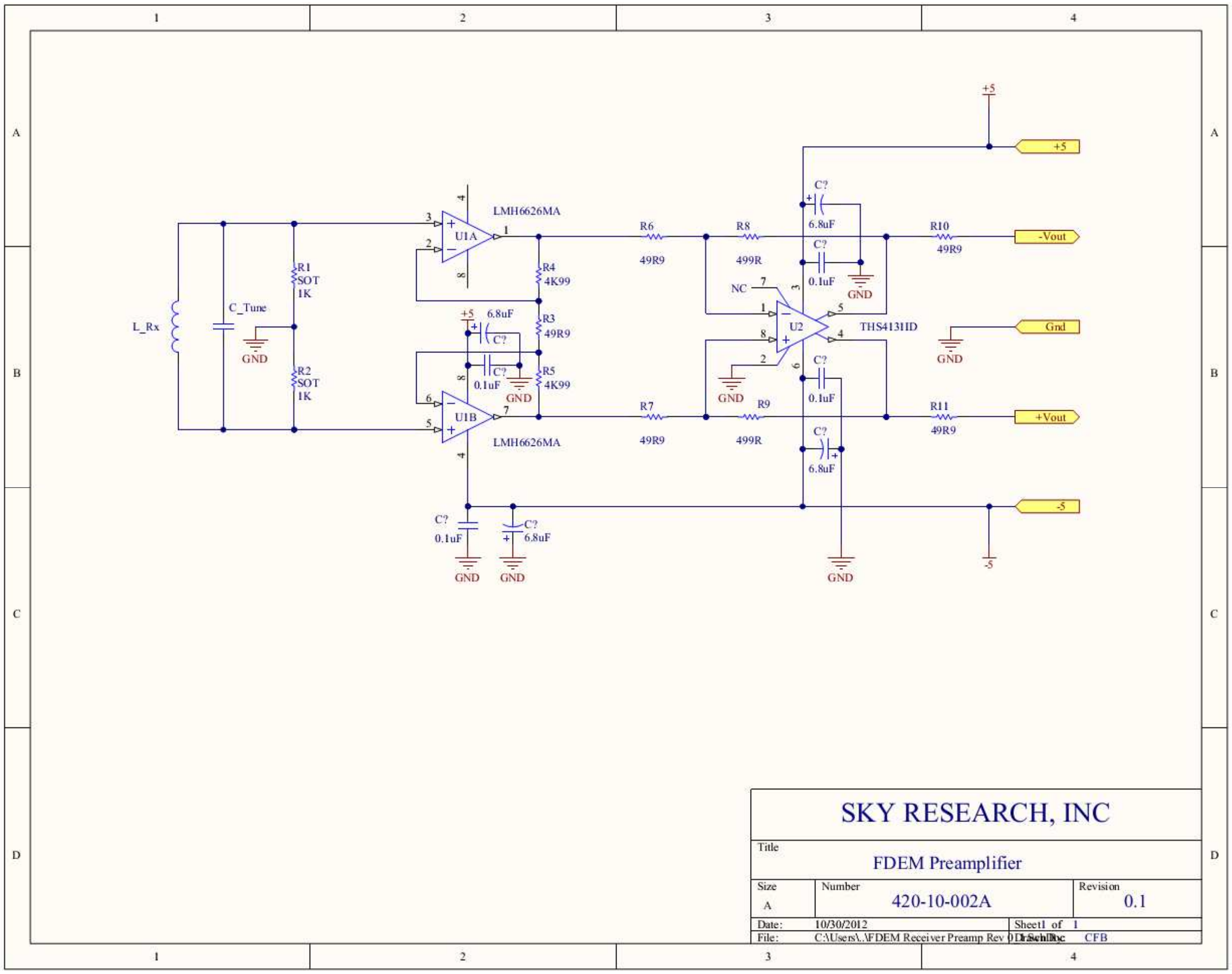

Figure 6. FDEM Preamplifier Schematic

The pickup area (NA) of the receiver coil is calculated:

NA_{RX} = (4100)(5.07 cm^2) = 2.08 m^2

The effective area due to the ferrite core is:

2.08 m^2 x 2000 (u_r) = 4157 m^2

3 Milestone status

3.1 Milestone description

The project is divided into three research phases corresponding to the three budget periods. The emphasis in Phase I (Budget Period: February 1, 2011 through February 1, 2012) is on site selection, numerical modeling of CO2 EOR flooring and associated expected geophysical signatures for a number of different geophysical sensing modalities for selected sites, and on sensing modality selection. The emphasis in Phase II (Budget period: February 1, 2012 through February 1, 2013) will be on sensing system assembly and testing and on inverse method development. The emphasis in Phase III (Budget period: February 1, 2013 through February 1, 2014) will be on the system field deployment on a selected site and on the interpretation of the field data. Table ... summarizes the project task and milestone schedule.

		Year1				**Year 2**				**Year 3**			
Task	Task title	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
1	**Project Management and Planning**												
2	**Test site selection, sensitivity and Cost/Benefit Studies and Sensing Modality Selection**												
2.1	Test site commitment	M1											
2.2	Literature Study								M2				
2.3	CO2 EOR Model Development												
2.4	Geophysical Forward Model coupling to CO2 induced changes in physical properties								M3				
2.5	Sensing Modality and Geometry Selection								M4				
3	**System Prototype Construction**												
3.1	System Design												
3.2	System Construction and									M5			

	Testing												
4	**Processing Flow Development and Linking with CO_2-EOR Models**												
4.1	TDEM Processing Code Development								M6				
4.2	Geophysical Processing Framework Development												
4.3	CO_2-EOR Model Linking with Geophysical Framework Output									M7			
5	**Field testing**												
5.1	Final Site selection												
5.2	System Deployment and Data Collection								M8				
5.3	Data processing												
6	**Data Analysis**												M9
7	**Technology Transfer**												
	DECISION POINTS								1,2				

3.2 Milestone status

1: Test site commitment

This milestone consists of obtaining commitment letters to allow for field deployment of the geophysical monitoring system from one or more sites where CO2 EOR is being done. Meeting of this milestone will be demonstrated by providing these letters to the DOE program office.

Status: COMPLETED 4/1/11.

2: Literature study

This milestone consists of completion of a literature study about the use of geophysical characterization and monitoring of CO2 EOR. Meeting of this milestone will be demonstrated by providing this literature study to the DOE program office.

Status: COMPLETED 5/1/11. After review with program office, revisions will be made to the literature review to include additional information. Will determine if/when original PI will be able to make additions to the literature review. expected completion date - 12/1/12

3: Forward Model coupling

This milestone consists of the coupling of the PNNL developed GS 3 model for CO2 injection with Sky Research developed geophysical forward models such that the coupled models can predict the geophysical signal associated with CO2 EOR efforts. Meeting of this milestone will be demonstrated by performing a series of numerical simulations which the coupled models. The results of the simulations will be documented in a letter report which will be provided to the DOE program office

Status: PHASE 1 MILESTONE - Coupled modeling code completed, with numerical simulations carried out. Tests on Yates and Katz field carried out. Report on simulations will be submitted to DOE program office following completion of Phase III continuation application presentation on 8/22/12. expected completion date - 10/15/12

4: Modality selection

This milestone consists of selection of the sensors and configuration of these sensors which will be used in the field demonstration. This milestone will be demonstrated by a report describing the sensor selection and providing the theoretical, field and numerical data supporting the sensor selection. This report will be provided to the DOE program office.

Status: PHASE 1 MILESTONE - Downhole sensor modality selected based on modeling studies. Modeling details will be reported to DOE program office following completion of Phase III continuation application presentation on 8/22/12. expected completion date - 10/15/12

5: Prototype completion

This milestone consists of the completion of the initial prototype sensor system (note that several of these will be constructed for deployment, but this milestone concerns the construction of the initial one). This milestone will be demonstrated by documenting the prototype design specifications, physical assembly (both component and system level) and test data resulting from the prototype. The documents will be provided to the DOE program office.

Status: PHASE 1 MILESTONE - Receiver components purchased and tested. Transmitter and receiver design and assembly in progress. Partnership with company specializing in downhole instrumentation has been agreed upon. - expected completion date 1/30/13

6: TDEM (Time Domain Electro Magnetic) inverse code

This milestone consists of the completion of a TDEM inverse code which can estimate changes in subsurface conductivity from TDEM data. This milestone will be demonstrated by processing a number of synthetic (and possibly field) TDEM datasets and demonstrating that the code can obtain realistic estimated of changes in subsurface conductivity from this data.

Status: PHASE 2 MILESTONE - UBC data inversion code applied to synthetic models based on Yates and Katz reservoirs. - expected completion date - 10/15/12

7: Model linking

This milestone consists of the linking of the GS3 model with the geophysical codes to allow for inverse property estimation. This milestone will be demonstrated by executing a number of scenarios on synthetic data to show the coupling and property estimation. A document summarizing the results of these scenarios will be provided to the DOE program office.

Status: PHASE 3 MILESTONE - In Progress. to be completed in 2013

8: System deployment

This milestone consists of the deployment to the field site of the monitoring hardware and the start of data collection. This milestone will be demonstrated by documenting field deployment activities and data collection progress (which will be accessible through a password protected interface). A document summarizing field site deployment and a password/username allowing access to the data portal will be provided to the DOE program office.

Status: PHASE 3 MILESTONE - to be completed in 2013

9: Data analysis completion

This milestone consists of the completion of the data analysis and processing of the field data collected in the field demonstration. This milestone will be demonstrated by a data analysis report which will document field data and processing results. This document will be provided to the DOE program office.

Status: PHASE 3 MILESTONE -To be completed in 2014

3.3 Any changes in approach or aims and reasons for change.

The project objectives will primarily remain unchanged. However, the implementation of cyber infrastructure task will not be pursued within this project. The resources (time and cost) to complete this aspect of the project are not sufficient to implement the necessary infrastructure in an effective manner.

3.4 Actual or anticipated problems or delays and actions taken or planned to resolve them.

We do not anticipate any delays in project execution for the remainder of Phase II and III.

3.5 Any absences or changes of key personnel or changes in consortium/team arrangement.

Changes to the project team were documented in the previous quarterly report. There have been no further changes since then.

4 Appendix A. Statement of Project Objectives

4.1 PROJECT OBJECTIVE

The objective of the project is to design, develop and validate a real time, semi- autonomous geophysical data acquisition and processing system to monitor CO_2-EOR flood performance.

4.2 SCOPE OF WORK

The goals of the project are threefold. First, to design the components of the monitoring system based on a combination of a literature study and numerical modeling of CO2 EOR evolution and associated geophysical signatures. Second, to construct and verify performance of this monitoring system, and to develop the required processing framework allowing for the processing of the data from this system, and third to field test this system at an actual CO2 EOR site and to process the collected data to show the ability to monitor CO2 EOR performance

Expected results: The expected results of this work are fieldable systems (combination of hardware an software) for CO2 EOR floods monitoring. These systems would provide economically affordable monitoring of CO2 EOR floods, and thus could be used to optimize these floods. This would potentially increase production and

4.3 TASKS TO BE PERFORMED

The detailed schedule for all tasks for each funded year is shown in table B1-B3 at the end of the PMP. This shows the detailed breakdown of project staff for each year and each task and subtask. The narrative below describes concisely the approach or methods which will be used to achieve the objectives of each task and subtask

Phase I

Task 1.0 – Project Management and Planning

The Recipient shall execute the project in accordance with the approved Project Management Plan (PMP) covering the entire project period. The Recipient shall manage and control project activities in accordance with their established processes and procedures to ensure subtasks and tasks are completed within schedule and budget constraints defined by the Project Management Plan. This includes tracking and reporting progress and project risks to DOE and other stakeholders.

The Recipient shall work with the DOE Project Officer to modify and update the PMP submitted as part of the original application package, as necessary. The revised PMP shall be submitted within 30 days of the award. The DOE Project Officer shall have 20 calendar days from receipt of the Project Management Plan to review and provide comments to the Recipient. Within 15 calendar days after receipt of the DOE's comments, the Recipient shall submit a final Project Management Plan to the DOE Project Officer for review and approval.
This task shall include all work elements required to maintain and revise the Project Management Plan, and to manage and report on activities in accordance with the plan. The Recipient shall review, update, and amend the Project Management Plan (upon request of the DOE Project Officer) at key points in the program, notably at each Budget Period transition or GO/NO-GO decision point (if required) and upon schedule variances of more than three (3) months and cost variances of more than 15%.

It shall also include the necessary activities to ensure coordination and planning of the project with DOE/NETL and other project participants. These shall include, but are not limited to, the submission and approval of required National Environmental Policy Act (NEPA) documentation.

The Applicant is restricted from using Federal funds to take any action that would have an adverse affect on the environment or limit the choice of reasonable alternatives prior to DOE providing final NEPA decision regarding this project.

Task 2.0 – Test site selection, sensitivity and Cost/Benefit Studies and Sensing Modality Selection

The recipient shall secure commitments from CO_2 EOR site operators for the system deployment associated with task 5 (field testing). The recipient shall perform a literature study to identify potential sensing modalities. The recipient shall assess the sensitivity of each potential geophysical sensing modality to changes in physical properties associated with CO_2-EOR and the cost/benefit provided by each sensing modality in terms of information (both alone and in conjunction with other sensing data). From the results of this sensitivity study the recipient shall select the specific sensing modalities for the system as well as the performance characteristics (e.g. acquisition lengths, sensitivities, number of units required, spacing between units). This task shall also include an analysis of the optimal deployment configuration of sensors. This task shall include a modeling study to determine the physical changes associated with EOR which will be coupled to geophysical forward modeling studies performed by the recipient (Subtask 2.3 – Geophysical forward model development).

Subtask 2.1 – Test site commitment

The recipient shall obtain commitment letters from at least one but preferably multiple CO_2 EOR site operators to serve as system testing sites for the effort to be performed under task 5 (field testing). The commitment letter shall include information on site location, required site access and resource needs (e.g. space required, power requirements and so on) and length of site access, as well as auxiliary data which will be required by the project and provided by the operator. The recipient shall provide the results of subtask 2.1 (including the sites considered, general site properties, and test site commitment letters) and a preliminary ranking of potential test sites to the DOE Project Officer.

Subtask 2.2 – Literature Study

The recipient shall evaluate the CO_2 Measurement, Monitoring and Validation (MMV) literature (including both reports from specialized workshops and meetings, as well as literature from SEG, SPE, AGU and EAEG and other relevant geophysical and geological societies) to evaluate all different potential sensing modalities and monitoring approaches. This study shall inform and guide the efforts under task 2.3 -2.5. A comprehensive topical report shall be submitted by the recipient at the end of this subtask. This shall have a bibliography and a description of the literature sources used for the report

Subtask 2.3 – CO2 EOR Model Development

The recipient shall develop and implement a forward model that allows the simulation of changes in physical properties (electrical, electromagnetic, density and acoustic properties) associated with the injection of CO_2 for typical EOR field applications. This model will be used as input into subtask 2.4

Subtask 2.4 – Geophysical Forward Model coupling to CO2 induced changes in physical properties

The recipient shall execute forward geophysical modeling tools to map the changes in physical properties provided by subtask 2.2 to calculate observable changes in geophysical measurements for a number of sensing modalities and instrument configurations, including electrical, electromagnetic, active and passive seismic and gravity measurements in surface, single borehole, borehole to borehole and borehole to surface configurations as well as other potentially possible modalities and configurations. This task shall include a detailed numerical sensitivity analysis listed under Task 2.0 which shall quantify the relative and absolute changes in each sensing modality and the expected noise signatures for each sensing modality, and from this the likely probability of detection by the sensing modality/configuration combination

Subtask 2.5 – Sensing Modality and Geometry Selection

The recipient shall select the final combination of sensing modalities, sensor specifications and deployment geometries for the system based on the results of subtask 2.2-2.4.

Phase 2

Task 3.0 – System Prototype Construction

The recipient shall construct a prototype acquisition system that includes both commercial sensors as well as a recipient developed Time domain Electromagnetic TDEM receiver (if selected as an appropriate sensing methodology in task 2). Data from these sensors shall be acquired by data acquisition software and hardware based on recipient-developed geophysical acquisition systems used for high quality geophysical surveys. This system shall be designed to be fully autonomous and environmentally rugged capable of collecting continuous data under expected testing field conditions (changes in temperature, rain, etcetera).

Subtask 3.1 – System Design

The recipient shall design the system (power requirements, form factor, auxiliary components, and sensor placements). This design shall be supported by field tests to minimize noise and component interference. It shall also include the selection of specific geophysical sensors for the sensing modalities selected under task 2 which meet or exceed the sensitivity requirements.

Subtask 3.1 – System Design

The recipient shall design the field data acquisition system which shall has as objective to collect the data as identified as a result of task 2. This system shall consist of an environmental enclosure (which will contain data acquisition hardware, power distribution system, a dedicated system control unit and internal geophysical sensors) and external geophysical sensors. The system components are described under the following subtasks

> **Subtask 3.1a: Environmental enclosure:** The recipient shall design an environmental enclosure: this enclosure shall enclose all the data acquisition elements and be watertight against expected field conditions (including extreme events). The environmental enclosure shall provide industry standard, watertight connectors for system power (either DC or AC power) and wired ethernet connectivity and required connectors to the external geophysical sensors. The recipient shall provide for wireless internet connectivity which shall be integrated in the environmental enclosure. The environmental enclosure shall be designed so that the temperatures in the enclosure will be in the range provided by component manufacturers.
>
> **Subtask 3.1b: External geophysical sensors:** The recipient shall decide on the number, placement and orientation of external geophysical sensors based on the results of task 2. Each

external sensor shall be provided in an environmentally tight enclosure designed for the appropriate environment (e.g. surface mounting or placement in well) with appropriate mounting and orientation capabilities. Each external geophysical sensor shall be connected to the data acquisition hardware in the environmental enclosure through a wired connection which shall meet all applicable site safety requirements.

Subtask 3.1c: Internal geophysical sensors: The recipient shall decide on the number, placement and orientation of internal geophysical sensors based on the results of task 2. The internal geophysical sensors shall be permanently mounted in the environmental enclosure and be connected to the data acquisition hardware through a wired connection which shall meet all applicable site safety requirements. The internal sensor placement shall be optimized to minimize noise and cross sensor interference.

Subtask 3.1d: Power distribution system: The recipient shall decide on the power requirements of the field data acquisition system. Based on these, the recipient shall design a power distribution system which shall receive its power from the external source. The power distribution system shall be able to automatically accommodate a broad range of voltages and currents and fluctuations therein and shall provide clean power to all of the system components. The power distribution system shall be equipped with surge protection capabilities which shall be easily resettable from the outside of the environmental enclosure.

Subtask 3.1e: Data acquisition hardware: The recipient shall provide for data acquisition hardware which will record and store the data from the internal and external geophysical sensors. The data acquisition parameter shall be derived from task 2.

Subtask 3.1f: System control unit: The recipient shall provide for a system control unit which shall control and monitor overall system behavior. This system control unit shall control and monitor the data acquisition hardware, power output and environmental conditions in the environmental enclosure (temperature and humidity) and transmit data collected by the data acquisition hardware systems.

Subtask 3.2 – System Construction and Testing

The recipient shall construct and test the system. This shall include deployment of the prototype system for at least two weeks under field conditions representative of the planned field test site (task 5) to assess system stability and performance in agreement with the design specifications. During the test, geophysical data from each of the selected sensors as well as data describing system health and conditions (power, temperature and humidity) shall be acquired and saved and transmitted continuously. Data assessment shall include but not be limited to data quality, sensor drift, system noise, effect of environmental conditions and the ability to detect specific known changes in the subsurface. For this test the system shall be located at a well- instrumented site where such changes are known from auxiliary observations.

Task 4.0 – Processing Flow Development and Linking with CO_2-EOR Models

The recipient shall develop a processing flow for all geophysical data selected under task 2, which were integrated in the system developed under task 3. The result of the processing flow will be linked with the CO_2-EOR modeling framework. This processing flow shall map the geophysical field data to changes in physical properties which can be ingested by the CO2 EOR modeling framework. The recipient shall integrate the results of all these processing flows into a geophysical processing framework and link the results with a CO2 EOR model

Subtask 4.1: Geophysical Processing Flow Development

The recipient shall design, develop and implement a processing for all the selected geophysical and acquired sensing modalities. This processing flow shall exist of a number of well described data processing steps (data receiving from the field units, QA/QC, data storage in relational database, preprocessing, inversion and finally delivery of a spatiotemporal map of physical properties with associated resolution and confidence matrixes).

Subtask 4.2 – Geophysical Processing Framework Development and linking with CO_2-EOR Model

The recipient shall develop a geophysical processing framework which will utilize the individual processing flows developed under task 4.1 to provide the CO2 EOR model timelapse values of changes in physical properties. This data shall be used by the CO2 EOR model to provide estimates of flood performance.

Phase 3

Task 5.0 – Field Testing

The recipient shall test the system performance by deploying multiple units at a selected field site and collecting and processing data autonomously for a period of 3-6 months. The number and relative placement of units and length of data acquisition shall be based on a numerical modeling effort as well as on programmatic constraints.

Subtask 5.1 – Final Site Selection

The recipient shall select one appropriate site for the system test out of the sites which have committed to serve as potential test sites (task 2.1). Criteria for final test site selection shall include existing infrastructure, favorable conditions in terms of expected geophysical data, ability to collect base line data before and during CO_2-EOR, availability of auxiliary data and the ability to model the underlying system. The recipient shall provide information relative to the selected site, design criteria, and planned testing duration to the DOE Project Officer for approval prior to commencement of testing.

Subtask 5.2 System Deployment and Data Collection

The recipient shall deploy the data acquisition system at the selected site and collect data for approximately 3-6 months. Initial data acquisition length shall be based on the modeling effort. Actual data acquisition length and termination of the field test shall be based both on project constraints and the success full acquisition, processing and interpretation of timelapse geophysical data associated with CO2 EOR. During the field deployment the recipient shall frequently brief the DOE program manager on testing progress and results.

Subtask 5.3 Data Processing

The recipient shall apply the geophysical data processing described under Task 4 to the collected data.

Task 6. Data Analysis

The recipient shall analyze the overall system developed under this effort (both acquisition hardware and processing framework). The recipient shall evaluate the success and limitations of the developed methodology. This shall include both the predicted and actual performance of the data acquisition system, the performance of the data processing flow from both a numerical, computational and result perspective, the match between results obtained from this system and data provided by the site operator, as well as the merit of the resulting data as assessed by the site operator, and the potential benefits of such data to other sites.

Task 7: Technology Transfer

The Recipient shall disseminate the findings of this project, including advances in theory, modeling, processing, and imaging. The mechanisms for transferring these results shall include the development of a project website to report results, presentations at annual SEG and AGU meetings or at other appropriate conferences, at least 1 paper per year in relevant journals, and organization of a workshop or research forum at the appropriate annual meeting of a national organization (e.g., SEG, AAPG, SPE) or in conjunction with PTTC.

5 Cost/Plan Status

Budget	2011	2012	2013	Total
DOE requested funds	$247,158	$247,158	$247,158	$741,474
Sky Research	$172,158	$132,158	$162,158	$466,474
Pacific Northwest National Laboratory	$75,000	$15,000		$90,000
Computational Geophysics Inc.		$100,000	$85,000	$185,000
Non federal matching funds				
Sky Research	$61,789	$61,788	$61,789	$185,366
Totals	$308,947	$308,946	$308,947	$926,840

February 1, 2011 to January 31, 2012	Sky				
Phase I: Task Elements	Roelof Versteeg	Erik Russell	Leonard Pasion	Sam Segal	Jon Miller
Task 1 Project Management and Planning	120	100			
Task 2.Test site selection, sensitivity and Cost/Benefit Studies and Sensing Modality Selection					
Task 2.1 Test site commitment	40				
Task 2.2 Literature Study	100				100
Task 2.3 CO2 EOR Model Development					
Task 2.4 Geophysical Forward Model coupling to CO2 induced changes in physical properties	100		225	50	100
Task 2.5 Sensing Modality and Geometry Selection	140			50	50
Task 3 System Prototype Construction					
Task 3.1 System Design				150	150
Subtotals (hours)	500	100	225	250	400
Subtotals (approximate months)	3.1	0.6	1.4	1.6	2.5

Table B1. Detailed task breakdown associated with project in year 1.

September 1, 2012 - December 31, 2012			
Phase II: Task Elements	Elliot Holtham	Eldad Haber	Livia Mahler
Task 1 Project Management and Planning	50	50	10
Task 2.Test site selection, sensitivity and Cost/Benefit Studies and Sensing Modality Selection	10	40	
Task 2.1 Test site commitment	20	20	5
Task 2.2 Literature Study	25		

Task 2.3 CO_2 EOR Model Development	50	100	
Task 2.4 Geophysical Forward Model coupling to CO_2 induced changes in physical properties	200	260	
Task 2.5 Sensing Modality and Geometry Selection	20	60	
Task 3 System Prototype Construction			
Task 3.1 System Design	40	40	
Subtotals (hours)	390	595	15
Subtotals (approximate months)	2.4	3.72	0.09

Table B2. Detailed task breakdown associated with project in year 2 for Computational Geosciences, Inc.

February 1, 2012 to January 31, 2013	Sky					
Phase I: Task Elements	RV	ER	LP	CB	JM	LB
Task 1 Project Management and Planning	50	40	50			50
Task 2.Test site selection, sensitivity and Cost/Benefit Studies and Sensing Modality Selection	10					
Task 2.1 Test site commitment	20		5			5
Task 2.2 Literature Study	25					
Task 2.3 CO2 EOR Model Development	50		50			50
Task 2.4 Geophysical Forward Model coupling to CO2 induced changes in physical properties	50		40			40
Task 2.5 Sensing Modality and Geometry Selection	20					
Task 3 System Prototype Construction						
Task 3.2 System Construction and Testing				200	160	
Task 4. Processing Flow Development and Linking with CO_2-EOR Models						
Task 4.1 TDEM Processing Code Development			40			40
Task 4.2 Geophysical Processing Framework Development	20		20			20
Task 4.3 CO_2-EOR Model Linking with Geophysical Framework Output	20		40			40
Task 5. Field testing						
Task 5.1 Final Site selection	20		10			10
Task 5.2 System Deployment and Data Collection						
Task 7. Technology Transfer			20			20
Subtotals (hours)	285	40	275	200	160	275
Subtotals (approximate months)	1.8	0.25	1.7	1.25	1	1.7

Table B3. Detailed task breakdown associated with project in year 2 for Sky. RV = Roelof Versteeg. ER = Erik Russell. LP = Len pasion. CB = Chet Bassani. JM = Jon Miller. LB = Laurens Beran.

February 1, 2012 to January 31, 2013	PNNL			
Phase I: Task Elements	Alain Bonneville	Charlotte Sullivan	Debbie Fagan	Signe Wurstner
Task 1 Project Management and Planning	40			
Task 3 System Prototype Construction				
Task 3.2 System Construction and Testing				
Task 4. Processing Flow Development and Linking with CO_2-EOR Models				
Task 4.1 TDEM Processing Code Development				
Task 4.2 Geophysical Processing Framework Development				
Task 4.3 CO_2-EOR Model Linking with Geophysical Framework Output	40			80
Task 5. Field testing				
Task 5.1 Final Site selection				
Task 5.2 System Deployment and Data Collection				
Task 7. Technology Transfer				
Subtotals (hours)	60			80
Subtotals (approximate months)	0.9			0.5

Table B4. Detailed task breakdown associated with project in year 2 for PNNL.

February 1, 2013 to January 31, 2014	Sky				CGI		
Phase I: Task Elements	Pasion	Beran	Bassani	Segal	Holtham	Haber	Mahler
Task 1 Project Management and Planning	80	80			40	40	20
Task 5. Field testing							
Task 5.2 System Deployment and Data Collection			300	300	80	40	
Task 6. Data analysis			200	200	240	240	
Task 7. Technology Transfer	20	20					
Subtotals (hours)	100	100	500	500	360	320	20
Subtotals (approximate months)	0.6	0.6	3.1	3.1	2.25	2.0	0.13

Table B5. Detailed task breakdown associated with project in year 3.