Preliminary Cruise Report

Marine CSEM Surveys of Green Canyon and Walker Ridge Gas Hydrate Prospects, Gulf of Mexico

R.V. Point Sur, June 29 – July 11, 2017

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November 2, 2017

The R.V. Point Sur tied up at LUCMON's facility in Cocodrie, Louisiana

INTRODUCTION AND MOTIVATION

Current geophysical surveying methods for identifying seafloor gas hydrates, such as seismic methods and well logging/coring, are limited in various ways. A characteristic seismic signature associated with hydrate is the bottom-simulating reflector (BSR). The BSR tracks the phase change of solid hydrate (above) and free gas (below) that is controlled by the intersection of the hydrate stability field with the local geothermal gradient. Because of this, the BSR usually tracks parallel to the sea floor and often cross-cuts sedimentary structures. However, the strong seismic signature associated with traces of free gas at the BSR is almost completely independent of the amount of hydrate higher in the section. Seismic blanking and seismic bright spots may be a better indication of hydrate in the section, but reveal little about the thickness and concentration of the material. Well logging or coring, while providing locally definitive data, is expensive, invasive, and provides only a point measurement for the direct presence of hydrate.

Quantifying the volume fraction of hydrate in sediments is possible with careful processing and inversion of seismic data, although the relationship between seismic velocity (or attenuation) and hydrate concentration is complicated. Electromagnetic methods, on the other hand, are sensitive to the concentration and geometric distribution of hydrate. Resistivity measurements made during well logging indicate that regions containing hydrate are significantly more resistive when compared to water saturated zones, and direct laboratory measurement of methane hydrate confirms that fully hydrate-saturated sands have a resistivity of about 2,000 Ωm, a thousand times higher than typical host sediments.

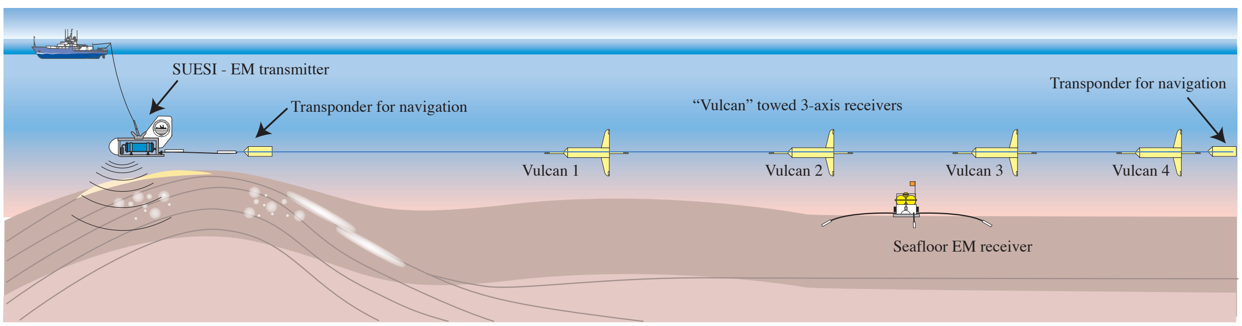

Figure 1. The Vulcan system for mapping the shallow seafloor.

Marine controlled-source electromagnetic sounding is a standard tool for offshore hydrocarbon exploration, but seafloor gas hydrate is a challenging target for traditional seafloor node based CSEM surveys because it is difficult to obtain close spacing on the receiver array, Furthermore, navigation errors corrupt short offset data needed for resolution in the near surface. The current state of the art for imaging gas hydrate using EM methods is represented by the Vulcan system developed by Scripps Institution of Oceanography (Figure 1). This system uses multiple, 3-axis EM receivers towed at source-receiver ranges of up to 1,600 m behind an electric dipole transmitter. The whole array (transmitter and receivers) is "flown" 50—100 m above the seafloor. During instrument development, the Vulcan system was used to collect data offshore California, and has been used to collect several thousand line-km of proprietary data over gas hydrate prospects in Japan for the Japanese National Institute of Advanced Industrial Science and Technology (AIST).

The purpose of the cruise described in this report was to collect (publishable) Vulcan data over four hydrate prospects in the Gulf of Mexico. This work is funded by the US Department of Energy (DE-FE0028972), the Bureau of Ocean Energy Management (M17AC00015), and the Scripps Seafloor Electromagnetic Methods Consortium.

IINSTRUMENT SYSTEMS

The **Scripps Undersea Electromagnetic Source Instrument** (SUESI) is towed close to the seafloor using a standard UNOLS 0.680" (17 mm) coaxial deep tow cable. Power is delivered via the tow cable from a topside power supply that converts ship's 3-phase power to 2000 V at a frequency of 400 Hz which is stabilized by a GPS clock signal. In SUESI the high voltage power is transformed to 40 VAC, rectified, and switched using IGBT modules. The output waveform is a custom, compact binary signal that has 1–2 decades of usable frequencies, and is synchronized using the GPS stabilized 400 Hz power signal. Maximum output current is 500 A zero to peak, but on the smaller transmission antennas used for hydrate studies we are limited to 200–300 A. A frequency shift keyed (FSK) 9,600 baud bidirectional communication signal is overlain on the power transmission and allows SUESI navigation data (depth, altitude, water sound velocity, long baseline acoustics), operational information (input voltage, output voltage, output current, temperature throughout the system), and Vulcan telemetry (see below) to be monitored in real time. We can also issue commands to set operation parameters and synchronize the output on the minute.

In this project we used a neutrally buoyant 100 m transmission antenna with an output current of about 260 A with a fundamental frequency of 0.5 Hz. We carried full redundancy for the SUESI system on this cruise, with two SUESI underwater systems, two topside power supplies, and two antenna arrays and winches. However, SUESI worked perfectly for this project and we did not need to substitute any equipment.

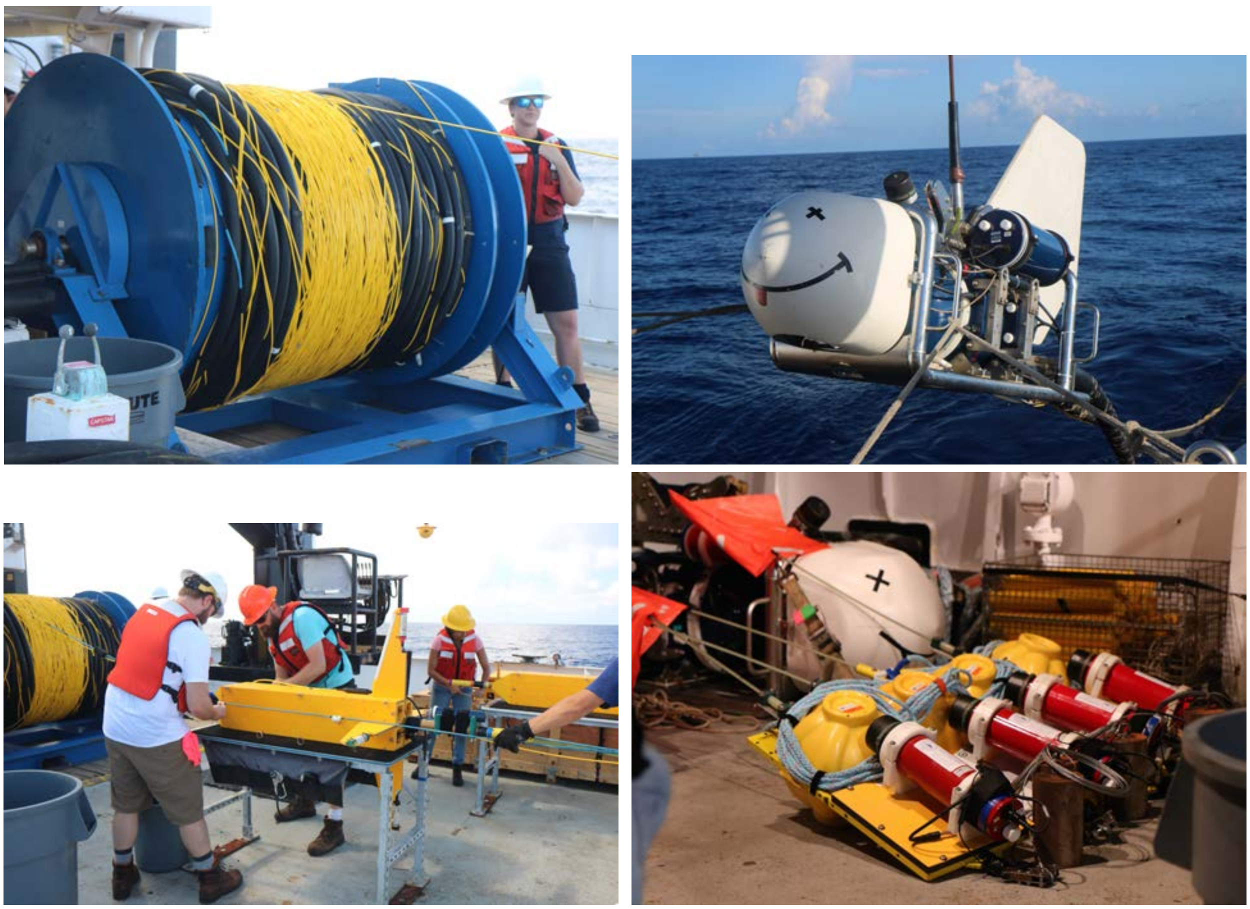

Figure 2. Instrument systems. Top-left: Winch with transmitter antenna (black) and Vulcan electromechanical tow cable (yellow). Top-right: SUESI, the deep-towed EM transmitter. The blue pressure case mounted on the left side contains the LBL ranging system (the acoustic transponder head is located just forward of the cable termination). Bottom-left: Vulcan receiver systems being prepared on deck. Bottom-right: An array of four LBL transponders prepared for deployment.

The **Vulcan system** records 3 axes of electric field using the same recording electronics as the Scripps OBEM instruments in a neutrally buoyant package. Horizontal inline fields are recorded on a 2 m dipole, while horizontal crossline and vertical fields are recorded on 1 m dipoles. The crossline field allows a total field magnitude to be calculated, but otherwise is a null measurement in an ideal dipole geometry. The vertical field is useful for total field calculations, but is also particularly sensitive to lateral changes in seafloor electrical resistivity.

The Vulcan instruments contain Paroscientific precision pressure (depth) gauges along with pitch/roll/heading sensors, in order to determine navigation and orientation. These data are time stamped and recorded internally, but also telemetered to SUESI using a custom, multi-drop serial communication protocol over a twisted pair of copper wires in the towing cable. SUESI passes the navigation data up to the vessel. The onboard clocks in the Vulcans drift about 1 ms per day, but SUESI waveform polarity transitions are sent down the towing cable and recorded on the Vulcans to correct for clock drift. Although this puts very little noise on the Vulcan data, the timing signal is only turned on during turns between lines.

Our pre-cruise modeling showed that having a larger transmitter–receiver spacing than we have used in the past would be desirable for the deeper targets at WR 313, and so we arranged to use an array of 6 Vulcan receivers a little over 1,600 m long, which is a first for us (in the past our longest array has been about 1200 m long). The six Vulcan systems were placed at 200 m intervals between 600 m and 1600 m behind SUESI, sampling at 250 Hz. Two instruments (Mullet and Barramundi) also recorded DC-coupled electric fields to supplement the standard AC-coupled electric field measurements. The Vulcan array also includes an acoustic relay transponder and an acoustic altimeter at the end of the array, as well as a depth recorder at the end of the transmission antenna (to record antenna angle from horizontal).

The Vulcan instruments worked perfectly for this project, although instrument Morwong leaked a little water during the first deployment, and was replaced by a spare instrument (HumuHumu) for subsequent deployments.

We also deployed a **long baseline (LBL) acoustic navigation array** consisting of 4 transponders moored 10 m above the seafloor at each of the four prospects. A Benthos DS-7000 acoustic ranging system forms part of SUESI's navigation suite and ranges directly to the moored transponders, allowing SUESI position to be triangulated. The relay transponder at the end of the Vulcan array allows the end of the array to be navigated from the same data. The LBL acoustic system worked very well, except that for the second deployment one transponder was accidentally disabled during checkout and was deployed that way. However, combined with depth measurements, we only need ranges to two of the four transponders to compute position.

DESCRIPTION OF OPERATIONS

We used the R.V. Point Sur, owned by the University of Southern Mississippi and operated by the Louisiana Universities Marine Consortium (LUMCON) for this project. We originally planned to use the R.V. Pelican, also operated by LUMCON, but the Pelican's schedule filled up during our preferred time slot and LUMCON asked if we could use the Point Sur. Since the Point Sur is slightly bigger, and has an installed 0.680" winch, this worked well for us. In late June all the instruments were given final tests and shipped off to Cocodrie, Louisiana, where we mobilized the vessel. We were originally scheduled to set sail on June 26th, but this was moved back to the 29th because of tropical storm Cindy, which would have impacted science programs preceding ours. By slipping our project three days, the R.V. Point Sur could stand down during the bad weather without loss of science. Fortunately, we were easily able to comply with the delay.

Mobilization started at mid-day on the 28th June and proceeded smoothly. This included terminating the deep-tow cable, installing high voltage slip rings on the winch, plumbing 3-phase power to the topside power supply units, and deck testing the transmitter. Transmitter installation and testing was accomplished by late evening, and by early morning we had finished securing equipment in the inside laboratory in order to set sail at 08:00 on the 29th.

Figures 3 and 4 show the locations of the four survey areas. We arrived on station at Walker Ridge 313 in the early hours of the 30th June and deployed the transponder net and CSEM array. The deployment went well and by 09:00 we were testing the transmitter prior to launch. We were collecting data at 50 m altitude above the seafloor by 11:35 and continued through 18:15 on the 2nd July. At that time we recovered the CSEM array and the transponder array, transited to WR 100 and re-deployed the transponder net. The CSEM array was in the water over WR 100 at 17:00 on the 3rd July. The bathymetry over WR 100 was somewhat rugged, so we made the initial tow line at 150 m above the

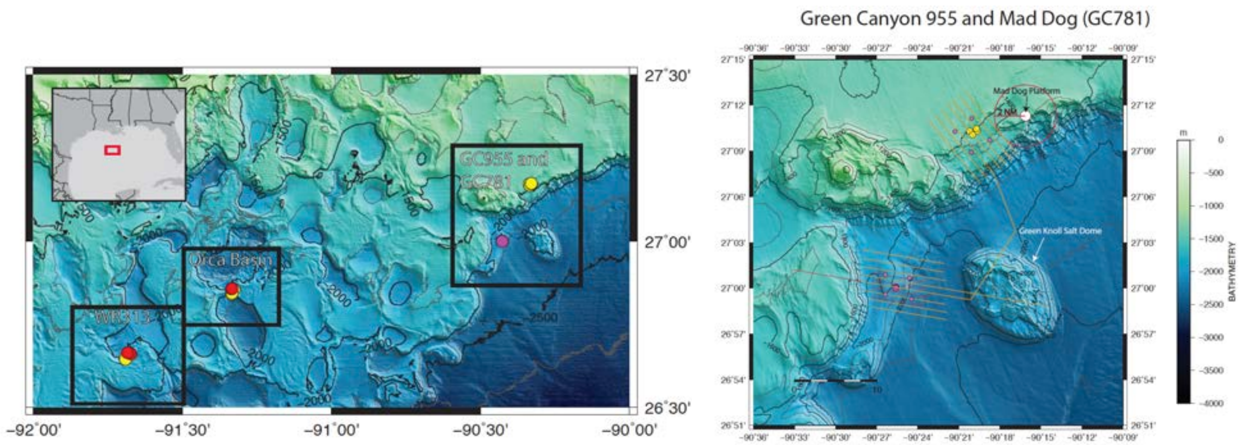

Figure 3. Left: Locations of the three work areas in the Gulf of Mexico. Right: Planned survey lines for the Green Canyon areas. Orange lines are CSEM track lines. Light purple circles are transponder drop locations. Red and yellow circles are primary and secondary drill sites, respectively, for the 2020 GOM^2 drilling campaign. Purple circles at GC955 were drilled earlier this year as a pressure coring test. Thin red lines are USGS 2D seismic lines.

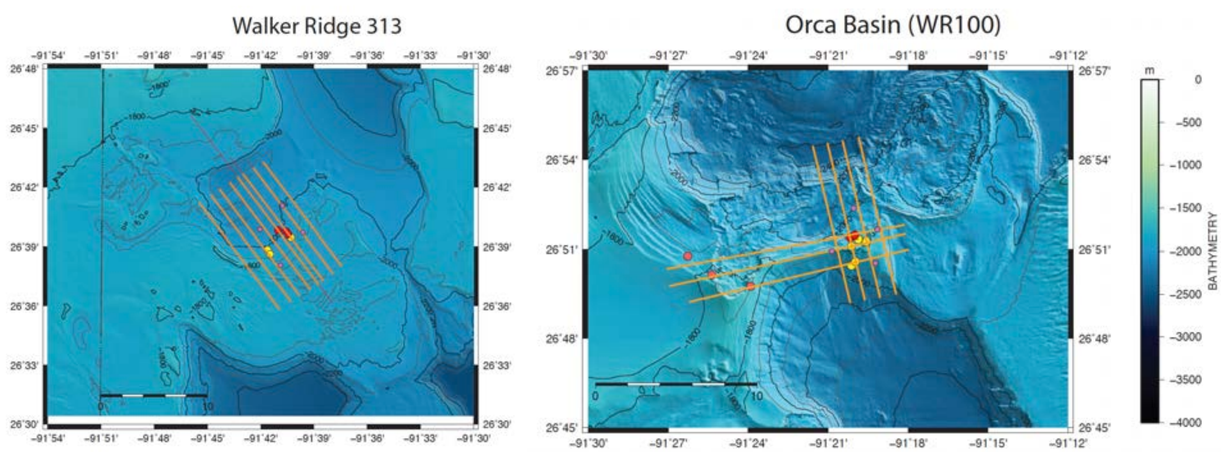

Figure 4. Left: Planned survey lines for Walker Ridge. Right: Planned survey lines for Orca Basin. Orange lines are CSEM track lines. Light purple circles are transponder drop locations. Red and yellow circles are primary and secondary drill sites, respectively, for the 2020 GOM^2 drilling campaign. Thin red lines are USGS 2D seismic lines.

seafloor, but our 1600 m long receiver array did a good job of following the topography, so we dropped the transmitter down to an altitude of 100 m for the rest of the survey. We finished WR 100 at 10:00 on the 5th and recovered the CSEM and transponder arrays.

We had decided that Green Canyon 955 and 781 could be surveyed together, towing the CSEM array over Green Knoll between the two prospects, but this required putting transponder nets down over both prospects for our transmitter and receiver navigation. This was accomplished by 07:00 on the 6th and we were collecting data over GC 781 by about 10:00 on the 6th. We surveyed GC 781, towed over Green Knoll to GC 955, and finished the survey by early July 10th. We had a few hours in the schedule, so we towed the last line back over Green Knoll before recovering the arrays at 10:00 am. By midnight we had navigated and recovered the transponder arrays and were heading back to Cocodrie, tying up around noon on the 11th. We demobilized the vessel on the morning of the 12th and were done by noon. Appendix A includes a daily log of operations.

Throughout the survey, the CSEM equipment worked as designed and without any failures or problems. One minor issue we had was that one navigation transponder was deployed disabled as a consequence of accidentally receiving a disable command during deck testing the acoustic releases of other units. Since we can navigate the CSEM transmitter using ranges from two acoustic transponders and depth, this should not compromise our survey. Another small issue is that one of the Vulcans leaked a little water on the first deployment, and although it did not affect the data we swapped it out with a spare instrument for subsequent deployments.

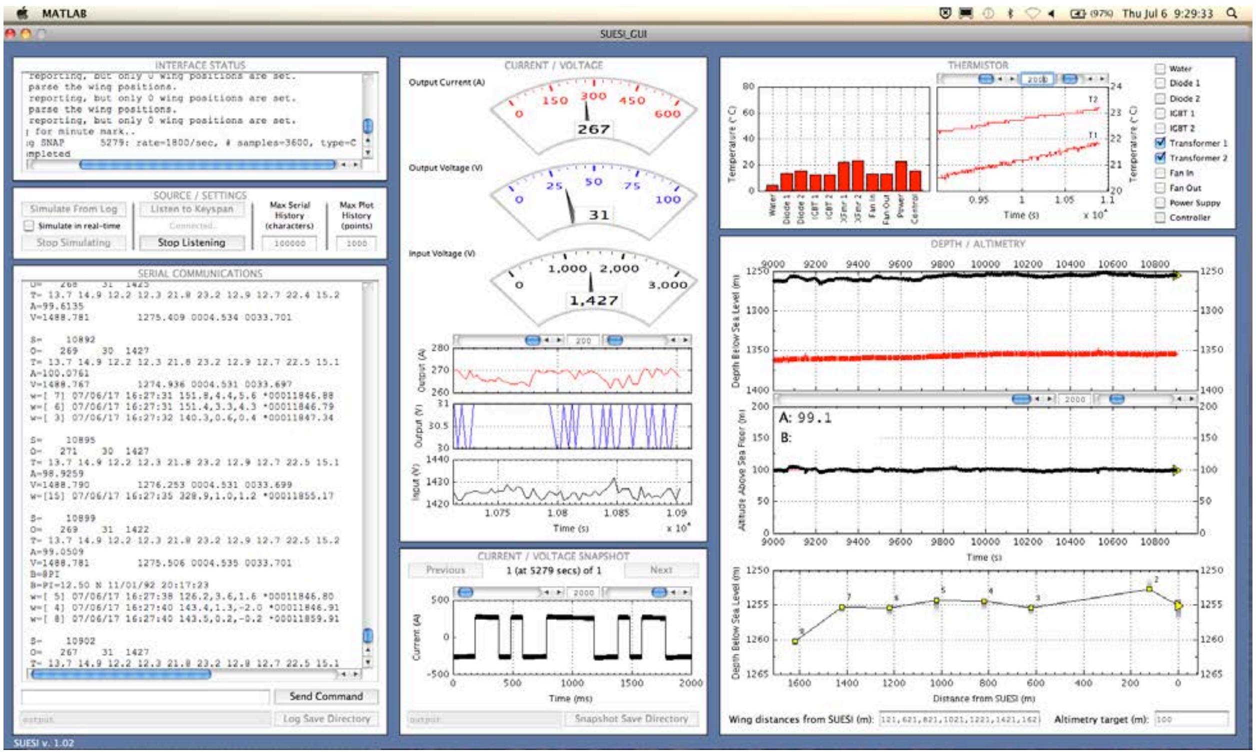

Figure 5. Screen shot of the GUI interface to SUESI during the Walker Ridge survey. On the left is the data stream from SUESI. In the center are the input and output voltages and output current, along with a snapshot of the output waveform (a single cycle is sampled at 1.8 kHz, buffered, and sent in the data stream at 9,600 baud). On the right we see the depth and altitude of SUESI, along with the depths of all the Vulcan instruments. The instruments are flying level to within ±5 m along the entire 1,600 m array.

We had some trepidation about extending the Vulcan array to 1,600 m long, but we had no trouble keeping it off the seafloor. Indeed, the array flew remarkably level, as shown in a screen shot of the user interface shown in Figure 5. All told, we collected 359 line km of data, which exceeded our target of 200 line km. Certainly, we were very lucky with the weather (the time window was chosen with this in mind, but hurricanes can happen), but all our equipment operated well and we had excellent support from LUMCON and the Point Sur's crew.

PRELIMINARY RESULTS

Our first data quality assessment comes from computing spectrograms immediately on recovery of the instruments. Figure 6 shows an example from the cruise, chosen not to be the best example but rather from the Vulcan at the largest source–receiver offset (i.e. lowest CSEM signals) for the longest deployment (over both Green Canyon prospects). Although spectrograms are better for assessing noise, rather than CSEM signal, lines associated with the CSEM harmonics are visible. There is also a band of noise visible at the frequency of motion in the vessel towing the array, and general noise at low frequencies. All of these signals and noise diminish during turns between lines. The CSEM signal gets smaller because the signal from the more resistive seafloor is lost. During turns we were no longer using the winch to maintain the array altitude over the seafloor. It appears that hauling in exacerbates the transfer of ship motion to the instruments (winching in at the beginning of the turns is evident as vertical stripes in the spectrograms), but that during pay-out to lower the array back to the seafloor, motion, and thus noise, is diminished, possibly because the winch is acting as a heave compensator as a result of varying load.

If one looks at the signals associated with the CSEM signals carefully, one can see increased amplitudes during the tow over the (resistive) salt associated with Green Knoll, at about 09:00 on the 8th and also just before recovery.

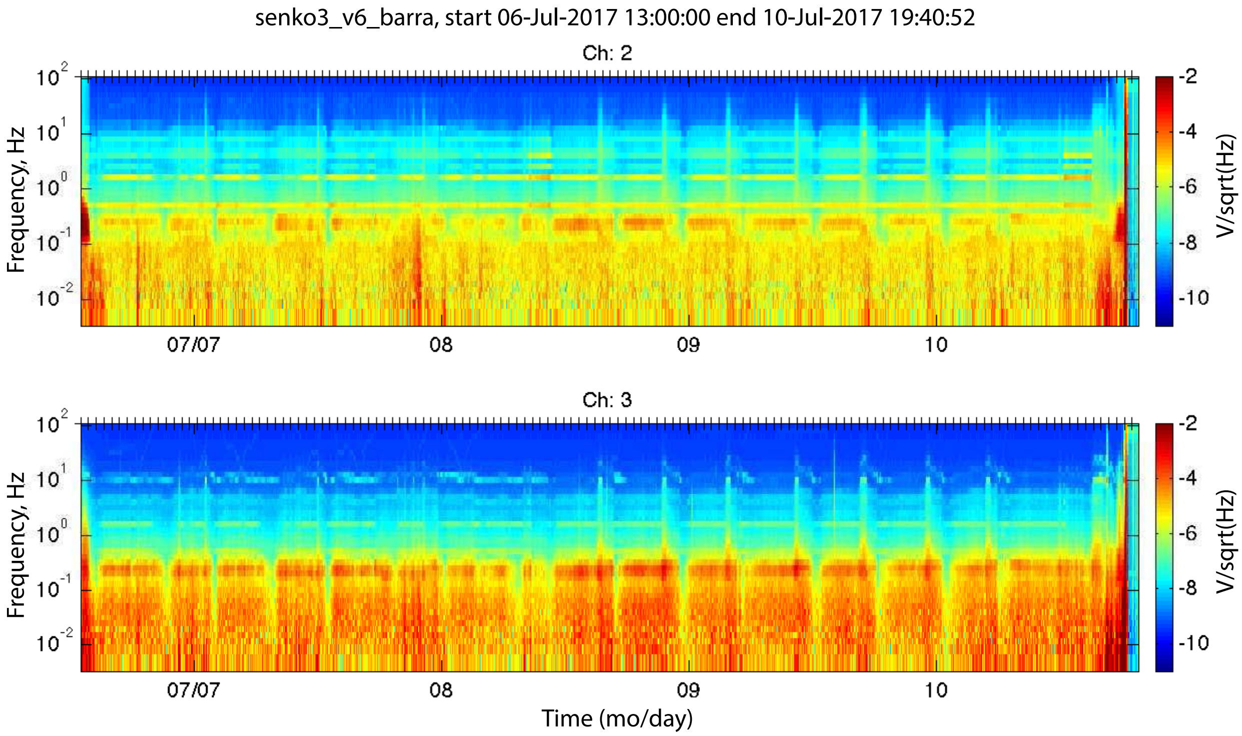

Figure 6. Spectrograms of the sixth Vulcan, at a source-receiver range of 1,500 m, on the Green Canyon tows. Ch 2 is the inline horizontal fields (Ey) and Ch 3 is the vertical fields (Ez). The horizontal lines at 0.5 Hz and odd harmonics are the CSEM signal. The horizontal band at about 0.25 Hz is wave motion transmitted from the ship, down the tow cable, and along the array. Both these signals are diminished during turns (about 4 per day, marked by peaks in high frequency noise)

The next step in data assessment would normally be to compute apparent resistivity pseudosections, but this requires processing the navigation data and merging it with the CSEM data in order to properly account for the experimental geometry in half-space forward calculations. This labor intensive process has been delayed because one of us is trying to submit their PhD thesis and deal with newborn twins (hint - this is not the PI). So, we have developed a quick-look metric by processing the phase of the CSEM signals, which will be proportional to seafloor resistivity for constant source-receiver offset (fixed by the tow cable), altitude (held approximately constant at 100 m), and pitch/roll/heading (which have less impact on phase than amplitude).

In Figures 7–9 we plot the phase of the CSEM responses at a frequency of 1.5 Hz (the third, and largest, harmonic of the 0.5 Hz transmitter waveform). The plots are divided into the three deployments of the CSEM system, and further divided by the 6 Vulcan receiver instruments, positioned at 557, 757, 957, 1157, 1357, and 1557 m source-receiver spacings (higher Vulcan numbers = larger spacings). We have not yet processed the acoustic transponder navigation data to derive accurate transmitter locations, so these plots have been made using an approximate navigation solution by taking the ship’s position as a function of time and using the fact that the center of the CSEM array is about 1

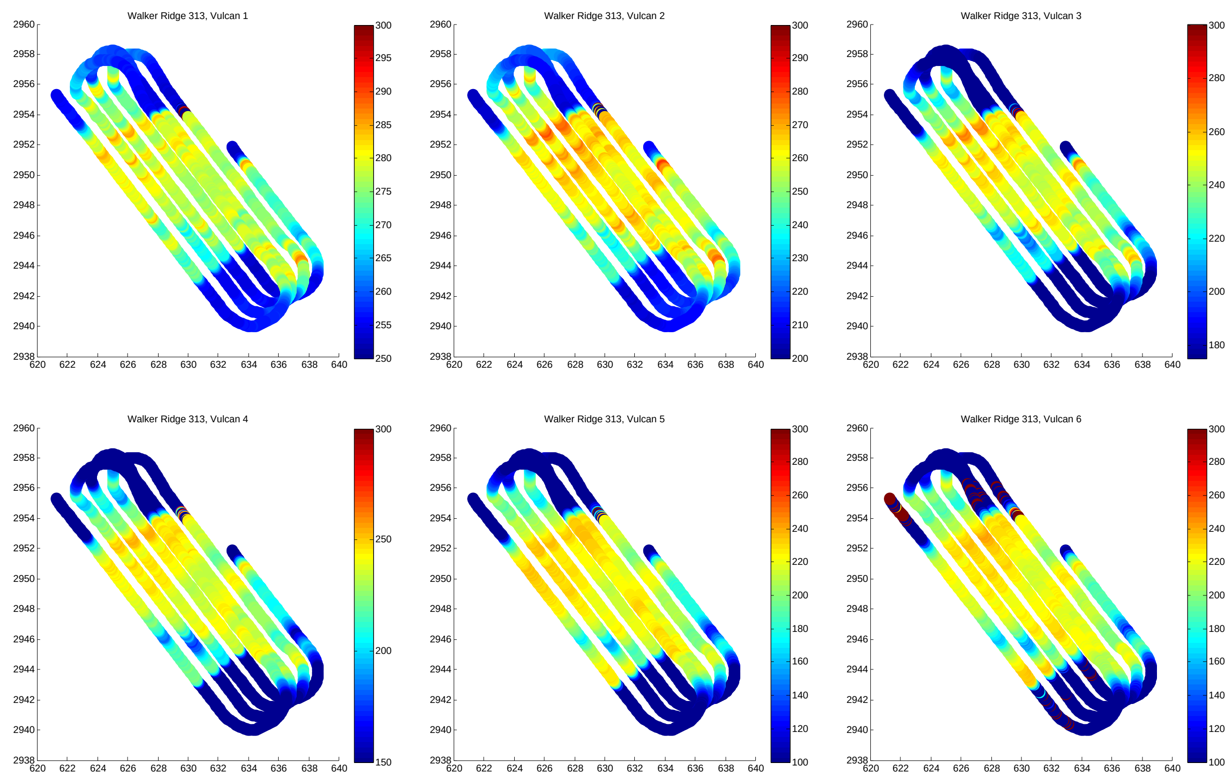

Figure 7. Phase (degrees) of CSEM fields at 1.5 Hz over WR 313, plotted in UTM coordinates (km). The sense of the phase is that red colors represent more resistive seafloor, and the blue colors represent turns at the end of the lines.

hour behind the ship at the normal survey speed of 1.5 knots. Although this is only approximate, it does provide a reasonable picture of the data coverage and quality.

The convention used here is phase lead, projected into positive numbers. The effect of this is that red colors (larger phase lead, smaller phase lag) represent more resistive seafloor, while blue colors (smaller lead, larger lag) represents higher conductivity, and in this case highlights the turns where the array was lifted from the seafloor and into midwater. The plotting scale is somewhat arbitrary in order to highlight the phase variations for each Vulcan, so one should not read too much into any Vulcan to Vulcan variations in color.

In Figure 7 (WR 313) we can see phase variations of around 50° that are highly coherent between lines. This is encouraging both from a data quality/reproducibility point of view, and an indication of our ability to get meaningful results using 2D inversion, which will be our next step.

At WR 100 (Figure 8) we see more complexity it the signals, and while some line-to-line consistency is evident, there is significant variation between lines. Most obviously, there is a very resistive area (red phases) in the north-east part of the survey, most likely associated with near-surface salt.

Figure 9 shows the two Green Canyon prospects, which again show good line to line coherence, and a pronounced resistive signature, especially at longer source-receiver offsets, associated with Green Knoll.

It should be noted that we have sixteen times the amount of data shown in these figures. Although we have plotted only one harmonic (1.5 Hz), we also have data at 0.5 Hz, 3.5 Hz, and 7.5 Hz, with signals above the noise floor on all Vulcans, as well as vertical electric field components for all Vulcans and all frequencies. Finally, we have amplitude, as well as phase, for every measurement.

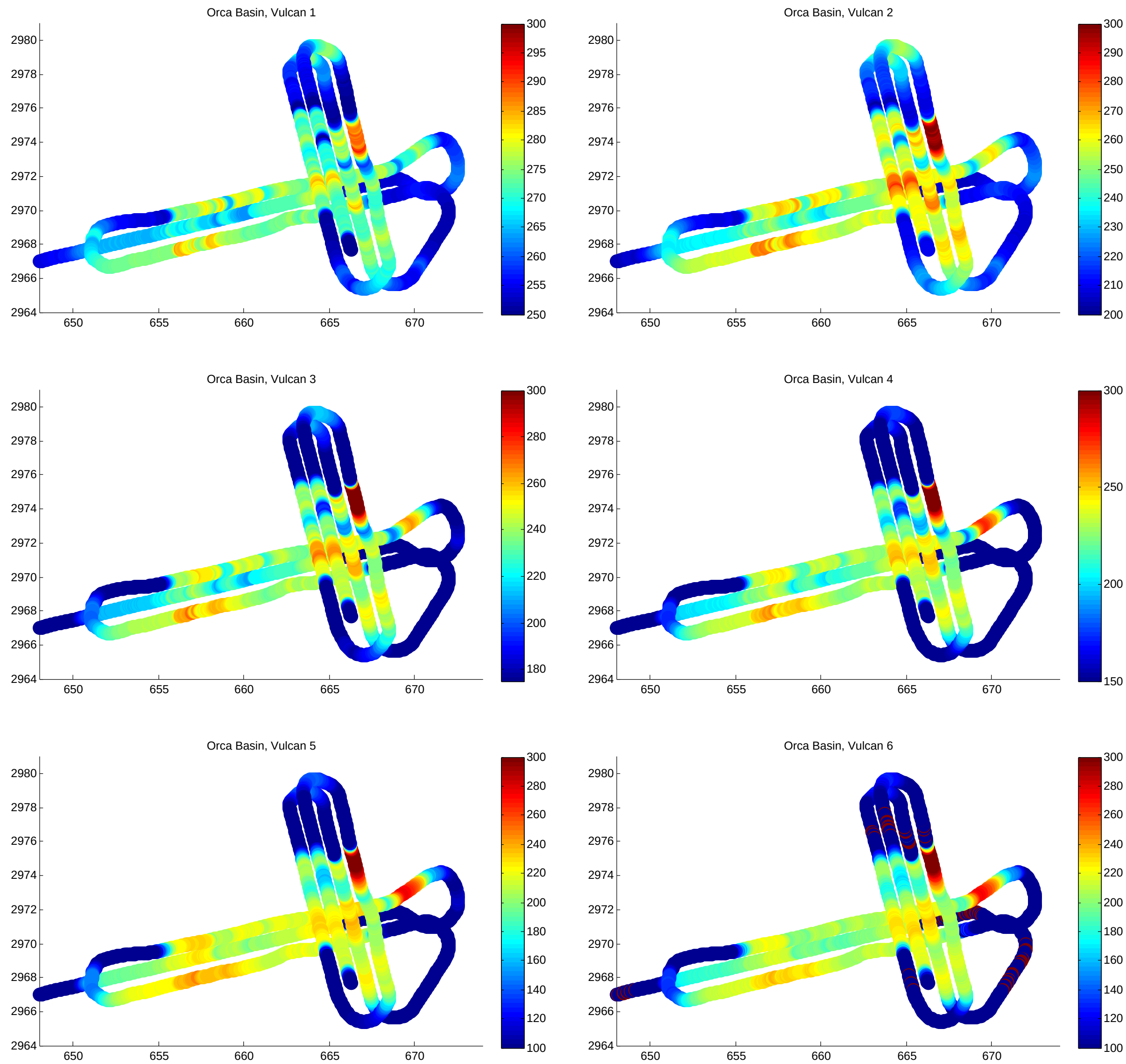

Figure 7. Phase (degrees) of CSEM fields at 1.5 Hz over WR 100 (Orca Basin), plotted in UTM coordinates (km). The sense of the phase is that red colors represent more resistive seafloor, and the blue colors represent turns at the end of the lines.

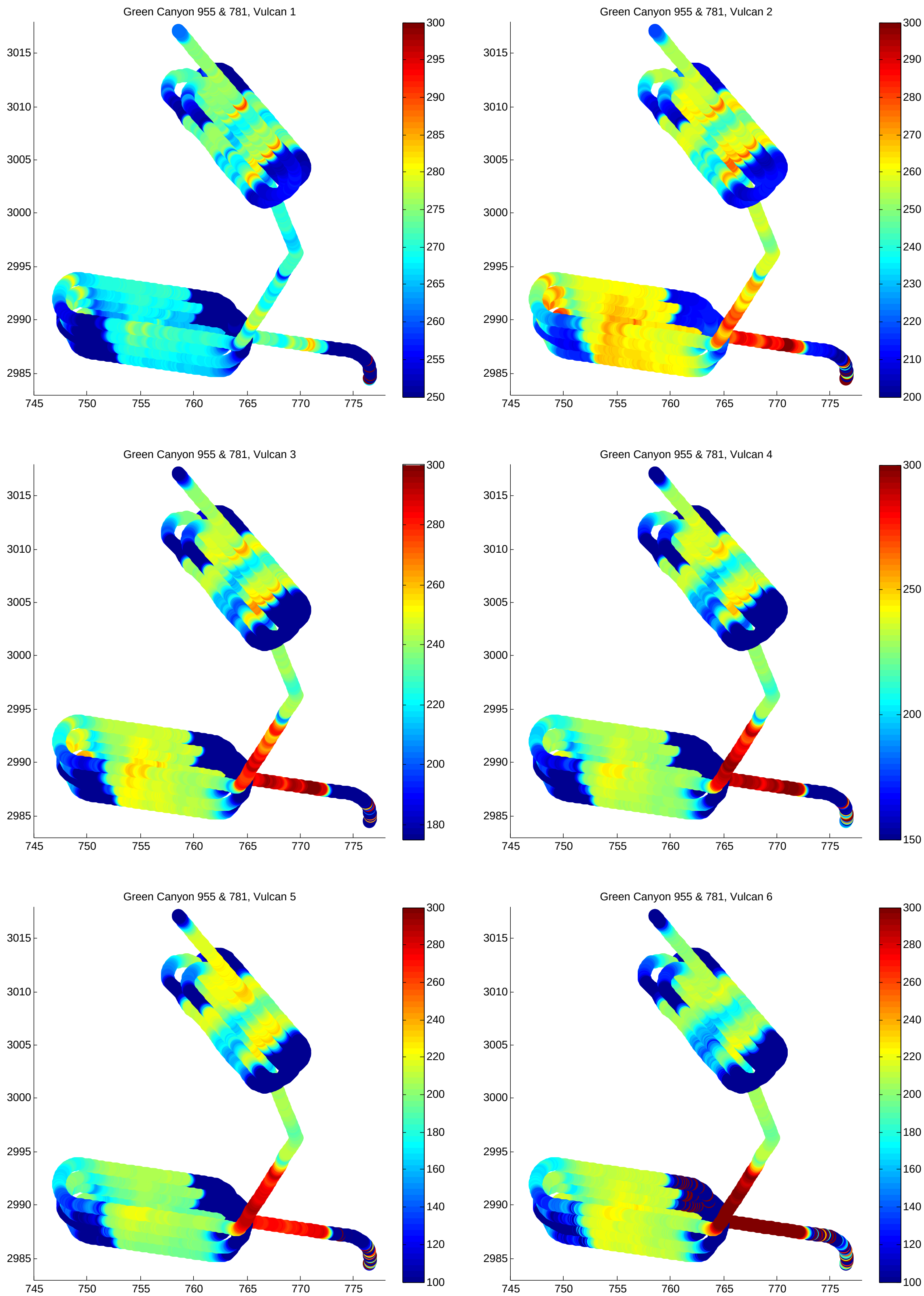

Figure 9. Phase (degrees) of CSEM fields at 1.5 Hz over GC 781 (Mad Dog, to the north) and GC 955 (to the south), plotted in UTM coordinates (km). The sense of the phase is that red colors represent more resistive seafloor, and the blue colors represent turns at the end of the lines. The red colors to the NE of GC 955 is the resistive response of salt in Green Knoll.

Appendix A
Daily Log

All times are local.

28 June	
10:00	Arrive LUMCON and start loading.
20:00	SUESI tests OK on deck.
29 June	
08:00	Push off.
30 June	
03:20	Arrive on station WR 313 and deploy transponder net.
04:45	Transponder 4 in water. Transit to deployment run-in.
06:00	On station.
06:20	Array going in.
09:10	SUESI tests OK.
09:22	SUESI in water.
11:35	SUESI at flying altitude.
1 July	
	Towing WR 313.
2 July	
10:44	Crewmember accidentally pushed emergency stop. Restart SUESI.
18:15	End of survey. Hauling in.
20:10	SUESI on deck.
22:00	Array on board. Transit to transponder recovery.
23:15	Start transponder navigation and recovery.
3 July	
04:20	Transponders recovered, transit to WR 100.
06:46	Deploy transponders.
07:30	Transponder 4 in water. Transit to deployment run-in.
09:00	Array going in.
12:00	SUESI in water.
4 July	
	Towing WR 100.
5 July	
10:00	End of survey Hauling in.
12:30	SUESI on deck after break for lunch.
14:00	Array on board.
20:00	Transit to Green Canyon.
6 July	
01:20	Deploy transponders on GC 955.
03:26	Deploy transponders on GC 781.
08:20	SUESI in water GC 781.
7 July	

	Survey GC 781.
8 July	
9 July	
10 July	
10:00	Haul in for final recovery.
12:00	SUESI on deck. Break for lunch.
13:25	Array on board.
14:05	Start transponder navigation and recovery.
23:45	Transponder recovery complete. Heading to Cocodrie.
11 July	
13:00	Tie up and demob.
12 July	
11:00	Science party leaves.

Appendix B
SUESI synchs

These are the times that SUESI's onboard clock is synchronized to GPS time, and the second counters in SUESI's data stream start at these times.

June 30 2017	181:15:23:00	
July 2 2017	183:10:51:00	(accidental trip of Elgar).
July 3 2017	184:17:04:00	
July 6 2017	187:13:26:00	

Appendix C
Vulcan array dimensions

2017 Gulf of Mexico DoE SUESI/Vulcan towed system arrangement

Spooled on blue InterOcean winch and updated 12-14-16, CA

0	meters	SUESI 1	SUESI 1 Altimeter Valeport Benthos Serial Communication and timing 2015 in ext. pressure case

70 ft lead-in rope used on 100m long antenna on winch

10.0	meters	end of 10 m x 1.46"near antenna
15.0	meters	center of near antenna copper electrode (10m of 1/2" copper tube)
65.0	**meters**	**DIPOLE CENTER**
110.0	meters	end of 100 m 1.46" antenna on 10n
115.0	meters	center of long antenna copper electrode (10m of 1/2" copper tube)
120.0	meters	End of copper on long (110m) antenna

VMG-4-FS

125 meters Falmat 4 conductor RS-422 cable (spiral wrapped on 110m SUESI antenna)

VMG-4-FS

Tested Dec 2016:
pin 1 - 6.6 Ω
pin 2 - 6.6 Ω
pin 3 - 6.6 Ω
pin 4 - 6.6 Ω

121.8	meters	LBL ATET 2013 Antenna Tail End Telemetry (center of harness)	Acoustics, LBL — transmit X.X kHz, receive X.X kHz Optical isolation and serial communication 2012. Address=1 Termination required RS422 Serial communication 2013 Address=2 Paroscientific Depth Gauge to SDL 2013 Compass to SDL 2013

VMG-4-FS VMG-4-MP

VMG-4-FS VMG-4-MP

chinese finger
15/32" ss quick link
3.5 m 1/4" Amsteel Blue Pair SN1310
15/32" ss quick link
chinese finger

VMG-4-FS

500 meters Falmat 4 conductor RS-422 cable SN 500M-1302

VMG-4-FS

Tested December 2016:
pin1 - 24.0Ω
pin 2 - 25.5Ω
pin 3 - 25.5Ω
pin 4 - 26.0Ω

622.0	meters	Vulcan Data Logger System (center of Y-axis dipole)	8 channel data logger ch.1 E-field, X, wing, horizontal ch.2 E-field, Y, stinger, horizontal ch.3 E-field, Y, fin, vertical ch.4 Accelerometer, X, wing, horizontal ch.5 Accelerometer, Y, stinger, horizontal ch.6 Accelerometer, Y, fin, vertical Serial communication and timing 2015 Paroscientific Depth Gauge to SDL 2015 Compass to SDL 2015	dipole 1 meter 2 meter 1 meter Address=3

VMG-4-MP
VMG-4-FS
VMG-4-MP

chinese finger
15/32" ss quick link
3.5 m 1/4" Amsteel Blue Pair SN 0826
15/32" ss quick link
chinese finger

VMG-4-FS

200 meters Falmat 4 conductor RS-422 cable SN 200M-1301

VMG-4-FS

Tested December 2016:
pin1 - 9.2Ω pin 2 - 9.8Ω
pin 3 - 9.5Ω pin 4 - 9.6Ω

822.0	meters	Vulcan Data Logger System (center of Y-axis dipole)	8 channel data logger ch.1 E-field, X, wing, horizontal ch.2 E-field, Y, stinger, horizontal ch.3 E-field, Y, fin, vertical ch.4 Accelerometer, X, wing, horizontal ch.5 Accelerometer, Y, stinger, horizontal ch.6 Accelerometer, Y, fin, vertical Serial communication and timing 2015 Paroscientific Depth Gauge to SDL 2015 Compass to SDL 2015	dipole 1 meter 2 meter 1 meter Address=4

VMG-4-MP
VMG-4-FS
VMG-4-MP

chinese finger
15/32" ss quick link
3.5 m 1/4" Amsteel Blue Pair SN 1307
15/32" ss quick link
chinese finger

VMG-4-FS

200 meters Falmat 4 conductor RS-422 cable SN 200M-1302

VMG-4-FS

Tested December 2016:
pin1- 9.7Ω pin 2- 10.1Ω
pin 3- 10.2Ω pin 4- 10.0Ω

1022.0	meters	Vulcan Data Logger System (center of Y-axis dipole)	8 channel data logger ch.1 E-field, X, wing, horizontal ch.2 E-field, Y, stinger, horizontal ch.3 E-field, Y, fin, vertical ch.4 Accelerometer, X, wing, horizontal ch.5 Accelerometer, Y, stinger, horizontal ch.6 Accelerometer, Y, fin, vertical Serial communication and timing 2015 Paroscientific Depth Gauge to SDL 2015 Compass to SDL 2015	dipole 1 meter 2 meter 1 meter Address=5

VMG-4-MP
VMG-4-FS
VMG-4-MP

chinese finger
15/32" ss quick link
3.5 m 1/4" Amsteel Blue Pair SN 1303
15/32" ss quick link
chinese finger

VMG-4-FS

200 meters Falmat 4 conductor RS-422 cable SN 200M-1305

Tested December 2016:
pin1- 9.8Ω pin 2- 10.4Ω
pin 3- 10.2Ω pin 4- 10.2Ω

Continued on next page...

Array continued...