# Sub-Audio Magnetics (SAM) – Ground-based and HeliSAM FLEM Trials at the Forrestania EM Test Range


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## SUMMARY

Sub-Audio Magnetics (SAM) is a rapid sampling survey technique capable of simultaneous acquisition of data related to the magnetic and electrical properties of the earth. SAM surveys have historically been used for the acquisition of high resolution magnetometric resistivity (MMR) and total magnetic intensity (TMI) data. Recent developments in SAM receiver instrumentation and signal processing have now made the extraction of electromagnetic (EM) data possible due to the exceptionally high data quality now being achieved. SAM data are acquired from a moving platform which makes the technique amenable to applications ranging from ultra-detailed, man-carried or vehicle-towed ground surveys to helicopter-borne acquisition.

This paper describes ground-based and helicopter-borne SAM Fixed Loop EM (FLEM) trials conducted over the Forrestania EM Test Range in Western Australia and compares the results with conventionally-acquired (stationary) SAMSON surveys. The trials have demonstrated that SAM FLEM surveys are able to detect high conductance ore bodies at significant depth from a moving survey platform. In either ground or airborne acquisition mode, the SAM technique is shown to be a significant advance toward reducing the cost of deep exploration for high conductance orebodies.



**Key words:** SAM, SAMSON, HeliSAM, Forrestania, FLEM.


## INTRODUCTION

Airborne EM (AEM) surveys are typically conducted using either fixed wing or helicopter platforms which carry or tow an airborne transmitter. They are used extensively for regional scale exploration. They are characterised by continuous acquisition, require no ground access and can survey large areas very cost-effectively. However, the depth of exploration achievable from airborne systems is limited by low transmitter power, short stacking periods and the requirement to use high transmit frequencies.

Ground-based EM systems are capable of good depth penetration as they can use large ground loops, high-powered transmitters and low transmit frequencies. They typically use vector sensors which require levelling and orientation and readings are taken and the sensors must be kept very stable during measurement. However, conventional ground level EM surveys have several drawbacks. To achieve adequate S/N levels at low frequencies, stationary readings are necessary. They are consequently slow and expensive to deploy. Budget constraints usually dictate both wide line spacing and station intervals and consequently, EM profiles are generally spatially under-sampled.

As exploration ventures deeper and budgets tighten, the industry will require techniques capable of significantly improving the depth penetration and cost-effectiveness of ground EM surveys. Sub-Audio Magnetics (SAM) is capable of continuous acquisition of high quality EM data as it uses a total B-field, Cs vapour sensor which doesn't require any levelling or orientation whilst taking a measurement. This Paper describes trials of Sub-Audio Magnetics (SAM) and HeliSAM Fixed Loop EM surveys conducted at the Forrestania EM Test Range.

The primary objective of the trials was to provide Proof-of-Concept for an EM survey technique capable of:

- Rapid data acquisition
- High spatial resolution
- Reduced cost of deployment, and
- Deeper exploration than conventional EM techniques

To meet the above requirements it was necessary to achieve:

- High signal-to-noise ratios
- From a moving platform
- Using a Transmitter source capable of generating high dipole moments.

The trials demonstrated that SAM FLEM can meet all the above objectives at Forrestania. In either ground or airborne acquisition mode, the SAM technique has been proven as a cost-effective deep search EM tool for the detection of high conductance orebodies.

## METHODS

Sub-Audio Magnetics is described in an International Patent by Cattach et al (1991) and in a subsequent concept paper and PhD Thesis by Cattach et al (1993) and Cattach (1996) respectively. The SAM method requires a time-varying electric current to be artificially applied to the ground. This is achieved with a geophysical transmitter producing a broadband (low frequency square wave) signal that is introduced into the ground either through distant electrodes as for conventional gradient array ER or MMR surveys, or induced into the ground through a loop as for conventional EM surveys. In either case, the electromagnetic signal from the time-varying current induced in the ground is then measured simultaneously with the Earth’s spatially varying magnetic field using a rapid sampling, total B-field magnetometer.

The combined signals are sampled at a fast-enough rate to adequately measure the full spectrum of the artificial waveform. The signals from the two magnetic sources are spectrally distinct and with the aid of digital signal processing techniques, they may be separated and processed independently. The benefit of having this ability is the efficient, concurrent, high definition mapping of parameters related to the electrical characteristics of the ground as well as the spatially varying magnetic field.

### SAM Instrumentation

*Receiver*

The instrument used for all surveys was a Gap Geophysics TM-7 SAM Receiver, coupled with a Geometrics 8-822 Cs Vapour sensor. (see Figure 1). The TM-7 is a high performance total field magnetometer, capable of sampling the earth’s magnetic field at up to 9600 samples per second from up to four sensors. It is precisely synchronised to GPS timing strobes and can acquire information from a range of inputs including differential GPS, accelerometers and altimeters.

The TM-7 is a very versatile system which may be either hand-carried or deployed from a range of survey platforms which include towed arrays, helicopter and unmanned aerial vehicles (UAV). The control software includes real-time navigation and quality control.


**Figure 1 The Gap Geophysics TM-7 SAM Receiver. The TM-7 is controlled by software running on a handheld computer.**

*Transmitter*

The transmitter used for the trials was a Gap GeoPak HPTX-70 high powered transmitter (shown in Figure 2). The HPTX-70 is capable of up to 70kW output power and currents of up to 350A.

The HPTX-70 features internal GPS synchronisation or can be timed with an external controller.


**Figure 2 The Gap GeoPak HPTX-70 High Power Geophysical transmitter.**

**Survey Acquisition Modes**

Three survey acquisition modes were employed and compared for the trials. These included:

1) SAMSON Stationary acquisition, provides highest precision measurements
2) SAM Dynamic ground-based acquisition, provides highest spatial definition
3) HeliSAM Helicopter-borne acquisition, provides most cost-effective acquisition for larger survey areas.

In all acquisition modes, the acquired EM parameter is described as Total Field EM (TFEM) as it represents a pseudo-component oriented in the direction of the earth's total magnetic field. As per conventional time domain EM, it is normalised by current and has the units pT/A.

SAMSON is the most sensitive mode of acquisition and was used to provide high-quality control data for the trials. The sensor is mounted on a tripod (see Fugure 3), kept stationary and at a distance (10-20m) from the receiver for the duration of the recording.

SAMSON surveys are necessary where very low transmit frequencies are required. Being a scalar measurement, the sensor requires no levelling or orientation. It is quick to deploy and relatively immune to wind and vibration.

Station occupation times depend on the transmit frequency and are typically 3-5 minutes per station. A single SAMSON system will acquire 40-50 stations per day.

**Figure 3 SAMSON survey showing the Cs vapor sensor mounted on a fibreglass tripod.**

SAM is a ground-based survey mode which involves dynamic (non-stop) acquisition. The Cs vapour sensor and TM-7 are mounted on non-metallic frames and kept separated by a distance of 4-5m to minimize interference from the acquisition system (see Figure 4).

Continuous acquisition at walking speed is possible with transmit frequencies of 3.125-15Hz. Towed operations are possible with frequencies as low as 1Hz in stable terrain.

Production rates of 15-20 km per day are achievable with sample rates of 0.5m for TMI and 5.0m for EM. Survey speed is dependent on Tx frequency, sensor elevation and magnetic noise.

**Figure 4 SAM hand-carried survey mode showing the sensor carrier and TM-7 operator.**

HeliSAM refers to airborne acquisition using either a helicopter or helicopter-style UAV (still in development). The Cs sensor, GPS unit and laser altimeter are mounted in a towed "bird" as shown in Figure 5. The bird is towed with a sling to mitigate interference from the helicopter. No compensation is required for aircraft pitch, roll or yaw.

HeliSAM is used for large scale SAM MMR and FLEM surveys and typically uses Tx frequencies 3.125-15Hz. Achievable sample intervals are nominally 5.0m for TMI; 20m for MMR and TFEM (depending. on Tx frequency).

**Figure 5 HeliSAM system showing the helicopter and towed "bird". A prototype UAV system is currently still in development.**

## LOCATION

### Forrestania EM Test Range

The Forrestania EM Test Range is situated approximately 85 km by road/track east of Hyden and approximately 155 km by road/track SSE of Southern Cross (see Figure 6). It has been used for trialling various electromagnetic methods (surface, airborne and downhole techniques).

The Test Range is managed by Southern Geoscience Consultants (2014) who describe the targets as "two, discrete and varying bedrock conductors defined during previous geophysical exploration completed on behalf of Image Resources NL. The two bedrock conductors defined and drilled by Image Resources successfully tested these targets, intersecting barren, semi-massive to massive sulphides (po-rich)".

The western conductor (IR2) is of limited areal size (<75x75m), shallow depth <100m, high conductance >7000S and dips northward ~30-40 degrees. This conductor is strongly defined by surface and downhole TEM and has been detected by airborne EM systems.

The eastern conductor (IR4) is extensive in strike/plunge extent (~500-600m+) and reasonably well constrained in depth extent (~100-150m). The conductive source is situated at considerable depth ~300-325m (western side) to ~400m+ (eastern side), is highly conductive ~5000-10000S and dips northward ~30-40 degrees. IR4 is a more challenging conductive target for surface TEM methods with smaller transmitter loops and hasn't been detected by airborne EM.


**Figure 6 Map showing the location of the Forrestania EM Test Range (from Southern Geoscience Consultants, 2014).**

## OBJECTIVES

The main objective in conducting the Forrestania SAM trials was to determine if SAM FLEM technologies could be used for cost-effective, deep penetration, rapid acquisition surveying for the detection of high conductance orebodies. The Forrestania SAM trials were conducted in two Phases. The execution of the second phase survey was contingent on the success of the Phase 1 trials.

Phase 1 Objectives:

- To determine if IR2 and/or IR4 could be detected with dynamically-acquired ground-based SAM FLEM surveys
- To compare data quality, production rates and cost-effectiveness with a high-quality, conventionally-acquired (stationary) data set acquired as SAMSON.

Phase 2 Objectives:

- To determine if IR2 and/or IR4 could be detected using HeliSAM acquisition
- To determine if Tx frequencies as low as 2Hz would be possible given the safety constraints on survey speed for low elevation helicopter surveys.

➢ The Phase 1 SAM FLEM surveys were conducted successfully in February 2014.
➢ The Phase 2 HeliSAM trial was flown successfully in September 2017.

## PHASE 1: SAMSON AND SAM FLEM TRIALS

### Field Procedure

*Transmitter Setup*

Two large EM loops named L1 and L2 were designed to optimally couple with conductors IR2 and IR4 respectively. Figure 7 shows the location of the loops with respect to the location of the modelled plates for IR2 and IR4. The loops were each 1000m x 800m in size (3.6km in total length) and consisted of one turn of 35 $mm^2$ cable. The HPTX-70 transmitter achieved 150A for both loops.

The SAMSON profiles were designed to cover the main anomalies as shown in Figure 7. SAMSON stations were acquired at 50m intervals along lines spaced 100m apart. A low transmit frequency of 0.125Hz was used to provide control data for the trials.

Because of the high speed of acquisition possible with SAM, the survey lines were extended beyond the area covered by the SAMSON stations. Infill lines were also acquired. Data were effectively sampled at 5m stations along lines spaced 50m apart. The transmit frequency used for the trials was 3.125Hz, the lowest frequency typically used for continuous acquisition at ground level.

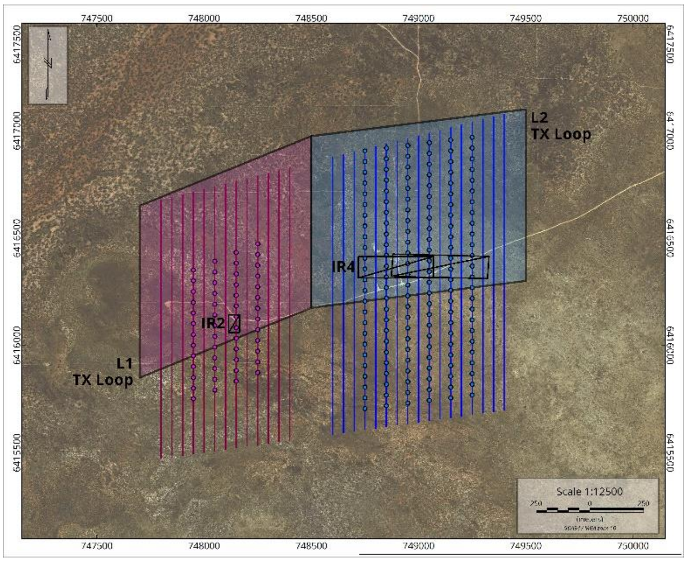


**Figure 7 Diagram showing the locations of Loops L1 and L2, the planned SAMSON and SAM survey Lines and outlines of the conductors IR2 and IR4.**

## RESULTS

Initial processing and data reduction were performed using Gap Geophysics MagPi software. The data were then imported into EMIT's Maxwell software for analysis and display.

*IR2 SAMSON*

IR2 SAMSON Profile 748050E is shown with a colour image of IR2 TFEM Channel 20 in Figure 8. The SAMSON surveys detected IR2 very easily. The SAMSON data were of very high quality with almost perfect repeatability (profiles are showing error bars). Close inspection of the decays revealed resolution of better than 0.005pT/A at late time. It is interesting to note that, because of the limited size of IR2, only one SAMSON line actually defined the anomaly well. The anomaly could feasibly have been undetected if a line spacing of 200m had been used.

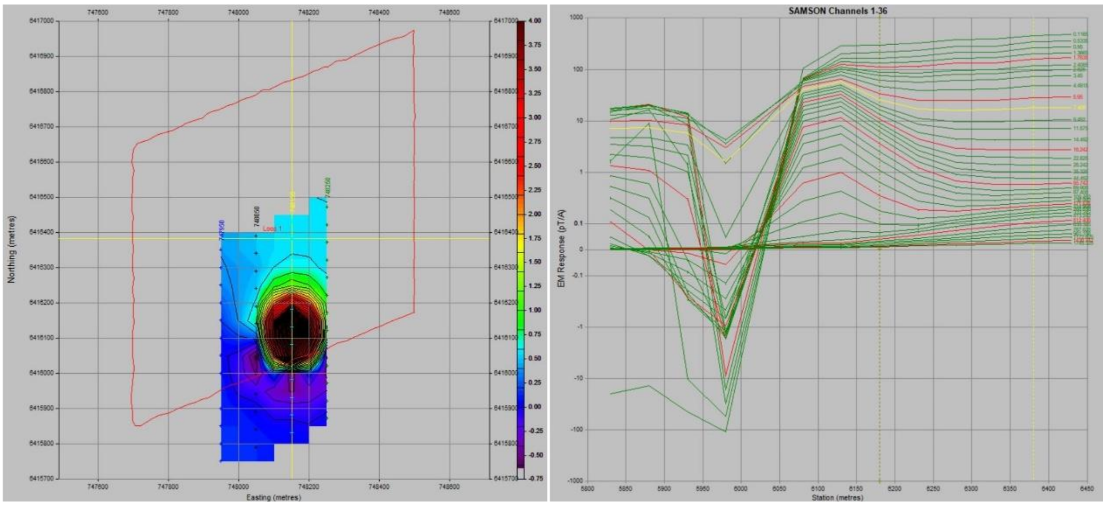

**Figure 8 IR2 SAMSON: Profile from Line 748050E (CH10-36) and colour image of CH20 (55 ms).**

*IR2 SAM*

IR2 SAM Profile 748050E is shown with a colour image of IR2 TFEM Channel 18 in Figure 9. The SAM survey also detected IR2 very easily. An obvious difference between SAMSON and SAM is that the SAM profiles are much more continuous due to the finer sample interval (5m), thus enabling better resolution of inflection points for modelling purposes. Being a strong conductor, there is still plenty of signal at the end of the OFF time at the frequency used (3.125Hz). The SAMSON data had more time to decay with a 2s OFF time. The closer line spacing of 50m provided better definition of the anomaly with at least three lines crossing it.

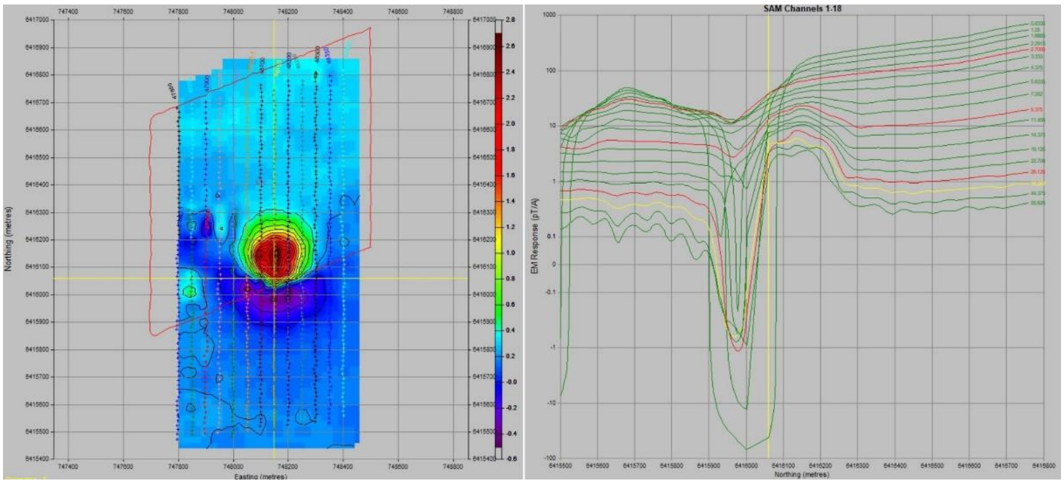


**Figure 9 IR2 SAM: Profile from Line 748050E (CH1-18) and colour image of CH18 (55 ms).**

*IR4 SAMSON*

IR4 SAMSON Profile 749050E is shown with a colour image of IR4 TFEM Channel 20 in Figure 10. The SAMSON surveys detected IR4 very easily as a very broad dipolar anomaly. Again, the SAMSON data were of very high quality with almost perfect repeatability (profiles are showing error bars). Late time noise levels are difficult to determine due to the very strong response. The wavelength of the anomaly spans a distance of over 1.4 km north-south and has not been completely defined in the east-west direction.

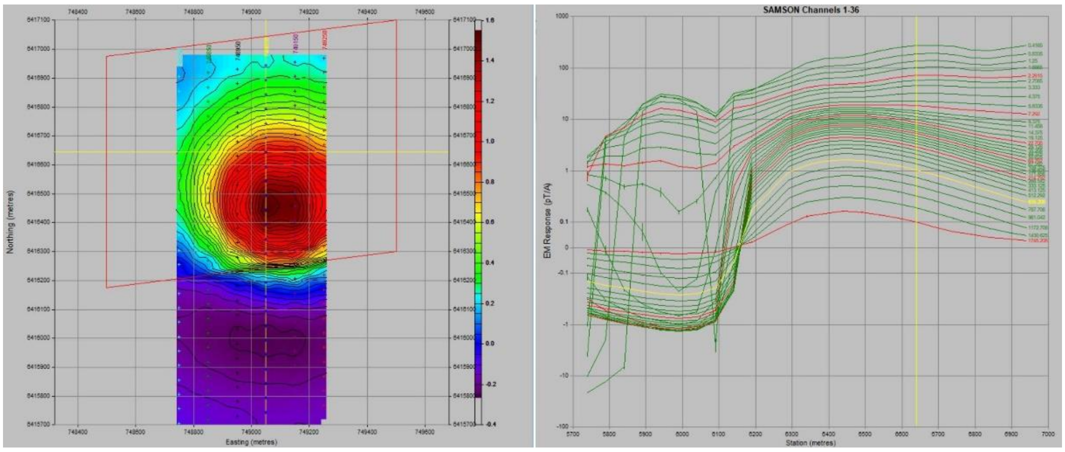


**Figure 10 IR4 SAMSON Profile from Line 749050 (CH1-36) and colour image of CH20 (55ms).**

*IR4 SAM*

IR4 SAM Profile 749050E is shown with a colour image of TFEM Channel 18 in Figure 11. The SAM survey again detected IR4 very easily as a very broad dipolar anomaly. As seen on IR2, the SAM data are more continuous with more noise evident on the late channels. The survey has better defined the size and shape of the anomaly as a result of having better coverage. The 50m line spacing was found to be overkill in this case, given the depth of the source and the wavelength of the anomaly.

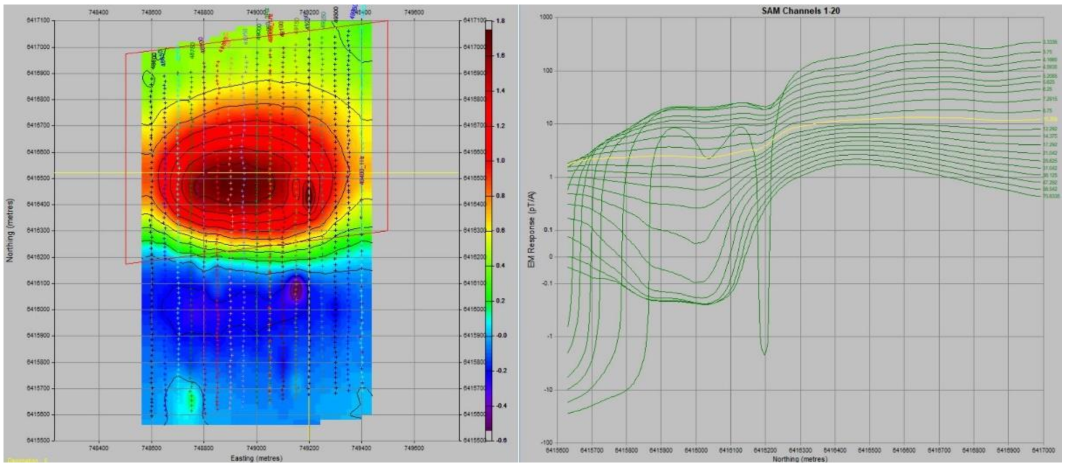


**Figure 11 IR4 SAM Profile from Line 749050 (CH1-18) and colour image of CH18.**

**PHASE 2: LOW FREQUENCY HELISAM FLEM TRIALS**

For the HeliSAM trial, adjustments were made to the acquisition system and flying specifications to enable the aircraft to fly at a slower speed. To distinguish this mode of surveying from standard HeliSAM, it has been called LF (Low Frequency) HeliSAM. The survey was flown with a nominal bird height of 35m.

A third Tx Loop (L3) was designed to optimally couple with IR4 and sub-optimally couple with IR2. L3 was 1200m x 800m in size and consisted of a single turn. The location of L3 with respect to the conductors as well as Loops L1 and L2 is shown in **Figure** 2.

Various transmit frequencies were tested to determine the lowest practical transmit frequency possible. A frequency of 2.083 Hz was used for the trial. A current of 150A was achieved for the survey.

The survey lines were extended to the north and south of the SAM and SAMSON lines with a view to determining signals levels at a distance from the loop. The total line length was 3km. Twenty lines were surveyed for a total of 60km of acquisition. Acquisition time was approximately 90 mins.

A colour image of the LF HeliSAM TFEM Channel 15 is shown in Figure 13. As can be seen from the image, the survey succeeded in detecting the responses from both IR2 and IR4.

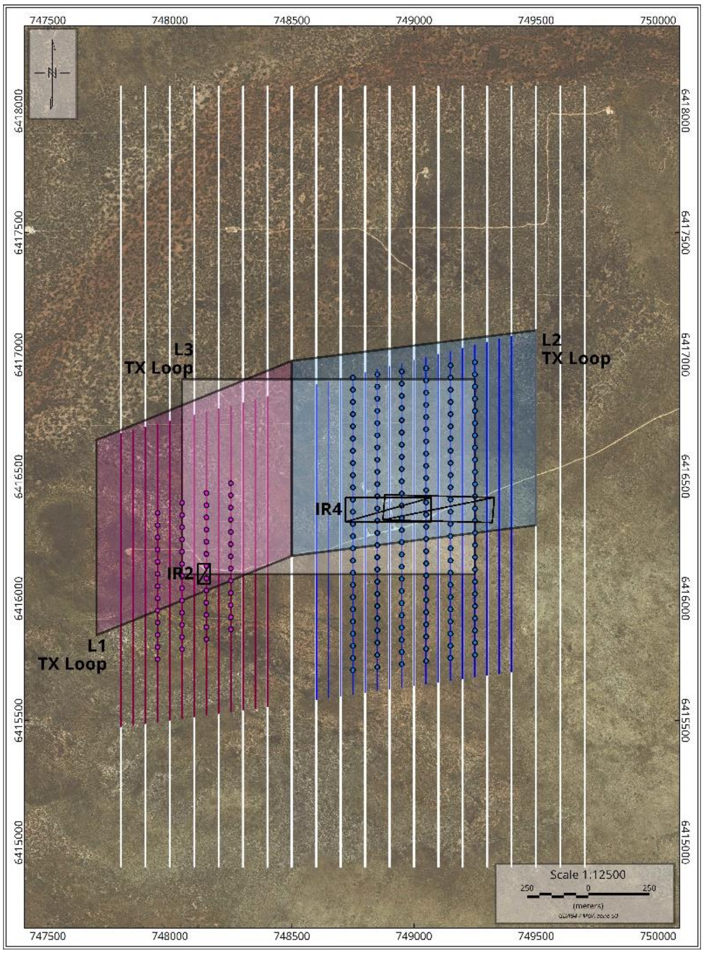


**Figure 12 HeliSAM survey layout showing Loop and survey lines relative to the SAM and SAMSON loops.**

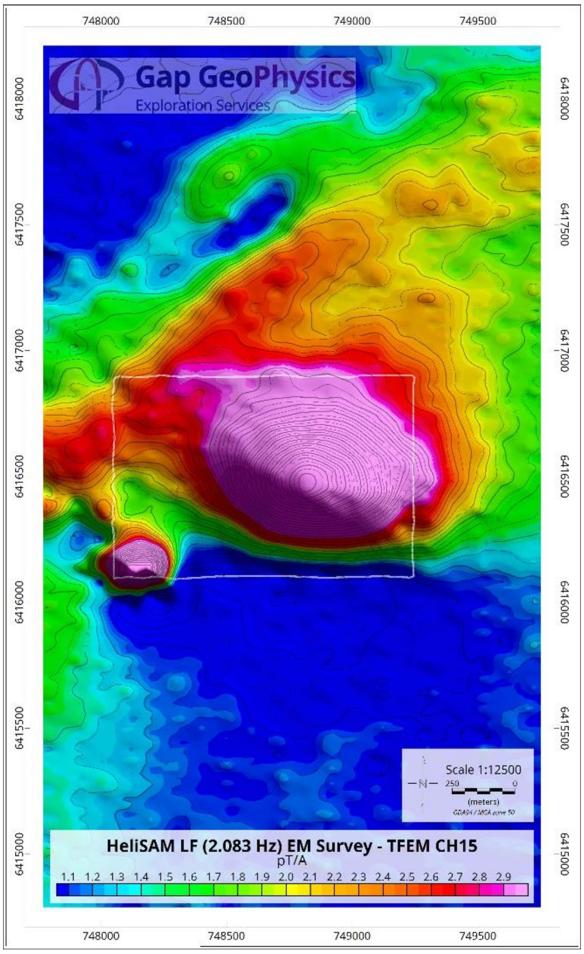


**Figure 13 Colour image of LF HeliSAM CH15 showing the location of Loop L3.**

**CONCLUSIONS**

The trials at Forrestania provided an excellent insight into the pros and cons of each of the three different survey approaches. Table 1 summarises the survey specifications and production performance for each survey technique.

1. The SAMSON surveys were characterised by exceptionally high precision, high quality late-time data, providing an excellent control data set. Both IR2 an IR4 were clearly detected. The low transmit frequency of 0.125 Hz enabled characterisation of the decays for modelling purposes.

2. The SAM FLEM surveys also readily detected both conductors. The SAM profiles display much higher spatial definition than the SAMSON data and are likely to be more diagnostic in determining the precise locations of maxima, minima and inflection points in the profiles. There is ten times the data density along line in the SAM data than in SAMSON and given the speed of acquisition, closer line spacing may also contribute to much higher definition data. The higher definition data achievable with SAM enables utilisation of one or two dimensional filters. These largely compensate for the minimal sacking possible compared to stationary measurements. For SAM frequencies, data quality can therefore be very high.

3. The LF HeliSAM survey was also very successful in mapping both IR2 and IR4. Data quality was high. The speed of acquisition enabled a much larger area to be cost-effectively surveyed than what would be possible at ground level.

**Table 1 Survey Summary**

| | SAMSON | SAM | HeliSAM |
|---|---|---|---|
| **Mode** | Stationary | Dynamic | Dynamic |
| **Tx Frequency** | 0.125 Hz | 3.125 Hz | 2.083Hz |
| **Parameters** | TFEM, TMI | TFEM, TMI | TFEM, TMI |
| **Line Spacing** | 100m | 50m | 100m |
| **Station Spacing** | 50m | ~5m | ~25m |
| **Acq. Time** | 80 half periods | 40 half periods | 8 half periods |
| **Acq. Speed** | 0.4 km /hour (8 stations) | 4 km / hour (600 stations | 60 km / hour (3000 stations) |
| **No Stations** | 48 | 3120 | 2400 |
| **Distance** | 2.2 km | 15.6 km | 60 |
| **Acq Time.** | 6 hours | 4 hours | 1.5 hours |

The Forrestania Trials have demonstrated that dynamic mode acquisition is now viable with SAM FLEM surveys. This is partly possible due to the currents achievable with the high-power transmitters as the high signal means that minimal stacking is required. The main restriction is likely to be in areas of very conductive cover where frequencies lower than those possible with SAM are required.

Modelling of the LF HeliSAM data was conducted for the IR4 conductor:

- This resulted in a robust fit which also matches well with previous SQUID ground EM programme results.
- It has been determined from modelling that with optimal loop coupling, the IR4 conductor would be defined/delineated at ~550m depth and most likely to ~600m depth given the signal-to-noise levels achieved.
- The LF HELISAM modelling highlighted the IR4 conductive source at being ~6000-6500S (at the modelled time frame) and consistent with geometry as per previous surveying/model results.
- It has also been determined from modelling that, given a less than optimal loop position/configuration (average coupling), the IR4 conductor would be defined to ~350-550m pending coupling variation. Overall, a realistic estimate would be ~450m depth.

In summary, all of the three techniques will have their advantages and disadvantages, depending on geology but also on survey size, ground access and survey logistics.

- SAMSON is is a very effective deep penetration technique where stationary acquisition is required for surveys needing very low Tx frequencies due to the presence of conductive cover.
- SAM FLEM has the benefit of very rapid acquisition and high spatial definition and is cost-effective, deep exploration for high conductance orebodies. It’s application is restricted to Tx frequencies above 3Hz.
- HeliSAM has been shown to be a viable, rapid acquisition, deep penetration technique which is suited to systematic surveys over larger areas. It is an effective tool which bridges the gap between airborne EM and ground techniques by combining the power of ground Tx systems with the efficiency of airborne acquisition.

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