Cave Telephones Enter the 21st Century

***Stuart France** presents recent developments of the single-wire cave telephone system which add modern features and fix the operational issues encountered with earlier versions from both cave rescue and design viewpoints.*

I built a batch of single-wire Michie phones in 1988 for the cave rescue teams in South Wales after stumbling upon this 1974 circuit in a New Zealand caving journal in the SWCC library. These field telephones worked so well for cave rescue purposes, with good speech communications over kilometres of single-core cable, that I published an article in the UK (France, 1988) to publicise it, and adding a base station circuit with a loudspeaker and pips/tones generator for line testing. Some of my sets built in 1988 are still in use after 25 years. Some variations have appeared in CREGJ since then: a high impedance version using more modern ICs being the most significant advance, as described by Nigel Lovell (Lovell, 1993). However, the underlying Michie design has stood the test of time for almost 40 years and nothing has surpassed it.

These cave phones are unique in that they need only a single strand of wire laying in the cave passages and the return signal travels back to the surface team through the ground. They are for simplex communications where only one person talks at a time. The audio transducer is a standard telecom moving armature telephone earpiece, known in British Telecom as a 4T Capsule. There are three parts to the inventive genius in the original Michie design:

- realising the 4T earpiece could be used both as a speaker and a microphone
- switching an op-amp between being unity gain follower when in receive mode to being an amplifier with gain when in transmit mode by means of a DPDT (double-pole double-throw) switch. This has 6 soldered connections to the main PCB and acts as a PTT (push-to-talk) button in a similar way to the talk button on a handheld VHF radio.
- returning the audio signal through the ground so that only a single wire in any network topology has to be laid in the cave. This cabling economy did, however, require the underground handset user to hold a metal phone handset in one bare hand and touch the cave floor or wall with the other bare hand to complete the circuit via the earth.

Earpiece and Microphone

The quality of 4T capsules used in domestic telephones dropped over the years. Good second-hand ones became hard to find. They are not something you can buy from general component suppliers. Before the privatisation of BT, formerly Post Office Telephones, the UK government made plenty of money from its citizens by renting out telephone handsets to them at high rates, along with high call charges, and they never sold their equipment outright. Only approved kit could be connected legally to the UK public network and of course POT approved little but their own kit. From a caving point of view, this state monopoly meant that the eventual supply of scrap telephone parts to cave rescue was all standardized and good quality. Nowadays, the dominance and diversity of third-party telephones connected to the public network has shrunk the use of 4T capsules in the domestic market.

One could beg a BT engineer, as I once did, to find and donate old telephones from the 1970s, or even the 1960s, which were excellent quality, to harvest the 4Ts from them. But even that source dried up. So when I was asked in 2009 to build replacements for the 1988 cave rescue phones, I went directly to a 4T manufacturer, **hbl.co.uk**, and there discovered a 'tropicalized' version which is of military standard and with a NATO part number. UK caves are hardly tropical, but I hope this equates to reasonable damp-proofing.

I bought 40 of HBL part number R4AWZ300, certified only as commercial grade however, to meet HBL's minimum order value and to gain access to brand new military-style parts.

Call Tones and Pips

Using the 1988 telephones during rescue incidents exposed some practical issues. Some of these relate to the caving environment, others to rescue roll-outs, and some to people factors. The audio level of the handset earpiece was good so long as it was held next to the ear, as with a domestic telephone, but nothing much could be heard if the handset was put down on the ground. So a strong call-tone generator was needed to attract the attention of underground groups, to get them to pick up their phone and talk again with surface control. A pips generator was also needed so that the line-laying team could test their cable as they laid it out in the cave. My 1988 design did include a pips and call-tone generator based on a 7556 timer chip and a 3-way toggle switch to select pips–speech–tones as part of the base station box. This was all long long ago, in the era before PICs. Nowadays, it is simple to generate call tones, pips, roger beeps, tunes and any other sounds with a microcontroller. The new 2013 cave handsets create the sounds shown in *Table 1* with a PIC.

Feature	Purpose
Single beep	Generated when batteries are fitted, indicating that the firmware has booted and gone into sleep mode
Start-up tune (Beethoven Ode to Joy)	Generated when turned on (i.e. moved from sleep to receive mode) as confirmation that the set is running.
Roger beep	One beep is output when the PTT button is released to prompt the other party to start talking
Call tones	Call tones begin by double-clicking the PTT button. These tones will stop after 10 rings or sooner if the PTT button is pressed again.
Line test pips	Base stations only. After sending 10 rings as above the set will continue to send a pip every 10 seconds until the PTT button is clicked. This allows line-laying teams to test new line as they progress. In between pips the set reverts to receive mode and will play any speech on the phone line.
Shutdown sound (a downward glissando)	Indicates that the handset is turned off (i.e. gone into sleep mode). Base stations turn off with an isolating switch on their volume knob so there is no sound.

Table 1 – Sounds Generated by the Cave Telephone

Switches

The next practical issue concerned the style and resilience of switches. The 1988 sets used RS toggle switches which, at about £2 each then, were not cheap. The on-off power switch had a tendency to get knocked into the off position and so communication was lost until an underground group realised they had accidentally turned their set off. The converse was also true after a rescue – people returned their units to the rescue stores still turned on and so this flattened the battery prior to the next use and possibly provoked a battery leak. The PTT switch was spring-loaded and would return to the receive position when released. All these switches tended to get dirt and damp inside and failed after some years or with rough treatment, and even rubber caps fitted on top did not seem to stop them sticking and deteriorating with damp. Also some rescuers managed to push or bang the toggle levers so hard that these broke off. Mechanical spring-loaded push-down style switches with coloured plastic caps fared no better.

Nowadays, in the touch screen and mouse era, everyone is familiar with the idea of context-sensitive clicks: switches that do different things depending on when they are pressed and in precisely what way – held down for a few seconds, just a short click, or a double click. So this revolution in the way that ordinary people interact with gadgets now makes it possible to implement all the control functions of a modern cave telephone with just one momentary-action waterproof low-profile membrane switch plus the firmware to interpret switch gestures. The idea of 'interpreting switch gestures' would have been regarded by every-one as nonsense in 1988, had it even been possible to do then. The Michie op-amp reconfig-uration trick bet-ween receive and transmit modes still has to be performed, and the former DPDT mechanical switch is now done with a miniature 12V DPDT relay under firmware control in the 2013 phones.

Figure 1 – The Handset showing the 4T Earpiece

Switch Click / Gesture	Purpose
Holding the button down for 3 seconds in the sleep state until the music **starts**	Turns on the cave handset (wakes it from sleep). The start-up tune plays. The set is now in receive mode as a cave handset. Base stations are turned on with an isolating switch in their loud-speaker volume knob.
Holding the button down when in the receive state	Goes to the transmit state. The relay reconfigures the op-amp for gain. The button is now the PTT function.
Double clicking when in receive state	Sends 10 call tones. On base stations, this is followed by indefinite line-test pips. In between each tone or pip the set is in receive mode and will relay speech.
Short click when sending call tones or line-test pips	Stops the tones or pips. Reverts to receive state.
Holding button down for 3 seconds during call tones	Turns off the cave handset, i.e. it enters sleep state. Handsets will also enter sleep state after 8 hours of no clicks. Base stations can only be turned off by using the isolating switch within their volume knob.
Holding the button down for 3 seconds in the sleep state until the music **stops**	Turns on the cave handset and runs it in base station mode. It will not power off after 8 hours of no activity, and it can also now generate line-test pips.

Table 2 – Switch Clicks

Batteries

In no circumstances should any field telephone be powered from a mains-derived DC supply, such as a mains transformer or a modified mobile phone charger or other 'wall cube' AC-DC adaptor. They must all be run from low voltage batteries only.

The battery in the 1988 cave telephone handsets, and indeed all the Michie derivatives to date has been a 9V PP3 conn-ected with a push-on PP3 clip. People could easily try to fit this the wrong way around so reverse-polarity pro-tection was needed in the current path, usually as a diode. PP3 clips also had a tendency to corrode if damp remained inside the diecast box during storage. Worst of all, alkaline PP3s only have a small energy capacity and their voltage droops quite quickly, causing a weak sound level since the 4T does not perform well below its design voltage. An-other issue was the unavailability of new PP3 batteries at short notice, for example when needing more stock at isolated locations outside of normal shop hours or with no supermarkets nearby.

DC-DC converter chips have been widely available since the mid-1990s, and the AA alkaline battery has become ubiquitous for hand-held gadgets and is available everywhere. For the 2013 cave handsets, I chose 3×AA batteries which gives 4.8V when new down to 2.7V when spent. This voltage range suits a PIC perfectly and it is easily boosted to a steady 12.0V with a DC-DC converter to power the audio comp-onents. I chose the MAX761 chip that conveniently has a battery-low logic level output for firmware so that a warning can be given to the user or other action taken.

When I showed my 2013 models to local cave rescue teams they were very happy with the alkaline AA batteries in the cave handsets but did not like having D batteries inside the base station. Instead they wanted a small external 12V lead-acid battery, as per their HeyPhones. The battery endurance table below shows this objection was unfounded in terms of endurance but they nevertheless were insistent on this external battery. For me it meant re-designing the base station power supply to use a 78L05 to regulate the external 12V down to 5V internally instead of using a DC-DC converter raising roughly 4V internally to 12V. The battery-low warning function was then lost too as a consequence of removing the MAX761.

This was unamusing as it came after the PCB design had all been done and all the bare PCBs manufactured, and it also looked unjustifiable from a technical viewpoint. So there are now two base station versions: the original model which runs with 3 internal alkaline cells and a rescue version that runs with a 12V external battery. The production

LED Pattern	Meaning
Single flash every 10 seconds	Power is on. Battery is good
Double flash every 10 seconds	Power is on. Battery is low
Lit continuously	Phone is transmitting. PTT button is down.

Table 3 – LED Patterns

versions of these phones were shown at the 2013 BCRC conference where other rescue teams seeing this kit for the first time asked if the 12V base station could be modified to use internal batteries too! So there is no pleasing all the people all the time, except by offering choice.

I did not alter my original PCB layout or remanufacture any boards to make the 12V base stations. Instead, I just hacked the 4.5V through-hole boards by finding a way to stuff them with a 78L05 instead of the MAX761 DC-DC converter. This was untidy, but it worked and was expedient, given the circumstances, and I expect that a base station with an external lead-acid battery will eventually be regarded by everyone as somewhat retro.

Indicator LED

Most earlier phones incorporate LED indicators for power on, and maybe a second LED for transmit. But LEDs use significant current unless flashed, and LEDs are an even more serious issue when using PP3 batteries. In Lovell's sets the LED flashes green once at power-on and red once at power-off. This is economical, but it fails to meet the common sense requirement of having some sort of permanent power indicator. Flashing an LED continuously in the 1980s would have meant using a 7555 chip, or similar, which itself might consume significant current to generate timing pulses. The solution nowadays is to control an LED with firmware, as one of several software processes being run. Several different flashing patterns can then be realised to give different types of information to the user. The 2013 cave rescue phones use the LED flash patterns in *Table 3*.

Enclosure and Connections

The 2013 cave handsets still use a bare diecast box but now with a neoprene gasket in the lid. This does not make the box fully waterproof, nothing ever does, but it is quite an improvement. The lid will still need unscrewing and batteries removing before drying out the units prior to shelf storage following rescues. The new cave PCBs are conformal coated several times to waterproof them, rather than potted as formerly, since this permits repairs. But the PCBs may eventually be fully potted in resin when we are all confident and happy with the new phones.

The 1988 version had a metre of flying lead emerging from a rubber grommet which terminated with a crocodile clip for attachment to the cave phone line. The problems encountered were that the crocodile clip either fell off the phone line or the rescuer put the bare metal part of the clip on damp ground, thus shorting out the phone line to earth which ruined the performance. So with the 2013 cave handsets, I have replaced that flying lead and its vulnerable grommet with a box-mounted screw-down cable binding post that also accepts a 1m plug-in croc-clip lead as an accessory item.

The base station units are built into plastic boxes as they are intended for use in a vehicle or a building. These too have red binding posts for the phone line and also green earth binding posts for a ground connection out of the nearest window via a 15m green cable terminated with a 25cm stainless steel peg that can be pushed into soil.

Feature	1988 Design	2013 Design
Cave handset battery	9V as 1×PP3 internally	4.5V as 3×AA internally
Base station battery	12V lead acid externally	Either 4.5V as 3xDs internally, or 12V lead acid externally, but not both
Base station external battery leads	Banana plugs to spades	HeyPhone plug to spades, or HeyPhone plug to vehicle cigarette lighter socket
Audio operating voltage	9V, but droops with the battery discharge state	Regulated to constant 12V
Call tones and pips	7556 chip in base station operated with a three-way pips-speech-tones switch	Firmware tone generation
Handset switches	SPDT alternate action for on-off. DPDT momentary action for PTT function.	One SPST momentary action switch
Switch type	Toggle switches with levers. Not IP rated.	IP68 low profile membrane switch
Auto switch off	No	Yes, for cave handsets
Sleep mode	No	Yes, for cave handsets
Roger beep	No	Yes, for all sets
Military quality microphone and speaker	No	Yes, for all sets
Line connection	Fixed 1m flying lead with croc clip	Binding post, or croc-clip cable as an accessory
Enclosures	Non-IP rated	IP66
Power on indicator	Dim LED on constantly or momentary in Lovell type	Single bright flashes every 10 seconds on all systems
Low battery warning	No	Double flashes every 10 seconds on handsets only
Transmit indicator	No	LED is on continuously
PCB style	Single-sided through-hole	Single-sided through-hole

Table 4 – Comparison between 1988 and 2013 Designs

The 1988 and 2013 Versions Compared

Having explored the practical caving issues and the impact of new technology and component obsolescence issues, it is now useful to summarise the comparison of 2013 telephone features with those of 1988 in *Table 4*. The sections that follow explain more about the 2013 design, in particular its power supply and microcontroller.

Wire and Reels

Lightweight 7×0.1mm PVC insulated equipment wire works well electrically. It is however easy to snap, and so in caves it needs laying to the side of the passage or in the roof when crossing from one side to the other. On the surface it may be worth laying a more robust cable such as 14×0.1mm PVC. White or yellow cables are the easiest to see and thus avoid snagging.

Some tight sections of caves, where a cable running on the floor would be abraded and soon damaged by rescuers dragging themselves and tackle bags, have been cabled in advance with a strong line running in the roof (e.g. the Daren Cilau entrances). There will be small plastic junction boxes at strategic locations with a stainless bolt on which a phone handset is connected with a croc-clip lead. 'Pigtails' made of coiled 3mm stainless bar inserted into plastic Rawlplugs make good roof anchors for cable in tight places with any narrow rift above. Some South Wales caves with a history of

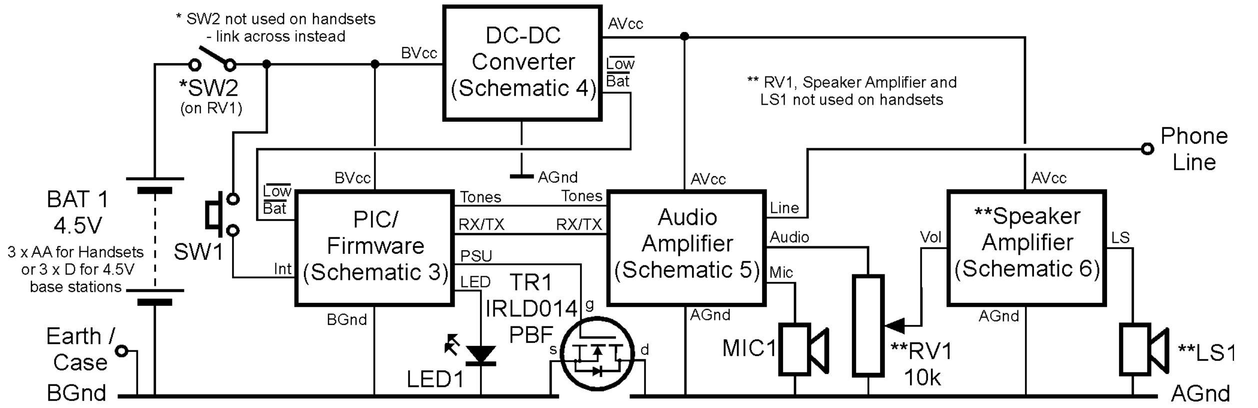

Diagram 1 – Block Diagram of 4.5V Internal Battery Handset and Base Station

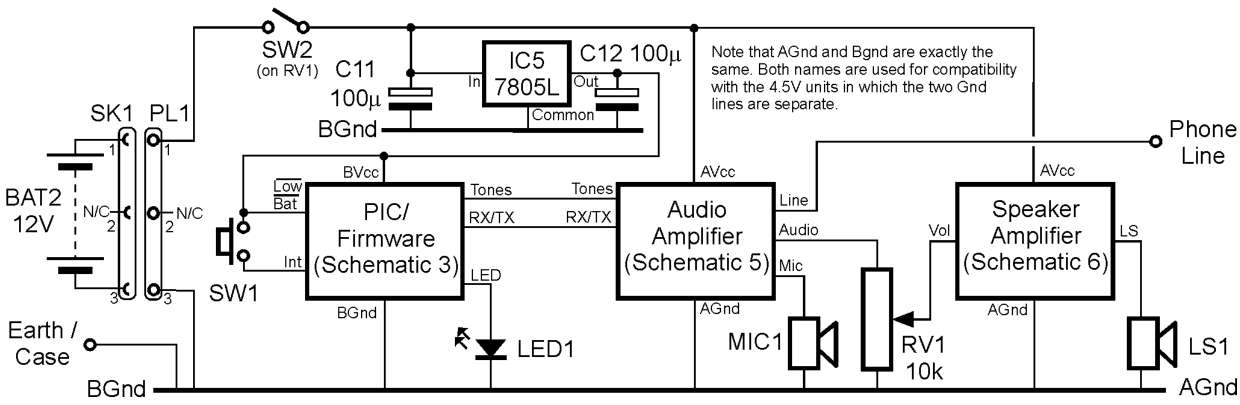

Diagram 2 – Modified Block Diagram for 12V External Battery Base Station

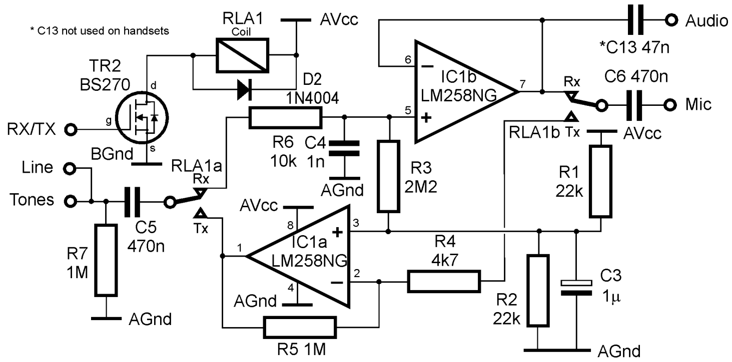

Diagram 3 – Audio Amplifier

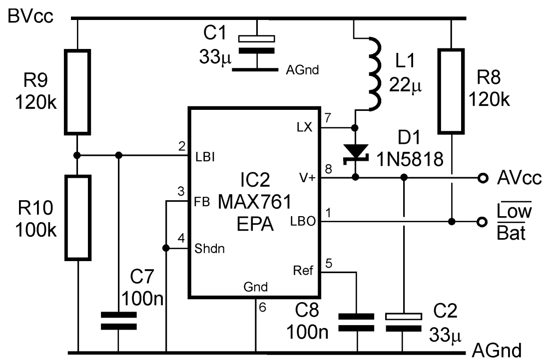

Diagram 4 – DC-DC Converter

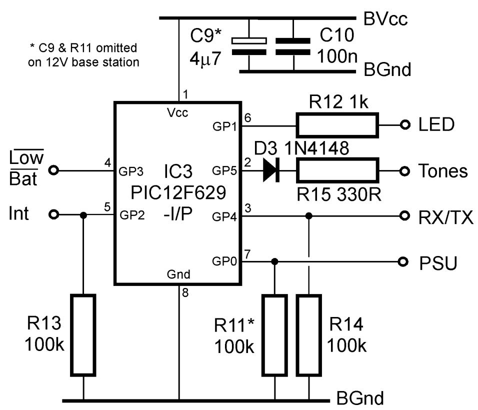

Diagram 5 – Microcontroller

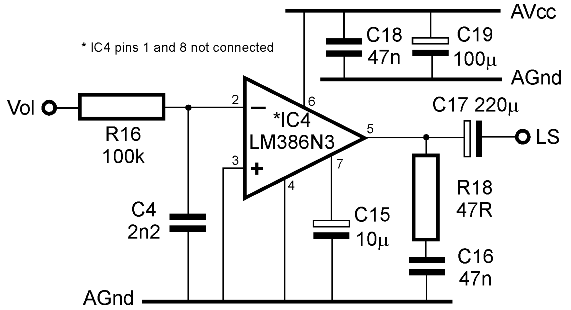

Diagram 6 – Loudspeaker Amplifier for Base Stations cavers trapped beyond flooded sections now have permanent lines installed (e.g. the Dan-yr-Ogof lakes and Little Neath River Cave). Cables running through sumps need to be armoured where any movement in water might otherwise cause abrasion.

Figure 2 - Cordwheel

Plastic reels holding 500m of single-wire cable are convenient for laying and removing cable in caves. The South Wales team uses the large size Unipart Cordwheel shown in *Figure 2* and available online from Amazon and various caravan accessory suppliers at the time of writing. The drum in the photo here is loaded with twin cable however – no doubt because it was acquired for free.

Phone Overview

Circuit diagrams 1-6 describe the two types of base station and also the cave handsets. *Diagram 1* is the block diagram for all 4.5V internal battery systems, and is the original concept. *Diagram 2* is the later version for 12V base stations when rescue teams want an external battery.

Diagram 3 is the audio amplifier using a relay instead of the DPDT switch of the earlier phones. *Diagram 4* shows the DC-DC converter used in all internal battery versions to generate 12V. *Diagram 5* shows the microcontroller block, which varies slightly according to the type of set being built. *Diagram 6* is the loudspeaker amplifier for base stations, identical to that of the 1988 sets, and using an IC that by some miracle is still in production after 25 years.

Diagram 1 has two ground lines in the 4.5V systems: AGnd, for the DC-DC converter and the audio amplifier and the loudspeaker amplifier in base stations, is switched to BGnd through a low-side FET by firmware. So the internal 12V supply is created only on demand. BGnd is the battery ground, which powers the PIC and is thus a permanent supply line. Pressing SW1 when the PIC is in sleep mode will wake it and restart its internal clock by generating an interrupt on the INT pin. The firmware will then interpret this and the subsequent button press gestures. The MAX761 DC-DC converter does have a sleep mode, but when put into this mode it simply passes the raw battery voltage through to the rest of the circuit without boosting it. In other words, the internal 12V circuit would still be powered at about 4V, and thus not fully disabled, which is wasteful in terms of energy. The MAX761 can only be fully turned off by isolating it from its power supply, and in the 2013 phones this is achieved by preventing current sinking to the battery ground by turning off TR1 with firmware.

Figure 2 for the external 12V battery base stations shows AGnd and BGnd permanently linked, and a 78L05 regulator provides a permanent local 5V supply to the PIC. Its audio sections are powered directly off the external battery, or a vehicle. The battery-low function has not been implemented and the PIC firmware will always read the LowBat line as high. The voltage of a sufficiently large freshly charged external battery will not droop much in normal use, so a low battery warning is unnecessary.

Microcontroller Block

The microcontroller is a PIC12F629. This is an 8-pin device that operates from 2-6 volts. It has clocking option choices. The internal 4MHz clock was selected, giving a 1MHz instruction speed. This gives generous processor power with no wastage of I/O pins for external oscillator parts. The downside is that the frequency varies with battery voltage, and from chip to chip, and this is by as much as 20%. For the phone application it does not matter if Beethoven is flat by a few semitones or the LEDs flash every 12 seconds instead of every 10. This clocking strategy leaves six I/O pins free, of which one (INT) can wake the device from sleep when the internal clock has been halted in firmware to save power. Five of these I/O lines are bi-directional, and the sixth is for input only. This architecture provides good flexibility and the table below reveals just how much is possible now with a simple 8-pin processor costing pennies not pounds.

The firmware for the cave handsets and the base stations is slightly different, but one source code file generates both types. This firmware handles both a 16Hz internal timer and push-button interrupts within an event loop defining a state machine, the detail of which is beyond the scope of this article.

DC-DC Converter

DC-DC converter chips are a very useful invention of the 1990s. They come in two types: buck or boost. The boost type raises a battery voltage to a target level while the buck type reduces it, at high efficiency if well designed. For instance, a boost converter can raise a pack of three AA alkaline batteries, which are 4.8V when fresh and 2.7V when nearly exhausted, to a constant 12V output at low currents suitable for audio circuits. Most commercial LED lighting controllers are the buck type, reducing a higher voltage down to a lower current-limited voltage to drive an LED array, as this suits high current applications

PIC I/O line	PIC Pin	Firmware Name	Purpose
GP0	7	PSUPIN	Controls the FET linking AGnd to BGnd to power up rest of circuit
GP1	6	LEDPIN	Powers the red LED on handset to show various flashing patterns
GP2 (int)	5	BUTPIN	Reads the SPST membrane switch button gestures. Changes on this pin will wake the processor from sleep and restart its internal clock
GP3	4	BATPIN	Low battery input from MAX761. GP3 is the input-only I/O pin
GP4	3	RLAPIN	Energises the relay coil via a FET
GP5	2	BUZPIN	Generates various tones on the phone line, and thus the speaker
n/a	1 & 8	BVCC & BGND	Permanent 3-5V power supply

Table 5 – PIC Pins

better. There may be a battery-low logic line which firmware can monitor. I have used Maxim products since the 1990s and have kept on using these mainly for reasons of familiarity. The device selected for this project is the MAX761. This chip is now obsolete, but not before I had persuaded Maxim Europe to donate 50 of them to cave rescue, and we are grateful to Maxim for their help and generosity. Newer DC-DC converters from Maxim and others do a similar job, but that would have meant re-design work for me, and by the time I discovered that I faced an obsolescence issue, I had already done the PCB layout and manufactured all the milled-out bare boards.

Handset	Run Time
Cave Handset	**3× AA Alkaline Cells**
Sleep	2 years
Receive	20 days
Transmit	30 hours
95% RX 5% TX	12 days
Base Station	**3× D Alkaline Cells**
Off	5 years (shelf life)
Receive	32 days
Transmit	10 days
95% RX 5% TX	30 days
Base Station	**1.3Ah External 12V**
Off	6 months (self-discharge)
Receive	5 days
Transmit	40 hours
95% RX 5% TX	4 days

Table 6 – Battery Endurance

Battery Management and Endurance

In professional work with low power battery circuits over the past decade or so, I have used thousands of alkaline batteries of various brands, including all the well-known ones. Some of these do not take kindly to being left on ultra-low drain for years on end, and they should be replaced in equipment every two years to avoid any leakage even if their voltage still looks fine for a microcontroller left mainly in sleep. A market-leading position is no guarantee against leakage in later battery life – you have been warned. Other than this end-life issue, alkaline batteries are an excellent choice for low power equipment where long standby endurance and high energy density at low cost are needed.

On rescue incidents it will be best to issue handsets already turned on to prove they have batteries in good condition and are working. The batteries in the 2013 handsets are packed with foam so they cannot jump out even if the sets are dropped on rock. Underground rescuers cannot turn sets off easily, as the procedure is not obvious, which is all good news. Personnel should already be familiar with PTT buttons from using VHF radios, but need to be told to double-click the sets to send call tones. Team members, however, need to be trained to:

- hold the underground handset without rubber gloves
- earth themselves during handset use by putting a bare hand on the wall or floor
- put the handset metal case on the ground to earth it when not being used so it plays any call tones loudly
- avoid shorting the phone wire to earth anywhere.

In other words, they need have a grasp of the economies, practicalities and constraints of using a single wire telephone network with an earth return.

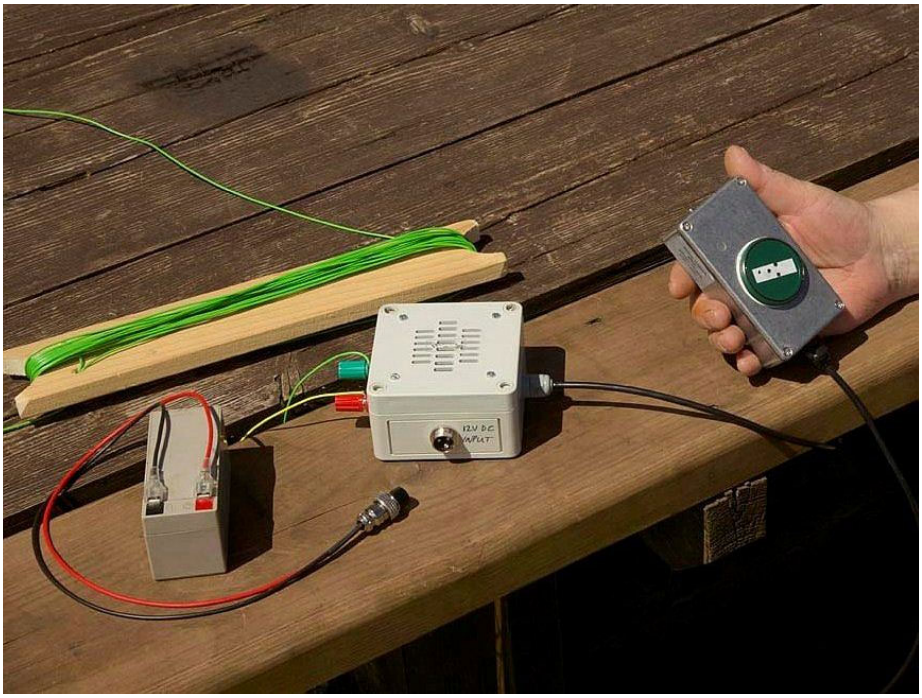

Figure 3 – Base Station and Cave Handset

Self-Build Resources

All the design documents for this project will be posted on the **chelseaspelaeo.org.uk** website and I am on their contacts page. This includes the text of this article, the circuit diagrams drawn so tidily by Mike Bedford, the PIC software written in MP-ASM, PCB layouts and stuffing diagrams, bill of materials (BOM), a construction manual, and a PowerPoint user guide. These contain the photographs used in this article and some others, all kindly taken by Brendan Marris to support this project.

The BOM on the website took into account minimum order quantities and quantity price breaks. The eventual yield from the parts I bought was 34 sets issued to teams plus a base station and handset retained by myself to provide ongoing support. I manufactured 50 bare PCBs for cave/surface handsets and 50 bare loud-speaker boards. The parts cost of £1500 including VAT and delivery was recovered by selling cave handsets for £40 and base stations for £60 each to participating teams. A small stock of paid-for PCBs, MAX761 chips, 4T capsules, and partly assembled boards thus remains as spare parts or for making a few extra sets in the future.

I finished the equipment build for rescue teams in 2013 and I used a production line system where the same step was applied to all the units in turn, so none of the sets were ready until all were ready to dispatch. This caused some frustration for cave rescue personnel who did not understand why the sets were not appearing a few at a time. At, say, 2 hours per unit this work took up a lot of days of my hobby time spread out over a long period. This is leaving aside the initial R&D and subsequent writing up.

If any more sets are needed then another volunteer will have to build them – or use commercial assembly. My thanks go to Brian Jopling who milled out all the metal and plastic boxes for me, and to everyone for their patience in what turned out to be a bigger and far longer job than was first imagined.

References

France, Stuart (1988), *Earth Return Phone for Cave Rescue*. BCRA Caves & Caving Vol.**40**, pp 36-38, Summer 1988.

Lovell, Nigel (1993), *Practical Earth Return Telephone Design*, CREGJ **14**, pp 3-6, Dec 1993.

CREG