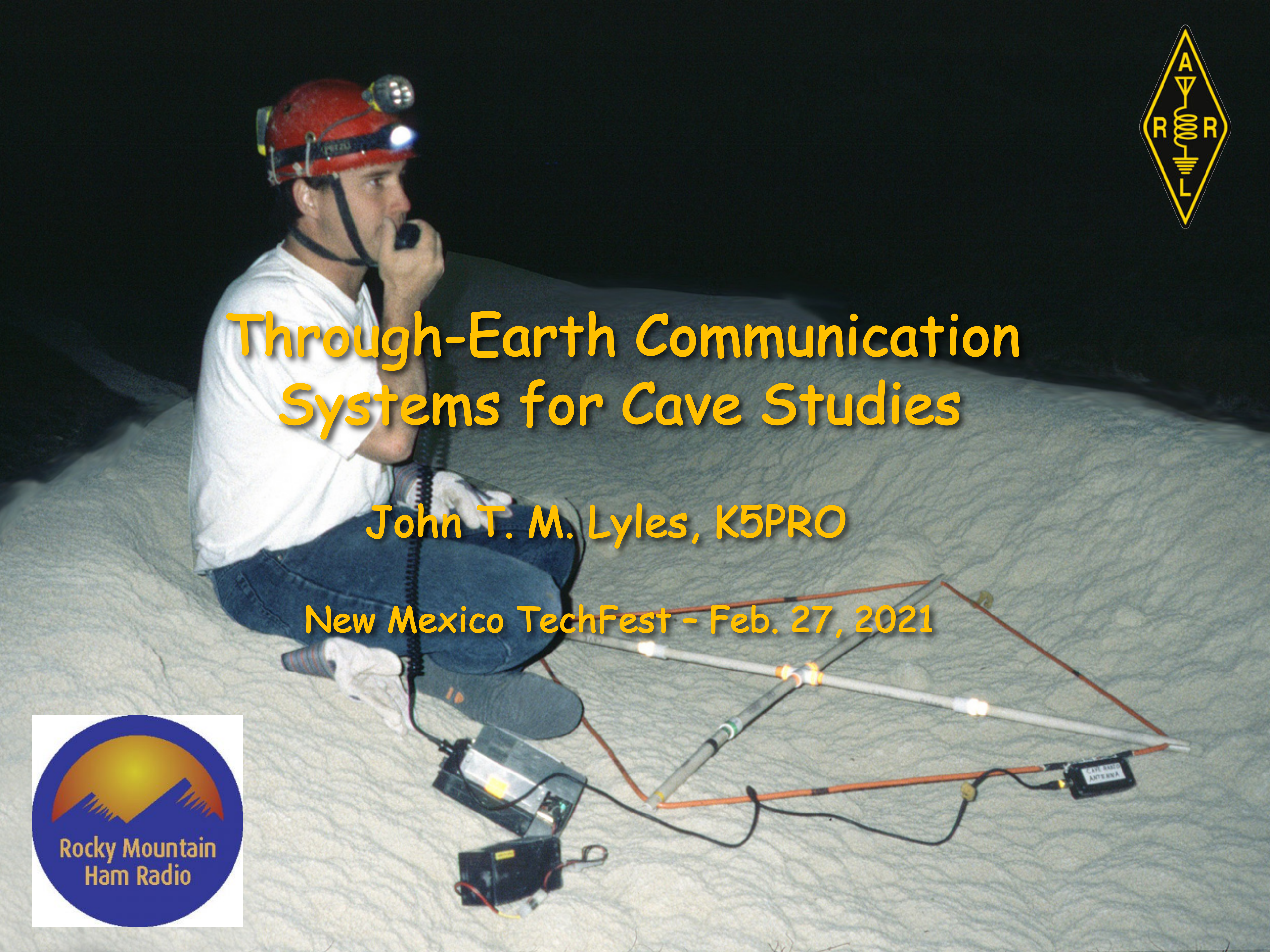
Through-Earth Communication Systems for Cave Studies

John T. M. Lyles, K5PRO

New Mexico TechFest – Feb. 27, 2021



Rocky Mountain Ham Radio

Have Compelling Need for Through-Earth Communications

- Underground exploration and scientific research in large cave systems benefits from having real time communications

- Often teams travel as much as 8 hours from the entrance, so these projects often require underground camping for days or weeks.

- Simple communication systems connecting with surface teams enable handling of logistics, transport of remote sensor telemetry, radiolocation, safety information and rescue coordination.

- This talk will highlight some custom systems that have been built and put to use domestically as well as overseas. Some examples from a large New Mexico cave are presented.

Variety of Relatively Simple Techniques can Provide Through-Earth Communication

- Communications systems may use induction fields, RF propagation, telephone wires, leaky feeders, and even banging on rocks.
This presentation is about the first two methods.

- Not free space (where ε_r and $\mu_r \sim 1$)

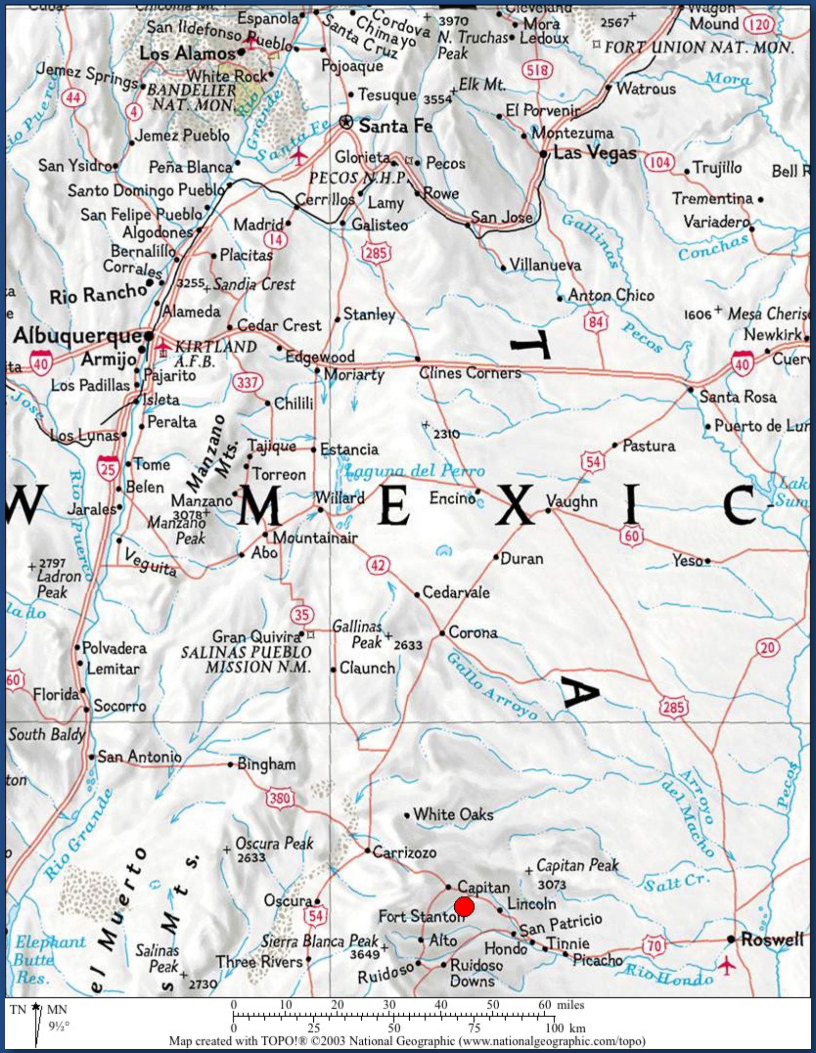
- Challenges include making equipment portable, low power for reduced size and weight, and moisture/dirt proof.

- This is not a new development, as homebrew VLF/LF sets were put into use ~50 years ago. Expensive commercial installations are in service in mines but depend on mains power and must comply with federal regulations - MSHA as well as FCC.

- Both voice radios and digital (text) radios have evolved and cover from ELF to microwave frequencies as shown.

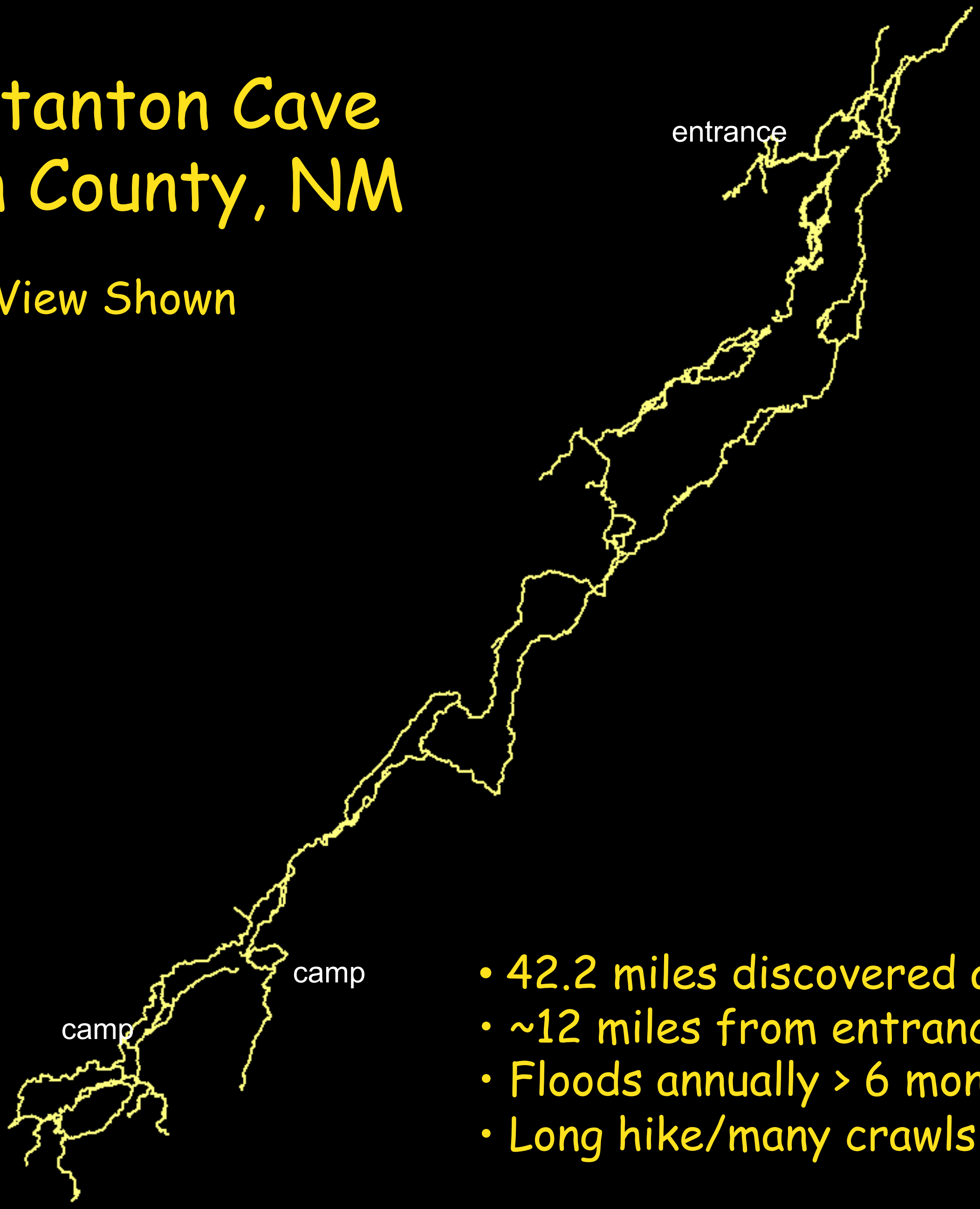
About the Caves…
Here are two that are nearby

Fort Stanton Cave/ Snowy River National Conservation Area

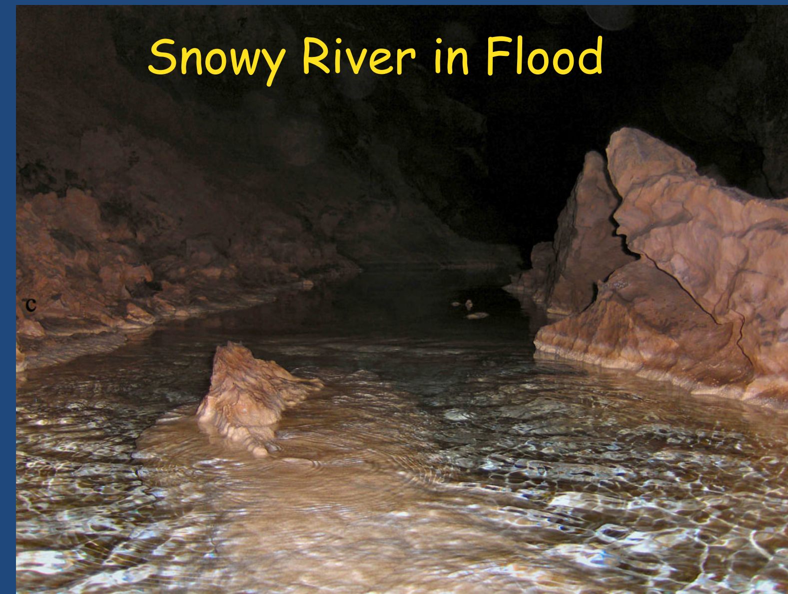


Fort Stanton Cave
Lincoln County, NM

Plan View Shown



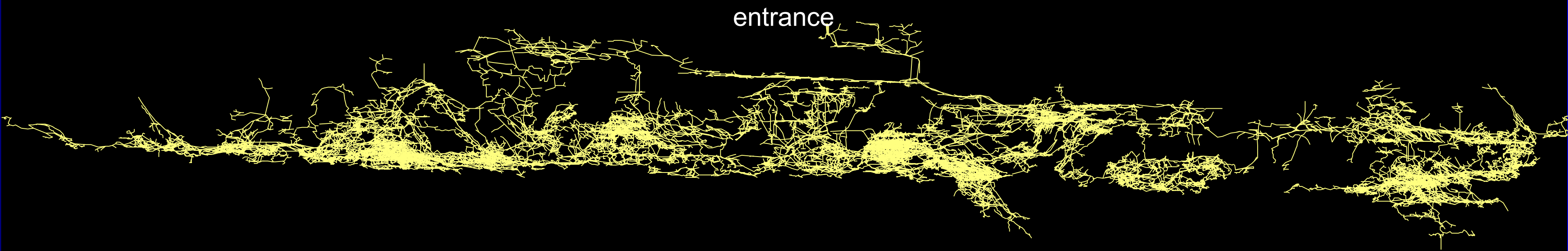
- 42.2 miles discovered and mapped
- ~12 miles from entrance to frontier
- Floods annually > 6 months a year
- Long hike/many crawls


Snowy River in Flood

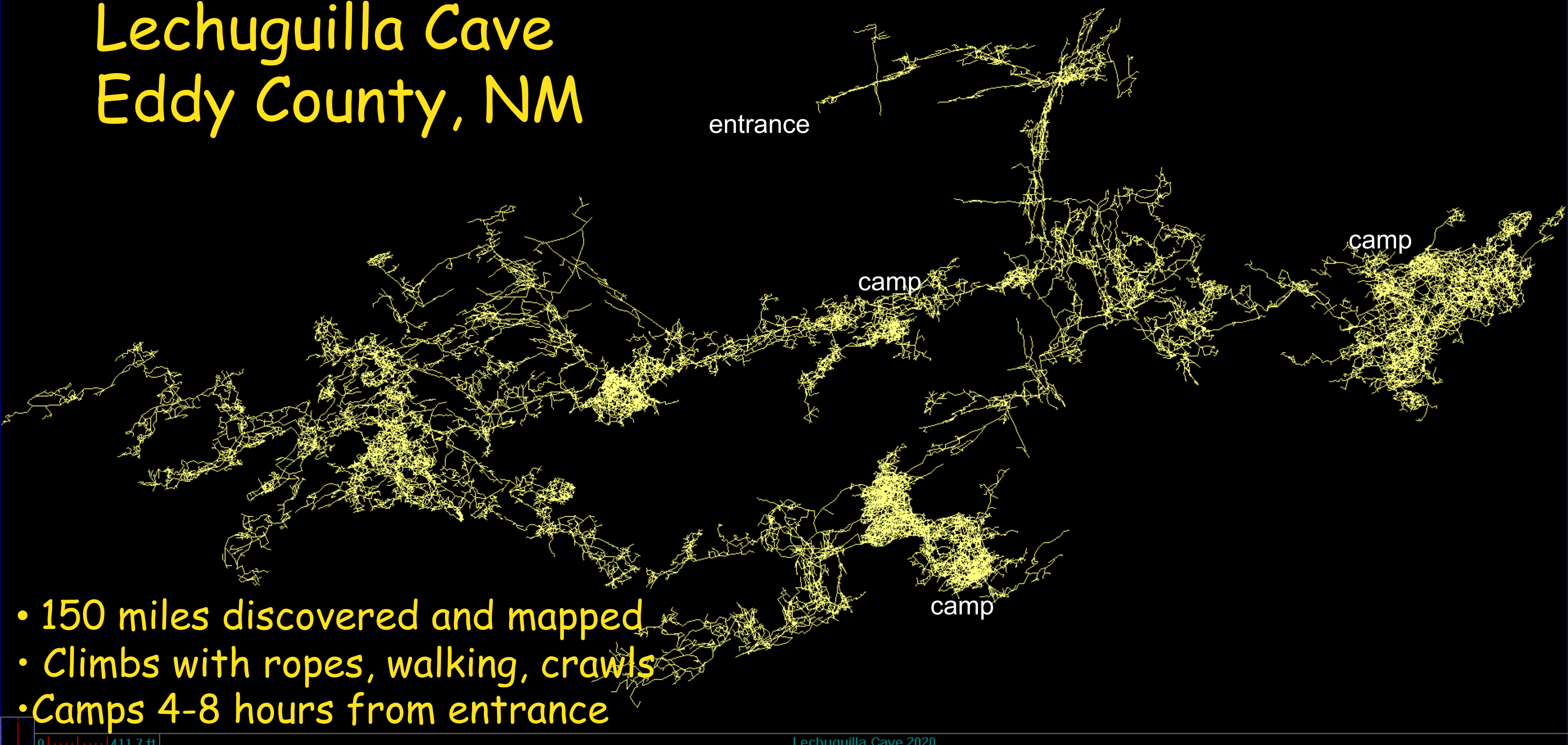

Snowy River


Midnight Creek


Lechuguilla Cave
Carlsbad Caverns National Park



Lechuguilla Cave
Eddy County, NM



- 150 miles discovered and mapped
- Climbs with ropes, walking, crawls
- Camps 4-8 hours from entrance


UP

The Radios

3 Different modes for LF/VLF Comms

- Magnetic field (loop)
  - High Q gives bandpass filtering, adding noise immunity
  - Modulation limitation when run at VLF
  - Loop tuning critical for maximum current, dependent on shape
  - Plane of loop oriented horizontally for vertical field component
- Earth current (pseudo-dipoles)
  - Broadband, can transmit analog voice with less degradation
  - Prone to VLF/LF noise, RCVR needs internal bandpass filtering
  - Requires matching transformer with adjustments for various conductivity
  - Doesn't require vertical alignment with surface unit
  - Longer range (depth) in moist limestone areas
- Leaky feeders – not practical over miles in a cave

CREG Journal 79, Sept 2012

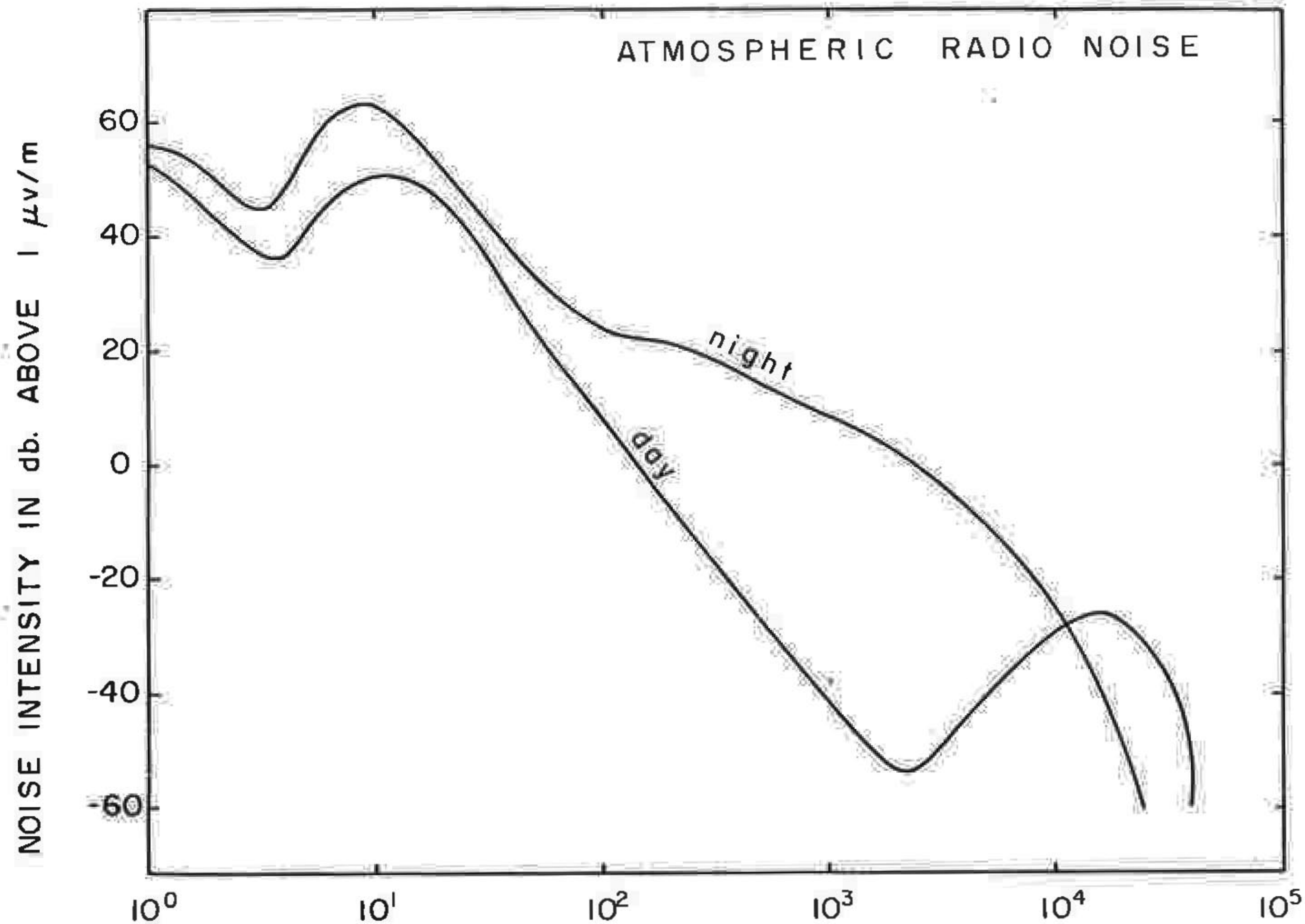


Figure 1

From N. Davis, 1970

Commercial Systems for Mining

- These are not cheap ($10K-100K), and not particularly compact/lightweight. They are intended for shift work and then are replaced with a freshly charged unit.

- They must comply with MSHA regulations in the US, including intrinsic safely (to prevent explosions from sparks). They are focused on coal mining due to the frequency of deadly accidents.

- Natural caves do not usually have this hazard.

Real Time Wireless Two Way *Through-The-Earth Communication*™ of Voice & Data

VITAL ALERT
THROUGH-THE-EARTH COMMUNICATION™

Canary Link

Wireless *Through-The-Earth Communication*™

- Real-time 2-way voice & data through solid matter
- Small, light-weight terminal relocates easily
- No line-of-sight required
- Use with your own UHF/VHF radios, interop platforms & data devices, or with *Canary*™Link headset
- Uses AC or DC power, or external 24V battery
- Rugged & water/dust resistant (IP-67)
- Call today to arrange a demo

The Vital Alert ***Canary*™Link *Through-The-Earth Communication*™** system transmits voice and data through solid earth, rock and more that blocks other wireless technology and it is rugged enough for the most challenging underground environments – mines, tunnels, subways, and more.

***Canary*™Link** provides an essential communication link for emergencies and day to day operations that complements traditional underground systems and links them to the surface or to areas that are not yet equipped. It is a life line where you need it most.

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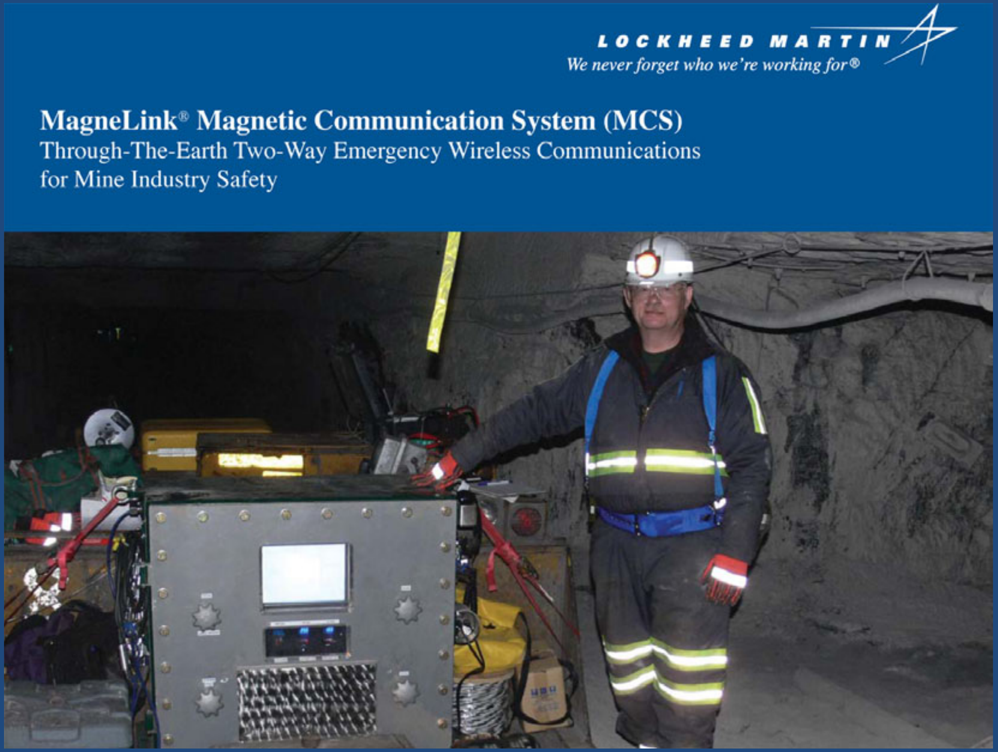
Toll Free: 1-888-99-VITAL (84825), Local: 1-647-930-1534, Fax: 1-647-930-1539, www.VitalAlert.com

The PED integrated cap-lamp receiver

The PED 1.2kW Transmitter



Homebrew Systems for Caving

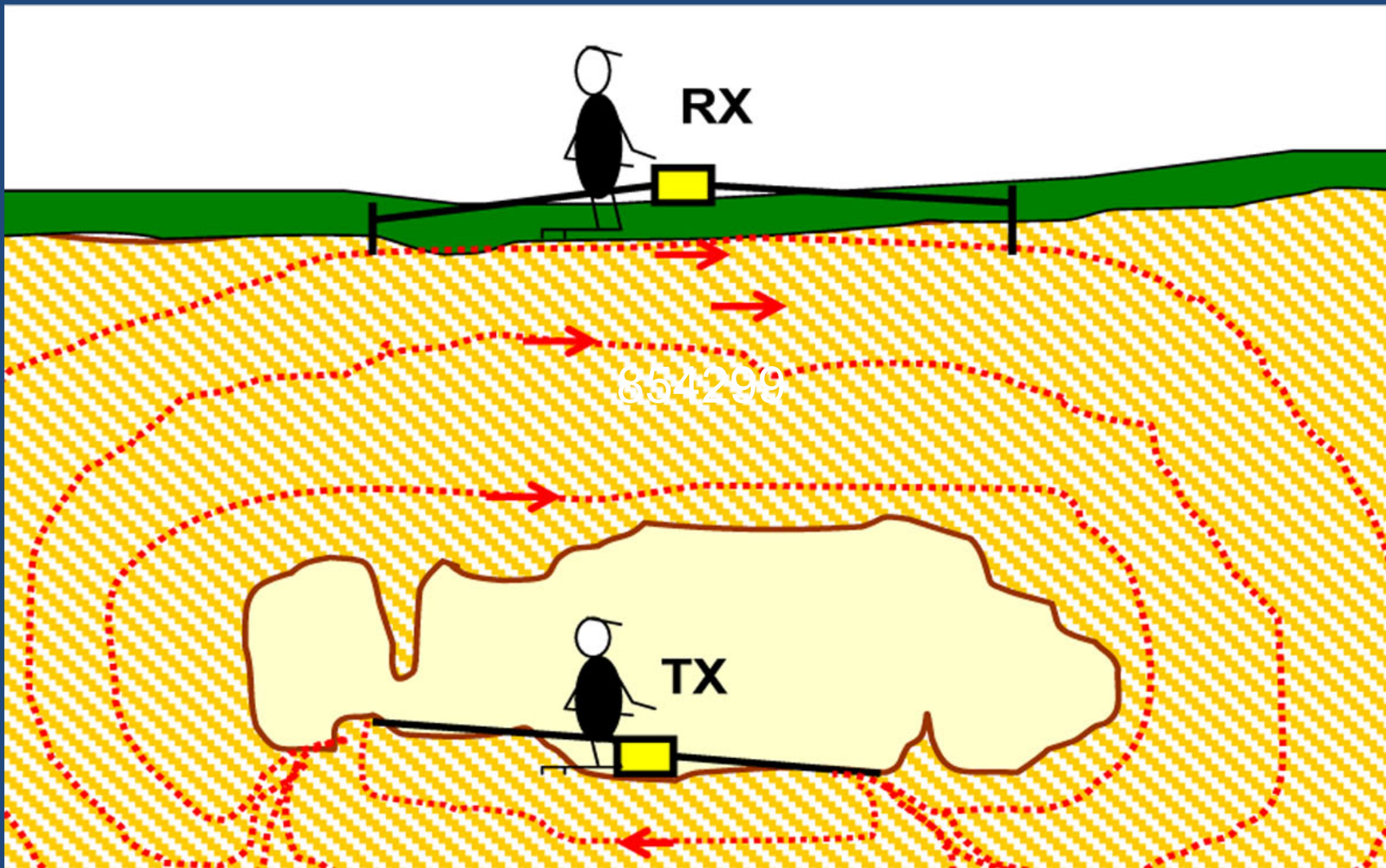
- Many use VLF in near magnetic field, also called induction radio. No FCC license required
    - $1/r^3$ Near Field Decay

- Earth Current is popular in EU. It works well for direct AF as well as VLF RF current injection

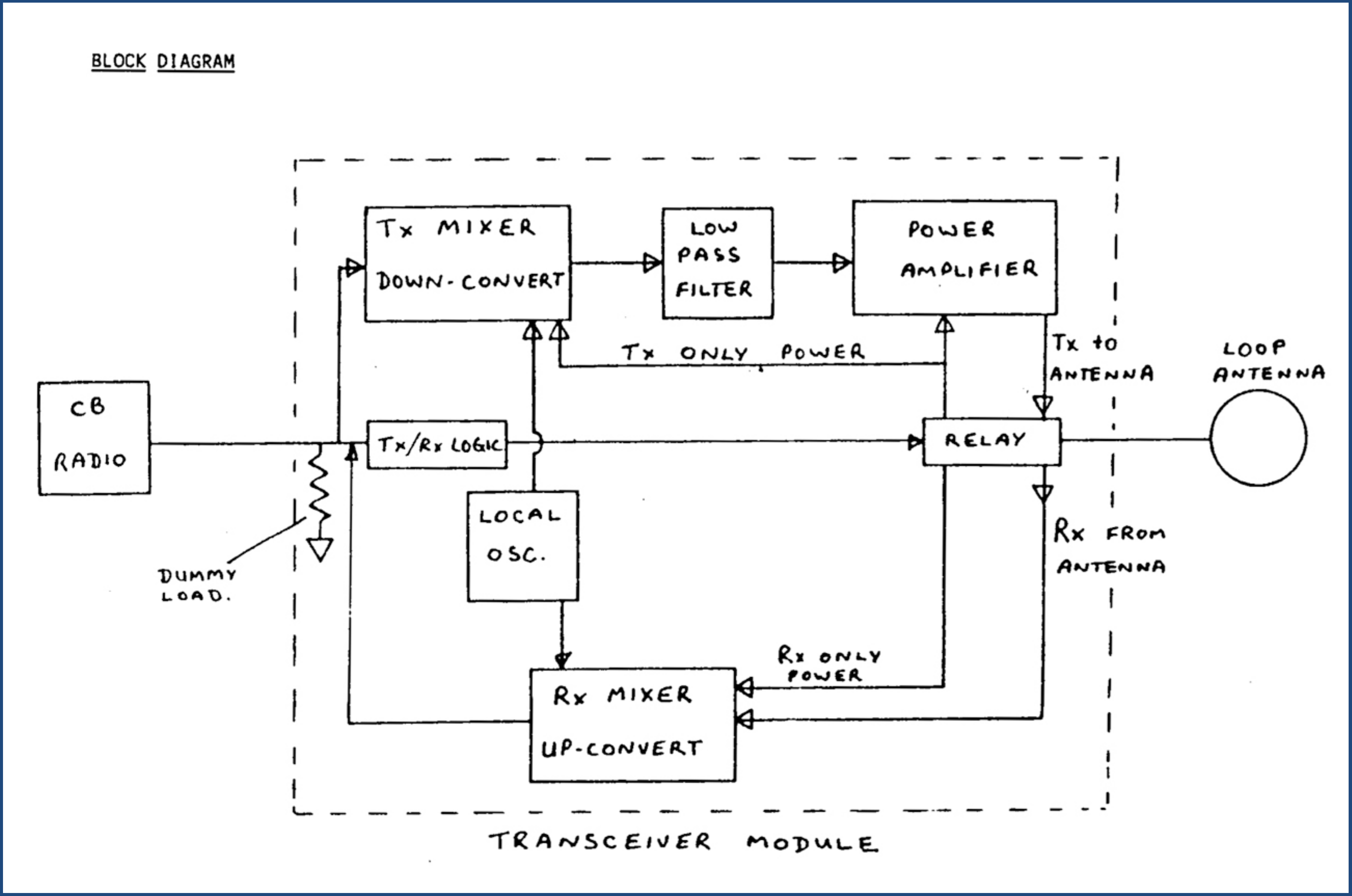
- Frequency chosen to avoid noisy powerline harmonics from earth currents. Lots of lightning noise, sferics

- Originally AM, then SSB voice, and later text modes were developed. Frequencies have evolved around 87 KHz (EU) and 185 KHz (North America-1750 meters) but there are many other odd frequencies that have been tried.

Earth Current Injection

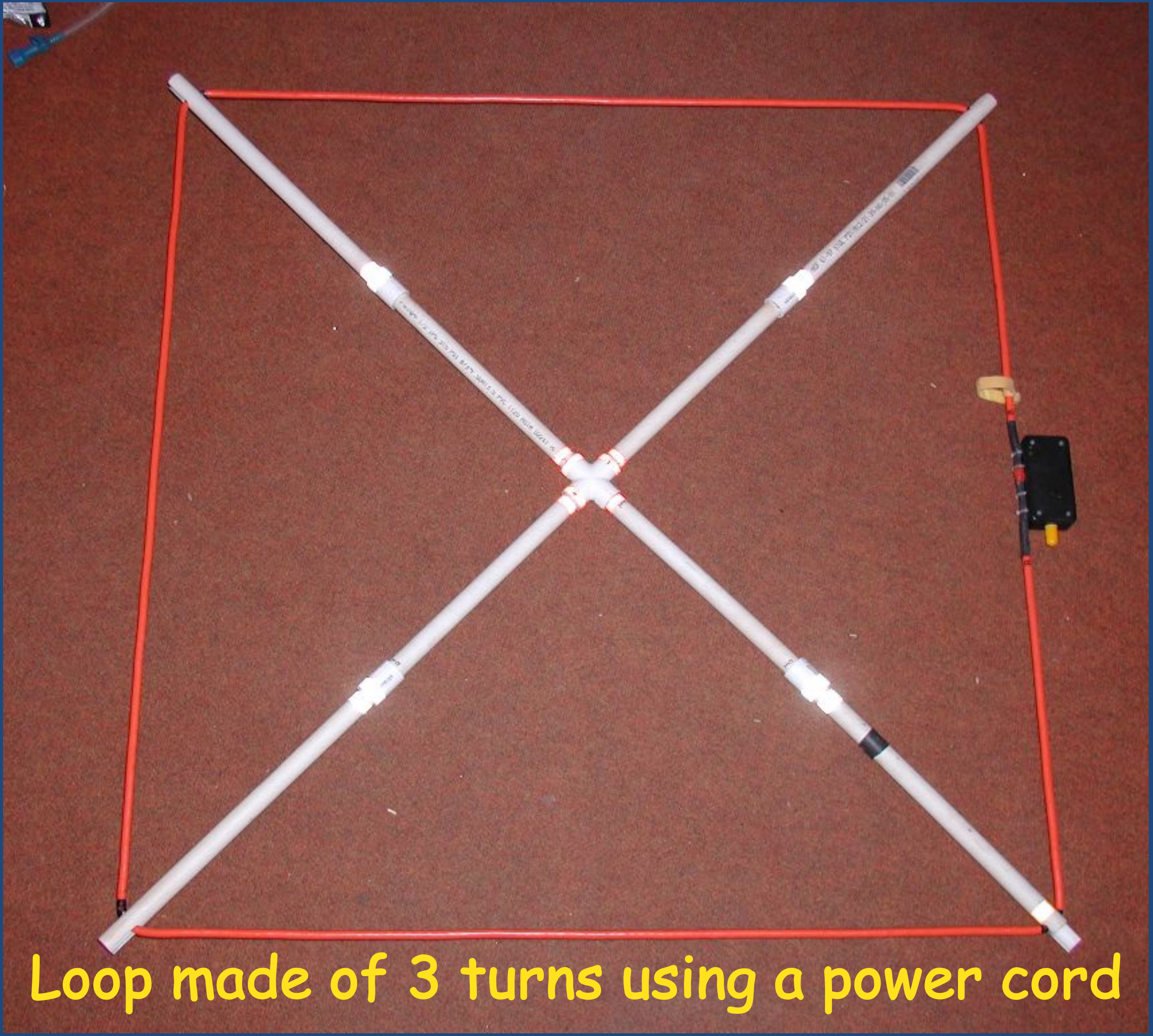


Popular design from the 1990s was CB +Transverter



BLM cave radio in New Mexico - 2003


Cave Voice Radio-185kHz
PVC Antenna Frame
Antenna
Wire
SSB CB Radio
Transverter
CHEROKEE
CB Channel 11 Only!



Loop made of 3 turns using a power cord

Fort Stanton Cave - 2003

NM Senator Pete Domenici using cave radio in 2005

The CB/185 KHz transverter design is electrically inefficient as CB runs at 4 watts output, and is complicated for non-technical users, and too bulky

Common European Designs

- The classic UK design was the 87 KHz Molefone, made by Lancaster University for profit. It remained proprietary and became obsolete in the 1990s.

- Two newer open source designs were kitted in small quantities beginning around 2000, both using 87 KHz SSB

  - Nicola II was designed and named after a young woman died in a cave that flooded in the French Alps.

  - Heyphone was designed by John Hey, G3TDZ, and became defacto UK radio, dozens were built.

- Both designs are now difficult to support due to some unavailable components

Lead Feature

The 'HeyPhone' to the Rescue

By Mike Bedford, G4AEE *

After 15 years of yeoman service, the 'Molefone', caving's standard transceiver, was approaching the end of its useful life. This is the story of its replacement - the 'HeyPhone'.

THROUGHOUT the UK, a band of enthusiasts spends its weekends squirming around in horrible, dark muddy holes in the ground. This, at least, is the public perception of the sport of caving or potholing. As someone who finds a fascination in that mysterious world below the ground, though, I'd be inclined to use rather different language. I'd be more likely to come out with clichés such as "caverns measureless to man" and talk about a personal voyage of discovery. I would enthuse over the beauty of pure white straw stalactites and the awesome grandeur of thundering subterranean waterfalls. I might even tell tales of exploration and heroism, and bandy around names such as that of the Victorian cave explorer, Edouard Martel. But, despite my enthusiasm over this world of darkness, I would have to admit to the commonly-held view that potholing is dangerous, or at least potentially so, to those who are inexperienced, careless or plain unlucky. And when accidents happen, members of the volunteer cave rescue teams are called out to help those who are lost, cut off by rising water, have fallen, or are the victims some other catastrophe.

RESCUE COMMUNICATIONS

NOT ALL CAVING trips are as quick or as easy as a jaunt into a tourist cave. Some cave systems contain tens of kilometres of passages, progress is often barred by vertical pitches which have to be abseiled down, and even horizontal motion can be a mixture of crawling and squeezing rather than walking. It's not surprising, therefore, that it can often take rescuers many hours to reach a casualty, and even longer to return to the surface with the hapless caver strapped on a stretcher.

Traditionally, therefore, the rescue team could be out of contact with the surface controller for hours on end. And if additional equipment or personnel were required, the only option would be to send a 'runner' back to the surface. This delay could easily cost lives. Cave rescue made a giant leap forward, therefore, when the 'Molefone' was introduced in the early 80s. Developed by Bob Mackin of Lancaster University, a member of the Cave Rescue Organisation in Clapham, North Yorkshire, it revolutionised cave rescue. Operating at a low frequency of 87kHz in order to penetrate the rock and employing the principle of induction rather than radiation to avoid the need for huge antennas, the Molefone allowed underground rescue teams to talk directly to rescuers above ground. Operating in the inductive near field doesn't provide long range communication, as the signal strength decays with the cube of the distance. However, it does penetrate limestone to a depth of a few hundred metres which is perfectly adequate for most British caves. There are undoubtedly people walking around today who owe their survival to the Molefone.

* 4, Holme Houses, Oakworth, Keighley BD22 0QY.

A HeyPhone in use on the surface above Carlswalk Caverns in Derbyshire.

NEEDED – A NEW CAVE RADIO

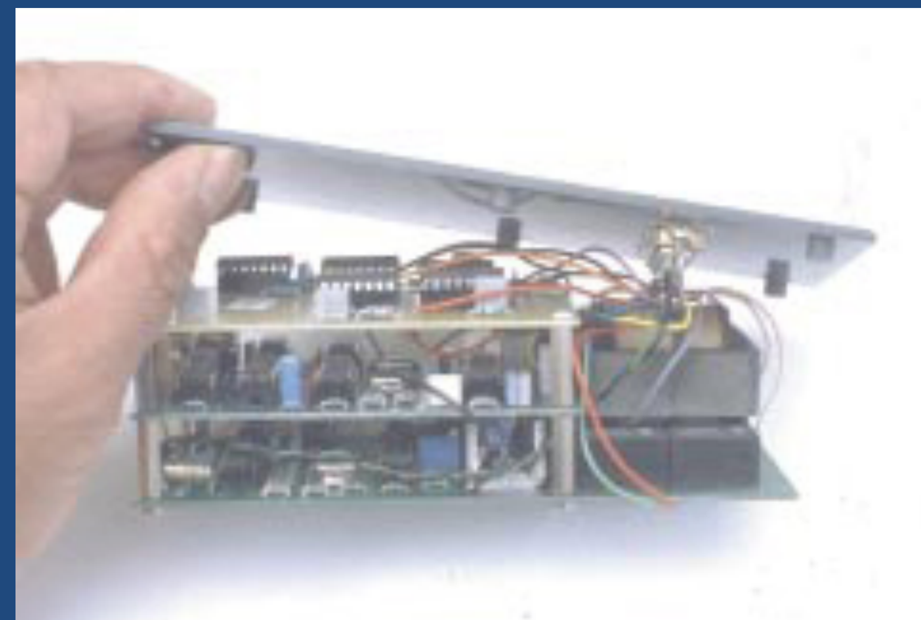
BUT TIME moves on and, a couple of years ago, the British Cave Rescue Council (BCRC) recognised that they had a problem. Although the Molefone had done sterling service, fifteen years is a long time to expect electronic equipment to survive in what must be one of the most hostile of environments. Being dragged along cave floors, being subjected to the occasional dunking, being dropped and generally abused for this length of time had taken its toll on the Molefones and the BCRC's member teams were starting to report failures.

To make matters worse, repair was difficult, if not impossible, because the PCBs had been potted in epoxy resin to improve their immunity to physical shock and some of the components were obsolete. It looked as if the Molefone was coming to the end of its useful life.

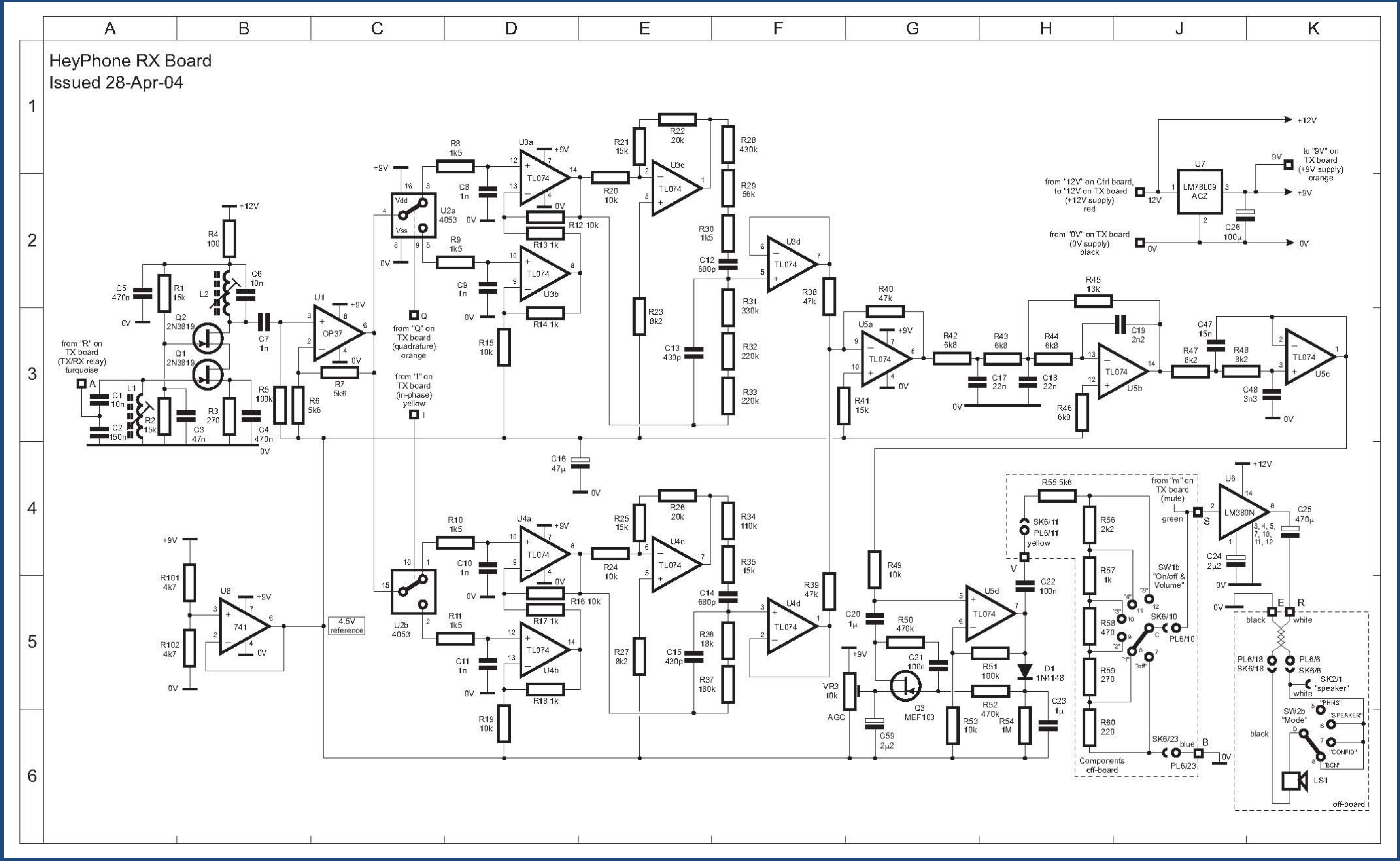
RADIO AMATEURS TO THE RESCUE

WITH A LOSS of communications capability looking ever

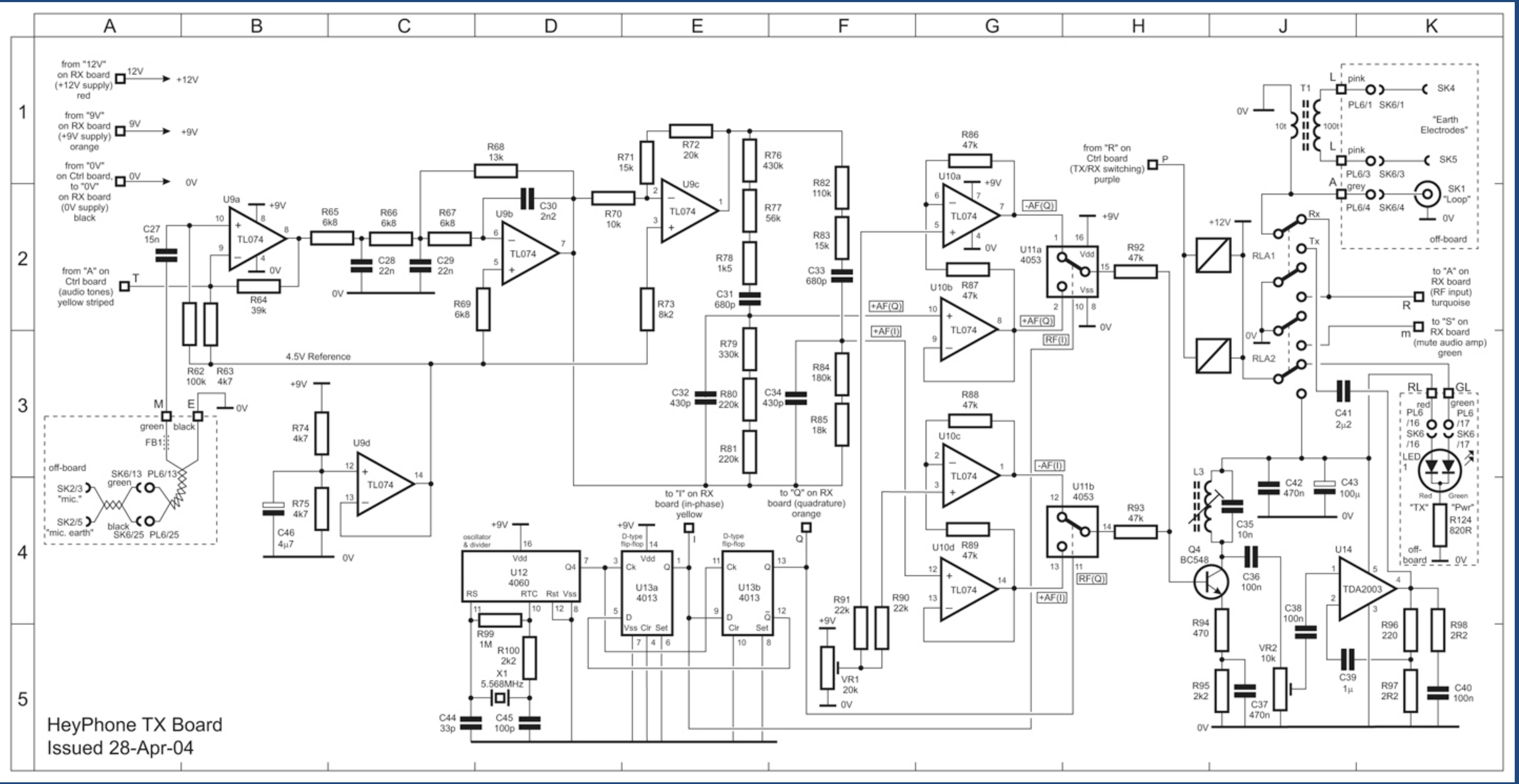
16 RadCom ♦ January 2002



87 KHz Baseband Design without RF tuning,
Phasing SSB, Earth current antenna



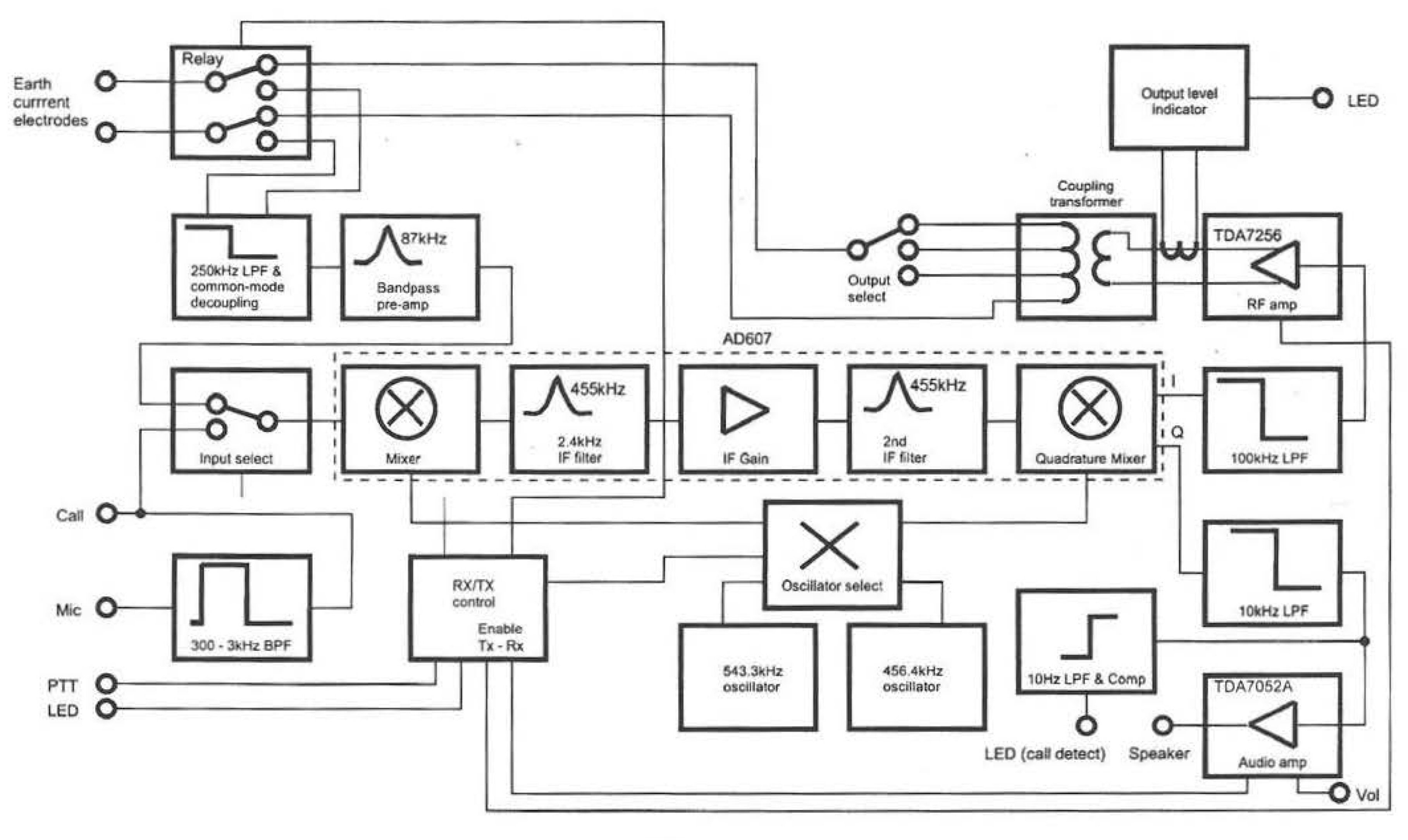
HeyPhone RX Board
Issued 28-Apr-04



HeyPhone TX Board
Issued 28-Apr-04
from "12V" on RX board (+12V supply) red
from "9V" on RX board (+9V supply) orange
from "0V" on Ctrl board, to "0V" on RX board (0V supply) black
from "A" on Ctrl board (audio tones) yellow striped
4.5V Reference
off-board
SK2/3 "mic."
SK2/5 "mic. earth"
to "I" on RX board (in-phase) yellow
to "Q" on RX board (quadrature) orange
oscillator & divider
D-type flip-flop
U12 4060
U13a 4013
U13b 4013
X1 5.568MHz
from "R" on Ctrl board (TX/RX switching) purple
U11a 4053
U11b 4053
to "A" on RX board (RF input) turquoise
to "S" on RX board (mute audio amp) green
"Earth Electrodes"
SK1 "Loop"
Q4 BC548
U14 TDA2003
"TX"
"Pwr"
R124 820R

These Heyphones were successfully used in 2018 during the rescue of teens from a soccer team who were trapped in a flooded cave in Thailand.

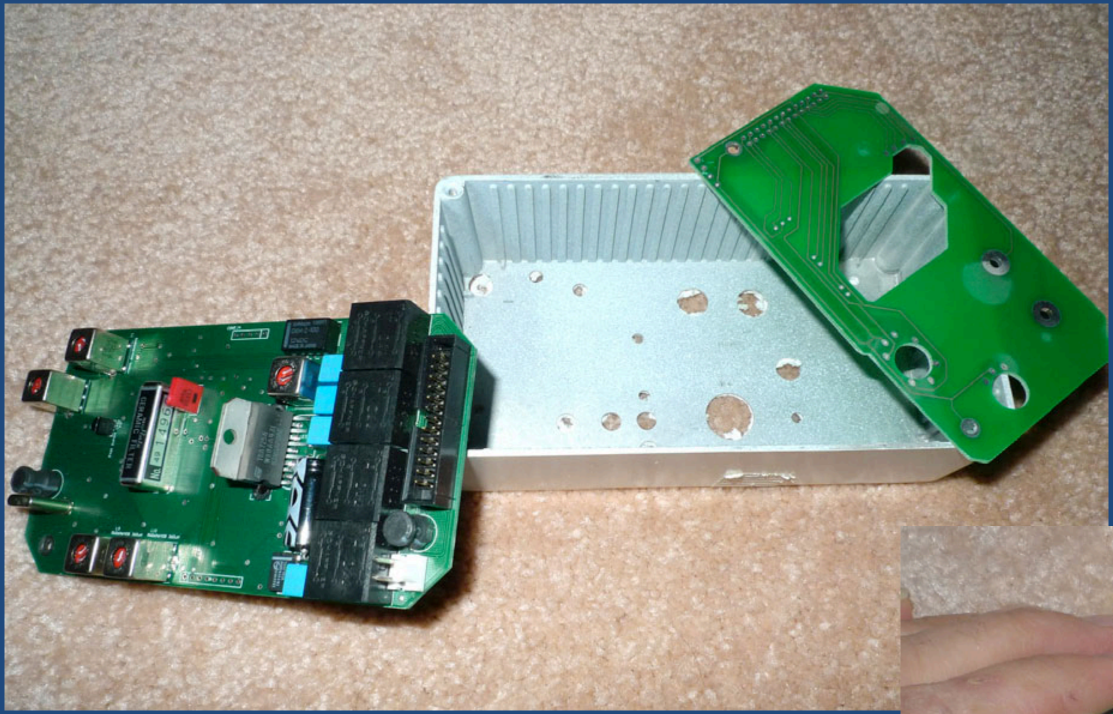
Nicola II

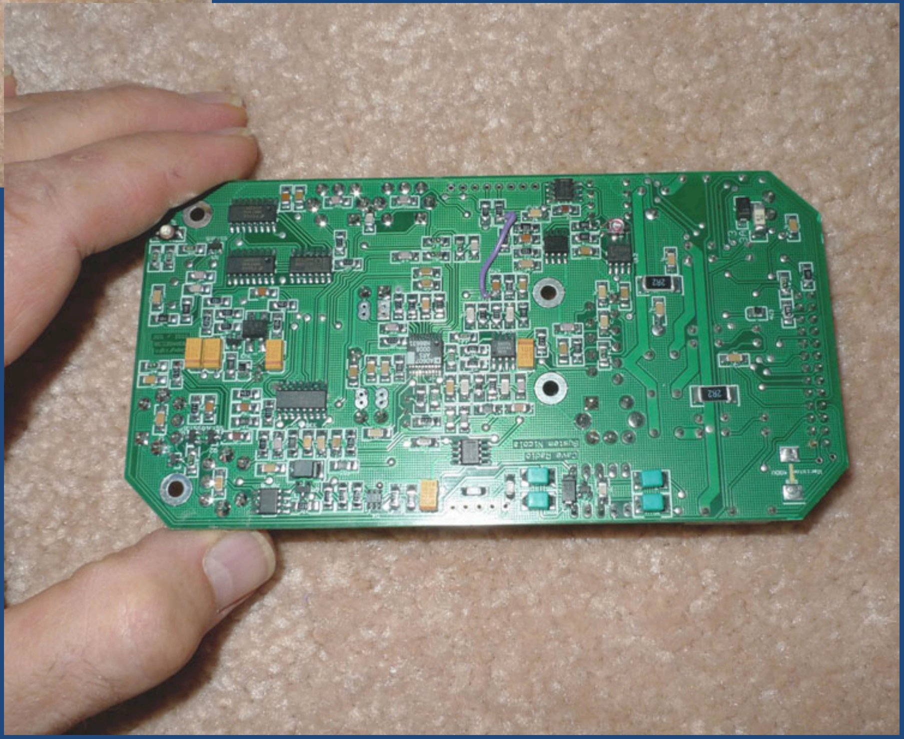


Nicola II Block Diagram

- 87 KHz heterodyne design using filter-generated SSB, surface mount, earth current antenna. Tested to 3900 ft depth

Nicola II





Nicola III is FPGA-based DSP, in prog

- John Hey developed a simplified DSB radio that reduced component count, 10 fewer IC's, 66 fewer resistors and 23 fewer caps.

- Tradeoff is wider BW, but reduced DC current

- 90 deg phasing networks not needed for LO or audio

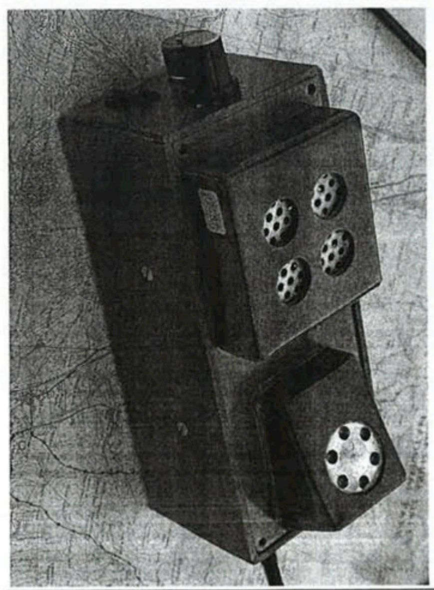
A Portable Double-Sideband Cave Radio

***John Hey** describes his "handiphone", a double-sideband cave radio that is intended to be compatible with the single-sideband HeyPhone. It does not offer ideal demodulation of the incoming SSB signals and some power is wasted by transmitting an unwanted sideband but, conversely, the DSB circuitry is simpler and allows the construction of a portable, hand-held device.*

At Hidden Earth 2004 in Kendal, two members of the Combined Services Caving Association asked if it was possible to design a truly portable cave radio, small enough to be carried in one's caving clobber, even if it meant carrying a small loop aerial.

Reduction in size could be achieved by a reduction in circuit complexity, using smaller, surface mount devices (SMD), or both. There wasn't a requirement for fancy refinements, bells and whistles, just a reliable talk box to enable communication with base or the main underground station over a range of 100m while investigating new passage.

The radio has to be compatible with existing equipment such as the HeyPhone (Hey, 2000) or similar and have built-in batteries and microphone. One thought came to mind: why not try double sideband (DSB), which would reduce the component count substantially.



A scribbled circuit which had the same gain, filtering and power output as the HeyPhone, would have – especially without the control circuitry – 10 ICs, 66 resistors and 23 capacitors fewer than the HeyPhone. Circuit elements plucked from the HeyPhone made the scribbled idea worth trying.

"But isn't DSB less efficient?" you might ask. It is true that transmitting two sidebands where one is sufficient for communication is wasteful, but the current saved by omitting ten ICs has to be considered.

A DSB signal is received normally by the HeyPhone; likewise the SSB signal from the HeyPhone is resolved by the DSB receiver without problem. (for a further discussion, see the Box on page 7)

Circuit Description

No longer able to master surface mount construction (poor old soul), a test unit has been built using 'ordinary' through-hole components. Already-proven circuit elements taken from the existing HeyPhone designs were rearranged into a neater formation.

Receiver

The RF input stage is retained, though it is suggested, if designing with surface mount, that the two FETs could be replaced by a single dual gate MOSFET. The second RF amplifier acts as an impedance converter with a modest gain of 3.7 (11dB). The local oscillator section is simplfied because this double sideband design no longer requires twin 90° signals. Consequently, the 4013 of the HeyPhone design is dispensed with; the output derived from pin 4 of the 4060.

Both receive and transmit mixers are in one 4053. Two-stage filtering is retained, as is the AGC circuit. There is no requirement for audio phase shifting components between mixer and filters.

Transmitter

The microphone amplifier and filter feed just one switching mixer or modulator; the single transistor and PA stage are retained from the HeyPhone design, as they do such a good job.

At the time of construction, a four pole change-over relay of low enough profile couldn't be found; so two DPDT relays were fitted. Further searching might unearth a suitable component.

The battery used in this prototype was a standard, small lead acid type similar to those used in the HeyPhone.

Performance

Trials indicate that the prototype Handiphone works well, with a range of between 150m and 200m when communicating with a HeyPhone and using a 300mm diameter loop antenna as previously described for use with a small cave radio (Hey, 1998). Of course, communications range would be greater if a full size loop or earth current antenna was used, but that would be defeating the object!

As expected, there were no problems of compatibility between this DSB transceiver and the SSB HeyPhone.

Further underground trials will take place at the forthcoming CREG field meeting.

Further Size Reduction

The photographs show that, despite the significant reduction in size in comparison with a HeyPhone, the prototype is larger than desirable, measuring approximately 165mm × 70mm × 60mm. Even so, it is possibly just small enough to be of use when investigating a small passage. Obviously, surface mount construction and a slim-line battery pack

CREG Journal 59, March 2005

- G3TDZ became SK
- The original HeyPhone was difficult to build anymore due to obsolete parts (Toko coils)
- Ian Cooper redesigned it to use SMT components and added microcontroller

Original HeyPhone (left) compared to new Micro HeyPhone (right)

Micro HeyPhone kitted with SLA battery, earth current stakes and long wires in Pelican case

CREG Journal 100, Dec. 2017

Concept for a New Cave Radio

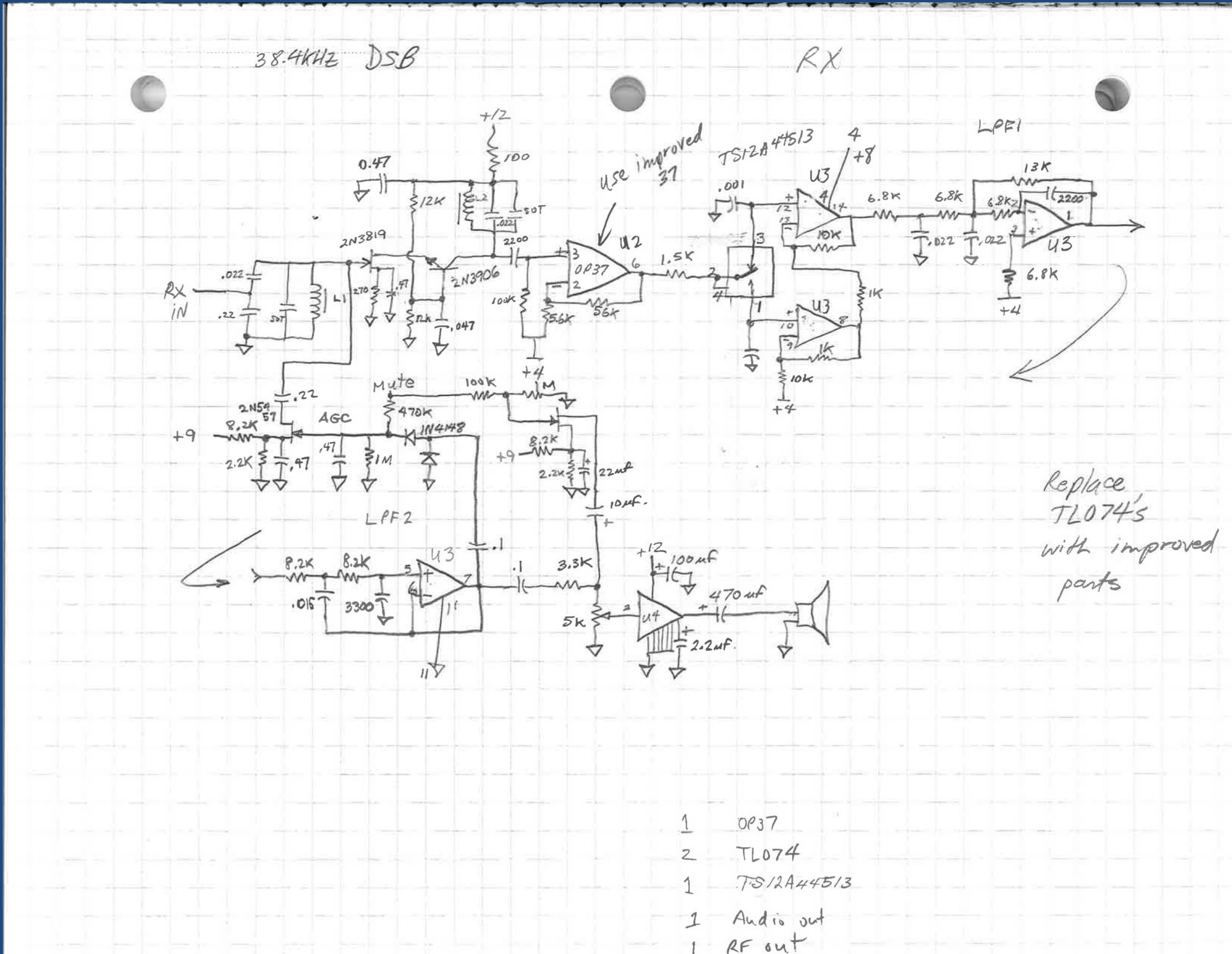
- Before Cooper's Micro HeyPhone report was published, I was investigating lightweight voice comm set that would work at depths of 500 feet, that is tolerant to summer atmospheric noise, for use in camp in Fort Stanton Cave.

- Lower frequency like 30-40 kHz is desirable for optimum signal over noise, but bandwidth of loop aerial would restrict audio reponse.

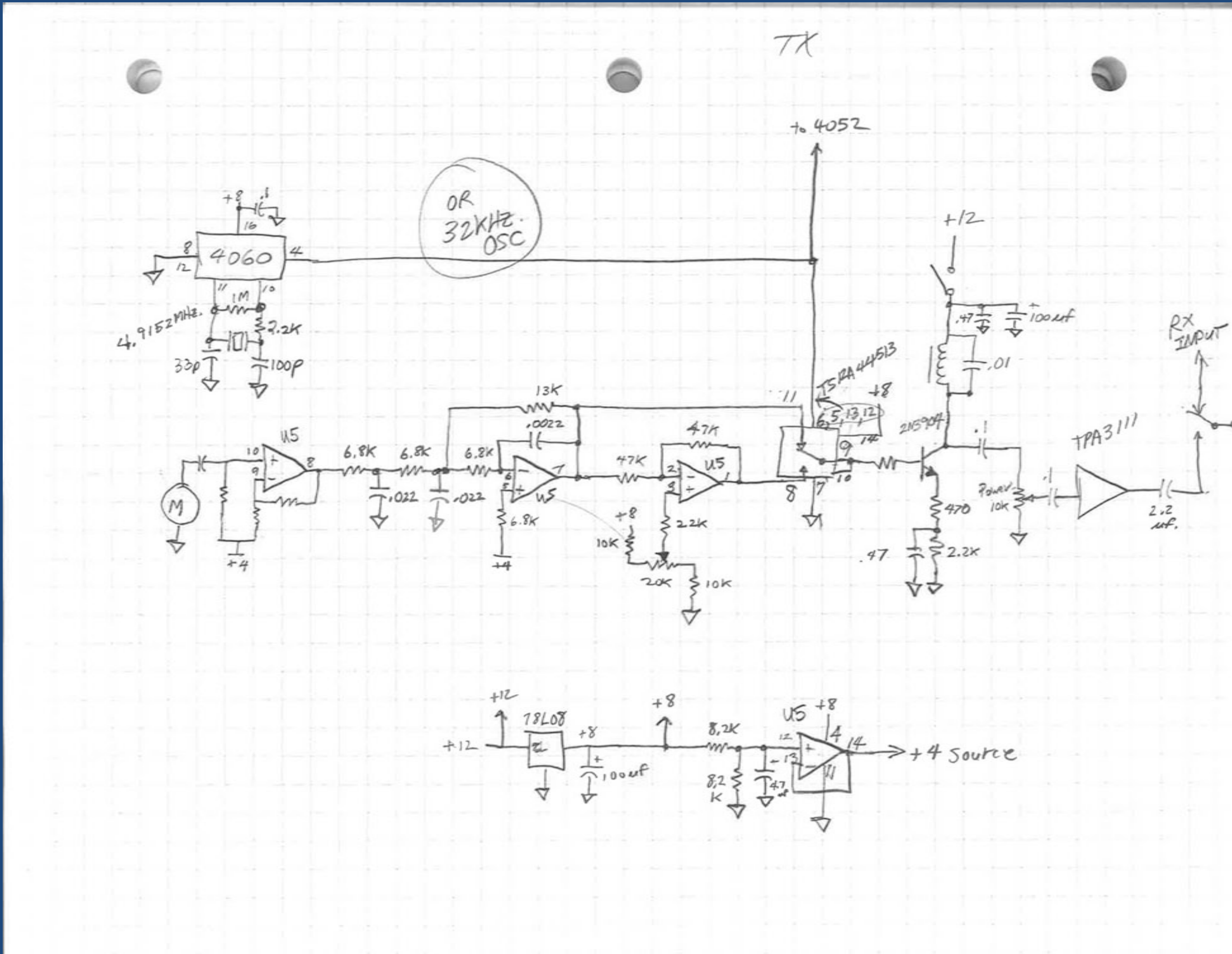
- Earth current injection like HeyPhone is a simple solution to bandwidth and extended range, as long as matching is accomplished.

- The simple radio uses a combination of the improvements and simplifications from John Hey's suggestions including double sideband + lower frequency

- Using SMT parts, this radio would be very compact and might use a high efficiency audio output driver (class D) for the RF.



Receiver side



Transmitter side

“RF” Output Stage Possibilities

TDA2003A

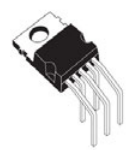
10 W car radio audio amplifier

Datasheet — production data

Features

- Improved performance over the TDA2002 (pin-to-pin compatible)
- Very low number of external components
- Ease of assembly
- Cost and space savings

Pentawatt (vertical)



Pentawatt (horizontal)

Description

The TDA2003A is capable of providing a high output current (up to 3.5 A) with very low harmonic and crossover distortion.

Completely safe operation is guaranteed due to DC and AC short-circuit protection between all pins and ground, a thermal limiting circuit, load dump voltage surge protection up to 40 V and protection diodes in case of accidental open ground.

TDA2030

14 W hi-fi audio amplifier

Features

- Wide-range supply voltage, up to 36 V
- Single or split power supply
- Short-circuit protection to ground
- Thermal shutdown

Pentawatt (horizontal)

Description

The TDA2030 is a monolithic integrated circuit in the Pentawatt® package, intended for use as a low frequency class-AB amplifier. Typically it provides 14 W output power (d = 0.5%) at 14 V/4 Ω. At ±14 V or 28 V, the guaranteed output power is 12 W on a 4 Ω load and 8 W on an 8 Ω (DIN45500).

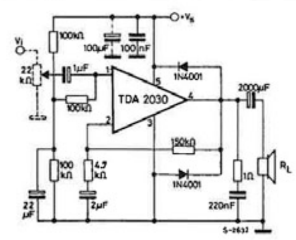
The TDA2030 provides high output current and has very low harmonic and crossover distortion.

Furthermore, the device incorporates an original (and patented) short-circuit protection system comprising an arrangement for automatically limiting the dissipated power so as to keep the operating point of the output transistors within their safe operating range. A conventional thermal shutdown system is also included.

Table 1. Device summary

Order code	Package
TDA2030H	Pentawatt horizontal

Figure 1. Ex: Functional block diagram



Have Samples

TEXAS INSTRUMENTS

TPA3111D1

10-W FILTER-FREE MONO CLASS-D AUDIO POWER AMPLIFIER with SPEAKER GUARD™

Check for Samples: TPA3111D1

FEATURES

- 10-W into an 8-Ω Load at 10% THD+N From a 12-V Supply
- 7-W into an 4-Ω Load at 10% THD+N From a 8-V Supply
- 94% Efficient Class-D Operation into 8-Ω Load Eliminates Need for Heat Sinks
- Wide Supply Voltage Range Allows Operation from 8 to 26 V
- Filter-Free Operation
- SpeakerGuard™ Speaker Protection Includes Adjustable Power Limiter plus DC Protection
- Flow Through Pin Out Facilitates Easy Board Layout
- Robust Pin-to-Pin Short Circuit Protection and Thermal Protection with Auto-Recovery Option
- Excellent THD+N/ Pop Free Performance
- Four Selectable, Fixed Gain Settings
- Differential Inputs

APPLICATIONS

- Televisions
- Monitor/Laptop
- Consumer Audio Equipment

DESCRIPTION

The TPA3111D1 is a 10-W efficient, Class-D audio power amplifier for driving a bridge tied speaker. Advanced EMI Suppresion Technology enables the use of inexpensive ferrite bead filters at the outputs while meeting EMC requirements. SpeakerGuard™ speaker protection system includes an adjustable power limiter and a DC detection circuit. The adjustable power limiter allows the user to set a "virtual" voltage rail lower than the chip supply to limit the amount of current through the speaker. The DC detect circuit measures the frequency and amplitude of the PWM signal and shuts off the output stage if the input capacitors are damaged or shorts exist on the inputs.

The TPA3111D1 can drive a mono speaker as low as 4Ω. The high efficiency of the TPA3111D1, > 90%, eliminates the need for an external heat sink when playing music.

The outputs are fully protected against shorts to GND, V_{CC}, and output-to-output. The short-circuit protection and thermal protection includes an auto-recovery feature.

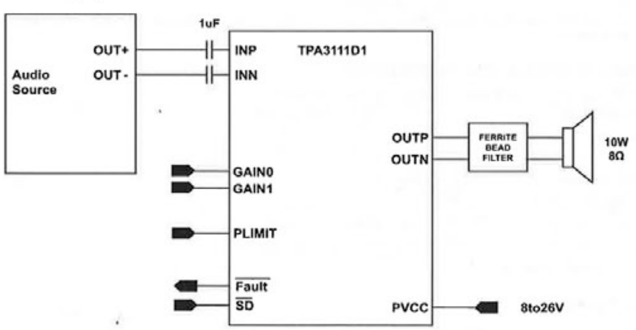


Figure 1. Simplified Application Diagram

Please be aware that an important notice concerning availability, standard warranty, and use in critical applications of Texas Instruments semiconductor products and disclaimers thereto appears at the end of this data sheet.

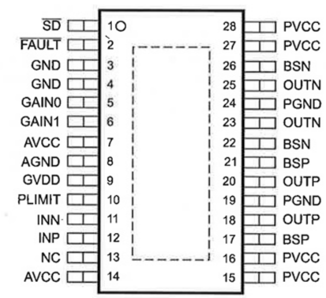
SpeakerGuard is a trademark of Texas Instruments.

AC CHARACTERISTICS

T_A = 25°C, V_{CC} = 12 V, R_L = 8 Ω (unless otherwise noted)

PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
K_{SVR}	Supply ripple rejection	200 mV_{PP} ripple from 20 Hz–1 kHz, Gain = 20 dB, Inputs ac-coupled to AGND		–70		dB
P_O	Continuous output power	THD+N ≤ 10%, f = 1 kHz , R_L = 8Ω		10		W
P_O	Continuous output power	THD+N ≤ 0.1%, f = 1 kHz , R_L = 4Ω		10		W
THD+N	Total harmonic distortion + noise	R_L = 8 Ω, f = 1 kHz, P_O = 5 W (half-power)		<0.06		%
V_n	Output integrated noise	20 Hz to 22 kHz, A-weighted filter, Gain = 20 dB		65		μV
				–80		dBV
	Crosstalk	P_o = 1 W, Gain = 20 dB, f = 1 kHz		–70		dB
SNR	Signal-to-noise ratio	Maximum output at THD+N < 1%, f = 1 kHz, Gain = 20 dB, A-weighted		102		dB
f_{OSC}	Oscillator frequency		250	310	350	kHz
	Thermal trip point			150		°C
	Thermal hysteresis			15		°C

PWP (TSSOP)Package
(TopV iew)

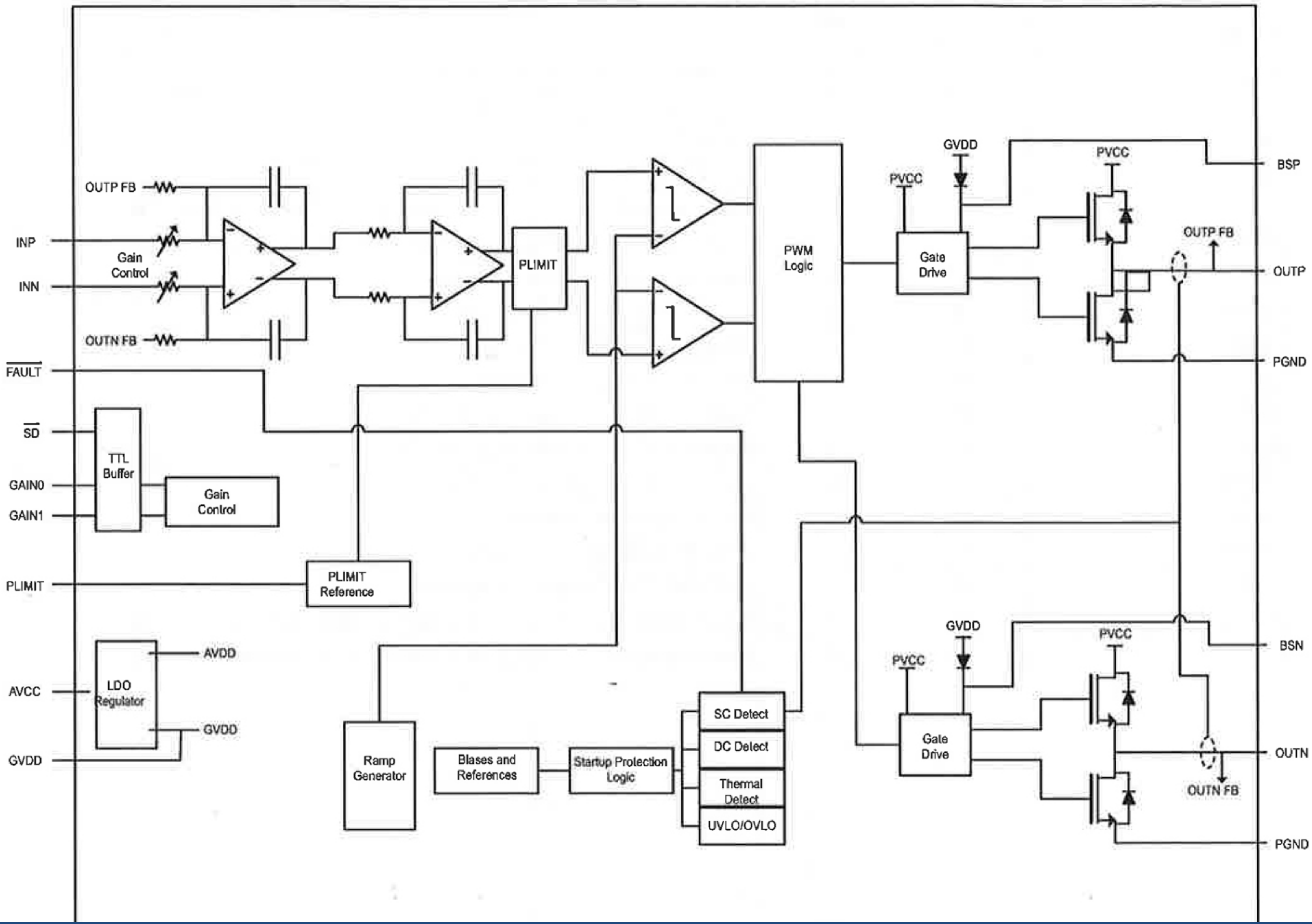


PIN FUNCTIONS

PIN		I/O	DESCRIPTION
NAME	Pin #		
$\overline{SD}$	1	I	Shutdown logic input for audio amp(LOW = outputs Hi-Z, HIGH = outputs enabled). TTL logic levels with compliance to AVCC.
$\overline{FAULT}$	2	O	Open drain output used to display short circuit or dc detect fault status. Voltage compliant to AVCC. Short circuit faults can be set to auto-recovery by connecting $\overline{FAULT}$ pin to $\overline{SD}$ pin. Otherwise bothe short circuit faults and dc detect faults must be reset by cycling PVCC.
GND	3		Connect to local ground
GND	4		Connect to local ground
GAIN0	5	I	Gain select least significant bit. TTL logic levels with compliance to AVCC.
GAIN1	6	I	Gain select most significant bit. TTL logic levels with compliance to AVCC.
AVCC	7	P	Analog supply.
AGND	8		Analog supply ground. Connect to the thermal pad.
GVDD	9	O	High-side FET gate drive supply. Nominal voltage is 7V. May also be used as supply for PLILMIT divider. Add a 1μF cap to ground at this pin.
PLIMIT	10	I	Power limit level adjust. Connect directly to GVDD pin for no power limiting. Add a 1μF cap to ground at this pin.

Higher Efficiency Alternative Output Stage

FUNCTIONAL BLOCK DIAGRAM



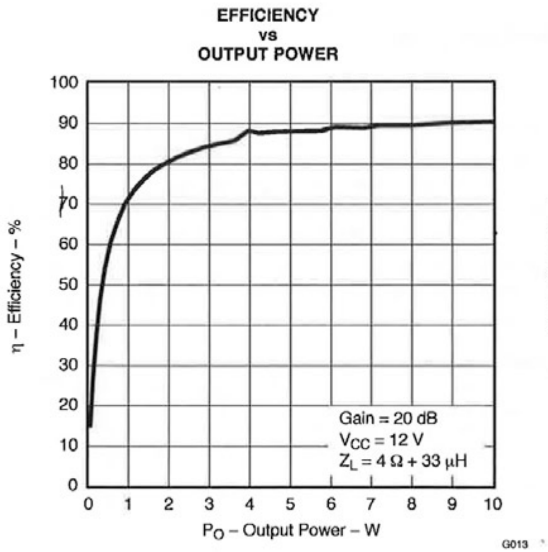


Figure 12.

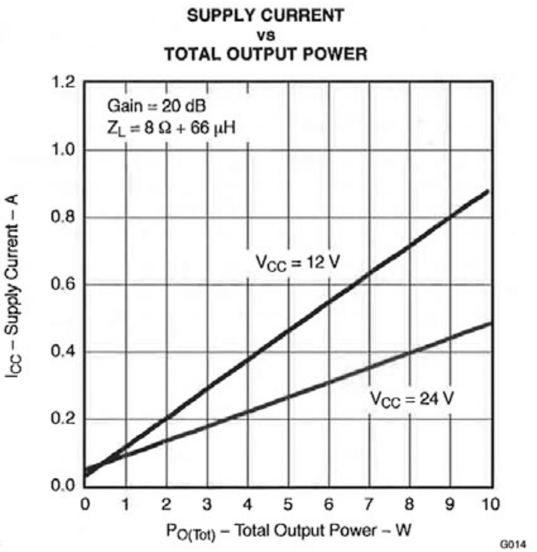
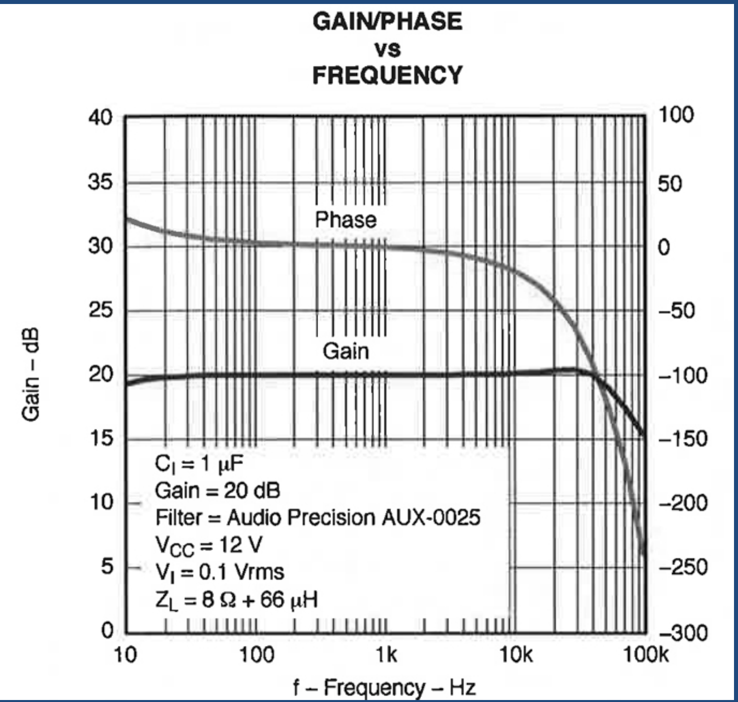


Figure 13.



- Before building another sideband radio, it was worth considering a text only system.

- Text/Data mode is robust due to narrow bandwidth. It also can work at lower frequency where the Q of the loop would distort voice modulation severely.

Digital Modulations of Interest

Category	Mode Designation	Baud Rate (Hz)	Phases / Frequencies	Data Throughput		Bandwidth (Hz)	Forward Error Correction	Minimum Signal-to-Noise Ratio (dB)
				Upper Case Only	Full ASCII			
Phase Shift Keying	BPSK31	31.25	2	51	37	80	N	-11.5
	QPSK31	31.25	4	51	37	80	Y	-11.5
	BPSK63	62.5	2	102	74	160	N	-7
	QPSK63	62.5	4	102	74	160	Y	-8
	PSK63F	62.5	2	42	N/A	160	Y	-12
	PSKFEC63	62.5	2	28	N/A	160	Y	-14.5
MFSK	MFSK8	7.8125	16	N/A	26	316	Y	-15.5
	MFSK16	15.625	16	N/A	42	316	Y	-13.5
	WSPR	1.4648	4	5.4	N/A	6	Y	-28
	JT65	2.69	64	3	N/A	180	Y	-24
Reference Modes	SSB (speech)	N/A	N/A	N/A	N/A	2,500	N/A	+6
	CW (Morse)	10	2 levels	12	N/A	48	N/A	-12
	QRSS (Slow Morse)	0.008	2 levels	0.02	N/A	0.017	N/A	-33

CREG Journal 97, March, 2017

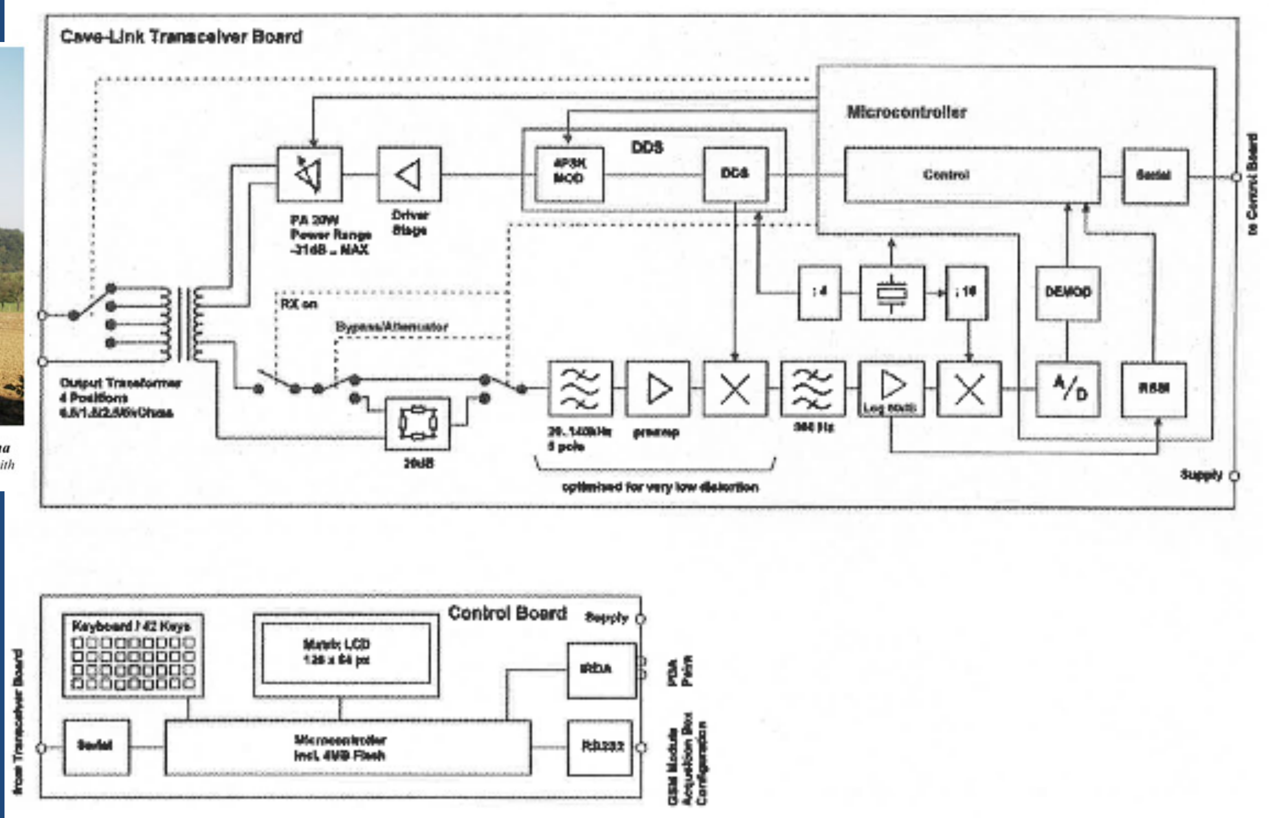
Robust Text and Data Exchange with Earth-Current Transceivers

Jacques Hurni, Felix Ziegler HB9CPZ and Christian Ebi HB9ZG *describe the development of a pollution warning system using robust earth current data transmission linked to a GSM modem to monitor water level, flow and fluorescence. Link status and battery levels are also reported, with data presented on a regularly updated web page.*

- 20-140 KHz QPSK
- Earth current
- 3160 ft depth

Underground Equipment
All equipment apart from sensors is contained in a single waterproof enclosure

Surface Equipment with GSM antenna
Keyboard and display aid communication with cave station during configuration



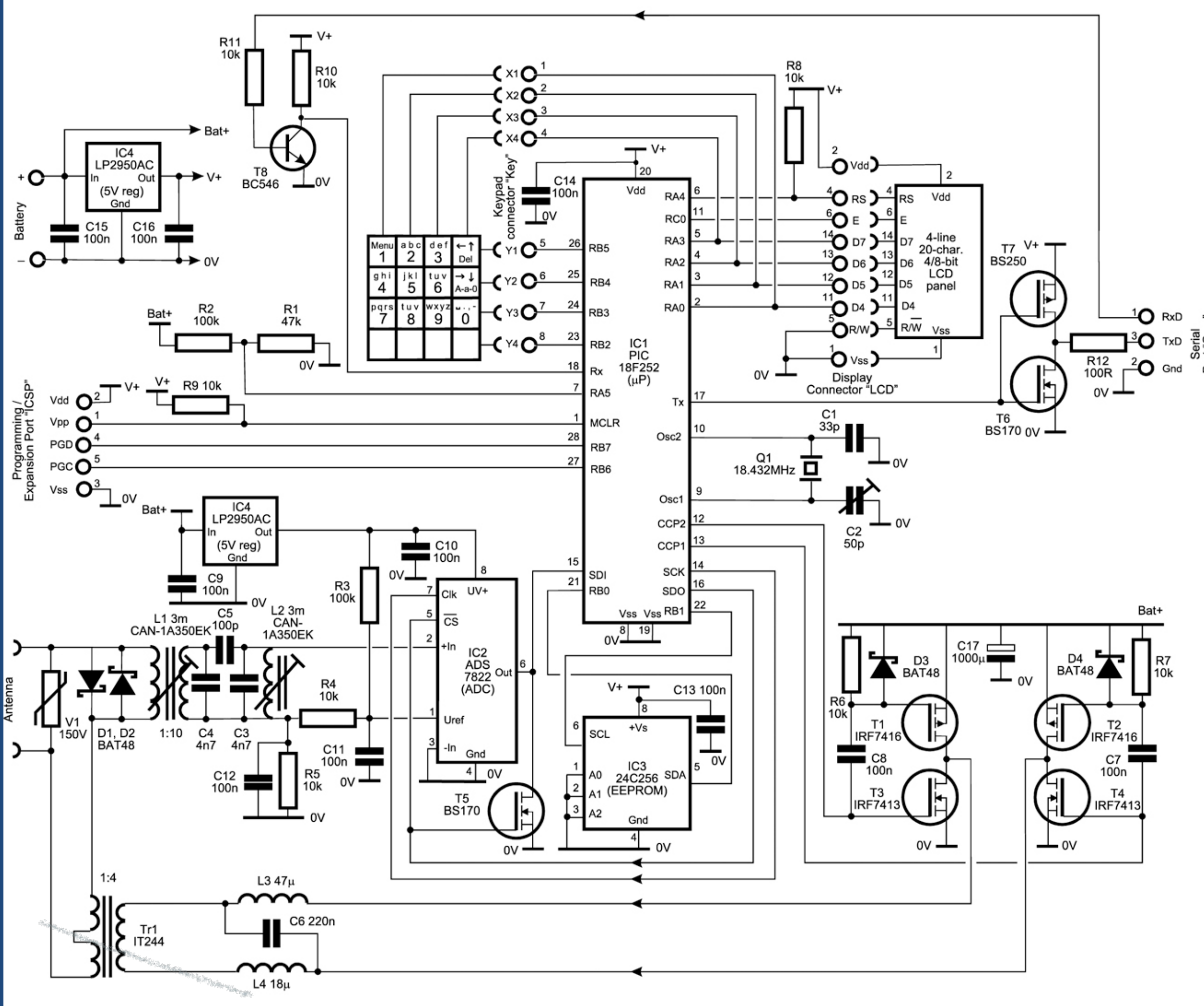
Transceiver and Control Modules

CREG Journal 63, June 2006

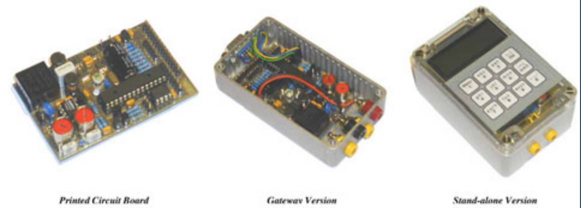
Underground Text Messaging

*This cave radio transmits text and features a keypad and display not unlike a mobile phone. Data packets feature several levels of coding for error detection and correction, and are transmitted at 55 bit/s D-BPSK on a 42.6kHz carrier. Designer **Beat Heeb** has achieved cave communications at up to 1000m for 5W power.*

- 42.6 KHz BPSK
- Earth Current
- 3300 ft depth

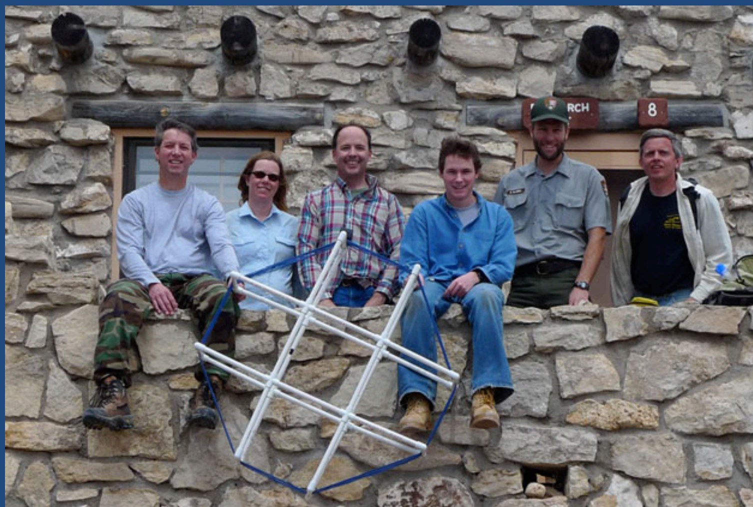


Schematic of Stand-alone Version

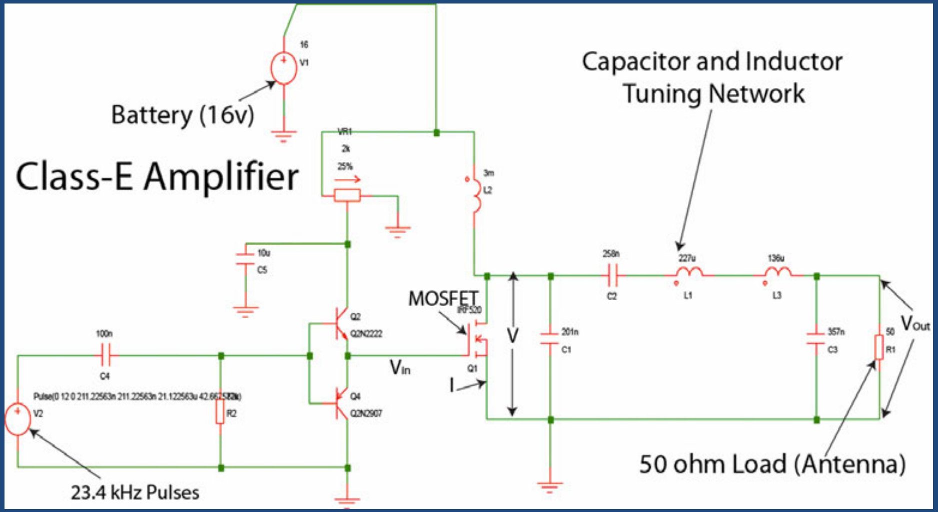


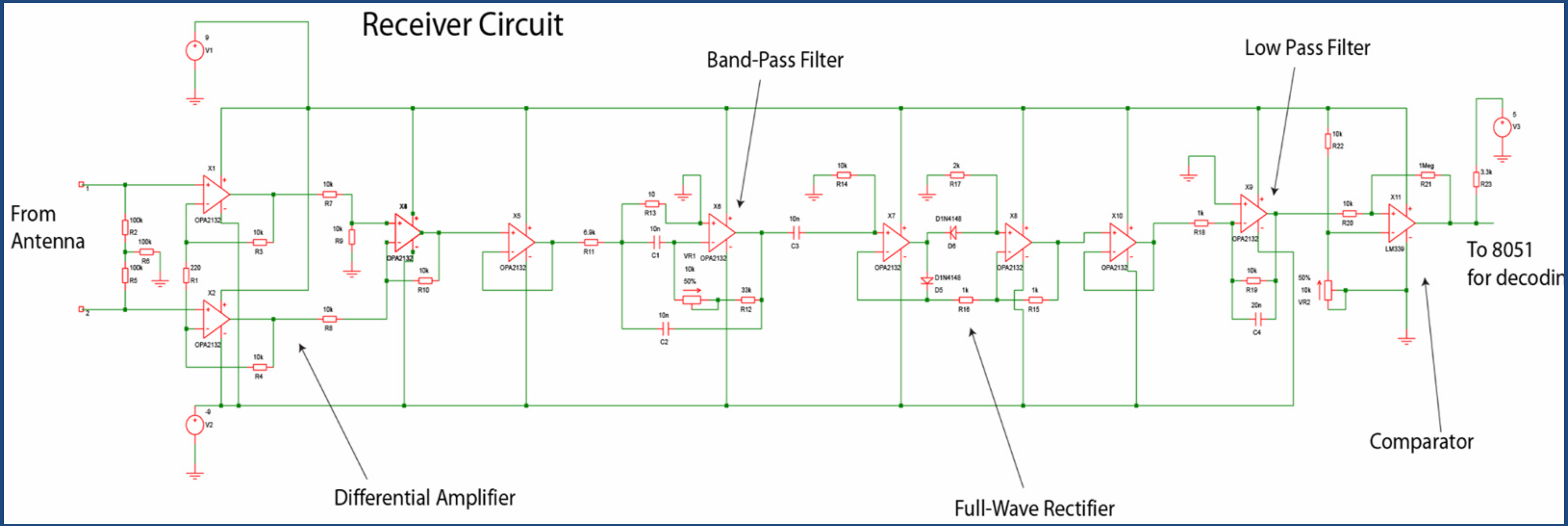
CREG Journal 57, Sept. 2004

Alex Kendrick's digital radio, winning school science project (2009), heard on NPR Radio



- 23.4 KHz prototype
- 25 turn loop
- Simple on/off keying
- Custom alpha code using PWM
- Noise reduction circuit





23.4 KHz, On-Off Keyed, Data Slicer in Detector

Profile Map of Carlsbad Caverns

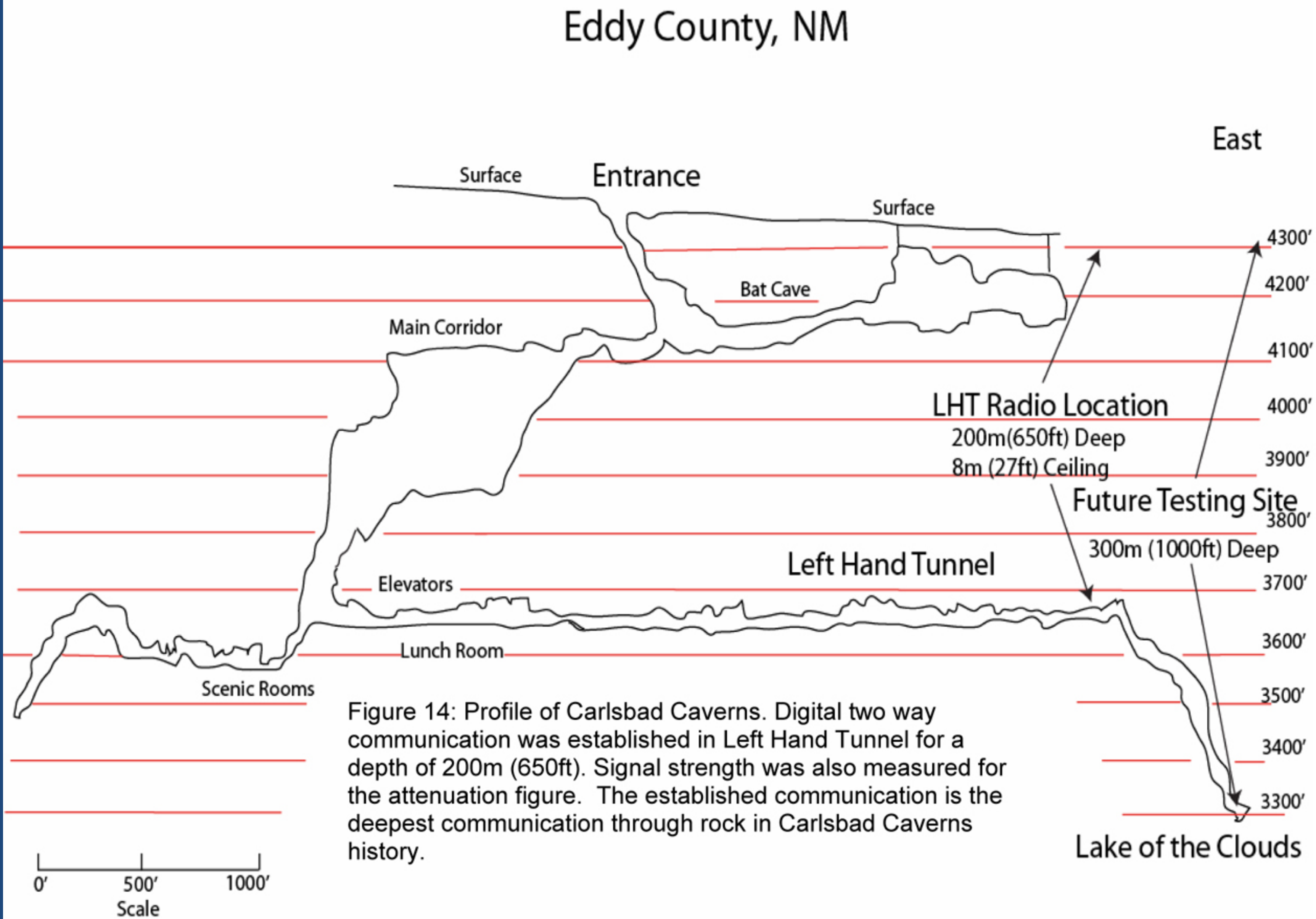


Figure 14: Profile of Carlsbad Caverns. Digital two way communication was established in Left Hand Tunnel for a depth of 200m (650ft). Signal strength was also measured for the attenuation figure. The established communication is the deepest communication through rock in Carlsbad Caverns history.

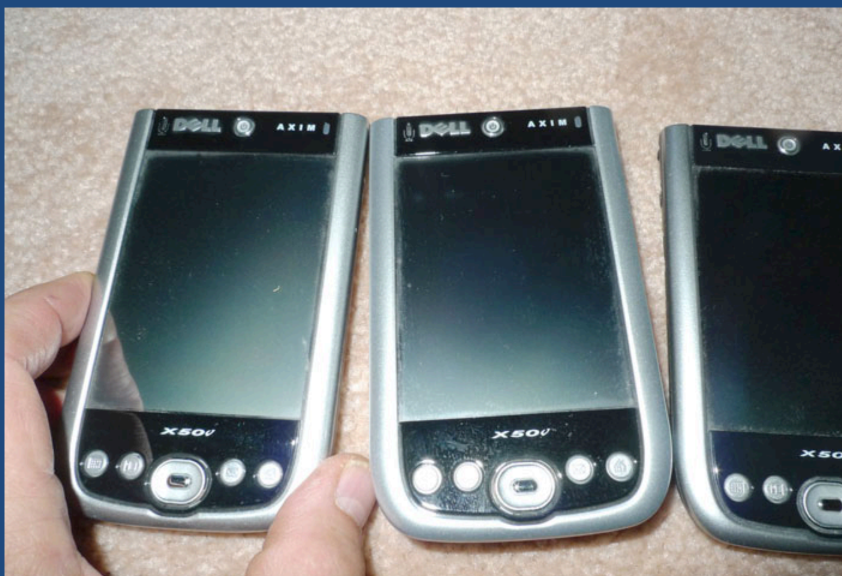
- PSK31 is a reasonable choice for a simple digital cave radio, using varicode symbols for a simple alphanumeric character set. No error correction, acceptable for a type-along text mode. It was developed 20 years ago and is occasionally heard on HF bands.

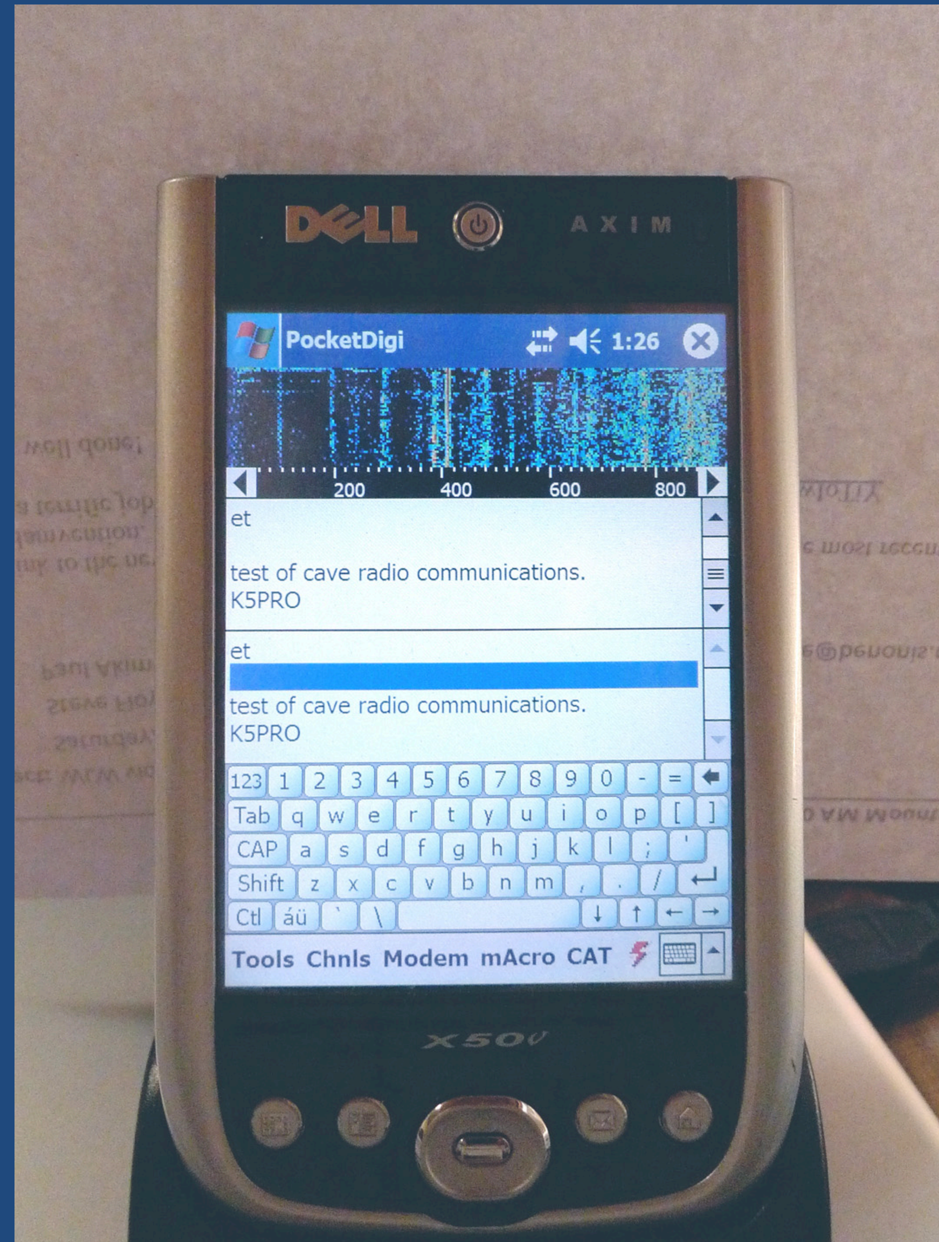
- Being narrowband, it would work with tuned loops or earth current transmission if used with LF/VLF carrier. In fact, it could be directly injected as PSK audio (~1500 Hz) into the ground with two stakes, requiring a small audio PA.

- Binary phase shift keying, reversing a carrier 180 deg, with 31.25 Hz bps rate.

- Dell Axim X50 series PDA uses Windows CE ("Win Mobile") and has hardwired audio in/out ports like a sound card. It is no longer made so I bought a handful of them on ebay in 2012.

- Smartphones can similarly produce the signal these days *(AndFlmsg)* but often lack the direct 3.5mm connection of transmit and receive audio.


DELL AXIM
X50v


DELL AXIM
PocketDigi 1:26
200 400 600 800
et
test of cave radio communications.
K5PRO
et
test of cave radio communications.
K5PRO
Tools Chnls Modem mAcro CAT
X50v

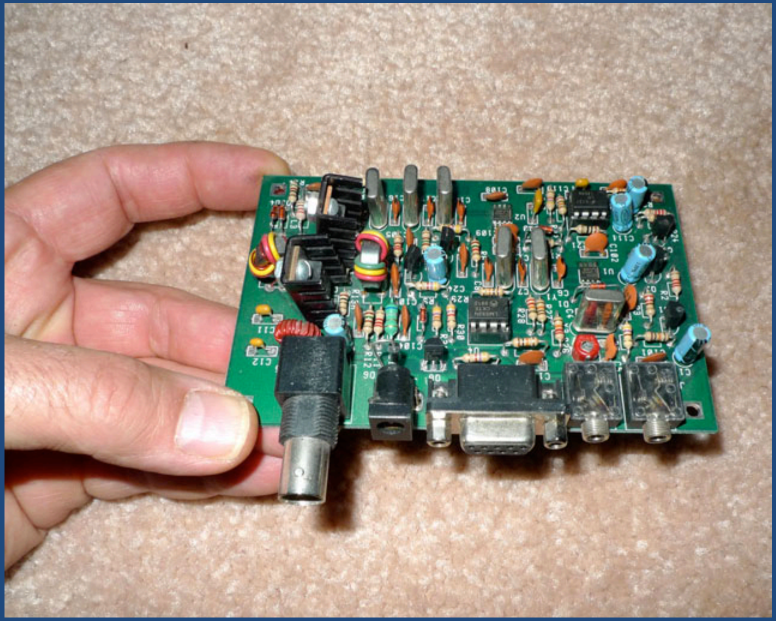
There are at least two ways to implement PSK31 underground

- Direct earth current drive from H-bridge with power FETs from the baseband audio. Reversals of phase of the audio tone could be done by opposing switches in the bridge. Peter Martinez (of PSK-31) suggested this to me. This can be a high efficiency class D audio driver. Receiving side requires decent band pass filtering as there is plenty of electrical noise inthe earth.

- Use of SSB RF as we use as hams, but LF. This could use earth current or a loop. PSK-31 has amplitude (envelope) modulation at the phase transitions, to reduce the signal bandwidth. This can be ignored or clipped off for cave radios, as who is listening? Nonlinear amplifiers like class D or E would suffice, as there is only a pair of radios on a single channel.

- In March 2001 QST, Dave Benson introduced his PSK-80 ‘warbler’ radio transceiver. It was first commercialized by NJQRP club for over a year, then Benson sold them for a decade as a kit from Small Wonder Labs. They were discontinued years ago.

- It was a direct conversion low power radio using cheap 3.579 MHz colorburst crystals from analog television. Using them as crystal filters as well as the LO for the first mixer, it downconverts directly to audio from 80 meter ham frequency. Warbler skimped on tuned RF networks, using crystals for selectivity. Sensitivity was not a strength.



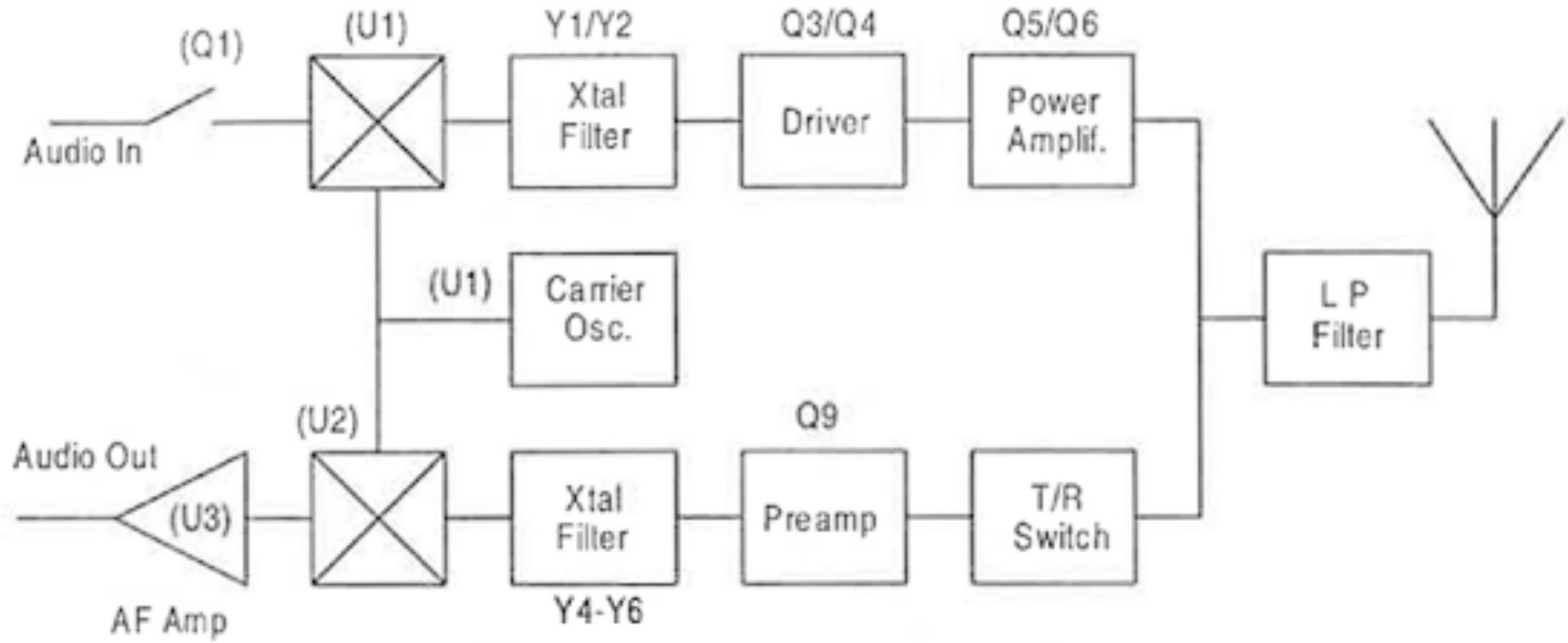
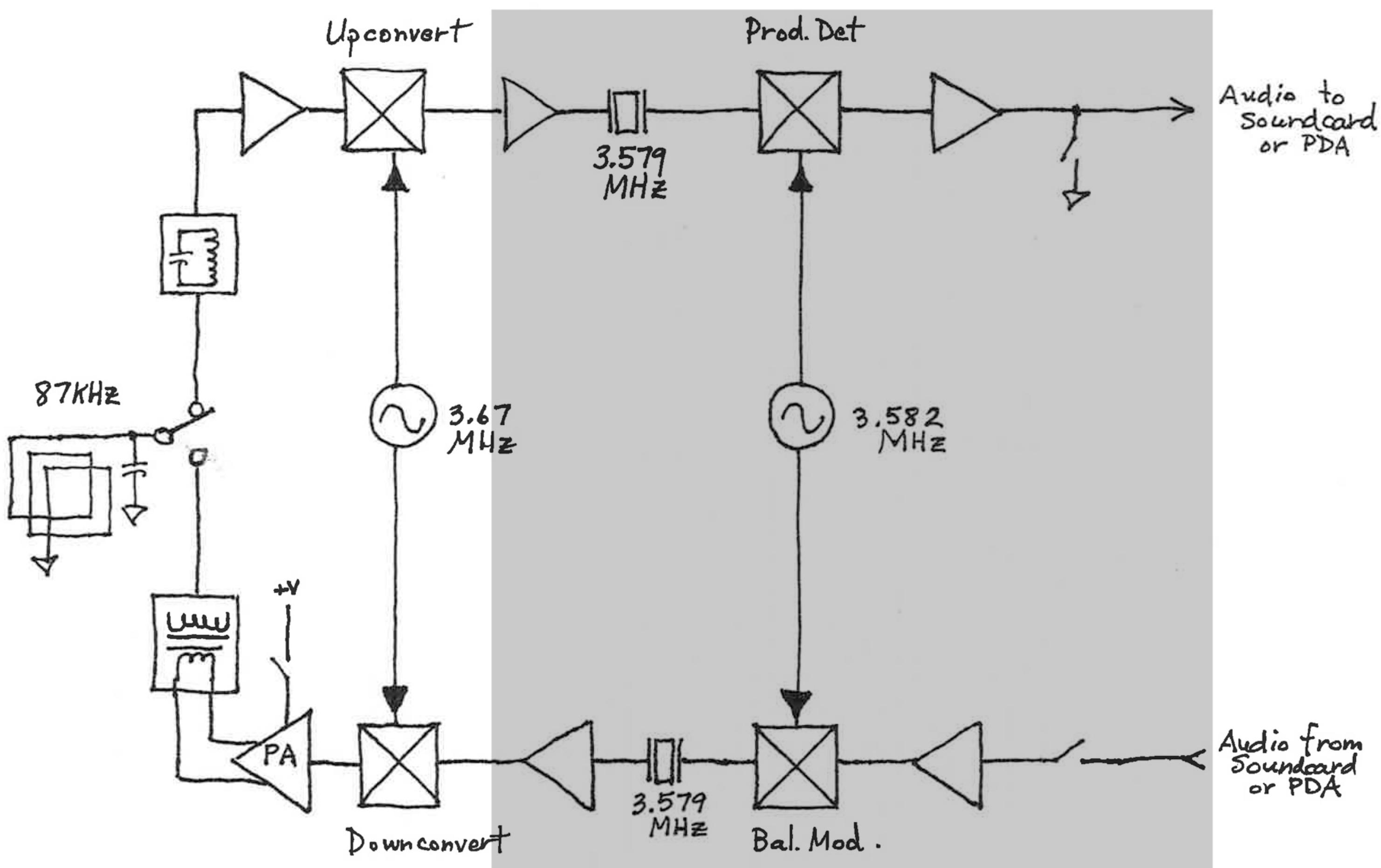


Figure 2: Warbler block diagram

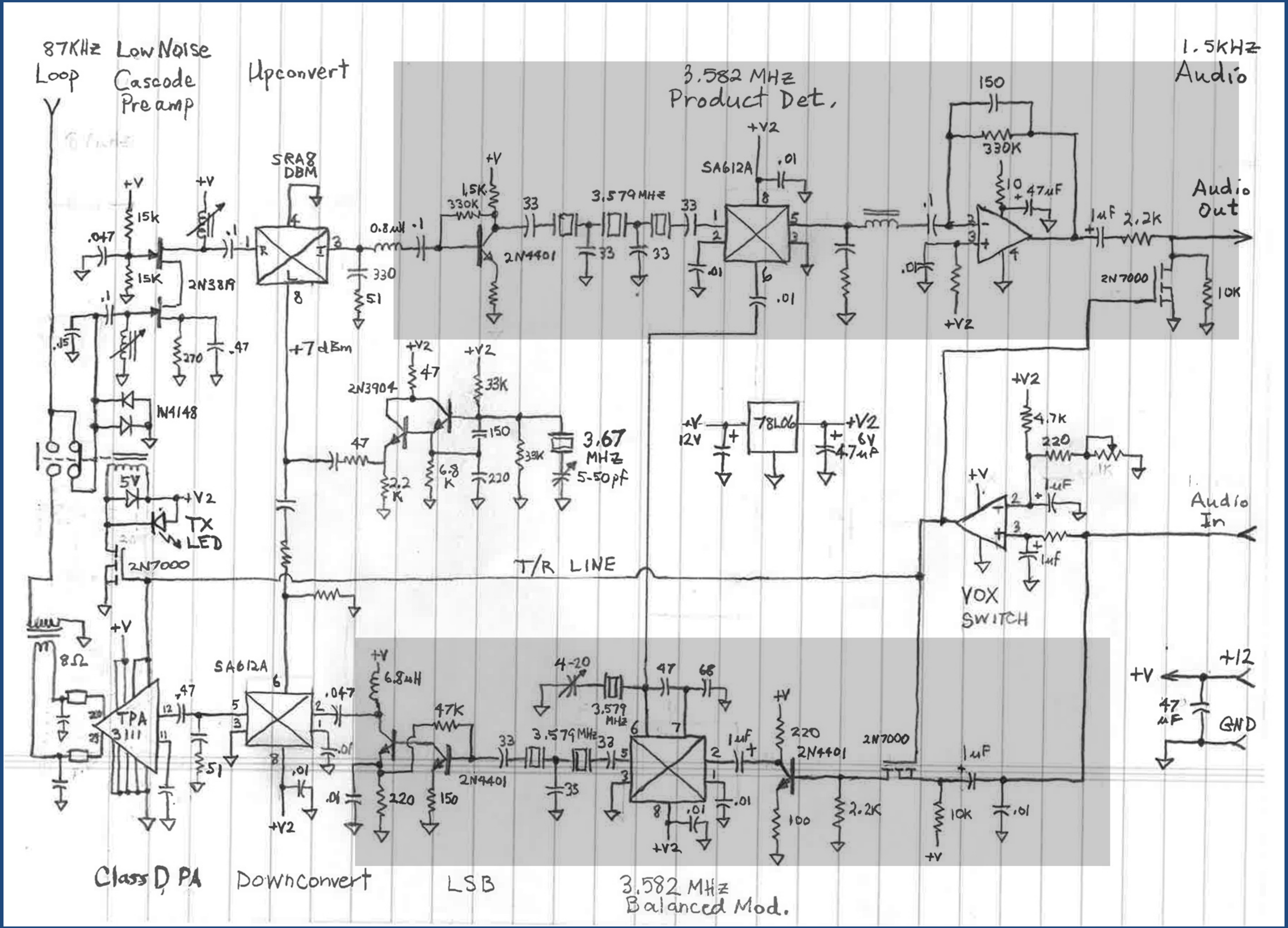
- This simple direct conversion design could be modified using mixers to upconvert VLF to 3.58 MHz and vice versa
- 3.541, 3.5 and 3.68 MHz crystals are available for second LO, to make XCVR that can tune 21 or 82 KHz.

87KHz PSK-31 RADIO



ALL SWITCHES SHOWN IN RECEIVE POSITION

2013 K5PRO



Superhetrodyne Warbler for 87 KHz PSK31

Is it worth it?

10-W FILTER-FREE MONO CLASS-D AUDIO POWER AMPLIFIER with SPEAKER GUARD™

Check for Samples: TPA3111D1

FEATURES

- 10-W into an 8-Ω Load at 10% THD+N From a 12-V Supply
- 7-W into an 4-Ω Load at 10% THD+N From a 8-V Supply
- 94% Efficient Class-D Operation into 8-Ω Load Eliminates Need for Heat Sinks
- Wide Supply Voltage Range Allows Operation from 8 to 26 V
- Filter-Free Operation
- SpeakerGuard™ Speaker Protection Includes Adjustable Power Limiter plus DC Protection
- Flow Through Pin Out Facilitates Easy Board Layout
- Robust Pin-to-Pin Short Circuit Protection and Thermal Protection with Auto-Recovery Option
- Excellent THD+N/ Pop Free Performance
- Four Selectable, Fixed Gain Settings
- Differential Inputs

APPLICATIONS

- Televisions
- Monitor/Laptop
- Consumer Audio Equipment

DESCRIPTION

The TPA3111D1 is a 10-W efficient, Class-D audio power amplifier for driving a bridge tied speaker. Advanced EMI Suppresion Technology enables the use of inexpensive ferrite bead filters at the outputs while meeting EMC requirements. SpeakerGuard™ speaker protection system includes an adjustable power limiter and a DC detection circuit. The adjustable power limiter allows the user to set a "virtual" voltage rail lower than the chip supply to limit the amount of current through the speaker. The DC detect circuit measures the frequency and amplitude of the PWM signal and shuts off the output stage if the input capacitors are damaged or shorts exist on the inputs.

The TPA3111D1 can drive a mono speaker as low as 4Ω. The high efficiency of the TPA3111D1, > 90%, eliminates the need for an external heat sink when playing music.

The outputs are fully protected against shorts to GND, V_{CC}, and output-to-output. The short-circuit protection and thermal protection includes an auto-recovery feature.

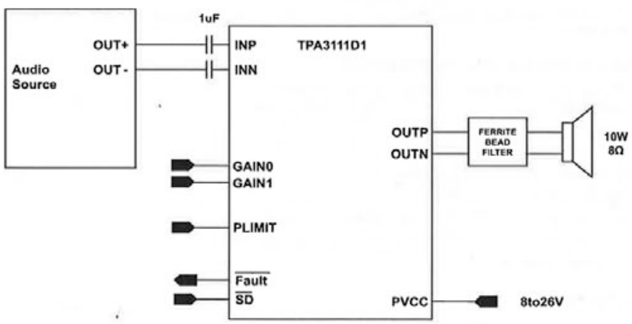


Figure 1. Simplified Application Diagram

Please be aware that an important notice concerning availability, standard warranty, and use in critical applications of Texas Instruments semiconductor products and disclaimers thereto appears at the end of this data sheet.

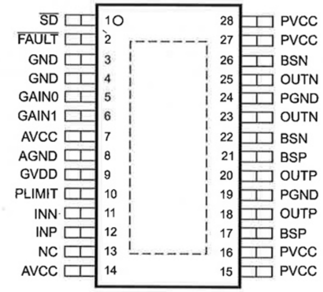
SpeakerGuard is a trademark of Texas Instruments.

AC CHARACTERISTICS

T_A = 25°C, V_{CC} = 12 V, R_L = 8 Ω (unless otherwise noted)

PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
K_{SVR}	Supply ripple rejection	200 mV_{PP} ripple from 20 Hz–1 kHz, Gain = 20 dB, Inputs ac-coupled to AGND		–70		dB
P_O	Continuous output power	THD+N ≤ 10%, f = 1 kHz , R_L = 8Ω		10		W
P_O	Continuous output power	THD+N ≤ 0.1%, f = 1 kHz , R_L = 4Ω		10		W
THD+N	Total harmonic distortion + noise	R_L = 8 Ω, f = 1 kHz, P_O = 5 W (half-power)		<0.06		%
V_n	Output integrated noise	20 Hz to 22 kHz, A-weighted filter, Gain = 20 dB		65		μV
				–80		dBV
	Crosstalk	P_o = 1 W, Gain = 20 dB, f = 1 kHz		–70		dB
SNR	Signal-to-noise ratio	Maximum output at THD+N < 1%, f = 1 kHz, Gain = 20 dB, A-weighted		102		dB
f_{OSC}	Oscillator frequency		250	310	350	kHz
	Thermal trip point			150		°C
	Thermal hysteresis			15		°C

PWP (TSSOP)Package
(TopV lew)



PIN FUNCTIONS

PIN		I/O	DESCRIPTION
NAME	Pin #		
SD	1	I	Shutdown logic input for audio amp(LOW = outputs Hi-Z, HIGH = outputs enabled). TTL logic levels with compliance to AVCC.
FAULT	2	O	Open drain output used to display short circuit or dc detect fault status. Voltage compliant to AVCC. Short circuit faults can be set to auto-recovery by connecting FAULT pin to SD pin. Otherwise bothe short circuit faults and dc detect faults must be reset by cycling PVCC.
GND	3		Connect to local ground
GND	4		Connect to local ground
GAIN0	5	I	Gain select least significant bit. TTL logic levels with compliance to AVCC.
GAIN1	6	I	Gain select most significant bit. TTL logic levels with compliance to AVCC.
AVCC	7	P	Analog supply.
AGND	8		Analog supply ground. Connect to the thermal pad.
GVDD	9	O	High-side FET gate drive supply. Nominal voltage is 7V. May also be used as supply for PLILMIT divider. Add a 1μF cap to ground at this pin.
PLIMIT	10	I	Power limit level adjust. Connect directly to GVDD pin for no power limiting. Add a 1μF cap to ground at this pin.

Output stage

HF is another possibility

- Work by hams suggests that HF attenuation through rock in arid regions is not as severe as thought. For decades LF and VLF were the only methods used.

- The increased efficiency of tuned half-wave dipoles and loops at HF has advantage over electrically short LF antennas.

- Magnetic loops only have one turn instead of dozens but would be high Q and have sensitive tuning. Probably not practical underground.

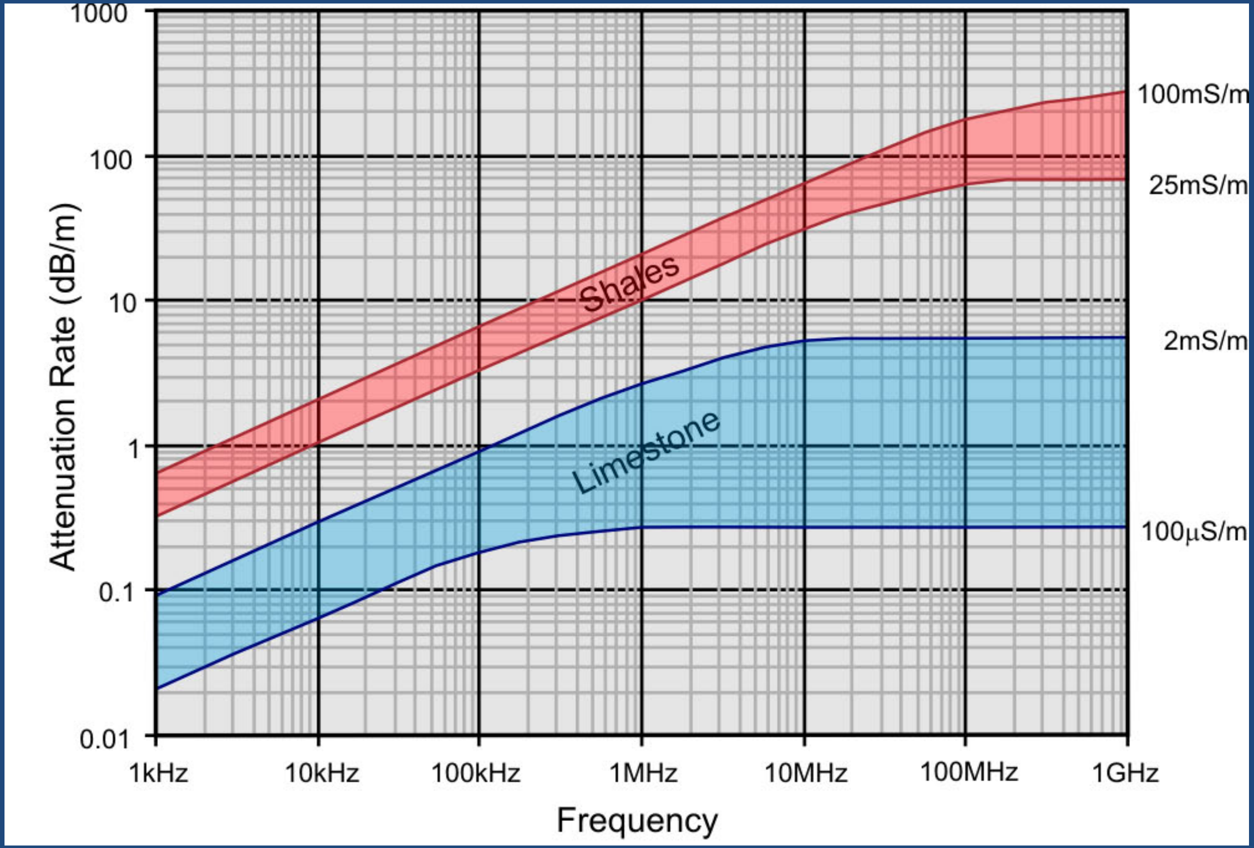
A common equation for the attenuation of an EM signal due to passage through conductive media relates to the skin depth as follows:

$$\delta = \sqrt{2/\omega\mu\sigma}$$

σ is the electrical conductivity of the media in S/m. The skin depth is the distance over which the signal is attenuated by 1/e which equates to 8.7dB.

While this gives a reasonable estimate at LF, it applies only when the rock can be considered a good conductor. This does not apply to limestone throughout the HF band.

This shows how the skin depth attenuation varies with frequency for a typical range of limestones and a typical range of sedimentary rocks such as shale. It can be seen that the attenuation in limestone at 7MHz may be 1.6 to 6 times greater than that at 185 kHz, less than the factor of 9 expected from skin effect using conductive approximation.



CREG Journal 92, Dec. 2015

- HF radio brings the convenience of using COTS rigs instead of hand-made LF radio equipment
- It requires having an amateur radio license, but many cavers have that so not an issue
- HF propagation from the surface radio will cover long distances, compared to LF induction-mode (magnetic) communication
- Using conventional radio wave propagation, $1/r^2$ decay
- Also consider 630 meter ham band - no equipment (yet)

- Work by Paul Jorgensen, KE7HR, proved that HF frequencies had some potential for through-earth communication and vice versa.

- Tests at Carlsbad Cavern using FT817-ND with 3.9 MHz SSB and 5 watts demonstrated reliable voice communications to 780 feet depth.

Grand Canyon Caverns, AZ
Using FT817ND and K2 on 3.9 MHz in 2006

Paul, KE7HR

Ray, KE7CPI

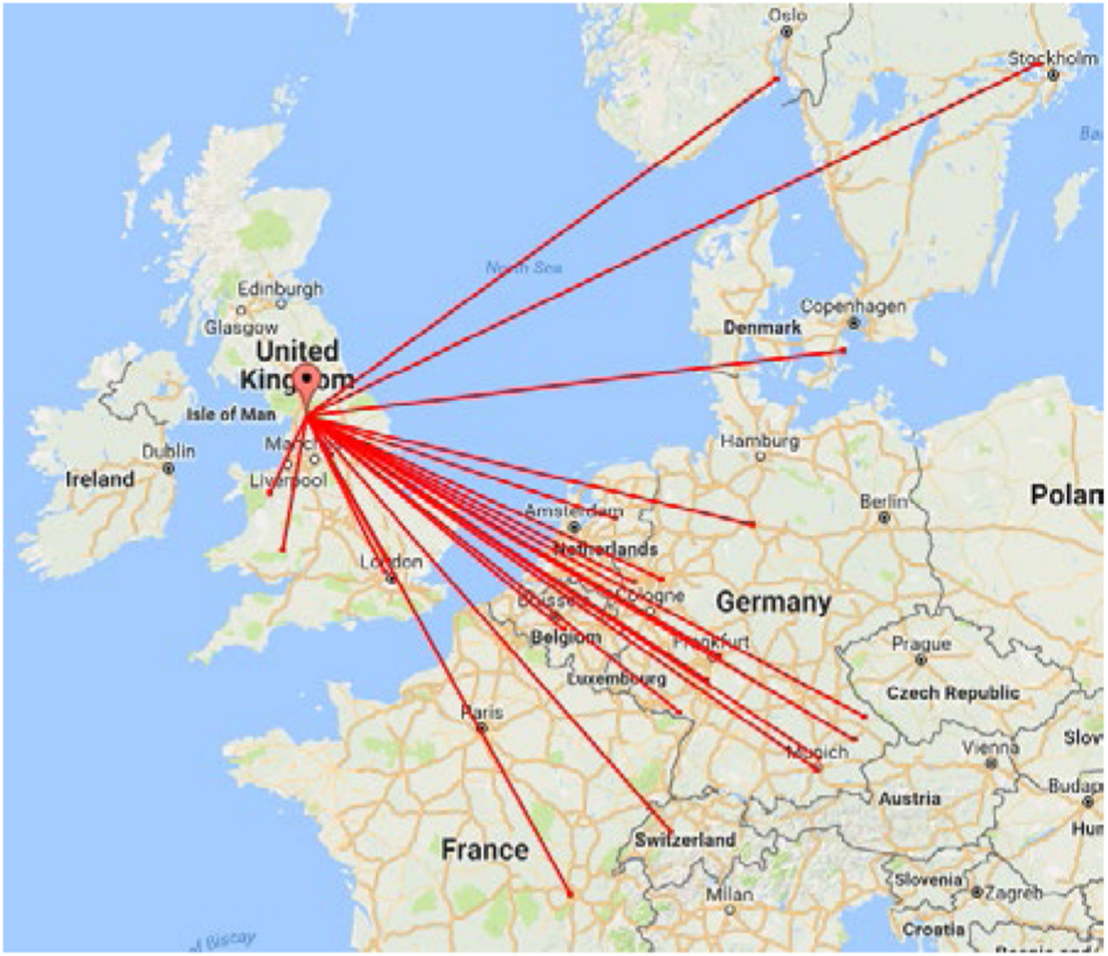
In 2015, the UK Cave Radio and Electronics Group published HF communications results with 7.135 MHz SSB using FT706 and 20 watts with half wave dipole antennas. Depth was about 330 feet, and slant distance between radios was about 1270 feet.

The communication can be heard here:

https://youtu.be/cOIgXozmE1Y

CREG Journal 95, Sept. 2016

CREG Journal 92, Dec. 2015

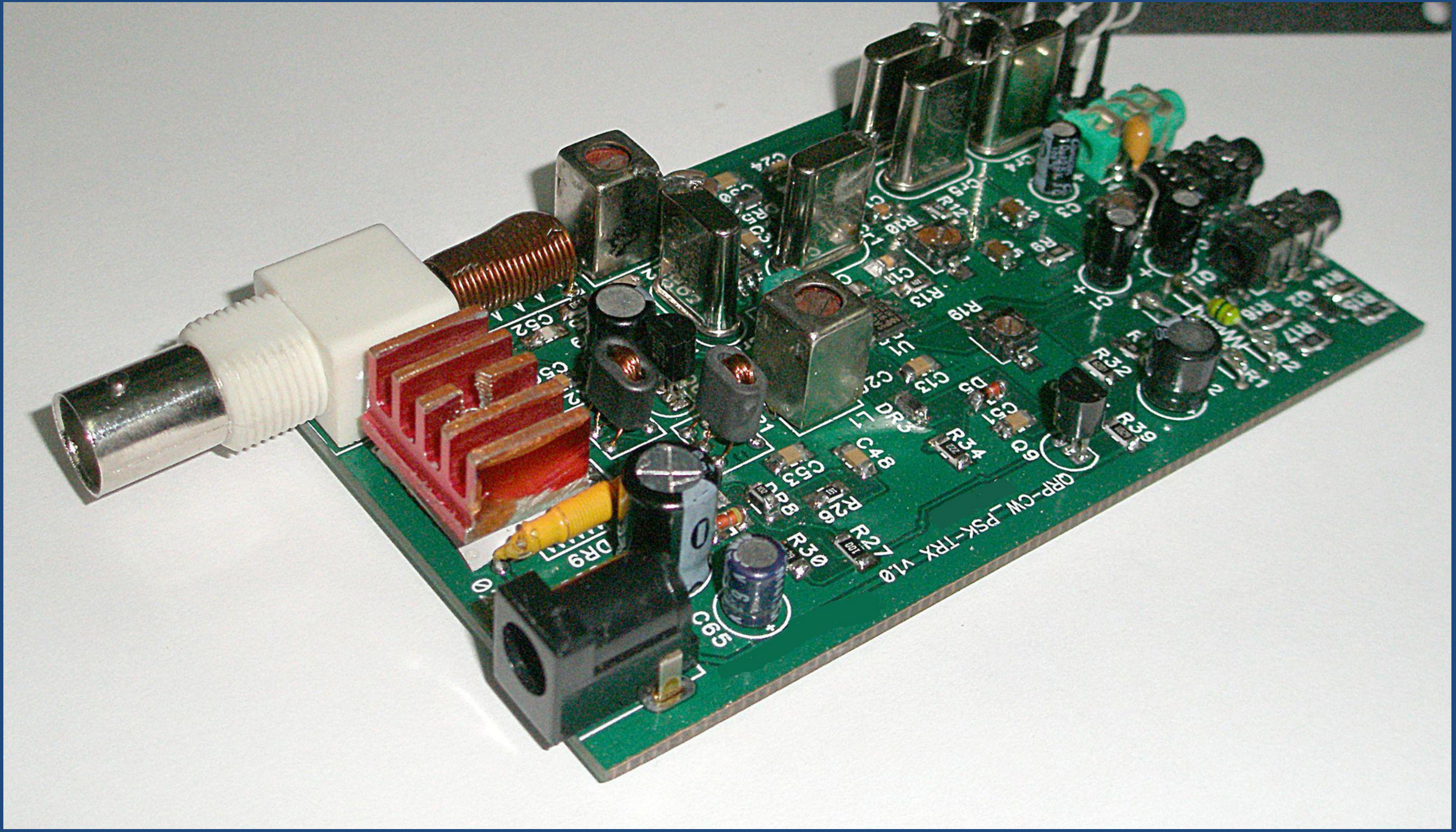


7MHz WSPR transmissions from nine countries were received 100m underground. Map Data ©2016 Geo-Basis/DE-BKG (©2009), Google Inst. Geogr. Nacional)

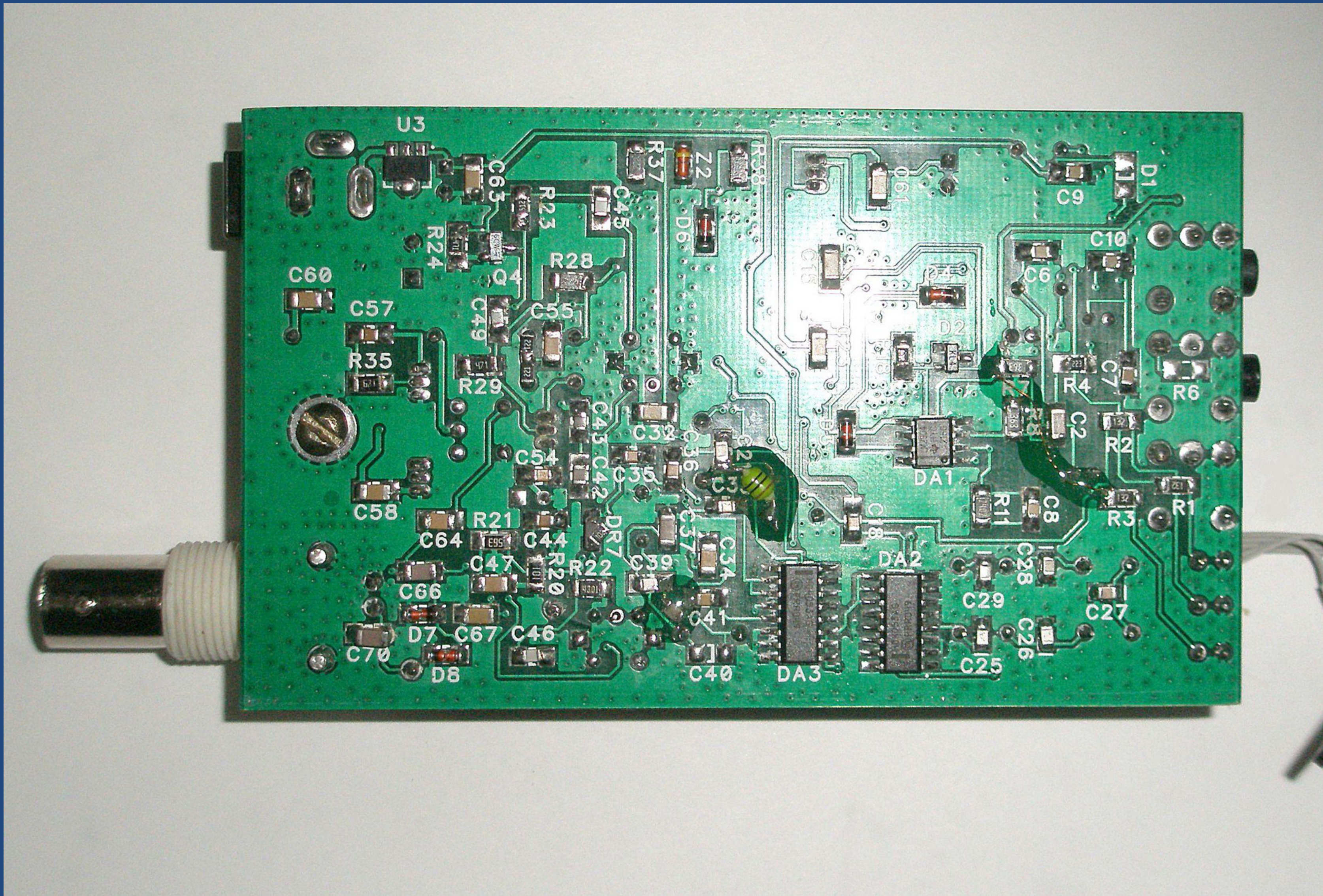
- I previously talked about a proposal for 87 KHz digital communicator using PSK31

- With HF, sources of integrated PSK-31 radios still exist

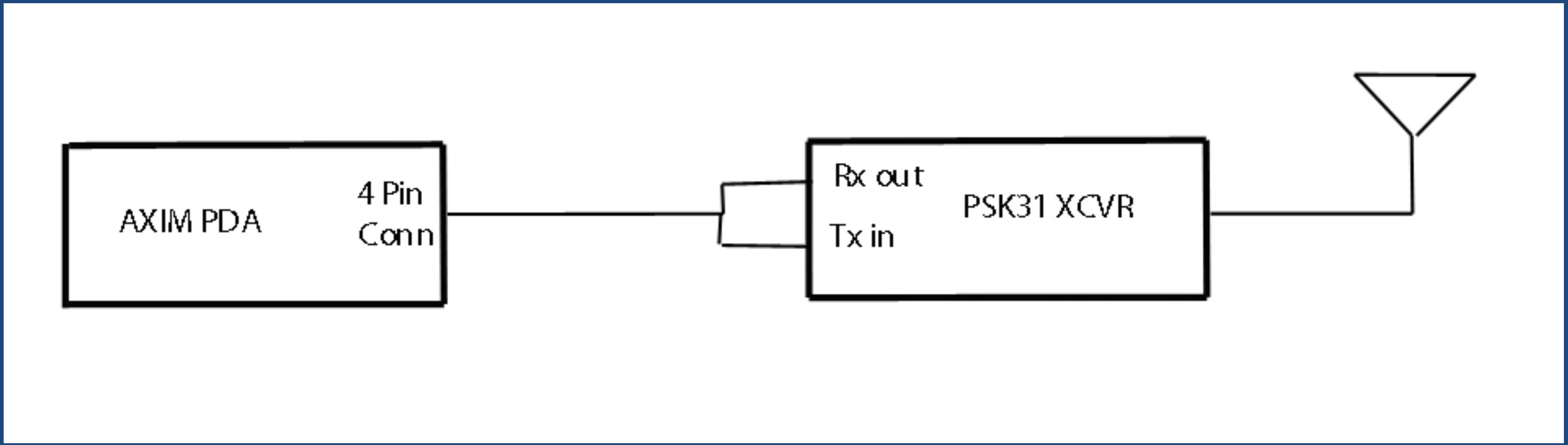
- Ukranian source of compact HF PSK radios provides PSK transceivers for 40, 30 and 20 meter amateur bands. Serge, UT5JCW, sells these through the ebay business "transverters-store"



30 meter band (10.148 MHz) was chosen as there is lower usage and less radio traffic/noise


U3
R37
Z2
C63
R23
C45
D6
C9
D1
R24
Q4
R28
C10
C60
C6
C57
C49
C55
D2
R35
R29
R4
C7
R6
C43
C32
C36
C2
C54
C42
C35
R2
DA1
R11
C8
R3
R1
C58
R21
C64
C44
DR7
C37
DA2
C28
C47
R20
R22
C39
C34
C66
C29
C27
D7
C67
C46
C41
C70
D8
C40
DA3
C25
C26

Very simple setup, audio cable and RF, 12 V battery for PSK transceiver



Total cost is ~$150 + antenna, battery, box

MFJ 30 meter mobile antennas mounted back to back.
System to be tested in two NM caves in 2021

How about UHF or microwaves?

- Fort Stanton Cave Study Project, in collaboration with the Bureau of Land Management, is developing a distributed communication network for data, using a Wireless Mesh Network.

- Goal is to establish a quasi-real time sensor network to measure air conditions such as temperature, movement, direction, and CO_2 content, and measure similar water conditions in the intermittent Snowy River stream channel from the closest point at Turtle Junction back to the surface and to a nearby facility.

- Distance is about a mile. The Passage dimensions vary from giant walking trunk to low crawls. Muddy floors, pools, hills, several gates and many bends will affect signal. 915 Mhz band chosen for best potential.

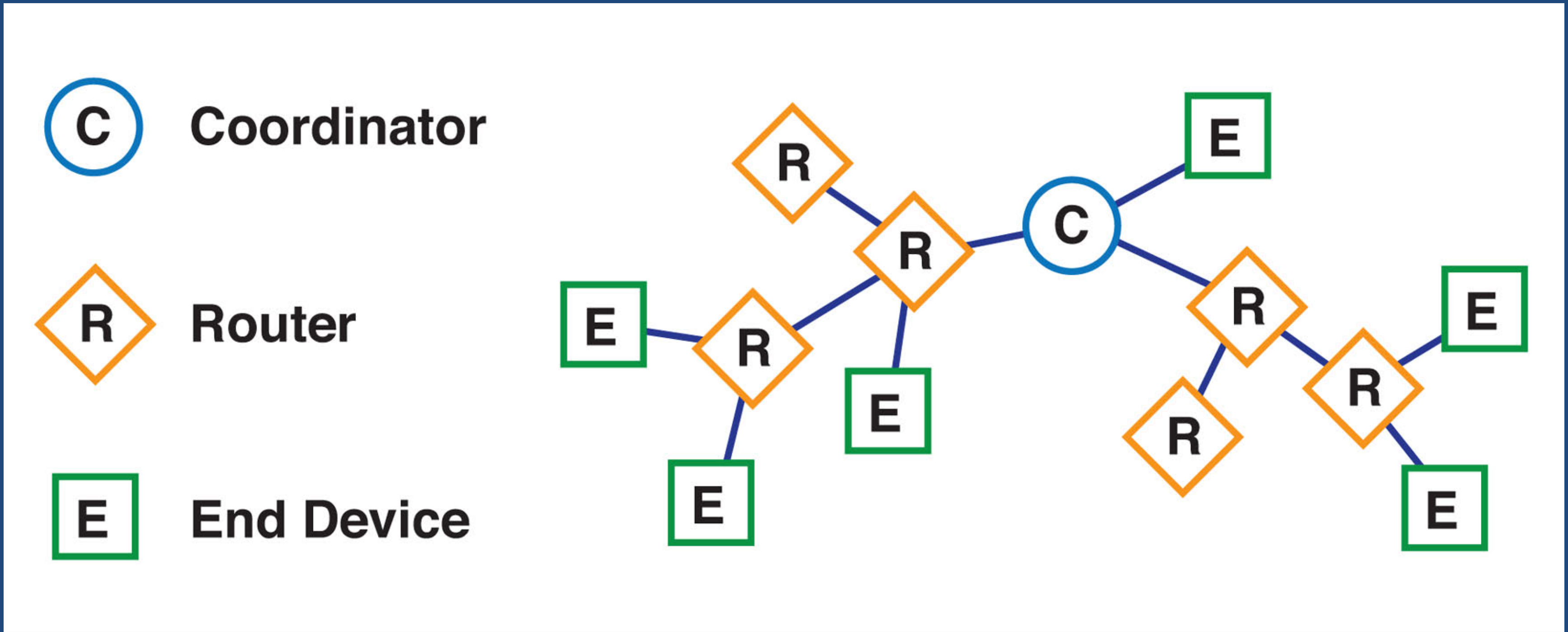
- Data throughput is not critical spec. Power consumption and reliability are priorities.

- 2021 goal is less than a mile, if we can make it work.

- Goal in 2021 is to test a few radios (nodes)
- Minimum of 10 may be needed to get to 20 Steps
- 2 Year goal is to get to Turtle Junction

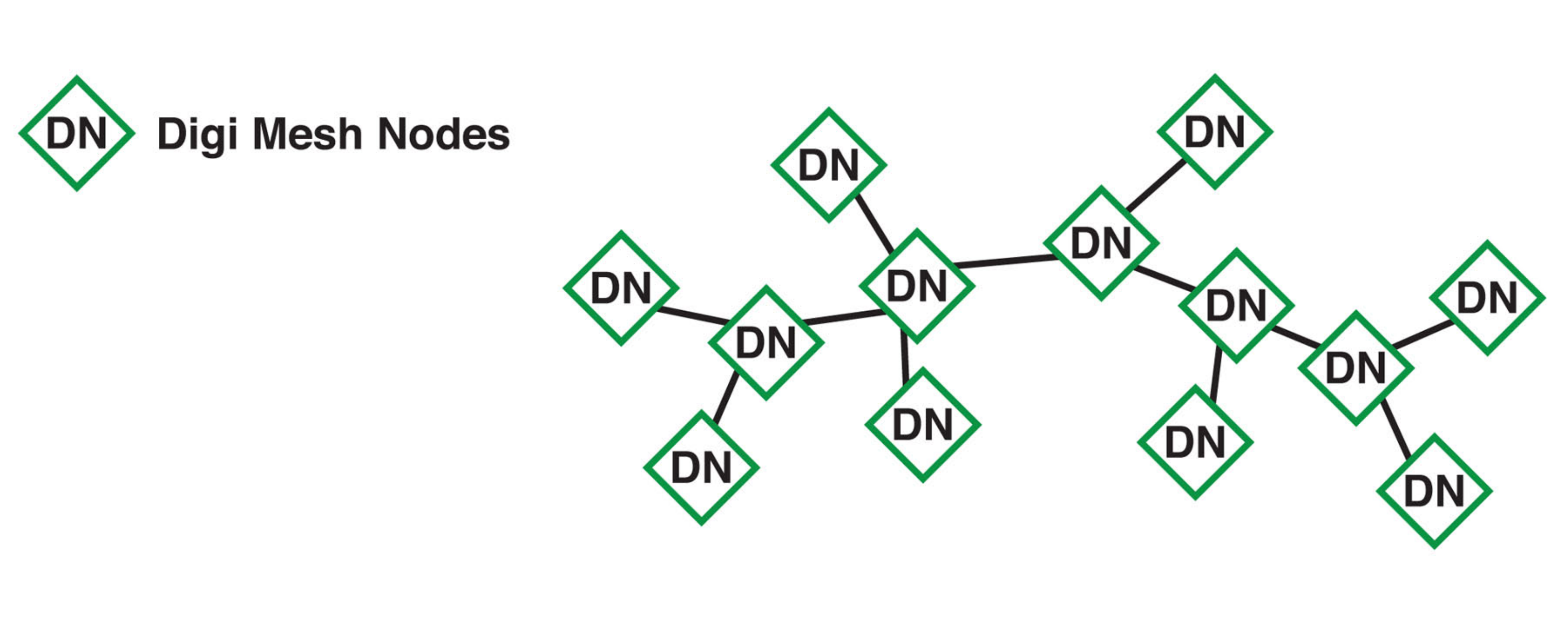
Zigbee Protocol

- Zigbee has three types of modules:
  - One coordinator, many routers and end devices at sensors and gateway
- Widely available from hundreds of manufacturers
- All modules must remain active, need continuous power (~50 mA)



Digimesh Protocol

- Digimesh has homogeneous modules, all interchangeable.
- Adopted by a few manufacturers.
- Optimal for battery power as it runs very low duty factor, with asynchronous sleep mode, 2.5 uA
- Larger frame size and simpler address and header = higher throughput

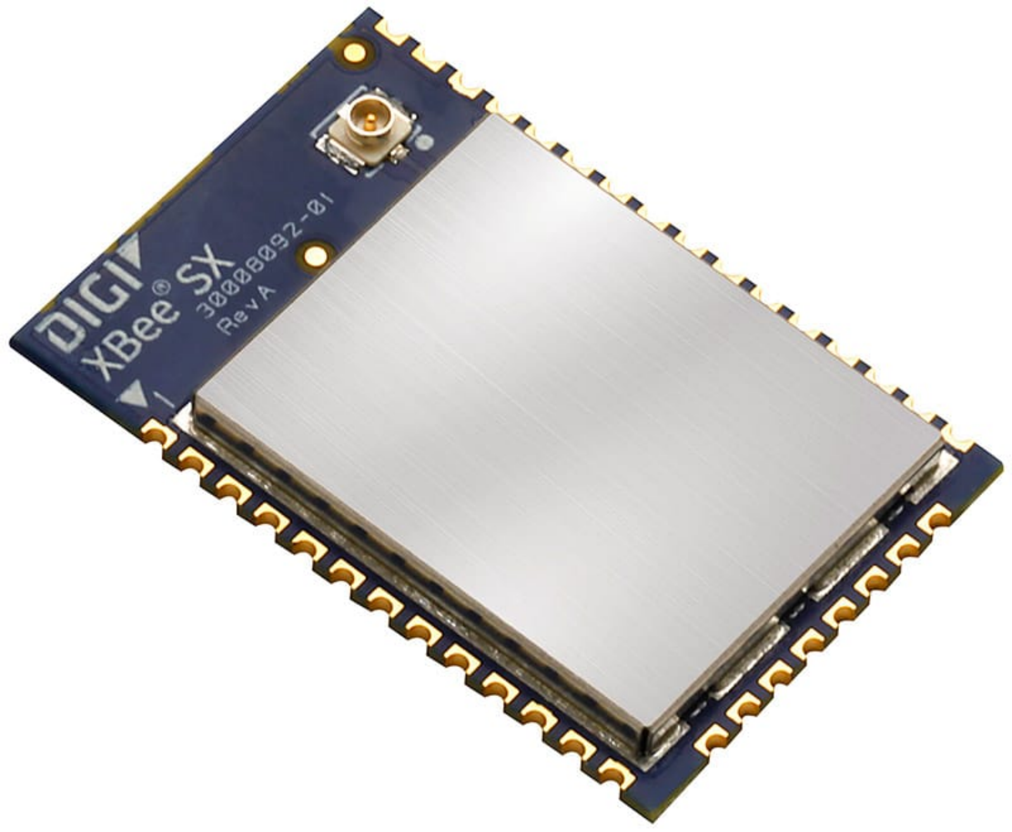


Comparison Table

	ZigBee® Mesh	DigiMesh
Node Types, Benefits	Coordinators, Routers, End Devices. End Devices potentially less expensive because of reduced functionality.	One type, homogenous. More flexibility to expand the network. Simplifies network setup. Increases reliability in environments where routers may come and go due to interference or damage.
Sleeping Routers, Battery Life	Only End Devices can sleep.	All nodes can sleep.No single point of failure associated with relying on gateway or coordinator to maintain time synchronization.
Over-the-Air Firmware Updates	Yes	Not currently scheduled.
Long Range Options	Most ZigBee devices have range of less than 2 miles (3.2 km) for each hop.	Available on XTend™, with range of up to 40 miles (64 km) for each hop.
Frame Payload, Throughput	Up to 80 bytes.	Up to 256 bytes, depending on product. Improves throughput for applications that send larger blocks of data.
Code Size	Larger. Less room for growth in features.	Smaller (about half ZigBee PRO). More room for growth in features.
Supported Frequencies and RF Data Rates	Predominantly 2.4 GHz (250 kbps). 900 MHz (40 Kbps) and 868 MHz (20 Kbps) not widely available.	900 MHz (10, 125, 150 Kbps). 2.4 GHz (250 Kbps)*.
Security	AES encryption. Can lock down network and prevent other nodes from joining.	AES encryption.**
Interoperability	Potential for interoperability between vendors.	Proprietary
Interference Tolerance	Direct-Sequence Spread Spectrum (DSSS).	900 MHz: Frequency-Hopping Spread Spectrum (FHSS). 2.4GHz: Direct-Sequence Spread Spectrum (DSSS).
Addressing	Two layers. MAC address (64 bit) and Network address (16 bit).	MAC address (64 bit) only.
Maintenance	More sniffers and diagnostic tools available on market.	Simpler addressing can help in diagnosing problems and setting up a network.

* 2.4 GHz coming soon
** Coming soon to all platforms

XBEE Radio Module



DIGI XBEE SX 900 radio module
902-928 Mhz ISM
Up to +13 dBm (20 mW)
Freq hopping spread spectrum
GFSK modulation
10 kb/s up to 330 ft
Rx Sensitivity -113 dBm
40 mA Rx, 55 mA Tx, 2.5 uA Sleep
3.3 VDC
1.33 x 0.87 x 0.12"

- Possible package for a radio, will include a large battery for long life and a quarter wave monopole antenna

- We hope to make an annual battery change, will balance duty factor of awake time against consumption

- Tx Pwr – Rx Sens + Ant Gain must exceed Path loss

  + 13 dBm - (- 113) dBm + 0 dB = 126 dB

  Path Loss ~ 41 dB if this were freespace outside

  Tunnel Path Loss ~ 70 – 80 dB for 915 Mhz, 100 m path, according to Zhou

- Prototype test is necessary to determine spacing
- Bends and hills require additional units
- Metal cave gates will present interesting problems

- At surface BLM is planning to build a small shed with solar PV and battery for last module of Digimesh network that will feed gateway module to LTE using directional antenna
- Data collector for sensors will need separate development and will include Xbee module
- We will be able to determine the flooding status of Snowy River year round, even during closures
- Scientific experiments can be monitored in near real-time without needing to download loggers in cave

Wireless Mesh Networking References:

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Khalifeh, A., Salah, H., Alouneh, S., Al-Assat, A., Darabkh, K., "Performance Evaluation of DigiMesh and ZigBee Wireless Mesh Networks", IEEE (online)

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Signal Propagation References:

Bedford, M., Kennedy, G., "*Underground Wireless Networking: A Performance Evaluation of Communitation Standards for Tunnelling and Mining"*, Tunnelling and Underground Space Technology 43 (2014) pp. 157-170.

Bedford, M., Kennedy, G., *"Modeling Microwave Propagation in Natural Cave Passages"*, IEEE Trans. Antennas and Propagation, V.62, n.12, Dec. 2014, pp.6463-6471.

Bedford, M., *"Modelling Microwave Propagation along Passages using LiDAR and Ray Tracing"*, BCRA Cave Radio and Electronics Group Journal #111, Sept.22, pp. 5-7

Hussain, I., Cawood, F., van Olst, R., *"Effect of Tunnel Geometry and Antenna Parameters on Through-the-Air Communication Systems in Underground Mines: Survey and Open Research Areas"*, Physical Communication 23 (2017) pp. 84-94.

Rak, M., Pechac, P., *"UHF Propagation in Caves and Subterranean Galleries"*, IEEE Trans. Antennas and Propagation, V.55, n4, April 2007, pp. 1134-1138.

Zhou, C., Plass, T., Jacksha, R., Waynert, J., "RF Propagation in Mines and Tunnels", IEEE Antennas and Propagation Magazine, Aug. 2015, pp. 88-102.

Digi International, *"Indoor Path Loss"*, App Note XST-AN005a-Indoor, June 2012.

ELF Radiolocation

Cave Radiolocation System

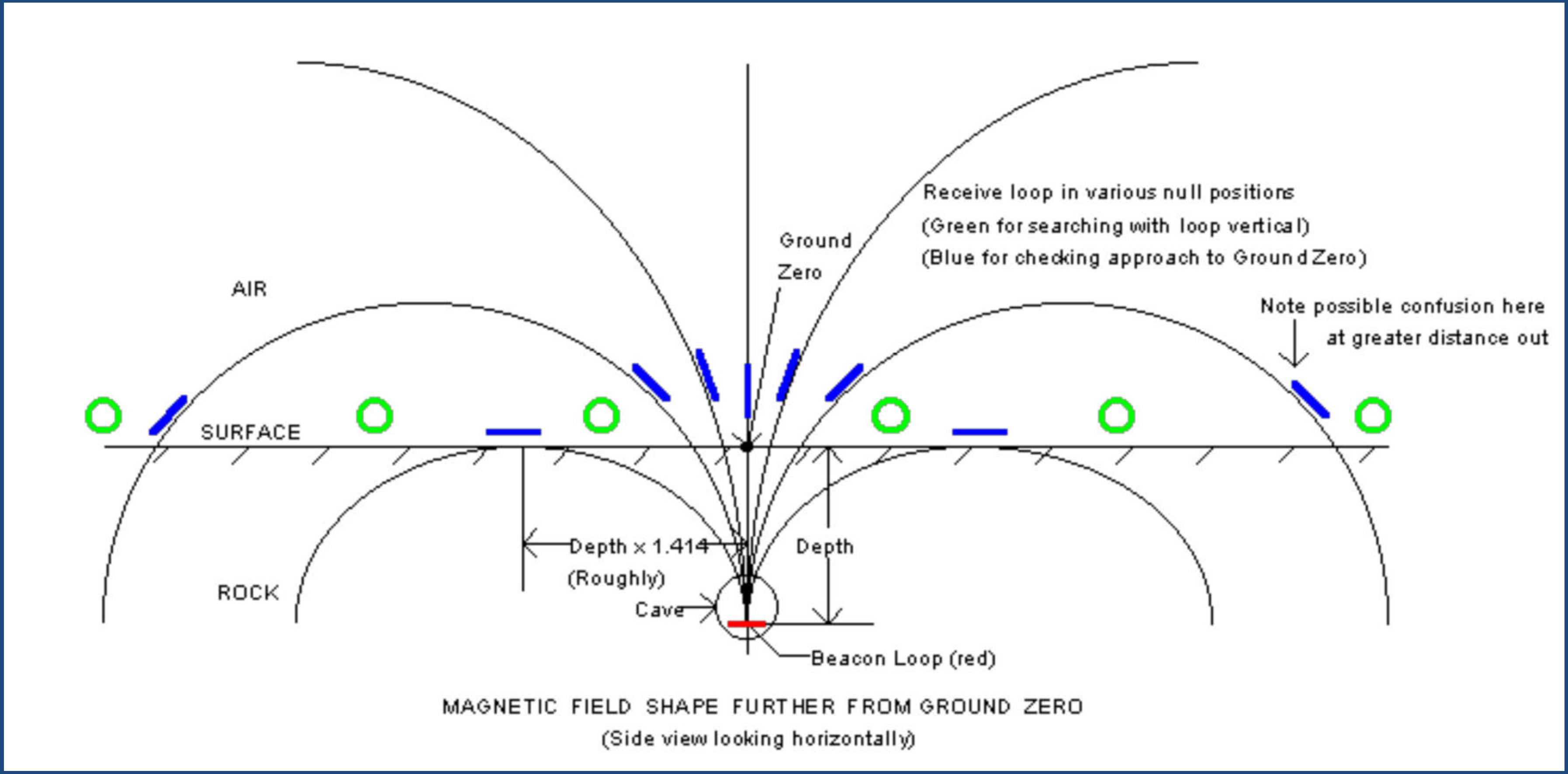
- Cave maps were developed using precision compasses and inclinometers along with distance measuring devices like measuring tapes

- Now we use laser rangefinders integrated with flux gate magnetometers and multi-axis accelerometers

- But the technique always relies on survey lines starting from the entrance and errors build up over distance. No GPS underground…

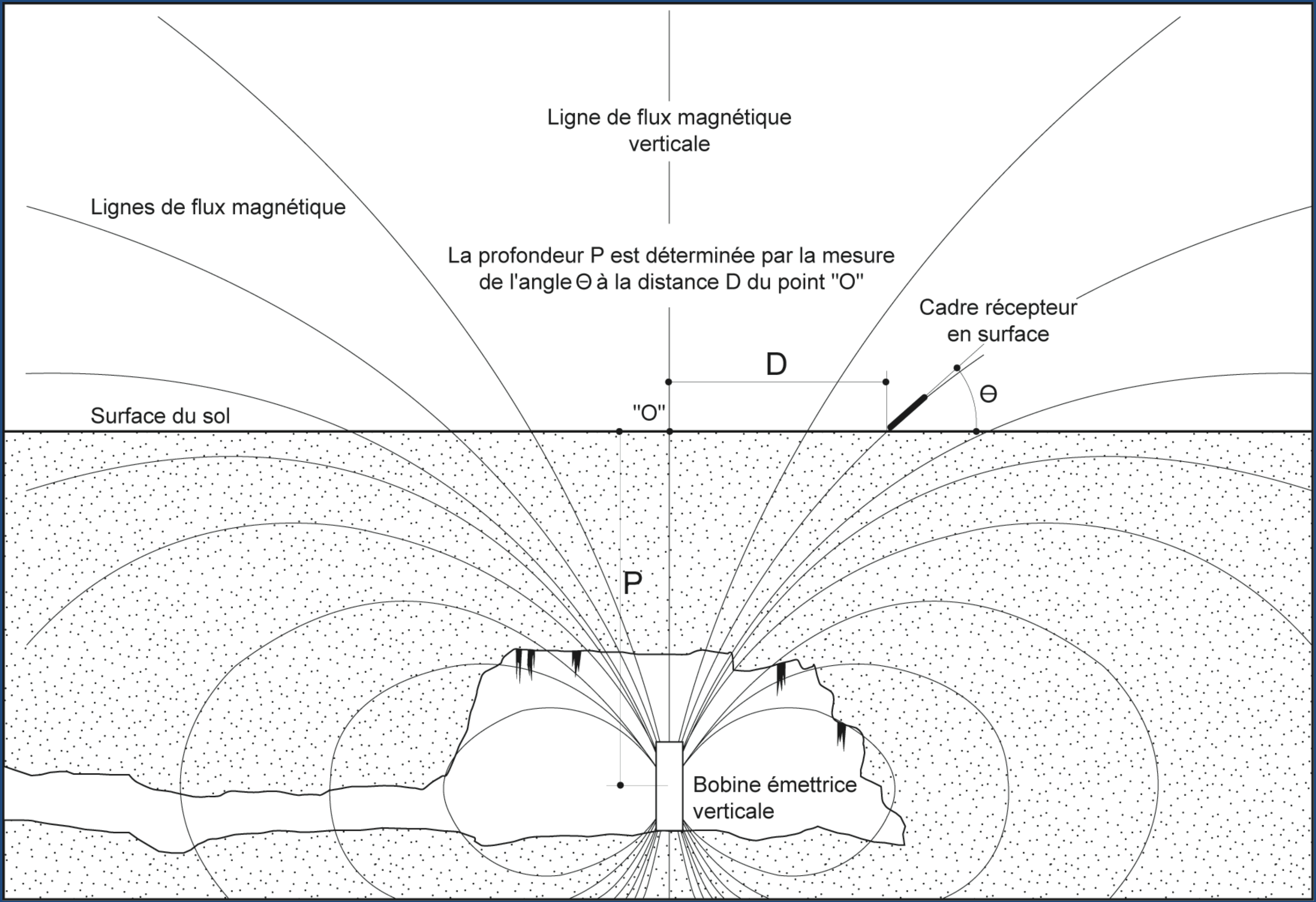
- Radiolocation is a technique used to establish control points for cave surveys by using a surface survey (GPS) linked to an underground beacon

- The 3.496 KHz beacon loop is horizontal and establishes vertical magnetic field that reaches the surface. By using orthogonal loop on the surface, can null the signal and triangulate to a point directly over the beacon loop.

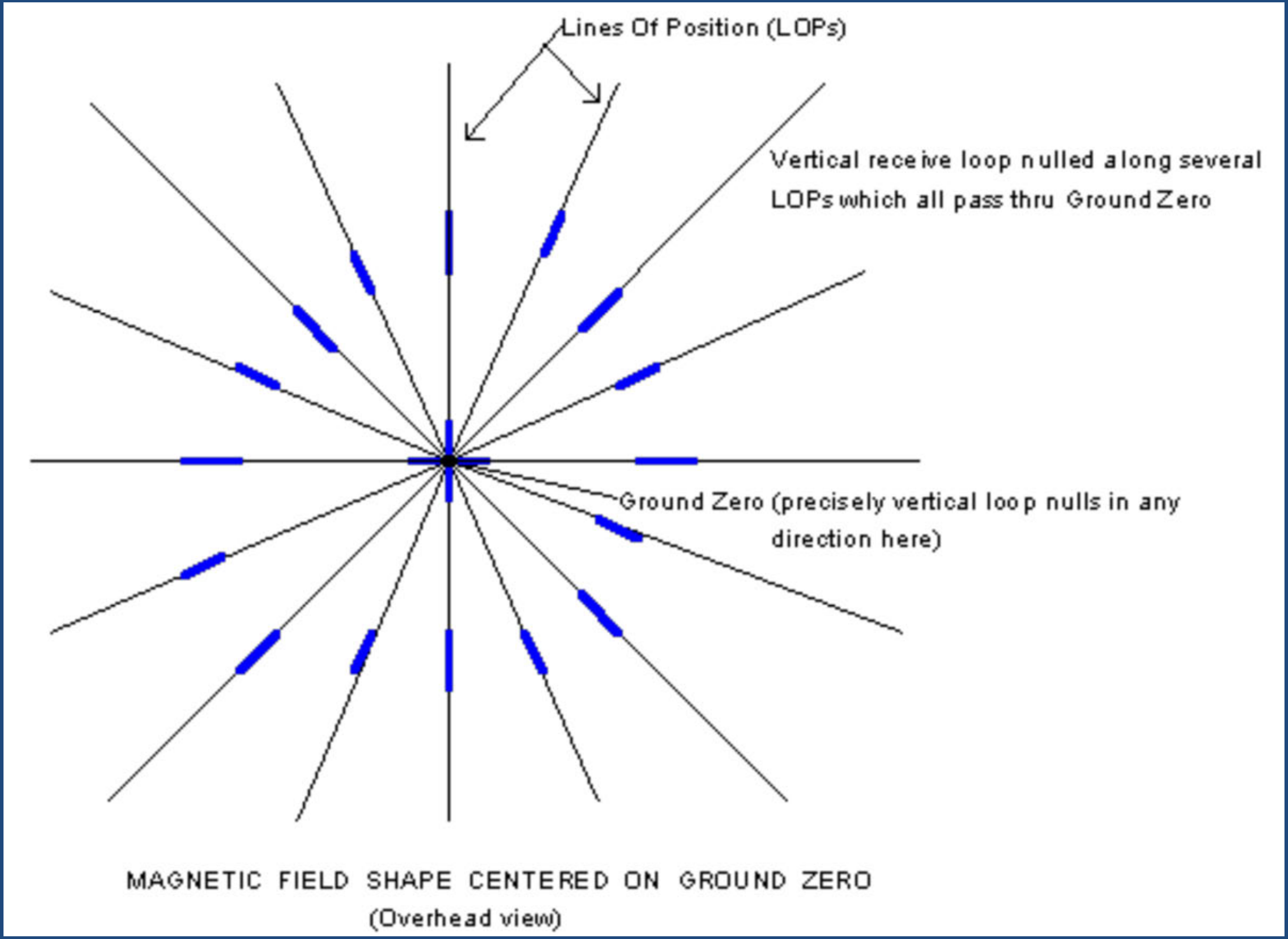


W1IR, Brian Pease

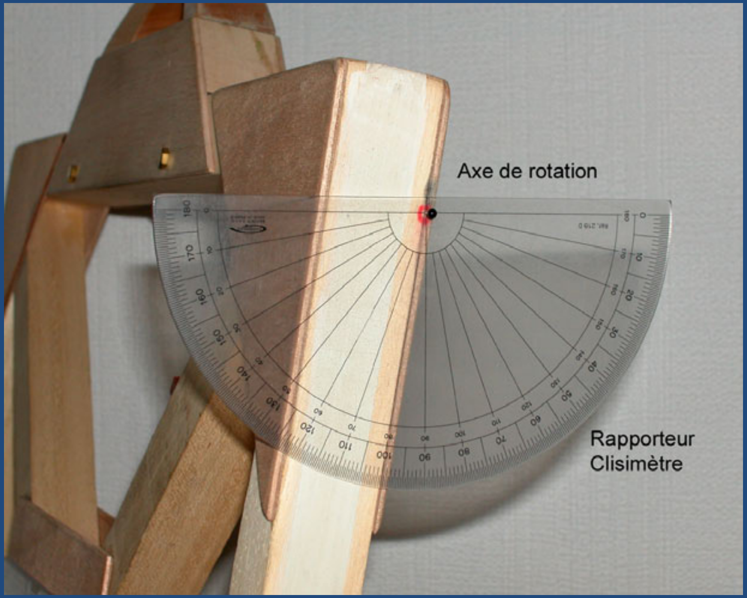
Alternate is Ferrite Rod for Beacon Magnetic Field



Daniel Chailloux, Speleonics 26, 2004

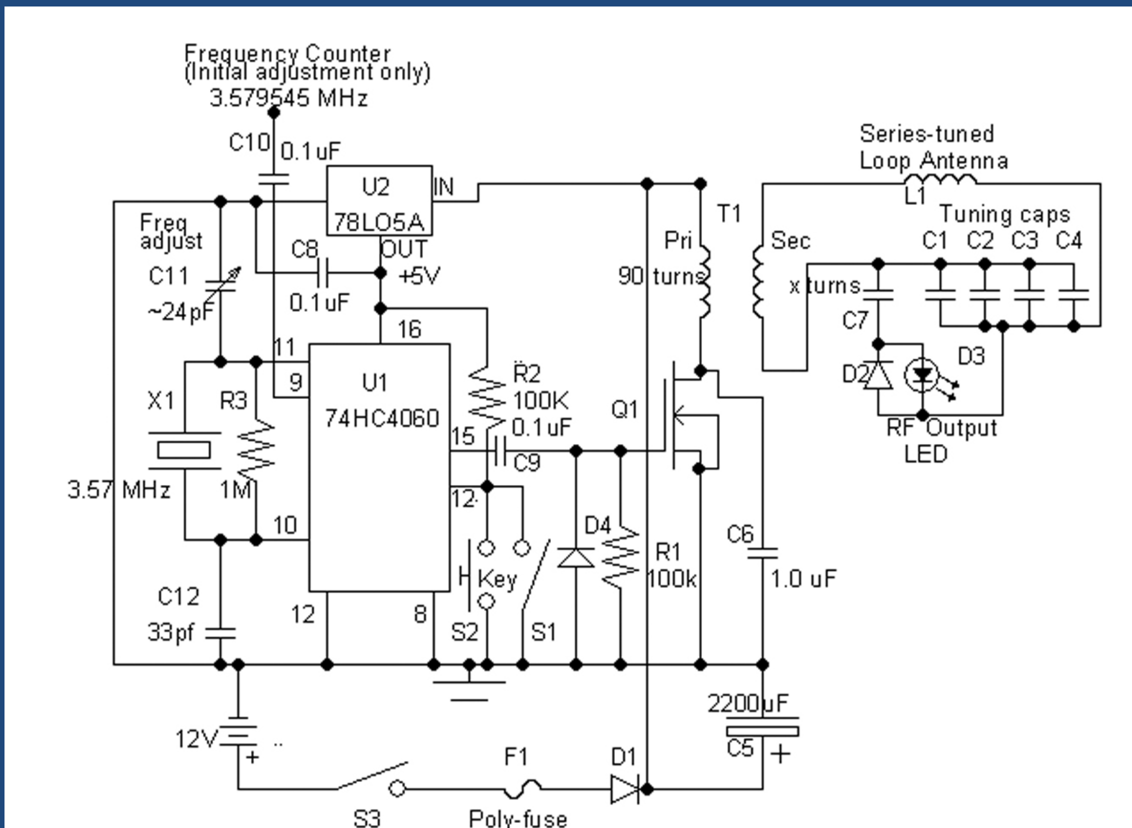


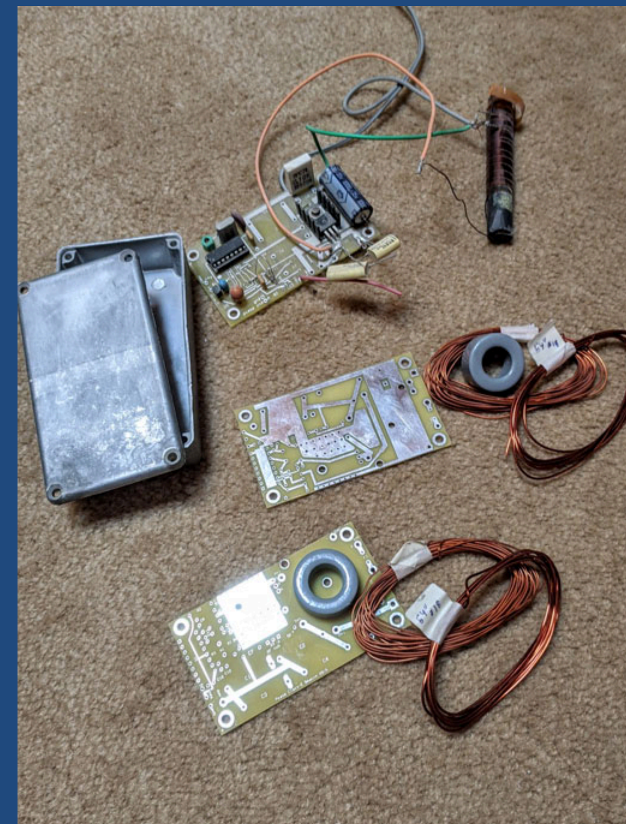
W1IR, Brian Pease

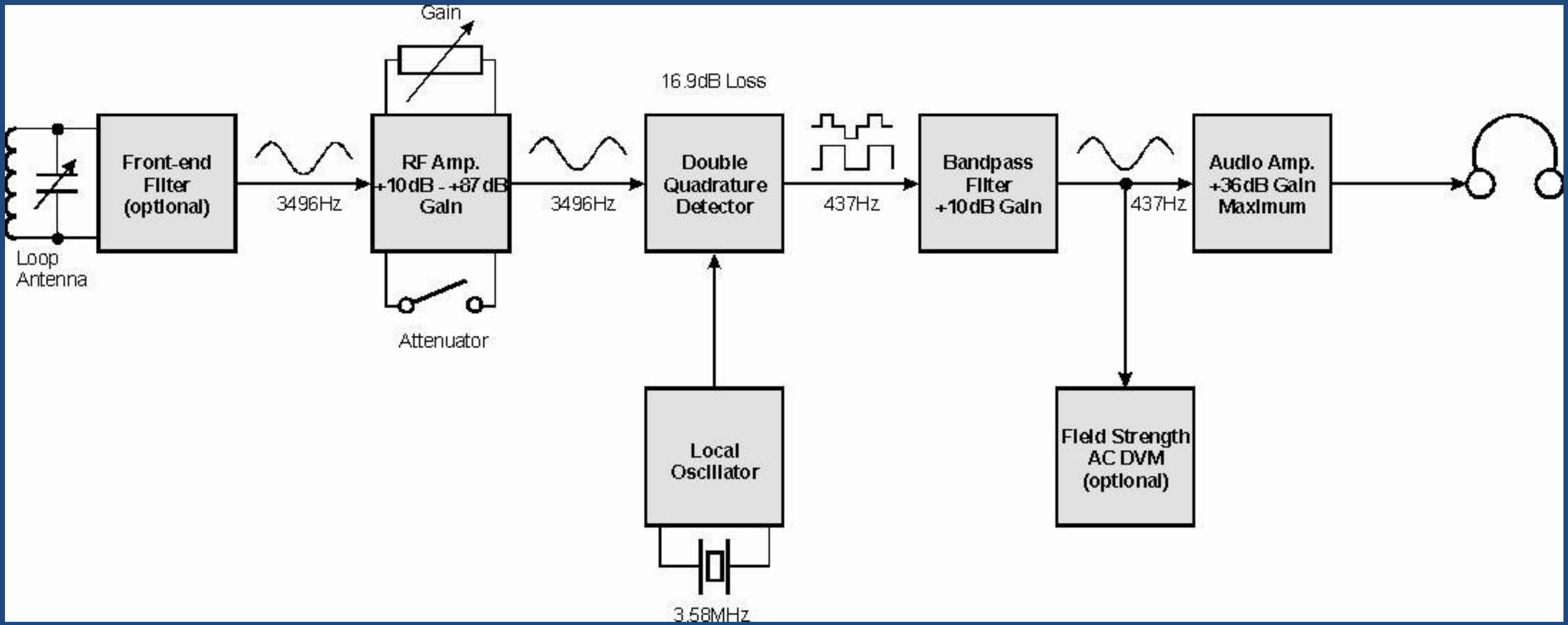


Daniel Chailloux, Speleonics 26, 2004

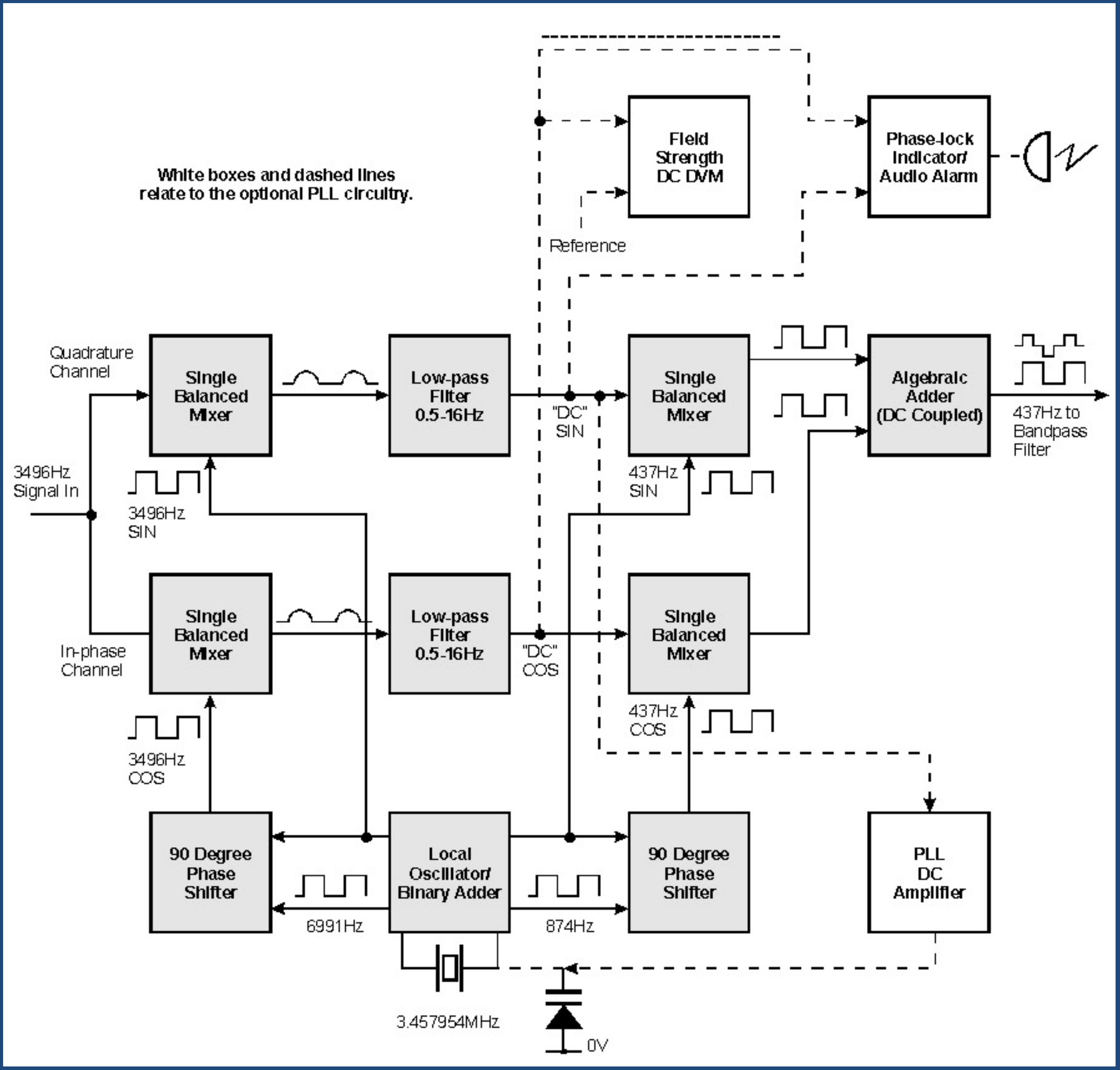
3.496 KHz Beacon Transmitter Runs Class E





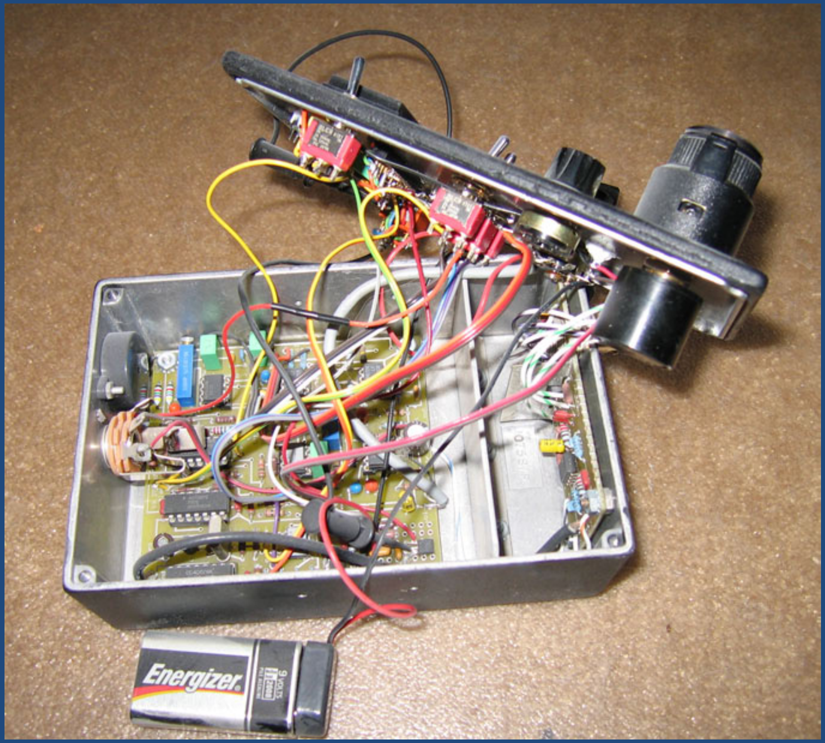


- Thermal noise at input (Hi Gain mode)=13.4nV/1Hz BW
- The primary receiver signal BW is 1HZ.
- 32 Hz BW mode is primarily for RFI identification and Morse Code
- Noise current at input =.01pA/1Hz BW
- Optimum input noise resistance=1.34 Megohms
- RF amp gain varies 36-98dB over the range of the gain pot
- Input attenuator is 0dB (Hi) or –40dB (Lo)
- RF amp dynamic range is 129dB in a 1Hz BW (plus the 40dB pad)
- Battery drain is 30mA (two 9V batteries)
- Sensitivity is determined from the thermal noise of the loop aerial



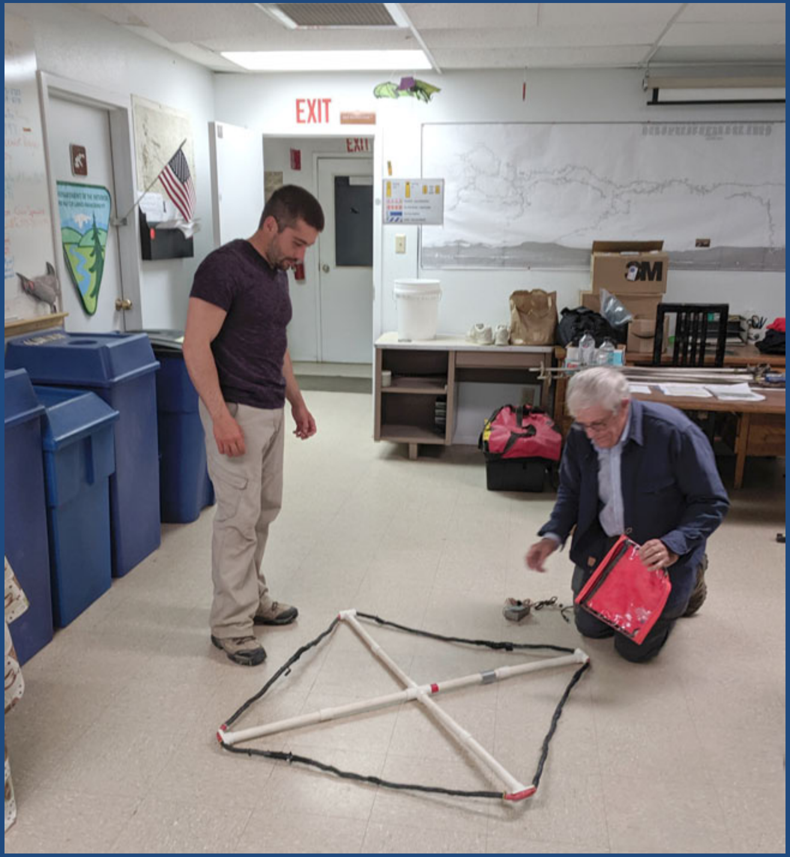
W1IR double quadrature detector loop

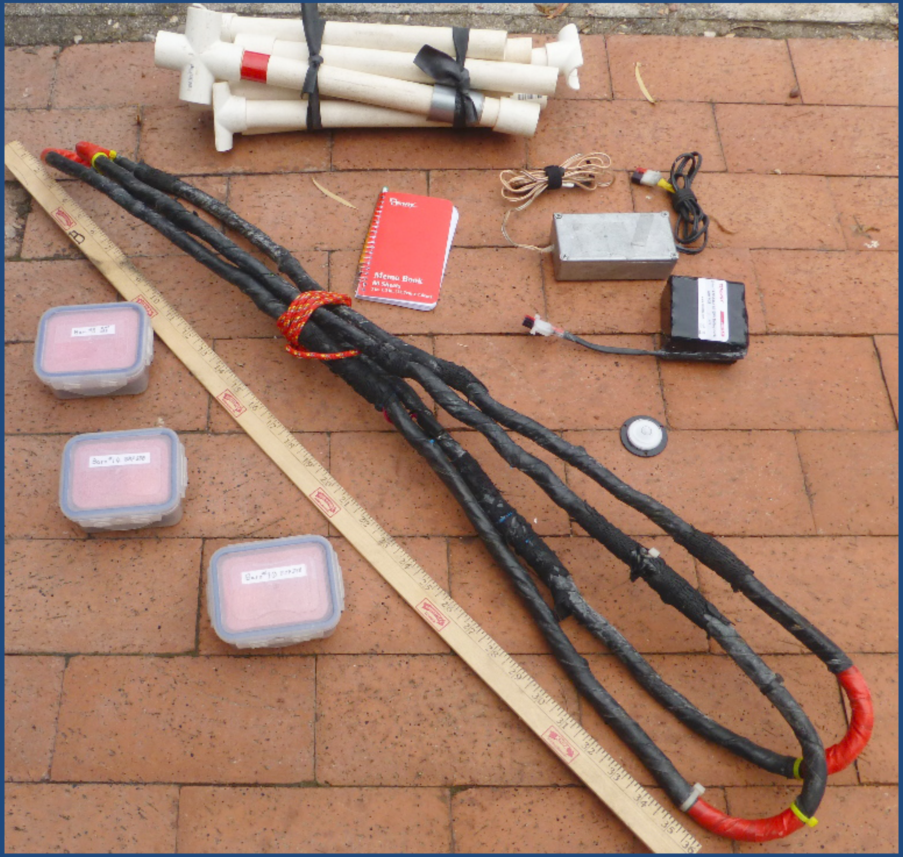
3.496 KHz Double Quadrature Receiver



K5PRO's on left, W1IR built on right

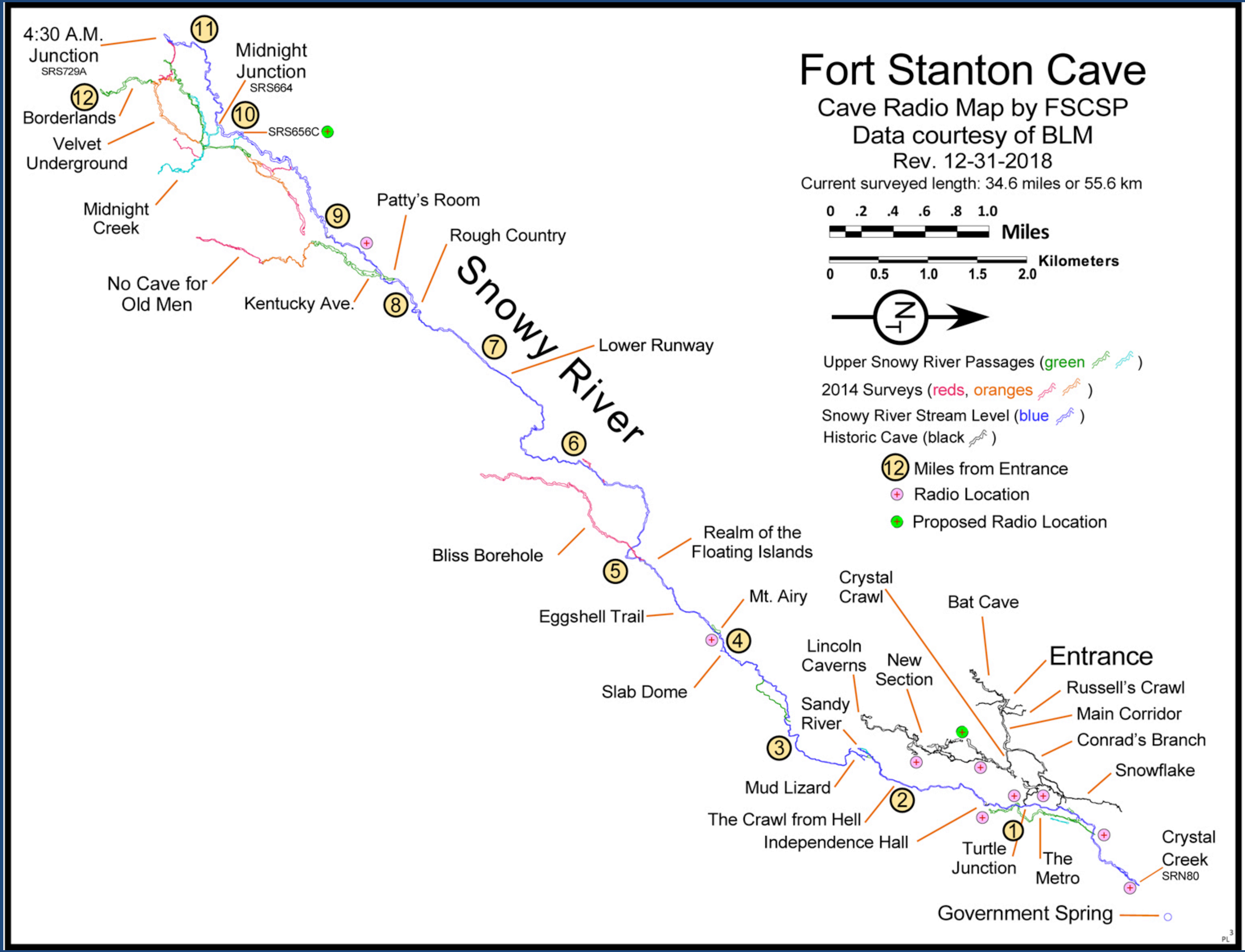
3.496 KHz Beacon - Ready to Haul into Cave







- May 2013 was last radiolocation in Fort Stanton Cave
- After ~40,000 ft of surveys, we determined < 300 ft x-y error (<1%) using radiolocation
- Depth ~ 425 feet, within 3 feet of precision barometer



Fort Stanton Cave
Cave Radio Map by FSCSP
Data courtesy of BLM
Rev. 12-31-2018
Current surveyed length: 34.6 miles or 55.6 km
0 .2 .4 .6 .8 1.0 Miles
0 0.5 1.0 1.5 2.0 Kilometers
N
Upper Snowy River Passages (green)
2014 Surveys (reds, oranges)
Snowy River Stream Level (blue)
Historic Cave (black)
12 Miles from Entrance
Radio Location
Proposed Radio Location
4:30 A.M. Junction
SRS729A
Midnight Junction
SRS664
SRS656C
Borderlands
Velvet Underground
Midnight Creek
Patty's Room
Rough Country
No Cave for Old Men
Kentucky Ave.
Snowy River
Lower Runway
Bliss Borehole
Realm of the Floating Islands
Eggshell Trail
Mt. Airy
Crystal Crawl
Bat Cave
Slab Dome
Lincoln Caverns
New Section
Entrance
Russell's Crawl
Main Corridor
Conrad's Branch
Sandy River
Snowflake
Mud Lizard
The Crawl from Hell
Independence Hall
Turtle Junction
The Metro
Crystal Creek
SRN80
Government Spring

Tracking beacon on an autonomous vehicle under the ice.
Bonnie Lake in the Dry Valleys, Antarctica

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