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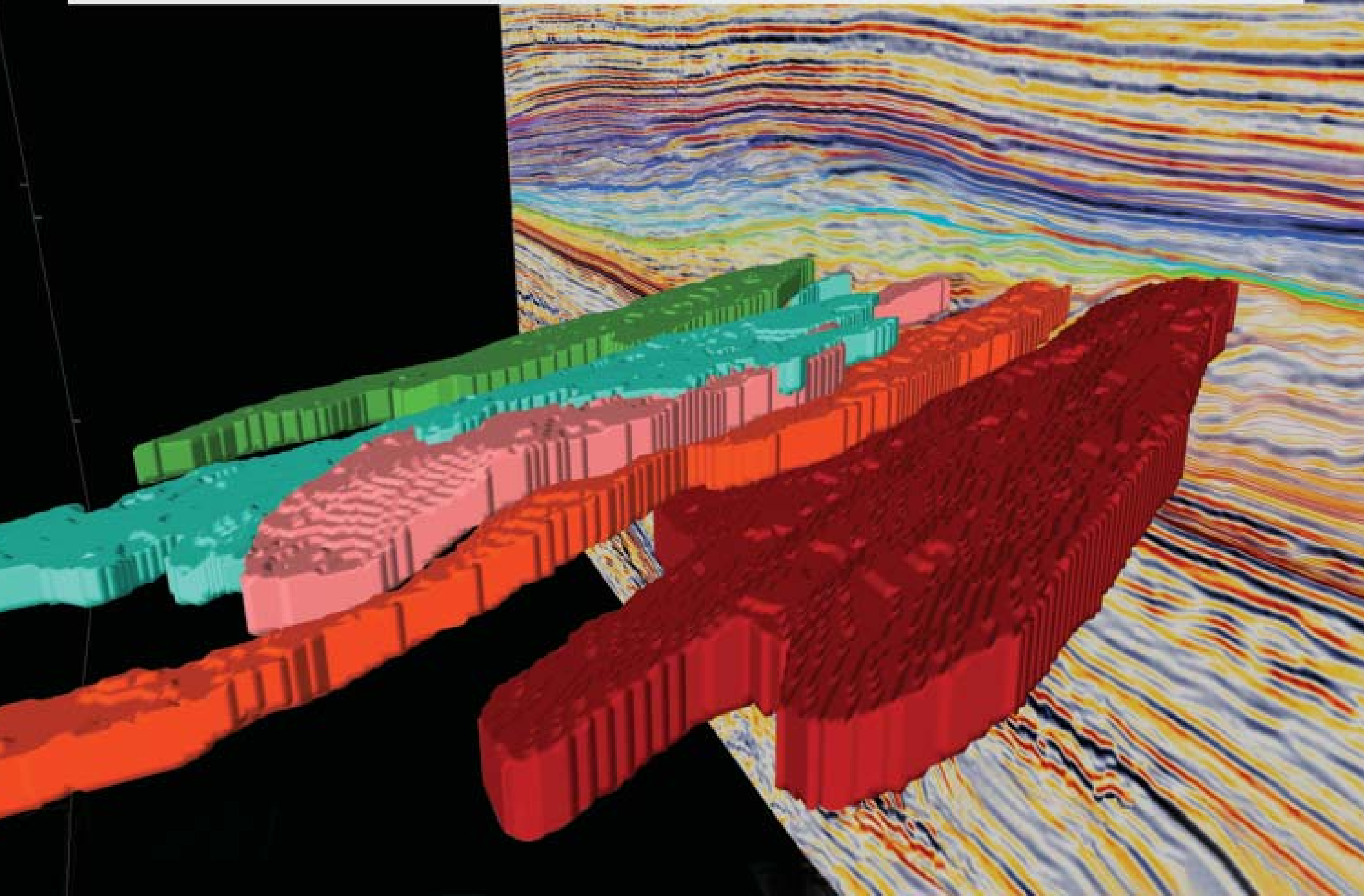
Global seismic interpretation techniques are coming of age

The advances in seismic technology over the last few years have been phenomenal, particularly in the areas of seismic acquisition, processing and interpretation. Global seismic interpretation include a variety of different methods, such as 'Age Volumes', 'PaleoScan', 'Volumetric Flattening' and 'HorizonCube'. Such techniques share a number of algorithms in common with their aim being to correlate seismic positions along geologic time lines to arrive at fully interpreted seismic volumes



Cableless seismic in difficult environs: Comparisons for Explorationists

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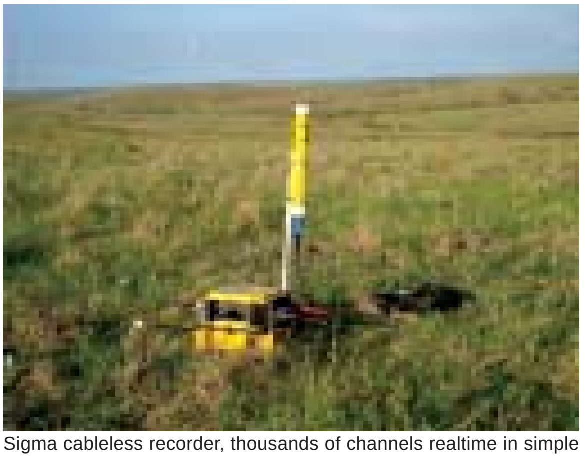
There is no doubt that cableless systems have a lot to offer to both active and passive geophysics. However, unlike earlier recording approaches, there are many different cableless methods and instruments to choose from and some technologies can have hidden dangers for certain types of seismic data acquisition.

This article has tried only to compare three major characteristics of cableless systems, and listed several others which should also be considered, it should be clear that each category for comparison relates to others. Weight is related to power usage. Power usage is related to what batteries can be used. This usage is related to communication capability. Comms ability is related to QC and security. Comms capability is also related to options in where and how 2.4 GHz transmissions can be used. So unsuspecting users may think that picking a system based on one feature is all that is required. However, this inter-relationship between all features in cableless recorders and the effect each has on the geophysics which can be undertaken, means that one must be most careful.

The geophysicist is recommended to familiarise him or herself as fully as possible with all areas of this technology and physics behind all of these exciting new tools but come to the exercise with some idea of the precise geophysical problems that need to be solved. This is not such a simple task as it was in the days of cabled telemetry but some cableless systems come with an ability which was just not available before, that of being able to be configured to solve very many geophysical problems. If nothing else, while the industry fully gets to grips with the flexibility offered by new technology, configurable systems at least provide choice and insurance.

In many ways, acquisition geophysicists typify the classical performer of all practical science experiments. They know what must be measured and to what accuracy to provide the information necessary to verify their hypotheses and to reach their own particular scientific goals. In this case of our industry, such "experiments" may be active seismic data acquisition or one of the growing number of types of passive recording.

To support this, they strive to understand how various characteristics of the equipment restrict what the experiment can achieve. This is not just in relation to technical issues such as the limit on noise or the dynamic range of signals which must be recorded but just as importantly in terms of the commercial restrictions which often have a greater effect on the quality of gathered data. When users of equipment understand well these limitations, they are in a better position to make suggestions as to how equipment can be employed to minimize data quality problems and even to how hardware may be enhanced so that better experiments can be undertaken.



Sigma cableless recorder, thousands of channels realtime in simple environment. Note low cost external battery, hyMesh ultra high bandwidth antenna raised only 50 cm. The latest in configurable acquisition. But what must change for any cableless system to succeed in tougher environments?

Nowadays, radically new technologies are being introduced into exploration geophysics which can have a dramatic effect on what is achievable. Just as before, getting the most out of instrumentation will require experimenters to understand equipment functionality and limitations.

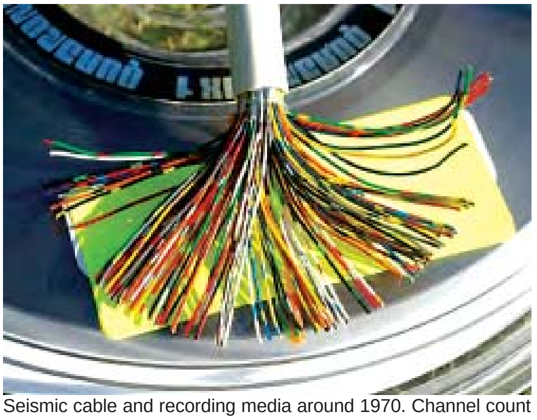
A brief hardware history

The responsibility for developing suitable seismic equipment has rested with "independent" system developers for some while - in other words, companies who generally have little intention to use it commercially themselves. This did not used to be the case fifty years ago when oil companies often designed their own equipment. Arguably, this was theoretically a better approach as this closeness to the development process gave geophysicists of those times the luxury of being able to understand without training the relationship between their equipment's versatility and how experiments (seismic surveys) should be conducted with it to lead to the most successful outcomes.

An example of this relates to the geophysical parameters which must be adhered to in seismic reflection digital recording. Nyquist criteria must be met in terms of sample rates to match bandwidth of interest and this has been no real problem for any equipment for quite some while. Instruments must also be able to cope with the huge range of signals coming from deployed sensors, where the largest to be handled without significant distortion is many orders of magnitude greater than the smallest. If electronics subsystems could not function to these basic levels, or geophysicists did not know how to get the best out of them, the result may be data of potentially such poor quality that it would not suit any experiments' objectives.

However, equipment requirements are not simply about the electronics specifications aimed at frequency domain issues. Just as important are characteristics relating to how many independent recording channels may be available in order to sample in the spatial domain so as not to degrade the experiment. This density of channels will determine how well noise as well as signal is captured, while the length of line(s) over which these channels are deployed effectively determines to what depth data may be clearly registered. Obviously, an instrument must be technically and commercially capable of being employed to acquire the number of channels equal to the product of the channel sampling density and the line length.

Unlike the frequency domain, dealing with spatial domain requirements has for most of the history of seismic instrumentation posed significant problems with geophysicists using many tricks to overcome the limitations. And some may say the spatial challenge is still far from being met. Even in simple 2D exploration, adequate noise sampling may imply two hundred channels for every line kilometre, and perhaps offsets each side of the source of six kilometres meaning a total of almost two and half thousand channels on one line just to comply with theory. When the experiment starts to involve 3D recording, and obviously depending on the density of lines, it is easy to see that many tens of thousands of channels would be the minimum. Even if electronic hardware had been able to cope, one overlooked restriction was that recording media limitations came into play.



Seismic cable and recording media around 1970. Channel count limited by number of separate electrical conductors and recording media. System capacity far below ideal capability.

Until about 1980, the industry had to settle for channel counts which had difficulty making it into three figures. Anything much more than 120 channels simply made the whole process too unwieldy, unreliable and costly. The reason was that each channel required its own pair of wires from where sensors were deployed running all the way to where digitising electronics were housed, usually in a truck containing a central system with built-in digitizing capability. The cables used in these seismic lines thus were very heavy, generally with weight proportional to the number of channels that had to be recorded.

By distributing the digitizing electronics inside grounds units laid along the seismic line, data could be put onto a digital data bus which joined all ground units. This bus consisted simply of a few pairs of conductors twisted around their common centre, and which had the characteristics of being able to carry digital data of sufficient bandwidth the necessary distance (normally just as far as the next digitising box) using an acceptable amount of battery power.

Whereas the earliest versions of the distributed systems which output many bits in their analog to digital conversion had a capacity of a few hundred channels, during the same era the GeoCor IV instrument from

GeoSystems output a sign bit per sample and this allowed around a thousand channels to be acquired - so it sacrificed frequency domain sampling to improve spatial domain sampling. Both approaches had their benefits and adherents. It took various technological developments for "full dynamic range" convertor systems to pass the thousand channel barrier. By this time, recording instruments had enough capability fairly to claim that 2D lines could at last come close to being properly sampled in all domains, while simple low density 3Ds could be also carried out. It is clear to see how improvements in technology enabled better experiments to be undertaken, and the steps they permitted towards the ultimate goal of ideal sampling. It was also the case throughout this era that experienced hardware users recognized equipment limitations.


1980's distributed cable based telemetry system. More flexible equipment meant improved acquisition geophysics.

The next technological advances were in electronic components themselves. With improved reliability, and a sufficient reduction both in power consumption and cost, it became economic and practical to make another jump in terms of viable channel capacity. This simultaneously needed improvement in data bus transmission technology to permit around a thousand channels to be carried by one pair of wires where, a few decades earlier, there had been one pair for a single channel.

However, as each cable allowed more channels to be connected, and as manufacturers fought to reduce weight, the technology began to find some insurmountable obstacles. One was that of the susceptibility to damage, or fragility of cables, when pushed to their data bandwidth limits. Another was the serial dependency of this instrumentation approach. Here, a problem with just one cable or connector or electronic repeater within any interconnected spread of equipment meant that all channels behind would be lost too. Data rerouting, invented by the Canadian company GeoX Systems Ltd., and copied later by others, to some level tried to deal with serial dependence but generally it meant adding yet more cables which consequently often imposed further weight problems.

Whereas the two decade history of digital cable telemetry had witnessed dramatic improvements in hardware allowing ever better seismic acquisition, it seems explorationists recognised that the technology - and the type of geophysics that could be planned, had gone almost as far as it could. It was difficult to reduce weight, costs or power consumption, so the industry started to look for something new which would permit the next quantum leap in experimentation. The obvious step was to work without such cables.

Geophysics without seismic cables

Before looking at life without cables, we should acknowledge one of their benefits: cabled systems are easy to understand. The idea is simply to attach basic system elements to one another in long lines, with the requisite number of batteries, until the stated maximum data capacity of that line is reached. There is only one way to plug such units together, and the only major option available to the user (and that usually only at the time of system purchase) is how much telemetry cable there is between digitizing units.

Clearly, the technology has few complications but this inherent simplicity also means that it is rather restricted in what it can do, the corollary to which is that the range of geophysics it allows to be undertaken is similarly limited. Indeed, it has been claimed (and mentioned by the ENI paper referred to below) that some explorationists or their crew personnel, having grown up only with cabled systems and their inherent limitations, may take some time to get used to the far broader range of operations which can only be accomplished by more flexible instrumentation. Any move to new technology in any industry, while offering more versatility and a bigger spectrum of experimentation, always comes at a price. This is that users must understand how the technology works to get the most out of it, and to be sure they do not inadvertently encounter problems which inflexible earlier technology would not have allowed anyone to make.

It is nowadays fairly easy to be scathing about some aspects of cabled recording systems, in fairness it must be stressed that they represented the culmination of massive research effort. Such products claim some millions of man hours cumulative development and because of this outlay - which any newcomer would have had to match to enter the market - at the peak of the technology the number of well known manufacturers operating at the international level could be counted on the fingers of only one hand. As already stated, that the technology was reaching the pinnacle of what it could do became clear when looking at specifications such as weight and power consumption, and the number of active channels that could be used on a single receiver line. All these have been asymptotically approaching their limit for some while - a limit which is easy to determine by engineering and physics basics. But any new technology introduced into the industry would hopefully allow much more capacity, variety and competition.

Further, there was rather little to differentiate the capability of each cable system from this small number of suppliers. As absolute and relative functionalities were so limited the types of geophysical techniques that could be undertaken also varied little between each system. This lack of choice and restricted number of features were also some of the reasons the industry was so keen to find something better.

The initial push to develop new forms of acquisition system came at a time when several technologies which could coincidentally be useful to seismic recording were being developed for industrial and domestic use. This includes mobile phones, laptop computers, ethernet and internet subsystems, digital cameras and WiFi. Therefore, many of the basic hardware building blocks needed to bring out cableless recording were becoming available virtually off the shelf.

Working without cables was not new to land exploration. From the 1970s, various wireless recorders had been developed but most of them had only some hundreds of channels' capability. What the industry wanted in the 1990s was effective technology with essentially unlimited channel counts, such that geophysics would be far less restricted.

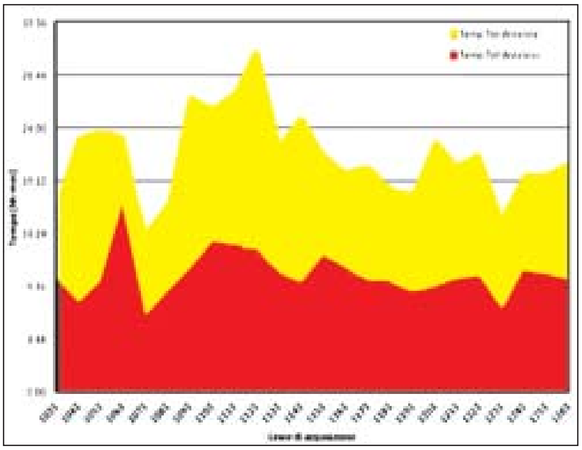
The new-era cableless systems, as we will show, for many types of seismic acquisition can be superior to cabled systems but in some ways this new choice in technological approach also turns out to have a downside. Most of the instruments developed work rather differently to the one another, each coming with widely varying limitations or benefits which are often not always instantly apparent. Therefore, the acquisition geophysicist can no longer assume, as he could with cabled recorders, that there is little to distinguish each instrument in capability. When planning seismic surveys from now on, and in order to avoid costly mistakes it has become essential to know, at least at some generic level, the subtleties of what each system can and cannot do.

Autonomous recording

The first big difference between the old technology and the new is that the majority of cableless systems have the advantage of offering autonomous recording. The many benefits of this to explorationists should be obvious. It means that each ground unit does not rely on eventual connection to the central system in order to record seismic data; for most cableless instruments there is fortunately no more of the feature which cost crews so much time in the days of cabled hardware - serial reliability.

This does not mean there are no benefits to being able to communicate cablelessly with the central system. Indeed, systems which can guarantee flexible connection between all deployed ground units and one or more control/monitoring systems are the most advanced and safest systems to use. However, with few cableless exceptions, the hardware is not serially dependent and if connectivity fails for any reason, ground units default to their autonomous operation mode. In this way, we can make the statement that cableless systems bring great potential benefit to recording of geophysical data, whether active or passive, and represent for most geophysicists the only way to take on new exploration challenges.

Apart from the issue of system autonomy, there has been a number of other comparisons between cabled and cableless systems, including the side by side field use of both technologies. The most recent and also perhaps the most well conducted has been by the Italian oil giant ENI, who gave a paper on their results at the 2012 SEG Convention (Pellegrino *et al*, 2012). Given that ENI acknowledged Sercel for their "important support" it seems the systems under test may have been a Sercel cable telemetry system with a Sercel cableless system. Their conclusions were both interesting and enlightening, and this unbiassed paper is



Comparison of effort needed to deploy cabled (yellow) and cableless system (red). Courtesy ENI E&P. SEG 2012 expanded abstracts.

recommended to all who are seriously considering use of cableless technology.

In broad terms, they found that cableless systems can provide a 50% time saving for layout. It should be noted that they were working in an area of Italy described as "plain ground, densely inhabited and characterized by the presence of little towns, several small rivers and watercourses". In other words, a location which may be somewhat easier to work in than some Indian survey areas. The paper claims some surprise at finding an increase in fold (albeit slight) thanks to cableless equipment versus cabled. However, this should not be astonishing as many, including this author, have stated that an advantage of cableless ground units is that they can be placed almost anywhere and, therefore, can acquire data which would not be so easily be available to a cabled or serially dependent cableless system.

Their paper goes on to suggest that it would have been desirable at least to have had available realtime noise monitoring in the cableless system used. It warns that shooting blind, in not allowing noise monitoring of external noise sources, risks acquiring data which is not complaint with technical specifications and which may be difficult to process. These are important points as for some reason noise monitoring was not enabled for this operation even though it was working in "plain ground". Later we will review the physics to understand why some systems, even if they have built in communication capability, find difficulty in maintaining communication in all but simple terrain which does bring us to an extremely important point. Whereas it is educational to compare cabled and cableless systems, given that the latter technology has now attained some level of maturity, it is just as important to compare one form of cableless technology with another.

The other major issue highlighted by the ENI paper is that they found the cableless system to be heavier than the cabled system, and that this was related to total battery weight. It is not clear from the paper if the cableless system used was a single channel per box product, or one with a few channels per box. This particular issue has a significant effect on weight, and is of course yet another reason to compare cableless technologies with one another.

What should be compared?

The difficulty is to decide which system attributes should be compared when looking at all seismic cableless approaches. The majority of papers to date have made the simple comparison of shootblind hardware against systems which have some form of communication. We now see that such a simplistic comparison is of limited value. If any recording technology designed to offer a level of communication cannot actually provide this facility in typical seismic environments and then must be used to "shoot blind" any comparison in terms of radio communication must include under what circumstances communication is possible. We will return to this point later.

Comparing analog 3C using Sigma cableless system with two different MEMS cabled systems.

As possibly inferred by ENI, another area of useful comparison would be one which considered the number of channels per ground unit as this will have significant bearing on weight and, as it turns out, many other issues of convenience to

Comparison in varying cableless seismic acquisition technologies

- Shootblind and non shootblind.
- Non-shootblind with assurance of communication and those offering no assurance.
- No. of channels per ground unit.
- Batteries: internal or external (or both).
- Battery chemistry choices available, or forced.
- Ability to work on water.
- Suited to wide range of passive/ permanent.
- Suitability for analog 3C.
- Ease of deployment.
- Ability to use multiple different passive and active sensors.
- Multiple types of harvesting methods, or only 2.4 GHz-based.
- Serially dependent comms architecture or other.
- Recording to stop during harvesting or recording continues.
- Full support for SPS, SEGD, SEGY.
- Levels of built in hardware and data security.
- Ability to work side by side other cabled recorders, or none.
- Ability to add sight to other cableless recorder, or can only be used on its own.
- Configurable system, for optimisation in different environments or non-configurable.
- Price to purchase, including all initial software and peripherals.
- Price to operate, including software upgrades.
- Level of source control integration


Sensor testing for passive recording. iSeis cableless system also shows use of external WiFi antenna for improved connectivity.


Shallow marine/TZ operations. Mesh comms can work over salt water allowing some land standard cableless hardware to be used to reasonable water depth.


High specification 3C analog geophone with Sigma cableless 3 ch recorder. Outperforms MEMS devices in most field and laboratory tests. Hauer et al 2008.

differing seismic operations. Another comparison is most certainly a review of batteries which any particular cableless instrument may be forced to use and the surprisingly significant and varied new issues this can bring to acquisition.

One more comparison would be in terms the suitability of varying systems for different types of survey. For example, all cableless systems are capable of working on flat open land but how many are suited to jungles, villages, areas of rapid elevation change, marsh, salt water, quickly moving water bodies and similar? Related to this would be to look at which cableless technologies could cope with passive and land 4D as well as active data recording. Given the large range of passive acquisition methods that now exist, how does each cableless system cope with the many challenges, and can a broad range of sensors be used on each system? This is especially important as manufacturers of very sensitive transducers - those with better low frequency response and very low noise, have much to offer the passive/ permanent monitoring industry which MEMS cannot given the high levels of noise such devices can inflict on important parts of the seismic pass band. These superior “Guralp type” sensors, which tend to be active/ powered, need to be attached to suitable cableless acquisition systems where an important feature is the ability remotely to control external power to the sensor.

An initial pass at the requirements of passive recording was made by (Heath, First Break, 2011) but this was not in the form of a comparison between differing cableless approaches. This may be extended to look at which cableless recorders can also cope with 3C data, and especially multi-component acquisition in difficult environments which can impose different requirements on a cableless system to those when working in dry simple locations.

Apart from the noise levels and the high power requirements of digital sensors - a special disadvantage when battery power is so precious in cableless acquisition - there is the related issue of multi-component acquisition with cableless hardware. Some analysts of 3C data in difficult environments believe that analog 3C geophones are superior for a variety of reasons, but the one pertinent to areas of significant rainfall is the level of noise susceptibility which digital sensors face. For example, because the inertia of the suspended MEMS device is not so different to that of a rain drop (which is a very different situation to the mass inside an analog geophone) MEMS may demonstrate additional noise modes in locations where rain and some other types of environmental noise are prevalent. If the cableless system employed has no method of real time QC reporting/ noise display, then the situation is even worse. Stated differently, if users are choosing to switch to cableless kit because they are easier to use in tough environments, then they should also consider carefully their choice of sensor and noise monitoring capability in such locations. None of these issues had to be compared or considered when operating 3C acquisition in dry flat locations or with cabled systems.

On this subject, one should consider whether any more it is geophysically appropriate or commercially advantageous with any cableless recording to think of multi-component instruments as devices distinct from those designated for single component acquisition. If the cableless system has sufficient channels and noise monitoring functionality, and one accepts that 3C may well be better acquired using appropriated high quality analog geophones (Hauer *et al*, 2008), then the instrument can be used for single component one day and multi the next.

As intimated, a most important comparison would surely be to look at what is involved in ensuring different levels of reliable communication (data rate, range, deployment effort etc). However, it turns out that most instruments on the market can neither guarantee any level of full time link at any bandwidth, nor have actually ever worked through difficult areas, such as thick canopy rain forest or even paddy field, and thus likely need their data to be downloaded from ground units at some later time. Therefore, comparing data harvesting options would also be another very useful one to undertake.

Operations with Sigma system, cableless mesh in operation, 50 cm repeater antenna for noise, QC, status and security monitoring in high humidity, marsh and fairly thick jungle (no visual line of sight). Courtesy CellSeis Geophysical.

Advanced cableless systems can benefit from the latest advanced source controllers and sources.

Data collection operations may require significant investment in additional hardware and/or extra personnel so any company considering a move to cableless should investigate the commercial issues. This will affect not only costs but also the level of acquisition data quality control which can be exercised. The same applies to system and data security: if data cannot be sent in real time, then it remains at risk of theft until the time it is harvested. The geophysicist must then allow during his planning that, if the ground unit is stolen and this not be known for perhaps days, or that his data is useless for some other reason (see later for examples) his fold will be affected, perhaps enough such that reshoot is required. So users must also comprehend details relating to which systems have a better record against theft because it seems there are rather major differences reported.

An often overlooked comparison would be the ease of integration with source controllers. While recording instruments have been developing furiously over the last decade, so too have source controllers and even impulsive sources themselves. This is an area not often covered in the geophysical literature, but the most recent reference that I can find is by Fleming (June 2013) in a magazine published in India: Drilling and Exploration World, where source control for cableless systems is touched on in detail.

Additionally, in today's market, it would also certainly be of value to know which instruments can be made to work side by side others, be they cabled or cableless. This is also related in many cases to source control capability, and the level of integration between these major subsystems. Guaranteed comms and good source control integration determine how well an operation can run off a standard SPS file. This comparison would be important because the days when all surveys undertaken make use of only one recording system may soon be far behind us as multi-recorder


Comparison of three cableless systems (including iSeis Sigma) and a cabled recorder, undertaken by University of Texas. Sigma system chosen as baseline system against which data comparisons made. Information available from U of T. The future requires that any recorder can be used with any other, or multiple recorders.

operations are becoming more common. In fact, many believe that the near term future for cableless acquisition is more likely to be in such side by side use. In anticipation of this, one cableless system has already developed the ability to link its cableless ground units together with cables, where both cabled and wireless comms are available in a fully networkable configuration on the same spread. However, a cableless system offering a networkable cabled option for some or all of the survey is not the same as a cabled system which can only offer cableless for some part of the operation. If one were to make this comparison, the former architecture seems to be much more flexible.

This brings us to needing to know something about data formats. SEGD, while suited cabled systems, is not always ideal for cableless since data from one shot but different channels can arrive at different times (perhaps days apart) due to various harvesting techniques or data paths, and also not always in a timescale suited to full channel real time QC. It is almost impossible conveniently to generate a single SEGD file per record using cableless or mixed system recording despite some claims to the contrary but I know of few processing centres which are worried about this.

Indeed, a growing application for cableless systems which can guarantee some level of connectivity is to mix such technology (some tens of few hundred channels) to a crew using any cableless systems which cannot assure communication. This "adding sight to shoot blind operations" permits noise monitoring, QC, security monitoring and so on. If users also wish to add data from the "guaranteed comms" recorder (which can filter match data to the master system) to the master (effective shootblind) cableless system, then it may need to be capable of SEGY and SEGD. For some instruments, mixing systems from different manufacturers is now not only fairly easy, it is a useful way to employ older recorders (cabled or cableless) at the same time. These are all areas fit for making comparisons.

Finally, one may also look at prices of different technologies both to purchase and operate. Although such commercial issues are beyond the scope of this article, this is one of the areas where most surprises may be likely. This is because technologies, which may appear to be lower in cost to buy and use due to their simplicity or limited list of features, may turn out not to be so economic when all things are taken into consideration. For example, some systems need a variety of expensive peripherals which others do not, and thus also need extra people to operate them.

In turns out that none of these possible comparisons are independent from any other, and that there are most certainly other important features of differing cableless recorders one could plot against others to facilitate interesting comparisons. Such characterisations were neither necessary nor possible with cabled systems but it should by now be apparent that some knowledge of all these issues is very useful for the geophysicist who plans a switch to working without cables, or to side by side operations.

If potential users are not interested in investigating in great detail this huge hardware choice, there may be a shortcut of interest. Just as most of us configure our own computers and mobile phones to be most efficient to how we want to work, one simple and obvious recommendation for the exploration industry is to look first at cableless technologies which are also configurable. This will at least allow choices to be made as the user gains experience with this new technology.

For those who want to get the most out of what this new type of acquisition method has to offer, it should be clear that there is much to consider and multiple interconnected issues to compare. However, for brevity, we shall now concentrate on only three major areas: communications capabilities, ground unit power options, and finally data quality and system security which are very closely related. These few comparisons will also cover how the process of acquisition geophysics is affected by each.

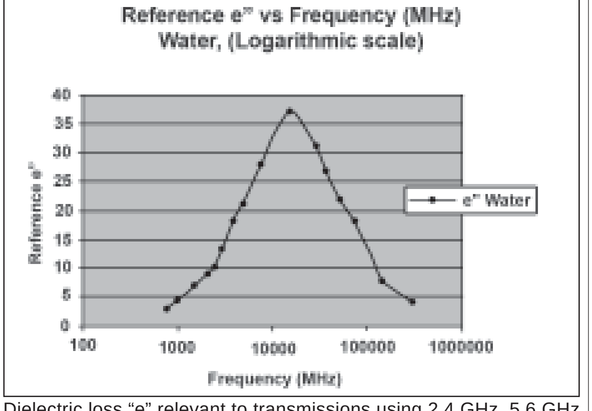
Comparing communications

Commencing with the issue of communication capabilities between ground units and central system on the seismic crew, we should recognise that most of the first cableless systems on the market were of the shootblind type and thus cannot be included in any comparison which considers communication links. However, they will not be excluded from the next two comparison sections. Shootblind hardware has had success albeit in a rather limited number of geographical areas, but even in those there is now growing interest to "add sight" to shootblind operations by deployment on the crew of cableless hardware with assured communication capability, sometimes only at a relatively sparse level e.g. a few hundred channels.

A few cableless technologies claim an ability to provide a realtime radio communications link. But when it comes to working without telemetry cables in the seismic environment this comparison must consider what "realtime" actually means. In cable-based acquisition the definition of "realtime" is unambiguous. It is the transmission of both seismic DATA and STATUS (e.g. system health, QC, noise monitoring etc.,) from ALL deployed grounds units to the central recorder with virtually NO DELAY. This is not the case for cableless systems.

The challenge for all non-shootblind cableless instruments is their reliance on the only internationally acceptable radio transmission frequency - the "2.4 GHz ISM band" (2.4000 - 2.4835 GHz which is usually divided up into a number of overlapping sub-bands of around 22 MHz) with power restricted in most countries to 100 mW EIRP or less. This broad band of frequencies is readily absorbed by water molecules, either in liquid or gaseous form, by a process called dielectric heating. This is the reason that most microwave ovens work at 2.45 GHz. Ovens have perhaps ten thousand times as much power at their disposal compared to a cableless system, and obviously domestic users are happy to heat their food rapidly relying on the efficient absorption of such energy. But geophysicists should be concerned about the very same physical process strongly affecting how far very low power 2.4 GHz transmissions can travel. This issue is well described in the document "2.4 GHz Issues" to be found at www.iseis.com/ documents.html. In some countries, other frequency bands are available for use in the geophysics domain, in the 5 - 6 GHz region, but these generally offer no essential advantages which are not cancelled by some greater disadvantage, so will not be considered further herein.


Line of sight. If a ground unit can visually see its neighbour, transmission is much simpler. But in many locations this is not possible not matter how ground units are deployed. Here, Sigma cableless system in thick jungle and in depression so no visual line of sight. Notice use of half metre mesh repeater antenna to assure communication in dip. Compare with next picture.



Dielectric loss "e" relevant to transmissions using 2.4 GHz, 5.6 GHz and 5.8 GHz bands.

As part of the discussion about radio signal absorption, it should be noted that GPS signals are at a lower frequency, around 1.23 and 1.57 GHz, which is still affected by dielectric losses but to a smaller extent. Depending on the impurities present, ice is also much less affected by 2.4 GHz microwaves (which is why ovens have a defrost cycle to switch power on and off in the hope some ice will melt and, once in liquid form, much higher levels of energy absorption start to take place).


Transmission is improved compared to earlier figure as it is just possible to see through vegetation which can make a significant difference. Mesh relay antenna here deployed on pole with Sigma ground unit to act as relay point for multiple channels in noise and security monitoring.


Directional antenna set up behind dry and wet bales of straw to investigation significant absorption differences.


Measuring RSSI through loose vegetation (new sunflower plantation).


Testing PC (notice MRN bridge and mesh network on screen) and measuring of RSSI.

Trying to transmit high bandwidth data over any useful range without appropriate antenna and careful deployment, especially in areas of dense green vegetation, conflicts with the laws of physics. Transmitting through vegetation which is not damp or wet, such as dry wood or straw, is much easier simply due to the radio wave encountering far fewer water molecules. However, if one were to soak dried vegetative matter with water, as long as it does not freeze, one could see a major increase in absorption characteristics. Further, trees without broadleaves pose far less problem for transmission, especially in dry weather but when they become wet absorption quickly increases. This means that, unlike cabled recorders, modern systems may be essentially weather and vegetation-dependent.

iSeis conducts many tests in its proving grounds in Oklahoma to characterise communication functionality on its Sigma cableless system. At this test site can be found flat areas without vegetation, fields of cereals and other planting, forests of varying densities, some small valleys and dips, with weather conditions (ignoring occasional tornadoes) which include drought and torrential rain, as well as temperatures which seasonally range from about -20C to +45C. Iseis company also has at its disposal a wide range of 2.4 GHz communication systems and differing antenna, as well as instruments to record received signal strength indication (RSSI). iSeis believes that few, if any, other companies undertake such detailed investigations with such a range of equipment and publish results.


Preparations for antenna testing (range, data rate etc) with Sigma cableless system.

Recent tests used a wide variety of antenna in different conditions (see photos). Depending on the equipment, RSSI can be shown on the antenna itself or on separate instruments. The most definitive testing here was with directional antenna which have the capability to give greatest range and bandwidth, so that various absorption effects can be

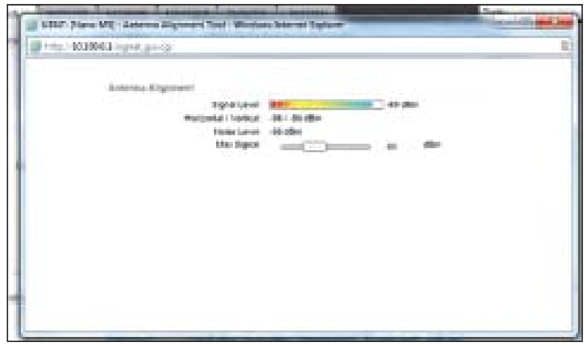

Forest of average vegetation density, area of elevation changes. This poses difficulties for high data rate transmission even over short range of no visual line of sight.

better measured over a wider range. Such antenna, in flat terrain with close to zero vegetation have ranges of the order of 1,000m if properly directed even with antenna within 0.5m of the ground. However, as soon as any vegetation is put in the way, the received power can drop very quickly and often not predicably. The effect can be dramatic, though in line with theory.

For example, at temperature of 30-35C a dry thick bale of straw posed not problem for radio transmission and neither did a very large pile of old wood (a fallen tree). However, after rain, the straw was far more impenetrable for radio waves as the hay acts like a water sponge, while the pile of dead wood affected propagation little since the amount of water it could absorb was minimal. Had this test been repeated in the depths of winter, any water absorbed would have turned to ice would have impeded the 2.4 GHz signal somewhat less.

Any live vegetation (see photos, including low density planting of sunflowers, of high density of cereal) rapidly decreased signal unless the antenna was placed above the tip of the vegetation. Placing of Sigma-based test equipment in forests, especially with changing elevation, made directional antenna essential for high data rates in some locations, but this depending much of visual line of site. Conversely, in all circumstances, the low data rate built-in mesh radio network device (far less directional) was able to make connection without visual line of sight, though sometimes repeaters were needed.

The issue of "line of sight" must also be understood by any explorationist planning a seismic survey. When considering 2.4 GHz transmissions, even though of course there is huge difference in the frequency of visible light compared to microwaves, one can roughly say that if a transmitter/receiver pair literally have visual sight of each other, then the quality and reliability of the communication link is very much superior compared to when there are


Some seismic instruments permit RSSI to be measured by application running on PC connected to transmission system. Its a very useful feature.


Portable RSSI meter for 2.4 GHz band. May be used to test reliability of communications in different seismic environments with differently configured seismic instruments.


Large stack of dead vegetation after rain storm measuring RSSI using directional antenna.


Testing through high density cereal plantation. Absorption significant.

bushes, grasses or other forms of vegetation or wet obstacles in that path. There are some surveys where simply raising the ground unit's antenna by, for example, the height of a battery box, is enough to give that visual line of sight. Some systems advocate putting the box on a pole maybe 1m above the ground to achieve reliable communications. Others, if their layout topology permits, can move boxes a little in each direction so that there is box to box visibility rather than being blocked by a bush, tree trunk or hut.

Seismic Source Co., early trials of WiFi & seismic recorders. (2001) Raised and/or directional antenna required for high bandwidth/range comms.

If these efforts are practical, if the crew is willing to take the extra time, and if transmission/reception quality can be monitored by the deployment crew as they lay out equipment, this may be something well worth considering. However, in difficult locations, for example in the sort of rain forest or village where one cannot sometimes see many metres ahead, or with thousands of channels to contend with, or with systems whose layout geometry is restricted due to the method communication employed, the extra effort required may be significant. So when considering claims about the communication capability of any technology, operations in fairly flat desert with no vegetation and low humidity is rather simple to achieve. But elsewhere, one must take into account just how thick or dry the vegetation is, how high antenna can be placed and so on.

Long before the new generation of cableless recorders emerged, at least one company had been using WiFi for years to communicate with existing seismic recorders. In all probability the first company in the world to do this was Seismic Source Company of Ponca City, Oklahoma. SSC was more known for development of advanced vibroseis and impulsive source controllers but it also had international success in making very flexible seismographs, so in 2001 it saw integrating WiFi into these recorders as a natural step. However, it quickly found, given the inherent limitations of this form of communication which will be reviewed later in more detail that WiFi tended to need directional antenna deployed at least 1m above ground to allow useful ranges or high bandwidths to be reliably achieved.

When the term "WiFi" is employed it can refer to exactly the technology most of us employ to go on line. However, some technologies, in referring to the 2.4 GHz band or to WiFi itself, mean some non-standard version of it. Being subject to the same laws of physics especially as regards absorption, there are few advantages to using bespoke 2.4 GHz susbsystems even where they are legal. Especially when it comes to keeping seismic systems future-proof there may be many significant disadvantages. Over one billion dollars of R&D goes into WiFi equipment around the world every year which our industry could take advantage of. There are some exciting new technologies already on the horizon, most of them will be backward compatible and adhere to industry standards. For example, many will be usable with a cableless recorders with standard ethernet connection. So choice of any seismic recorder which cannot take advantage of such new features is automatically self-limiting.

With all radio transmission there is a trade-off between range, bandwidth and ease of set up. Very simply put, for a certain deployment, one can either transmit longer range with less data, or more data with less range. Just as in geophysics, the major issue is the sensitivity of the radio receiver (analogous to sensor and ground electronics in seismic exploration) versus the signal it receives (the energy of the source available at the receiver compared, the path it takes along which it is attenuated, and various ambient noise levels in seismic exploration). To get a feel for what is possible and not just marketing hype in modern cableless systems it is essential to understand this three-way relationship.

So let take an example. Assume it is necessary to use a certain amount of energy to have one bit transmitted a certain range by some radio link to a destination (the receiving apparatus) where it is able to be picked up and recognized with high probability as that bit. This bit may be part of a much larger data train of a certain bandwidth and, therefore, the bit can only occupy a certain time period. Clearly, the higher the bandwidth, the smaller the time period that the bit can occupy.

Throughout the transmission path of the signal, there will be various loss and interference mechanisms acting, some of which are obviously related to the distance it must travel. By the time the signal arrives, due to these various energy loss processes, the energy gathered above the threshold noise level of the receiver must be sufficient that it can be recognised reliably as the bit of information. This energy can be considered as the power picked up by the receiver multiplied by the period of time taken up by that bit.

Standard Sigma field unit using mesh radio repeater and directional high bandwidth WiFi connected through Sigma ground unit's ethernet port, on passive operations, China. As power usage is well under control, also possible to use simple/small external lead acid battery.

If the range is now increased the amount of power received will naturally decrease due to the signal spending more time being attenuated. In order for the receiver to have a good chance of recognising the bit, it still needs to accumulate the same amount of energy as before. So to make up for the decrease in power, the bit must take up more time, which means lower bandwidth is necessary. Conversely, if the bandwidth/data rate is increased, the necessary energy can only be gathered at the receiver by there being greater power of transmission. Losses can often also be reduced by elevating either or both the transmit and the receiver antenna if system architecture permits. Alternatively, or as well, better antenna could be used such as directional units. However, both these examples may require more deployment effort than the crew is able or willing to adopt.

Do not be fooled by communication capability claims. Foliage is thick but simple visual line of sight is possible due to cut path through jungle so communication is simple, requiring no raised or external antenna. If path cannot be cut, the problem is very different.

Whereas this is a major simplification and ignores several issues which any radio engineer will instantly recognise, it is probably enough to understand when it comes to having a sense for how well cableless recorders will send data in various seismic acquisition environments. Therefore, in a comparison of cableless seismic data transmission using the troublesome 2.4 GHz ISM band, the sort of questions which must be considered include:

- For even minimal assured communications in all environments, what type of deployment is typical for each recorder, i.e. what set up effort is involved?
- To improve flexibility and reliability of communication, does the instrument permit multi-path (mesh topology) or only point to point?
- Is it possible or necessary to use directional or external antenna?
- How high above ground must these antenna be deployed?
- What bandwidth can be expected with each set-up?
- What radio range can be expected between two adjacent units which must form part of the communication path?
- What transmission delays are there between ground units acquiring data and this data being received by the observer, and how is this affected by obstructions?
- What happens if the communication path is broken - does the system effectively cease to function, or does it default to an autonomous shootblind configuration?

The physics relating to some of the absorption issues of 2.4 GHz signals has been referred in the document sited above. However, it is useful to have some knowledge of what ranges can be expected using this frequency. If nothing else, likely useable range

Higher foliage density and elevation changes compared to previous figure, means lower range or lower bandwidth due to increased path loss.

will determine how a seismic recorder has to be deployed and when transmission can be expected to become intermittent or fail. Armed with this knowledge, the geophysicist may not only be able to pick out instruments which have the best chance of reliable on-going operations in his environment, it will also give some idea of what level of deployment effort is going to be necessary for any particular seismic survey that is planned.

To determine the range of a wireless system, it is necessary to know various items:

- Transmit Power, Pt: this is sometimes given in milli-Watts but most often it is given in dBm, which is decibels relative to 1mW. In most countries, a maximum of only 100mW (20 dBm) EIRP can be used but for various reasons, in real life it may be closer to 60-80mW which is also about the maximum available in most domestic WiFi access points. Some geophysical systems have far greater transmit power available which also uses very much more battery energy, partly because the amplifiers used may be only 20-30% efficient. But as we will see, often this extra radio output gains little even if it is legal to use. Operating systems with greater power may subject that operation to shut down by radio regulatory authorities and possibly equipment confiscation. Some countries do not even allow import of equipment exceeding local RF limits. There can be a temptation in marketing for some to specify range based on such higher radio power, while their battery power consumption figures may be based on the lowest radio output. The conversion from Watts to dBm is given as follows:

$$P \text{ in dBM} = 10 \log \left(\frac{\text{p in watts}}{0.01}\right)$$

- Transmit and receive antenna gain - Gt and Gr respectively. These are given in dBi, or decibels relative to an isotropic radiator, i.e. one that radiates equally in all directions.
- Sensitivity of the receiver, Pr: this is the minimum signal a receiver can detect and receive data with little error. It is also given in dBm and is usually a negative number.
- The wavelength of the carrier λ, or the frequency of operation, f where $\lambda = c/f$ (c is the speed of light).

Early trial with Sigma system. Due to low density of forest and leaves, and unit on a hill, mesg radio range was very long.

The sum of the transmit power in dBm, transmit antenna gain in dBi, and receive antenna gain in dBi minus the receiver sensitivity in dBm is known as the "Link Budget" in dB. The Link Budget is what can be spent to achieve range between the device (e.g. seismic ground unit) transmitting some information useful to exploration geophysicist, and its associated receiver which may be the central system or other ground units. The maximum theoretical range is when the Link Budget is equal to the Free Space Path Loss (FSPL).

Free Space Path Loss represents the reduction of energy per unit area as the waves spread out from an isotropic antenna, where d is the distance or range.

$$FSPL = 10 \log \left(\frac{\lambda}{4\pi d}\right)^2$$

The maximum range is obtained when FSPL = Link Budget

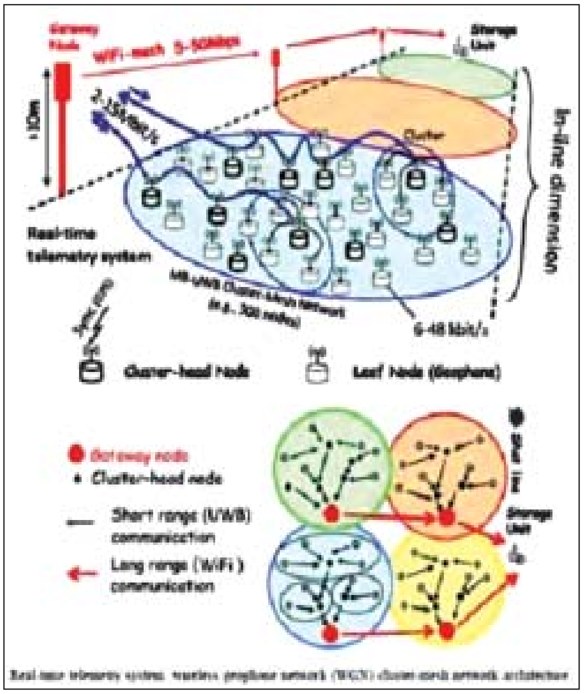
$$10 \log \left(\frac{\lambda}{4\pi d}\right)^2 = Pt + Gt + Gr - Pr$$

This equation can be re-written as:

$$d = \log^{-1}\left\{\left(\frac{Pt + Gt + Gr - Pr}{20}\right) + \log\left(\frac{\lambda}{4\pi}\right)\right\}$$

However, this is the maximum range that can be attained with the system under the most ideal conditions, which are probably not going to be attainable on even the most simple seismic operations.

Metallic objects will reflect the RF waves which helps when the multipath signals add up constructively but impedes it when



The future of cableless recording as envisaged by Milan Polytechnic. Note use of mesh topologies, local storage, variable bandwidth transmissions, long range communications to join submseshes. Independently, similar technology was being developed in Calgary by SRD Innovations, called hyMesh optionally used with Sigma recorder. Graphic courtesy of IEEE.

the multipath signals add up destructively. Moreover, metal objects, for example a truck moving slowly or parking in the transmission path, can block the 2.4 GHz waves completely unless it supports mesh topology. Any obstruction is a serious concern for recording unless the ground units can default to an autonomous mode and have been designed with sufficient onboard memory to buffer on-going acquisition during the period of the blockage.

On the average seismic crew, there are many types of obstacle which will affect 2.4 GHz signals including water vapour and rain, foliage, trees, grasses, buildings and animals. Rain and water vapour add their effects by attenuating the RF over the whole path. This should be accounted for by reducing the claimed range in actual deployment by using a “Fade Margin”. Where obstacles are of the dimension of the wavelength of this frequency, about 12 cm, other transmission problems are caused. For example, many trees have low level branches of this sort of size.

Fade margin is a very important concept for the seismic application and all system manufacturers ought to be able to describe to some approximation the fade margin associated with their system under differing conditions. If nothing else it indicates how susceptible the instrument is to various often-encountered environments in seismic acquisition.

One example of this reported elsewhere is technology which could be set up to work during the afternoon in a certain density of mostly coniferous forest (such vegetation naturally has lower absorption characteristics than the type of vegetation found in the tropics) but which would not work well during the mornings. This was because dew in foliage and atmospheric humidity, which the sun burnt off as the day progressed, were enough to reduce transmission below what was useable. Such a system would be described as having a poor fade margin. It may be that some manufacturers refer only to their free space range, or downplay their fade margins to reduce fears about communication reliability, so it is always advisable to see proof of worst case performance.

The level of fade margin varies with the type of application, how the system designed and used, and with the amount of absorption or interference anticipated which can often be worse in one direction than another, thus subjecting the recorder to anisotropic behaviour. Users of cabled systems never had to worry about such things.

Typically for metropolitan area networks operating in the unlicensed bands a 15 dB fade margin is often used. As an example of a manufacturer which knows its fade margins, in the case of the hyMesh™ system developed by SRD in Calgary, Canada, because the distances involved are smaller, a 6 dB fade margin was found to be sufficient to account for weather effects.

The range equation with fade margin becomes:

$$10 \log\left(\frac{\lambda}{4\pi d}\right)^2 = Pt + Gt + Gr - Pr - FM$$

In the same manner, the effect of going through a canopy of trees can be accounted for by subtracting the absorption by trees from the Link Budget. Going through a tree canopy can easily cause 30 dB of extra loss. This is far more than the 10 dB gain, available for example by going from 100mW to 1W transmission, where such power is permitted. In other words, higher power systems in some cases may make little real difference.

In this case, the equation for the free space range has to be modified by subtracting the amount of Absorption Loss (AL) from the link budget:

$$10 \log\left(\frac{\lambda}{4\pi d}\right)^2 = Pt + Gt + Gr - Pr - FM - AL$$

It should be noted that if the path includes several absorbers, which is quite likely for difficult exploration environments, there would be a term for each absorber. So the most general version of the range equation would be:

$$10\log\left(\frac{\lambda}{4\pi d}\right)^2 = Pt + Gt + Gr - Pr - FM - \sum_{n=1}^{m} AL_n$$

The general equation for range under practical condition becomes:

$$d = \log^{-1}\left\{\left(\frac{Pt + Gt + Gr - Pr - FM - \sum_{n=1}^{m} AL_n}{20}\right) + \log\left(\frac{\lambda}{4\pi}\right)\right\}$$

The table shows a very simplified comparison between Free Space Range, Free Space Range with Fade Margin and Range at 2.4 GHz with several values of absorbers and different antenna, using a typical transmit power of 16 dBm. The purpose of this is to show how much difference is made for the seismic application by various antenna and different absorbers.

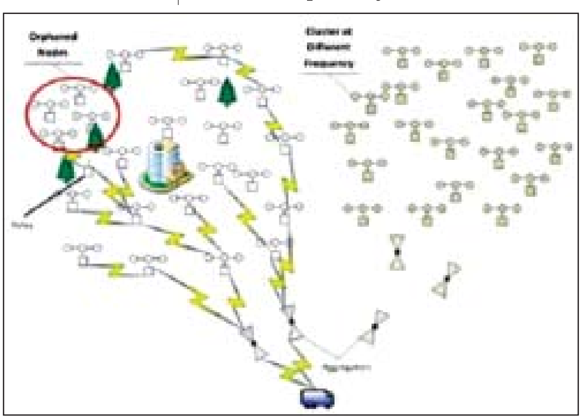
What is clear from this table is that there is a huge difference between the minimum and maximum ranges possible under differing deployment conditions and varying system architectures and antenna. Two seismic recorders which claim realtime capability with similar data rates could be described by the second example in this table, in which fairly high bandwidth data theoretically can be transmitted about 790m, including allowance for fade margin.

However, if using point to point transmission schemes, with even a single bush in the path, the range of one of these falls to only a theoretical 79m. This may be helped if it is possible to change and/or elevate antenna but most cableless manufacturers make the antenna an integral part of the ground unit because this is much easier for them, thus making such flexibility impossible. In these cases, attempts to improve range can only come from elevating the whole ground unit perhaps with its battery. This clearly represents a significant increase in deployment effort while instruments which allow just antenna to be raised as far more field-friendly.

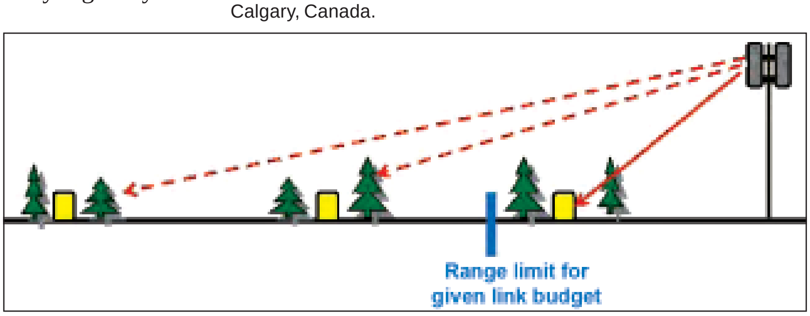
For a seismic recorder with one channel per box ~80m range would be acceptable but this would then need the use of far more batteries. These in turn would be more expensive to buy/deploy than, for example, ground units with three channels though these of course must

Chemistry	Lithium iron polymer ($LiCoO_2$)	Lithium iron phosphate ($LiFePO_4$)	Lead acid	NiCad
Theoretical capacity mAh/g	274	170	low	30
Cycle life/times	500	2000	med-high	500
Working Temperature/°	-20 to 60	-20 to 60	-40 to 80	-20 to 60
Charge Temperature/°	0 to 40	0 to 40	-20 to 60	-10 to 30
Specific Energy	high	middle	low	low
Low Temperature Performance	good	bad	mid-good	good
High Temperature Performance	bad	better	mid-good	good
Safety Characteristics	good	better	good v.good	good
Memory Effect	small	small-mid	yes	yes
Environmental Pollution	no	no	yes	yes
Cost	middle	middle	cheap	cheap-medium
Weight for same capacity	low	low	high	medium
Price of battery	high	high	very low	medium
Price of charger	high	high	very	low medium

All figures and indications are approximate and may vary from country to country. Batteries with superior and inferior performances can be found.



hyMesh system from SRD Innovations. Mesh clusters permit any geometry, data rate and range. Coupled to the iSeis Sigma recorder, hyMesh technology can be used side by side other cabled or cableless systems, and is also inherently upgradeable, with various subsystems being replaceable as technology changes. Courtesy SRD Innovations, Calgary, Canada.



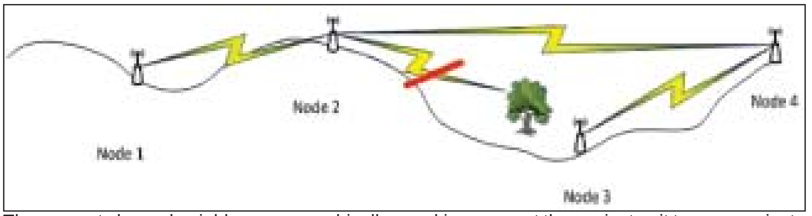
Due to signal absorption, even raising antenna in areas of bush, tall grasses and especially trees, range can be limited. In this example only one box can achieve reliable communication (antenna height & ranges not to scale). This may be partially overcome with greater radio power but this is illegal in most countries and very battery hungry. Beware of ranges which are only quoted using maximum radio power if that level of power is illegal in your territory. The same 2.4 GHz characteristics which may have affected realtime transmissions will also fundamentally affect how wireless harvesting can take place using this frequency and alternatives are very useful.

in general be capable of longer ranges. This ~80m range is in any case subject to further significant reduction in the presence of greater vegetation. Even using the same power, allowing different types of deployment to be used can permit much longer ranges.

Here we see an example of how the type of radio communications dictates how many channels per ground unit a system might expect to be able to operate with, which in turns affects price, battery choice, weight and so on. But consider when there is more than one bush, or the tall grass is thicker - range can fall to 25m or less. Now even a single channel per box ground unit may not be useful for all the surveys that an operator would want to undertake.

Ways round this would include dropping the data rate so range is improved, use different antenna, or use more units as repeaters stationed between seismic channels. This latter approach would either have the disadvantage of decreasing the number of live channels that could be deployed on a R-line where mesh topologies are not available, or add a lot of extra cost and deployment effort. This can be an expensive way of trying to overcome transmission issues and users would need to budget for more equipment.

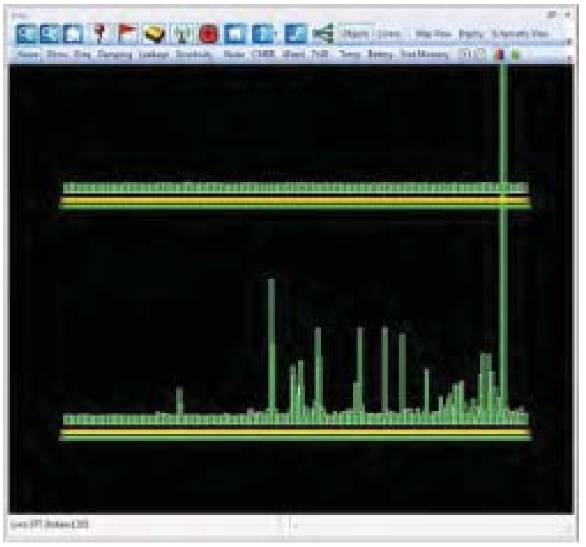
There is yet another topology in which a number of seismic boxes deployed at ground level is serviced by one or more WiFI access point type devices whose antenna are raised 5-10m typically above the ground. Such instruments can claim longer range in free space simply because one antenna is higher and thus normally the transmission path will encounter fewer obstructions. However, as well as not being best suited to the way that WiFi likes to connect to multiple users, this approach is more susceptible to other problems, such



The nearest channel neighbour geographically speaking may not the easiest unit to communicate with when radio absorbers are present. This gives rise to communication anisotropy and means mesh communications have advantages over point to point in tough seismic environments.

as canopy or even small bushes in the radio shadow of which the ground unit may have to be deployed. This may be why such systems can become shootblind even under conditions would be seen as benign for other types of non-shootblind cableless recorder.

Other WiFi-based systems do not follow a point to point topology but allow meshes of communication paths to be formed. In other words, one ground unit is trying only to communicate with some nearest neighbours and, given that operating environments can be rather anisotropic, nearest neighbours from the radio perspective may not necessarily be those from the geographic perspective. This is extremely useful when working in awkward locations and, as long as the



Mesh communications provides realtime noise monitoring even in thickest jungle. Courtesy CellSeis Geophysical, Indonesia.

Density of vegetation increase thus requiring taller antenna (equivalent to greater deployment effort in this example) to maintain high data rate. Compare with earlier and next figure.

Sigma system with hyMesh attached permitting realtime communications with thousands of channels. Requires only short antenna as terrain is very simple. Compare with next figure.

As vegetation density increases, for same (very high) data rate antenna must be raised further, here to 1.8m, to assure high data rate communications, here with Sigma and SRD hyMesh option. Therefore, recorder needs option of external antenna connection and ability easily to deploy it according to environment.

technology enables the deployment crew to monitor the mesh communication as they lay out equipment, then is an excellent feature to have available.

In heavy vegetation, meshes tend inherently to be fairly short range devices (low 100's metres), so they do not always need to operate at the permitted maximum power levels. Therefore, they are able to use smaller batteries (or those of a cheaper, simple, lighter and safer chemistry, or far fewer people involved in battery handling). Meshes also do away with the need there is in some cableless technology to rigidly follow certain layout geometries with backhauls because meshes allow virtually full random deployment. Clusters of meshes can be joined by long range/ high data rate devices.

The Politechnico di Milano in Italy is an independent organisation which specialises in researching wireless technology for the geophysical application. In a seminal and highly recommended article (Savazzi *et al*, 2013) they described what they saw as the ideal cableless system with good communication capability. It consisted of clusters of local seismic nodes with high memory capacity, deployable randomly if required, connecting together by self forming and self healing meshes. Multiple meshes could be handled by long range gateway devices. Something similarly was already being developed in Calgary by SRD Innovations and is useable as an option to the Sigma cableless system which also has a variety of other communication capabilities.

In summary, it is apparent there are many issues to consider when it comes to communications. Perhaps the ideal would be a system with three channels per unit to reduce battery, box and deployment costs and effort, (and allow the same system to be used for 3C whenever required), be simple to deploy with assured communication allowing each box to form mesh-like links with its neighbours at a bandwidth suited to the geophysical problem. Multiple links formed would provide paths back to the recording system and allow reliable two way communication. If more data rate is required the system should allow use of peripherals which cover the range of bandwidth from some minimum of data rate (for QC, noise, security etc) to the full seismic bandwidth of tens of thousands of channels.

Power options

The ENI paper referred to above exhibited some surprise that cableless systems can sometimes be heavier than cabled systems. The obvious issue here is to compare the combined weight of telemetry cables plus the few (but usually much heavier) batteries of a cabled system against the larger (sometimes very much larger) number of (usually lighter) batteries for cableless. But this is where the situation often becomes more complex whether it is simple total system weight as the most important issue for any particular operation, or a myriad of others.

Cabled systems tend to use large car or truck type batteries, with lead acid chemistry. Depending on trace interval and I-squared-R power losses in the cable, which is often where most power is used on a cabled system, one large battery could be enough to power around fifty cabled channels. However, each cableless ground unit, being an autonomous system, requires its own battery. Some systems even suggest the use of two batteries per box. If these ground units have only one channel, then *in extremis*, such equipment can need around one hundred times as many batteries as a cabled system. If the crew is not well versed at the logistics of battery handling, then the geophysicist planning surveys should take that into account as a priority. Obviously, a cableless recorder with, for example three channels per box and which only suggests use of a hot-swappable single battery, will need six times fewer batteries than the cableless unit referred to above. This will make a huge difference to weight all other things being equal, but also radically simplifies logistics on the crew.

The next issue in respect of powering ground units is the battery chemistry itself. The exploration industry has been used to using lead acid batteries in the field for many years. The amount of energy a battery can supply is often listed in amp-hours at a nominal voltage at some temperature, usually 20C. This is not always a useful figure since most instruments talk about their power (not energy) consumption, and this is given in milliwatts per channel so a conversion needs to be made before users have any indication how long batteries will last. In cabled systems, this figure was usually very misleading because it did not account for the energy lost in the whole DC power transmission system. However, as cableless instruments do not lose energy in power distribution, then more of the power they use tends to go towards doing something useful. But this is still not the whole picture when trying to calculate how long a battery on cableless operations will last and thus how many personnel must be devoted to handling them, and so facilitate comparisons between different cableless systems.

It is inappropriate to consider power consumption when talking about cableless systems and is much more useful to consider energy usage. Not only is this how the capacity of batteries is listed but also the instantaneous power consumption of a ground unit may have very little bearing on how much energy is consumed in the course of a survey. This is because if the ground unit cannot be remotely controlled, which is the case for all shootblind systems and even some designed to be non-shootblind cableless systems, it will take power from the moment it is switched on until the time is switched off. This may mean consuming power for 24 hours/day, even though acquisition itself may carry on for only eight or ten of those hours and perhaps less when shooting impulsive source surveys. Therefore, it is easy to envisage a situation where the quoted instantaneous power consumption is low while practically speaking the energy usage is high.

External 20 AH, 12V LiFe battery. For operations lasting long periods, ideal compromise between weight, safety and energy density? Less risk than Lithium Ion. Less weight than Lead Acid.

Some shoot blind systems, very conscious of this waste of energy, allow the user to programme ground units to wake up at certain times then go back to a sleep mode some time later. This has been called “alarm clock seismic” and is a good method if the user can be sure that he never will need to record at any other time than what has been programmed in. Otherwise, it comes with some dangers as one hears stories of frustration with this alarm clock method. For example, suppose one expects to take the last shot of the day by 5 p.m. when perhaps the crew may be able to move the spread up, but there has been a delay in shooting and the final shots cannot be completed prior to 5 p.m. at which time all the boxes switch themselves off. In such cases, the operator may have to wait until the spread wakes itself up the next day before being able to resume recording.

This can lose serious amounts of time and the first occasion this happens, the crew may decide they will not use this programme mode again and just leave hardware switched on all the time. This is when battery characteristics and the system the battery is used on become important. These include its nominal capacity and the ability to remotely monitor battery voltage. Both of these, as will be described, have complexities associated with them which may not be obvious to those used to the luxury of working with

Description	Tx Antenna Gain	Rx Antenna Gain	Fade Margin	Absorption Loss	Range
Two 4dBi omni antennas with no fade margin or absorption	4 dBi	4dBi	0	0	1.58 km
Two 4dBi omni antennas with 6dB Fade Margin	4 dBi	4dBi	6	0	790m
Two 4dBi omni antennas with 6dB FM and 20dB Absorption Loss	4 dBi	4dBi	6	20	79m
Two omni antennas with 6dB FM and 30dB Absorption Loss	4 dBi	4dBi	6	30	25m
One omni and one sectoral.	4 dBi	19 dBi (120deg)	6	30	140m

Sigma cableless crew unexpectedly encounters illegal surface mining activity in jungle and TZ location. Assured line communications become essential for data QC and hardware security monitoring. Crew suffered no equipment loss or data degradation.

far fewer batteries on a cable system where full time power monitoring is a well established feature. Additionally, power distribution by line cable means that even if one battery dies or is stolen, the line may still be powered from another battery. Cableless units simply cannot afford to lose or waste power.

Clearly, shootblind systems by definition have no remote control and so tend to end up using far more energy than one would gather simply looking at specifications. When non-shootblind systems lose the ability to communicate, or it becomes annoyingly intermittent in environments less difficult than those typical in India, then with no way to control or to monitor deployed ground units, either the system has no simple way remotely to switch off the unit once it's on, or no way to switch it on once it's off.

In such circumstances it may be possible to deploy all units using an alarm clock mode, or just deploy them with power on all the time, if such features exist in that system. As we have seen, having to do this, means that more energy is used than is desirable, and the weight of the system inevitably increases. Therefore, manufactueres who cannot guarantee communication (and thus energy consumption) force use of the some of the most expensive and troublesome battery chemistries, such as lithium ion, just to get sufficient energy density to keep weight down. Perhaps this would not have been such a drawback if one were not confronted with this reality that perhaps a hundred times as many batteries are now required as for the same channel count of a cabled system, so battery cost and logistics problems now are greatly amplified. So we see that any cableless unit which can guarantee under virtually all circumstances the ability to monitor and to remotely control (and so save) energy has some unexpected but very important advantages in terms of battery choice, weight, cost and personnel requirements, and logistical effort.

Cableless ground units put in shade to cool down prior to moving inside to airconditioning for data downloading and battery charging.

Having demonstrated that some cableless systems need far fewer batteries than others, and the significant difference this makes at all stages of operations, now take a closer look at the issue of the battery chemistry itself. As we have seen, a cabled system may need only twenty batteries for one thousand channels while the best cableless systems may need 334 and the most battery-hungry cableless systems may need 2,000 batteries for a thousand channels, plus possibly a significant number of spares. This is not an issue to be ignored - most planners, when considering seismic operations, can factor in a small mistake and multiply it by twenty as a contingency, but when any mistake must be multiplied by 2,000, then it can have a severe effect on operations.

Almost all shootblind systems, plus those which have a tendency to become shootblind due to limited communication capability, rely on some form lithium chemistry which may be because they tend to use the most amount of energy. 2 4 Such chemistries include lithium ion (LiO), lithium polymer (LiCoO) and lithium iron phosphate (LiFePO sometimes called LiFe). Given that there are differences between each type of lithium battery, any of which could affect operations, cost etc, potential users should be sure to know which lithium battery type is being referred to. There are one or two systems which can use nickel metal hydride (NiMH) cells but only one which as standard offers a wide choice in battery chemistries, from lead acid to most forms of lithium and which does not force the use of any particular chemistry or capacity on its users. After all, the ideal battery for the desert states of USA is unlikely to be ideal for tougher locales.

Due to the importance of understanding battery chemistry and the effect it has on seismic operations, a table has been drawn up highlighting the major differences between various chemistries. If weight is the main issue for a particular seismic operation, then it may seem preferable to use some lithium chemistry. But one should not jump to conclusions based merely on energy density; one must also compare how different cableless technologies use that power. As mentioned already, the difference between the power consumption figures stated for cabled and cableless systems is that generally cabled systems are "dishonest" about real power usage as so much may be lost on the transmission system, including DC-DC convertors and the cable itself, whereas when a cableless system states it power usage, it is probably much nearer to the truth. But with cableless systems one must also know if it is possible to control power usage and thus ultimately energy requirements. This is because one can think of energy requirements on a crew as being equal to some extra weight to carry around. If a cableless system can guarantee remote control of power, it may be able to get away without having to use lithium batteries and may still end up lighter than the cableless system which cannot provide power control and which is using some form of lithium.

When comparing batteries, especially when the exploration is in warm–hot environments or in areas with difficult logistics, it is often the case that "the simpler the battery, the better". This is because generally lead acid batteries can stand more abuse, they and their chargers may be ten times cheaper than lithium options, and perhaps can undergo more charge/discharge cycles at a wider range of temperatures and which are available locally atlow cost Of special importance is the situation regarding temperature. Recorders with lithium chemistry generally have a lower operating range than those systems which offer other chemistries.


Ground units under air-conditioning for further cooling prior to battery charging.

Further, whereas the charging temperature for lithium batteries may be quoted with some fairly large spread, perhaps 10-40C, in reality many such batteries may only offer the full number of charge/recharge cycles if they are charged up at much more limited temperature range. When bringing batteries off the line in any warm or hot climate, it is may be necessary to allow batteries to cool first by putting them in the shade or even in airconditioning. If this is not done, not only could the battery not take all the charge it should, but as stated, the number of charge cycles can be much reduced.

Special attention should be paid to lithium ion chemistries. Whereas this is one of the most common battery types used in mobile phones and laptop computers, its use on the seismic line needs to come with a number of warnings. Despite its weight advantage, some seismic system manufacturers refuse to offer lithium ion due to various hazards which it may present, including causing fires or "erupting", difficulties in shipping - most countries require notification of shipping lithium batteries on board aircraft as they come under "dangerous good management" rules. The Post Office in Great Britain refuses to send parcels containing lithium ion batteries due to these hazards and there are the well publicised problems of lithium batteries even on the Boeing 787 Dreamliners which allegedly was the cause of some fires and the fleet of planes being grounded for some while.

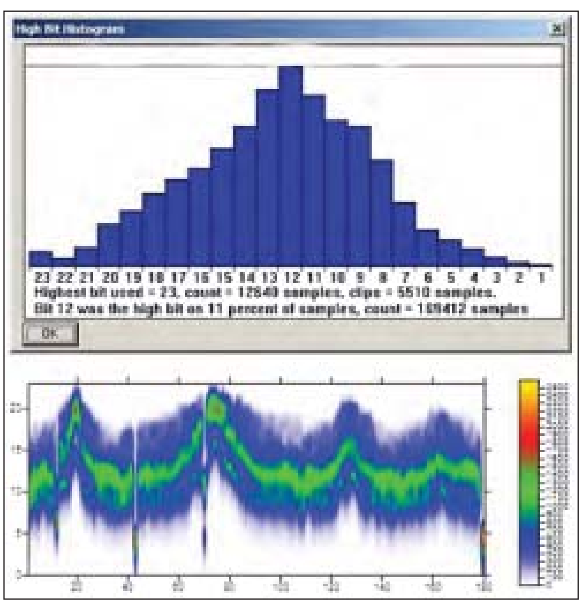
The final important issue when comparing power options is whether batteries should be internal or external. There are advantages to both methods which will affect how seismic operations, whether active or passive, may be carried out. Superficially, it can seem advantageous to install a battery inside each ground box, on the basis there are then fewer units to carry around. However, this comes with drawbacks. Firstly, with the exception of one cableless system, all recorders with internal batteries provide no choice as to the chemistry which is installed. One offers NiMH and the rest insist on lithium. Yet as we have seen, some lithium can be unstable and to have it in close proximity to ground electronics and the valuable seismic data it may contain, is not the ideal situation. Further, as one would want to avoid certain chemistries in certain environments for reasons given above, users of systems with internal batteries are being deprived of a very importance choice - that of battery chemistry.

For systems which have no means of sending all the data back in real time, there needs to be a data harvesting phase. Whether this takes place on the line or after grounds units are collected up and taken to some central download rack location, the ideal operation allows those units to be back on the line gathering data as quickly as possible. If ground units also have to be taken off the line in order to be charged up (and this itself may be delayed if the boxes have to go through some cooling phase prior to recharge) then they can be off the line for a considerable period. This would mean users need to buy a large number of additional ground units.

Further, it is inevitable, especially for all those systems which cannot always monitor what is happening on the line, that equipment will get stolen. Some systems have a number of layers of security features to reduce this. For example, data and hardware security-related information (available at http://www.iseis.com/documents) claims that the Sigma system has suffered no ground unit theft even though it has been used in some of the toughest and remote areas of the world. However, if something is to be stolen, it is better that an external battery is taken and the observer notified cablelessly than it is to have a ground unit stolen in order to get hold of its battery - which tends to be the most valuable thing for those inclined to theft of seismic equipment. Therefore, installing a battery into a ground unit gives thieves an excuse to steal the electronics.

Some manufacturers, conscious of theft issues, recommend burying ground units on the basis “out of sight is ought of mind”. This issue of burying or not burying could itself be the subject of a lengthy comparison. Growing numbers of crews, primarily those with no guaranteed monitoring ability, are reporting large equipment losses, although this is very area-dependent. Burying boxes can be a significant logistical undertaking with in some cases some tens of tons of earth needing to be dug up, usually by hand, for each thousand channels. This is exchanging the problem of dealing with cables with a problem of dealing with burying or use of augers. Units have to be buried just far enough so as to try to fool thieves, but not so deep that GPS (and where relevant, WiFi) communication is affected by a dielectric loss process. Burying also may imply that the survey requires the deployment of each channel for several days, and where buried equipment cannot be remotely controlled or battery power monitored, one has to have confidence, especially as batteries age, that burying that channel is worth the effort. Some cableless systems do not recommend burying, so as to be sure that comms and GPS is always at its best, to save on the labour needed to do this and because they believe it is not a necessity given the security features of that particular system.

In summary, there are many things which could form the bases of comparisons when it comes to batteries with cableless recording. The ideal cableless system provides full choice in terms of battery chemistry and whether batteries are internal, external or both. Each seismic survey can benefit from different combinations of these options.



32 bit systems are being more common in cableless systems. They provide slightly better quality related specifications for active data acquisition and a number of other benefits for cableless active and passive recording.

Data quality and system security

Some users of cableless systems are surprised about any statements made in regard to data quality differences between various cableless systems. For active data acquisition, at the most there is some minor data quality advantages with those recorders which have 32 bit convertors, and this difference may be especially useful when it comes to passive acquisition, and where there is some doubt about the optimum pre-amp gain setting. But this is not the main point by any means.

This industry for decades has been used to various ever-improving methods of data quality control during recording. Many acquisition contracts and survey plans are built around the availability of rapid QC. When using cabled systems in very difficult areas - the sort of places where it would be better to use cableless because of their logistical and handling advantages - planners were especially keen to see at least some system, sensor or data attributes coming from these awkward receiver locations. Typical of such difficult places to deploy channels are where longer offsets are being recorded, in-fill locations where cabled systems could not stretch, near and in population centres, or other sources of noise or interference. If we are to benefit from the improvement in data quality which can come from having cableless channels in places we could not have them before then surely the ability to monitor those channels is still essential. In fact, the ENI SEG 2012 paper covering the comparison between a cabled recorder and the cableless system stated that it would have been beneficial for the cableless recorder to have some method of noise monitoring.

How should data harvesting be performed? If it is necessary to take ground units back to a central locations for downloading, then more personnel and much more equiment maybe needed. Data QC is also probably delayed.

So one aspect of quality control in cableless geophysics relates to the ability to monitor noise levels during acquisition, which may come from wind, rain hitting the sensor, movement of people, animals or traffic and so on. It is especially important for surveys using dynamite where there may not be much stacking available to reduce noise, and where each shot is expensive. But for similar reasons, it is important with cableless systems also to be able to remotely initiate and gather data from instruments and sensor tests at any time if data quality is to be the best it can be.

The issue of how systems are powered has been covered above but the importance of monitoring this power is one which must also be considered in the context of quality control as a box with no power, for whatever reason, is one which is getting no data at all. The ability to remotely control grounds units and get some minimum levels of noise, IT results, sensor and battery testing, are all important issues for data quality. Therefore, if data quality is so important, then what is required from any cableless system is a minimal guaranteed communication capability suited to all environments which can support QC-oriented data rates.

As almost all cableless systems rely on reception of GPS transmission to time stamp data, this is another area where data quality can be affected in ways which did not bother us in the days of cabled telemetry. Time stamping seismic data requires the reception of signals from only one GPS satellite but reception is not guaranteed everywhere and at all times. In an informal web pole carried out by this author, respondents said they had lost all GPS reception in a variety of conditions, for periods extending from minutes to hours. Some of these were to do with weather including sandstorms, others were more location-dependent such us in thick jungle canopy. Most surprising was the reported loss of all GPS signals in locations of wide open sky with no obviously adverse weather, and just as suddenly as it went, the signal would come back some while later Various systems have quite different approaches to handling GPS signal loss, apparently with some believing such loss will never occur and others offering alternative timing options. The absolute minimum system capability is that one can monitor GPS reception and send back this status from all boxes. There is no other feature of potentially more importance to data quality.

The final issue for QC is the ease and speed with which the full seismic data record can be taken out of the ground units and to a secure location. After all, until it is transcribed to somewhere safe, it cannot contribute to the overall quality of the entire project. We have already considered the technical requirements of establishing high data rate 2.4 GHz-based radio links and the scepticism with which all manufacturers should be treated when making excessive claims in this regard, especially in awkward seismic environments. But we should also consider how easy it is to harvest data from ground units at those times when realtime link cannot be reliably set up because it may often be simpler to trade off the extra deployment effort needed to achieve full bandwidth in tough areas against lower bandwidth (while still enough to allow QC to take place) and some simple harvesting method.

So what ways are there to harvest data if it is agreed that overall quality, and general crew security, is going to be enhanced by use of methods which are quick rather than slow? Most non-shootblind technologies do not require the ground units to be collected up and taken to some central harvesting rack in order to download data. Instead they allow the user to go to the box, while it is still recording and take the data out while the box is *in situ*.

Due to the shortcomings of 2.4

GHz transmission which prevented high bandwidth communication being viable, one should be wary of relying on that same frequency band when it comes to harvesting, and here also there may be more issues than are at first apparent. For example, there is the type of antenna used for 2.4 GHz communication. Some are internal while others are offered as options to be external. Internal antenna tend to be pointing more upwards than sideways so radio-based harvesting may work well only in environments where the receiver is almost directly above the ground unit, but less well in other transmitter-receiver geometries. However, airborne harvesting is probably not suited or economic to most areas of seismic operations, so land based pass-by harvesting is then necessary. Now other issues come into play, such as whether the box has been buried and in what type of soil with what level of dampness which may attenuate transmissions. The amount of vegetation between box and harvesting device will also make a significant difference and harvestors may need to get quite close and at the right angle to achieve useful transmission rates. If data retrieval is slow, that will delay any QC process, perhaps beyond the time when some of the line has been picked up. It is therefore important to have alternatives to 2.4 GHz-based harvesting including direct hardware harvester connection to the box, or most convenient of all, copy to external memory from the ground unit.


Direct memory copy-based harvesting. Where 2.4 GHz comms is difficult.

The subject of data quality is also related to that of security. It would seem that the most secure systems are those which can guarantee at least a minimal level of communication (and thus line monitoring) in ALL situations. Cabled systems had many disadvantages but a good feature was that if someone accidentally or deliberately cut a cable, or destroyed a line box or battery, the observer's screen showed this immediately and remedial actions could be taken. One reason for moving to cableless instruments is that they are supposed to allow acquisition in tougher areas, including roads, paths, villages, cities etc, i.e. where population density is higher. This naturally exposes the line equipment to more potential damage and theft, and so in a number of ways the issue of security requires more consideration with cableless operations than it did with cabled kit.


Sigma cableless system working in low density forest and marsh . Elevated antenna not required – simple deployment.

Geophysical magazines have no shortage of stories of significant amounts of theft. Some examples are the online New Technology magazine which reported a crew which experienced vandalism and theft of the units and batteries losing about $100,000 of equipment. Also, the excellent article by Lansley (First Break Jan 2012) refers to "very large" numbers (the exact number not specified) of Unite channels stolen from a crew which started with 8,500 units but only "300 recovered" later recovered. What is common between the systems described in these sources is that both were either designed to be, or became, shootblind, unable apparently with any simple to deploy method to offer enough transmission of security-related data from all deployed channels to the operator. Such data may included line noise, disturbance of ground units or sensors and so on - very basic things for a cabled system but not so simple for many cableless technologies.

Conclusion

There is no doubt that cableless systems have a lot to offer to both active and passive geophysics. However, unlike earlier recording approaches, there are many different cableless methods and instruments to choose from and some technologies can have hidden dangers for certain types of seismic data acquisition.

Whereas this article has tried only to compare three major characteristics of cableless systems, and listed several others which should also be considered, it should be clear that each category for comparison relates to others. Weight is related to power usage. Power usage is related to what batteries can be used. This usage is related to communication capability. Comms ability is related to QC and security. Comms capability is also related to options in where and how 2.4 GHz transmissions can be used. So unsuspecting users may think that picking a system based on one feature is all that is required. However, this inter-relationship between all features in cableless recorders and the effect each has on the geophysics which can be undertaken, means that one must be most careful.

The geophysicist is recommended to familiarise him or herself as fully as possible with all areas of this technology and physics behind all of these exciting new tools but come to the exercise with some idea of the precise geophysical problems that need to be solved. This is not such a simple task as it was in the days of cabled telemetry but some cableless systems come with an ability which was just not available before, that of being able to be configured to solve very many geophysical problems. If nothing else, while the industry fully gets to grips with the flexibility offered by new technology, configurable systems at least provide choice and insurance.

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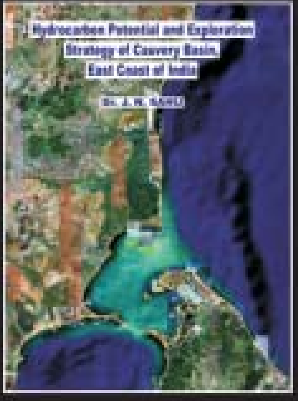

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