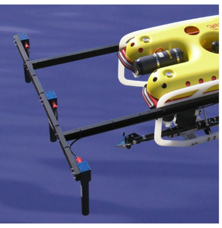
INNOVATUM
Theory of Operation



INNOVATUM PRODUCT REFERENCE MANUALS

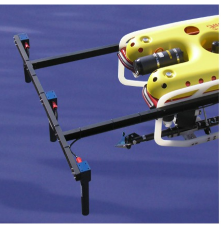
Section 2

MAGNETIC SUBMARINE CABLE & PIPELINE SURVEY SYSTEMS

THEORY OF OPERATION

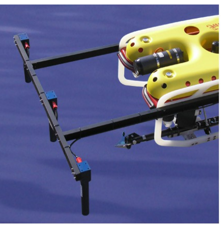
The electronic version of this document is the controlled copy. All printed versions are thus uncontrolled and may not be current. Latest revisions are posted on www.innovatum.co.uk

COPYRIGHT



SUPPORT INFORMATION

	Mail	Innovatum Ltd Units 11/12, Woodside Business Park Thetford Road, Ingham Bury St Edmunds IP31 1NR ENGLAND
	Telephone	+44 (0)1284 729123
	Email Web	support@innovatum.co.uk www.innovatum.co.uk



DOCUMENT CONTROL

In order to ensure only up to date information is presented, the master copy of this document is the electronic copy. All printed copies are thus uncontrolled, and are possibly NOT UP TO DATE.

The up to date copy of any document may be accessed at www.innovatum.co.uk

SYMBOLS

The following symbols are used within these manuals

Important Note: items of particular importance.

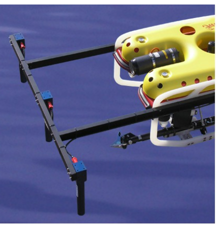
Caution: items where care is required.

Danger: items where a hazard may exist.

ESD Hazard: items where ESD precautions may be required.

ERRORS and OMMISSIONS

Innovatum will be pleased if errors or omissions are notified to our offices in **Bury St Edmunds.**



Date	Issue	Amendment	Section	Page
1 Mar 11	1	Initial Issue	All	
29 Nov 12	2	Review	All	

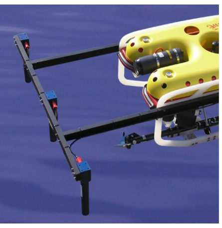
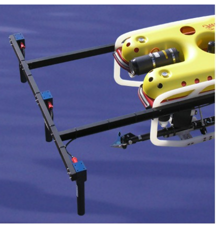


Table of Contents



1. Magnetic Tracking Systems Description

1.1 Innovatum Magnetic Tracking Systems are designed to locate, track and survey submarine pipeline, cables and other objects in an underwater environment. The equipment is usually deployed via a Remote Operated (underwater) Vehicle (ROV), an Autonomous Underwater Vehicle (AUV), a manned submersible, a Remote Operated Towed Vehicle (ROTV), a towed sled or a surface vessel. The systems may be permanently mounted on the carrying vehicle, or mobilised for a specific task and then removed on completion of the task. All units are designed for easy interface to a wide variety of vehicles.

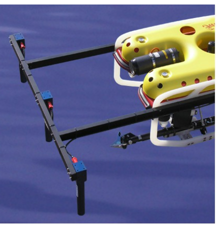
1.2 The Innovatum Magnetic Tracking Systems are the most versatile and accurate units available which utilise magnetic detection principles.

1.3 The systems locate and track cables, pipelines and other objects by their magnetic fields. They can also be used for fault location, salvage, search and recovery, ordnance location, pig tracking, hazardous waste canister location and identification etc. Innovatum tracking systems are capable of locating and tracking targets using passive magnetic fields, and A.C. or D.C. magnetic fields produced by currents flowing in the product. The A.C. frequency range is tunable from 10 to 100 Hz. The systems can be powered from 115 to 230 VAC, 50 to 60 hz. for surface equipment, and 12 to 64 volts D.C. for subsea equipment.

1.4 The system sensor array consists of fluxgate gradiometers (grads) and fluxgate triaxial sensors. The grads have four axes of measurement, and are manufactured with the two primary sensing elements mounted in line and separated by an accurately controlled distance, and with two other elements mounted at right angles to both each other and the primary fluxgates. They are normally mounted in a vertical plane as shown on related drawings. The sensor array is connected to an electronics container called a Sensor Interface Pod (SIP). The SIP consists of an embedded computer coupled to a high accuracy data acquisition and filter system. Other component parts provide power for the sensors, route data to the correct parts of the hardware, and provide communications with the surface units. The data is transmitted to the surface using RS-232, or RS 485 serial interfacing standards. The data is normally sent at 9600 baud. A detailed description of the data format is shown elsewhere in this manual.

1.5 The software systems are menu-driven for a particular location/tracking requirement. All features, including the frequency in the A.C. mode, are selectable from the main processor menu. The A.C. tracking frequency is selected via a menu and the desired frequency is transmitted to the SIP via the data command downlink.

1.6 All pertinent data related to the located/tracked object are available in the combined alpha and graphics displays of the surface computer. They are displayed in real time and can also be sent to a survey computer to be merged with all other data associated with the survey task. Computer menu selections/options are detailed with explanations and parameters for ease of operator implementation.



2. System Configurations

2.1 All Innovatum systems can be ordered in a configuration to suit the needs of the customer, whilst retaining the capability for upgrade to additional facilities in the future. It is thus possible to specify a "Tone only" tracking system, a "Passive only" unit, or a combination unit. A simple numeric code designates a particular system configuration.

2.2 Each system is built from a basic subsea unit, called a Sensor Interface Pod (SIP), fitted with a universal package of data acquisition and transmission electronics. This subsea unit communicates via a single twisted pair of wires to the surface, terminating at a simple dedicated electronics interface unit. The surface unit is known as the **Interface & Overlay Unit** (IOU). The IOU then passes data in USB serial format to the PC where all data is processed and the displays and data outputs are generated. Several additional sensors may be interfaced to the SMARTRAK unit. These are:

a) Altimeter (Echo sounder) - to provide true depth of burial data

(Caution - the altimeter gives a single point seabed reading, which may NOT accord with some interpretations of "Depth of Burial")

(Caution - the altimeter may have a different pressure rating from the SIP and sensors, and may thus limit the usable depth rating of the complete system)

b) Pressure Transducer – to provide a water depth reading. The range of the transducer must be specified at time of system purchase.

(Caution - the pressure transducer may have a different pressure rating from the SIP and sensors, and may thus limit the usable depth rating of the complete system)

3. Innovatum System Designation

Each Innovatum system is designated by a simple code, indicating the sensor array configuration. The code consists of two numerals, followed by optional letters, as follows:

First number "3"	=	Passive magnetic with 3 fluxgate gradiometers
First number "6"	=	Tone only with 2 fluxgate triaxial sensors
First Number "9"	=	Passive and Tone Combined system

Suffix “A”	=	Altimeter (this code is normally omitted)
Suffix “P”	=	Pressure transducer fitted
Suffix “R”	=	Rear sensor capability

Thus:

SMARTRAK 3	=	Passive Magnetic only
SMARTRAK 6	=	A.C. (Tone) only
SMARTRAK 6R	=	A.C. (Tone) only, with 2 rear sensors
SMARTRAK 9	=	Passive Magnetic and A.C. (Tone) tracking

Other combinations are available.

Passive magnetic tracking requires at least 3 fluxgate gradiometers (grads) and A.C. tone tracking requires at least two triaxial sensors.

4. Modes Of Operation

Innovatum Cable & Pipeline Survey Systems have several different modes of operation. Not all modes are possible with all systems.

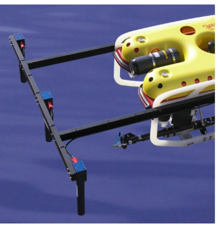
4.1 Passive Magnetisation Mode

a) The magnetic fields measured by the array of at least three gradiometers are the passive magnetic fields associated with the ferromagnetic material of the target. These fields are mainly due to two effects:

b) The deformation of the ambient earth's magnetic field (geomagnetic field) which is "focussed" into the target surface due to its magnetic permeability.

c) The intrinsic magnetic field of the target which was induced during its fabrication and machining, or subsequently artificially enhanced. This field is also affected in the vicinity of pipe welds (field joints) by procedures of the welding process, and typically the target intrinsic magnetic field is weak and highly complex near each weld. Artificial enhancement removes (or overwrites) the weak and complex joint fields.

A mathematical model of the earth's field and the physics of its interaction with the target is incorporated into the Innovatum computer code, and this model allows separation and identification of this field and the target field, allowing solution for target horizontal and vertical displacement relative to the sensor array. Because of the complicated superposition of target fields and effects of the earth's field, the strongest field gradients may not be centred exactly above the target, but may be slightly dis-placed to one side. However, the best signal-to-noise ratio and greatest tracking depth capability are obtained by keeping the sensor array centred within the region of strongest gradients. Steering information may thus be presented by two methods:



a) Colour graphics position display (the computer screen) which is updated every 0.15 to 0.3 seconds, and indicates true horizontal and vertical displacement with respect to the array, shown in 3-D perspective.

b) Pilot steering information display (via an optional video overlay) which is updated 4 - 5 times per second and guides the pilot to the region of maximum signal strength for greatest depth coverage and positional accuracy.

The pilot video overlay display shows bar graphs of signal strength and approximate depth, with a cursor moving horizontally to show target horizontal displacement relative to array centre.

In addition to these visual displays, complete position information is available via a serial (RS-232) interface for transfer to a separate computer for autopilot control, data logging, or display. Transferred data are formatted as ASCII character strings.

4.2 Active D.C. Current Mode

This mode may be used to track non-ferrous pipes or cables carrying net direct current (D.C.). (Note that a twisted pair or coaxial line carrying equal and opposite currents carries zero net current, and so cannot be tracked in this mode. Also, a ferrous pipe or armoured cable will produce large passive D.C. magnetic fields which will mask the small D.C. fields due to the direct current, and should be tracked in the PASSIVE magnetisation MODE).

In this mode, the array of gradiometers are used to measure the D.C. magnetic fields generated by the D.C. current. As in the PASSIVE mode, pilot video overlay and colour computer graphics displays are provided for tracking control, and data output via RS-232 is provided for survey use.

Active D.C. Current tracking can operate with net currents from 1 ampere at 1 metre up to several thousand amperes. Data accuracy can be very good.

Twin conductor D.C. power cables have very polarised external fields, and these may be surveyed with power “on”, using a separate tracking mode.

4.3 Active A.C. Current Mode

This mode may be used to track any pipe or cable carrying net alternating (A.C.) current. In a typical cable tracking array consisting of 2 or 4 triaxial fluxgate sensors, the vector A.C. components from the triaxial sensors are used to determine cable position and orientation.

The alternating current frequency must be between 10 and 99 hertz (higher frequencies are possible by special order), and ideally the net current flow should have a diffuse (seawater) return path. Great care must be taken if a tracking signal is injected to ensure the return path is not close to the feed path or the tracking array.

(CAUTION. Very large errors may occur if a return path is close to the tracked cable)

Active A.C. mode can be used to track a 3-phase A.C. cable provided there is some imbalance in the phases. Such imbalances are normal, although they may be affected by the total power transmission load. It should be noted that tracking an A.C. cable with an ROV powered from a similar AXC frequency may be very difficult, if not impossible.

Video overlay, colour graphics and data transfer in the ACTIVE A.C. MODE are similar to the other modes.

4.4 Pulse Induction Mode

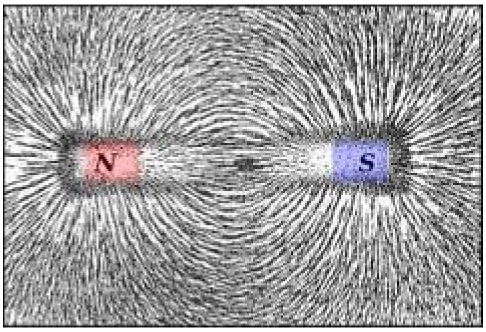
Pulse Induction Mode is not currently used in Innovatum products

5.0 Operation Principles - Passive Magnetic Mode

5.1 Passive Magnetic Fields Of Pipes, Cables, And Ferrous Objects

The passive magnetic fields of pipes and cables, as mentioned in the preceding section, is primarily due to two separate effects: intrinsic magnetisation and induced fields caused by magnetic permeability. We now consider the physics of these two effects.

5.2 Intrinsic Magnetisation Of Pipes



Each separate pipe section, when it was formed from molten steel, "captured" the magnetic field existing at its location (on the cooling rack, etc.) when it cooled through the Curie temperature (the temperature at which the metal solidified from its molten state). Because of the geometry of the pipe section (long and thin) and the high permeability of the material, the "captured" field is mainly parallel to the pipe section's long axis, which results in each separate pipe section resembling a bar magnet (dipole), with one end magnetised as a "North" magnetic pole, and the other end as a "South" magnetic pole, as shown in figure 1 (above). If we look along the length of the pipe, the magnetic field lines at any point along it appears to point radially toward or away from the pipe centre, as shown in the figures 2. and 3. When pipe sections are welded together to form a continuous pipeline, two important things happen:

a) First, in order to keep the molten metal near the weld from being repelled from the weld by magnetic repulsion, the pipe is usually de-magnetised near the ends before welding. When the pipe near the weld cools, it then may "capture" a different field than that intrinsic to the rest of the pipe section. In general, this results in a weaker and more disordered magnetic field near the weld joining two pipe sections.

b) Second, since the pipeline is assembled by adding sections with random directions to this magnetisation, at some places along the pipeline adjacent pipe sections may have magnetic fields that reinforce each other, and at other places adjacent pipe sections may have magnetic fields that oppose each other. The result is a magnetic configuration due to intrinsic magnetisation along the pipeline which is highly variable and unpredictable, but which is generally strong and radial except near field joints (welds), where the field is weaker and disordered. An example of pipe magnetisation along several sections of pipe is shown in figure 4:

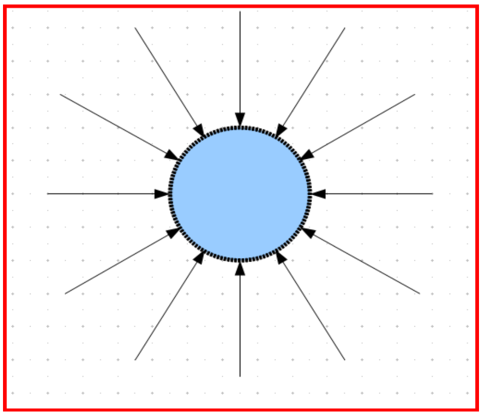


Figure 2

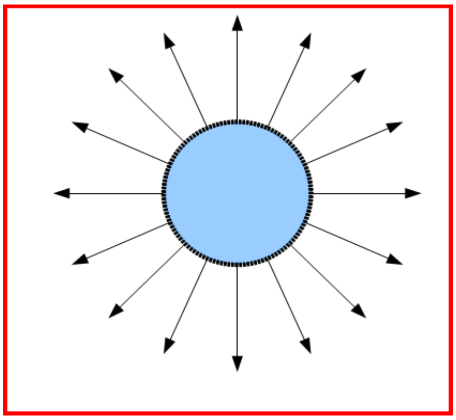


Figure 3

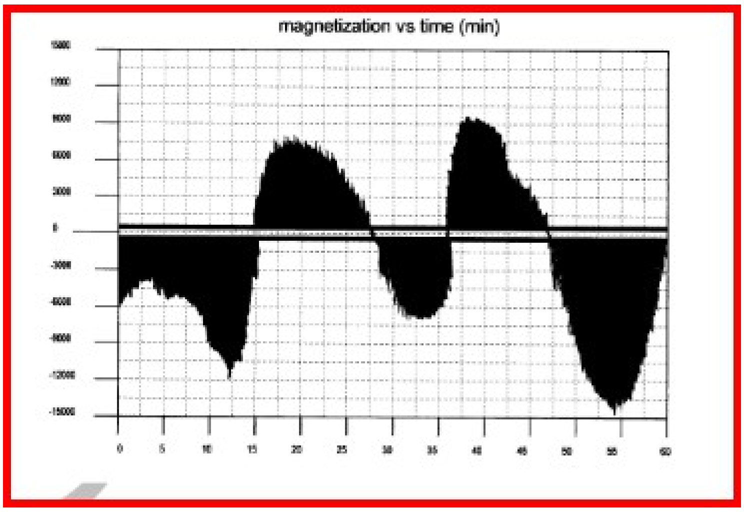


Figure 4

5.3 Intrinsic Magnetisation Of Cables

The intrinsic magnetisation of cables is almost always due entirely to the intrinsic magnetic field of external ferrous armour strands surrounding the cable, given that pre-stretched ferrous wire rope used at the centre of the cable for strength produces very small external magnetic fields. The magnetic field produced by the armour generally spirals along the cable as the armour spirals, producing a regular sinusoidal magnetic field signature whose wavelength is the armour spiral pitch. In multi-layer armour, the outer most layer is likely to determine the periodicity of the field variation.

5.4 Enhanced Magnetisation Of Cables

The magnetisation of cables may be enhanced artificially by impressing a repeating reversing field into the armour wires or strength members. This patented process is carried out by a mechanical device for cables up to 40mm overall diameter, and by an electrical device for larger cables. The enhanced field greatly improves the range and accuracy of surveying cables, with reliable accurate data obtained from cables as small as 13mm at ranges of 3m. This process has also been applied to flexible flowlines and oilfield umbilical cables with excellent results.

5.5 Intrinsic Magnetisation Of Ferrous Objects

The intrinsic magnetisation of elongated cylindrical objects is generally similar to the intrinsic magnetisation of a separate pipe section, as described in a previous section. However, as the object becomes more compact (spherical, for example) the intrinsic magnetisation may become more complicated than a simple dipole, especially close to the object. Because of the differences, SMARTRAK use a different technique (algorithm) for locating ferrous objects than that used for pipes or cables in the passive magnetisation tracking mode. SMARTSEARCH is a separate system based on gradiometer technology which has up to 12 sensors in an array up to 7m wide, and is widely used for ferrous object location, especially for UXO detection. It may also be used for wreck hunting and finding lost objects.

5.6 Induced Fields Of Pipes And Cables

The induced field of a pipe or cable is caused by the magnetic permeability of the pipe wall or cable armour, which "focusses" the earth's magnetic field into the pipe or cable, as shown in the next diagram. Physically, this occurs because the magnetic field configuration in which the magnetic field lines go through the permeable material represents a lower energy state than the configuration in which the field lines go around the permeable material. Although the magnetic field configuration in the vicinity of the pipe or cable due to this effect is more complicated than the simple radial configuration due to intrinsic magnetisation, the effect is predictable if the size of the pipe or cable and the direction and magnitude of the earth's field are known. For this reason, the SMARTRAK system software incorporates a world-wide model of the earth's magnetic field, and using the menu inputs of pipe or cable size and lay direction, together with geographic latitude and longitude, this effect may be calculated.

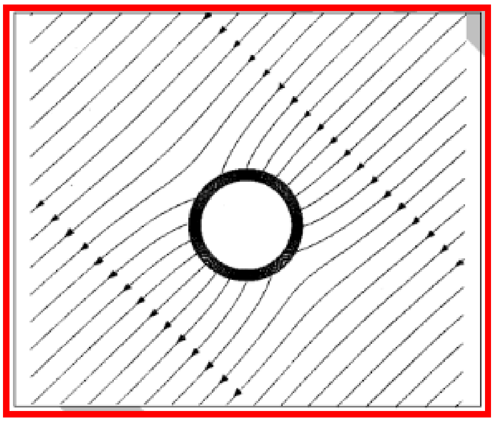


Figure 5
Magnetic Field Lines Of The Earth Near A Pipe (End View)
The field lines are 'focused' into the pipe wall as a result of magnetic permeability of the wall material

5.7 Induced Fields Of Ferrous Objects

The induced field of a ferrous object, caused by magnetic permeability as explained in the preceding section, is generally impossible to predict without very specific information on the object's dimensions, orientation, and geographic location.

However, the induced magnetic field is usually much smaller than the intrinsic magnetic field for a variety of object dimensions and orientations, and the algorithm ignores this effect in trying to determine the position of ferrous objects.

5.8 Detection And Location Of Pipes, Cables And Ferrous Objects By Passive Magnetic Field

As discussed in previous sections, the passive magnetic field in the vicinity of pipes, cables, and ferrous objects is the sum of the fields caused by intrinsic magnetisation and the induced field due to permeability. Since the purpose of this location and tracking system is to locate track and survey buried objects below the seabed, the primary concern is to determine what magnetic fields are detectable **above** the object we wish to locate and track.

5.9 Passive Field Components Above Source

Referring separately to the diagrams showing the magnetic fields due to intrinsic magnetisation and induced fields, we see that the radial fields due to intrinsic magnetisation will be mainly vertical fields when a detector is located above the object producing them. In the case of induced fields caused by permeability, the primary distortion of the field occurs parallel to the earth's field direction, which is mainly vertical at mid-to-high latitudes (north or south), and is mainly horizontal only very close to the magnetic equator. Since the field due to intrinsic magnetisation is usually the stronger field, this suggests that detectors which sense the vertical magnetic field component should be better than detectors which sense the horizontal magnetic field component. For example, in the North Sea, the earth's magnetic field is close (~20°) to vertical, so both the intrinsic field and the induced field would produce strong vertical components and weak horizontal components, whereas at the equator, the intrinsic field effect would produce strong vertical field components, with weak horizontal field components produced by the induced field effect. In addition, the strongest fields which occur right over the top of the pipe or object are vertical.

As a further example, measurements of magnetic fields were obtained at a mid-latitude location where the earth's magnetic field was roughly 45 degrees from vertical. At this location, the vertical magnetic field due to a 12-inch pipe 3 meters below the point of measurement was 775 nanoTesla, while the horizontal magnetic field was only 228 nanoTesla. This clearly shows that the vertical field component is most detectable. However, both these field components due to the 12-inch pipe are insignificant in comparison to the earth's own field components there. At the point of measurement, the earth's field has equal horizontal and vertical components of 46,350 nanoTesla, which is 60 times larger than the vertical component due to the pipe and 200 times larger than the horizontal component due to the pipe. This shows that the main problem in detecting the vertical component of the pipe field is not the strength of the pipe field, but the large background field of the earth itself. However, since the earth's field is nearly constant over distances of hundreds of meters, while the field due to the pipe varies substantially over distances of meters, it is possible to effectively eliminate the overwhelming effect of the earth's field while retaining the ability to detect the pipe. As explained in the next section, this is accomplished through the use of magnetic gradiometers.

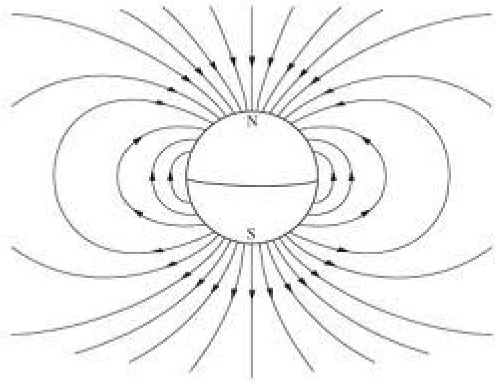
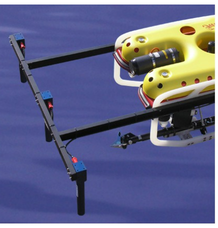


Figure 6
Magnetic field of Earth

5.10 Passive Field Gradients

As explained in the preceding section, the presence of the earth's huge magnetic field represents a problem in detecting the much weaker magnetic fields due to pipes. Since cables contain much less ferrous material than pipes, cable detection is even more difficult. Because of the extremely small variation in the earth's field within a large area, it is possible to remove the earth's field by making simultaneous measurements separated spatially by a small distance. This is the principle of the magnetic gradiometers used in the SMARTRAK system. Consider the measurements made by two separate sensors which can detect the vertical magnetic field component at two vertically separated locations, as shown in Figure 7. We assume that the vertical



separations of the sensors is ‘S’, and the lower sensor is a distance ‘d’ from the centre of the pipe. The fields at the two sensors are the sums of the earth's field and the pipe field at each sensor. But if the earth's field does not change over distances of order ‘S’, and the field due to the pipe varies significantly over distances of order d+S then by subtracting the measurement of the upper sensor from the measurement of the lower sensor, we may eliminate the effect of the earth's field and detect the difference due to the change in the pipe's field between ‘d’ and ‘d+s’.

Bearth = Vertical Magnetic Field Component of Terrestrial Field
Bpipe = Vertical Magnetic Field Component Due to Pipe

GRADIOMETER OUTPUT = Bearth(d) **+** Bpipe(d) **+** Bearth(d+s) **-** Bpipe(d+s)

but Bearth(d) **=** Bearth(d+s)

Thus:
GRADIOMETER OUTPUT = Bpipe(d) **-** Bpipe(d+s)

This ability to eliminate the earth's magnetic field depends on the ability of the upper and lower sensors to make exact measurements of the same component of the earth's field, which places very severe constraints on the precision and alignment of the upper and lower sensors. We separately consider both effects:

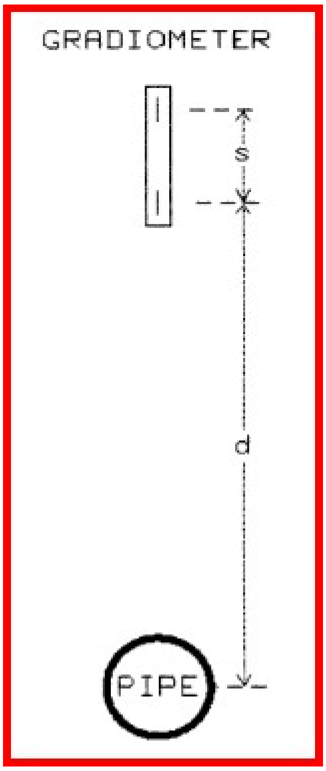


Figure 7

a)**Sensor sensitivity precision.** If the two sensors do not have exactly identical sensitivities, then they will measure different values for the earth's field component and this difference represents an error in compensating for the earth's field. In the worse case, in which the earth's magnetic field is aligned along with axes of the two sensors in the gradiometer, a sensitivity difference of as little as 1% can cause errors of 600nT, as large as typical pipe magnetic fields.

b)Sensor angular alignment. In order for the two sensors in the gradiometer to be used to cancel the large magnetic field of the earth, the two sensors must be nearly perfectly co-linear. Any misalignment between the sensors within a gradiometer will produce errors that vary with sensor orientation with respect to the earth's field. In the worse case, in which the earth's magnetic field is perpendicular to the axes of sensors, the error caused by a one-degree misalignment will produce a sinusoidal error of 600nT, comparable to the expected signal due to a pipe.

Because of these problems, the gradiometers used in the Innovatum Systems are very carefully constructed and adjusted to produce very nearly identical sensitivity and very exact alignment. Typical sensitivities are exact within 0.01% and alignments are exact within 0.01 degree. Each sensor is electronically aligned and the information is held in non-volatile memory in each sensor.

Caution

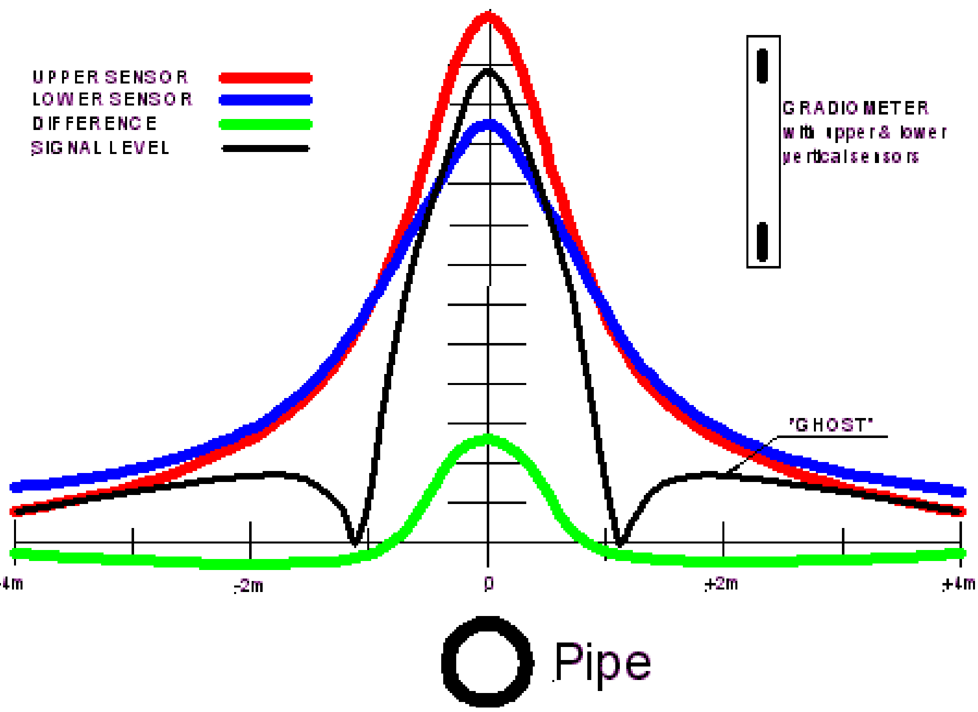
Gradiometer sensors MUST NOT be opened in the field. Any mechanical disturbance will destroy the sensor's internal calibration, and the unit must be returned to Innovatum Ltd for recalibration.

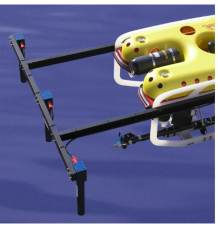
If we use the gradiometer configuration discussed above, which measures the difference in the vertical magnetic field component at two different sensors to eliminate the effect of the earth's field, the gradiometer difference output may be simply described. The next figure shows the separate outputs of the upper and lower sensors within the gradiometer as a function of horizontal displacement from pipe centre at a constant height of 1 meter (lower sensor) above pipe centre. The earth's field contribution has been subtracted from both the upper and lower sensor outputs in this figure. Note that the lower sensor output has a larger maximum reading (since it is closer to the pipe) than the upper sensor output, but that the upper sensor output displays a broader peak than the lower sensor. This effect causes the gradiometer output, labelled "difference", to reverse sign on either side of the difference peak. (The difference output reverses sign at roughly +45° from vertical in the figure.) The "signal level" of the gradiometer output thus exhibits 3 separate peaks, with the 2 smaller side peaks, lying on either side of the main peak, having opposite signal polarities than the main peak. This results in the existence of small signal "ghosts" on either side of the real pipe signal peak, as shown by the label in the figure. The recognition of these "side-lobe" signals or "ghosts" is further discussed in **SMARTRAK OPERATIONS Section 4-2.**

Gradiometer Outputs Due To Intrinsic Magnetic Field of Pipe

These outputs correspond to horizontal movement of the gradiometer across the pipe, with the lower sensor in the gradiometer kept exactly 1 meter higher than the pipe centre (Signal Level is proportional to absolute value of Difference)

Figure 8





5.11 Magnetic Effects Caused By Vehicles

In addition to the errors caused by differences in sensor sensitivity and alignment described above, which may be removed by adjustments to the gradiometers themselves, there are several other types of errors which may be caused by the vehicles used to carry the Innovatum SMARTRAK System sensors. These effects are:

a) Permanent magnetic fields of vehicle components.

b) Induced magnetic fields in magnetically permeable materials on the vehicle.

c) Transient magnetic fields associated with moving vehicle magnetic components or changing electric currents.

We now separately consider these vehicle effects:

5.12 Permanent Vehicle Magnetic Fields

These fields are due to the presence of fixed permanently magnetised objects attached to the vehicle, and include ferrous fasteners, such as nuts and bolts, stationary magnets in electric motors, etc. These various fields, produced by objects at different positions in the vehicle, may be very different at the positions of different sensors used in the SMARTRAK array. However, since these fields are constant in time, they may be simply measured at each sensor position when no other magnetic object (pipe, cable, etc.) is nearby and the corresponding value for each sensor subsequently subtracted from the total field measured at each sensor. This procedure, called neutralisation, will be discussed in a later section (see **SMARTRAK OPERATIONS Section 4.2**).

5.13 Induced Magnetic Fields In Permeable Vehicle Materials

These fields are due to the interaction of the earth's background magnetic field with magnetically permeable materials on the vehicle, with the earth's field "focussed" into the permeable material. The mechanism is the same as that producing the induced steady-state field of a pipe or cable which was described in a previous section. However, in the case of the induced field of a pipe or cable, the orientation of the induced field is constant since the pipe or cable direction is constant and the earth's field direction is fixed. Since the relative orientation of the permeable vehicle materials to the earth's field direction changes as the vehicle heading changes during manoeuvres, the induced fields measured at the Innovatum System sensors vary as a function of vehicle heading. However, it is possible to measure the induced fields as a function of vehicle heading by storing the separate sensor values for each heading as the vehicle is rotated 360° at a location where no other metallic targets (pipes, cables, debris) are found. This procedure, called heading calibration, is discussed in **SMARTRAK OPERATIONS section 4.2-2.59 para b)**.

5.14 Transient Magnetic Fields Of Vehicles

These fields are caused by low frequency motion of magnetic components on the vehicle or changes in D.C. electric currents. Typical examples of vehicle components producing transient magnetic fields by mechanical motion are pumps with ferromagnetic shafts or pistons, magnetic latching relays, rotating sonar elements and magnetic hardened steel cutters or grippers in manipulator arms. Examples of devices causing transient magnetic fields by changing D.C. electric currents are solenoid D.C. relays, D.C. current supplies with unpaired leads, and D.C. battery chargers recharging sonar transponders. In general, these transients may be avoided by:

a) Placing all large electric pumps and motors as far to the rear of the vehicle as possible and placing SMARTRAK sensors as far to the front of the vehicle as possible.

b) Stowing manipulator arms in a fixed configuration as far away from the sensors as feasible.

c) Pairing and twisting all wires carrying D.C. currents to reduce external magnetic fields

d) Placing rotating sonar heads and relays at least 70 centimetres away from sensors.

The SMARTRAK also has two separate means via software to limit the errors caused by these transient fields. When the system is not close to a magnetic target, a software filter prevents transients from causing false indications of target detection. When the system is tracking a target, data averaging techniques are used to minimize the errors in target position due to such transients.

6. OPERATION PRINCIPLES – ACTIVE CURRENT MODES

6.1 Magnetic Fields Due To Electric Currents

As previously described, the Innovatum SMARTRAK System also has the capability to track wires, cables and pipes carrying net (unopposed) electric currents. These currents may be either direct (D.C.) or alternating (A.C.). In the following discussion we consider the magnetic fields produced by electric currents and describe the sensor arrays and techniques used to locate these currents.

6.2 Ampere's Law

The basic physics relating the magnetic fields produced by a net electric current **I** to the current itself is given (for a long straight wire) by

$$B = \frac{MoI}{(2)\pi r} \qquad \text{(Ampere's Law)}$$

Where **Mo** is a constant and **r** is the shortest distance from the point of measurement to the wire carrying the current. If we measure current **I** in amperes, distance **r** in metres, and magnetic field **B** in nanoTesla (gammas) then numerically:

$$B\,(nT) = \underline{200\ I\,(amps)}$$

r (metres)

The magnetic field direction is everywhere perpendicular to the wire, so the magnetic field lines form circles around the wire as shown in the next figure.

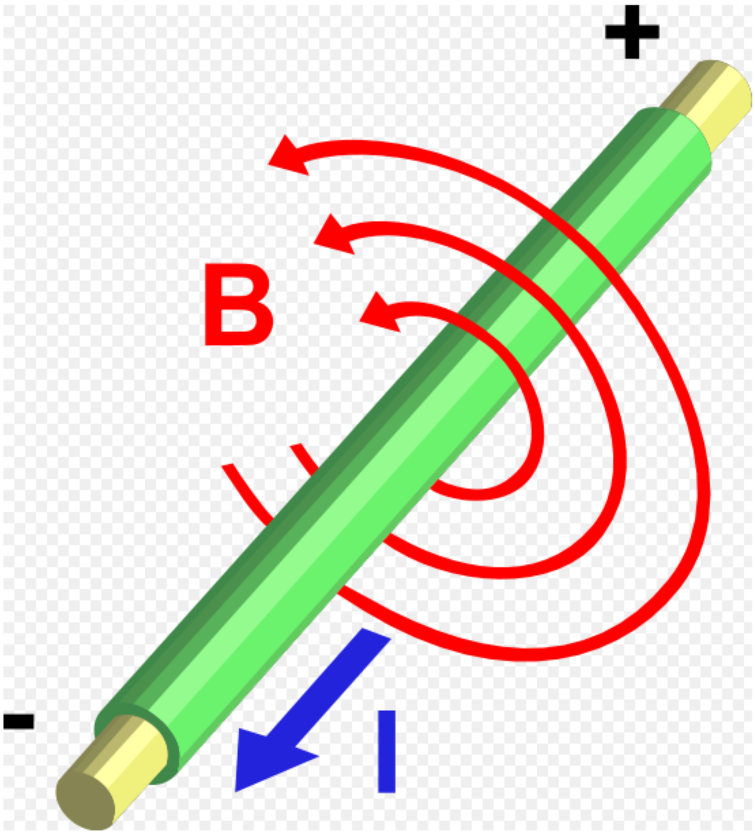
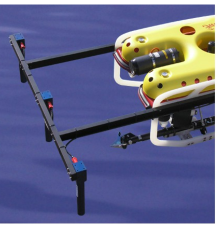


Figure 9
Magnetic Field Lines Due To Current In A Cable

The direction of the magnetic field may easily be found by the "right-hand rule", which states that if we grasp the wire in our right hand, with our right thumb pointing in the direction of current flow, the fingers of the right hand curl around the wire in the same direction as the magnetic field. (All of our discussion of Ampere's Law applies to D.C. as well as A.C. currents, but for A.C. currents the currents and the direction of the magnetic field keep reversing.)

It should be noted that in Ampere's Law the current described by **'I'** is the total or net current. If a cable or wire has more than one conductor, with equal and opposite current returning in another conductor, then the net current is ZERO, and there will be not detectable magnetic field near the wire. Co-axial cables or twisted pairs of wire with equal return current must have additional current superimposed to be detected.

It should also be noted that the statement of Ampere's Law given applies only to long



straight wires and cables carrying the same current everywhere. If the cable is not long and straight, or if the current in the cable varies along its length (current leakage to sea water, for example), then the simple version of Ampere's Law given above does not exactly apply. A further discussion of these complications is given in **Section 2 6**.

6.3 Detection And Location Of D.C. Electric Currents

The detection and location of small D.C. (where small means currents of less than 10 Amperes) electric currents is difficult for several reasons. First, by Ampere's Law, even a D.C. current of 1 ampere only produces a magnetic field of 50 nanoTesla at a distance of 2 metres, and this field is entirely horizontal exactly over the wire carrying it. Second, the magnetic field of a steady D.C. current is indistinguishable from a passive magnetic field of an object, or from the earth's field, which means that we must use gradiometers to remove the earth's field, as described in **Section 2- 5.10**. However, gradiometers which measure the difference in the vertical magnetic component are not suited for measuring the horizontal fields exactly above the D.C. current, and will measure the strongest vertical magnetic gradients when they are off to the sides of the current.

For these reasons, detection and location of small D.C. electric currents requires currents greater than about 0.5 amperes and is limited to a detection range of several metres. Specific capabilities and problems associated with the SMARTRAK D.C. tracking mode are discussed further in Sections **5.2-5.2** and **4.2-6.2**.

6.4 Detection And Location Of A.C. Electric Currents

The detection and location of A.C. electric currents is in principle easier than either of the other two modes, passive and active D.C. current modes. This advantage stems from several factors. First, the magnetic field of a current is less complicated than the passive magnetic field resulting from intrinsic and induced magnetisation, and the field caused by a current decreases more slowly with distance than the passive magnetic fields. Second, the earth's magnetic field, which has a very large D.C. (steady) magnetic field, does not have any appreciable A.C. components, so gradiometers are not needed in the A.C. mode. Third, vehicle A.C. magnetic noise is generally either very low in frequency (<20 hz) as a result of mechanical motors or confined near the frequencies and harmonics of the vehicle A.C. electric power (e.g. 50 hz and 100 hz, or 60 hz and 120 hz). This means that sensor sensitivity can be very great within a narrow A.C. bandwidth, provided the frequency and bandwidth is selected to minimise vehicle background interference. By measuring the vehicle A.C. noise levels at all frequencies of interest (1 to 200 hz, for example), the selection may be made. In most applications, a frequency of 25 hz has the least vehicle background noise and is the standard frequency used by the various public and military subsea cable owners worldwide. The Innovatum SMARTRAK System incorporates a spectrum analyser function to measure the vehicle's A.C. spectrum as an aid to diagnosing and eliminating vehicle noise in the chosen frequency range (See **Section 4.2-4.3**).

The ability to measure A.C. fields without the need for gradiometers allows the use of 3-axis vector magnetometers equipped with tunable filters to determine the A.C. vector magnetic field caused by an A.C. current. By making 3-axis vector measurements in 2 or more separated sensors, it is then possible to uniquely determine the location of the current-carrying wire, its orientation with respect to the sensors and the amount of current carried. Also, since the A.C. magnetic fields caused by the current vary inversely with distance and the low vehicle noise levels allow high sensitivity sensors to be used, the A.C. current mode allows very long distance detection for very low A.C. current levels. As an example, a cable carrying 150 milliamps of current at 25 hertz can be located from roughly 30 metres away.

6.5 Effects Of Non-Uniform Currents And Crooked Cables

As explained in **Section 2- 6.2**, the simple form of Ampere's Law describes the magnetic field due to uniform continuous currents in long straight wires. Two important exceptions should be considered:

a) Non-uniform currents

Non-uniform currents are currents which change in magnitude along the wire, usually caused by intentional or unintentional electrical contacts along the wire with the surrounding seawater. The usual intentional contact is through amplifiers ("repeaters") at intervals along long communications cables, with the current return to the seawater ("ground") used to provide electrical power to the repeater, or at field joints in pipelines where active cathodic protection currents return. Unintentional current return to seawater is usually associated with damage or defects in the sheath or coating of a cable or pipeline.

If the current carried by a cable or pipeline changes abruptly at a localized position along the cable or pipeline, then the effect on the external magnetic field may be summarized as follows:

- At large distances away from the point at which the current changes abruptly, the magnetic field is given correctly by the form of Ampere's Law given in **Section 2- 6.2**, with the current being that measured locally.
- Near the point where the current changes abruptly, the magnetic field goes through a smooth transition between the valves at large distances on opposite sides of the point where the current changes abruptly, with the magnetic field exactly at the point of abrupt current change given by Ampere's Law using the average current before and after the change.

As previously indicated, the SMARTRAK System is capable of determining the amount of D.C. or A.C. current carried and hence may be used to find intentional or unintentional changes in current along a cable or pipeline.

b) Crooked Cables

The magnetic field at a particular point along the cable is determined by the direction and magnitude of the current over some distance ahead of and behind the point of measurement. Thus a crooked cable, with bends and loops, will have a more complicated magnetic field than a long, straight cable since the currents in the curved sections will contribute to the magnetic fields measured some distance away. If the cable has simple sinusoidal "S-bends" with wavelength much smaller than the distance between the cable and the sensors, this effect will result in the average position being calculated. However, if the "S-bend" wavelength is large compared to the distance between the cable and sensors, then the cable position calculated will be approximately that of the nearest point on the cable.

The relative importance of the current segments at various distances in front of and behind the point of magnetic measurement is given in the accompanying table and diagram. In the table, a given segment of cable refers to the two segments (in front of and behind the point of measurement) at that relative distance, with "% of total" giving the relative contribution of those two currents segments to the total magnetic field measured by the sensor.

The "cumulative" amount refers to the sum of all current segments inside the outer limit d/r, while "remainder" refers to the sum of all current segments outside the outer limit d/r. As an example, the diagram shows shaded regions corresponding to the two segments d/r from 0.5 to 1.0.

The "% total" column indicates that these two segments contribute about 26% of the total magnetic field at the sensor, while the "cumulative" column indicates that about 71% of the total magnetic field at the sensor results from d/r = -1.0 to d/r = 1.0. The "remainder" column indicates that about 29% of the field at the sensor is due to currents at distances d/r greater than 1.0.

Current Segment Contribution To Sensor At Height 'r' Above Cable				
Segment (+/-) d/r	Angles(+/-)	% Total	Cumulative	Remainder
0.0 – 0.5	0.00 - 26.57	44.72	44.72	55.28
0.5 – 1.0	26.57 - 45.00	25.99	70.71	29.29
1.0 – 1.5	45.00 - 56.31	12.49	83.21	16.79
1.5 – 2.0	56.31 - 63.43	6.24	89.44	10.56
2.0 – 2.5	63.43 - 68.20	3.4	92.85	7.15
2.5 – 3.0	68.20 - 71.57	2.02	94.87	5.13
3.0 - 3.5	71.57 - 74.05	1.28	96.15	3.85
3.5 – 4.0	74.05 - 75.96	0.86	97.01	2.99
4.0 – 4.5	75.96 - 77.47	0.6	97.62	2.38
4.5 – 5.0	77.47 - 78.69	0.44	98.06	1.94
5.0 – 5.5	78.69 - 79.70	0.33	98.39	1.61
5.5 - 6.0	79.70 - 80.54	0.25	98.64	1.36
6.0 – 6.5	80.54 - 81.25	0.2	98.84	1.16
6.5 – 7.0	81.25 - 81.87	0.16	98.99	1.01
7.0 – 7.5	81.87 - 82.41	0.13	99.12	0.88
7.5 – 8.0	82.41 - 82.87	0.1	99.23	0.77
8.0 – 8.5	82.87 - 83.29	0.09	99.32	0.68
8.5 – 9.0	83.29 - 83.66	0.07	99.39	0.61
9.0 – 9.5	83.66 - 83.99	0.06	99.45	0.55
9.5 – 10.0	83.99 - 84.29	0.05	99.5	0.5

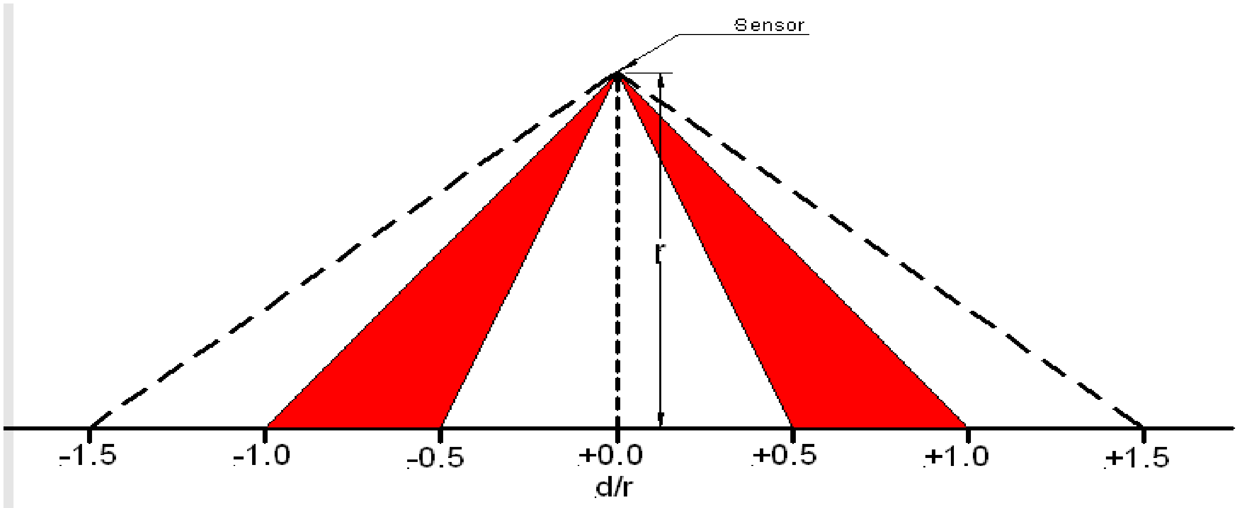


Figure 10

7. Measurements, Error Bars, Limitations And Calibrations

7.1 Depth Of Burial

The vertical displacement of the pipe or cable calculated in any of the various modes is the vertical distance in metres from the bottom of the central sensor to pipe centre. Sensor height above vehicle skids and cable or pipe radius are input to the operational menu in the computer code. The computer calculates depth-of-cover by subtracting these two quantities from total vertical distance. Note that this is depth-of-burial if the vehicle skids are on the seabed. If the vehicle is travelling along with skids at a height ***h*** above the seabed, then ***h*** must be subtracted from calculated depth-of-burial to obtain true burial depth. The SMARTRAK also has the capability of directly incorporating an altimeter input to determine height above seabed and adjust burial depth calculation.

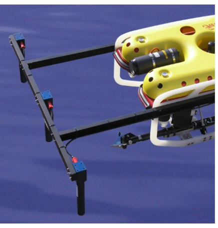
7.2 Passive Magnetisation Mode - Estimated Error

Because of the complexities of the superposition of the earth's field and the pipe or cable field, and also because of varying vehicle noise levels, it is impossible to state a single error percentage which would apply to all measurements. Instead the computer code takes all these factors into account to determine point-by-point the probable errors in horizontal and vertical placements calculated. Typically, this error is a function of cable armour or pipe size and burial depth as well as vehicle noise (measured during neutralisation of vehicle fields), and is locally affected by target intrinsic magnetisation in the vicinity of the gradiometer array. Because of the weak and disordered fields near pipe field joints, in some cases the computer program will be unable to obtain a solution in these regions. Error estimates and solution existence information are included in the set of Innovatum data available to the survey computer for logging, plotting, etc. Twenty-five years of operation over many thousands of kilometres of cables and pipes of various sizes in all parts of the world (from New Zealand to Alaska) have shown typical solution coverage to be 80% or more (~80% of data points sampled along pipe result in good solutions for positions) with typical survey speed of 1 knot giving 5 data points per metre. With a typical ROV, ~60% of data points will usually give accuracies on burial depth of +/-5cm for a 12-inch pipe at 2 metres.

It should be noted, however, that these estimated errors are based on an assumed physical model of the pipe or cable magnetic fields. If the field model does not accurately describe the actual field for whatever reason (complex magnetisation during fabrication, welding, etc.) then the estimated errors may not apply. However, the usual result in this case is that the computer code cannot find a solution for target position and rejects the data as invalid. (See**: Depth of Bury Comparisons Chart**.)

7.3 Active D.C. Current Mode And Active A.C. Current Mode

In these modes, the primary source of position error is vehicle D.C. and A.C. noise caused by vehicle power systems (measured during neutralisation of vehicle fields). As in the PASSIVE mode, the computer code uses these measured noise levels and the instantaneous measured signal strength and target position to calculate point-to-point the probable errors in horizontal and vertical position. These error estimates are displayed on the computer screen and are included in the data transferred for logging,



plotting, etc. via RS-232.

7.4 Seabed Composition Effects

The SMARTRAK is generally insensitive to seabed composition covering buried pipes or cables, having been successfully used to locate pipes under gravel, rock, mud, sand, shell and clay. Even soils with high magnetic concentrations generally have been found not to affect system precision if the composition of the cover in the trench matches that of the surrounding soil. An exception is the use of highly magnetic rock for backfill in an otherwise non-magnetic bottom, which causes errors and a worse signal to noise ratio in the PASSIVE or ACTIVE D.C. current modes. The ACTIVE A.C. mode is unaffected by seabed composition.

7.5 Effects Of Array- Horizontal, Vertical And Angle Offsets

Nominal target orientation (as-laid) is a menu input to the Innovatum software and geometric effects of horizontal, vertical and cross-pipe angle offsets are included and corrected for in the software code. An optional calibration for vehicle heading allows complete freedom of vehicle manoeuvring after neutralisation of vehicle magnetic fields. Horizontal and vertical offsets and crab angle are displayed graphically on the computer display.

7.6 Effects Of Vehicle Pitch And Roll

Since the SMARTRAK calculates horizontal and vertical displacements with respect to the array centreline, tilts of the array due to pitch and roll will result in small errors in horizontal and vertical positions. These errors are not significant for small pitch and roll angles. However, at high magnetic latitudes, correction of the SMARTRAK magnetic compass may be required to prevent erratic changes in apparent heading. The internal Pitch/Roll Sensor is used for this purpose. An alternative is to use the output from a gyro in place of the Innovatum sensor derived heading, and indeed this will be essential when surveying power cables carrying large (>20A) monoconductor currents. It is vital for the system that “Heading Error Calibration” is used when the vehicle has minimal pitch/roll motion.

7.7 Effects Of Pipe/Cable Size

In the passive magnetisation mode, the primary effect of differences in pipe or cable armour size is to determine the maximum burial depth/vertical distance from which the pipe may be tracked and depth calculated. Since the strength of the measured fields varies directly with size, this also affects the errors in position determination.

Typical detection and tracking distances (without depth measurement) for various pipe/cable sizes are:

Object	Approximate Tracking Distance
2" dia. armoured cable	2 m
4" dia. pipeline	3 m
16" dia. pipeline	5 m
48" dia. pipeline	9 m

A secondary effect of pipe size occurs close to large diameter pipes. In this case, non-uniform wall magnetisation in a large pipe close to the sensor array (ex.24-inch pipe 50 cm below array) may result in such complex fields that the pipe mathematical model is inadequate and no solution may be found for pipe position. Pipe/cable size has no effect in the ACTIVE D.C. or ACTIVE A.C. CURRENT modes.

7.8 Effect Of Latitude/Longitude (PASSIVE Magnetisation Mode Only)

As previously stated, the Innovatum software incorporates a mathematical model of the earth's magnetic field and this allows correction of field effects at all latitudes and longitudes. This has been verified through the use of Innovatum systems in the Gulf of Mexico, Caribbean, Alaska, California, New Zealand, Japan, Borneo, Thailand, Singapore, India, Dubai, Suez, Africa, Mediterranean, North Sea and South America. The nature of the terrestrial magnetic fields results in the largest heading errors towards the poles, and the largest depth measurement errors being encountered close to the magnetic equator.

8. Calibrations

As previously discussed, the SMARTRAK gradiometer sensors are carefully aligned and calibrated during fabrication and testing and even after many months of subset deployment it has been shown that little calibration is necessary.

In order to minimize vehicle effects the Innovatum System utilizes two independent vehicle calibration procedures:

8.1 Neutralisation Of Vehicle Fields

This procedure, initiated by computer keyboard when the vehicle is away from the pipe or cable, measures the average A.C. and D.C. vehicle fields noise levels at all sensors in the array for a single vehicle heading. The software then subtracts the average for each sensor from subsequent readings to cancel vehicle field effects. The noise levels are used to set the maximum system sensitivity possible for the vehicle. After each neutralisation, the calculated average neutralisation values are stored on the disc and used until a new neutralisation occurs.

8.2 Calibration Of Vehicle Heading Errors

This optional procedure, initiated by computer keyboard when the vehicle is away from the pipe or cable, measures vehicle fields at the sensors during the rotation of the vehicle through an arbitrary angle. These field values are stored on the disc as a function of vehicle heading and are used to cancel errors associated with vehicle heading changes when operating in PASSIVE or ACTIVE D.C. modes. In many instances a heading error calibration is unnecessary, as the SMARTRAK sensors have very small heading errors.

Procedures (a) and (b) may be used together or separately to remove vehicle field effects. In practice, vehicle heading errors do not change if the sensors are not changed and the vehicle configuration stays the same, so only one calibration of heading errors is normally performed at the start of a job. Neutralisation for vehicle fields is needed whenever changes occur due to movement of magnetic objects near the sensor array (e.g. manipulator movement, camera focus, pan or tilt, etc.). In addition, periodic neutralisation checks (every kilometre for example) are helpful to screen inadvertent and unnoticed changes such as accidental camera movements, hydraulic creep of manipulators, etc.