

**Title: Method and Apparatus for Providing Permanent
Magnetic Signatures in Buried Cables and
Pipes**

BACKGROUND OF THE INVENTION

This invention is concerned with magnetization of ferromagnetic material in elongated objects such as fiber optic cables and is more particularly concerned with
5 providing cables and pipes with permanent magnetic signatures to facilitate their detection magnetically.

Many types of buried pipelines and power and communication cables are either fabricated of ferromagnetic material or employ ferromagnetic material as strength or
10 armor members, making them susceptible to detection magnetically. Larger pipes and cables may, to a certain extent, be detectable magnetically by virtue of their natural magnetization (e.g., due to the earth's magnetic field), but smaller pipes and cables are more difficult to
15 detect magnetically.

Submarine fiber optic communication cables, which are strung by ships across the oceans of the world, must be buried beneath the seabed for protection from sea life,

anchors, and trawls, but subsequently they must be located for repairs or maintenance. Conventional means of locating, tracking and determining burial depth of unpowered buried fiber optic communications cables magnetically are limited in capability. Smaller cables in current use are difficult to detect by passive magnetization techniques at slant ranges greater than roughly 0.8 meters. Nevertheless, projected world-wide expansion of the subsea fiber optic communications networks will result in a greater proportion of small cables which are the most difficult to detect.

BRIEF DESCRIPTION OF THE INVENTION

The present invention provides fiber optic cables, and other elongated objects comprising ferromagnetic material, with enhanced permanent magnetic signatures which allow detection, location, tracking and burial depth determination of the objects at unprecedented slant ranges. The invention involves unique methods and apparatus for producing magnetization in ferromagnetic material of elongated objects and provides the objects with strong distinctive magnetic signatures. The invention will be described in its application to fiber optic communications cables, such as those employed in subsea fiber optic communications networks, but it will be apparent that the invention is not limited to such applications and may be employed, more generally, with regard to cables, pipes, or other elongated objects comprising ferromagnetic material.

Magnetization of unpowered fiber optic cables in accordance with the invention can be achieved during the cable laying process, or during the manufacture of the cables, for example, and does not require changes in cable construction or the laying process itself, nor does it interfere in any way with the operation of the fiber optic cable or cause mechanical stress or damage to the cable.

Submarine fiber optic communications cables typically have an optic fiber surrounded by a steel wire strength rope or steel armor. It is known that such cables may have unintended natural magnetization resulting from local magnetic fields (primarily the earth's field) captured at the time of fabrication, but such naturally occurring magnetization of both armored and unarmored cables is generally far less than the saturation field level of the ferromagnetic materials in the cable and is not easily detected. Moreover, the external magnetic fields resulting from naturally-occurring magnetization tend to follow the helical arrangement of the armor or wire ropes and are not uniformly radial or cylindrically symmetric. Passive magnetic detection of the external fields is quite limited. For example, with available detection equipment, burial depth measurement is limited to about .9 to 1.2 meters on 40mm cable, and to about .5 to .8 meter on 10mm cable.

Continuous tracking and burial depth measurements are made difficult by variations in magnetic field strength along the

cables associated with the pitch length of armor or wire ropes.

5 The present invention produces magnetic fields near saturation in ferromagnetic material of fiber optic cables, or other elongated objects, inducing permanent remnant magnetization. The produced magnetization is much stronger than any natural magnetization of the ferromagnetic material by the earth's magnetic field. An axial gradient in the applied axial magnetization produces a radial external
10 "leakage" magnetic field around the cable that is substantially cylindrically symmetric and that varies periodically along the length of the cable, providing a strong permanent magnetic signature that can be readily detected by passive magnetic detection methods. The
15 periodic variations in the radial external magnetic field along the cable may have a square wave or a sine wave pattern, for example. If the wavelength of the variations is long enough, the external field strength over most of the cable decreases approximately linearly with distance from
20 the cable.

The desired magnetization can be achieved by the use of a unique magnetizer having a pair of mirror-image magnets (or a plurality of pairs) disposed at opposite sides of the cable, for producing a strong magnetic field adjacent to the
25 cable, which varies repetitively as the cable is moved longitudinally relative to the magnets.



BRIEF DESCRIPTION OF THE DRAWINGS

The invention will be further described in conjunction with the accompanying drawings, which illustrate preferred (best mode) embodiments, and wherein:

5 Fig. 1 is the diagrammatic plan view showing a first embodiment of a magnetizer in accordance with the invention;

 Fig. 2 is a similar view of a second embodiment;

 Fig. 3 is a diagrammatic elevation view, with the fiber optic cable shown in cross-section, of a third
10 embodiment;

 Fig. 4 is a diagrammatic cross-sectional view showing radial flux lines around a fiber optic cable;

 Fig. 5 is a diagrammatic longitudinal sectional view of a fiber optic cable magnetized in accordance with the
15 invention and showing internal axial magnetization and external magnetic flux lines in accordance with a square wave magnetization pattern;

 Fig. 6 is a diagrammatic longitudinal sectional view of a fiber optic cable magnetized in accordance with the
20 invention and showing internal axial magnetization and external magnetic flux lines in accordance with a sine wave pattern;

 Fig. 7 is a plot of magnetic field radial component magnitude versus radial distance from a cable for various
25 magnetization wavelengths, for square wave magnetization;

Fig. 8 is a plot of magnetic field radial component magnitude versus radial distance from a cable for various magnetization wavelengths, for sine wave magnetization;

Fig. 9 is a perspective view of an actual magnetizer
5 for small fiber optic cables; and

Fig. 10 is a diagrammatic perspective view of a magnetizer for large diameter fiber optic cables.

DETAILED DESCRIPTION OF THE INVENTION

Fig. 1 shows, diagrammatically, a simple apparatus for
10 producing desired magnetization of a fiber optic cable. The apparatus comprises a magnetizer that includes a pair of strong mirror-image magnets (e.g., rare earth magnets with pole strengths of about 20K Gauss) supported on counter-rotating non-magnetic disks 10 (of aluminum or plastic, for
15 example). Each magnet may be a long permanent bar magnet extending across a disk or shorter bar magnets oppositely mounted adjacent to the periphery of the disk and joined by a length of highly permeable magnetic material.

The cable 12 is driven longitudinally by a suitable
20 tractor drive (not shown), for example, and the disks are disposed close to opposite sides of the cable. Each disk is supported for rotation about an axis perpendicular to the plane of the figure. The rotation of the disks is synchronized so that, while the strength of the magnetic
25 field adjacent to the cable varies with disk rotation, the polarity of the field at one side of the cable is the same

as the polarity of the field at the opposite side. A drive mechanism for rotating the disks includes a drive roller 14 driven by the longitudinal movement of the cable and linkages (not shown) connecting the drive roller and the disks. Suitable linkages will be described later.

The applied magnetic field in ferromagnetic material of the cable is near saturation and is much stronger than any natural magnetization (due to the earth's magnetic field, for example), so that it overwrites or erases the natural magnetization throughout the length of the cable (except perhaps at regions of applied field polarity transitions).

The arrangement shown in Fig. 1 produces a repetitive sinusoidal gradient in the cable magnetization and a sinusoidal variation in the radial external magnetic field. Other external magnetic field patterns can be produced by using magnets with various spacings, orientations, and pole strengths around the disk circumference. For example, the magnetizer shown in Fig. 2 comprises a pair of counter-rotating disks 10A of non-magnetic material supporting a plurality of pairs of magnets arranged diametrically, as shown. This arrangement produces repetitive square wave variations in the radial external magnetic field.

The embodiments shown in Figs. 1 and 2 are appropriate for magnetizing the strength member or armor of relatively small diameter fiber optic cables. For larger diameter cables, multiple pairs of mirror-image magnets 10B can be employed as shown in Fig. 3, in which a fiber optic cable 12

is shown, diagrammatically, in cross-section. Each magnet of an opposed pair of magnets is rotatable about an axis A that is perpendicular to an axial plane of the cable, and that lies in a plane perpendicular to the longitudinal axis of the cable. The rotation of the magnets is synchronized so that the polarity of the magnetic field applied at all sides of the cable is the same. Of course, the polarity changes as the magnets rotate.

The magnetizers shown in Figs. 1-3 magnetize the ferromagnetic material of the strength member or armor of the cable such that a cylindrically symmetric radial external field is produced that varies periodically along the length of the cable. As shown in Figs. 4-6, the cylindrically symmetric external magnetic field has flux lines that extend radially with respect to the cable. The radial flux lines F1 are parts of flux loops having axial parts F2 that extend parallel to the length of the cable, on the surface and/or internally of the cable, and axial parts F3 that extend parallel to the length of the cable externally of the cable.

Along the length of the cable, the external magnetic field includes, repetitively, a region of one polarity followed by a region of the opposite polarity. The alternating regions or zones are of length $L/2$, where L is the wavelength of the magnetic field variations. In accordance with the invention, it is highly preferred that L be substantially greater than the width or diameter d of the

cable perpendicular to its length. In that case, the strength of the external magnetic field decreases approximately linearly with increase in distance from the cable, i.e., there is an inverse relationship between the field strength and the distance from the cable. The relationship may be expressed as $1/R$, where R is the distance from the centerline (axis) of the cable perpendicular to the centerline and is small relative to L .

As shown in Figs. 7 and 8, for the $1/R$ relationship, the magnetic field radial component magnitude $|B_r|$ at distances from the cable that are small relative to wavelength L is substantially greater than that for a $1/R^2$ relationship except at positions very close to the cable. The curves shown in Figs. 7 and 8 are for wavelengths of 10, 20, 30 meters, and more. It is apparent that the longer the wavelength L the closer the approximation to $1/R$.

For any given wavelength, the wave shape may be adjusted from square wave to sinusoidal. However, for any shape other than sinusoidal (e.g., square wave) the variation in radial field strength with distance R away from the cable is not constant along the cable. The radial variation of the radial field component is a function only of wavelength for sinusoidal magnification, but varies also with position along the cable for non-sinusoidal magnetization. Thus, the "best" shape for any wavelength is sinusoidal, which also requires the simplest magnetizer configuration (rotating bar magnet).



Fig. 9 shows an actual magnetizer for magnetizing small diameter fiber optic cables in accordance with the invention. The drive roller 14 is driven by a cable (not shown) as the cable is moved longitudinally over the drive roller by a conventional tractor drive (not shown). The drive roller is connected to a pair of counter-rotating mirror-image magnets M arranged to be disposed at opposite sides of the cable, by linkages that include drive shafts 16, belt and sprocket couplings 18, and gear boxes 20 to rotational shafts. In this instance, each magnet M is constituted by a pair of oppositely poled short magnets at the end of a bar of highly permeable magnetic material mounted on a rotational shaft 22. The magnetizer also includes a housing 24 having a cover (not shown) with a guide channel for the cable and a notch for exposing the drive roller.

Fig. 10 shows, diagrammatically, a magnetizer for a large diameter cable, including two pairs of counter-rotating disks 26 carrying mirror-image magnets, the pairs of magnets being arranged around the circumference of a cable 12 that drives a drive roller 14. The drive roller is connected to gear boxes 26, on which the magnet disks are rotatively mounted, by linkages 28 that are shown diagrammatically. These linkages may include belt and sprocket couplings and may also include electrically operated variable gear ratios clutches and/or brakes in

order to vary the pattern of rotation of the disks in response to rotation of the drive roller.

Cable and other elongated objects magnetized in accordance with the invention can be detected, located, and tracked using well-known magnetic detection equipment employing arrays of magnetic sensors such as fluxgate magnetometers or gradiometers. See, for example, the magnetic detection equipment disclosed and claimed in U.S. Patent , incorporated herein by reference.

In actual tests of the invention, on both 51mm armored cable and 11mm lightweight unarmored cable, strong external magnetic field signatures were produced, which greatly facilitated accurate horizontal and vertical cable position determination. In both cases, the cables were easily tracked at vertical distances of two meters. The magnetization achieved for the 51mm armored cable was roughly the same as for a 20-inch diameter steel pipeline, with detection, tracking and depth determination possible at vertical distances approaching 6 meters. The magnetization of the 11mm unarmored cable was approximately that of a 12-inch diameter pipeline, with detection, tracking and depth determination possible at vertical distances in excess of 4 meters. Both tests involved magnetization that produced a sinusoidal external magnetic field pattern.

Although the magnetizers shown and described employ permanent magnets, electromagnets may also be used. Fixed polarity rotating electromagnets can simply replace the bar

magnets. Alternatively, stationary electromagnets can be employed adjacent to a moving cable, and the polarity and strength of the applied magnetic field can be varied electrically. This arrangement can easily be employed to
5 encode data magnetically on the cable, in a digital bar code, for example, which can be read by the magnetic tracking system. Such an arrangement may be used, for example, to mark repeaters or splices along the cable for future location. Similar encoding of data magnetically on
10 the cable can be achieved by varying the rotation of permanent magnets or electromagnets with linear movement of the cable. For example, a microprocessor can be used to control the rotational drive trains via clutches, brakes, and/or variable gear mechanisms.

15 While preferred embodiments of the invention have been shown and described, these embodiments are intended to be exemplary, not restrictive, and it will be apparent to those skilled in the art that modifications can be made without departing from the principles and spirit of the invention,
20 the scope of which is set forth in the appended claims.

What is claimed is:



1 1. A method of producing magnetization in
2 ferromagnetic material of an elongated object, comprising
3 applying to said object a magnetic field that magnetizes the
4 ferromagnetic material in a manner that results in a radial
5 external magnetic field around the object that is
6 substantially cylindrically symmetric and that varies along
7 the length of the object.

1 2. A method according to Claim 1, wherein the external
2 magnetic field has radial flux lines the polarity of which
3 varies repetitively along the length of the object.

1 3. A method according to Claim 2, wherein the radial
2 flux lines are parts of flux loops having axial parts that
3 extend along the length of the object on a surface of the
4 object or internally of the object, and having axial parts
5 that extend along the length of the object externally of the
6 object.

1 4. A method according to Claim 3, wherein the
2 variations in the radial external magnetic field are
3 periodic and have a wavelength along the length of the
4 object that is substantially greater than the width of the
5 object perpendicular to its length.

1 5. A method according to Claim 4, wherein the
2 wavelength is such that the magnitude of the external





3 magnetic field decreases approximately linearly with
4 distance from the object.

1 6. A method according to Claim 5, wherein the
2 wavelength is of the order of 10 or more meters.

1 7. A method according to Claim 1, wherein the magnetic
2 field is applied by relative lengthwise movement of the
3 object and a magnetizer, and the field applied by the
4 magnetizer has a polarity that varies repetitively.

1 8. A method according to Claim 7, wherein the
2 repetitive variations have a square wave pattern.

1 9. A method according to Claim 7, wherein the
2 repetitive variations have a sine wave pattern.

1 10. A method according to Claim 7, wherein the
2 magnetizer includes a pair of mirror-image magnets disposed
3 at opposite sides of the object and the polarity of which
4 adjacent to the object varies repetitively during the
5 relative movement.

1 11. A method according to Claim 10, wherein the
2 magnetizer includes a plurality of said pairs of magnets
3 disposed around the object.





1 12. An elongated object comprising ferromagnetic
2 material that has magnetization substantially stronger than
3 intrinsic magnetization by the earth's magnetic field and
4 that provides an external magnetic field around the object
5 that is substantially cylindrically symmetric and that
6 varies repetitively along the length of the object.

1 13. An elongated object according to Claim 12, wherein
2 the external magnetic field has radial flux lines the
3 polarity of which varies along the length of the object.

1 14. An elongated object according to Claim 13, wherein
2 the radial flux lines are parts of flux loops having axial
3 parts that extend along the length of the object on a
4 surface of the object or internally of the object, and
5 having axial parts that extend along the length of the
6 object externally of the object.

1 15. An elongated object according to Claim 12, wherein
2 repetitive variations in external magnetic field are
3 periodic and have a wavelength along the length of the
4 object that is substantially greater than the width of the
5 object perpendicular to its length.

1 16. An elongated object according to Claim 15, wherein
2 the wavelength is such that the magnitude of the external





3 magnetic field decreases approximately linearly with
4 distance from the object.

1 17. An elongated object according to Claim 16, wherein
2 the wavelength is of the order of 10 or more meters.

1 18. An elongated object according to Claim 12, wherein
2 the repetitive variations have a square wave pattern.

1 19. An elongated object according to Claim 12, wherein
2 the repetitive variations have a sine wave pattern.

1 20. Apparatus for producing magnetization in
2 ferromagnetic material of an elongated object, comprising a
3 magnetizer that includes a pair of mirror-image magnets
4 arranged to be disposed adjacent to the object at opposite
5 sides thereof, the object being movable longitudinally
6 relative to the magnets, and a mechanism that repetitively
7 varies the polarity of the magnets adjacent to the object as
8 the object is moved relative to the magnets.

21. Apparatus according to Claim 20, wherein the magnetizer includes a plurality of said pairs of magnets arranged to be disposed around the object.

1 22. Apparatus according to Claim 20, wherein each of
2 said magnets has a pair of opposite polarity end portions





3 and the magnets are counter-rotated about axes that are
4 substantially perpendicular to a longitudinal axial plane of
5 the object and that lie in a plane substantially
6 perpendicular to the length of the object, and wherein the
7 rotation of the magnets is coordinated with the movement of
8 the object.

1 23. Apparatus according to Claim 22, wherein the
2 rotation of the magnets is produced by a drive train that
3 includes a drive roller arranged to be rotated by
4 longitudinal movement of the object and a linkage that
5 causes the magnets to rotate in response to rotation of the
6 drive roller.

1 24. Apparatus according to Claim 23, wherein the
2 linkage includes a device that permits variation of the
3 rotation of the magnets in response to rotation of the drive
4 roller.

1 25. Apparatus according to Claim 22, wherein the
2 magnets are supported on rotary disks.

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