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Magnetic Resonators for Locating Underground Assets

Exploring latest technology that helps improve path marking capabilities.

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Abstract

The objective of this paper is to review the operating principle and intrinsic features of a magneto-acoustic or magneto-mechanical resonator as it relates to using it for an electronic path marking solution for buried utilities. Magneto-mechanical (MM) resonators, in contrast with electro-magnetic (EM) resonators, are easily scalable in length for tuning, consisting of only two elements: amorphous ribbon and neodymium magnets inside a high-density polyethyle (HDPE) plastic case, with a long, thin form factor that can be adhered to tape or conduits, providing a lowest cost solution for marking the path of buried infrastructure.

Path marking electronic markers or tags virtually eliminate the need for access points that are used to apply a transmitter signal onto a tracer wire or a metallic cable before locating its path. Electronic marker resonators are passive (no battery) and are detectable underground with a compatible locator.

This new advancement in buried resonator technology allows for a natural extension into remote sensing for buried utilities that can measure various attributes, such as temperature, water presence, pressure or other, using the same locator technology. Path marking tags can be used in combination with point radio frequency identification (RFID) markers for advanced asset protection, asset management, and mapping solutions.

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Introduction

Electronic markers are detectable passive resonating devices buried along utility assets to mark specific points of interest for the purpose of notifying a utility technician of the location of a marker in order to help prevent damage or gain access to maintain or repair an asset.

Electronic Marking Systems

A handheld locator is used to pinpoint the exact location of a buried marker for the above stated purposes. The locating device emits a local magnetic field at a frequency that matches the buried resonator for a very short time, enough to energize the buried resonator element, then it stops transmitting and listens to any reflected magnetic field from the buried device. The received signal from the buried resonator is indicated by a numeric value and audible means.

An operator typically moves the locator to find the position of the maximum signal, which will be on top of the buried marker.

The system of locator and electronic marker is commonly referred to as electronic marking system (EMS). See Figures 1 and 2.

Figure 1: Examples of 3M™ Dynatel™ Locators X Series.

Figure 2: Examples of 3M™ Point Markers.

Usages and Benefits

Electronic marking technology was first used for marking buried assets in the mid-1970s in the United States. Buried electronic markers operate in the very low frequency (VLF) range below 170 kHz. This frequency range exhibits minimal signal loss in wet soil. Unique frequency markers were used for identifying each utility. In the last couple of decades, RFID was added as an option for identification of a specific point of interest, such as a specific splice or valve etc. RFID provides physical marking locations that are tied to a GIS/GPS mapping system for advanced asset management.

A natural extension to the point marker described above were electronic marker devices for marking the path. Path marking products appear on caution tape as shown in Figure 3.

The standard method of locating buried cables path is to use a transmitter that applies an AC signal to the target cable by conduction or induction and uses the earth for the return current. A closed circuit is required to locate the target cable. The applied AC signal current generates a magnetic field around the buried conductor, making it detectable with a compatible portable receiver. A technician uses a locator tuned to the applied AC signal, walks around and looks for an indication of a local maxima, or equivalent, where a buried conductor carrying a portion of the transmitted current might be located. Often, ground return currents on adjacent conductors can cause significant errors or detect an incorrect utility. In the worst case, if the target cable is electrically open and cannot create a closed electrical circuit, the transmitter current can only flow through stray capacitance between the cable and earth, which may prevent detection of the location of the buried cable.

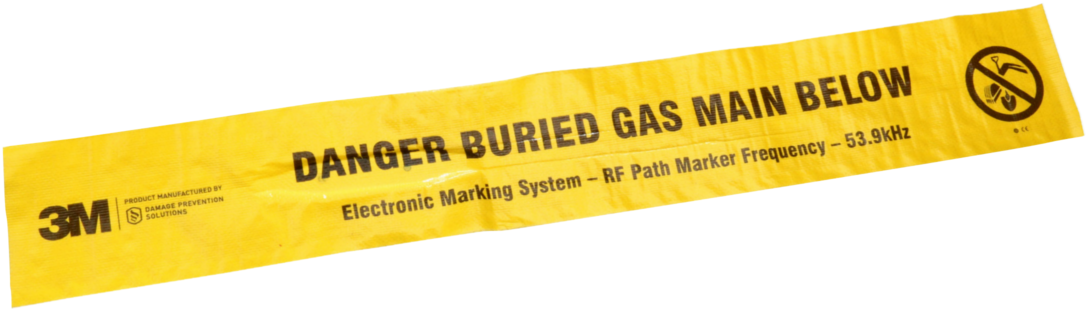

Figure 3: Example of 3M™ Electronic Marketing System (EMS) Warning Tape 7900 Series.

Do All Utilities Have a Need for Path Marking?

It was demonstrated that magneto-mechanical resonators, constructed as shown in Figure 4, are used for path marking and are robust enough to survive harsh installations when housed in high-density polyethylene housing.

In Figure 5, see a cross-section of path markers' detection pattern as arcs when spaced at 2.4 m.

Figure 6 shows a top view signal detection pattern using a handheld locator when path markers are buried 1.2 m deep and placed every 2.4 m. Note that one can go unlimited distances with electronic path marking, as far as the path marking tape is installed!

In recent years, the developmental product 3M™ Intrinsically Locatable Plastic Pipe (ILPP) has been assessed in the field by several gas companies in the U.S. The 3M™ ILPP is based on the new magneto-mechanical resonators as show in figure 4. The focus of this research effort was to mitigate third-party pipeline damage and resulted in a successful outcome[1].

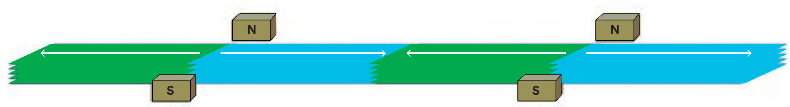

Figure 4: New MM resonator with 5 ribbons, 4 magnets.

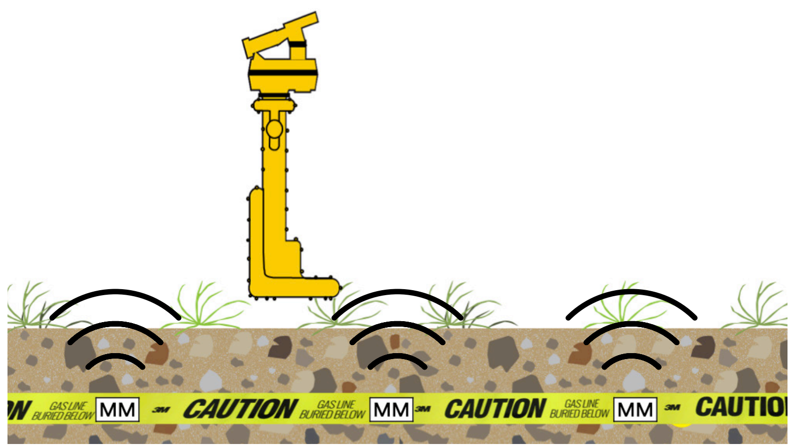

Figure 5: Cross-section signal pattern above path markets. Path markers are shown as "MM" on the EMS caution tape.

Figure 6: Top view detection pattern for path markers.

[1] Operations Technology Development ("OTD"), Gas Technology Institute ("GTI"), and 3M, 'Intrinsically Locatable Technology for Plastic Piping Systems' U.S. DOT Contract No. DTPH56-15-T-00019. Public report issued February 2018. https://primis.phmsa.dot.gov/matrix/prjHome.rdm?prj=654

Types of Electronic Path Markers

There are two types of long-form markers available for path marking applications. One type uses a ferrite core wound antenna with a tuning capacitor (LC resonator), and the other is a magneto-mechanical-tuned material resonator. When path markers are used, they make that utility segment intrinsically locatable, making it so the path marking user does not have to connect to the utility to apply a transmitter signal.

Methodology

The new resonator performance capability is assessed against environmental influence, its stability, and longevity. Furthermore, the appropriate form factor is assessed along with manufacturability and backward compatibility.

Determining the Necessary Operating Axis

Electronic markers used for path marking are typically placed every 2.4 m. They have a long form factor in order to be placed flat along the cable, conduit, or pipe and should function normally at every rotation angle around the long axis. Therefore, ferrite rod antenna forms of LC markers and magneto-mechanical resonator types are used for path marking applications. To detect a long form marker laying horizontally, it's best to use the same matching horizontal orientation in the detector antennas. This will provide a maximum signal detection directly over the marker.

Selecting the Resonator Type

The resonating devices used today are largely based on electro-magnetic resonators such as an LC-resonant circuit (L is an inductive element such as an air coil or ferrite antenna, and C is a tuning capacitor that is selected for a specific resonance frequency).

The selection criteria consist of basic attributes, such as: detection distance, stability over time, and environmental conditions (temperature and Earth's magnetic field), in addition to form factor, robustness, and cost.

Resonance Principle of EM vs MM

Resonator types available in the VLF range are either EM or MM. Resonators are devices that oscillate or vibrate at an intrinsic frequency when excited with an impulse, like a bell. Figure 7 shows EM resonators for ferrite core and for air core antennas. The magnetic coupling axis for the ferrite is along the ferrite's long axis and for the air core antenna, the axis is along a direction normal to the coil area.

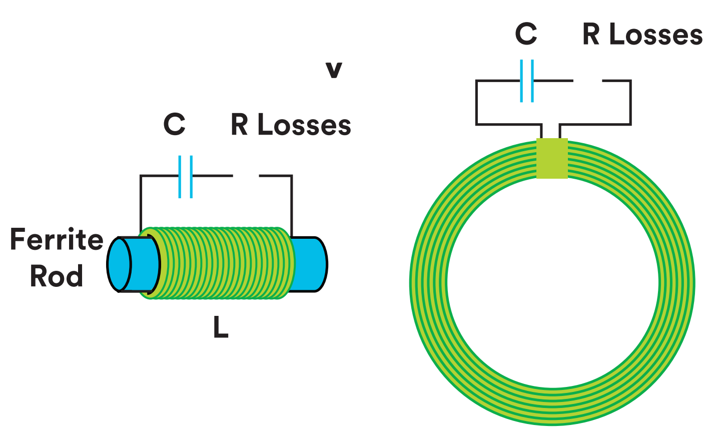

Figure 7: Ferrite-core antenna, left, and air-core antenna.

An important aspect of resonators is the ability to transfer stored energy from one state, such as when all the energy is in stored on a capacitor, to another state, such as when all the energy is stored in the inductor, without losing too much energy in the process of back-and-forth energy transfer. These EM resonators are commonly known as LC resonators, where "L" refers to the inductor antenna and "C" refers to the charge storage capacitor. The losses in the LC electric circuit are designated by R and they control the Q, the resonance quality.

Figure 8 shows the interactive signal exchange between a locator and a buried electronic marker with a vertical magnetic coupling axis. When an LC marker is excited from a marker locator, energy builds up in its LC circuit. As the excitation is stopped, the LC marker will continue to resonate at its intrinsic resonant frequency with an exponentially decaying magnitude, dissipating any stored energy. The locator receiver looks at the signal from the marker during its ringdown period and displays a number relative to the received signal, as shown in Figure 9.

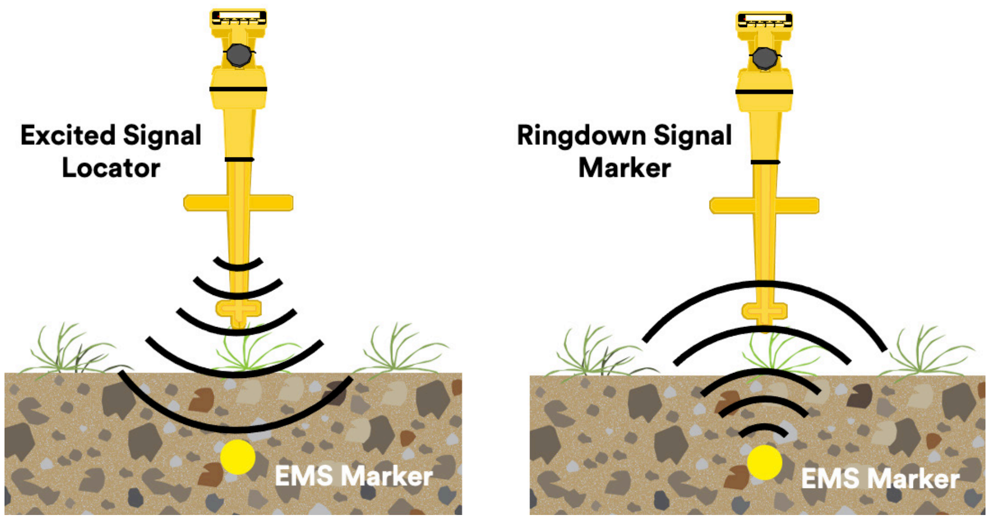

Figure 8: Locator to marker excitation and reflection.

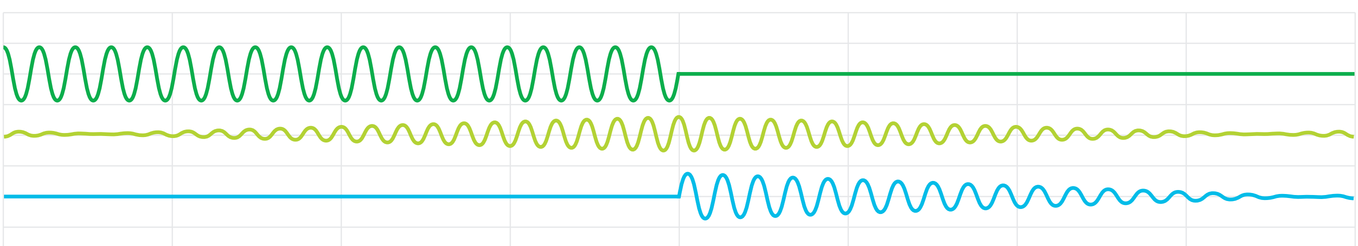

Figure 9: Top: signal from locator. Middle: signal from marker. Bottom: ringdown signal from marker.

Magneto-Mechanical Resonators

Another type of resonator is the MM resonator. In MM resonators, the energy is stored in mechanical vibrations excited with an external magnetic field. Resonance is a function of the ribbon length, ribbon characteristics, and magnetic field bias from the magnets. To explain MM resonators, we'll look at magnetostriction first.

Magnetostriction is a property of magnetic materials that makes them change dimension under the influence of a magnetic field. The inverse is also true; if a magnetic material is stretched, it will generate a magnetic field. Note that a 180-degree reversal of the magnetic field causes the same magnetostriction effect. Therefore, for a positive or a negative direction of the same magnetic field, the expansion in the material will be the same.

If a constant magnetic field is applied to the ribbon, along its long axis, the ribbons will stretch. A place where the ribbons are pre-stretched is referred to as a "bias point." To achieve best resonance, the amount of pre-stretching of the ribbon is set to be high enough for maximum elasticity of the magnetic domains without getting to the saturation point.

Amorphous metal ribbons are a type of ferromagnetic magnetic materials used for resonators. They are made by cold wheel drip quenching of molten magnetic material mix, making a thin (20 μm thick) metallic ribbon form factor. If the quenching is conducted while the ribbons are subjected to a saturating magnetic field along the ribbon cross axis (along the width), an easy axis is established for the magnetic domains, whereby the domains will have a preferred, lower-energy state. Since the net magnetic field from the ribbon is zero due its very low magnetic remanence, the magnetic domains remain in the easy axis; however, they must alternate direction. This process enhancement was applied for decades for electronic article surveillance (EAS) tags and is well known in the field[2].

MM resonator components consist of an amorphous ribbon and a magnet used to bias the amorphous ribbon, as described above. When an external alternating magnetic field is coupled to the resonator's long axis, the ribbons will stretch slightly more when the excitation field is in phase with the bias field and will shrink from the bias position when the excitation field reverses direction. Note that the shock waves travel along the ribbon length at around 3400 m/s. Since the ends are kept free to move and vibrate, the waves get reflected at the ends.

Resonator Construction, EM vs MM

EM components: Ferrite rod, magnet wire wound on ferrite, capacitor, electronic PCB, and housing with soldering.
MM components: Amorphous ribbon, bias magnet, and housing.

Electronic Marker Signal vs Distance

The return signal from a resonator in the VLF frequency range is proportional to the inverse 6th power of distance. For example, a marker at 1.2m from the detector will receive 2-6 or 64 times less signal than the same marker at 0.6m depth. Therefore, in order to achieve a 2-times increase in the detection distance to a VLF marker of any type, the locator output signal has to be increased by a factor of 64, which increases the output power by 4096 times!

Note that although much higher frequencies than VLF can give longer detection distances in the air, the distance drops very quickly in wet soil and becomes unusable at normal utility-burial depths.

[2] Herzer, G.: 'Magneto-acoustic marker for electronic article surveillance having reduced size and high signal amplitude', U.S. Patent 6359563 B1, March 2001.

Earth's Magnetic Field Influence

The Earth's magnetic field influence is assessed for magneto-mechanical resonators because it shifts the ribbon's average bias field. A simulated external field was applied to the magneto-mechanical resonators to assess the frequency and gain shift. Frequency and gain stability over temperature and aging are a common assessment for electronic markers and would be assessed for the new magneto-mechanical resonator.

A Novel MM Resonator for Path Marking

The commonly used configuration for a magneto-mechanical resonator consists of a magnetized strip used as bias for the ribbon, a plastic separator with a couple of ribbons, as can be seen in Figure 10.

The length of the ribbon corresponds to a half wavelength at resonance and the ribbon stack is all biased in the same direction along the long axis. Any external static field will shift the resonance frequency, which gives inconsistent performance based on Earth's magnetic field strength.

The resonant frequency of the longitudinal mechanical vibration of an elongated strip is given by:

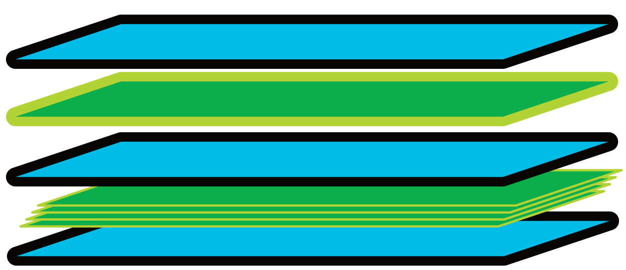

Figure 10: Prior art of magneto-mechanical resonator.

L is the length, EH is Young's modulus at the bias field H and ρ is the mass density[2].

$$Fr = \frac{1}{2L} \cdot \sqrt{EH/\rho}$$

[2] Herzer, G.: 'Magneto-acoustic marker for electronic article surveillance having reduced size and high signal amplitude', U.S. Patent 6359563 B1, March 2001.

A New Advanced Performance Design

A novel construction of the new advancement in this resonator technology uses multiple ribbons and differential biasing with permanent magnets, a configuration that allows for longer or shorter total resonator length based on the number of half-wavelength sections used (longer = more signal = deeper).

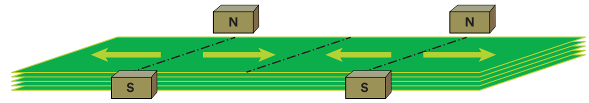

Figure 11: Long form of the new MM resonator.

The novelty consists in its differential biasing scheme from the side edges of a stack of amorphous ribbons. This gives it all of its claimed advantages of stability and performance. At each magnet position, the bias field in the ribbon stack, indicated with yellow arrows in Figure 11 below, changes direction relative to the adjacent stack[3].

Assessing the effects of Earth's magnetic field (Oe), Figure 12 illustrates the MM resonator's significant improvement in resonant frequency (Hz) stability, approximately 9 times of the new art compared to the conventional art performance, Figure 13[3]. Gain (dB) represents the received signal from the MM resonator.
In the new art, when excited with an external alternating magnetic field, one stack section, which corresponds to a half wavelength at resonance, will expand because the external and internal (bias) fields are in the same direction, while the adjacent stack section will contract because the external and internal (bias) fields will be in opposite directions. This keeps the resonant frequency stable.

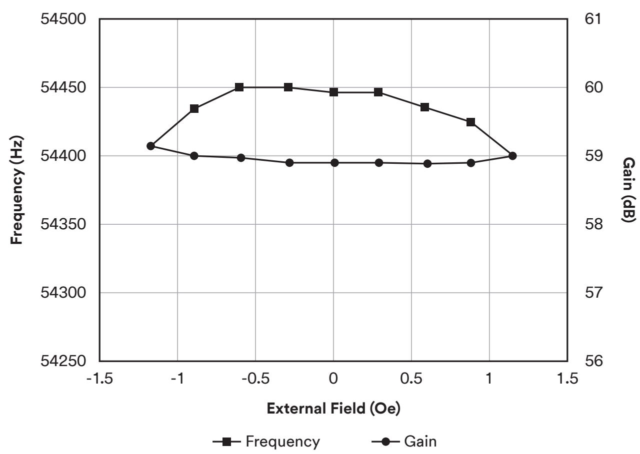

Figure 12: Novel MM construction.

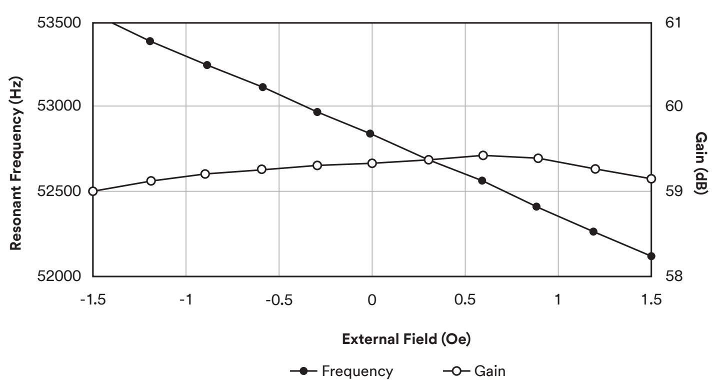

Figure 13: Conventional MM.

A long-form MM construction with multiple half-wavelength sections increases the gain significantly. The net gain increases about 28 dB compared the conventional MM resonator, Figure 13[3].

[3] Doany, Z.: 'Magneto-mechanical Marker With Enhanced Frequency Stability And Signal Strength'. U.S. patent application number 16/308992, August 2019.

Results

Environmental Stresses

The effect of ambient temperature was studied, and its effect on the resonant frequency, Q, and gain on the magneto-mechanical markers measured with plots show performance is not noticeably affected by temperature[3].

Effect of the Earth's Magnetic Field

Since the resonant frequency of the magneto-mechanical resonator is a function of the magnetic bias level in the ribbon, it is expected that the frequency will shift based on the direction of Earth's magnetic field. The effect of Earth's magnetic field on resonant frequency of the new resonator shows 10 times better stability than conventional MM types over ± 0.6 Oe. See Figures 12 and 13.

[3] Doany, Z.: 'Magneto-mechanical Marker With Enhanced Frequency Stability And Signal Strength'. U.S. patent application number 16/308992, August 2019.


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Conclusion

The highlights of the new material resonator consist of the following key attributes: very high gain and stability, simple to construct with low part count and cost, easily tunable to different frequencies, and it's rugged and bendable. With these performance improvements in the new resonator, magneto-mechanical resonators became a viable competing technology for buried infrastructure path marking applications for buried utilities compared to conventional LC resonators. LC resonators are ideal for point marking RFID applications, while MM resonators are ideal for path marking applications.

It's critically important to select VLF frequencies that do not interfere with each other, like adjacent airwave radio stations' spacing considerations. A minimum frequency spacing of 10% should maintain enough isolation for proper detection with appropriate filtering. Furthermore, electromagnetic compliance limits the maximum output power allowed by frequency, which should be assessed carefully. There are restricted frequency bands in the FCC code (90 k~110 k with exception for 101.4 k), while CE limits the output power above 145 kHz, unless waived by the country. Furthermore, the selected frequencies should avoid ambient sources that are in band, such as fixed long wave radios and retail stores' RFID gate readers if they're in the same band.

The technology direction is toward simpler, lower cost, and effective asset management solutions. The new resonators may enable large scale path marking using MM technology, along with LC RFID point markers at the nodes. Having unique serial numbers with user information in the RFID marker means all the information can be tied to a geographic information system (GIS).

Finally, any new technology or solution for buried asset location should be backwards compatible and be able to detect the very large embedded buried base. The actual frequencies used for the last 50 years should be formalized in a standard per the current best practices. The standardization should be extended and formalized to RFID point marker frequencies and formats, at least at the template level, for seamless information sharing.

References

1. Operations Technology Development ("OTD"), Gas Technology Institute ("GTI"), and 3M, 'Intrinsically Locatable Technology for Plastic Piping Systems' U.S. DOT Contract No. DTPH56-15-T-00019. Public report issued February 2018. https://primis.phmsa.dot.gov/matrix/prjHome.rdm?prj=654
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3. Doany, Z.: 'Magneto-mechanical Marker With Enhanced Frequency Stability And Signal Strength'. U.S. patent application number 16/308992, August 2019.

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