A Novel Communication and Radar System for Underground Railway Applications

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A system allowing data to be exchanged between two successive trains in a tunnel, while simultaneously measuring the distance between them, would help to optimize train traffic in very long tunnels, without lowering safety standards. A study including both theoretical and experimental phases was conducted to design and optimize such a system and focused on the Channel Tunnel, between France and England, where a minimum range of 5 km is necessary for operational use. A prototype, operating at 2.45 GHz and based on this new concept, produced successful results. Given that this technique would also be useful in any underground rail system, particularly those that are automated, the prototype was also tested on subway lines, in Lille and Paris.

1. Introduction

In order to increase the density of rail traffic in very long tunnels while maintaining high safety standards, an exchange of data between trains, concerning train ID and type (passenger or freight, for example) as well as the distance between the two trains, could prove quite interesting. This is particularly important for the Channel Tunnel, given the rapid succession of shuttle trains transporting heavy-weight, multi-axle vehicles loaded with goods or people, interspersed by high speed passenger trains traveling between England and France. A study was conducted to examine and then test the feasibility of an additional new system, based on microwave transponders, that would be able to measure the distance and exchange information between trains.
It must be emphasized that this new system is not at all intended to replace the classic anti-collision protections now in use in Europe and whose migration to the European Rail Traffic Management System (ERTMS) is strongly supported by the EU High-Speed directive on interoperability. ERTMS enables train to operate on compatible signaling systems across

European borders and provides Automatic Train Protection (ATP) systems. It is divided in various levels, as explained in the Strategic Rail Authority Website [SRA 2004]. Level 1 corresponds to the simplest configuration with fixed blocks and consists of trackside equipment that monitors individual signals and passes this information to the train via track-mounted transponders. Level 2 is also a fixed block system but a radio link allows a continuous exchange of data between train and trackside, through the GSM-R mobile communication network, and allowing the train to reach its maximum permitted speed within its block while maintaining safe braking distances. In this case, balises are placed along the track. However, because the Channel Tunnel Rail Link must be compatible with the Channel Tunnel, it utilizes a non-ERTMS signaling system that still provides ATP.

The TGV system relies on cab signaling, the information transmitted through the rails being picked up by antennas placed under the train. This track to train transmission is based on a block system, the track being divided into fixed segments, and only one train may occupy any block at one time under normal operation. Train separation and ATP are carried out by a computer-based system known as TVM 430 (Transmission Voie Machine - Train to Track Transmission). Audio frequency jointless track circuits are used both for train detection and data transmission to the train. A 27 bit digital word transmitted from the track is detected by two pairs of coils on the locomotive, allowing the on-train equipment to calculate the instruction to be given to the driver and the maximum safe speed for the ATP. In the Channel tunnel, the fixed block sections are 500 m long, thus shorter than a train's braking distance, allowing to run trains on shorter headways. Shuttle trains operate at speeds up to 140 km/h. International freight and passenger trains run through the tunnel at 100/120 km/h and 160 km/h respectively. Shuttle trains are 750 m long and have a normal service braking distance from 140 km/h of about 1500 m [Robins, 1993]. Therefore, the braking sequence for a lorry or passenger vehicle shuttle begins 2 km from the occupied section but this distance is extended to achieve a minimum separation of 4 km for trains following lorry shuttles.

To complement the anti-collision protection afforded by the signaling system, based on discrete train detection, there is an operational need to determine the distance from a lorry shuttle with greater precision. Indeed, a radar sensor would inform drivers of the distance between their train and the preceding train, allowing them to adjust speed and thus avoid entering into a braking sequence. Since the objective of this system is to give additional information to the driver only in the tunnel, the on-train transponder will be activated by a fixed beacon when the train enters the tunnel, the minimum safe space headway distance in the open air approach and exit being ensured by the ATP system, as in the tunnel. This additional system does not include communications with a central traffic control.

To measure the distance separating a train from a lorry shuttle, a link must be established between the trains inside the tunnel whenever the distance between them reaches or falls under 4.5 or 5 km. Reaching such a large range in a confined area, in non line-of-sight conditions and by keeping the transmitting power to a reasonable value, typically 1 W, is one of the challenging aspects of the study. Indeed, as will be discussed later in the text, signal propagation in tunnels leads to a very significant attenuation of the radio waves, even in the microwave range. Since radars operating in the road transportation domain [Wenger, 1998, Moldovan et al. 2004] do not successfully work in long and curved tunnels, a complete study starting with the propagation channel characteristics and ending with the design and construction of a new measurement system, named FOLOMIE, had to be undertaken.

In the first part of this paper, we briefly present the results of an experimental study designed to characterize signal propagation in tunnels, in the 2 GHz - 10 GHz frequency range. After completing this preliminary step, the solution retained for measuring distance was one based on spread spectrum techniques [Haykin, 1994], and thus the exchange of orthogonal pseudo random sequences, using transponders located in each train. This method allows the double objective of distance measurement and data transmission to be attained. The various FOLOMIE parameters, such as the effective bit rate and the spreading factor, were optimized in order to attain the desired range while minimizing the bit error rate of the link. A prototype, operating in the 2.45 GHz frequency band, was constructed and tested in diverse sections of the Channel Tunnel. In the second part of this paper, we provide the preliminary performance results, both in terms of range and measurement accuracy. The FOLOMIE system was also tested successfully on shorter distances in underground rail system tunnels, whose geometry is much more complex than that of the Channel Tunnel, and especially on the Paris and Lille subway lines.

2. Characterization of the propagation channel

2.1 Description of the test site

The Channel Tunnel consists of two rail tunnels and a service tunnel. The service tunnel runs between the two rail tunnels, except in the vicinity of the two cross-over points, where the rail tunnels link up to permit the trains to change tunnels during maintenance operations. The radii of curvature of both the rail and service tunnels are quite large, of the order of several kilometres. However, the curves of the service tunnel are sharper in the cross-over zone, which can thus be considered as a critical zone in the preliminary testing phase. The cross-sections of the rail tunnels and the service tunnel have diameters in their circular parts, of 7.1 m and 4.8 m respectively. Measurements were first taken in the service tunnel and then, during maintenance operations, in the railway tunnels. Because the tunnel must act as an oversized waveguide in order to avoid prohibitive signal attenuation at great distances from the transmitter, the wavelength has to be much smaller than the transversal dimensions of the tunnel [Delogne 1976, Mahmoud, 1991]. A transmission frequency ranging from 2 GHz to 10 GHz was thus considered.
In most of the tests discussed in this paper, the transmitting antenna remained stationary while the receiver was loaded either in a car or on a train. The tests were repeated in different sections of the tunnel. In addition, by monitoring two trains moving through the tunnels at a relatively constant speed, we were able to determine, under sustained testing conditions, the influence of the tunnel's diverse curves on the performances of the distance measurement system.

2.2 Propagation in the service tunnel

Let us first consider a rectilinear part of the tunnel. Modelling the signal propagation precisely is a difficult task because the exact geometry of the tunnel must be taken into consideration. An extreme simplification would be to consider a cross section of the tunnel as a rectangle with the same surface area as the actual tunnel. In this case, ray theory would be directly applicable [Mahmoud et al., 1974]. For example, the curves in Fig. 1 represent the variation of the received power versus the transmitter-receiver distance, for a frequency of 2.45 GHz. Comparison of the theoretical results (curve a) and the experimental results (curve b) reveals a quite significant disagreement: the attenuation per unit length, which theoretically should be 3.3 dB/km, is in reality 20 dB/km.

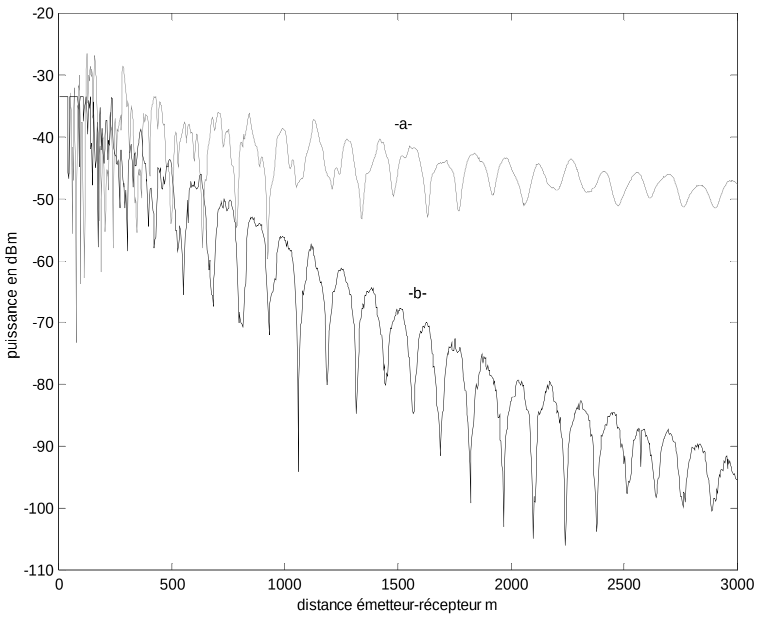

Figure 1. Variation of the received power, expressed in dBm, versus distance. Comparison between theory (a) and experiments (b)

The form of the tunnel certainly plays an important role, but the presence of conduits and cables attached to tunnel walls also contributes to the increase in signal attenuation. However, since the objective of this study was not to elaborate a complicated numerical model to better accord theory and experience, we opted for a purely experimental approach requiring numerous measurements be taken in different zones of the tunnel. A similar approach was followed in the rail tunnel, and is described in the next paragraph.

2.3 Propagation in the rail tunnel

The first test measurements were taken in a straight 2-km section of the tunnel followed by a succession of curves and straight lines over 2.5 km. Curve (a) in Fig. 2 represents the variation of the received power versus the transmitter-receiver distance in the rail tunnel, for a frequency of 2.45 GHz. As a comparison, curve (b) was obtained in the cross-over zone of the service tunnel.

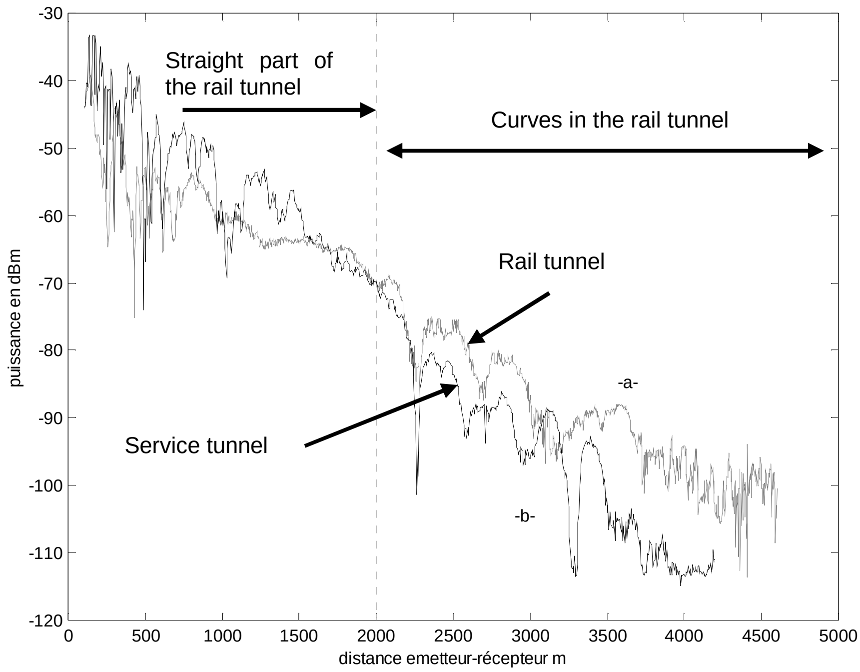

Figure 2. Received power versus distance at 2.45 GHz. (a) In the railway tunnel, (b) in the service tunnel.

Despite the large size of the cross section in the rail tunnel, average signal attenuation is more or less the same as in the service tunnel: 20 dB/km. This result can be explained by the complicated geometry of the cross section, particularly at the ground level because the rails, held in place by crossties that act as a series of discrete signal reflectors, are bordered by walkways on either side at a height of 1.5 m.
The statistical values of the channel characteristics, as the signal attenuation, the direction of arrival of the rays and the noise level have been determined owing to successive measurement campaigns. These values were introduced in a simulation tool to optimize the transmission chain presented in the following paragraph.

3. Principles of distance measurement and data transmission

Given that the application under study does not require very high transmission rates, we chose to use a half-duplex operational mode. This choice greatly simplified the construction of transmission and reception chains, allowing us to avoid the problems associated with the synchronization of the vehicle-borne system [Anderson, 1999].
The calculation of the distance between two trains is based on the measurement of the time interval between the transmission of a frame by the interrogating beacon, called Master Station (MS) and the reception of another frame retransmitted by the transponding beacon called Slave Station (SS). We chose the principle of transmission via the spread spectrum

technique [Haykin, 1994] in order to be able to measure distance and transmit data simultaneously.

The MS sends a 32-bit frame of useful data, using a PN1 code. On receiving the message, SS re-transmits another data sequence, using a PN2 code of the same length as and orthogonal to the PN1 code (Fig. 3).

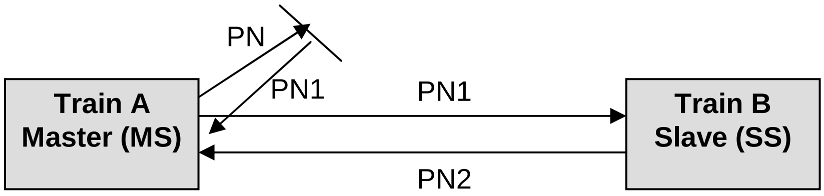

Figure 3. Principle of data transmission and distance measurement based on pseudo-random sequences

The original beacon (MS), recognizing the returning PN2 code, identifies the mobile unit and measures the time between the emission of PN1 and the reception of PN2, by determining the correlation peaks of the first bit of the transmitted and received pseudo random sequences and subtracting the response time of the transponder [Lienard et al., 2004]. This time is defined as the time needed to switch from the receiving to transmitting mode, given that the general operating system is based on a half duplex communication. MS systematically sends a message every 200 µs if it does not receive a response from SS, for instance when the train to be detected is too far away. Because the PN1 and PN2 codes are quasi orthogonal, the disturbing echoes produced by reflections of various tunnel structures are avoided. It is also worthwhile mentioning that the use of pseudo random sequences offers an important protection against unintentional or deliberate interference. Indeed, the signal is extracted through a correlation technique implying that the transmitting code is known by the receiver. If it is not the case, or in presence of a white noise or a narrow band noise, the correlation will only produce a slight increase of the signal to noise ratio.

To attain the desired distance of about 5 km, the transmission-reception chain was numerically simulated. By limiting the transmitting power to 1 W and using an antenna with a 10 dBi gain, a bit rate of 174 kbits/s can be achieved. A chip duration of 90 ns, was chosen to insure the best compromise between the range and precision of the ranging system. The error in determining the position of the correlation peaks corresponds to the accuracy of the distance measurements, theoretically equal in this case to 20 m. To improve this accuracy, an instantaneous measurement being not useful, a running mean was calculated on a time window of 100 ms.

Given that the study of signal propagation in the 2.45 GHz – 10 GHz bandwidth showed that the received power does not vary significantly in this range, we chose a transmission frequency of 2.45 GHz both to keep costs down and to facilitate prototype development.

4. Results obtained with the prototype

4.1 Results in the service tunnel

In this step, the transponding beacon SS remained stationary and the master beacon MS was loaded into a car. A coding wheel attached to the vehicle sent an electrical pulse every 10 cm, thus providing a reference measurement of the distance between SS and MS. A comparison of the results produced by FOLOMIE and those of the coding wheel yields the curves shown in Fig. 4 which are nearly superimposed. The vertical bars in the Fig. 4, provided as additional reference points, correspond to the reading of the various indications marked on the tunnel walls. However, given the difficulty of synchronizing the reading on the wall with the passing of the vehicle, the estimated degree of inaccuracy is between 5 m and 10 m.

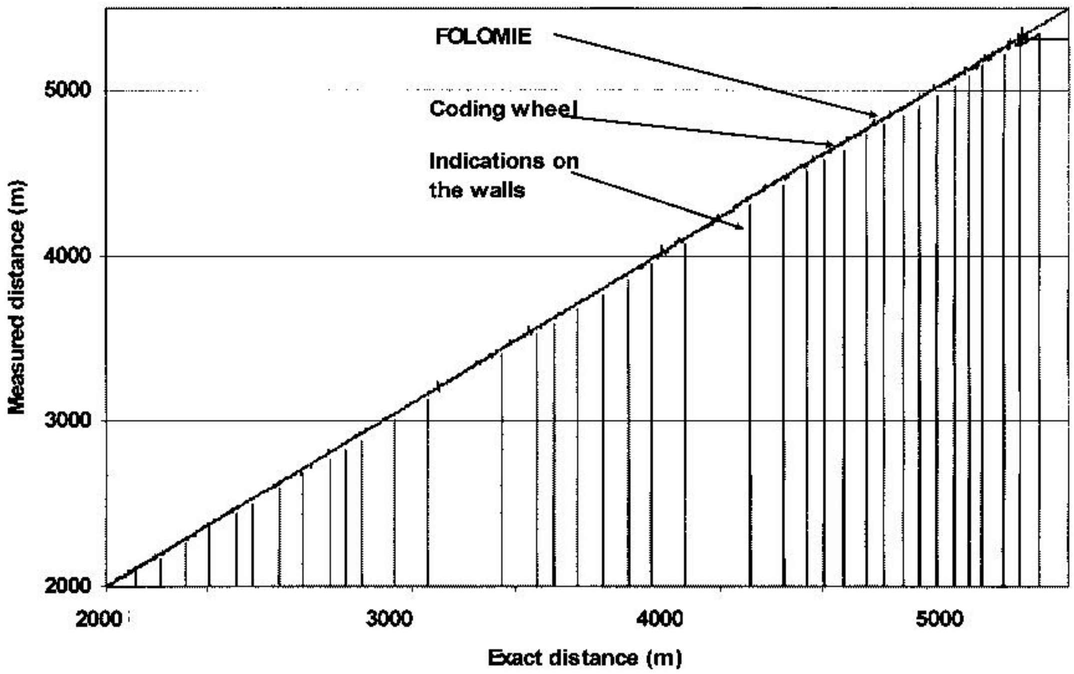

Figure 4. Measured distance versus "exact" distance. Comparison between the FOLOMIE results to those given by the coding wheel or by indications on the walls.

Similar series of measurements taken in other zones of the service tunnel show that the difference between the results of the FOLOMIE system and the coding wheel is on average +/- 15 m; this difference remained under 30 m in every case.

4.2 Results in the rail tunnel

During maintenance operations in the tunnel, the antenna of the transponding beacon was situated in a stationary position at a height of 2 m above the track; the receiving beacon was loaded on a train. Unfortunately, in this configuration, it was not possible to use a coding wheel, and since the trains are not equipped to provide information concerning distance traveled, comparing the distance measured by FOLOMIE with the "real" distance is also impossible. However, there is no particular reason for the results in the rail tunnel to differ from those obtained in the service tunnel. The overall results obtained in the different zones of the tunnel show that the range of the system in the rail tunnel is about 5.5 km. The good functioning of the system was checked by comparing the displayed results to the indications written on the tunnel wall. Other measurements - taken using the beacon system loaded on two trains following one another through the tunnel at an average interval of 5 km over a total distance of 12 km - confirmed this result.

4.3 Results in subway tunnels

Since FOLOMIE could easily be applied to underground rail systems, several additional tests were completed in the Metro in Paris and the VAL in Lille. In totally automated systems like Lille's VAL, one of the principal causes of cost-producing delays is the time needed for one train, called the second train, to couple up to another (the “first train”) that has broken down on the line. Because the distance between the two trains is unknown, the second must slow its speed to the authorized final approach speed as soon as it enters into the section of the tunnel occupied by the now motionless first train. Measuring this distance would allow the second train to approach the first train at a higher speed, which would obviously be an advantage, especially if the first train had broken down at the very end of the section in question.

Most of the trials took place on a test line in the Paris subway, between the stations "Porte des Lilas" and "Haxo", this section being quite representative of a metro line. A plane view is given in Fig. 5. The geometrical configuration can be divided into two parts.

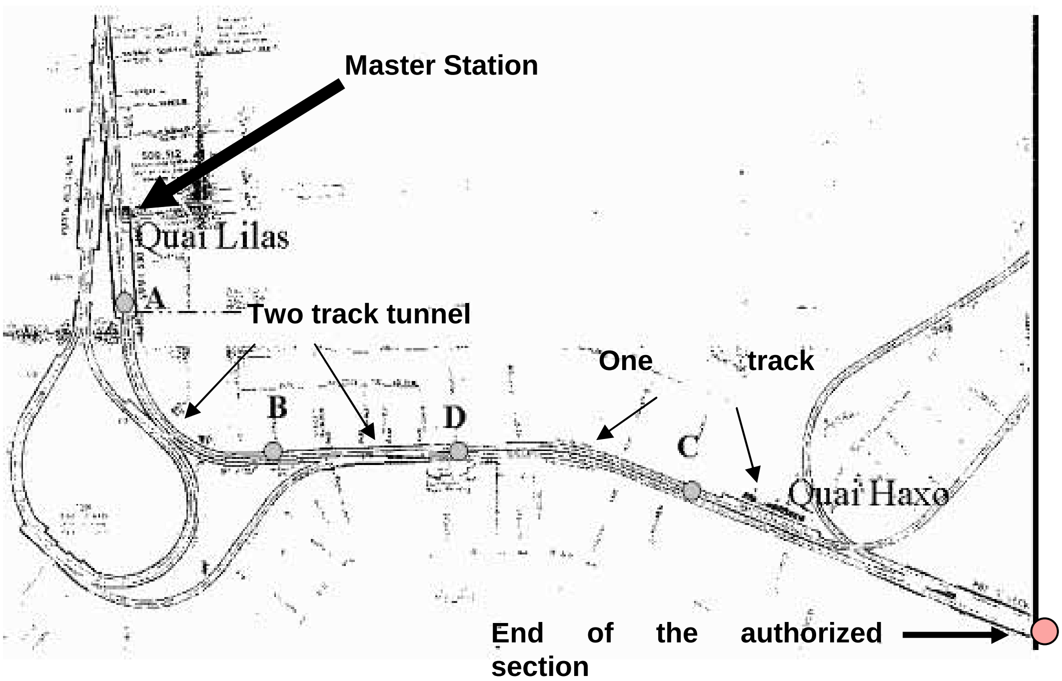

Figure 5. Configuration of the test line of the Paris metro.

First, the 2-track tunnel curves sharply from Quai des Lilas to point B, 200 m apart, it is then straight along a distance of about 100 m, up to point D and finally narrows to a 1-track tunnel running 300 m up to Haxo.
The Master Station (MS) was placed on the platform at Quai des Lilas, while the train with the Slave Station onboard moved, from a starting point near point D to Quai Haxo and beyond at a speed of about 9 km/h which was the maximum authorized speed for the trials. Curve in Fig. 6 represents the variation of the distance between MS and SS versus time since no absolute position reference was available in the train. The slope of the curve decreases at the end only because the train must slow down and stop at the end of the available section, i.e. at 900 m from Quai des Lilas. Along this section, the ranging system correctly functions and the slight fluctuations appearing on the curve, corresponding to the measurement accuracy, is of course related to the duration of each transmitted chip.

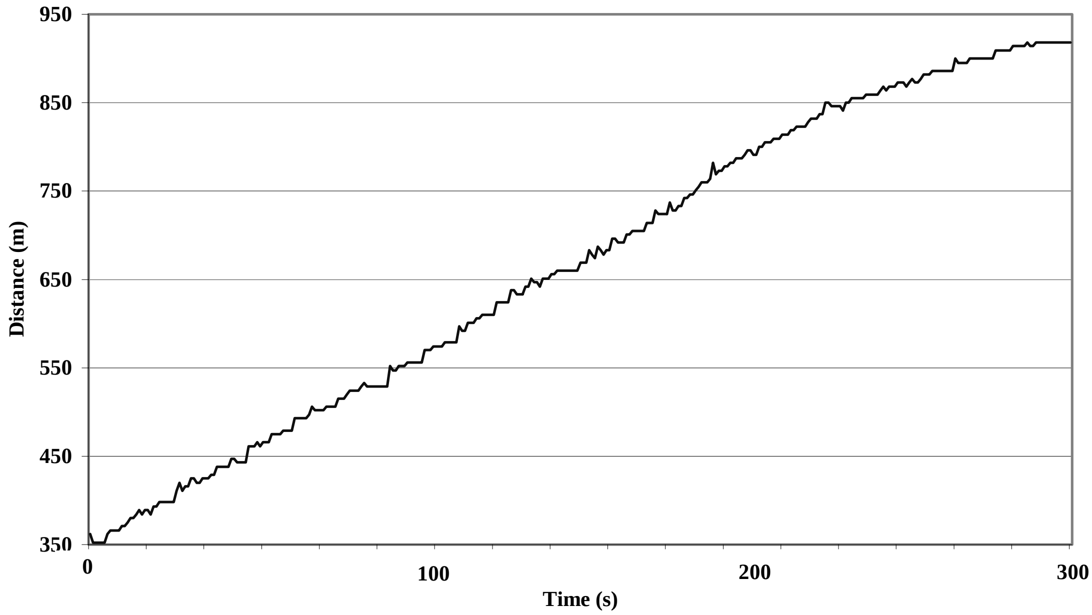

Figure 6. Test line of the Paris metro: Measured distance versus time

Other experiments took place in the underground rail system in Lille whose tunnel cross sections are much smaller than those of the Paris subway. The tunnels are either semi-circular or rectangular. The line curves frequently, and in the vicinity of certain stations, 2-track tunnels sometimes separate to form two 1-track tunnels. For our tests, two trains were added to the regular traffic during passenger service. The nominal speed of the trains is 60 km/h, the commercial speed being 36 km/h and the mean inter station distance is 750 m.
Pausing only briefly at each station, the two trains followed one another through the network, the second train launched 1 minute 30 seconds after the first. The curve in Fig. 7 shows the variation of the measured distance between the two trains versus time; the numbers, from 1 to 13, refer to the different stations on the VAL line. For example, point 7 corresponds to the station "Gare de Lille", and consists of a 1-track tunnel section. The distance between trains

varies from 800 m to 1100 m, depending on the time that one train or the other paused in a station.

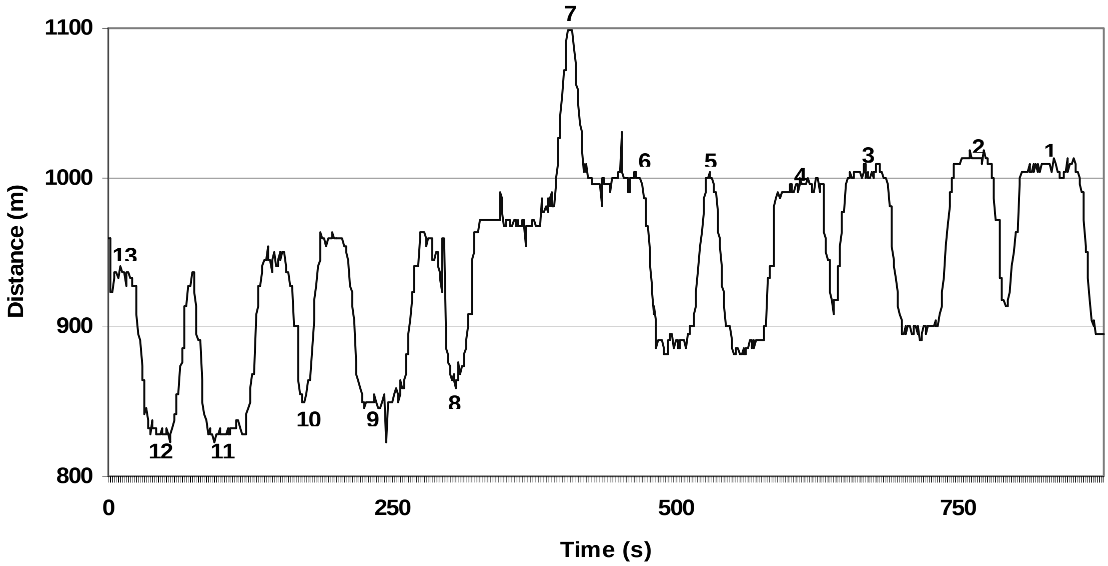

Figure 7. Distance between two successive trains running on the VAL line versus time

Worth noting is the fact that no operational errors occurred in the system at the moment when two trains passed side by side in the 2-track tunnels. As mentioned in paragraph 3, using orthogonal sequences for the transponders helps to avoid erroneous measurements. It must be outlined that the shunting speed and shorter headways are constrained by the existing train detection and safety system, which cannot simply replaced by the proposed radar technology. However, the signaling system is permissive, in that a train may proceed at reduced speed after having being order to stop. The knowledge of the distance between the two trains would thus allow the optimization of the approach speed.

5. Conclusion

We have designed and constructed a new system that allows the distance between two successive trains in a rail tunnel to be measured while simultaneously transmitting other useful information. This system is based on microwave transponders and of a spread spectrum technique using quasi orthogonal sequences. Test results show that with a transmitting power of 1W and an antenna gain of 10 dBi, a range of 5.5 km can be obtained in the Channel tunnel using a 2.45 GHz transmission frequency. The average accuracy of these measurements is +/- 15m. Note that more precise measurements can be obtained by reducing the elementary duration of each chip in the PN sequence, although this would obviously also reduce the range of the system. This system can track numerous trains in the

tunnel, given that the number of quasi orthogonal sequences that can be generated, is quite large.
In underground rail system tunnels, the range is reduced to 800 m - 1 km in most cases; the geometry of the tunnel cross section, in addition to the complicated configuration of lines composed of several branches and curves exhibiting low radii of curvature, tends to attenuate the signal. Still, the prototype performed successfully in these configurations and such a range corresponds to practical operation needs for metro lines.

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