Precise Location of System Flaws Using Egress and Ingress Signal Data Streams Separately and in Combination

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ABSTRACT

Precise location of leakage signals is a challenge. Models of leakage detection are presented and used to guide the development of signal processing strategies for improving the accuracy of source localization.

A range of strategies are examined together with both simulated and real data to identify the potential performance of fully developed systems.

PROBLEM SUMMARY

System Flaws

Flaws in a CATV system result in both the leakage of rf energy into the environment and a weakness at which external signals can more easily ingress into the CATV system, posing the potential for upstream and downstream interference.

Leakage monitoring from vehicles is often done either manually or with logging equipment collecting data at relatively low sampling rates and at a single receiver frequency. In an earlier paper a system capable of ingressing position and leakage data on a narrow band carrier into an operating cable system was demonstrated. [1]

Improvements

Preliminary assessments of data drawn from the initial experiments suggested several improvements:

1) Increase the sampling rate to ensure that constructive and destructive interference patterns can be resolved.
2) Explore signal processing methods to estimate the position of system flaws based on analysis of the received egress and ingress data streams.
3) Provide for differential GPS post-processing to anchor data to precise position.

In the discussion that follows we will describe the theoretical framework in which we intend to examine the issue of flaw localization, we will discuss certain fundamental issues which restrict the performance of any flaw localization system, and we will illustrate a set of flaw localization strategies using both modeling and experimental data.

THEORETICAL FRAMEWORK

In the context of CATV system integrity we will define a *flaw* as a non-uniformity in the system where rf energy can both leave (egress/leakage) and enter (ingress/interference) the system. A flaw has a location and a set of properties which define it as an unwanted antenna. Due to these properties it will admit or emit energy in different degrees and with different characteristics as a function of frequency.

Detection of flaws is accomplished by observing phenomena which arise from the presence of the flaw. The primary phenomenon is just the egress or ingress of energy. The use of egress/leakage is the traditional method of finding leaks. Ingress has also been used through the expedient of keying CB transmitters while someone monitors the return path. [2] at the headend.

The flaw may be considered an unconventional antenna, and as such the path between a conventional antenna and the flaw may simply be considered an example of a two way transmission path. In the case of egress, the transmission path is the CATV downstream being broadcast through the flaw, in the case of ingress an external transmission is received through the flaw.

The Friis transmission formula describes the power transfer between a transmitter and receiver in free space.

Eq'n (1): $$\frac{P_R}{P_T} = \frac{\lambda^2 G_T G_R}{(4\pi r)^2}$$

where

λ= wavelength of transmission,
r = distance between transmitter and receiver,
G_T = transmitter antenna gain in direction of receiver,
G_R = receiver antenna gain in the direction of transmitter,
P_T and P_R are respectively the transmitted power and the received power.

In practice this equation is too simple. The transmitted power does not arrive at the transmitter only by the direct path. Instead reflected power adds or subtracts from the signal from all directions depending upon the presence of reflecting, absorbing, and re-radiating elements in the surrounding environment. In addition to these various multi-path signals the transmitter and receiver gain terms vary with direction of arrival. Thus the actual power received is the coherent summation of all possible transmission paths which terminate at the receiver. This general situation is too complex to model. However there are various simpler situations which can be modeled and provide insight into the general process.

Ground Reflection

The simplest augmentation of our first equation is that involving a single reflection with the ground. It is normally the case with CATV egress signals that both the transmitter and the receiver are close to the ground. Thus ground reflections at moderate grazing angles are unavoidable.

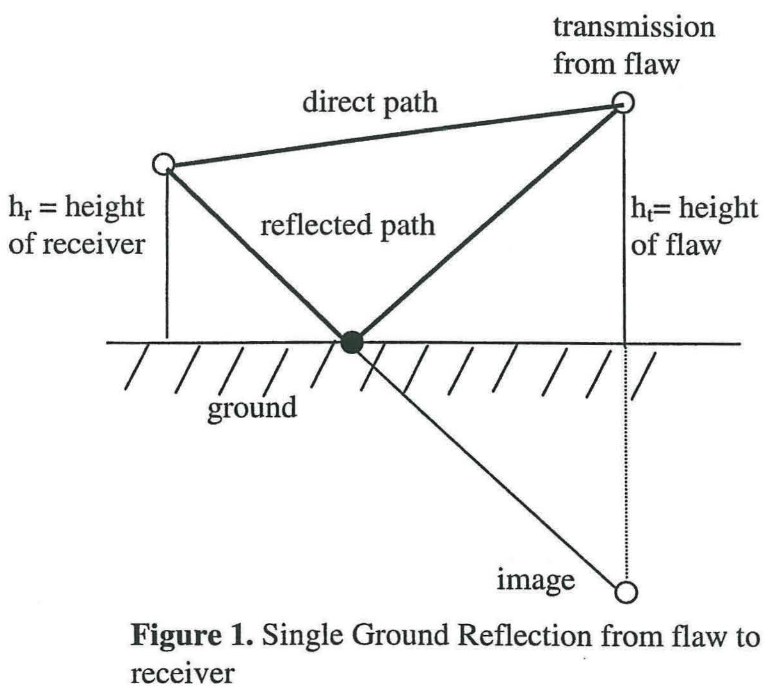

Figure 1. Single Ground Reflection from flaw to receiver

The analysis of a ground reflection can often be facilitated by the idea of a mirror. The conducting ground "images" the flaw and the resulting signal can be represented as the combination of the direct path signal from the flaw and a signal from the image.

As the a vehicle drives by the flaw the egress energy grows rapidly because the power goes as the inverse square of the distance. This variation in power is the dominant or primary effect. Smaller, secondary effects give character to the signal due to constructive and destructive interference between the direct and reflected path signals, and due to details of the radiation patterns of the equivalent flaw and receiving antennas respectively.

If we neglect the antenna patterns by assuming isotropic (omnidirectional) antennas, the magnitude of the electric field from the flaw can be written as:

Eq'n 2

$$|E_r|^2 = \left(\frac{|E_t|\lambda}{4\pi}\right)^2 \left(\frac{1}{r_d^2} + \frac{k^2}{r_r^2} + \frac{2k}{r_d r_r} cos\left(\frac{2\pi(r_r - r_d)}{\lambda} + \phi_o\right)\right)$$

where

$|E_r|$, $|E_t|$ are the magnitudes of the transmitted and received electric fields. The square of the electric field is proportional to power.

$$r_d = \sqrt{d^2 + (h_t - h_r)^2}$$

direct path distance from flaw to receiver
d = horizontal distance
h_t = height of flaw (transmitter)
h_r = height of receiver

$$r_r = \sqrt{d^2 + (h_t + h_r)^2}$$

reflected path distance from flaw to receiver

k = reflection coefficient
λ = wavelength of the radiation
$\frac{2\pi(r_r + r_d)}{\lambda}$ is the phase difference between the two paths, direct and reflected
ϕ_o = the phase change at the point of reflection

The terms in $\frac{1}{r_d^2}$ and $\frac{k^2}{r_r^2}$ as well as the term multiplying the cosine term of equation 2 generate a waveform with a single maximum. The phase variation caused by changing distances as the vehicle drives by the flaw can cause added structure in the signal, broadening the peak and putting ripple into it. Figure 2 illustrates a family of wave-forms generated by varying offsets (20' to 50' in 10' increments) generating the wave-forms one would receive as one drove by the flaw.

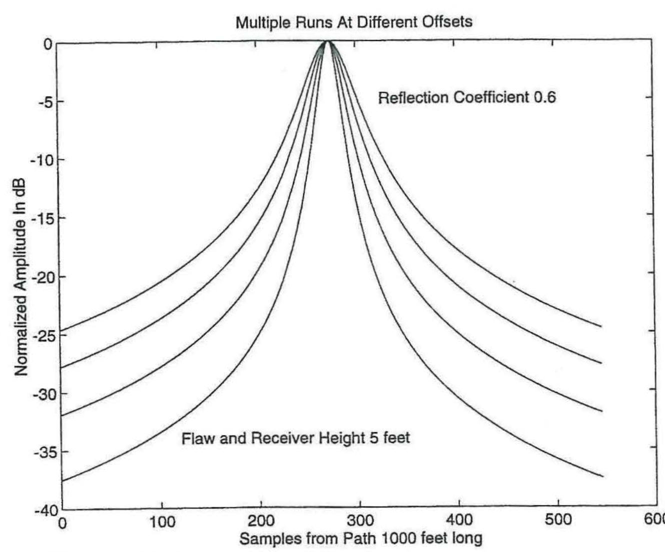

Figure 2. Runs Past Flaw at Different Offsets

This single peak aspect illustrated in Figure 2 is due to the fact that the flaw and the antenna are only five feet off the ground at a frequency of 113 MHz (a wavelength of 8.71'). Thus the phase difference between direct and reflected paths does not change very much. Note however that the paths with greater offsets have peaks that are broader than those with smaller offsets.

If the flaw and the antenna are both raised appreciably (or conversely if the frequency is raised proportionally) one sees many interference lobes. Figure 3 is an illustration of this effect using a height of 100'.

As the height is reduced, the interference lobes are fewer and only in the neighborhood of the peak.

Peak to Trough Ratio

If k is the reflection coefficient (≤ 1), the largest amplitude that the signal can acquire for a single ground reflection is (1+k), constructive interference, and the weakest amplitude would be (1-k) destructive interference.

Eq'n 3

$$dB_{ptt} = 20 \log_{10}\left(\frac{1+k}{1-k}\right)$$

Equation 3 calculates the peak to trough ratio in dB (dB_{ptt}). This is the worst case variation to be expected for a given reflection coefficient. For example, a 0.6 value of k, fairly typical for ground reflection computes to a value of 12 dB for dB_{ptt}.

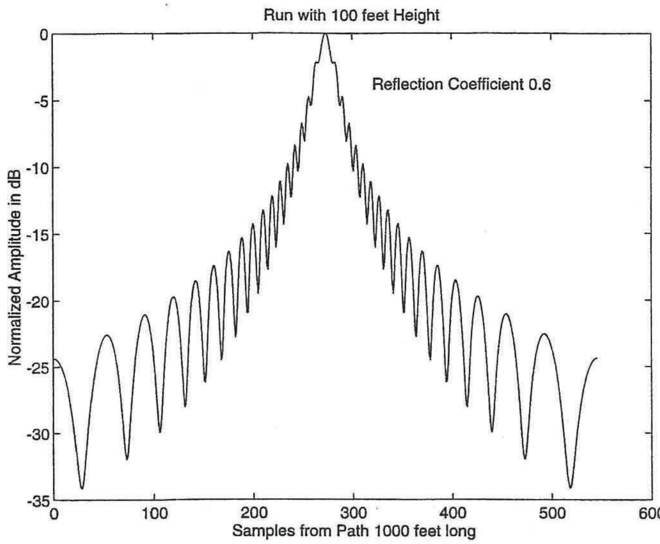

Figure 3. Path with Height of 100'

Faceted Reflections

In addition to ground reflection, large expanses of metal, as found on the sides of many buildings (ex. aluminum siding) provide highly effective reflectors. These reflectors may have reflection coefficients of 0.9 or more. At these reflection levels, multi-bounce reflections can sometimes play a role in the received leakage signal.

Figure 4 is a diagram which illustrates an example of multiple reflection modes based on the ComSonics facility. In the case of faceted reflection, one can use image ideas to calculate the expected signal paths. However the amplitude of the image will be limited by the size of the facet (reflecting area) and the visibility of the image from the line-of-sight being considered.

In Figure 4 the front of the south side of the ComSonics facility is the first facet and it has the effect of displacing the image of the flaw down the road to the north. The second mode illustrated is a corner reflector mode. In corner reflectors, energy is reflected off two walls that are 90° to each other and the energy emerges in the opposite sense displaced but parallel to the incoming sense. Because of the unusual shape of

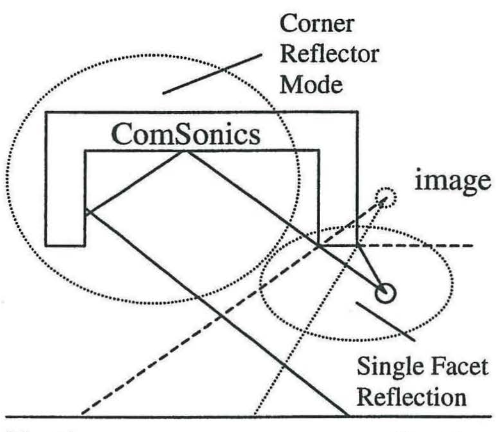

Figure 4. Multiple Facet Reflection Modes

the building a third mode involving parallel plate reflections may exist.

Faceted reflection modes produce more complex interference effects and also produce multiple *images* of the flaw distributed along the track of the surveillance vehicle. These effects are often masked by the fact that the vehicle travels at different speeds as it goes past a flaw, so that even with a graph of the signal it may not be evident that it arises from multiple reflections. Most leakage surveillance sampling is done at relatively slow sampling speeds. To guarantee that all interference effects are observed it is important to sample fast enough to capture the effects of small phase changes.

Figure 5 shows a data sequence including four runs past a large flaw intentionally inserted into ComSonics' model system. The flaw is located approximately 28 meters from the road running past the front of the building.

The vehicle ran past the flaw at varying speeds making two passes to the south and two passes to the north. These passes are annotated as p1s, p1n, p2s, and p2n respectively. Figure 5 shows the raw data prior to any processing. The strong peaks vary in width from pass to pass because the vehicle drove past the flaw at different speeds.

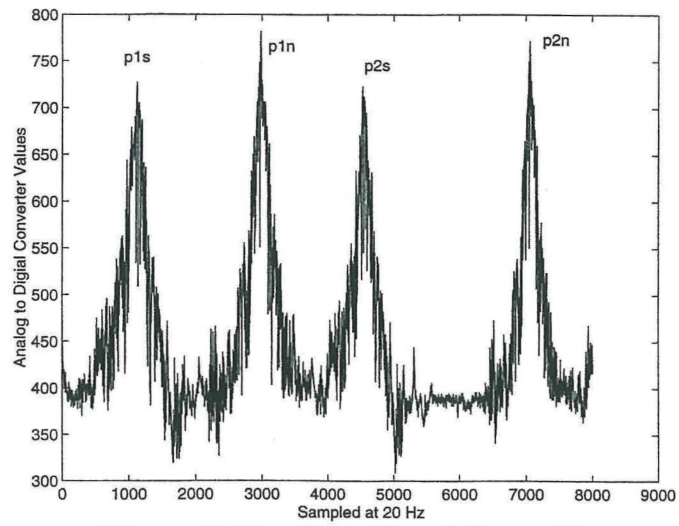

Figure 5. Four Runs Past A Large Flaw

Normally one would think that the spiky fine structure in figure 5 was noise. We compared data from different runs by first normalizing the data to position. Selecting the largest value in each run as a reference point, we calculated the distance of the vehicle from the reference using the GPS data. We interpolated intermediate positions by assuming the vehicle's speed did not change between GPS updates once a second. We could then compare runs directly.

Figure 6 is a direct comparison of p1n and p2n, the two northerly runs past the flaw. To make the visual comparison easier to perform, the data from the two runs has been offset by 100 A/D values by simply adding 100 to the data points of p2n. The data is plotted versus distance from the reference point in meters north and south of the peak. (note this is northerly and southerly since the road is not exactly N-S).

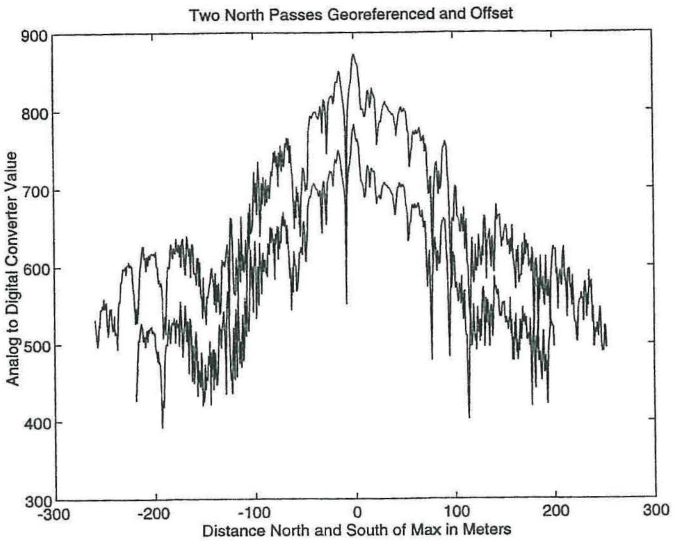

Figure 6. p1n and p2n Plotted Together for Comparison

What is significant in figure 6 is that each feature in the data is repeated in the two runs down to a very minute level of detail. The conclusion is that these details are due to physical and spatial properties of the flaw and its surroundings and not to temporal variations. Thus it should be possible in principle to analyze signal features and draw conclusions about the flaw and the environment in which it is active.

The primary objective is to be able to locate the flaws as precisely as possible. To accomplish that, one must be able to distinguish the apparent leaks caused by reflections and other signal distorting effects from the signal due to the direct path. This might be accomplished by simply picking the biggest signal except that one would need a means of telling that the next biggest signal wasn't just a reflection. Signal analysis methods seem likely to offer a means of making such distinctions.

<u>Finding Reflections Using Convolution</u>

There are a variety of signal processing techniques that can be employed to analyze data collected from flaws. Most involve convolution. One way to think about convolution is that it is like running a template along the data looking for a match. The better the match, the higher the value.

Figure 7 results from convolving a slice of the biggest peak of the data in figure 6 across the full data run. Notice the resulting peaks in the data. The central peak shows the result of the convolution when it exactly matches the peak of the data. Then there are three *image* peaks which are reflections, probably off the ComSonics building.

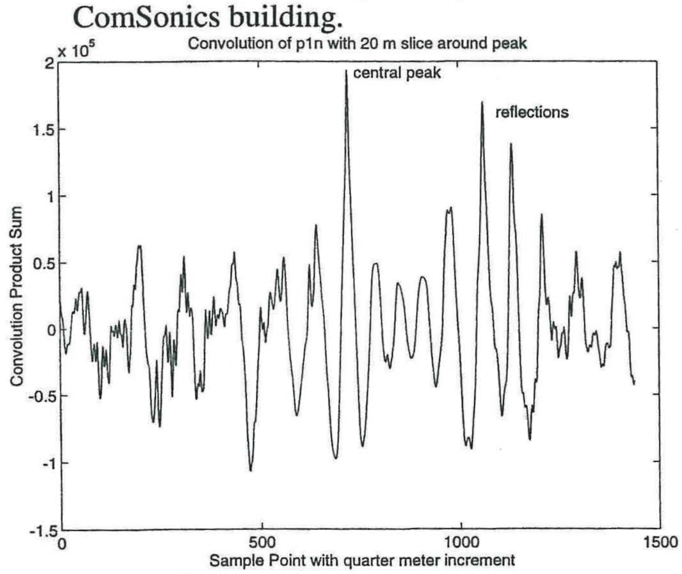

Figure 7. Convolution of p1n Showing Reflections

<u>Ingression</u>

If the surveillance vehicle is transmitting in the return path frequency interval, then ingress will take place in the

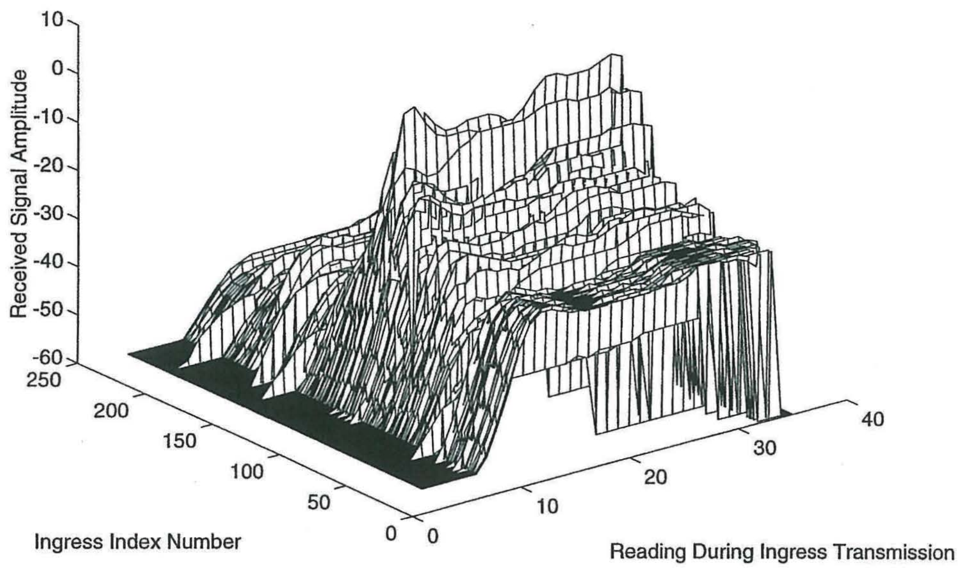

Figure 8. Headend Receiver Readings During Ingression

neighborhood of a flaw. The signal paths of the egress and ingress will be highly correlated due to the reciprocity theorem. Since the wavelength of the ingress is generally much larger than the wavelength of the egress, there will be less structure in the ingress signal. If the transmitted signal is modulated, information can be transmitted into the return path through the flaw. This was demonstrated in an earlier paper. [1]

During the transmission interval, an ingress signal received at the hub or headend location can be measured in amplitude. Fine structure due to path variation during the transmission interval can be observed. This fine structure can provide information about amplitude and phase variation used to infer relative distance to the flaw.

Figure 8 depicts an ingression run with 221 transmission intervals. Each transmission interval is triggered by a GPS reading, i.e once a second. GPS position data and leakage detector readings are transmitted and received and demodulated by a receiver at the headend. During the receipt of the data the carrier level is measured and recorded with the received position and leakage data. In figure 8 the receiver carrier levels are plotted slice by slice. Each interval is a few tenths of a second long and there are up to 35 readings per transmission. The readings taken in the vicinity of the ingression peak provide high density sampling.

FUNDAMENTAL ISSUES

The fundamental issue to be resolved is:

How does one detect and localize a flaw using ingress and egress information?

From the discussion above of the theoretical framework and some practical issues surrounding it, we find that flaws can be characterized by a strong peak due to the inverse square power relationship. This peak can be variously *ornamented* with attending peaks and troughs as a function of multipath constructive and destructive interference. It can also be surrounded by various *reflections* and *images* that confound its location.

Thus to detect and localize a flaw one must:

1) find a way to isolate the flaw from the surrounding *clutter* of unwanted reflections and images,
2) possibly use the detailed ornamentation of the flaw to classify it as to type and location, and
3) use the peaking characteristic to locate it precisely along the surveillance path.

Ingress coupled with egress provides not only an independent look at the flaw, but

4) positively confirms that the flaw is in the system under surveillance,
5) instantly transfers the location and vehicle developed flaw information to the headend, and
6) provides frequency diversity, hence spatially distinct information about the geometry of the flaw.

LOCALIZATION STRATEGIES

We have illustrated the difficulty of localization, even in the case of a large leak by showing what an isolated large leak in front of the ComSonics building looks like. Even this rather complex event is simple by contrast with the signals arising from multiple leaks in urban settings. The ongoing Ingressor development is focusing on the issues listed above. To deal with these issues we require a group of strategies which collectively can deal with the problem of detection, classification, and localization of flaws.

Flaw Isolation

To isolate flaws we are developing a compound strategy:

1) first isolate events which may be flaws using flaw-fitting methods (a group of specialized basis functions in a linear vector space)
2) perform event analysis to assign attributes to the events
3) cluster events that are spatially near one another and create cluster zones that may be related to a single flaw
4) perform the analysis in a time sequential, adaptive manner to minimize *time-late* flaw classification time

Analysis of Ornamentation

Ornamentation characteristics include such entities as semi-periodic fine structure on the inverse square characteristic caused by constructive and destructive interference associated with ground reflection and faceted reflectors.

The current strategy is to characterize these structures by their symmetry with the flaw event cluster peak, their peak-to-trough ratios, their periodicity, and period variations. This information increases the confidence that a flaw is correctly classified and in at least some cases provides estimates of off-path distance.

Peak Normalization

Because the flaw signals exhibit an inverse square peaking characteristic, peaking is a dominant feature of flaw event clusters. However, multiple flaws will add to the complexity of the situations creating cluster overlaps and *ghost* peaks.

The biggest peak in a group can be thought of as a spreading center. Image peaks are smaller than the biggest peak. Thus clusters will normally consist of a strong central peak and a family of smaller peaks. When this symmetry is broken it usually means that there is an overlap from another cluster of peaks centered on another flaw. As the peaks approach the noise level of the system they become more difficult to resolve.

Ingression Alert

Using the ingression path to send not only a unique signal which can be monitored at the headend, but a signal with egress information, and localization information provides a real-time path that absolutely demonstrates the presence of a system flaw.

The lower frequency of ingress produces different interference signals which can be compared with the higher frequency egress signals. Comparing the two signals provides a cross check on the information provided by either one alone.

FINDINGS AND CONCLUSIONS

Since this report is on a work in progress, the findings and conclusions are preliminary. So far this work has accomplished the following:

1) Intentional broadcast of modulated narrow band signals in the CATV return path interval allows egress measurements and localization information to be transmitted readily into system flaws.
2) The information can be decoded at the hub or headend and provides direct confirmation that the system has a flaw.
3) Measurement of the received carrier amplitudes allows comparison with egress levels reported across the link.
4) High speed sampling shows that egress and ingress signals are extremely repeatable, even in fine structure.
5) Signal processing methods can be employed to improve localization by both rejecting artifacts such as reflections and more precisely locating the point of closest approach to the flaw. Further work is expected to provide significant performance in these areas.

ACKNOWLEDGEMENTS

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REFERENCES

1. R. J. Schneider, "Utilizing Ingress as a Plant Maintenance Strategy," NCTA Technical Papers, 81-87 (1998)

2. R. V. C. Dickinson, "Centralized Cable Leakage Detection, Localization and Measurement," NCTA Cumulative Leakage Index / Flyover Seminar, Feb. 14-15, 1989.