Advances in Polarized Remote Acoustic Imaging

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Abstract

Small surface vibrations imparted from both internal and external driving acoustics, such as speech, machinery, or structural modes result in observable changes to the degree of linear polarization from light reflected off common materials such as windows, painted surfaces, and metals. We show that by passively sampling these oscillations, optical sensors measuring linear polarization can extract these signals and return them as both infrasound and audible sound. In this work we explore the physical signal characteristics and we additionally demonstrate a prototype instrument and its experimental results. From these results, we show simple sinusoids captured to provide a basis for SNR metrics. Additionally, we show more complex acoustic signals such as recorded human speech that were recovered from the vibrations of these polarizing surfaces.

Keywords: remote sensing, acoustic surveillance

1. Introduction

Common polarizing materials such as windows, walls, plastics, liquids, and reflective metals naturally oscillate in response to sound waves traveling through local media and disturbing their rest state. These acoustic waves may be externally generated such as human speech and the hum of an engine, or they may be internal such as carried resonant modes from ambient machinery or heat expansion. While these small motions are imperceptible to the human eye and ear, they instead can be used as local remote microphones. This ability to effectively eavesdrop from a distance or monitor intrinsic object acoustics stems from optically detecting these oscillations with the implementation of either an imaging or single cell photodetector at high sampling rates.

Several technologies already exist to remotely capture acoustics from optical intensity fluctuations and they can be categorized as either *passive*, where they perform with ambient light or *active*, where they require an illumination source such as a laser. The laser microphone being the most widespread of these remote surveillance technologies is an *active* technique but is difficult to use in practice. The difficulty stems from the strict pointing requirement that the illumination laser be perpendicular to the recorded vibrating surface and that there be sufficient reflectivity which may be achieved with a reflective target. Advancements in this technique have addressed this pointing limitation by relying on recording the speckle pattern from the laser source, however this technique becomes degraded by atmospheric turbulence limiting its effective range [1]. Additionally, the technique is highly subject to local sensor motions making the method difficult to implement in non-stationary applications. Recent advances in known *passive* techniques rely on sampling individual sub-pixel motions from deformed objects, however the major practical limitation is extending the method's range to beyond several meters for retrieving high-frequency spectral content [2].

The unique approach we take in this work is to *passively* measure the degree of linear polarization at high sampling rates from light reflected off acoustically driven surfaces. By relying on this polarization measurement, several inherent properties improve the recorded physical signal. The first that polarization is well preserved through the atmosphere because of its forward scattering nature compared to other optical properties such as frequency, phase, and amplitude - this allows for greater operating ranges [3, 4]. The second observation is that because the polarization measurement is a differential intensity measurement, the technique acts as a common-mode rejection filter for active noise sources such as scintillation, large variations in received power, and sensor pointing error. The last property we note and later demonstrate is that the measurement is not dependent on light at a single wavelength for either *active* or *passive* illumination and the method is not explicitly dependent on viewing geometry.

2. Motivation

The focus of this work has been to demonstrate this technique as a valid method to remotely retrieve acoustic content from object surfaces with both indoor and outdoor terrestrial experiments. From these experiments, the acquired data has been used to further refine the technique for audible intelligibility and spectral accuracy. We anticipate that our method may find use in surveillance applications for both horizontal path and downward looking scenarios for tasks such as intelligence gathering, structural monitoring, and object specific acoustic recognition.

In the context of space situational awareness, satellites are documented to have both transient high frequency and quasi-steady low frequency acoustic features. The LEO object IBUKI (ID 33492) which is an actively pointed satellite routinely experiences downward image degradation from passing through eclipse shadow. The image degradation is a consequence of the solar panel array oscillating the satellite bus from thermal shock and this motion has been confirmed by an on-board deployment camera [5]. Additionally, the ISS space acceleration measurement system (SAMS) is an ongoing experiment that continually measures the acoustics of the space station across each individual node with local accelerometers. The experiment has recorded the oscillations of solar panels and communications antennae, individual subsystems, the docking of vessels, and thruster firings for orbit keeping [6]. We observe that because of the growing need for additional capabilities from both ground and spaced-based EO/IR sensors to better monitor, characterize, and identify objects - building this capability to capture satellite acoustic properties may create powerful tools for satellite operators and the intelligence communities. As we have shown previously, the method does reveal unambiguous oscillatory behavior on GEO satellites [7].

3. Acoustic Sensing Via Modulating Polarization

The change in the degree of linear polarization from acoustic vibrations can be approximated by the Fresnel equations applied to a disturbed surface that is sampled discretely at two separate points in time. The physical argument begins by assuming the basic geometry shown in Figure 1 where randomly polarized light I_n is incident on a material surface at an angle of θ_i .

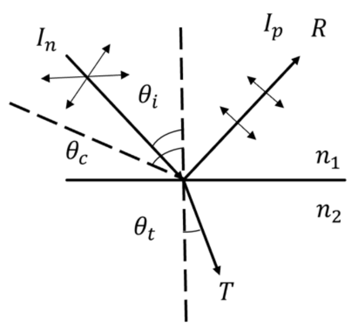

Figure 1. Illustrated is the geometry of a reflective polarizing surface.

Reducing the problem to 1-dimensional movement, any acoustic signal will drive the reflecting surface to a new incidence angle as θ_c. The light incident on the surface will have a reflective component as R and a transmissive component as T. The degree of linear polarization V (eq.1) for a single discrete measurement is written as the difference over the sum of the two orthogonal reflective components $R_{||}$ and $R_{\perp}$.

$$V = \frac{I_p}{I_p+I_n} = \frac{R_{\perp}-R_{||}}{R_{\perp}+R_{||}} \quad \text{(eq.1)}$$

As the incident light reflects from the surface, the transmissive component refracts with an angle θ_t which is governed by the two separate indices of refraction as n_1 and n_2. The two orthogonal reflective components are written as equations 2 and 3.

$$R_{\perp} = \frac{sin^2(\theta_i - \theta_t)}{sin^2(\theta_i + \theta_t)} \quad \text{(eq.2)}$$

$$R_{||} = \frac{tan^2(\theta_i - \theta_t)}{tan^2(\theta_i - \theta_t)} \quad \text{(eq.3)}$$

The difference in the degree of linear polarization V_c from two separate measurements is then written as equation 4.

$$V_c = V(\theta_c) - V(\theta_i) \quad \text{(eq.4)}$$

This change establishes a physical baseline dependent on illumination wavelength, viewing geometry, and driving force for any given surface material. We show as four separate case examples the change in the degree of linear polarization for materials that would be present on a satellite, those being fused silica, crystalline silicon, unpainted aluminum, and gallium arsenide. Figure 2 demonstrates the wavelength dependence for an assumed angle of incidence change of 1° and across the optical spectrum of λ = 550 – 900 nm for each material.

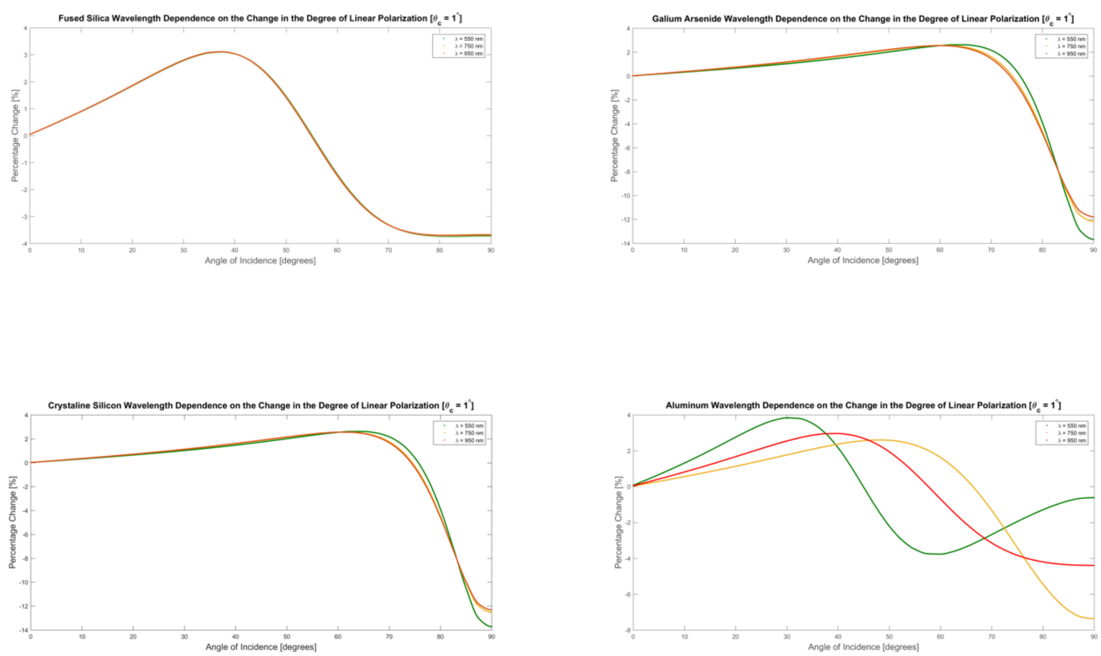

Figure 2. Shown is the wavelength dependence for the change in the degree of linear polarization for a 1° change in angle of incidence for four separate materials.

Figure 3 assumes an illumination wavelength of λ = 550 nm and separate changes in the angle of incidence of 1 – 0.001° that would be expected for a variety of vibrations. The detection of the smallest changes are dictated by system design and capability.

The first insight from these arguments presented as the wavelength dependence, is that the majority of materials exhibit little polarization dependence on the illumination spectrum which allows for broadband optical sampling. For metals where there is a chromatic dependence, the change is on scales smaller than 2%. The second insight from the change of incidence angles is that the geometry does change the signal amplitude as expected, but the viewing geometry is not constricted to a specific angle in practice.

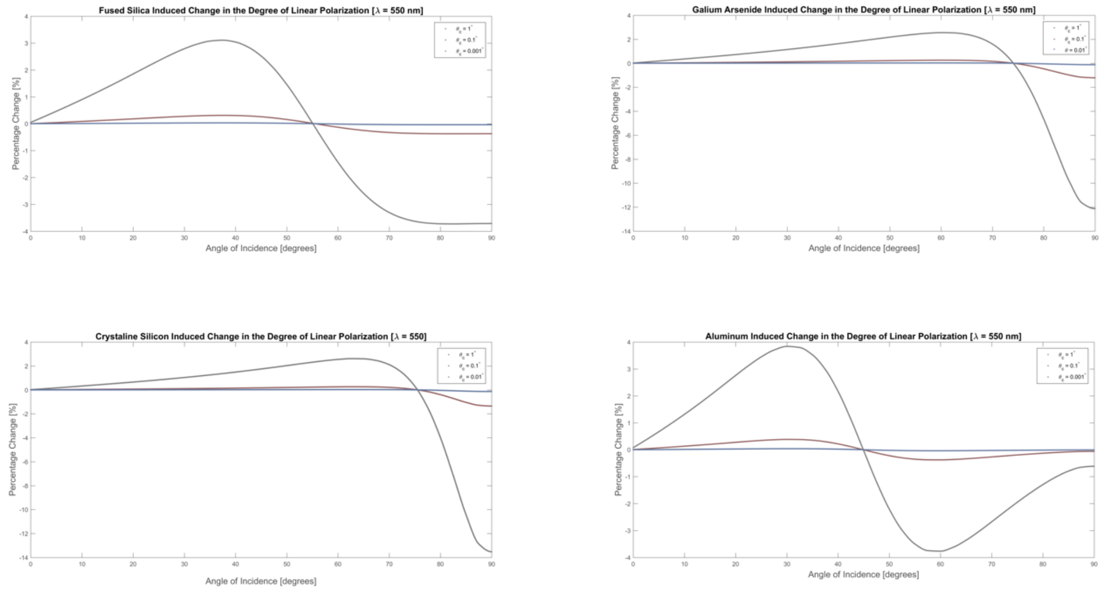

Figure 3. Shown is the changing incidence angle dependence for the change in the degree of linear polarization for the same materials as in Figure 2.

4. Experiments

Acoustic experiments were performed both indoors and outdoors with both passive and active illumination on acoustically driven surfaces with varying physical characteristics. The measurements were recorded with a prototype instrument mounted to a commercial 10" Cassegrain telescope. The instrument shown in Figure 4 utilized two separate high-frame rate Point Grey CMOS detectors separated by a linearly polarizing beam splitter cube across optical wavelengths.

Figure 4. The prototype instrument is shown piggybacked onto a 10" feed telescope. Light baffling, normally installed, is omitted here.

The imaging system has supported externally synchronized sampling rates of up to 650 Hz and independent laboratory testing of the individual cameras showed no significant time-delays from test sources. Further analysis of the cameras and sources through the polarizing element both individually and synchronized showed no appreciable artifacts in either the time or frequency domains. Additionally, an accelerometer was mounted to the instrument to measure any local vibrations that could corrupt the captured acoustic signal.

A visual diagram shown as Figure 5 outlines the premise for the experiments. The first set of experiments consisted of the indoor capture of pure sinusoid tones from 75 dB (the volume of loud conversation) – 95 dB (the volume of a food processor) driven by a loudspeaker 2 meters from the source and with the telescope and instrument approximately 50 meters away. All of the acoustically modulated sources were measured from the inside of an active machine shop environment with a varying audible noise background of 65-70 dB which acted as an artificial detection threshold. The different surfaces driven were uncoated window glass, white coated Krylon, copper, and unfinished aluminum. Each of the surfaces were placed at incidence angles of approximately 30 degrees and illuminated by broadband shop lights.

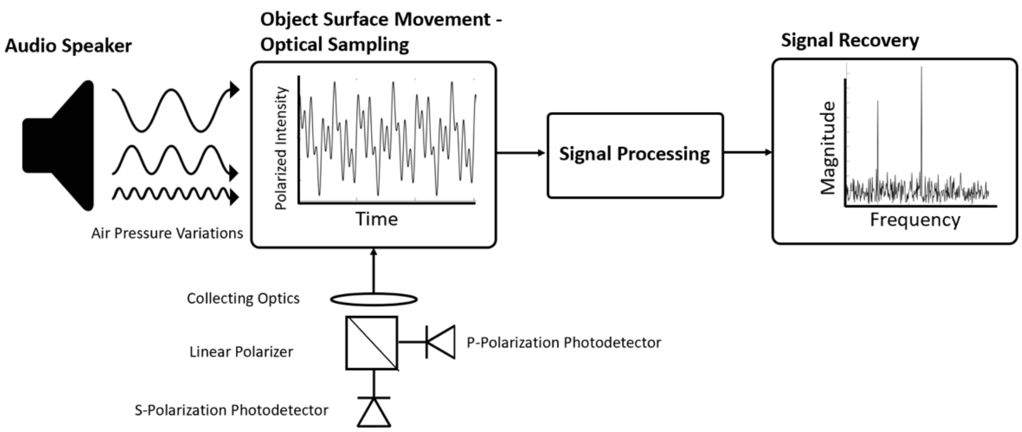

Figure 5. Outlined is an overview of the acoustic experiment where various test materials are driven by a nearby source speaker and sampled optically to measure the degree of linear polarization at fast sampling rates. The signal is then digitally processed where the original acoustic features are recovered.

Later experiments consisted of indoor tests with artificial illumination and outdoor tests with ambient solar illumination that were meant to measure complex acoustics with audibly intelligible ground-truth, these being speech and music as measured from the vibration of plate glass. The data sequence that demonstrates the capture of speech was measured indoors with active shop light illumination and with an audible volume ranging from approximately 70-80 dB.

5. Results and Discussion

5.1 Pure Tone Detection

The first series of experiments shown acts to establish the basic detectability of acoustic signals in noise by measuring a sine tone across a plate glass surface being driven by a range of audible amplitudes. Two representative sample experiments are shown in Figure 6 as power spectra for the measured degree of linear polarization measured at 500 Hz. These measurements were driven by a 55 Hz pure tone and at volumes of 80 and 90 dB. The accompanying accelerometer power spectrum is shown in Figure 7 where there is no empirical evidence suggesting that local instrument vibrations had introduced spurious feature detections. For all of the shown experiments, a varying artificial detection threshold of 65 - 70 dB is placed by the ambient acoustic environment.

From these sample results two significant observations may be noted. The first being the degree of linear polarization recovers the driving acoustic tone and this optical measurement is not induced from locally carried vibrations based on the empirical evidence of the instrument accelerometer. The second observation is that by increasing the driving force of the acoustic tone by 10 dB in audible power, the object response increases as is expected from a measured SNR of 4.26 dB to 13.26 dB. For these experiments, we define the measurement of the signal to noise ratio to be the detected peak ± 1 Hz in power as compared to the previous 30 Hz measured on a base-10 logarithmic scale.

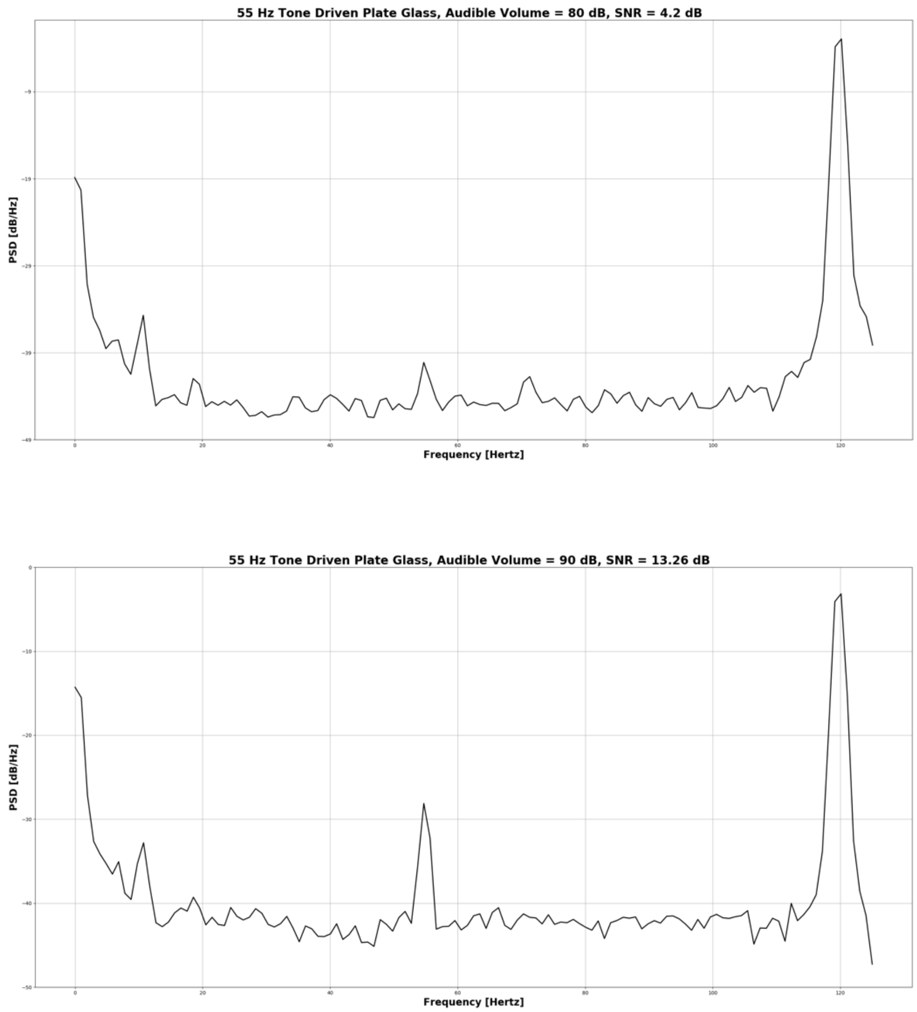

Figure 6. Shown are two power spectra for the measured degree of linear polarization sampled at 500 Hz for plate glass driven at 55 Hz from a nearby speaker at audible driving amplitudes of 80 dB (Top) and 90 dB (Bottom). We note that the 15 Hz and 120 Hz feature are a result of ambient source environment acoustics and AC power cycling respectively.

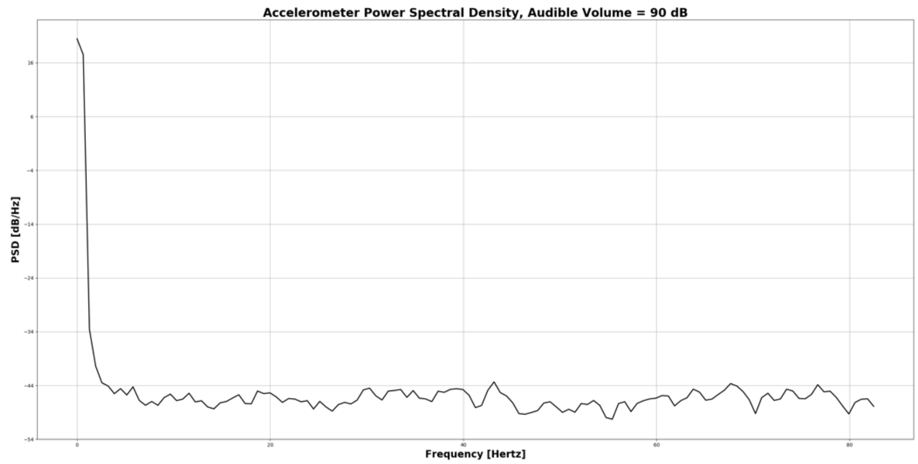

Figure 7. Shown is the spectrum computed from the instrument mounted accelerometer which empirically shows no features corresponding to the 55 Hz driving tone from the experiment. We note the 15 Hz feature is not apparent because the instrument was separated from the machine shop where the source was located.

5.2 Material Signal Response to Changing Acoustic Levels

Several materials were acoustically driven by a 55 Hz tone between the audible ranges of 75 – 95 dB to gauge the measurable polarization signal response to an increase in audible driving amplitude. We show in Figure 8 the results of these experiments for the 55 Hz tone where each material response is approximately linear.

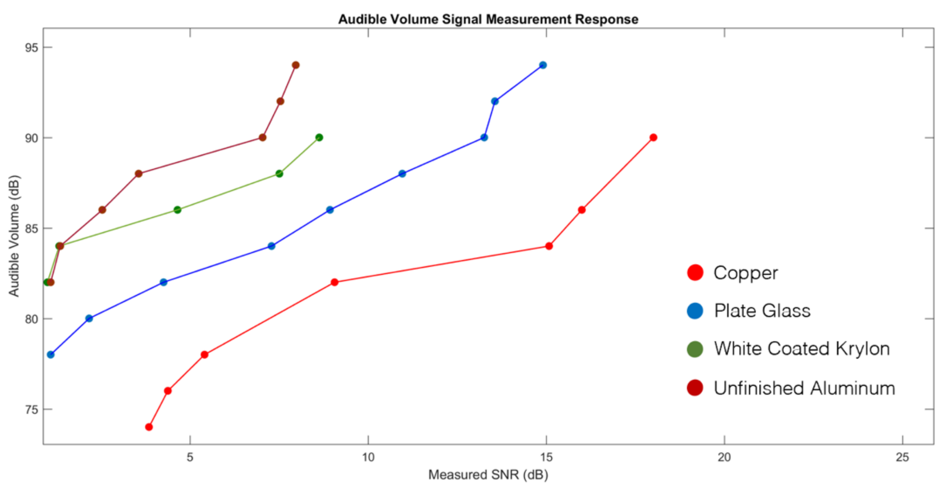

Figure 8. Shown are the measured signal responses to the increase in the audible driving acoustic amplitude. These material responses are measured for four separate materials where each separate response is approximately linear.

This experiment suggests that the response for these materials increases linearly with the increase in driving acoustic amplitude allowing the response to be modelled as a linear shift invariant system [8]. This assumption would allow more complex manipulations of the signal such as Wiener deconvolution for denoising audio and lower frequency infrasounds. This experiment though does not act as a measurement baseline for technique capability. A material's response is a complex function of incidence angle, propagation, mass, excitation response, ambient optical intensity, and the environmental audible detection threshold. Instead this experiment shows only that the measured signals may respond linearly to acoustic input and separate materials have different responses as suggested by the physical analysis.

5.3 Detection of Transient Complex Sounds

Quasi-steady tones sampled over an appropriate time period are readily detected in power spectra, however many interesting acoustic features are transient in time such as speech or the loud impulse of a drum kick. These transient signals if small are difficult to detect in long sampled noisy spectra so instead they may be detected by taking many short overlapping spectra over time in the form of a spectrogram. These frequency space tools show the evolution of acoustic content over time and demonstrate what makes each sound unique visually such as the signal's pitch and timbre. As a case example the same 55 Hz tone with an audible volume of 80 dB from Figure 6 is shown as a spectrogram in Figure 9. In this instance, the 55 Hz tone appears as a constant horizontal feature in the frequency space over time and at a near constant intensity.

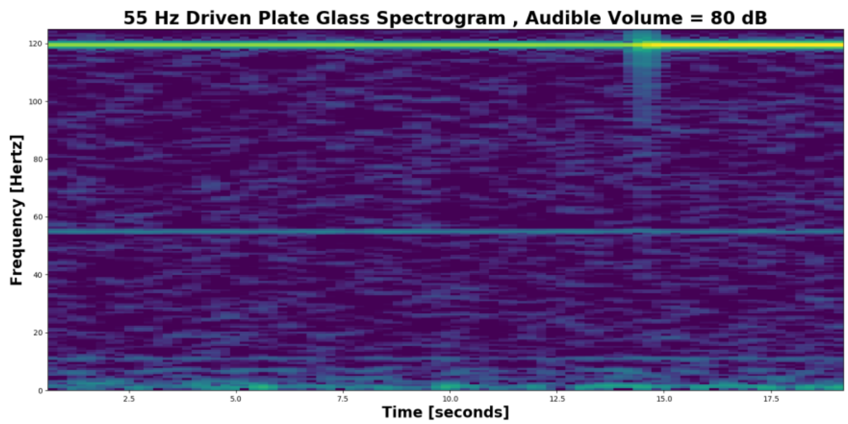

Figure 9. Shown is the 55 Hz driving signal as a spectrogram. The 120 Hz feature results from the 120 AC power cycle of the shop light and the lower acoustic features are a consequence of the experiment's acoustic environment.

The spectrogram also shows infrasound features unique to the experiment acoustic environment where the sources were measured. The fundamental ambient tone imparted from the environment can be seen at 5 Hz and the second and third harmonics are seen at 10 and 15 Hz respectively as weak visual detections. We note these same tones given the separation of source and sensor were not seen in the instrument's local acceleration measurements. This detection of infrasound while not important to the quantitative measurement of technique performance, is an important side note to highlight the applications for detecting minute vibrations imparted from ambient machinery. In this method, the technique is capable of discerning low signal spurious pink noise features from false positive detections in the standalone power spectrum.

The final series of experiments were to detect complex recognizable acoustic content such as recorded speech and music as played in the range of 70-80 dB and across plate glass. Because the instrument controller has an electronic sampling limit of 650 Hz, the recovered frequency content extends only to the Nyquist limit at 325 Hz. The result of recovered speech is shown in Figure 10. The sample input audio was the beginning adlib from Cannonball Adderley's "Mercy, Mercy, Mercy!".

The sample result for the recovery of complex acoustics from the measured degree of linear polarization is shown in Figure 10 (bottom) and the resampled input audio is shown in Figure 10 (top). We note the fully sampled audio was used as the acoustic driving force and Figure 10 has only been resampled for visual correspondence. The measured degree of linear polarization both for audible intelligibility and for feature matching has been processed with separate IIR notch filters placed at 120 and 240 Hz to remove the environmental noise features.

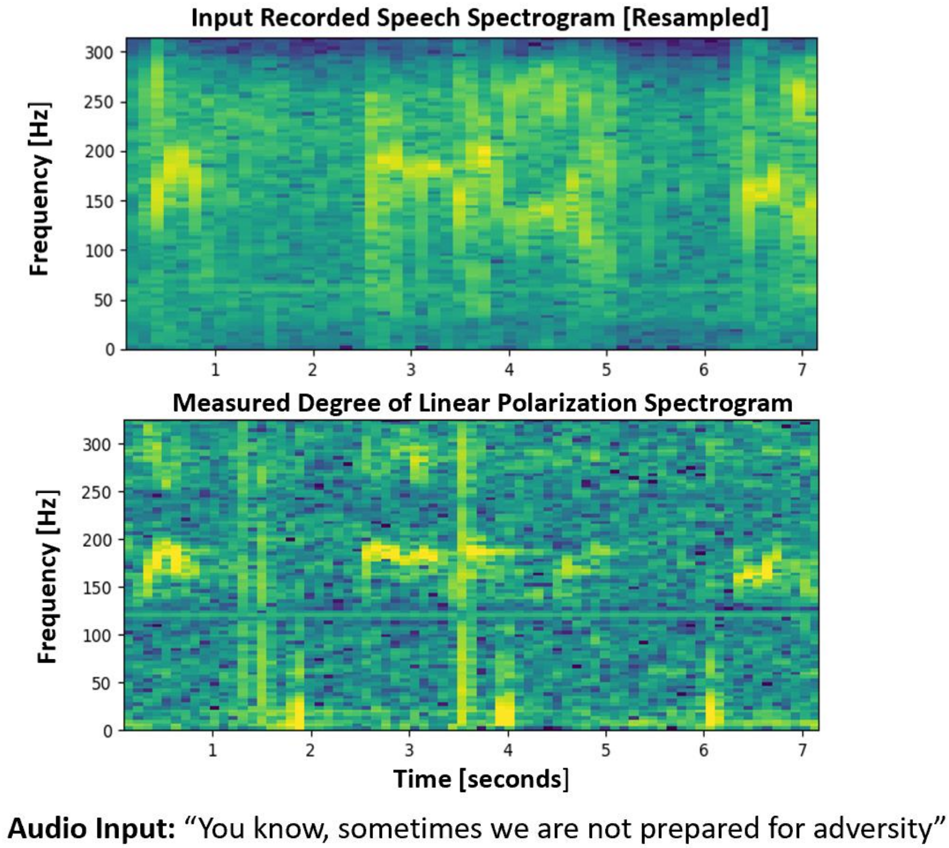

Figure 10. (Top) The input audio has been resampled only for visual correspondence. (Bottom) The measured degree of linear polarization spectrogram is shown to closely correspond to the resampled input audio.

The major observation from this sample experiment is the close visual match of the input speech to the acoustic features that have been measured in the changing degree of linear polarization. The visual complex forms correspond to the lowest harmonic of the speaker's voice and each bright feature corresponds to the slur of spoken words. The instrument's limited sampling rate does not allow for the next harmonic in the speaker's voice to be measured however audibly, acoustic content is still heard. Qualitatively, the vowels in the speech are present, however consonants are more difficult to parse out of context. We note though, that even for lower sampled acoustic spectra, tools such as acoustic feature matching may be used to discern speech and recognize pitch. The vertical features are recognized as signal impulses, or as in the recorded audio the kick of a background drum and audience clapping.

This detection strongly suggests that this technique acts as a valid method to remotely retrieve spoken speech and complex acoustic forms from the vibrations of nearby acoustically driven surfaces. This detection also demonstrates the technique's ability to detect short transient events such as the impulse of a clap or drum which would otherwise be undetected in the standalone power spectra.

6. Conclusions

We have demonstrated that the acoustics of vibrating surfaces may be recovered from measuring the degree of linear polarization as measured by a photodetector at high sampling rates. The recovered acoustics may be quasi-steady such as the tones created by ambient machinery or transient and complex such as those of speech. Analysis of the physical signal shows that these measurements may be made in broadband light and that the viewing geometry is not restricted to specific angles of incidence or observation. The analysis further shows that different materials have distinct responses to the polarization measurement which raises the possibility of material identification in the acoustic signals even of unresolved sources such as geosynchronous satellites.

The experiments conducted have demonstrated recovery of known signals across a wide range of audible amplitudes. Additional sensor acceleration measurements have strongly suggested that motions of the sensor were not propagated into the results. Several materials were shown to act as remote signal carriers each with unique responses which were approximately linear to the increase in driving amplitude. This series of experiments has demonstrated that many everyday surfaces may act as remote and passive microphones for uses in surveillance and that the measurements may be indicative of structural acoustics which may support efforts in space situational awareness.

7. Acknowledgements

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