Vibrometry challenges in measuring motion of faraway objects

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1. ABSTRACT

Vibrometry of objects at extended ranges poses several interesting challenges. Typical vibrometry use has the instrument measuring the motion from a small area over which it can safely be assumed that there is no velocity gradient. This assumption cannot hold true when preforming vibration measurements over the extended ranges involved in terrestrial vibrometry of a satellite. At extended ranges the area over which vibration is being measured could encompass the entire satellite, allowing for significant velocity gradients across the measurement area. In addition to this, there are speckle effects caused by the passage of the measurement beam through the atmosphere. This can result in dynamic preferential illumination of the satellite. This paper explores the viability of recovering meaningful vibrometry data from an object when the measurement beam is of the order of the target size. Additionally, determining if heterodyne systems have utility as tools with which to measure satellite vibration. Included is simulated data with and without atmosphere, and lab data measured with a scaled model. The simulated and experimental results both indicate that full illumination of an object does not preclude vibrometry measurement. Additionally, the simulated data implies that heterodyne systems could be used as long-range vibrometers. The utility of these measurements given the area of the measurement beam at such distances is limited, but the experimental data shown here indicates that different motion modes can be discerned with the beam held static over the target, e.g. in phase vs. out of phase panel vibration. Rastering the beam over the target could allow for vibration measurements of various satellite features individually, despite far field spot size limitations. While further investigation into SNR lower bounds and more rigorous simulation of object motion would better indicate expected performance, all current data indicates that terrestrial measurement of satellite vibration with existing systems could provide meaningful data about the target.

2. EXPERIMENTAL SETUP

The test setup included a commercial Polytec vibrometer, with OFV 353 sensor head and OFV 2601 controller and signal processor. The vibrometer uses a laser-doppler approach with a 1 mW Helium Neon laser sensing out-of-plane velocity from marginally reflective to highly reflective surfaces. Signal quality can be improved by using reflective tape. Typically, the vibrometer is focused to a spot on the surface measured using an onboard, adjustable lens. In this study, an actuated satellite model with reflective tape was designed to investigate the ability of the vibrometer to sense distributed motion of a satellite model. The experimental setup is shown in Figure 1.

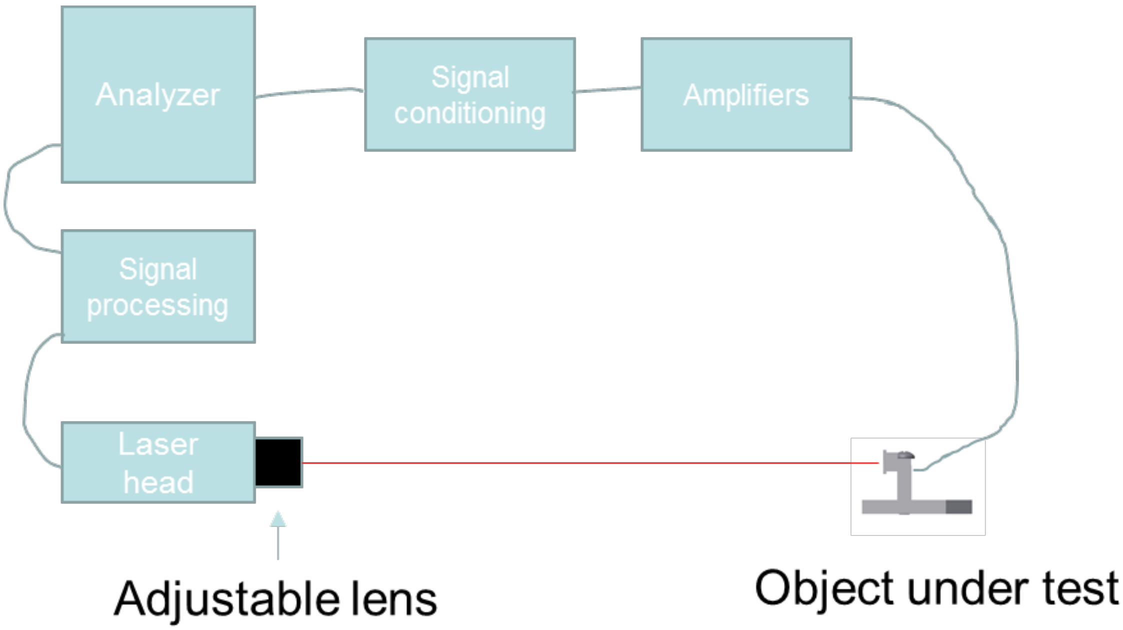

Figure 1 – Experimental setup

In this case, the actuated satellite model was designed to explore quasi-static and dynamic behavior by incorporating piezoceramic actuators in each of the solar arrays along with one in the base. The model was also required to be small enough to be fully illuminated by the vibrometer beam in a defocused condition. This constraint was set by the available space to project the laser beam and the maximum defocus of the adjustable lens. The diameter of the resulting circle of illumination was approximately 2 inches. An illustration along with a photograph of the model are shown in Figure 2, and a dimensioned drawing is shown in Figure 3. The blue components in the illustration in Figure 2 are PI P-883.51 piezoceramic actuator stacks that independently actuate each solar array wing. The orange component actuates the whole model in the direction that is parallel to the laser.

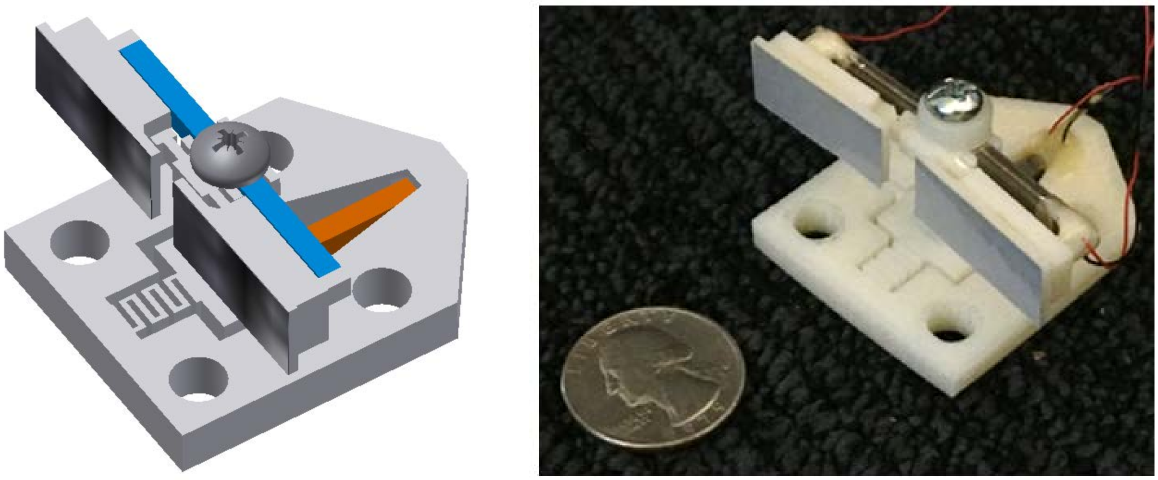

Figure 2 – Illustration and picture of the actuated satellite model

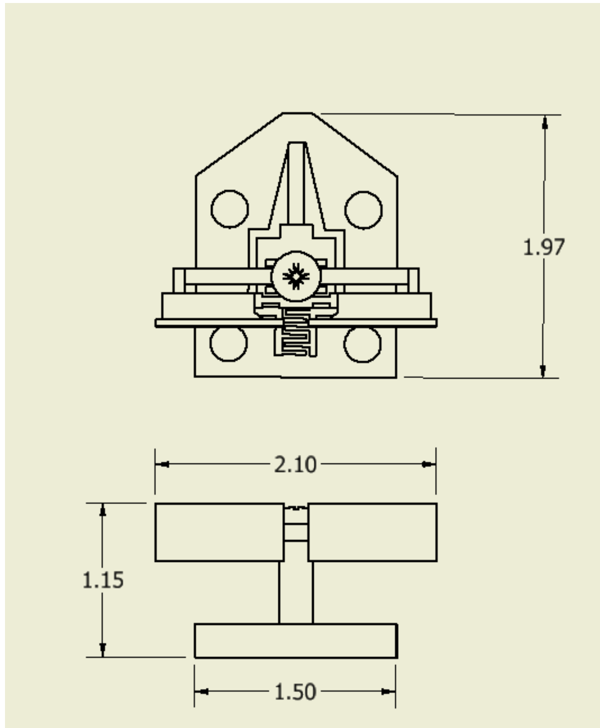

Figure 3 – Dimensioned drawing of actuated model [in]

The input to the actuators was an amplified signal from the analyzer through signal conditioning and a PI E-617 amplifier.

A relatively coarse finite element model was assembled to predict the motion of the model in response to the actuator inputs. Figure 4 illustrates the mode shapes of interest that were predicted by the finite element model. The mode on the left hand side is a symmetric mode where both solar arrays move in phase. The mode on the right is an asymmetric mode where the solar arrays move out of phase.

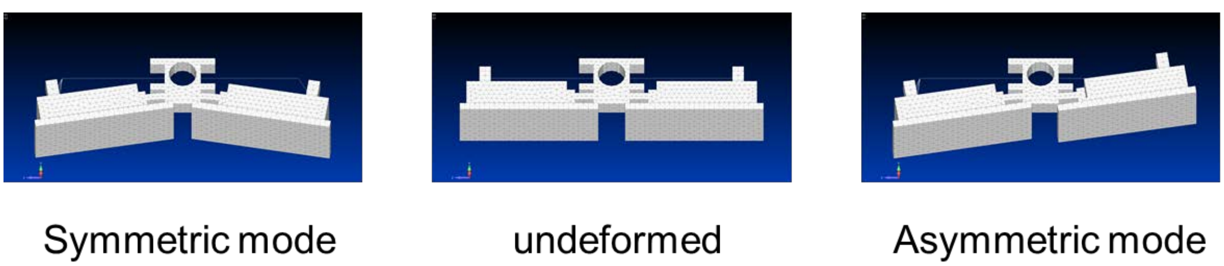

Figure 4 – Mode shapes of interest

3. TEST RESULTS

An example of a point measurement shows the vibrometer focused on the right solar array in Figure 5. Several transfer functions were measured between each of the actuator inputs and the vibrometer output. The same procedure was accomplished with the vibrometer focused on the left solar array and the hub between the solar arrays. All measurements displayed good signal quality and helped to identify the actual frequencies of the predicted modes shown in Figure 4. If you focus on the right solar array of the test article using the vibrometer as a point measurement and drive with the right actuator, you get excitation of symmetric and asymmetric modes as illustrated in the transfer function in Figure 6. Coherence between the output and input was also calculated for each measured transfer function. This is also shown in Figure 6. In this context, coherence shows where the output is linearly related to the input. Where coherence is high, there is high confidence in the transfer function.

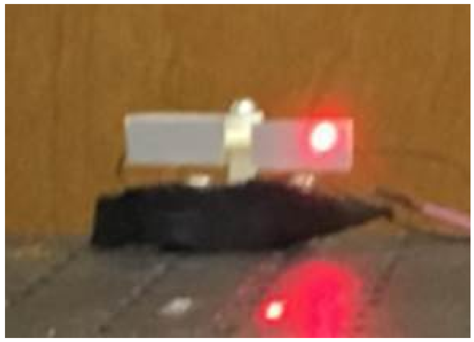

Figure 5- Actuated model with laser focused on the right solar array

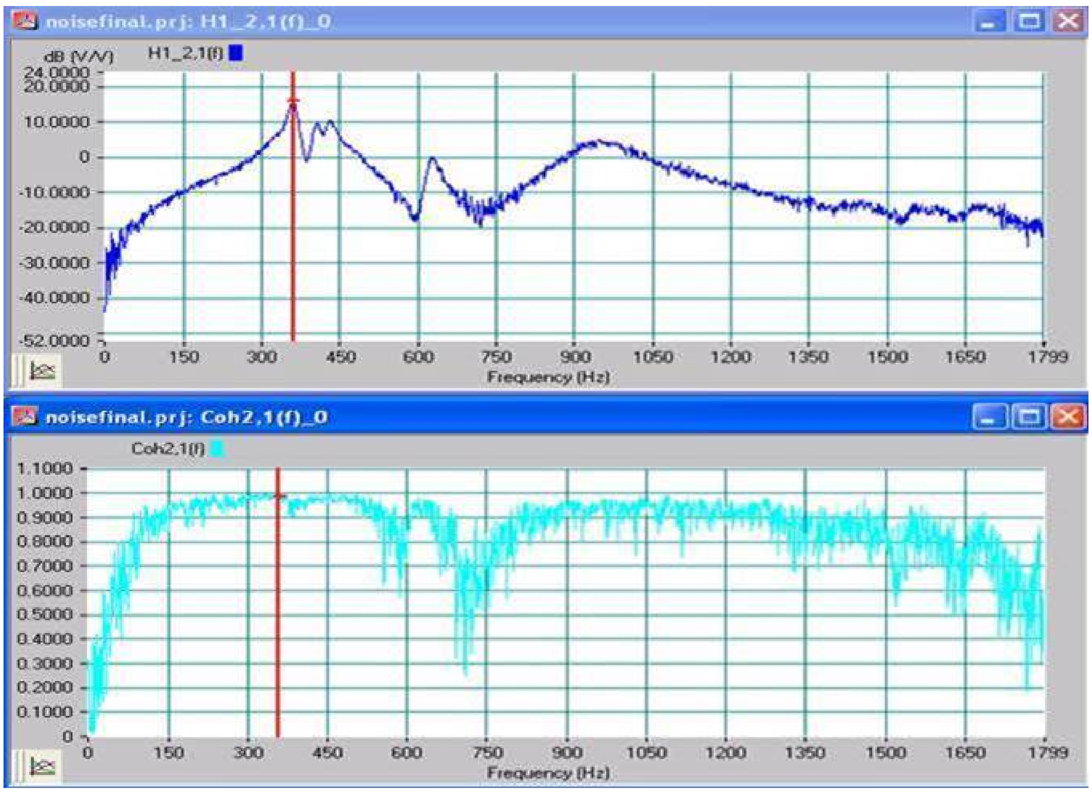

Figure 6 - Transfer function (top) and Coherence (bottom)

In Figure 6, the cursor is on the symmetric mode, meaning both wings flap in phase. At a slightly higher frequency, we see two modes that are likely not symmetric. There is another mode around 1000 Hz that involves a higher order symmetric flapping. When you drive the test article with the same excitation and illuminate the whole thing, you are still exciting the same behavior, but the vibrometer only “sees” the symmetric modes. Figure 7 shows the model fully illuminated and Figure 8 gives the corresponding transfer function and coherence.

Figure 7 – Full illumination of the model

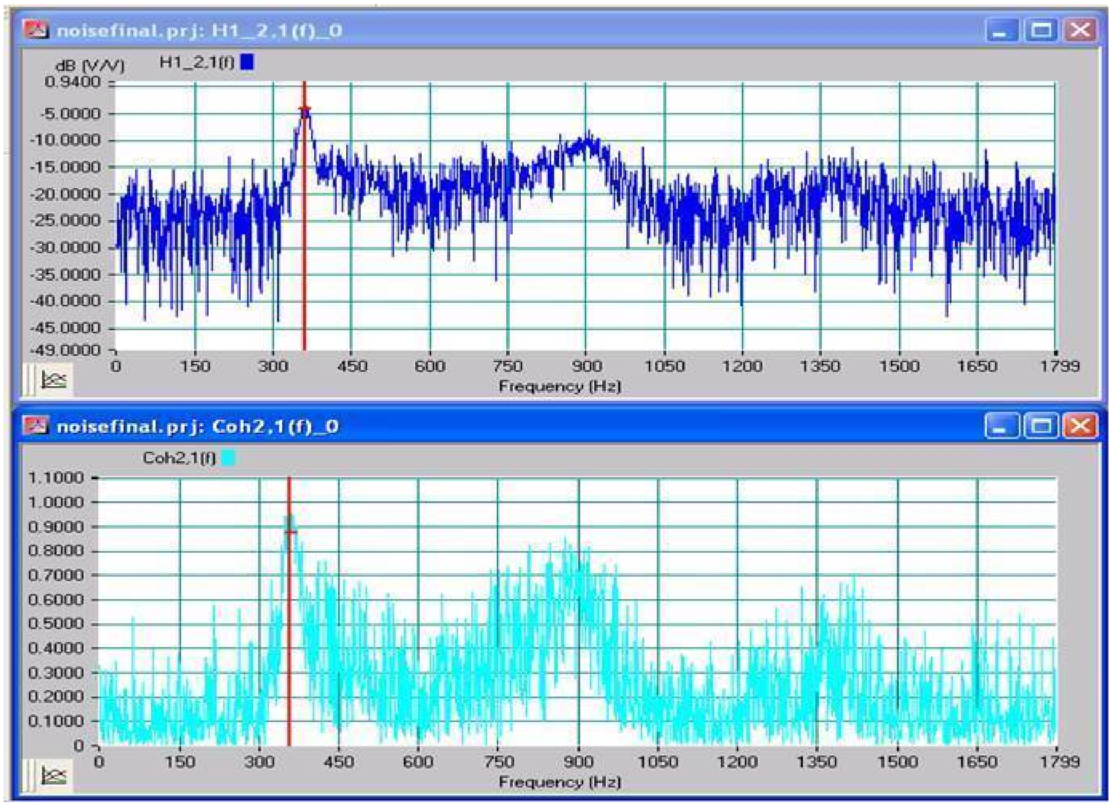

Figure 8 – Transfer function (top) and Coherence (bottom)

At frequencies well below resonance, the same phenomena was observed by driving the wings in and out of phase at 200 Hz as shown in Figures 9 and 10. These figures show the frequency spectrum on the top and the time domain signal on the bottom. In each case, the motion of the solar arrays in the order of 1e-6 m. Figures 9 and 10 clearly illustrate that a fully illuminated vehicle is much less sensitive to asymmetric motion than symmetric motion, whether it is symmetric modes in the case of the transfer function and coherence measurement or quasi-static motion.

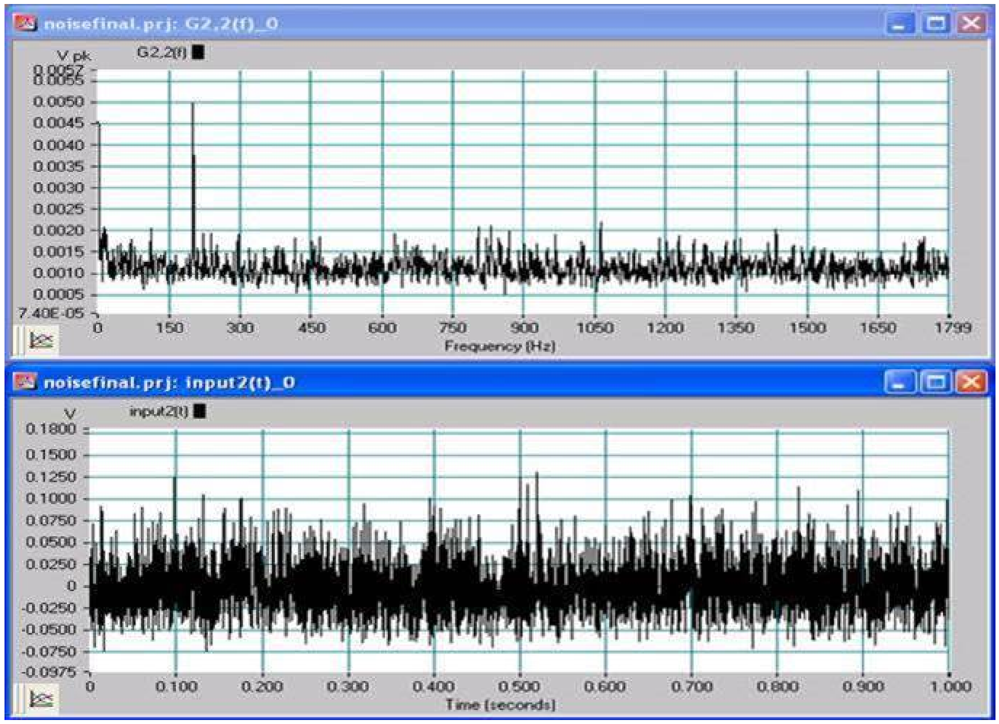

Figure 9 – Full illumination with both solar arrays actuated in phase: Frequency (top), Transient (bottom)

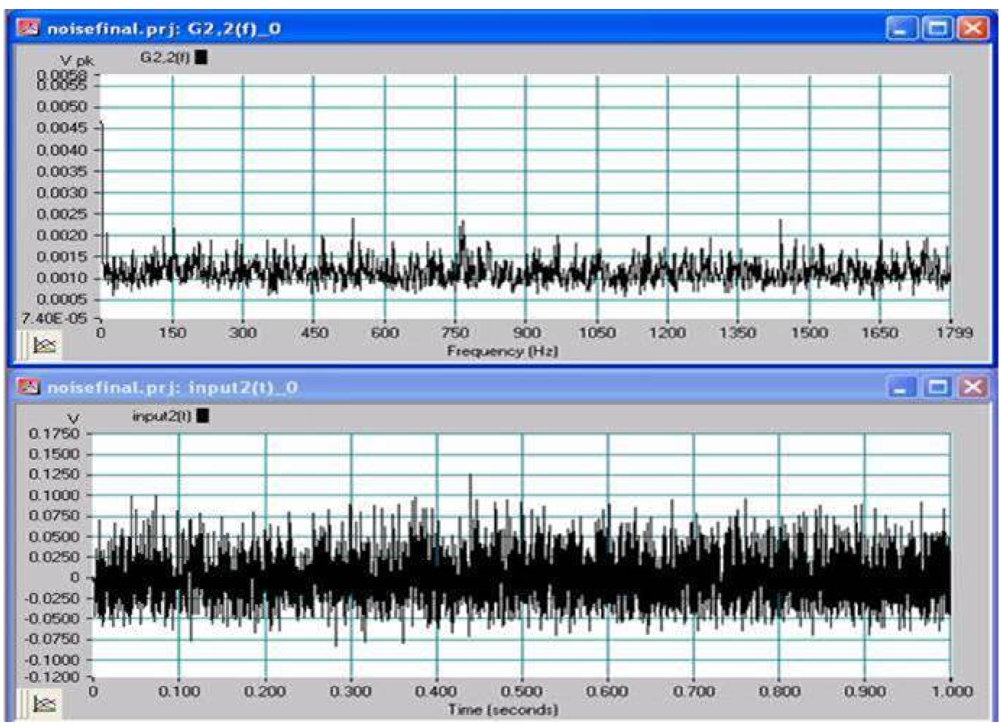

Figure 10– Full illumination with both solar arrays actuated out of phase: Frequency (top), Transient (bottom)

4. SIMULATION

A preliminary simulation was performed using a rendering of a satellite given simple sinusoidal motion with a frequency of 2Hz. The magnitude of the target motion was scaled to be representative of real satellite motion, however the motion as represented is a rigid body where the distance to the detector is varying in a sinusoidal manner. This is similar, but not identical to the 'in phase' case looked at experimentally (Figure 9). Velocity as a function of time was calculated from the signal return from this render as it would be seen on a heterodyne receiver with and without certain degrading effects (Figures 11 and 12). The simulation includes approximations for atmospheric degradation, speckle variation, and detector noise. The vibration frequencies used for the simulation and the experiment are different, however the 200Hz chosen for the experiment is much lower than the resonant frequency of the physical model, meaning that there is little to no difference in model motion for 2Hz and 200Hz. The velocity profile for the pristine signal (pristine meaning with only speckle variation considered) is shown in Figure 11.

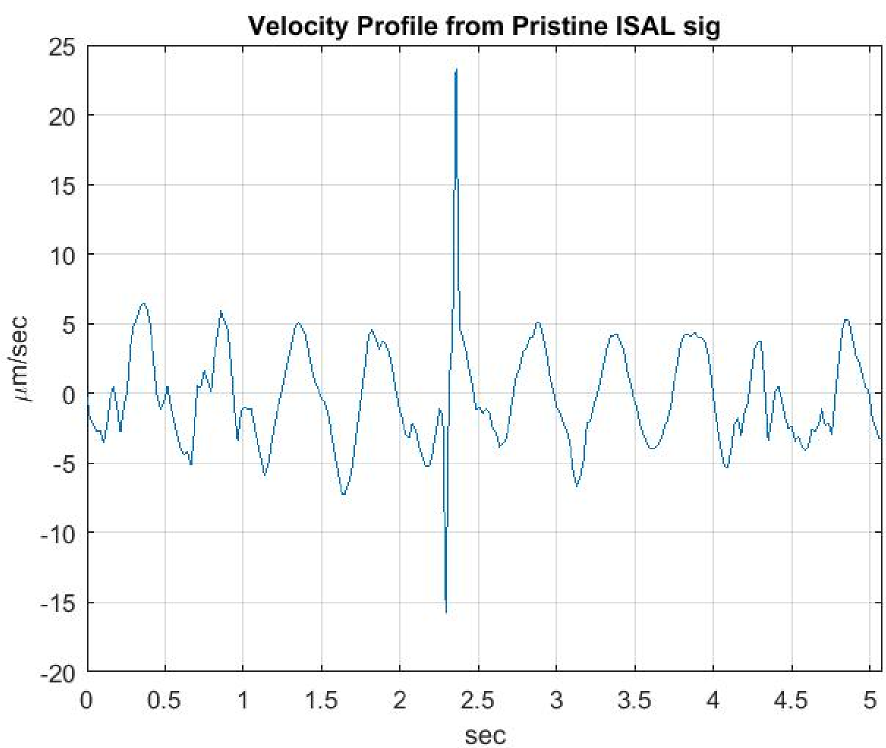

Figure 11 – Velocity Profile from signal considering only speckle effects.

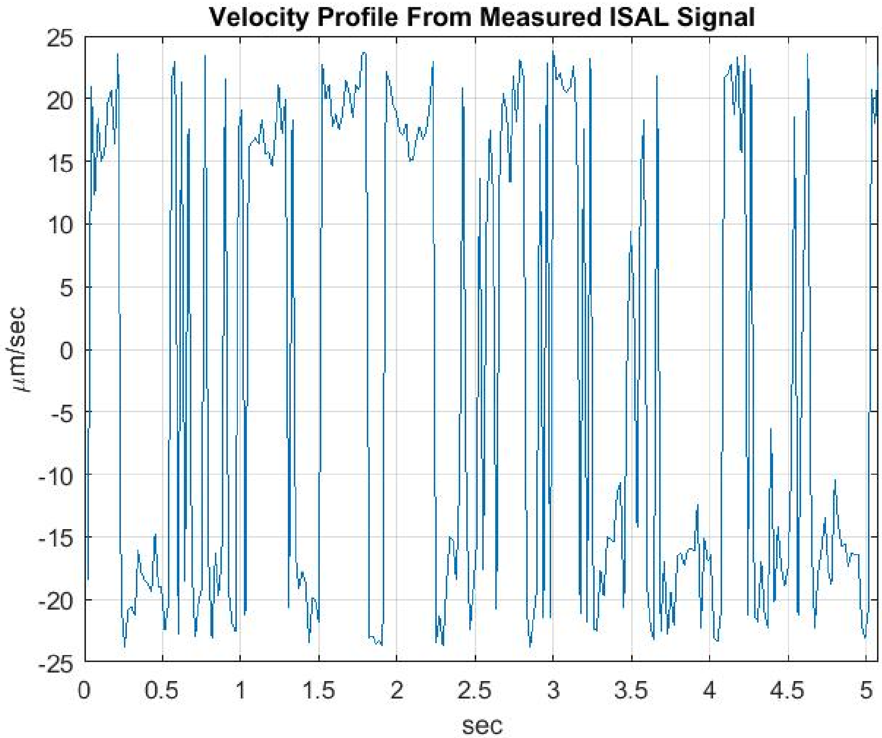

Figure 12 – Velocity profile from measured ISAL signal, includes atmosphere, speckle, and detector noise effects.

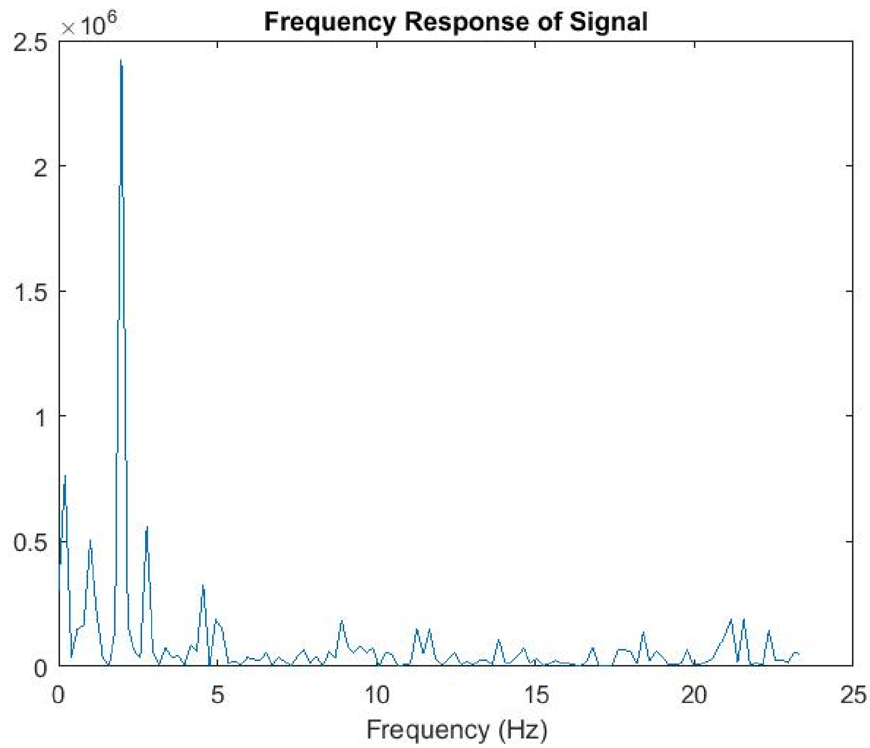

Figure 13 – Frequency content of velocity profile of measured signal. Note the strong peak at 2Hz.

It is very apparent in Figure 11 that there is a 2Hz oscillation in the signal. It is also apparent that the speckle variation is degrading the signal. Figure 12 is less clear. There is little visual evidence of the 2Hz sinusoidal target oscillation, however when the frequency content is examined (Figure 13) it retains a strong peak at 2Hz. From the simulated data it appears that the noise added to the signal due to transit through the atmosphere and measurement by the detector are insufficient to completely disguise the motion of the fully illuminated target.

5. Conclusions

The simulated and experimental results both indicate that full illumination of an object does not preclude vibrometry measurement. Additionally the simulated data implies that heterodyne systems could be re-purposed as long-range vibrometers. The utility of these measurements given the area of the measurement beam at such distances is limited, but the experimental data shown here indicates that different motion modes can be discerned with the beam held static over the target, e.g. in phase vs. out of phase panel vibration. Rastering the beam over the target could allow for vibration measurements of various satellite features individually, despite far field spot size limitations. While further investigation into SNR lower bounds and more rigorous simulation of object motion would better indicate expected performance, all current data indicates that terrestrial measurement of satellite vibration with existing systems could provide meaningful data about the target.