Development of the Dust Ejecta Radar Technology (DERT) to Determine Plume-Surface Interaction Ejecta Velocities on Planetary Surfaces

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***Abstract*— Here we present a novel use of millimeter wave doppler radar to measure the velocity of ejecta generated by the impingement of rocket plumes on a planetary surface. The Dust Ejecta Radar Technology (DERT) provides a unique dataset based on direct measurements of ejecta particle velocities during plume-surface interactions. DERT is a continuous wave (CW) 94 GHz radar unit that is being developed at Kennedy Space Center. DERT has measured velocities of a pendulum (~1 m/s), a rotating strip (60 m/s), projected regolith simulant BP-1 (~250 m/s) and rifle rounds (~820 m/s). Signal-to-Noise Ratios of up to 60 dB have been demonstrated. Data collected from DERT will inform the development of high-fidelity computational models of plume-surface interaction effects and will help address NASA Strategic Knowledge Gaps related to characterizing entry, descent and landing effects, and the risks associated with high-speed ejecta on the lander and lunar surface assets.**

Keywords—doppler radar, millimeter wave doppler radar, plume-surface interaction, plume-surface interaction ejecta, 94 GHz doppler radar

I. INTRODUCTION

Within the next decade, NASA plans to land astronauts on the surface on the Moon to explore more of the lunar surface than ever before. Longstanding human exploration and habitation plans for the lunar surface will require multiple landings and launches on the lunar surface in order to transfer equipment, supplies, and personnel between Gateway and the lunar surface. During descent and landing, a lunar lander's rocket exhaust plume will interact with surface regolith causing cratering and the generation of a stream of high-speed, abrasive particles. Depending on their speed and trajectory, the ejecta may pose risks to both nearby and distant surface assets. The speed of the ejecta particles may even be sufficiently large to inject them into lunar orbit where they would potentially risk orbiting assets. The subsequent ascent from the lunar surface may also produce plume surface interactions (PSI) that result in an ejecta stream. Therefore, risks associated with ejecta from plume-surface interactions must be better understood so that these risks can be mitigated.

The only data that exists on extraterrestrial ejecta velocities are from video footage of the Apollo lunar module landings. Analysis of the footage has indirectly estimated and modelled particle velocities >2 km/s from PSI [1] [2]. Such particles can impact any lunar latitude and can reach lunar altitudes that could intersect with objects in low-lunar orbit [3]. High-speed PSI ejecta pose a significant risk to lunar surface assets due to impact energy/flux and abrasive blasting effects [4]. Risk assessment requires knowledge of PSI ejecta particle size, velocity, and density. However, to-date, there has yet to be any direct measurements of particle velocities accelerated by PSI. DERT provides a unique dataset based on direct measurements of ejecta particle velocities during PSI, which will help inform risk assessments associated with impacts by high-speed PSI ejecta particles. The PSI data obtained by DERT will also inform the development of high-fidelity computational models of PSI effects and will help address NASA Strategic Knowledge Gaps

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related to characterizing entry, descent and landing effects, and the risks associated with high-speed PSI ejecta.

Here we present how Dust Ejecta Radar Technology (DERT), a 94 GHz millimeter wave doppler radar (MWDR), can be used to measure accelerated regolith particle velocities represented as a flight concept in Fig. 1. Our recent advances in the technology readiness level of such instrumentation for future lunar landers will also be presented.

II. METHOD

MWDR was originally proposed to measure the velocity and particle mass flow of rocket plumes by Youngquist and Starr [5]. MWDR has applications as landing radar, imaging, remote sensing, automotive radars, military and space applications, airport security screening, and telecommunications, to name a few. MWDR has also been used to study sand- and dust-storms [6], and dust devils [7]. It is currently being used by CloudSAT in the C-train Constellation in Earth orbit to study cloud abundance, distribution, structure and radiative properties [8].

Millimeter wave doppler radar works by transmitting RF waves that scatters off objects where the return signal's frequency is shifted in proportion to the velocity of the objects. Smaller particles (< 300 μm) are expected to have velocities from 0.1 – 2.5 km/s and are in Rayleigh Scattering regime ($D < 0.1\lambda$) [2]. The signal strength received depends upon particle diameter, index of refraction, particle count along the radar cone (mass flow rate from plume) and the physical parameters of the radar itself. The analog voltage received from the down converting heterodyne mixer is sampled, and then transformed into the frequency domain. Bulk velocity data are limited to returned signals that are sufficiently above the Noise Floor (~10dB Signal-to-Noise Ratio (SNR)) and frequency data that is not derived from known interference: i.e. backgrounds and vibrations, instrumentation artefacts, RF spurs, etc.

The MWDR instrument used for this work is a 94 GHz Continuous Wave (CW) radar with a Voltage Controlled Attenuator (VCA) that allows for a max transmit power of 24.5 dBm. Fig. 2 is a block diagram of our radar configuration built

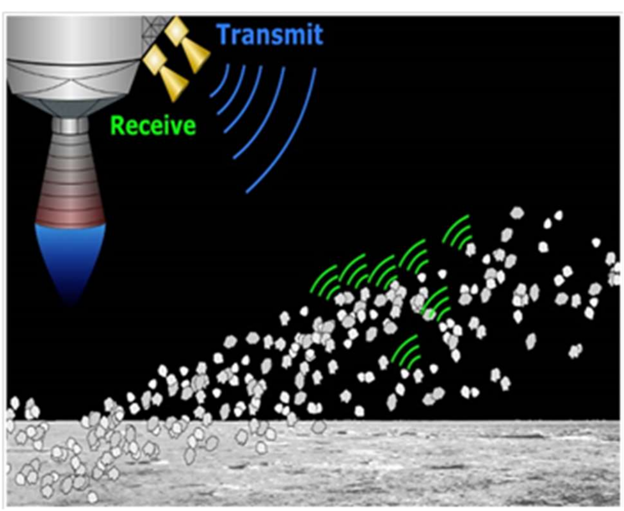

Fig. 1 The DERT flight instrument design concept

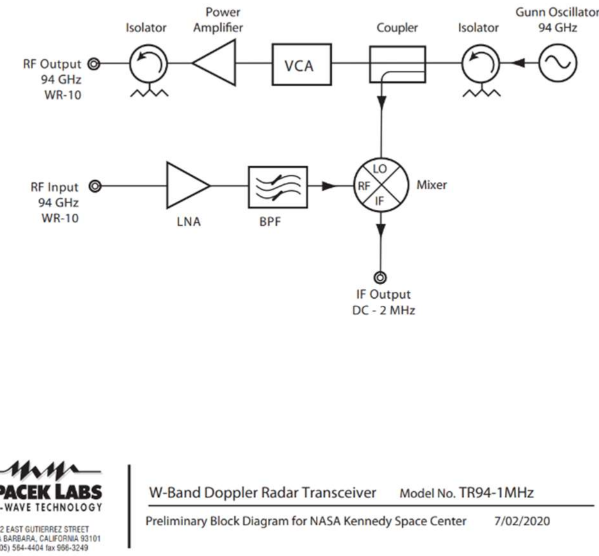

Fig. 2 The DERT instrument prototype unit used in this work; a custom vacuum compatible 94 GHz CW doppler radar unit built by SpaceK

by SpaceK Labs. Frequency spectrums have been generated with a Swept-Tuned Signal Analyzer, Real-Time Spectrum Analyzer and signal processing in the time domain. The data presented in this paper was produced by a Keysight N9020B Real Time Signal Analyzer with Noise Floor Extension hardware.

III. RESULTS

A. Pendulum and DC Motor Tests

To independently asses the accuracy of DERT, two well-known dynamic systems were chosen for calibrations: a pendulum, for simple harmonic motion, and rotating fixtures on a DC motor, for circular motion. In both cases, the dynamics can be derived from first principles, and the actual dynamics can be recorded with a high-speed camera (HSC).

In the pendulum setup, DERT is oriented in the direction of motion of a metal sphere attached to fishing line with the HSC perpendicular to the direction of motion with a ruler in sight. The HSC recorded images looking straight on the ruler and imaging the pendulum from the side, in order to image the full swing of the pendulum. DERT was placed at a 90° angle to the HSC and measured the velocity of the pendulum as it swung towards and away from the instrument. Fig. 3 is a plot of the velocity of the pendulum measured by both DERT and the HSC. The plot shows that the two independent measurements of the pendulum velocity are in excellent agreement with each other. The result of this pendulum test confirms that DERT is measuring the correct velocities up to 1.3 m/s.

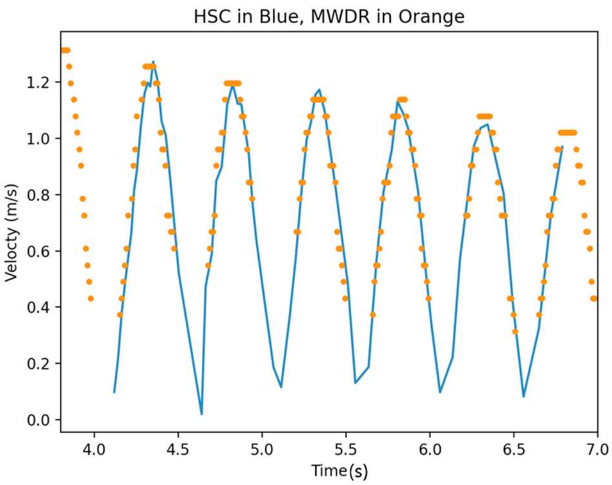

Fig. 3 HSC measured pendulum velocity compared to the MWDR measured pendulum velocity.

For the DC motor tests, a DC motor and an RF transparent strip of paper with two separately placed aluminum reflective targets were used to create controlled, circular motion. DERT and the HSC both viewed the DC motor setup from the side, and from a 90° angle from each other. Fig. 4a shows the DC motor setup images obtained by the HSC and the DERT spectrum analyzer waterfall graph. The length of the tape was measured and the HSC was set to a target frames-per-second (fps) that was well above the minimum required by the Nyquist-Shannon Sampling theorem. The number of frames that it took the piece of tape to complete one revolution to reach its longest length in the perpendicular orientation to the HSC was noted. The velocity of the outer edge of the tape was then calculated based on the period and radius of the tape. The DERT frequency data was then interpreted as a spectrum of velocities of up to 60 m/s with two distinct signal peaks. When these frequency data are observed on the spectrum analyzer waterfall graph, shown in Fig. 4b, it is apparent that the highly reflective areas on the piece of tape correspond to the higher signal return areas in the waterfall graph and the velocity shift and distribution is visible. This well-known dynamic system aided in verifying DERT velocity measurements in laboratory conditions up to 60 m/s. Therefore, this data combined with the pendulum data, validates DERT velocity measurements for low velocity particles in laboratory conditions.

B. *Kennedy Space Center Regolith Test Bin Tests*

The next results for testing DERT consist of tests using much higher speed projectiles and tests using Black Point 1 (BP-1) lunar regolith simulant. Tests were conducted in the Regolith

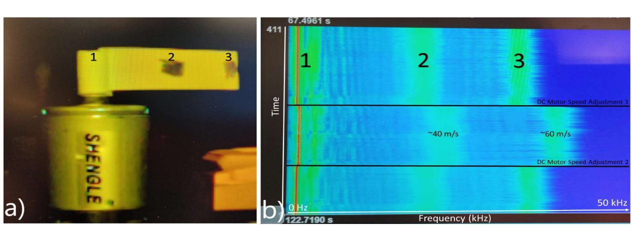

Fig. 4 a) HSC image of DC motor test setup and b) spectrum analyzer waterfall image of DC motor test with two targets

Test Bin at Kennedy Space Center to compare signal strengths with sieved lunar regolith simulants. The setup for these experiments consists of the MWDR focal point aiming directly at the exit of our regolith ejecta stream nozzle. The lunar regolith simulant, BP-1, was sieved into three different particle size ranges; (75-212 µm , 212-355 µm, and 500-850 µm). Unsieved BP-1 was also used for comparison. BP-1 is made up of approximately 50% fine particles (<75 µm) with a bulk density of 1.43 g/cm^3 to 1.86 g/cm^3 [9]. Before each test, the shop air was turned on for approximately 15 seconds to ensure there was no leftover regolith from previous runs. For each sieved simulant, three different volumes of regolith (5, 10, and 15 cm^3) were poured immediately into the funnel/eductor system with the shop air supply turned on.

Fig. 5 compares a.) signal strengths and b.) velocities measured by DERT of the three different sieved BP-1 particle size ranges. Table 1 shows the maximum recorded signal strengths in dBm compared to the sieved particle size range. There is a correlation between the sieved particle size range and back scattered signal strength. Stronger signals are expected from larger particles, though the dispersion of the particles in the flow will alter signal strength. The results indicate more data

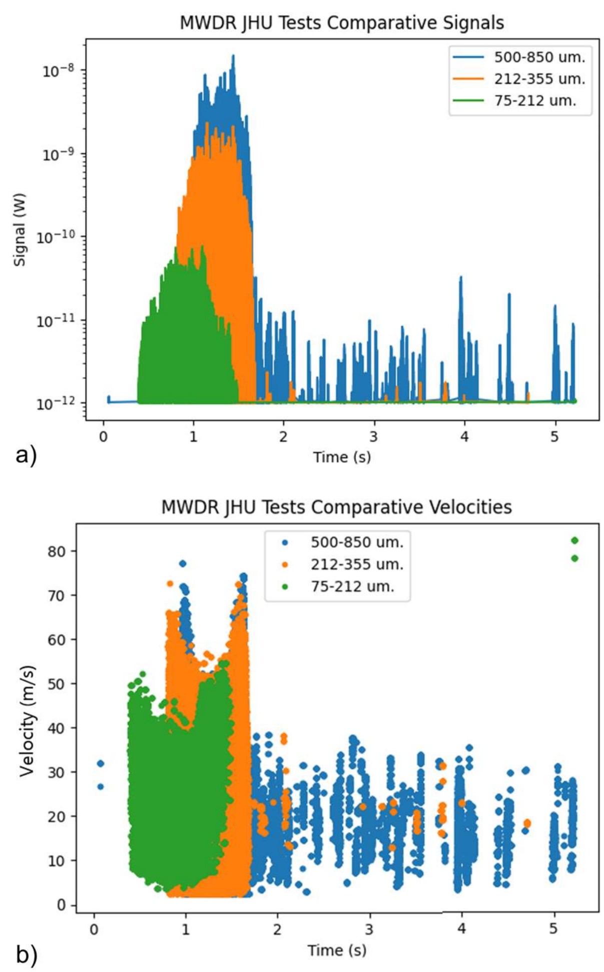

Fig. 5 Kennedy Space Center Regolith Test Bin eductor test results comparing a) returned signal strengths and b) velocities of sieved BP-1 lunar regolith simulant.

Table 1 Kennedy Space Center Regolith Test Bin eductor test peak signal strength compared to particle size of sieved lunar regolith simulant BP-1.

Background	-92
Full PSD BP-1	-60
500-850 µm BP-1	-48
212-355 µm BP-1	-56
75-212 µm BP-1	-71

points are needed to determine the relationship between signal strength and particle size. Regolith particle velocities of up to ~65 m/s were recorded during this experiment. Therefore, DERT has been validated for lunar regolith simulant particle speeds of up to 65 m/s in laboratory conditions.

C. Johns Hopkins University Tests

Testing was performed at Johns Hopkins University's (JHU) Whiting School of Engineering to determine the concentration sensitivity of DERT using various particle types, velocities, and concentrations. The JHU test setup consisted of JHU's steady-stream particle ejector, to generate a steady stream of particles, JHU's HSC shadowgraph setup, to measure the particle concentration and velocities, and the DERT instrument, to measure the particle velocities and determine the instrument concentration sensitivity.

Fig. 6 shows the results of the JHU tests of particle concentration, total number of DERT signal detections, and particle type. The results show a lower limit to the detection ability of small (<75 µm) BP-1 particle sizes, regardless of the particle concentration, as well as a decreased sensitivity to small (<70 µm) glass bead particle sizes, with particle concentrations <1000 cm^{-3}. However, the results show that DERT can adequately detect both glass beads and BP-1 particles of sizes >125 µm of various concentrations. Additional testing is planned to determine the DERT instrument's detection cut off limit for BP-1 of various particle sizes using the Lunar Regolith Ejecta Simulator (LuRES), currently in development by the Kennedy Space Center team.

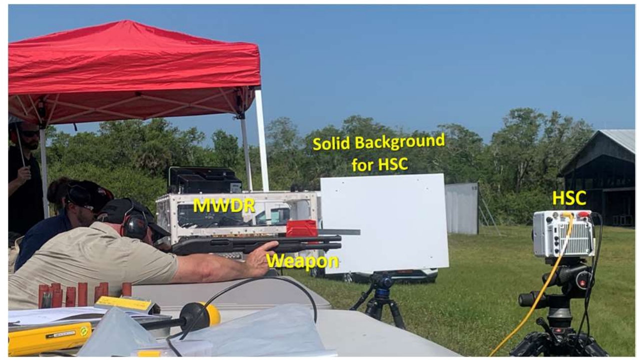

Fig. 7 DERT high speed projectile validation test setup at the Kennedy Space Center Weapons Training Area

D. Kennedy Space Center Weapons Training Area Tests

In order to get closer to validating DERT for PSI ejecta purposes, higher speed particles were needed for testing. This led to testing at Kennedy Space Center's Weapons Training Area. In May 2022, small arm projectile velocities were measured using DERT and the HSC. The test setup for these experiments are shown in Fig. 7. A solid, white background was placed behind the muzzle of each weapon, parallel to the direction of the muzzle, to provide a solid, high contrasting background for the HSC. DERT with the 35 dBi antennas was directed parallel to the muzzle, approximately 4 inches away from the transmitting antenna. The field of view, in the direction of the projectile, of the HSC is about 780mm. However, the DERT instrument range is about 25 meters in front of the antennas, based on the amount of signal that was above the noise floor. Various projectiles were used, including a 1 oz. rifled shotgun slug, 5.56mm NATO rounds, 00 Buck Shot, Winchester \# 8 Bird Shot, shell-loaded BP-1 and shell-loaded sieved BP-1 (212-355 µm). For the purposes of this paper we will discuss the results from the 5.56mm NATO round and the shell-loaded BP-1.

In Fig. 8 the DERT measured velocities from all the 5.56 NATO round tests are displayed. The graph clearly shows that

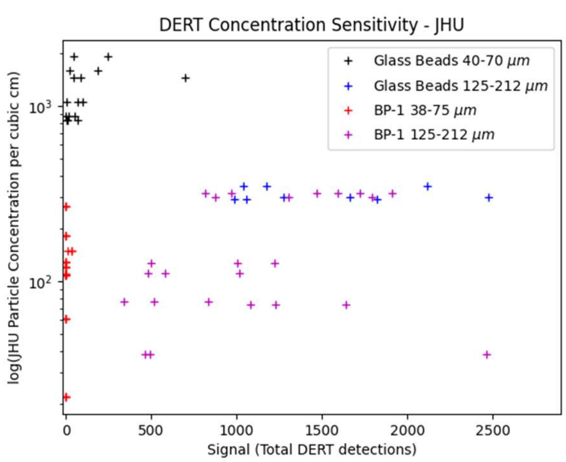

Fig. 6 JHU test results showing DERT's concentration sensitivity using BP-1 and glass beads of various sieved particle sizes

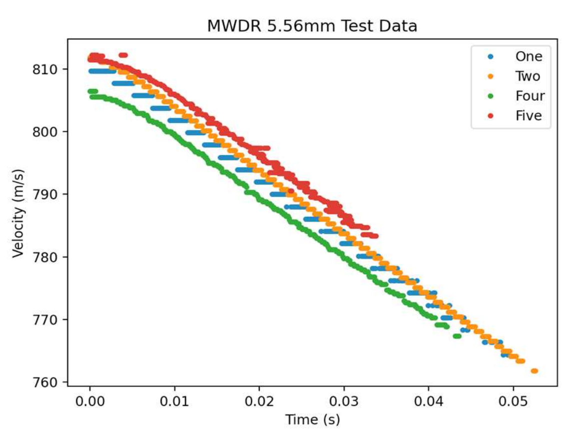

Fig. 8 Four different test runs to measure the velocity of the 5.56 mm NATO round using DERT with four bandwidths, resolution bandwidths, and acquisition times

the velocity of each round follows a similar trajectory. For each round that was fired, a different acquisition time was set on the spectrum analyzer so that the team could compare results. The variations in each signal due to the different acquisition times are apparent. It was observed from analyzing the spectrum data that there was a precession in the bullet throughout the entire measurement period. This precession, or "wobble", can be seen in the test "Four" data set in Fig. 8. To verify that DERT was accurately measuring velocities at these high speeds, the HSC was used to validate the velocity measurements of the 5.56 NATO round. This HSC data measures the velocity of the 5.56mm NATO round to be 820 m/s +/- 20 m/s. Fig. 9 compares the HSC and the DERT measured velocities of the 5.56 NATO round. This experiment verified the DERT velocity measurements for metallic projectiles of velocities up to 820 m/s.

After a single particle, high speed baseline was established with the 5.56mm projectile, both unsieved BP-1 and sieved BP-1 were loaded into separate shotgun shells for testing. Fig. 10 displays a portion of the data collected from firing the unsieved BP-1 shotgun shell. The data collected represents velocities of BP-1 measured at up to 250 m/s during a 10 ms window at SNRs of up to 40 dB. Fig. 10c figure depicts the rapid deceleration of regolith particles due to atmospheric drag. Therefore, DERT has been shown to be capable of measuring the velocity of lunar regolith simulant up to 250 m/s in laboratory conditions. It is important to note here that the HSC data from the BP-1 regolith firing contained too much source confusion due to the large cloud of particles and no direct dynamical comparisons with a single particle could be made.

IV. Conclusion

A millimeter wave doppler radar instrument for measuring PSI ejecta velocities has been developed. The instrument has acquired velocity data that has been validated by comparison to high-speed camera data of well understood pendulum motion, known radial velocity of a DC Motor, high speed velocity of metallic projectiles, and low speed velocity of regolith particles. As opposed to generating artificial frequencies for DERT to 'measure' for instrument validation, we used the high-speed camera data for independently verifying the velocities of the physical systems that were used as test cases. Velocities of up to 820 m/s have been verified with solid metal projectiles and velocities up to 250 m/s have been verified with a lunar regolith simulant (BP-1). Sufficient Signal to Noise Ratio's (SNR) of up to 60 dB have been demonstrated with our DERT radar system. Our future work for DERT is to advance the TRL of the instrument by testing in vacuum environments and with hot fire PSI testing in a large vacuum chamber at Langley Research Center, and validating DERT velocity measurements up to ~2,000 m/s at NASA's White Sands Test Facility. Additionally, the team at Kennedy Space Center is developing a Lunar Regolith Ejecta Simulator (LuRES), which will allow the team to further determine the DERT instrument's sensitivity and the desired data acquisition parameters using various particle materials and concentrations, for velocities up to 10 m/s. Our team is also looking for potential flight ready COTS avionics units for data capture and storage. Furthermore, extraterrestrial landers that will implement millimeter wave doppler radar as a landing radar would be an ideal opportunity to integrate DERT as an additional receiver chain on to a landing radar unit. In conclusion, this work informs the community of a technology capability of determining the velocity of PSI ejecta, and possibly the ejecta kinetic energy. Velocity and kinetic energy of PSI ejecta must be a well characterized parameter if we are going to have a sustained presence on the Moon or Mars.

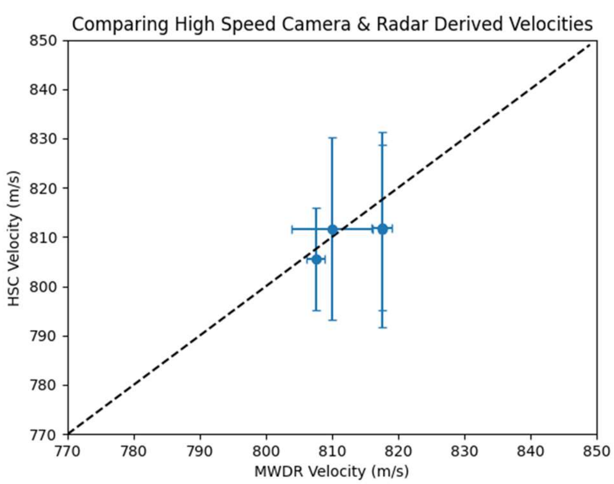

Fig. 9 Comparison of the HSC measured and the DERT derived velocities of the 5.56 mm NATO round

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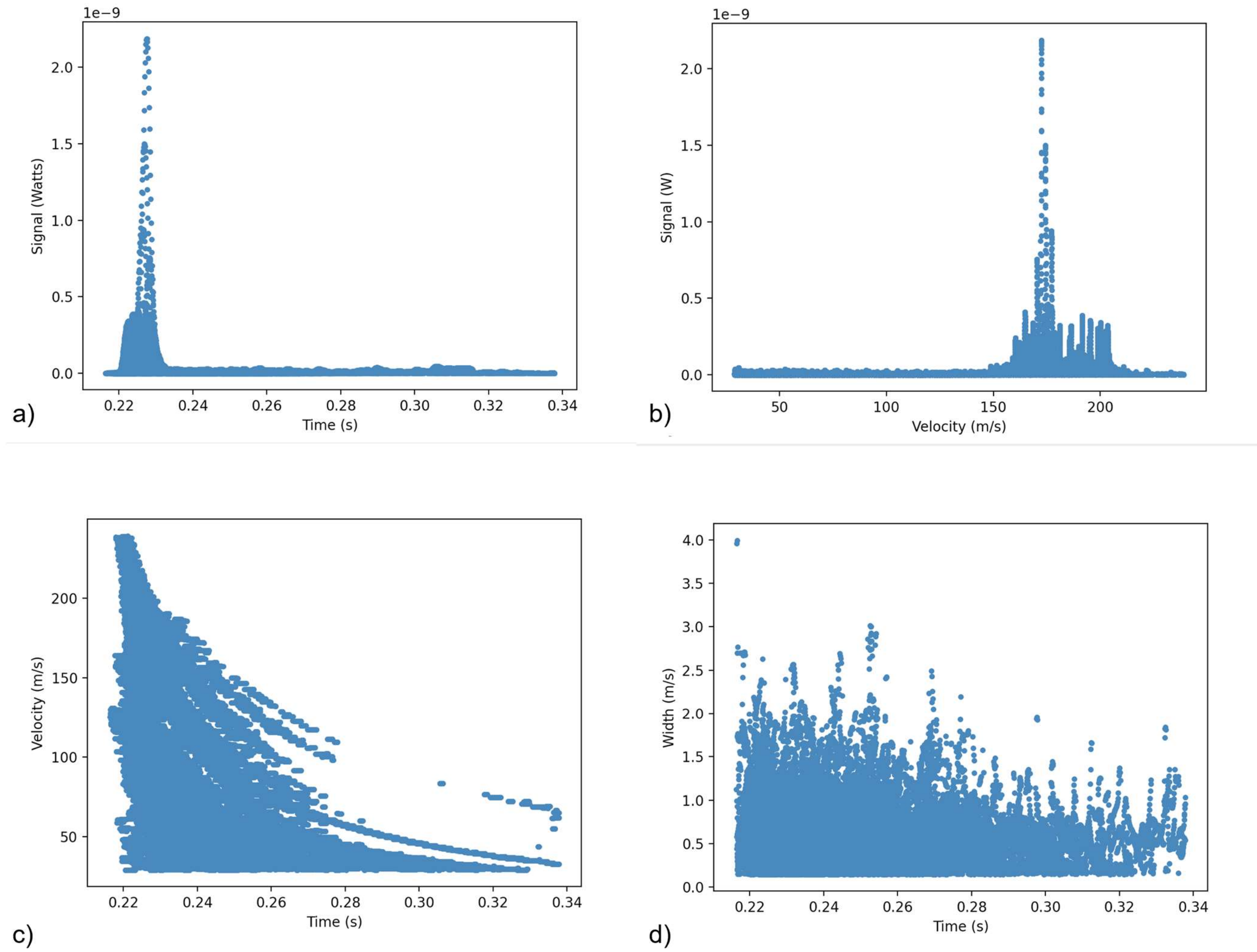

Fig. 10 DERT measured results from the shell-loaded BP-1 shotgun test; a) signal strength versus time, b) signal strength versus measured velocity c) measured velocity versus time d) fitted peak width (FWHM of the fitted velocity peak) versus time