

650 GHz bistatic scattering measurements on human skin

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ABSTRACT

Many groups are developing submillimeter cameras that will be used to screen human subjects for improvised explosive devices (IEDs) and other threat items hidden beneath their clothing. To interpret submillimeter camera images the scattering properties, specifically the bidirectional scattering distribution function (BSDF) must be known. This problem is not trivial because surfaces of man-made objects and human skin have topographic features comparable to the wavelength of submillimeter radiation - thus simple, theoretical scattering approximations do not apply. To address this problem we built a goniometer instrument to measure the BSDF from skin surfaces of live human subjects illuminated with a beam from a 650 GHz synthesized source. To obtain some multi-spectral information, the instrument was reconfigured with a 160 GHz source. Skin areas sampled are from the hand, interior of the forearm, abdomen, and back. The 650 GHz beam has an approximately Gaussian profile with a FWHM of approximately 1 cm. Instrument characteristics: angular resolution 2.9° ; noise floor -45 dB/sr; dynamic range > 70 dB; either s or p-polarization; $25^\circ \leq \text{bidirectional-scattering-angle} \leq 180^\circ$; The human scattering target skin area was placed exactly on the goniometer center of rotation with normal angle of incidence to the source beam. Scattering power increased at the higher frequency. This new work enables radiometrically correct models of humans. **Keywords:** submillimeter bidirectional reflectance distribution, human skin

1. INTRODUCTION

The bidirectional scattering distribution function (*BSDF*) and the area normalized bidirectional radar cross section (σ°) are related concepts and are needed to determine detection threshold levels in radars and other active imagers[1,9]. Since our measurement geometry is reflective, *BSDF* is equivalent to bidirectional reflectance distribution function (*BRDF*). The cosine corrected *BSDF* is [2]

$$BSDF = \frac{P_s / \Omega_s}{P_i} \quad (1)$$

where P_s is the power scattered into a detector with angular aperture subtending Ω_s steradians from the point of view of the scattering target surface, and P_i is total power incident onto the target surface.

The area normalized bidirectional radar cross section, σ° , is[3]

$$\sigma^\circ = \frac{\langle \sigma \rangle}{A_o} = \frac{\langle |E^s|^2 \rangle}{A_o |E^i|^2 / (4\pi R_r^2)} \quad (2)$$

where $\langle \sigma \rangle$ is the statistically averaged radar cross section of the target over the illuminated area A_o , E^s is the scattered field at the detector aperture, E^i is the incident field on the target, and R_r is the distance to the detector aperture.

Using these definitions it can be shown that $BSDF = \sigma^\circ / 4\pi$.

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Here we report *BSDF* results from a simple goniometer instrument of our own design. *BSDF* was measured on live human skin and selected materials. All results reported here are with incident radiation direction normal to the target surface (angle of incidence (*AOI*) is zero). The scattering plane was horizontal. Results were obtained at 160 GHz source frequency in p-polarization (E^s -field horizontal) and 650 GHz in p and s-polarizations (E^s -field horizontal and vertical, respectively). As far as we know, these are the first reported measurements of *BSDF* from human skin at 160 GHz or 650 GHz.

1.1 Instrument Design

Figure 1 shows the optical layout of the instrument. Coherent radiation source was focused onto a target and then the scattered radiation was focused onto a detector. The detector was mounted on a moving arm to vary the bistatic scattering angle (*BSA*). The *BSA* is the angle between the source and the detector and this terminology is adopted from bistatic radar. In general, the source angle of incidence on the target (*AOI*) could be varied over all angles, but all measurements reported here are with $AOI = 0^\circ$. To simplify the understanding of the instrument calibration, the source focusing optics and detector focusing optics were made as symmetrical as possible. For full instrument characterization the *BSA* was designed to have the range $25^\circ \leq BSA \leq 210^\circ$ providing the ability to partially map out the source beam as well as to directly observe the power from the source without using a mirror at the target position.

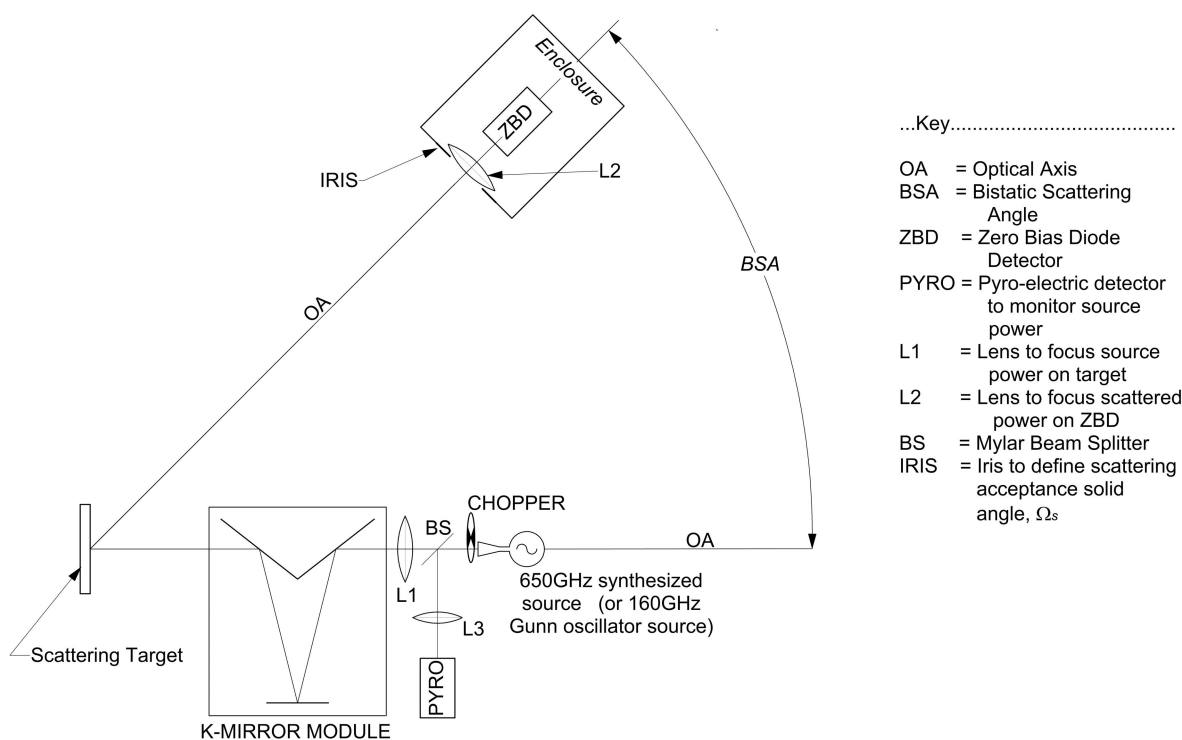


Figure 1: Optical setup (see text for explanation).

The 650 GHz synthesized source was based on a chain which started with a 20 GHz commercial synthesizer generated tone mixed with a 53.2 GHz oscillator. The up-converted tone (73.2 GHz) was amplified, multiplied by a commercial mm-wave tripler (219.6 GHz), amplified again by a custom MMIC, and then multiplied by a sub-mm tripler diode (658.8 GHz). The ~650 GHz source was coupled to free space with a pyramidal feed horn with the E field horizontal with respect to the scattering plane (p-polarization). Some of the source power was split off by a Mylar beam splitter (BS) and coupled by a lens (L3) into a pyro-electric detector for monitoring. After a 30 minute warm up the power from the source typically was stable to better than $\pm 0.5\%$ over a one hour period. The diverging beam from the pyramidal

feed horn was refocused by a 6.3 cm focal length polyethylene lens (L1) to form a focus at the target position approximately 700 mm (optical path length) from the target side of the vertex of L1. The beam from L1 was directed through an Abbe/König “K-mirror” in order to conveniently rotate the source E field for s-polarization measurements.

The constraints on the system design were as follows. (1) The optical path length from the output of L1 to the target was to be about 70 cm to accommodate the K-mirror (d_{out}). That criterion also provided a convenient working distance from the target to the detector since the instrument had to accommodate a human sized subject. (2) The source input beam waist, $w_{o_{in}}$ was fixed by the source feed horn dimensions and source frequency. (For 650 GHz, theory [4] predicted $w_{o_{in}} = 0.063$ cm, and for 160 GHz $w_{o_{in}} = 0.22$ cm.) (3) The focused beam spot size on the target, $w_{o_{out}}$ was to be about 1 cm or larger so that sufficient target area was sampled. (4) Most of the beam power was to be contained in the 50 mm diameter spot defined by a G10 fiberglass target aperture. The focal lengths of lenses L1 and L2 had to be selected to accommodate these constraints. To aid with this lens selection we used physical, “quasi-optical” formalism [4] as follows.

Figure 2 (left panel) show the predicted $w_{o_{out}}$ versus d_{out} for 650 GHz using a thin lens approximation. (d_{out} is the distance from the vertex of L1 to the target.) The contours in the plot are for lenses constant focal length, f , and they are parameterized in terms of d_{in} , the distance from L1 to source beam waist, $w_{o_{in}}$. (In the plots, the range of the parameter d_{in} is $f \leq d_{in} \leq 1.5*f$. $w_{o_{out}}$ increases as d_{in} decreases toward f .) A vertical line is drawn at the d_{out} position of 70 cm. Based on this modeling, we selected a lens with focal length $f=6.3$ cm since its contour plot intersects the d_{out} 70 cm line near $w_{o_{out}} = 1$ cm. As shown, the contour plot actually has two intersections with the 70 cm line. Keeping in mind that Figure 2 is just a thin lens model and also that it does not incorporate possible non-ideal beam behavior like astigmatism, our optical alignment procedure selected the best focus by adjusting the L1 and source horn positions until the power was peaked up at the target position. (Power was detected with a pyro-electric detector placed at the target position. The detector had a 2 sq. mm active area.)

After this optical alignment we measured the beam encircled power with an iris placed at the target position and the instrument detector arm at 180° . From this measurement the beam full width at half maximum (FWHM) was estimated to be about 10.7 mm (as described later). This estimate of the FWHM gave a $w_{o_{out}} = 9.1$ mm if the beam had a lowest order Gaussian profile, but this interpretation of the measurement is possibly an over simplification. In any case, this estimated $w_{o_{out}}$ is indicated by the “o” marker on the plot and it is nearer to the lower intersection point of the d_{out} 70 cm line and the $f=6.3$ cm contour.

The same procedure was used to select the lens for the 160 GHz measurements, and in that case we selected a lens with $f=10.5$ cm. The “o” marker in Figure 2, right panel, indicates the $w_{o_{out}}$ corresponding to a fit of the detector zero bias diode detector (ZBD) response (described later) to a double Gaussian (i.e., the detector ZBD Gaussian beam convolved with the source Gaussian power pattern at the target plane). This estimated larger spot size is not believed to adversely affect our measurements, although a future refinement would be to constrain the spot sizes to be nearly the same at different frequencies.

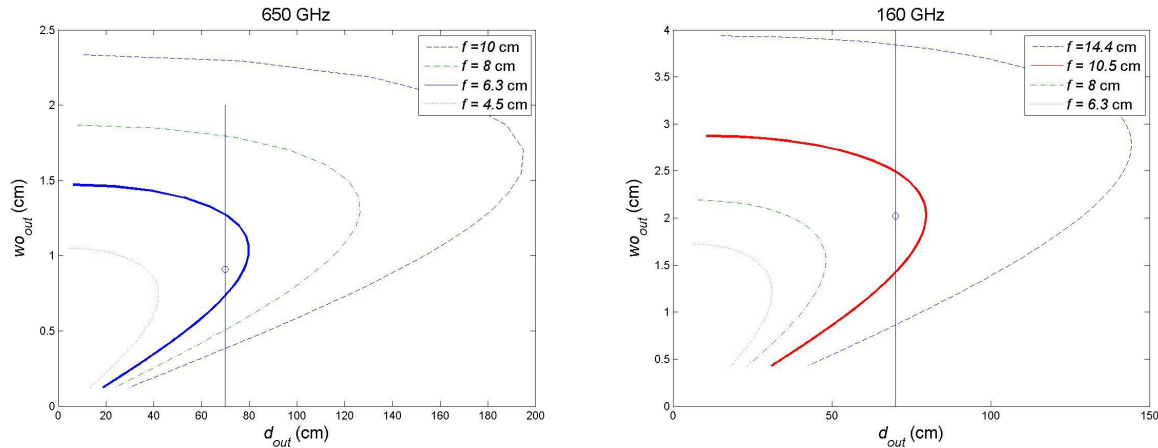


Figure 2: Predicted beam spot on target for various focal length lenses and output distances. The left panel is for 650 GHz and the right panel is for 160 GHz.

Source modulation was provided by a two-bladed chopper wheel at the exit of the source feed horn. The chopper modulation rate was approximately 19 Hz, and the chopper control electronics provided a reference synchronization signal to a commercial lock-in amplifier (not shown).

The detector for scattered radiation was housed in an enclosure mounted to a moving arm which had angular travel $25^\circ \leq BSA < 210^\circ$. The enclosure was lined with AN72 Eccosorb¹ to help absorb stray radiation. The enclosure was provided to mitigate stray radiation from being accepted by the detector and also to prevent air currents which can affect windowless pyro-electric detectors such as we used during some preliminary measurements. An approximately 1 Hz ripple was often, but not always, observed in the pyro-electric and ZBD detectors mounted on the moving arm which was either due to microphonics, or chopper speed variations, or due to radio frequency interference from other sources in our laboratory building. We did not establish the source of the ripple, but we mitigated its effect by integrating 15 seconds of scattering data from each angle. The output of the pyro-electric detector was fed to one (of two) lock-in amplifier signal input channels.

Scattered power from the target was focused onto a commercial, waveguide-coupled, ZBD by lens L2 which was of identical design to L1. The ZBD was coupled to the lens with a pyramidal feed horn identical to the one on the source. The ZBD detector used for the measurements reported here had a nominal noise power of 5.4 pW/sqrt(Hz). Our instrument had a dynamic range of over 70 dB and the ZBD response was not linear at the high power end of that range. We characterized the non-linearity of the ZBD by comparing its response to the monitoring pyro-electric detector, PYRO in Figure 1 as follows. The target was removed from the target holder and the BSA was set to 180° to observe the source beam power on the ZBD detector. The ZBD response along with the monitor pyro-electric detector was recorded. The source power was then reduced and the measurement repeated. (In a separate, earlier characterization the pyro-electric response was shown to be linear over the power range used here.) This comparison of ZBD versus pyro-electric detector response was used to fit to a second order polynomial and then used to linearize the measured ZBD power. The scattered power levels on the ZBD were typically more than 40 dB lower than the source power, well into the ZBD linear regime, but the linearization was necessary to properly establish the incident power on the target, P_i of Equation 1. Compression (saturation) in the ZBD response led to about a 2 dB correction in P_i . The output of the ZBD detector was fed to the second (of two) lock-in amplifier signal input channels.

To estimate the encircled power at the target position we placed an adjustable iris in the target plane and moved the detector ZBD to look directly at the transmitted beam ($BSA = 180^\circ$). We observed the response of the detector ZBD as the iris diameter in the target plane was varied. At 650 GHz the maximum detector response was observed when the iris aperture was 19 mm in diameter and 50% of maximum when the iris was 10.7 mm in diameter ($\sim$ FWHM). At 160 GHz the maximum ZBD detector response was when the target plane iris was 66.4 mm in diameter, 92 % of maximum at 50 mm diameter, and about 50% of maximum at 32.2 mm diameter. The measurement of the encircled beam power might

have been improved by placing a large area detector at target plane and masking it with an aperture, but in the case of 160 GHz we were limited by available instrumentation.

The acceptance solid angle of the ZBD detector, Ω_s , was controlled by an iris (IRIS in Figure 1). The plane of the iris was approximately 695 mm from the target center. The maximum usable Ω_s was limited by the illumination pattern of the detector feed horn on lens L2. Ω_s was determined by setting BSA to 180° and observing the source beam power versus Ω_s as the iris diameter was increased, see Figure 3. When the relationship deviated from approximately linear, that point was used to fix the iris diameter and Ω_s . That point is shown as the '+' marker in the figure and is 2dB below full power. For the 650 GHz source and optics the iris diameter was fixed at 35.5 mm ($\Omega_s = 0.002048$ sr and the angular subtense of the detector lens was about 2.9°).

For the 160 GHz optical system the same procedure was followed leading to an iris diameter of 66.1 mm ($\Omega_s = 0.007092$ sr, and the angular subtense of the detector aperture was about 5.5°).

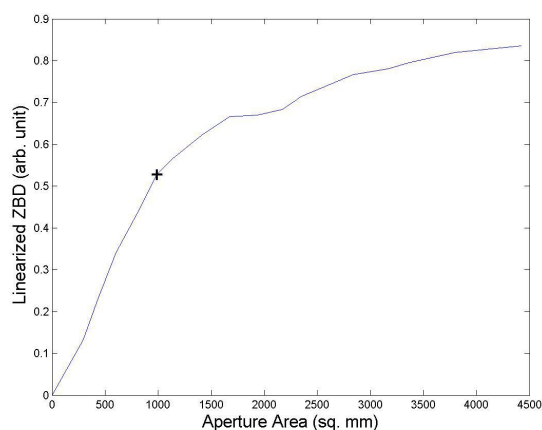


Figure 3: Beam power vs. aperture area.

The detector scattering arm was mounted on a motorized rotary stage interfaced to the control/data acquisition computer. The lock-in amplifier was interfaced to the same computer. Each measurement scan proceeded as follows: (1) the data acquisition program read the source monitor pyro-electric detector (PYRO in Figure 1); (2) the detector arm was moved to $BSA = 25^\circ$; (3) a 15 second integration of the ZBD response was performed by acquiring a time series of readings into the lock-in amplifier "curve" buffer, and then uploading the curve buffer to the control computer at the end of the measurement; (4) the data were averaged and stored in the control computer; (5) the BSA was incremented 2.5° and steps (3, 4) were repeated; (6) step (5) was repeated 27 times until $BSA = 90^\circ$ and then measurement was stopped and the data final data file named and stored. A single, entire measurement scan took about 15 minutes.

A solid model and photograph of the complete, operational instrument is shown in Figure 4. A platform was provided for a human subject to sit on and it was mechanically isolated from the optics support structure and the detector moving arm. The platform was cantilevered out over the optics support structure and was designed to allow the BSA range to travel over its full range (25° to 210°) without mechanical interference. A G10 fiberglass plate with a 50 mm diameter aperture was supported on an optical post centered on the rotation axis. The purpose of the G10 aperture plate was to exactly locate the human target skin area exactly at the nominal target plane and exactly on the goniometer center of rotation. The surface of the skin was fully free, not stretched or pressed flat against a window. Nevertheless, the aperture plate provided enough control over the orientation of the skin surface to ensure that no specularly reflected radiation entered the detection system. The G10 fiberglass plate was 6 mm thick and this thickness started causing vignetting of scattered radiation for $BSA > 70^\circ$. Therefore, in the final data reduction all data from $BSA > 70^\circ$ were excluded from the fits.

Figure 5 is a photograph of a human subject seated in the instrument with skin area from the inside of their forearm being sampled. For forearm and palm measurements an extra support was provided on which the subject's arm was resting.

Materials could also be sampled with this instrument by replacing the G10 support post with an auxiliary post designed to support a sample holder mounted on a motorized rotary stage so that the *AOI* of the sample could be varied under data acquisition system control if desired.

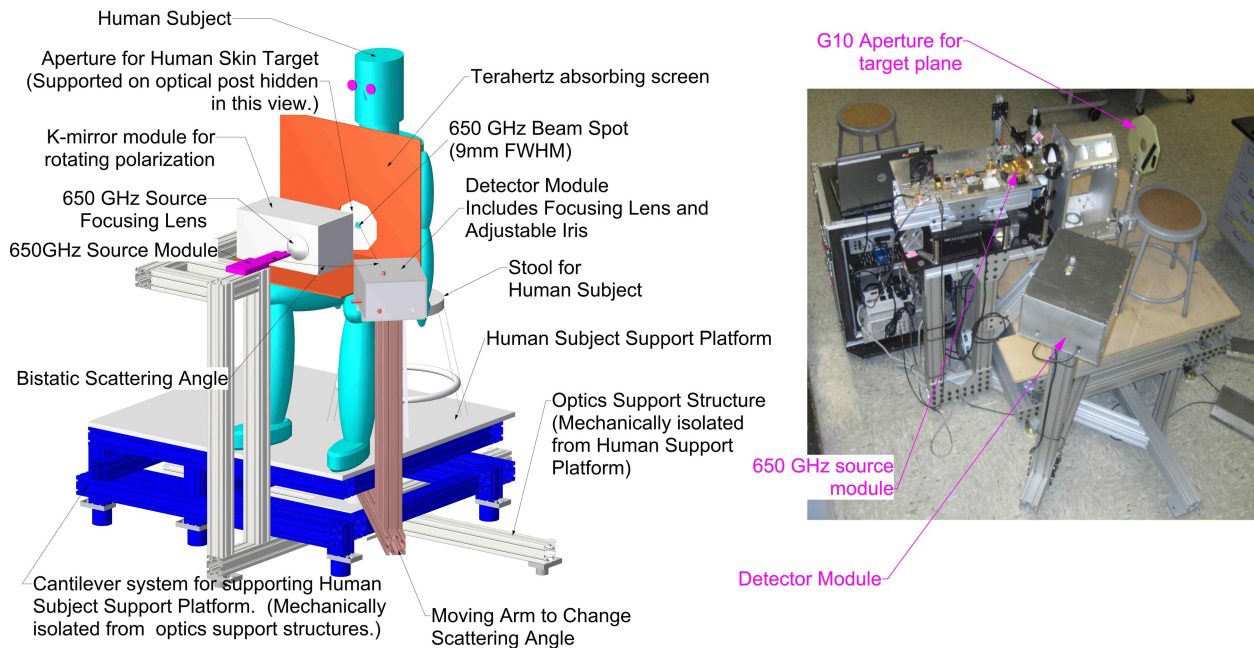


Figure 4: Solid model (as designed) and photograph of goniometer instrument (as built).

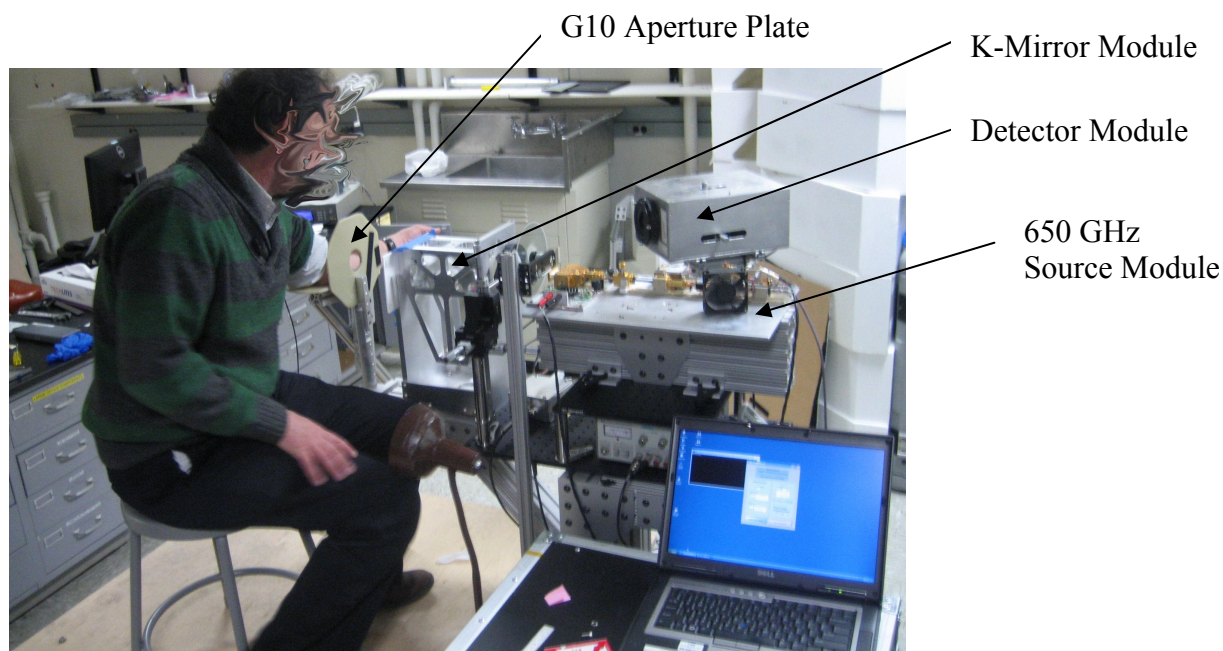


Figure 5: Human Subject seated in instrument with arm being measured. (Face is distorted to protect confidentiality.)

The overall performance of the system is characterized in Figure 6. The *BSDF* is expressed on a dB scale and here we call this unit dB/sr (i.e. 0 dB corresponds to $BSDF = 1 \text{ sr}^{-1}$). For these measurements, there was no scattering target in the target plane, but the G10 fiberglass aperture plate was in place. These measurements covered the full angular range of the goniometer instrument, 25° to 210° . The source beam profiles were included in these scans and they showed up as sharp peaks with symmetrical structures centered on 180° . The side lobes decreased to the noise floor about 17.5° from the peak for the 650 GHz beam, and about 25° from the peak for the 160 GHz beam.

These measurements indicate that the noise floor of the entire system from all sources including stray radiation was about -45 dB/sr for 650 GHz for $25^\circ \leq BSA \leq 90^\circ$ and the dynamic range was better than 70 dB. For 160 GHz the noise floor was about -51 dB/sr and the dynamic range was about 72 dB.

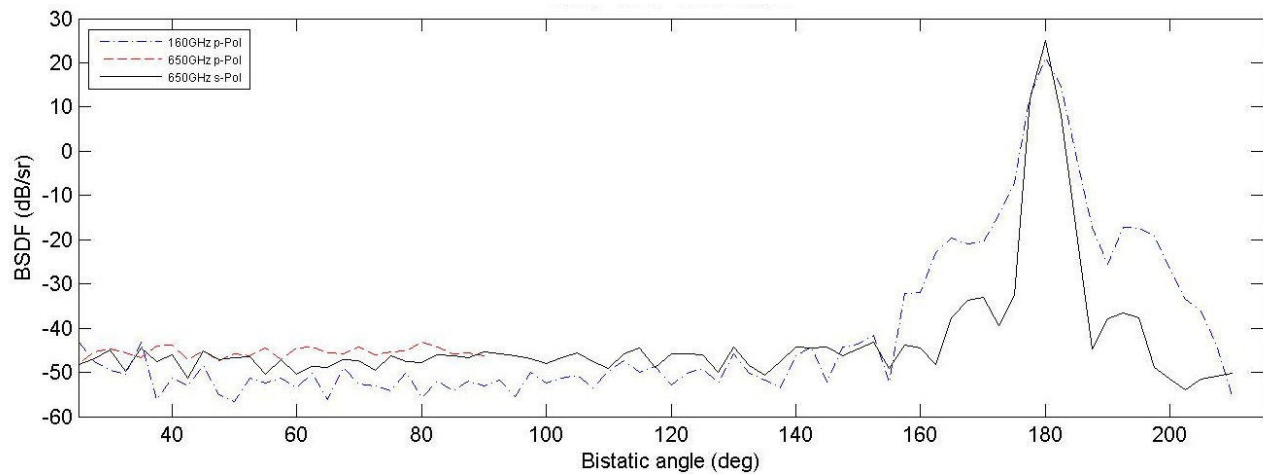


Figure 6: Response of the instrument with no target in the target plane. The 650 GHz p-Pol data shown here covers only $25^\circ \leq BSA \leq 90^\circ$. (Also, see text.)

2. EXPERIMENTAL RESULTS

2.1 Sample subjects

Five human subjects were studied: one female and four male, ranging in age from 19 to 56 years old. For each subject we measured scattering from the inside palm of the hand, the inside of the forearm, a region about 10 cm above the navel on the front of the abdomen and a region at a similar height above the navel on the back side of the abdomen. Many man-made and few natural materials were also sampled under the same conditions and here we report results from a small subset.

2.2 Data

Figure 7 shows the result from data scans at 650 GHz p-polarization. The four panels show results from scattering from skin on the four body areas: Palm, Arm, Abdomen front, and Abdomen back as described above. The results from all five subjects are overlaid in each panel. The BSA was varied from 25° to 90° and the sampling interval was 2.5° . In all cases the scattering signal from the subjects drops to about the noise floor level for $BSA > 70^\circ$ except for Subject 1. The Palm, Arm, and Abdomen Front of Subject 1 were measured at a reduced power level so the noise floor was higher. To improve the signal-to-noise ratio, subsequent measurements were made at a higher source power level.

The sharp variation of the scattering power with angle is consistent with speckle scattering. To mitigate the effects of speckle scattering on the data interpretation we performed box car smoothing of the data over eight adjacent channels reducing the effective angular resolution of the data to about 20 degrees. (The boxcar smoothing was done in linear space and transformed to logarithmic *BSDF* representation for display purposes.)

Figure 8 shows the results after smoothing. The thick blue lines overlaying the plots are the result of least squares fitting to the logarithmic *BSDF* representation, which is merely an effort to simplify the presentation of the results rather than an *a priori* expectation about the scattering phenomenology. Scattering data for $BSA > 70^\circ$ was excluded from the smoothing and subsequent line fit.

The least squares fitting is simple and well understood, but strictly speaking does not apply unless the variations in the parent distribution are normally distributed[5], and we did not measure enough subjects to know how the variation was distributed. Also, there is the problem of controlling the exact effective angle of incidence (*AOI*), which could bias averaging from a small sample set. (For example, we have observed that scattering from the heel of the palm rather than the ball of the palm had an effective *AOI* of about 12° and that the non-zero *AOI* noticeably affected the scattered

power.) Nevertheless, to make the problem tractable and give a result which is easy to express in a few numbers, we proceeded with the least squares fitting method for all the data.

Table 1 tabulates the results from the linear fitting to the *BDSF* data. The table also gives a formal uncertainty in the fits.

Table 1: Linear fit coefficients to human *BDSF* data. “Freq/pol/part” is the column descriptor for source frequency/ s or p-polarization/ and body part. The units of “Intercept” are dB/sr and the units of “Slope” are dB/sr/deg. The uncertainties (σ) are derived from the formal fit.

Freq/pol/part	Intercept	Int. σ	Slope	Slope σ
160/p/Palm	-7.86E+00	2.05E-01	-5.82E-01	4.25E-03
160/p/Arm	-2.13E+01	1.95E-01	-3.11E-01	4.03E-03
160/p/Front	-7.14E+00	5.06E-01	-5.23E-01	1.05E-02
160/p/Back	-1.66E+01	2.88E-01	-3.83E-01	5.97E-03
650/s/Palm	-1.35E+01	3.56E-01	-3.08E-01	7.38E-03
650/s/Arm	-1.62E+01	2.12E-01	-2.72E-01	4.40E-03
650/s/Front	-2.14E+01	6.33E-01	-8.93E-02	1.31E-02
650/s/Back	-1.51E+01	2.93E-01	-3.01E-01	6.08E-03
650/p/Palm	-1.87E+01	4.96E-01	-2.64E-01	1.03E-02
650/p/Arm	-1.83E+01	5.11E-01	-2.81E-01	1.06E-02
650/p/Front	-2.01E+01	4.13E-01	-2.20E-01	8.55E-03
650/p/Back	-1.80E+01	2.62E-01	-2.61E-01	5.43E-03

Figure 9 tries to capture some of the information in Table 1 in simple graphical form. The entries from the table were used to predict the power scattered from the target at an intermediate *BSA* of 47.5° . For all body parts the obvious trend is that there was more scattered power in 650 GHz s-polarization, 650 GHz p-polarization is intermediate, and 160 GHz p-polarization had the least scattered power

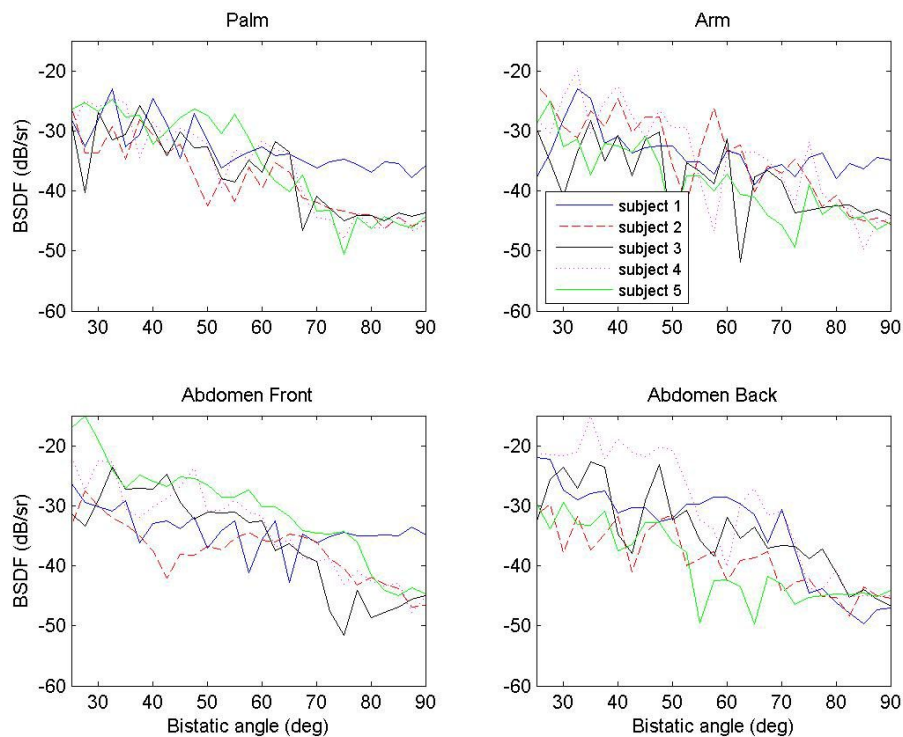


Figure 7: Raw data from 650 GHz human skin scans, p-polarization.

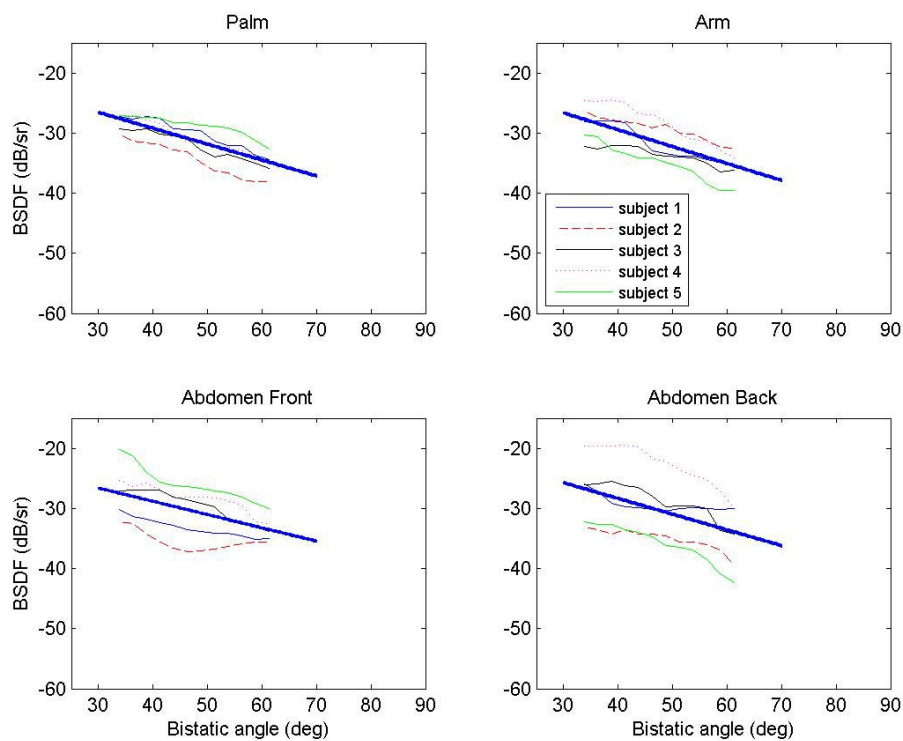


Figure 8: 650 GHz p-polarization data box car smoothed over 8 channels.

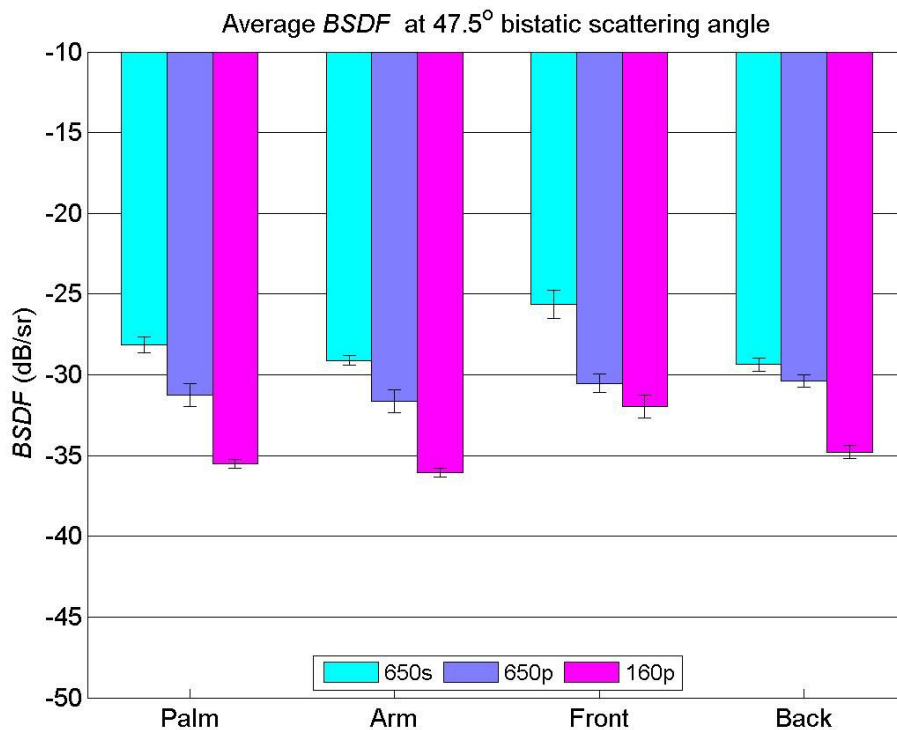


Figure 9: Comparison of scattering from different body parts at different frequencies/polarizations.

2.3 Materials

Scattering from many man-made and some natural materials was also measured under various conditions of source frequency, polarization, and AOI . For the sake of brevity only four materials are reported here with the data acquired under the same conditions as in Section 2.2 ($AOI = 0^\circ$, etc.). The data from the materials were reduced in the same way as the skin samples and the results are presented in

Table 2 and Figure 10.

The four selected materials are AN72 Eccosorb, an asphalt roofing shingle (“shingle”), a piece of denim fabric with the lay of the cloth diagonal to the scattering plane (“denim”), and a piece of thin fleece fabric.

Table 2: Selected Materials linear fit coefficients to the $BSDF$ data (as in Section 2.2). “Freq/pol/material” is the column descriptor for source frequency/s or p-polarization/and material. The units of “Intercept” are dB/sr and the units of “Slope” are dB/sr/deg. The uncertainties (σ) are derived from the formal fit.

Freq/pol/material	Intercept	Int. σ	Slope	Slope σ
160pAN72	-1.89E+01	1.71E-01	-3.44E-02	3.54E-03
650pAN72	-4.15E+00	1.26E-01	-3.11E-01	2.61E-03
6502AN72	-1.93E+01	2.50E-01	2.29E-03	5.17E-03
160pShingle	-9.63E+00	3.91E-01	-2.00E-01	8.10E-03
650pShingle	-3.84E+00	2.88E-01	-3.04E-01	5.96E-03

650sShingle	-1.25E+01	3.26E-01	-9.51E-02	6.76E-03
160/p/Denim	-2.84E+01	2.30E-01	-1.94E-01	4.77E-03
650/p/Denim	-8.42E+00	8.11E-02	-2.05E-01	1.68E-03
650/s/Denim	-2.37E+01	1.39E-01	2.69E-02	2.88E-03
160/p/Fleece	-3.35E+01	1.02E-01	-2.41E-01	2.12E-03
650/p/Fleece	-1.72E+01	1.92E-01	-3.86E-01	3.99E-03
650/s/Fleece	-1.73E+01	1.43E-01	-1.98E-01	2.96E-03

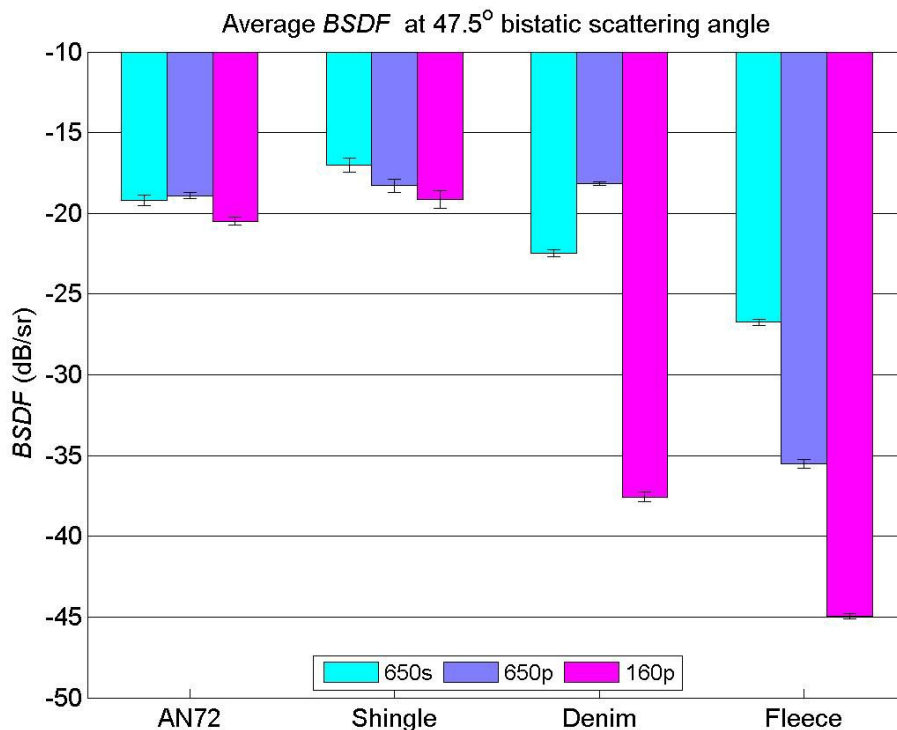


Figure 10: Comparison of scattering from selected materials.

3. DISCUSSION AND CONCLUSIONS

Electromagnetic scattering is controlled by the dielectric constant and topography (roughness) of the scattering surface. The terahertz dielectric constant of human skin has been the subject of considerable prior study. Pickwell *et al.* [6] used terahertz time-domain spectroscopy (TDS) to measure reflectance from the palm and the volar and dorsal forearms of 20 subjects, and thus derive a complex dielectric constant for the epidermis over 0 - 1.5 THz. In this type of measurement, the skin surface is pressed against a flat quartz window, and only the specular reflectance is analyzed. This work and that of [7] were both motivated by interest in using skin hydration contrast as a medical diagnostic technique; thorough understanding of skin's dielectric properties, including its variation among body sites, is a prerequisite. The model of [7] is comprised of three layers distinguished by their water content: the outermost layer, the stratum corneum with a large (linear) hydration gradient, the epidermis with a weak hydration gradient, and constant hydration in the underlying dermis. In this respect, the volar forearm and the palm were found to represent two opposite extreme cases.

The volar forearm has an extremely thin (10 μ m [6], 20 μ m [7]) stratum corneum and can therefore be well modeled dielectrically as a single homogenous layer with an dielectric constant that is slightly, but significantly, different from that of pure water. Moreover, it was found to show far less variation between subjects in the dielectric constant than the other two sites studied. On the other hand, the palm was found to show a stratum corneum thickness of 170 μ m on average. Its terahertz reflectance and that of the dorsal forearm showed much more variation between subjects.

An implication of the present study is that topography is much more important than dielectric constant in determining diffuse scattering. This may be seen from the fact that in the most realistic dielectric model of human skin the reflectance is much lower at 650 GHz than 160 GHz (see Figs. 6, 8, and 10 of [7]), whereas the diffuse scatter that we measure is in all cases higher at 650 GHz than 160 GHz (Figure 9 above). In other words, dielectric constant and surface roughness create frequency dependences of opposite sign in the diffuse scattering, and the observed frequency dependence corresponds to that determined by surface roughness.

In our data, the volar forearm and palm show the least variation from subject to subject (Figure 8, above). For the volar forearm, this lower variation does correspond to the greater consistency in dielectric constant found by [6]. Moreover, this site is also reported by Tchvialeva *et al.* [8] to present the most consistent values of skin roughness, and the least variation with age and gender, of sites studied. Largely because of its importance to the cosmetics industry, skin roughness has been studied for many years using a variety of techniques, traditionally based on measurement of molded polymer replicas. These traditional techniques have significant limitations, however. The results in [8], obtained using a more recent technique based on optical speckle measurements, are useful in interpreting the present sub-millimeter scattering measurements because of their comparison of absolute rms roughness values from different body sites, ranging from 15 μ m to 50 μ m.

In analyses of sub-millimeter radar imaging for concealed threat detection [9] [1], it is of course the scattering properties of the abdomen and back that are most relevant. The fact that our measurements show slightly higher scattering from these sites than from the volar forearm seems to be consistent with their reported roughness levels [8] lying near the middle of the observed range (versus lower levels for the forearm). Possibly more significant is the level of anisotropy in diffuse scattering that is exhibited in Figure 7 and Figure 8 and the fit values in Table 1. Prior analyses of radar imaging have assumed Lambertian (isotropic) scattering, and they will need refinement in order to model detection thresholds, false alarm rates, and other figures of merit accurately.

4. ACKNOWLEDGEMENTS

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