Potential application of a commercial mono-pulse radar

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Abstract

The Tyco Sequential Lobing Radar is a low yield radar operating at 24 GHz. The radar can detect a person at ranges up to 13 metres and within ±4 metres in side. The detected bearing decreases rapidly with range, from a detection span of ±40° at a range between 0.3 to 1 metre to only a few degrees at 13 metres, beyond this range detection can not be guaranteed for humans. Trees of average size and people are clearly distinguishable from each other when comparing their intensity. The radar can detect a metallic pole with a diameter of 10 cm and a height of 3 metres at a distance of 16 meters, in general metallic items with equal exposed area are detectable outside the detection range for humans. The radar can detect stone walls readily up to 10 metres, while having serious difficulties detecting walls parallel to the direction of propagation of the wave. Consideration to the geometry of the volume the radar is to measure has to be taken, as when in confined areas such as tunnels the path taken by the electromagnetic waves might create false echoes due to multiple reflections. The radar is sensitive to the alignment of the plane of the bearing detection, with this plane aligned vertical the radar can be used determine the inclination and presence of slopes and stone walls, even if the wave propagation not is orthogonal to the wall. With the radars plane of bearing detection in the horizontal plane it can detect vertical wires and walls directly orthogonal to the direction of the propagation.
ACKNOWLEDGEMENTS

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1 INTRODUCTION

1.1 Background

Utilising heavy machinery in cramped, shady or environments with otherwise limited visibility give rise to potentially dangerous situations for the driver, machine and its surroundings. Misinterpretation of the surroundings by the driver can be caused by various reasons; such as natural obstacles, protruding parts of the machinery obscuring the view for the driver, etc. One way of increasing the safety for the machine and driver would be to use some form of device that helps the driver to get an overview of the surroundings, the device in this study is a radar of the Sequential Lobing Radar (SLR) type. The radar data could be used to give the driver a simplified representation on a Graphical User Interface (GUI), enabling the driver to interact better with the surroundings. A future aim might be a fully autonomous vehicle.

1.2 Research Objective

To investigate what possibilities there are to gain useful information about the surrounding terrain that is in front of the vehicle with the aim to differentiate between different object in the terrain.

To investigate the radars ability to differentiate between different objects in the terrain, to enable different representation for different objects. To investigate possible drawbacks when using the radar.

1.3 Properties of the Tyco SLR Sensor Model C1

1.3.1 Description of the Tyco SLR

The Tyco SLR Sensor model C1 is a 24 GHz, high resolution, low yield radar, with a digital interface. The unit is slightly larger than a deck of card with the measurements 103*71*23 mm, and the primary use of the radar is installed in auto mobiles as a mean to simplify the procedure of parking and driving in slow moving car queues.

The unit is produced by M/A Com, a industry leading producer of microwave and radio frequency technology. Some of M/A Com’s major markets are wireless telecommunication, aerospace, defence and automotive. M/A Com is a subgroup of Tyco International, a multinational company specialised in the fields of Fire & Security, Electronics, Health care, Engineered Products & Services and Plastics & Adhesives.

1.3.2 Principle of Operation of the Tyco SLR

The Tyco SLR Sensor model C1 is a monopulse type radar. Monopulse is a method to, with a radar, determine the bearing to a target. Monopulse means, in theory, that the radar echo from one single transmitted pulse is enough to determine the radar antennas error angle, i.e. the angle between the target and the antennas main axis. In reality it is not possible to determine the error in
distance and error in angle with only one received pulse. The received pulses are subjected to noise and to compensate for this the received signal must be integrated over a number of pulses. The distance to the target is achieved in the normal fashion by measuring the time it takes for a transmitted pulse to return to the receiver. The Tyco SLR is an amplitude-comparison type monopulse radar. The amplitude-comparison monopulse radar works because the receiver pair antennas are slightly angled compared to the main axis of the transmitter antenna direction. This gives rise to a lobe configuration, with lobe overlapping along the main axis and single lobe coverage at the sides, the left and right lobes is processed in such fashion that the difference between the received signals indicate the error angle with respect to the main axis.

1.3.3 Settings of SLR

The Tyco SLR prototype has two modes of operation:

- Parking mode
  - Maximum detection range of 15 metres.
  - Range resolution of 7.5 cm.
  - Range accuracy of ±7.5 cm.

- Stop and go mode
  - Maximum detection range of 30 metres.
  - Range resolution of 15 cm.
  - Range accuracy of ±7.5 cm.

1.3.4 Additional data for the Tyco SLR Sensor model C1

The Tyco SLR Sensor model C1 is a pulse radar, operating on 24.125 GHz, with a pulsewidth around 1.0-1.5 ns and a pulse detection cycle of 30 ms. The antenna has a 3 dB detection limit within ±8˚ elevation and ±65˚ azimuthal, the lobe coverage is illustrated in figure 1 where the lobe is viewed from above (top) and from the side (bottom). Since the sensor is only able to give bearings in the azimuthal plane and not able to give the angle of elevation, the effect of this is that reflections from a target at a given range and bearing actually can be anywhere within the ±8˚ elevation boundary, numerical values for different ranges are tabulated in table 1.

The radar gives following data output: intensity, range, bearing, time stamp and spare data channel. The intensity is given in dB with respect to an uncalibrated power level, the range is given in cm, the bearing is given in degrees, the time stamp gives the number of the cycle and the spare data channel gives engineering information.

The sensor has a stated detection range from 0.2 to 30 metres, and a bearing detection range of ±40˚, the bearing is acquired by sequential lobing with the
Figure 1: Bearing and elevation coverage

<table>
<thead>
<tr>
<th>Range [m]</th>
<th>Elevation [m]</th>
<th>Azimuth [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.14</td>
<td>2.14</td>
</tr>
<tr>
<td>2</td>
<td>0.28</td>
<td>4.29</td>
</tr>
<tr>
<td>3</td>
<td>0.42</td>
<td>6.43</td>
</tr>
<tr>
<td>4</td>
<td>0.56</td>
<td>8.58</td>
</tr>
<tr>
<td>5</td>
<td>0.70</td>
<td>10.7</td>
</tr>
<tr>
<td>6</td>
<td>0.84</td>
<td>12.9</td>
</tr>
<tr>
<td>7</td>
<td>0.98</td>
<td>15.0</td>
</tr>
<tr>
<td>8</td>
<td>1.12</td>
<td>17.2</td>
</tr>
<tr>
<td>9</td>
<td>1.26</td>
<td>19.3</td>
</tr>
<tr>
<td>10</td>
<td>1.41</td>
<td>21.4</td>
</tr>
<tr>
<td>11</td>
<td>1.55</td>
<td>23.6</td>
</tr>
<tr>
<td>12</td>
<td>1.69</td>
<td>25.7</td>
</tr>
<tr>
<td>13</td>
<td>1.83</td>
<td>27.9</td>
</tr>
<tr>
<td>14</td>
<td>1.97</td>
<td>30.0</td>
</tr>
</tbody>
</table>

Table 1: Lobe coverage for the sensor at different ranges.
receiving antenna pair, the bearing accuracy stated in the technical specifications for the sensor at different bearings can be found in table 2.

<table>
<thead>
<tr>
<th>Bearing</th>
<th>Bearing accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>0° - ± 5°</td>
<td>± 2°</td>
</tr>
<tr>
<td>±5° - ± 25°</td>
<td>± 5°</td>
</tr>
<tr>
<td>±25° - ± 40°</td>
<td>± 10°</td>
</tr>
</tbody>
</table>

Table 2: Bearing accuracy.
1.4 RADAR THEORY

The main part of the theory in this section comes from Pebles’ book [1] on the principles of radar operation and wave propagation.

1.4.1 Wave Propagation

Take a source of radiation of energy in the form of electromagnetic waves (EM waves) at the angular frequency \( \omega \). The wave radiates outward in all directions carrying energy at the speed of light, \( c \), from the source. The locus of all points of the wave, with the same frequency, \( \psi \), creates a sphere around the source; the surface of this sphere can be considered a wave front. A line drawn from the source to any direction from the source is called a ray and defines the direction of the wave front. The wavelength, \( \lambda \), is the distance the ray travels in the time \( T \), where \( T \) is the period of the wave with frequency \( f = \frac{1}{T} \), the relationship is:

\[
\lambda = cT = \frac{c}{f} = \frac{2\pi c}{\omega}
\]

The intensity of the wave depends on its electric (E) and magnetic (H) fields. These fields intensities decrease with the distance \( R \) from the source by a factor \( \frac{1}{R} \) and their power by the factor \( \frac{1}{R^2} \), due to the fact the radiated power is distributed over a larger spherical surface with increasing distance. This type of uniform distribution is hardly ever the case in real life radar applications, but is a good approximation to build the theoretical reasoning on.

If the source is not isotropic in its radiation distribution, the intensity may vary along the wave front in the plane of propagation with angle \( \theta \), as seen in figure 2.

![Wave propagation in two dimensions](image)

**Figure 2:** Plane wave propagation in two dimensions.

This is true for small isolated sources but for larger distributed sources, such as antennas, the E- and H-field are the sums of all contributing fields from all
radiators that makes up the source. Wave fronts near these sources are not spherical, but at a distance known as the far field they are spherical.

In general the far field begins at distance \( R_F \), where the maximum dimension \( D \) of the source (normal to the ray direction of interest) is very small compared to the distance to the target. For radar, \( R_F \) is in general taken as \( \frac{2D^2}{\lambda} \). This gives that an object is in the far field if the distance \( R \) satisfies \( R \geq R_F = \frac{2D^2}{\lambda} \), see figure 3.

![Figure 3: Plane wave at the far field.](image)

Even for isolated practical antennas, waves are nearly spherical at distances in the far field. Targets for most radar are in the far field and are small enough, physically, to be approximated by a plane wave over the region of space occupied by the target.

![Figure 4: Spherical wave at distance R.](image)

From figure 4, if \( R \) is sufficiently large compared to \( L \), the spherical wave front can be approximated by a plane wave front if \( d \) is small. In general a sufficient condition is that \( d \leq \frac{\lambda}{20} \) and \( R \) and \( L \) are related, approximately, by \( R \geq \frac{2.5L^2}{\lambda} = \frac{25L^2}{4f_{\text{GHz}}}[\text{m}] \).

Since most waves from radars interact with targets at ranges were plane waves are good approximations and utilising this approximation simplifies calculations without loosing accuracy.

This approximation also gives that both the E- and H-fields lies in the plane orthogonal of the wave front and that they are spatially orthogonal, i.e. no electric or magnetic fields in the direction of propagation. This gives that the E- and H-field are related to each other by \( E = \eta H \), where \( \eta \) is the intrinsic
impedance of the medium the wave propagates through and \( \eta = \sqrt{\frac{\mu}{\epsilon}} \) [ohm].

Where \( \mu \) is the permeability of the medium, measured in H/m and \( \epsilon \) is the permittivity of the medium, measured in F/m. For vacuum \( \mu = \mu_0 = 4\pi \times 10^{-7} \) H/m and \( \epsilon = \epsilon_0 = \frac{1}{4\pi} \times 10^{-9} \) F/m.

Because the radar will be used in the atmosphere the permeability and permittivity not is the only thing affecting the waves propagation; consideration must be taken to other contributing factors such as humidity, density and temperature of the air.

In the troposphere, humidity, air density and temperature all decreases with increasing height above the ground. This results in that the refractive index of air decreases with altitude, as a result the velocity of the wave increases and this result in that the path of propagation of the wave bends down toward the earth. The amount of refraction depends on the angle of the ray’s path. Waves with a small angle relative to the earth’s surface will pass through the largest amount of atmosphere and thus suffer the most refraction. Due to this refraction the waves arriving have different ray path lengths and elevation angles as compared to the straight line path between target and radar. The difference between the measured and straight line quantity is an error that must be corrected in precision radars.

Beside refraction, for the usual radar frequencies, diffraction is another important mechanism that can give limited coverage of shadow zones. Diffraction is the bending of waves caused by the presence of a physical object, according to Huygens’ principle. This is the same principle as when light travels through a grate.

### 1.4.2 Attenuation

In a clear atmosphere there are a presence of oxygen and water vapour and at frequency 24 GHz the average attenuation from the air is 0.03 dB/km and from the water is 0.1 dB/km, as seen in figure 5 where attenuation due to various sources is summarised.

In unclear atmosphere; i.e. a clear atmosphere contaminated by added water content, most typically in the form of rain, snow, clouds, hail, sleet or fog, under these conditions the attenuation becomes slightly more complex. As can bee seen in the case of attenuation on a wave due to rainfall, this is a complicated relation, where the function depends of the rainfall rate, frequency, temperature, size distribution of raindrops and polarization of the wave. A good approximation for the attenuation of rain is the 1986 CCIR model, the model is based on the empiric expression

\[
\text{Attenuation} = ar^b [\text{dB/km}],
\]

where \( r \) is the rain rate measured in mm/h and \( a \) and \( b \) are frequency dependent coefficients, consideration to the polarization of the radar must be taken since these constants are slightly polarization dependent. Values for some different rain rates can be found in figure 5.
Figure 5: Attenuation due to various objects at frequency 24 GHz.

Another source of attenuation is clouds and fog, a case where the water particles are small, i.e. has a diameter less than 0.005 cm. From [Kerr, 1964] the one-way attenuation on a radar wave can be written as

\[
\text{Attenuation} = 0.438 \frac{m}{\lambda^2} = 4.867 \cdot 10^{-4} m f_{GHz}^2 \text{ [dB/km]},
\]

(3)

where \( m \) is the saturation of water in grams per cubic metre. The equation applies for a temperature at 18˚C and the frequencies between 3 – 60 GHz. For clouds \( m \) is usually in the range 0.05 to 2.5 g per cubic metre and for fog the value of \( m \) usually is around 1 gram per cubic metre. To compensate for temperatures other than 18˚C, a corrective multiplicative factor can be utilised.

Furthermore dry ice particles in the form of snow, sleet and hail also causes attenuation, although weaker than attenuation from rain of the same precipitation rate (in melted water content). For frequencies up to 20 GHz the attenuation can be written as

\[
\text{Attenuation} = 4.568 \cdot 10^{-8} r^2 f_{GHz}^4 + 7.467 \cdot 10^{-5} r f_{GHz} \text{ [dB/km]},
\]

(4)

where \( r \) is the snowfall rate (measured in melted water content).

When parts of the snow melts, the attenuation increases. For frequencies between 10 – 30 GHz and with 10% of the snow mass melted, this mixture has the same attenuation as rain. When the amount of melted snow increases to between 10 – 20% the attenuation is twice compared to the attenuation from completely melted particles.

1.4.3 Targets

- Point target: Physical dimension is small compared to the range extent of the transmitted pulse (range extent = \( cT/2 \); for monostatic radar), no FM. Point target is small enough so that no smearing over time occurs.
- Extended targets: Isolated target, large compared to the range extent of the transmitted pulse. Extended targets can cause spreading in received pulse and as a result of this a loss in performance of the radar.

- Distributed targets: Still larger targets than extended targets. Examples are: clouds, fog, rain and snow.

- Moving targets: Targets in motion relative to the radar.

- Active/Passive targets: Targets that either transmits and reflects E-M-waves or just reflects E-M-waves.

1.4.4 Radar Basics

A waveform \( s(t) = a(t) \cos[\omega_0 t + \theta(t) + \phi_0] \), where \( a(t) \) is the amplitude modulation, \( \omega_0 \) is the carrier frequency, \( \theta(t) \) is the frequency modulation and \( \phi_0 \) is an arbitrary phase angle.

Pulse repetition interval (PRI): \( T_R \)

Pulse repetition frequency (PRF): \( f_R = \frac{1}{T_R} \)

Thus the signal becomes; if the pulse duration is \( T \)

\[
s(t) = \begin{cases} 
  a(t) \cos[\omega_0 t + \theta(t) + \phi_0] & 0 \leq t \leq T \\
  0 & \text{elsewhere}
\end{cases}, 
\]

(5)

this gives that the pulse can be written as

\[
s(t) = a(t) \text{rect} \left[ \frac{t - T/2}{T} \right] \cos[\omega_0 t + \theta(t) + \phi_0]
\]

(6)

Basic equations and expressions:

- \( P_t \) average peak power output, per cycle
- \( P_{acc} \) average peak power accepted at the antennas input, per cycle
- \( L_t \) power loss, transmitter to antenna.
- \( L_{rt} = \frac{1}{\rho_{rt}} \geq 1 \) radiation loss of transmitting antenna.
- \( \rho_{rt} \) radiation efficiency of transmitting antenna
- \( P_{rad} \) peak radiated power

\[
P_{rad} = \frac{P_{acc}}{L_{rt}} = \frac{P_t}{L_t L_{rt}}
\]

(7)

\( L_{ch1} \) one-way power loss of channel on the path from transmitting antenna to target (sources: rain, fog, snow and atmospheric attenuation).

For an isotropic antenna, peak power density at the target at range \( R_1 \) can be expressed as:

\[
\frac{P_{rad}}{4\pi R_{1}^2 L_{ch1}} = \frac{P_t}{4\pi R_{1}^2 L_t L_{rt} L_{ch1}}
\]

(8)

A real antenna has directive properties that will increase the wave’s power density at the target. If the target is in the direction \((\theta_1, \phi_1)\), given in spherical coordinates, the wave’s average peak power density at the target is given as:
\[ S_t(R_1, \theta_1, \phi_1) = \frac{P_t G_{Dt}(\theta_1, \phi_1)}{4\pi R_1^2 L_L L_{rt} L_{ch1}}, \tag{9} \]

where \( G_{Dt}(\theta_1, \phi_1) \) is the directive gain in direction \( \theta_1, \phi_1 \).

Average peak power at the receiving antenna is:

\[ S_i = \frac{P_t G_{Dt}(\theta_1, \phi_1)\sigma}{(4\pi)^2 R_2^2 L_L L_{rt} L_{ch1} L_{ch2}} \left[ \text{W/m}^2 \right], \tag{10} \]

where \( R_2 \) is the path from target to receiver, \( L_{ch2} \) is the one-way power loss of channel on the path from target to the receiving antenna and \( \sigma \) is the target cross-section.

\( L_{rr} \), the radiation loss of the receiving antenna, can be expressed as:

\[ L_{rr} = \frac{1}{\rho_{rr}} \geq 1, \tag{11} \]

where \( \rho_{rr} \) is the radiation efficiency of the receiving antenna.

This gives the received average peak signal power, \( S_r \), at the output terminal and the result is the so-called Basic Radar Equation:

\[ S_r = S_i \frac{\lambda^2 G_{Dr}(\theta_3, \phi_3)}{4\pi L_{rr}} \frac{P_t G_{Dt}(\theta_1, \phi_1) G_{Dr}(\theta_3, \phi_3)\lambda^2 \sigma}{(4\pi)^2 R_1^2 R_2^2 L_L L_{rt} L_{ch1} L_{ch2} L_{rr}}. \tag{12} \]

The basic radar equation for a monostatic radar, a radar where the transmitting and receiving antenna is separated, but close enough to be considered the same. That is \( R_1 \) and \( R_3 \) can be considered as \( R \) and \( L_{ch1} \) and \( L_{ch2} \) can be considered as \( L_{ch} \), this gives the basic radar equation for a monostatic radar as:

\[ S_r = \frac{P_t G_{Dt}(\theta_1, \phi_1) G_{Dr}(\theta_1, \phi_1)\lambda^2 \sigma}{(4\pi)^5 R_1^2 R_2^2 L_L L_{rt} L_{ch}^2 L_{rr}} \left[ \text{W} \right]. \tag{13} \]

### 1.4.5 Polarization

A wave in point \( P \), see figure 6, can be described by its horizontal and vertical components, as

\[ E_\theta = A \cos(\omega_0 t) \tag{14} \]
\[ E_\phi = A \cos(\omega_0 t + \alpha) \tag{15} \]

Two parameters are needed to define polarisation; the ratio \( A/B \) between the fields’ peak amplitude and the phase angle \( \alpha \), as can be seen in figure 7.

This gives three types of polarization: elliptical, circular and linear, these can be either clockwise or anti-clockwise, as can be seen in figure 8.

When the wave reaches a surface of any material, a part of the waves energy is absorbed and the rest is reflected, generally a good conductor give a good reflection while a lossy medium is a good absorber. The reflection can be written as:

\[ E_{rV} = \Gamma_V E_{iV} \tag{16} \]
\[ E_{rH} = \Gamma_H E_{iH} \tag{17} \]
Figure 6: Geometry of polarized wave propagating from P.

Figure 7: Plots of a polarized wave propagating through a medium.
Where $\Gamma$ is the Fresnel reflection coefficient, where the subscript V and H stands for Vertical and Horizontal orientation, for a incident wave with the grazing angle $\psi$, $\Gamma$ is given as

$$\Gamma_V = \frac{\epsilon_c \sin(\psi) - \sqrt{\epsilon_c - \cos^2(\psi)}}{\epsilon_c \sin(\psi) + \sqrt{\epsilon_c - \cos^2(\psi)}} = \rho_V \exp^{-j\phi_V}$$

$$\Gamma_H = \frac{\epsilon_c \sin(\psi) - \sqrt{\epsilon_c - \cos^2(\psi)}}{\epsilon_c \sin(\psi) + \sqrt{\epsilon_c - \cos^2(\psi)}} = \rho_H \exp^{-j\phi_H}$$

where

- $\epsilon_c = \epsilon_r - j\epsilon_i = \text{complex dielectric constant}$
- $\epsilon_r = \epsilon/\epsilon_0 = \text{dielectric constant of surface material}$
- $\epsilon = \text{real part of dielectric dielectric permeability of surface material}$
- $\epsilon_0 = 10^{-9}/(36\pi)[F/m] = \text{dielectric permeability of free space}$
- $\epsilon_i = \sigma/(\omega \epsilon_0) \approx 60\lambda \sigma \approx 18\sigma/f_{GHz}$
- $\sigma = \text{conductivity of surface material}[S/m]$  
- $\rho_V, \rho_H = \text{magnitude of Fresnel reflection coefficient}$
- $\phi_V, \phi_H = \text{phase angle}$

The surface the wave is reflected from can be described as flat or curved and smooth or rough. A rough surface is a surface fluctuating around an average, and can be seen as smooth surface with a "'roughness'" loss. This can be approximated by:

$$\rho_s = \exp[-8 \left(\frac{\pi h_{rms}}{\lambda}\right)^2 \sin^2(\psi)],$$

Figure 8: Polarization traces for various B/A ratios.
where \( h_{rms} \) is the standard deviation of the height variations about the average flat surface and \( \lambda \) is the wavelength.

1.4.6 Radar Cross Section

Cross-sections

Definitions:

- \( \sigma_T \) = total scattering cross-section
- \( \sigma_a \) = absorption cross-section
- \( \sigma_e = \sigma_T + \sigma_a \) = extinction cross-section

\[
\bar{E}^i = E_{\theta_1} \hat{a}_{\theta_1} + E_{\phi_1} \hat{a}_{\phi_1} \tag{21}
\]

\[
\left\{ \begin{array}{l}
\text{Power per unit area in the wave incident on the target} \\
\end{array} \right\} = \frac{|\bar{E}^i|^2}{2\eta} \tag{22}
\]

\( \eta \) = the intrinsic impedance of the medium

\[
\bar{E}_2^s = E_{\theta_2} \hat{a}_{\theta_2} + E_{\phi_2} \hat{a}_{\phi_2} \tag{23}
\]

\[
\left\{ \begin{array}{l}
\text{Power per unit area in total scattered wave at the receiving antenna} \\
\end{array} \right\} = \frac{|\bar{E}_2^s|^2}{2\eta} \tag{24}
\]

Scattering cross-section, scattering at a point \((R_2, \theta_2, \phi_2)\) from the target.

\[
\sigma_s = \sigma_s (\theta_2, \phi_2) = \lim_{R_2 \to \infty} 4\pi R_2^2 \left\{ \begin{array}{l}
\text{Power per unit area in total scattered wave at the receiving antenna} \\
\text{Power per unit area in the wave incident on the target} \\
\end{array} \right\} = \lim_{R_2 \to \infty} 4\pi R_2^2 \frac{|\bar{E}_2^s|^2}{|\bar{E}^i|^2} \tag{25}
\]

Since in our case the direction of scattering is toward the source of the incident wave, \( \sigma_s \) is called the back-scattering cross-section. The total cross-section is found by averaging \( \sigma_s (\theta_2, \phi_2) \) over all directions:

\[
\sigma_T = \frac{1}{4\pi} \int_{\phi_2 = 0}^{2\pi} \int_{\theta_2 = 0}^{\pi} \sigma_s (\theta_2, \phi_2) \sin (\theta_2) \, d\theta_2 \, d\phi_2 \tag{26}
\]

Radar cross-section

\[
\sigma = \lim_{R_2 \to \infty} 4\pi R_2^2 \left\{ \begin{array}{l}
\text{Power per unit area in scattered wave at the receiving antenna, which is in the polarization of the receiving antenna} \\
\text{Power per unit area in the wave incident on the target} \\
\end{array} \right\} \tag{27}
\]
A good way of looking at this is like the wave consist of two waves, one with the polarization that the antenna responds to and one that it does not. These waves are orthogonal with respect to each other. Thus the

\[ \vec{E}_2^s = E_{\theta_2} \hat{a}_{\theta_2} + E_{\phi_2} \hat{a}_{\phi_2} = E_{\theta_2} (\hat{a}_{\theta_2} + Q_2 \hat{a}_{\phi_2}) = E_{\theta_2} \left[ \frac{1}{Q_2} \right] \]  

(28)

and the power density

\[ \frac{|E_2^s|^2}{2\eta} = E_{\theta_2} \left[ \begin{array}{cc} 1 & Q_2 \\ \frac{Q_2^*}{2\eta} \end{array} \right] E_{\theta_2} \left[ \begin{array}{c} 1 \\ \frac{1}{Q_2^*} \end{array} \right] = \frac{|E_2^s|^2}{2\eta} (1 + |Q_2|^2). \]  

(29)

Now take

\[ \vec{E}_A = A_1 \hat{a}_{\theta_2} + A_1 Q_2 \hat{a}_{\phi_2} = A_1 \left[ \frac{1}{Q_2} \right] \]  

(30)

\[ \vec{E}_B = A_2 \hat{a}_{\theta_2} + A_3 \hat{a}_{\phi_2} = \left[ \begin{array}{c} A_2 \\ A_3 \end{array} \right] \]  

(31)

\[ \vec{E}_2^s = \vec{E}_A + \vec{E}_B \]  

(32)

Condition \( \vec{E}_A \perp \vec{E}_B \) this gives

\[ \vec{E}_A \cdot \vec{E}_B = A_1 \left[ \begin{array}{cc} 1 & Q_A \\ A_2^* & A_3^* \end{array} \right] = A_1 (A_2^* + Q_A A_3^*) = 0 \Rightarrow A_2 = -Q_A^* A_3 \]  

(33)

and thus

\[ \vec{E}_2^s = E_{\theta_2} \left[ \begin{array}{c} 1 \\ Q_2 \end{array} \right] = \vec{E}_A + \vec{E}_B = A_1 \left[ \begin{array}{c} 1 \\ Q_2 \end{array} \right] + A_3 \left[ \begin{array}{c} -Q_A^* \\ 1 \end{array} \right]. \]  

(34)

Where

\[ A_1 = \frac{E_{\theta_2} (1 + Q_A^* Q_2)}{1 + |Q_A|^2} \]  

(35)

\[ A_2 = -\frac{E_{\theta_2} Q_A^* (Q_A - Q_2)}{1 + |Q_A|^2} \]  

(36)

\[ A_3 = \frac{E_{\theta_2} (Q_2 - Q_A)}{1 + |Q_A|^2} \]  

(37)

The power in the wave component \( \vec{E}_A \), the part the antenna can receive, its density can be written as:

\[ \frac{|E_A|^2}{2\eta} = \frac{|A_1|^2}{2\eta} (1 + |Q_A|^2) = \frac{|E_{\theta_2}|^2 |1 + Q_A^* Q_2|^2}{2\eta (1 + |Q_A|^2)} \]  

(39)

This gives
\[
\sigma_s = \lim_{R_2 \to \infty} 4\pi R_2 ^2 \left| \frac{E_2}{E_1} \right|^2 = \lim_{R_2 \to \infty} 4\pi R_2 ^2 \left| \frac{E_{b2}}{E_{b1}} \right|^2 \left( 1 + | Q_2 |^2 \right) \tag{40}
\]
and
\[
\sigma = \lim_{R_2 \to \infty} 4\pi R_2 ^2 \left| \frac{E_A}{E_i} \right|^2 = \lim_{R_2 \to \infty} 4\pi R_2 ^2 \left| \frac{E_{b2}}{E_{b1}} \right|^2 \left( 1 + | Q_A Q_2 |^2 \right) \tag{41}
\]
where \( \sigma = \sigma_s \rho_{pol} \), \( \rho_{pol} \) is the polarisation efficiency:
\[
\rho_{pol} = \frac{| 1 + Q_A^* Q_2 |^2}{(1 + | Q_A |^2)(1 + | Q_2 |^2)} \tag{42}
\]

Different types of back-scattering cross-section:

1.4.7 Flat sphere

Perfectly conducting sphere of radius a
\[
\sigma = \frac{\pi a^2}{(ka)^2} \sum_{n=0}^{\infty} (-1)^n (2n+1) \left( a_n - b_n \right) \tag{43}
\]
\[
a_n = \frac{\xi j_n (\xi)}{\xi h_n (\xi)} \tag{44}
\]
\[
b_n = \frac{j_n (ka)}{h_n (ka)} \tag{45}
\]
\[
k = \frac{2\pi}{\lambda} \tag{46}
\]

Where \( \lambda \) is the wavelength, \( j_n(\cdot) \) is the spherical Bessel function of the first kind and \( h_n(\cdot) \) is the spherical Hankel function of the second kind.

Can be divided into 3 distinct regions, calculated by Blake (1972). In the region where \( \xi \) is small, called Rayleigh region, the cross-section can be regarded as linear to \( \sigma/\pi a^2 \), as can be seen in figure 9.

1.4.8 Flat rectangular plate

Perfectly conducting, flat rectangular plate in the x-y plane, with centre in origo, as illustrated in figure 10. Incident wave along x-z plane with \( \theta \) as incident angle from z-axis. The plate has dimensions 2a in x-direction and 2b in y-direction. Yields the cross-sections:
\[
\sigma_V = \frac{4b^2}{\pi} \left| Z_{1V} - \frac{e^{j[\rho-(\pi/4)]}}{\sqrt{2\pi \rho^{1/2}}} \left[ \frac{1}{\cos \theta} + \frac{e^{j[\rho-(\pi/4)]}}{4\sqrt{2\pi \rho^{1/2}}} Z_{2V} \right] \right|^2 \tag{47}
\]
\[
\sigma_V = \frac{4b^2}{\pi} \left| Z_{1H} - \frac{e^{j[\rho+(\pi/4)]}}{\sqrt{2\pi \rho^{1/2}}} \left[ \frac{1}{\cos \theta} + \frac{e^{j[\rho+(\pi/4)]}}{2\sqrt{2\pi \rho^{1/2}}} Z_{2H} \right] \right|^2 \tag{48}
\]
\[
Z_{1V} = \cos[\rho \cos \theta] - j \sin[\rho \sin \theta] \tag{49}
\]
Figure 9: Radar cross section of perfectly conducting sphere as a function of the radius-to-wavelength.

\[
Z_1 = \cos \left[ \rho \sin \theta \right] + \frac{j \sin \left[ \rho \sin \theta \right]}{\sin \theta} \tag{50}
\]

\[
Z_2 = \frac{[1 + \sin \theta]e^{-j\rho \sin \theta}}{[1 - \sin \theta]^2} + \frac{[1 - \sin \theta]e^{j\rho \sin \theta}}{[1 + \sin \theta]^2} \tag{51}
\]

\[
Z_2 = \frac{e^{-j\rho \sin \theta}}{[1 - \sin \theta]} + \frac{e^{j\rho \sin \theta}}{[1 + \sin \theta]} \tag{52}
\]

\[
\rho = 2ka = \frac{4\pi a}{\lambda} \tag{53}
\]

These cross-sections are only valid if the shortest side dimension of the plate is at least two wavelengths.

When \( \theta = \frac{\pi}{2} \) then

\[
\sigma_V(\theta = \frac{\pi}{2}) = \frac{ab^2}{\lambda} \left\{ \left[ 1 + \frac{\pi}{2(2a/\lambda)^2} \right] + \left[ 1 - \frac{\pi}{2(2a/\lambda)^2} \right] \cos \left( 2\rho - \frac{3\pi}{5} \right) \right\} \tag{54}
\]

\[
\sigma_H = 0 \tag{55}
\]

For \( \theta \) small, \( 0^\circ < \theta < 30^\circ \), and plate dimensions up to 10 wavelengths, following approximation can be done:

\[
\sigma_V = \sigma_H = \frac{64a^2b^2\pi}{\lambda} \left\{ \frac{\sin [2ka\sin \theta]}{2ka\sin \theta} \right\}^2 \cos^2 \theta \tag{56}
\]

For cases where physical optics analysis procedures are valid, arbitrary illumination direction \( \theta, \phi \), as illustrated in figure 11. The cross-section can be written as:

24
\[ \sigma(\theta, \phi) = \frac{64a^2b^2\pi}{\lambda} \left\{ \frac{\sin[2ka \sin \theta \cos \phi]}{2ka \sin \theta \cos \phi} \frac{\sin[2kb \sin \theta \cos \phi]}{2kb \sin \theta \cos \phi} \right\}^2 \cos^2 \theta \]  (57)

**Figure 10:** Backscattering from a flat conducting plate.

**Figure 11:** Backscattering from a flat conducting plate illuminated from an arbitrary source.

### 1.4.9 Flat circular plate

Perfectly conducting, flat circular plate in the x-y plane, with centre in origo. Incident wave along x-z plane with \( \theta \) as incident angle from z-axis. The plate has radius \( a \). This gives the cross-section:
\[ \sigma(\theta) = \pi k^2 a^4 \left( \frac{2 J_1[2ka \sin \theta]}{2ka \sin \theta} \right)^2 \cos^2 \theta \]  

(58)

Condition: the disc must be relatively large so that the size corresponds to the optical region.

1.4.10 Circular cylinder

Cross-section for a linearly polarised wave incident on a smooth, perfectly conducting circular cylinder, as illustrated in figure 12, condition \( ka \sin(\theta) >> 1 \):

\[ \sigma = kaL^2 \left( \frac{\sin[kL \cos \theta]}{kL \cos \theta} \right)^2 \sin \theta \]  

(59)

Observe as \( \theta \) goes toward 0 the cross-section becomes more and more as the cross-section of a flat circular plate.

![Diagram of a circular cylinder](image)

Figure 12: Backscattering from a circular cylinder.

1.4.11 Straight Wire

Perfectly conducting wire, that is long and thin relative to the wavelength. Geometry same as for the cylinder, the approximate back-scattering cross-section, is given by:

\[
\sigma = \frac{\pi L^2 \sin^2 \theta \left\{ \frac{\sin[kL \cos \theta]}{kL \cos \theta} \right\}^2 \cos^4 \phi}{\left( \frac{\pi}{2} \right)^2 + \left\{ \ln \left[ \frac{2}{\gamma ka \sin \theta} \right] \right\}^2}
\]  

(60)

Where \( \gamma = 1.781 \).

Most complex target shapes can be approximated by superposition of the cross-section of the simple shapes.
1.4.12 Radar Resolution

Definition of resolution: imply that two or more targets are separated, or resolved.

The most important parameters a radar measures are: range, Doppler frequency and two orthogonal space angles.

What is range resolution?

Target range $R$ is proportional to time delay $\tau_R$ where $\tau_R = 2R/c$, for monostatic radars.

This means that resolution in range is the same as resolution in delay. Take two received waveforms $\psi_1(t)$ and $\psi_2(t)$.

$$\psi_1(t) = \alpha_1 \psi(t - \tau_{R_1}) e^{j\omega_{d_1}(t - \tau_{R_1})}$$
$$\psi_2(t) = \alpha_2 \psi(t - \tau_{R_2}) e^{j\omega_{d_2}(t - \tau_{R_2})}$$

where $\omega_{d_1}$ and $\omega_{d_2}$ are the Doppler frequencies. Let $\omega_{d_1} = \omega_{d_2} = \omega_d$, i.e. the received signals have the same Doppler frequency but different delays $\tau_{R_1}$ and $\tau_{R_2}$ and let $\alpha_1 = \alpha_2 = \alpha$, i.e. neither target have a power advantage.

This gives the received signals as:

$$\psi_1(t) = \alpha \psi(t - \tau_{R_1}) e^{j\omega_d(t - \tau_{R_1})}$$
$$\psi_2(t) = \alpha \psi(t - \tau_{R_2}) e^{j\omega_d(t - \tau_{R_2})}$$

A requirement of range resolution is that $\psi_1(t)$ and $\psi_2(t)$ should be as different as possible.

A practical criterion of resolution is the integrated squared difference magnitude, $|\epsilon|^2$, written as

$$|\epsilon|^2 = \int_{-\infty}^{\infty} |\psi_1(t) - \psi_2(t)|^2 dt$$

Good range resolution, for any $\tau_{R_1}$ and $\tau_{R_2}$, requires $|\epsilon|^2$ to be large. Inserting the expression for $\psi_1(t)$ and $\psi_2(t)$ into the expression of $|\epsilon|^2$ yields:

$$|\epsilon|^2 = 2|\alpha|^2 \left\{ E_\psi - \Re[e^{j(\omega_0 + \omega_d)\tau} \chi(\tau, 0)] \right\} = 2|\alpha|^2 \left\{ E_\psi - \Re[e^{j(\omega_0 + \omega_d)\tau} R_{gg}(\tau)] \right\}$$

where $\tau = \tau_{R_1} - \tau_{R_2}$, and $E_\psi$ is the energy in $\psi(t)$ and $\omega_0$ is the carrier’s angular frequency.

The function $R_{gg}(\tau)$ is the time autocorrelation function of $g(t)$, the complex envelope of the carrier.

$$\chi(\tau, 0) = \int_{-\infty}^{\infty} g^*(\xi)g(\xi + \tau)d\xi = R_{gg}(\tau)$$

Taking
\( \chi(\tau, 0) = |\chi(\tau, 0)| e^{i\theta_{xx}(\tau)} \) *(68)*

\( R_{gg}(\tau) = |R_{gg}(\tau)| e^{i\theta_{gg}(\tau)} \) *(69)*

Gives

\[ |\epsilon|^2 = 2|\alpha|^2 \{ E_\psi - |\chi(\tau, 0)| \cos [(\omega_0 + \omega_d)\tau + \theta_{xx}(\tau)] \} = 2|\alpha|^2 \{ E_\psi - |R_{gg}(\tau)| \cos [(\omega_0 + \omega_d)\tau + \theta_{gg}(\tau)] \} \]

\[ *(70)*\]

Since \( |\epsilon|^2 \) should be large and \( E_\psi \) can be seen as a constant, the second term in the expression must be small. To guarantee a small second term despite the angular contribution, set \( |\chi(\tau, 0)| = |R_{gg}(\tau)| \) small for all \( |\tau| \).

The ideal case is when \( |\chi(\tau, 0)| \) and \( |\chi(\tau, 0)|^2 \) are zero for all \( |\tau| \neq 0 \) and for \( |\tau| = 0 \) \( |\chi(\tau, 0)|^2 \) must equal \( E_\psi^2 \) for any chosen waveform. This would be the same as transmitting an impulse, in reality a very narrow pulse with no FM and large peak power can approach the ideal. The drawback of this is that the waveform is energy limited to the peak-power limit of the transmitter. A way around this is pulse compression, unfortunately pulse compression always produces side lobes, thus \( |\chi(\tau, 0)|^2 \) cannot be zero for \( |\tau| \) near zero.

Figure 13: Ambiguity function cut of arbitrary waveform.

\( T_{res} \) is the time resolution constant, \( T_{res} \) is the width of a rectangular function equivalent to \( |\chi(\tau, 0)|^2 \) in the respect same maximum amplitude and same area.

\[ T_{res} = \frac{\int_{-\infty}^{\infty} |\chi(\tau, 0)|^2 \ d\tau}{|\chi(\tau, 0)|^2} = \frac{\int_{-\infty}^{\infty} |R_{gg}(\tau)|^2 \ d\tau}{|R_{gg}(0)|^2} = \frac{\int_{-\infty}^{\infty} |R_{gg}(\tau)|^2 \ d\tau}{E_g^2} \]

\[ *(71)*\]

Since \( R_{gg}(\tau) \leftrightarrow |G(\omega)|^2 \)

Where \( G(\omega) \) is the Fourier transform of \( g(t) \) which defines \( \psi(t) \). Parseval’s theorem gives

\[ \int_{-\infty}^{\infty} |R_{gg}(\tau)|^2 \ d\tau = \frac{1}{2\pi} \int_{-\infty}^{\infty} |G(\omega)|^4 \ d\omega \]

\( E_g = R_{gg}(0) = \frac{1}{2\pi} \int_{-\infty}^{\infty} |G(\omega)|^2 \ d\omega \)

\[ *(72)*\]

\[ *(73)*\]
this gives $T_{res}$ as

$$T_{res} = \frac{2\pi \int_{-\infty}^{\infty} |G(\omega)|^4 d\omega}{\left( \int_{-\infty}^{\infty} |G(\omega)|^2 d\omega \right)^2} = \frac{2\pi \int_{-\infty}^{\infty} |G(\omega)|^4 d\omega}{2\pi E_g^2}$$  \hspace{1cm} (74)

To reduce $T_{res}$ for any given energy a wideband signal that corresponds to a narrow autocorrelation, $R_{gg}(\tau)$. Small $T_{res}$ alone does not guarantee resolution, since large amplitude targets in close proximity to a small amplitude target can prevent separation of the targets. $T_{res}$ can be taken as a measure on how hard it will be to resolve and that separation by time larger than $T_{res}$ increases resolution.

From $T_{res}$ the effective bandwidth, or frequency span, can be given by

$$B_{eff} = \frac{1}{T_{res}}$$  \hspace{1cm} (75)
2 MATERIALS AND METHODS

2.1 Materials

Materials used for sampling during the experiments

- Camera tripod with swivel tilt head, type: Velbon Maxi 343E.
- Metal profile, with precut fringes. Dimensions: 62.3x6.7x3.5 cm
- Electronic water level, type “Swiss+Level”
- M/A-Com 24 GHz Sequential Lobing Radar.
- USB/CAN-cables.
- Computers
  Two portable computers were used, as primary a Toshiba Portégé 4010 PIII 933MHz, 512MB, running Windows XP and as backup a Dell M30 1.3GHz, 512MB, running Windows NT.
- Homebuilt Tilt cradle
  Tilt cradle made of plexiglass, with attached servo and serial controller card, figure 14.

Figure 14: Tilt cradle with sensor beside

- Reflectors
  Reflectors with a cardboard skeleton coated with aluminium foil, figure 15. Each triangular section in the reflectors has the dimensions 9.5x9.5x13.4 cm.
- Software:
  DanView v3.0 and Matlab v6.5

2.2 Methods

The given data for the radar can be found in section 1.3 at page 9. Now consideration for the fact of the original purpose for this unit has to be taken into account. This unit is specially designed to operate in a traffic environment were the majority of the targets can be considered as reflectors made of metal with an average cross-section of the magnitude 1 square metre. A basic fact of
electromagnetics is that the better conductor a material is the better it reflects EM-waves, this has to be taken into consideration since the operating environment of the vehicle in this study might be in a forest or down in a mine. These environments might be full of trees or rugged stone walls. Considering the composition of trees and stones they should have a lower reflectivity compared to metal, in comparison with trees and stone how is the average reflectivity of a human. Just by intuition and argumentation the human reflectivity of EM-waves should be greater than that of wood and less of metal. The reflectivity of stones versus the reflectivity of humans might be dependent on the ore content of the stones.

Considering the limited information given about the sensor and taking into account the ordinary operating conditions, a number of tests were devised to find out the characteristic lobe of detection for a human and the detection ranges for a human and non human targets of the unit.

Since the radar is a prototype prefabricated and sealed unit, there are limits to what settings can be changed in the final version.

2.2.1 At Umeå University

To measure the bearing accuracy, a reflector was placed at a distance from the sensors. Both sensors were in horizontal orientation with respect to the ground. Measurements were made with the reflector at the same distance, but with different lateral distances until the reflector no longer was detected by either sensor.

To measure the relation between intensity and range for a person, a person was placed directly ahead of both sensors. Both sensors were in horizontal orientation with respect to the ground. Measurements were made at ranges with even increment of one metre.

To map how the sensors bearing behaved in the outskirts of the bearing detection range, a person walked in front of the sensors, in an orthogonal direction with respect to the sensors. The range increased evenly with each pass, both sensors were placed in horizontal orientation with respect to the ground.

To measure the sensors lobe coverage a person walked in front of the sensors,
both placed in horizontal orientation, in a direction orthogonal with respect to
the sensors. The person walked each distance twice and then increased the
distance with one metre, compared with the previous experiment the person
walked further in side and also in distance.

To measure the intensity versus range for a birch, one sensor were placed
in horizontal orientation on top of a trolley. Measurements were made continu-
ously as the trolley is rolled toward a birch, stopping at even increments of one
metre, until at a distance of one metre from the birch.

To measure the intensity versus range for a spruce, one sensor were placed in
horizontal orientation on top of a trolley. Measurements are made continous as
the trolley is rolled toward a spruce, stopping at even increments of one metre,
until at a distance of one metre from the spruce.

To test the possibility to automate the procedure of taking measurements, a
sensor was placed on a remotely controlled tilt cradle, the sensor was horizon-
tally oriented. Measurements were made continuously as the cradle increased
the elevation in even increments of 5˚.

2.2.2 In Kiruna

Down in the mine it was more important to consider the three dimensional en-
vironment compared with the environment in a forest or on a road. Thus the
set-up of the measurements in the mine differs some compared to the measure-
ments made at Umeå University.

In the tunnel containing the drop shaft the first measurement was with both
sensors in vertical orientation with respect to the ground, each measurement
was made at a specific angle of rotation around the centre axis of the tripod.

The second measurement in the tunnel with the drop shaft was made in
a similar fashion but now with one sensor in vertical orientation and one in
horizontal orientation with respect to the ground. As in previous section mea-
surements were made at specific angle of rotation around the centre axis of the
tripod.

The third measurement was made with both sensors in horizontal orientation
with respect to the ground. Each measurement was made at a specific angle of
elevation with respect to the ground.

For the tunnel with the sloping heap of gravel the approach was the same as
in the tunnel with the drop shaft, the first measurement was with both sensors
in vertical orientation with respect to the ground, each measurement was made
at a specific angle of rotation around the centre axis of the tripod.
The second measurement was made in a similar fashion but now with one sensor in vertical orientation and one in horizontal orientation with respect to the ground. As in the previous section, measurements were made at a specific angle of rotation around the centre axis of the tripod.

No measurements with both sensors in horizontal orientation were made due to lack of time, this since all measurements required a high degree of accuracy when setting up the experiment.

2.2.3 Processing the data

DanView, the program that collected the target data from the sensors saved the data in MATLAB-files. Each target acquired by the sensor was assigned to one of ten target channels, the target with shortest range was assigned to the first channel and the rest of the targets were sorted in ascending order. In these channels the data for range, bearing, intensity, time stamp and sensor temperature was stored. In the case of less than ten targets in a scan, the sensor would create an artificial target to fill the remaining target channels and assigned these the range 4096 and the bearing 256˚, this to see to that the arrays in the channels were of equal size. To be able to do something with the gathered data, the data had to be processed. To differentiate between the different target channels were of no interest, thus all targets in the ten channel was merged together into one array. The values for the rotation or elevation of the set-up was added in the process. Then all artificial targets were removed. From the values for range, bearing and intensity, the means and standard deviation for the different targets were calculated. Since all values were in spherical coordinates a coordinate transformation to Cartesian coordinates was performed. To illustrate the three dimensional space spanned by the targets, two types of plots were utilised; the incision plot and the contour plot. In the incision plot, all targets within the height \( z \) and \( z + \Delta z \) was plotted and viewed in the X-Y plane, where the X axis represents the distance from the sensor in the forward direction, named the range, and the Y axis was the distance to the left or the right of the sensor, named the lateral displacement. In some cases the values between the targets mean coordinates were linearly interpolated and plotted in contour plots, where the isograms indicates the height or intensity and the X and Y axis was defined as in the previous type of plot. To find out the relation between the intensity and range logarithmic fits were made, since the intensity is measured in dB and thus is the ratio between radiated power and received power. From the theory section, eqn. 7 on page 17 and eqn. 13 on page 18, from this it is evident that the relation between the intensity and range should be on the form

\[
I = 10 \times \log \left( \frac{G_D(\theta_1, \phi_1) G_D(\theta_1, \phi_1) \lambda^2 \sigma}{(4\pi)^3 L_{th} L_{rr}} \right) = 10 \times \log(\text{const.}) - 40 \times \log(R). \]

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3 EXPERIMENTAL RESULTS

3.1 Outdoor measurements at Umeå University

3.1.1 Reflector

To determine how well the given data for the sensors’ deviation in bearing and detection range, found in table 2, corresponded with reality a small reflector was placed in front of the sensors. The reflector and both sensors were placed at a height of one metre, the distance from the sensors to the reflector was five metres when it was placed directly ahead of the sensors. The reflector was placed at pre-measured distances along a line orthogonal to the sensors broadside direction, the pre-measured distances in side was, relative to the centre of the sensors, -5, -4, -3.5, -3, -2, -1, 0, 1, 2, 3, 3.5, 4 and 5 metres, where the negative sign indicates left of the centre line. For each reflector position the sensors measured the range and bearing over an interval of 10 seconds, then the reflector was moved to the next position sideways along the pre-measured line and this procedure was repeated until neither sensor were able to detect the reflector.

<table>
<thead>
<tr>
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<th>Range [cm]</th>
<th>Bearing</th>
<th>Range [cm]</th>
<th>$s_{Range}$ [cm]</th>
<th>Bearing</th>
<th>$s_{Bearing}$</th>
</tr>
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Table 3: Bearing parameters sensor 1.

<table>
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<tr>
<th>Side [m]</th>
<th>Range [cm]</th>
<th>Bearing</th>
<th>Range [cm]</th>
<th>$s_{Range}$ [cm]</th>
<th>Bearing</th>
<th>$s_{Bearing}$</th>
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</thead>
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<tr>
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<td>512</td>
<td>0.8</td>
<td>14.1491</td>
<td>0.3640</td>
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<td>536</td>
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<td>577</td>
<td>3.0</td>
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<td>4</td>
<td>649</td>
<td>38</td>
<td>633</td>
<td>9.6</td>
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<td>4.0947</td>
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<tr>
<td>5</td>
<td>707</td>
<td>45</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 4: Bearing parameters sensor 2.

From the experimental values in tables 3 and 4

- the majority of the difference between the mean range ($\overline{Range}$) and range,
are within twice the tabulated range resolution for the sensors.

- the standard deviation in range \( (s_{\text{Range}}) \) never exceeds 10 cm, a good indication on the sensors consistency and accuracy in measuring the range.

- the bearing follows the tabulated uncertainty in bearing well, table 2 on page 12.

- the deviation in measured bearing is small and never exceeds 5 \(^\circ\).

From the tables it is evident that the experimental values for the standard deviation in bearing is quite small and reasons for this might be the relative close proximity from sensor to target and the small size of our target and that the reflector was positioned with maximum exposure toward the sensors in mind. The small size of the reflector was needed to make the target a point target and minimize smearing due to size, i.e. deviation in bearing due to stray reflections from the sides of a larger reflector. The tables give that both sensors was equal in detection accuracy, while sensor 1 had slightly wider detection range. Both sensors, despite being able to detect a target, were not able to accurately determine the bearing to the target, this is illustrated in figure 16. The clustering in the figure indicates the upper range of the bearing for the sensors, and in this case it seems like \( \pm 30^\circ \) is the limit for this type of target.

![Graphical overview of reflector bearing](image)

Figure 16: Graphical overview of reflector bearing.

Since both sensors were prototypes, a degree of individuality was expected, as seen here where sensor 1 bearing range was slightly larger than that of sensor 2, the standard deviation was also lower for sensor 1.

From this it is evident that the sensors have good range accuracy and follows the given data well. The spread in measurements in the bearing was consistent, and the bearing while not very accurate is well within the tabulated data. Unless stated otherwise the deviation in bearing stated in the following experiments will be the tabulated deviation from section 1.3.4 at page 10.
3.1.2 A person at different distances

A test subject, approximately 1.75 metres tall, was placed directly ahead of both sensors, at distances spanning from 1 to 16 metres, with even increments of 1 metre, at each distance data sampling was done for 10-15 seconds. The sensors were placed side by side at a height of 1.1 metres above ground. The test subject had prior to the test removed from his body all items that possibly could interfere with the test, such as wallet, cellular, keys, etc. Looking at the plot of intensity versus range, figures 17(a) and 17(b), gave an indication of how the intensity decreases with range in the overlapping region of the receiver antennas for each sensor, and also a good approximation of the ratio of intensity versus range for a person moving around in front of the sensors.

![Graphs](image1)

Figure 17: Unedited sampled points, sensor 1 and 2.

As can be seen in figure 17(a) and figure 17(b), the intensity decreases quite rapidly, to level out at radial distance around 13 metres, at an intensity of 80 dB approximately 20 dB above the cut-off intensity.

![Graphs](image2)

Figure 18: Logarithmic fit of intensity vs. range.

To find the relation between the received intensity and the range to the
target, a logarithmic fit on the form $I = a + b \times 10 \times \log(R)$ was made. First all targets with intensity equal to zero and bearing outside $\pm 5^\circ$ was removed, the reason to remove targets with zero intensity is that the sensor has a -3dB cut-off level and thus targets with zero intensity is discarded. For the remaining targets the mean of the intensity was taken at all distances from the sensor to the maximum detected range, the increments in range is one centimetre. With the mean intensity versus radial range a logarithmic fit was made, the result can be seen in figure 18. The values in table 5 gives that the intensity decreases with range, approximately proportional to the inverse of the fifth and a third power of the range.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>a</th>
<th>95% confidence bounds</th>
<th>b</th>
<th>95% confidence bounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>135.2</td>
<td>133.8 - 136.7</td>
<td>-5.76</td>
<td>-5.95 - 5.56</td>
</tr>
<tr>
<td>2</td>
<td>128.4</td>
<td>126.2 - 130.6</td>
<td>-5.33</td>
<td>-5.61 - 5.04</td>
</tr>
</tbody>
</table>

Table 5: Coefficients for the logarithmic fit.

From the residuals of the fit it is evident that the fit is not so good, in the beginning it was alternating rapidly around zero and with range it was converging, but not toward zero. How well corresponds this with reality, since the exposed area of the target that reflects the E-M waves increased until the lobe entirely covered the target. This should be at a range of about 7-8 metres, taking into account the sensors position. A possibility was that the lobes elevation coverage decreases with range, and this would give that the coverage would increase over a longer distance and thus the drop would come further away. From figures 17(a) and 17(b) the expected drop does not come until at a range of about 10 metres, indicating a possible decrease in the elevation coverage at this range.

To check how well the sensors were aligned a comparison of the intensity values below 90 dB in figures 17(c) and 17(c) were made. Making histograms for the sensor data it is evident from figure 19 that for sensor 1 the bulk of the low intensity readings were centred around $\theta=0^\circ$, while for sensor 2 the bulk of the low intensity readings were centred around $\theta=4^\circ$. It is evident that sensor 2 was dislocated with respect to sensor 1 by an angle of $4^\circ$, this dislocation is evident in figure 21(a), after applying a $4^\circ$ correction of the data from sensor.
The large angular discrepancy in bearing at short distances was due to basic trigonometric relations, since the test subject was placed directly ahead of both sensors the difference in bearing should go toward 0 as the range to the subject increases, as in case of sensor 1.

Although the test subject was placed along a line orthogonal to the sensors, figure 20(a) and figure 20(b) indicates that the deviation of the bearing increases with range, in the plots the standard deviation for the bearing has been added and an overlap of neighbouring points can be seen. Since it was known that the target was stationary, the reason for the deviation of the measured points was probably uncertainties in the measurement due to fluctuations in the signal and also to some part the width and height of the target, since the target cross section increases with the distance. Taking into account that the bearing standard deviation, as seen in table 2 at page 12, increases quite rapidly, with the result clearly visible in figure 21(a).

From this it is evident that the lobes elevation coverage is less than the tabulated 8°, from the intensity versus range plots there is a significant drop at around 9 metres, taking \[ \arctan \left( \frac{1}{9} \right) = 6.97 \approx 7 \] this would give a lobe elevation value of 7° at 9 metres.
3.1.3 A person walking

A test subject walks in front of the sensors at distances 1, 3, 4, 5, 6, 7, 8 and 10 metres. The subject walks in right angle to the sensors and increases the distance for each pass. The sensors are placed side by side, at a height of 1.1 metres above ground. As the previous section all interfering equipment were removed from the test subject. As can be seen in figure 22(a) and figure 22(b) and in the previous section, 3.1.2, the intensity decreases quite rapidly to level out at an intensity of just above 80. The interesting part here is the distinct target at 16 metres; a lamp pole in the background.

![Figure 22: Unedited sampled points, sensor 1 and 2.](image)

The lamp pole had a diameter of 15 cm and gives an echo at a range of 16 metres, the intensity of the pole is approximately the same as that of a person at 9-10 metres. The high intensity of the echo is most certainly due to the fact that the pole is made of a material that is a good conductor, the pole can be seen as a cylindrical target made of a metal.

![Figure 23: Standard deviation of mean sampled points, sensor 1 and 2.](image)

As can be seen in figure 23 when the target is almost out of the sensors coverage the bearing becomes rapidly more uncertain, leading to the more zigzag like pattern in the plot when in the outskirts of the lobes coverage. When adding the standard deviation of the bearing and looking at the overlap, it is reasonable to assume that the accuracy of bearings over 25˚ is quite low. Comparing the data from both sensors it is clear from figure 23 that the sensors deviate little in range, while the deviation in the bearing increases rapidly at approximately 20˚. The overlay in figure 24(a) indicates good alignment of the sensor units,
and that both of the sensors detected the lamp pole. The effect of the deviation in bearing is illustrated in figure 24(b), which gives that the lamp pole was at 16 metres and had a lateral displacement somewhere between 1 metre and 4 metres, which gives a spread of 3 metres in side. This despite the relatively small standard deviation of the bearing, probably due to the fact that the target is a good reflector.

(a) Edited sampled points sensor 1 and 2. (b) Range vs. lateral displacement, both sensors.

Figure 24: Overlay of both sensors.
3.1.4 The coverage of the radar lobes

The test subject walked predefined, evenly spaced lines, with a spacing of one metre. The lines were parallel with the broadside direction of the sensors. These lines were placed from the sensors to a distance of 17 metres. The test subject walked in an evenly pace, at a speed of approximately 2 metres per second and made two passes per distance. As in the previous sections the test subject had prior to the test removed all items that possibly could interfere with the test. The sensors were mounted in horizontal position at a height of 1.1 metre.

This experiment holds similarities with the experiment in the previous section, but here the aim was to find the coverage of the sensor lobes. The range and width of the walked path was increased, all to give a more comprehensive plot of the coverage.

![Figure 25: Standard deviation of mean sampled points, radar 1 and 2.](image)

As can be seen in figure 25 the detected bearing decreases with range, this can be interpreted as range increases only the area with lobe coverage from both the receiver antennas of the sensor gives target indication. From the figure it is evident that both sensors had slightly better coverage on the left side, interesting is that the bearing coverage of the lobe continuously decreases until at a range of 13 metres where the lobe has almost no coverage and then from 14 to 15 metres suddenly both sensors had a coverage in bearing from $-15^\circ$ to $5^\circ$. At this long range the deviation in bearing, although small, gives large displacement in side, which is evident when the spherical coordinates is transformed to Cartesian, seen in figure 26.

Figure 26 is a good illustration of the sensors detection range and width for humans of normal size and build, but it is evident that the sensors can not guarantee detection at ranges farther than 13 metres, the area at range 13 to

41
15 metres, where there seems to be an outlier, this area can not be considered an area were the sensors can guarantee detection. From the figure it seems that the lobe is asymmetrical.

From figure 26 the area of good coverage can be outlined as:

- in the range from 0 to 4 metres the lateral coverage increases approximately linearly, with 0.8 metre laterally/metre in range.
- in the range from 4 to 10 metres there is $\pm 3.5$ metres lateral coverage.
- from 10 to 13 metres the bearing coverage narrowing to almost nothing.
3.1.5 A birch

A trolley with a sensor mounted on top of it, was rolled toward a birch, the birch had a diameter of 25 cm. On its way toward the birch the trolley stopped at even increments of 1 metre for a period of 10 seconds, this procedure was repeated until at a distance of one metre from the birch. Due to the fact that the ground was uneven, the trolley was unable to move in an exactly straight line, as can be seen in figure 27(b). From figure 27(a) it is evident that the intensity peaks at 120 dB at a distance of 1 metre and decreases with range.

![Sampled points](image1)

(a) Radar 1, range vs. intensity.  (b) Radar 1, range vs. lateral displacement.

Figure 27: Sampled points.

![Logarithmic fit](image2)

Figure 28: Logarithmic fit of intensity vs. range for the birch.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>a</th>
<th>95% confidence bounds</th>
<th>b</th>
<th>95% confidence bounds</th>
</tr>
</thead>
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<td>100.8 - 105.6</td>
<td>-3.44</td>
<td>-3.77 - -3.11</td>
</tr>
</tbody>
</table>

Table 6: Coefficients for the logarithmic fit.

To find the relation between the received intensity and the range to the birch a logarithmic fit is made on the target data, the fit is on the form $I =$
\[ a + b \times 10 \times \log(R) \]. As in the previous section, section 3.1.2, all targets with intensity equal to zero and bearing outside ±5° was removed, the reason to remove targets with zero intensity is that the sensor has a -3dB cut-off level. With the mean intensity versus radial range a logarithmic fit was made, the result can be seen in figure 28. The values in table 6 gives that the intensity decreases with range. Comparing with values from section 3.1.2 it is evident that there are some discrepancies but one possible reason might be the target, a birch constitutes a slender elongated target it is generally quite high, in our case around 5 metres. A person might also be considered a slender and elongated target, while the person is slightly wider than the tree, the person will hardly be taller than 2 metres. Thus a person would give a stronger reflection initially, but after a distance the total area of the person exposed for the sensor will be illuminated, while the illuminated area for the birch will continue to increase for a longer distance.
3.1.6 A spruce

The experimental set-up in this experiment is similar to the experiment in the previous section, but here the target were a spruce with the diameter 25 cm. A trolley, with a sensor attached to it, was rolled toward the spruce, on its way toward the spruce the trolley stopped, at even increments of 1 metre, for 10 seconds until it reached a distance of one metre from the spruce. Due to the fact that the ground was uneven the trolley was unable to move in an exactly straight line, as can be seen in figure 29(b).

Figure 29: Unedited sampled points.

Figure 30: Logarithmic fit of intensity vs. range for the spruce.

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</table>

Table 7: Coefficients for the logarithmic fit.

To find the relation between the received intensity and the range to the
spruce a logarithmic fit is made on the target data, the fit is on the form

\[ I = a + b \times 10 \times \log(R) \].

As in the previous sections, section 3.1.2 and section 3.1.5, all targets with intensity equal to zero and bearing outside ±5˚ was removed, the reason to remove targets with zero intensity is that the sensor has a -3dB cut-off level. Looking at the residuals of the fit it With the mean intensity versus radial range a logarithmic fit was made, the result can be seen in figure 30. The values in table 7 gives that the intensity decreases with range. Comparing with values from the previous tree section 3.1.5 it is evident that there are some minor discrepancies and one possible reason here might be that, while both targets are trees, they have different compositions and their branches are oriented differently; the birch has small slender hanging branches and the spruce's branches are a thicker and horizontal.
3.1.7 A grove

Comparison between a group of birches with and without a test subject. The radar was placed in front of a small birch grove, both sensors placed horizontally on the tripod, as can be seen in figure 31. As in the previous measurement with only one birch, see section 3.1.5, the target intensity of the birches are approximately 20 dB above cut-off.

Figure 31: A group of trees.

![Figure 31: A group of trees.](image)

(a) Radar 1, range vs. intensity.

(b) Radar 2, range vs. intensity.

(c) Radar 1, \( \phi \) vs. intensity.

(d) Radar 2, \( \phi \) vs. intensity.

Figure 32: Unedited sampled points for a group of trees, radar 1 and 2.

When comparing the intensity for the two samplings, figure 32 and 33, it is apparent that the person has a higher intensity and whilst among trees a person
Figure 33: Unedited sampled points for a group of trees with the test subject, radar 1 and 2.

is clearly discernible among the echoes. At least for trees with a diameter around 25 cm.

Figure 34: Histogram for the bearing.

To obtain the bearing to the targets can be achieved either by taking a histogram as seen in figures 34 and 35, or by taking the mean of the bearings at different ranges. A histogram gives a good indication on the different bearings, especially if two or more targets are adjacent and this would be represented by two or more peaks while taking the mean only would give one value.

The mean values for the bearing is rounded to integer since the sensor is only able to give the bearing in integers.

Comparing the target bearing given by the histograms with the means of the bearings, as found tabulated in tables 8 and 9, gives that the numbers corresponds well.
Table 8: Cluster targets, sensor 1.

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<tr>
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<td>3.3 m</td>
<td>30°</td>
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Table 9: Cluster targets, sensor 2.

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<tr>
<td>9 m</td>
<td>8°</td>
</tr>
<tr>
<td>3.5 m</td>
<td>35°</td>
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<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 36: Standard deviation of mean sampled points for the group of trees without the test subject, radar 1 and 2.
From figure 36 and figure 37 it is evident that the accuracy in range is good and that the size of the target clusters are small in comparison with the standard deviation in bearing of the sensors.

In figure 38, the spherical coordinates has been converted to Cartesian coordinates, comparing these figures with the photo of the set-up, figure 31, it is possible to identify the trees corresponding to target clusters in the plots.
3.1.8 Workshop test run

A test run with the experimental tilt cradle was done inside the TFE workshop. The experimental set-up can be seen in figure 39 and the results can be seen in figure 40, a three dimensional plot where the x-axis represents time, the y-axis target channels and z-axis intensity. Every time the cradle changes elevation angle the cradle goes from current angle to maximum elevation angle down to next elevation angle, this can be seen represented in figure 40 as small peak followed by a plateau followed by a second peak, the peaks are due to the fact that the radar for a short period of time looses all targets.

![Figure 39: The radar in the cradle in the workshop.](image)

![Figure 40: Plots for the ten targets.](image)

After extracting the data for each elevation and removing data representing
no targets, the data can be plotted in a plot for each elevation, as seen in figure 41.

Figure 41: Error in range.

Converting the spherical coordinates to Cartesian and making an incision plot, figure 42. From the picture of the shop it is evident that there were a lot of equipment and other metallic items in front of the radar, this is clearly visible on these plots.

As a conclusion of this test it is evident that the measurements can be simplified without reducing the accuracy, actually there might be an increase in elevation accuracy thanks to the servo’s stepper engine, since the accuracy has in previous and following measurements was limited to how well the alignment
of the tilt swivel head. This also increased the speed of measurements, since the majority of time used for each measurement were utilized to make certain that the sensors were well aligned, and what elevation angle they had.
3.2 Results obtained from the Kiruna Mine

In the Kiruna mine measurements were taken at two places; in a tunnel with a drop shaft and in a tunnel were a slope of gravel was primed for demolition. In the tunnel with the drop shaft the ore content of the rock was low, the rock constituted of what in Swedish is called ‘Gräberg’, while the rock in the tunnel with the slope were an ore rich environment, this was the case for both the gravel in the slope as the rocks surrounding it.

![Figure 43: An overview of the tunnel with the drop shaft.](image1)

![Figure 44: A close-up on the drop shaft opening.](image2)

In figure 43 illustrating the tunnel with the drop shaft, notice the wires hanging from the ceiling and how they bundle up at a height approximately 1.5 metres above the ground. These wires was used to guide the truck drivers to
the drop shaft and when to stop. Notice also the shafts reinforced opening, seen in figure 44, and the metal clad walls of the shaft.

![Figure 45: Schematic drawing of the tunnel.](image)

A representation of the distance from the radar to the wires, shaft and wall can be seen in figure 45.

An overview of the slope of gravel can be seen in figure 46, notice the electrical wires that lay on the slope. This is clearly visible in the close-up, figure 47.

![Figure 46: A picture of the slope.](image)

From the pictures it is hard to get a feel of the sheer size of these tunnels, but both tunnels were large, the height of both tunnels were in the range of 5 metres and the width approximately 7 metres.

The different sensor alignment used in the measurements in the mine can be seen in figure, 48, in the sensor pairs the left sensor is sensor 1 and the right sensor is sensor 2. When the sensors were in upright position the distance from the rotational axis to the centre of each sensor was 12.5 cm, when the
Figure 47: A close-up of the electrical wires on the slope.

Figure 48: Sensor positioning in the different measurements, seen from the front.
3.2.1 Dropshaft with both sensors in vertical orientation

In the first measurement for the tunnel with the drop shaft, both sensors were placed in a vertical position on the metal rail, the rail was in turn mounted on top of the tripod. The sensors were evenly spaced on the rail and the tripods swivel-tilt head was attached to the metal bar directly between the sensors. A photo of the tunnel can be seen in figure 43 on page 54, a close-up of the dropshaft in figure 44 and on page 54 and a schematic representation in figure 45 on page 55.

Six sets of data were taken, each set at a specific bearing angle, with respect to the tripods centre axis and the horizontal plane. The bearing angles were -70°, -50°, -20°, 0°, 20° and 50°, where the negative sign indicates the anticlockwise direction and 0° represents the direction straight ahead.

![Graphs showing range vs. intensity and elevation vs. intensity for sensor 1 and sensor 2.](Graphs)

Figure 49: Unedited sampled points.

Of the data the sensors gather, only the range, bearing and intensity is of interest, since both sensors are in upright position the measured sensor bearing becomes the elevation. The unrefined data of all targets can be represented in plots with radial range versus intensity, elevation versus intensity and range versus elevation, as seen in figure 49. Even if it is hard to get a good feel of what the sensors detect from these plots, it is visible that sensor 1 indicates three distinct areas where the intensity was higher than 90 and sensor 2 indicates only one distinct peak. The areas of interest for sensor 1 are at a radial range of 4-5 metres, at 7 metres and at 10 metres, The high intensity areas are all within the elevation of -5° - 25°. From sensor 2 only a minor peak in intensity at 4 metres and at elevation of -8° is detected, both sensors gives indication at a distance which corresponds to the distance of the hanging wires, figure 45.

Taking the mean radial range versus the elevation and the standard deviation for the elevation of both sensors and comparing for each specific angle of
Figure 50: Sampled targets with deviation in measured bearing.
rotation, it is obvious by inspection that there are a distinct difference between the two units, as can be seen in figure 50. Looking at the figures, a lot of smearing can be seen and as most of the standard deviation of the bearings overlap, the target reflections were probably due to a distributed target. Knowing that most of the targets were from the walls and floor in the tunnel, which constitutes a distributed target with a rugged surface and that the error in elevation increases according to table 2 and that the influence of the lateral error increases with range, as can be seen in table 1. Especially figure 50(e) indicates that there might be something in front of the sensors at a height higher than 1.1 metre at a distance around 4 metres and in figure 50(f) the convex smearing at range 4-4.5 metres might be reflections from the wall, even if the plot in spherical coordinates are good to indicate the deviation in bearing and how many of the targets in clusters might originate from the same point, it does not have good intuitive spatial mapping.

But there is a large amount of targets detected at distances beyond the rear wall at 7-8 metres, this is even more evident when converting the echoes from spherical to Cartesian coordinates, as seen in figure 51. Looking at figures 51(c), 51(d) and 51(e) in these figures the majority of the targets at a height of more than 2 metres is not located at the presumed distance of 7 – 8 metres, but at distances between 9-12 metres. The most probable reason for the echoes at distances beyond the rear wall is that the waves was reflected from more than one surface before the detected by the sensor, as an example a wave reflected from the ceiling to the wall and then to the sensor.

To illustrate this in a way that is easier to perceive all targets are transformed into the Cartesian coordinate system, from this incision plots are made with even
increments in height, illustrated in figure 52. One interesting thing is that the area where the wires were located, only the plots in figures 52(b) and 52(c) indicates a target while the rest of the plots show no sign of the wires. In figures 52(b)-52(f) the side walls are clearly defined by the lack of targets on the left side beyond 4 metres and the right side beyond 3 metres, and from these plots it looks like the wall behind the shaft is sloping. There were a slight inclination of the rear wall, but the most part of this is probably due to the multiple reflections of the waves on more than one surface. This shows that sensors in this orientation is relatively good at detecting walls, but not thin vertical objects, such as the wires. This might be because the wires are oriented in the same direction as the sensors azimuthal and thus the target cross-section per degree in azimuthal direction is very small and the sensors might ignore it for targets with higher intensity such as the walls, floor and shelf.

Another not so suitable, but easy to interpret, way to represent the data in Cartesian coordinates is to make a two dimensional extrapolated contour plot, taking the target data for sensor 1 and 2, and linearly extrapolating the points in between, where the isograms represents the height or the signal intensity. A serious drawback with this approach is that any outlier might skew the contour plot, as an example if the majority of targets at a specific range originate from the ground and a few reflections from ceiling, these reflections might increase the mean and thus give an elevation in the countour. Contour plots of the combined sampled data from radar 1 and radar 2 can be seen in figure 53. A ridge like formation is observable at a distance of 4-4.5 metres followed by a drop at 6-6.5 metres and then a new ridge at 7.5-8 metres, which could be interpreted as the rear wall. This corresponds well to the layout of the tunnel.

In the plot, figure 53, sensor 2 height contour a distinct dip in height is located at 6 metres, this dip is probably from reflections of the shaft but due to outliers in the measurements due to uncertainties when measuring the elevation in the shaft. In general these data corresponds well with the data from sensor 1.
Figure 52: Distance vs. lateral displacement.
(a) Sensor 1, height contour
(b) Sensor 1, intensity contour
(c) Sensor 2, height contour
(d) Sensor 2, intensity contour
(e) Sensor 1 and 2, height contour
(f) Sensor 1 and 2, intensity contour

Figure 53: Extrapolated values.
In the second experiment the measurements were taken with sensor 1 placed in horizontal position, while sensor 2 was placed in vertical position, as in the previous section. The set-up is rotated around centre axis of the tripod and measurements are taken at angles $-70^\circ$, $-50^\circ$, $-20^\circ$, $0^\circ$, $20^\circ$ and $50^\circ$, where the negative sign indicates anticlockwise direction of rotation and $0^\circ$ is straight ahead. This gives that the data from sensor 1 is only in two dimensions, actually this is not entirely true since the lobe has a spread of $\pm 8^\circ$ in the direction orthogonal to the azimuthal, the effect of this is illustrated in table 1 on page 11. The layout of the tunnel and positioning of the apparatus is the same as in the previous section, both sensors are placed on a rail, the rail was mounted on top of the swivel-tilt head of the tripod.

Figure 54: Unedited sampled points.

From figure 54 both sensors indicates a significant reflection at a radial distance of approximately 4 metres and a potential second reflection at approximately 7 metres and sensor 2 indicates a third reflection at 10 metres. From sensor 1 it is clear that the targets are at the bearing angles $-30^\circ$, $5^\circ$, $-15^\circ$ and $45^\circ$ and sensor 2 gives that the targets are at elevation angles $-10^\circ$ and $10^\circ$.

Since the sensors are orthogonal with respect to each other, the azimuthal of the lobe of sensor 1 lay in the horizontal plane and sensor 2 is in plane spanned orthogonal to this at each rotational angle. Thus the mean bearing with standard deviation of the bearing for sensor 1 can be plotted in one plot, figure 55. From this plot the walls seem to be located around bearings $-75^\circ$ and $75^\circ$, knowing where the wires were located it is clear that the echoes between $\pm 25^\circ$ at a range of 4-4.5 metres is the reflections from the wires.

For sensor 2 the mean bearing with standard deviation is plotted for each
Figure 55: Sensor 1 mean range vs. bearing and standard deviation of bearing, at elevation=0˚.

Figure 56: Deviation in bearing in sampling.
angle of rotation respectively, figure 56, as in previous section a lot of smearing can be seen, most probable due to reflections from the walls of the tunnel, potential reflections that would correspond to targets beneath the floor can most certainly be ascribed to the deviation in bearing, as can be seen in table 2 on page 12.

Since it is known that the wires are hanging down from the ceiling at around 4.4 metres, this is an interesting region in the plot, so is the 5-6 metre region where the dropshaft is located. From the close-up of the dropshaft, figure 44 at page 54, it is evident that the opening is a thick metallic plate with the shaft clad with metal, thus should give a better reflection than the surrounding rock surface. In both figures there are distinct echoes around the 4.5 meter region, figure 55 indicates several bearings in this region.

To simplify further analysis the sampled data is converted from spherical coordinates to Cartesian coordinates. In figure 57 incision plots in the X-Y plane can be seen, each plot represents spans values within one metre in height.

An easier to comprehend, but not so suitable, way to represent the data in one two dimensional plot is the contour plot, where the isogram represents the extrapolated values of the height or the signal intensity.

Combining the sampled data from sensor 1 and sensor 2 is only interesting for the intensity plots, since sensor 1 can not give accurate height information, the result can be seen in figure 60.
(a) Measured values below $z=0$ m.

(b) Measured values between $z=0$ m and $z=1$ m.

(c) Measured values between $z=1$ m and $z=2$ m.

(d) Measured values between $z=2$ m and $z=3$ m.

(e) Measured values between $z=3$ m and $z=4$ m.

(f) Measured values between $z=4$ m and $z=5$ m.

(g) Measured values above $z=5$ m.

Figure 57: Horizontal incision in the measured values.
Figure 58: Extrapolated contour plot, sensor1.

Figure 59: Extrapolated contour plot, sensor2.

Figure 60: Combined extrapolated contour plot.
In the third, and final, experiment in the drop shaft tunnel, both sensors were placed in a horizontal position on a rail, the rail is mounted on top of a tripod. The sensors were evenly spaced on the rail and the centre is directly above the tripods centre axle.

14 sets of data were taken, each set at a specific elevation angles, with respect to the tripods centre axis and the horizontal plane. The elevation angles were $51^\circ$, $32^\circ$, $28^\circ$, $24^\circ$, $19.5^\circ$, $15.5^\circ$, $7.5^\circ$, $4.5^\circ$, $0^\circ$, $-3^\circ$, $-9^\circ$ and $-16.5^\circ$.

![Figure 61: Unedited sampled points.](image)

Of the data the sensors gather, only the range, bearing and intensity, is of interest. the unrefined data of all targets can be represented in plots with range vs. intensity and bearing vs. intensity, as seen in figure 61. Even if it is hard to get a good feel of what the sensors detect from these plots, it is visible that sensor 1 indicates three distinct areas of higher intensity and sensor 2 indicates only one distinct peak. The areas of interest for sensor 1 are at a range of 4-5 metres, at 7 metre and at 10 metre. The high intensity areas are all within bearing $-5^\circ$ to $25^\circ$. From sensor 2 only a minor peak in intensity at 4 metres and at bearing $-8^\circ$ is detected, both sensors gives indication at a distance which corresponds to the distance of the hanging wires, figure 45.

Taking the mean and standard deviation for both sensors and comparing for each specific angle of elevation, it is obvious by inspection that there are a distinct difference between the two units, as can be seen in figure 62. It seems like sensor 2 might be more sensitive than sensor 1, since it has more sampled points.

Looking at figure 62, a lot of smearing can be seen. Notice the convex shape of the smearing, this is a good indication that the echoes comes from a flat surface, it is known that most of the targets were from the walls, ceiling and floor of the tunnel. The shelf where the drop shaft were located is slightly less
(a) Measurement at elevation=51˚.

(b) Measurement at elevation=32˚.

(c) Measurement at elevation=28˚.

(d) Measurement at elevation=24˚.

(e) Measurement at elevation=19.5˚.

(f) Measurement at elevation=15.5˚.

(g) Measurement at elevation=7.5˚.

(h) Measurement at elevation=4.5˚.

(i) Measurement at elevation=0˚.

(j) Measurement at elevation=-3˚.

(k) Measurement at elevation=-9˚.

(l) Measurement at elevation=-16.5˚.

Figure 62: Uncertainty in sampling, both sensors.
than half a metre above the ground and in figure 62(j) the shelf can be seen as convex smearing. Since it is known that the wires were hanging down from the ceiling at around 4.4 metres, this is an interesting region in the plot as is the 5-6 metre region where the drop shaft is located. A lot of targets at distances beyond the rear wall can be seen, a good example is figure 62(l), here the sensor was placed 1.1 metre above the ground and with a downward angle of $-16.5\,^\circ$ the floor should be detected at a distance of 3.7 metres. Taking into account the spread of the lobe, $\pm8\,^\circ$, the floor should be detected within 2.4-7.4 metres. From the figure a large number of targets were visible at 10.5 metres, it is highly likely that this is due to multiple reflections. Comparing these plots with the plots in the previous sections these gives the strongest indication to where the wires are hanging down, but instead the side walls are not detected at all, this might be because of the same reasons the wires are not detected with the sensors in vertical orientation, section 3.2.1.

From figure 64 it is evident that changing the orientation of the sensor does not prevent the occurrence of multiple reflections. There is a void located in the same region as in figure 51(d) in section 3.2.1.

Combining the sampled data from sensor 1 and sensor 2, and extrapolate the height and intensity, the result is illustrated in figure 65. From the figures there are observable peaks at 4 and 7 metres, corresponding to the wires and the wall. If the values beyond 8 metres were to be ignored it is likely that the contour plot in this case would be a quite good representation of the tunnel, but caution should be taken with respect to false readings.
Figure 63: Distance vs. lateral displacement.
Figure 64: Sideview of all targets.
Figure 65: Extrapolated contour plots.
3.2.4 Slope with both sensors in vertical orientation

In the first experiment in the tunnel with the slope of gravel, both sensors were placed in a vertical position on the rail, the rail is mounted on top of a tripod. The sensors are evenly spaced on the rail and the centre is directly above the tripods centre axle. A photo of the tunnel with the slope can be seen in figure 46 on page 55.

Six sets of data are taken, each set at a specific rotation angle with respect to the tripods centre axis and the horizontal plane. The rotational angles are -70˚, -50˚, -20˚, 0˚, 20˚ and 50˚, where the negative sign indicates the anticlockwise direction and zero rotation is directed forward.

![Sensor 1, range vs. intensity.](image)

![Sensor 1, elevation vs. intensity.](image)

![Sensor 2, range vs. intensity.](image)

![Sensor 2, elevation vs. intensity.](image)

Figure 66: Unedited sampled points.

As in the previous sections, of the data the sensors gather, only the range, bearing and intensity is of interest, in our case with both sensors in vertical position the bearing becomes elevation. The unrefined data of all targets can be represented in plots with range versus intensity and bearing versus intensity, as seen in figure 66. Even if it is hard to get a good feel of what the radars detect from these plots, it is visible that sensor 1 indicates three distinct areas of intensity higher than 100 in the range interval 3.5-5 metres and sensor 2 indicates only one distinct peak at a distance of 4 metres. These peaks are at a range that corresponds well with the distance to the electrical wires that lay on the slope.

Looking at figure 67, a lot of smearing can be seen, knowing that most of the targets are from the slope and some from the walls of the tunnel, which both
Figure 67: Deviation in bearing in sampling.
constitutes a rugged distributed target and that the influence of the lateral error increases with range, as can be seen in table 3.2.1.

Especially figure 67(d) indicates that there might be a slope straight ahead. From figures 67(b) to 67(f) it is evident that an object is positioned to give an echo at the range 6 metres and the elevation 20˚, taking a look at the picture of the slope, figure 46 on page 55, the conclusion would be that this echo is from the wires that hangs from the ceiling and converges with the slope.

\[\text{(a) Measurement at } -60^\circ\text{ rotation.}\]
\[\text{(b) Measurement at } -40^\circ\text{ rotation.}\]
\[\text{(c) Measurement at } -20^\circ\text{ rotation.}\]
\[\text{(d) Measurement at } 0^\circ\text{ rotation.}\]
\[\text{(e) Measurement at } 20^\circ\text{ rotation.}\]
\[\text{(f) Measurement at } 40^\circ\text{ rotation.}\]

Figure 68: Sampled targets with height and range in the measured bearings.

To illustrate the measured targets in a way that is easier to perceive the spherical coordinate system is transformed to the Cartesian and incisions are made at even increments in height, illustrated in figure 69.

Another not so suitable way to represent the data in Cartesian coordinates is to make a two dimensional extrapolated contour plot, where the isograms represents the height or the signal intensity. A serious drawback with this approach is that any outliers, as an example let the majority of targets at a specific range originate from the ground and a few from ceiling reflections, these reflections might increase the mean and thus give an elevation in the contour. Contour plots of the combined sampled data from sensor 1 and sensor 2 can be seen in figure 70.
(a) Measurement below $z=0$ m.
(b) Measurement between $z=0$ and $z=1$ m.
(c) Measurement between $z=1$ and $z=2$ m.
(d) Measurement between $z=2$ and $z=3$ m.
(e) Measurement between $z=3$ and $z=4$ m.
(f) Measurement between $z=4$ and $z=5$ m.

Figure 69: Distance vs. lateral displacement.
Figure 70: Extrapolated contour plots.
3.2.5 Slope with one sensor in vertical and one in horizontal position

Measurements were taken with the azimuthal orientation of sensor 1 vertical position and the azimuthal of sensor 2 in horizontal position. Both radars are placed on a rail on top of a tripod, the positions of the sensors are illustrated in figure 48(b). The set-up is rotated around the centre axis of the tripod and measurements are taken at angles -70°, -50°, -20°, 0°, 20° and 50°, where the negative sign indicates anticlockwise direction of rotation. This gives that the data from sensor 1 will only span two dimensions, actually this is not entirely true since the lobe has a spread of $\pm 8^\circ$ in the direction orthogonal to the azimuthal, the effect of this can be seen in table 1 on page 11.

Figure 71: Unedited sampled points.

Looking at figure 72, a lot of smearing can be seen. Knowing that most of the targets are from the walls of the tunnel, which constitutes a rugged distributed target and that the influence of the lateral error increases with range, as can be seen in section 1.3.4.

Figure 72 is a good illustration of the uncertainty in bearing, where each sampled mean is plotted with an error bar illustrating the uncertainties in bearing. An interesting aspect is to look at how the points are distributed and how they cluster around each other at certain distances.

To simplify further analysis the sampled data is converted from spherical coordinates to Cartesian coordinates. In figure 73 incision plots in the X-Y plane can be seen, each plot represents target values within a one metre span in height.

An easier to comprehend, but not so suitable, way to represent the data in one two dimensional plot is the contour plot, where the isogram represents the extrapolated values of the height or the signal intensity.

Combining the sampled data from sensor 1 and sensor 2, and extrapolate the height and intensity the result can be seen in figure 75.
Figure 72: Deviation in bearing in sampling.

Figure 73: Horizontal incision in the measured values.
Figure 74: Extrapolated contour plot, radar1.

(a) Sensor 1, intensity contour.

(b) Sensor 2, intensity contour.

Figure 75: Extrapolated contour plot, radar2.

(a) Sensor 2, height contour.

(b) Sensor 2, intensity contour.
3.2.6 Improving the accuracy in elevation and bearing

The sensors only report bearing in the azimuthal plane and in some situations it would be a good thing to be able to determine not only range and bearing, but also elevation to a target. One method to improve the bearing and elevation accuracy is to utilize two sensors, mounted orthogonal with respect to each other, and combine the overlapping measured target data, as illustrated by squares in figure 76.

![Figure 76: Area of overlapping data.](image)

As an example the data from the measurements made in sections 3.2.2 and 3.2.5 could be used.

The first step would be to remove all data that is outside the volume where the lobes intersect. Stated in the properties for the sensors, the sensor covers a volume spanned by ±8° in elevation and ±65° azimuthal, to compensate for the fact that the sensors are mounted a bit from each other, might be a slightly misaligned and the error in bearing, all the targets outside ±13° are removed.

The next step is how to combine targets that sensor 1 detects with target detected by sensor 2, considering that the number of targets each sensor detects varies, as illustrated in figure 77 only one rotation is illustrated.

![Figure 77: Overlapping targets at rotation 0°.](image)

The first step here is to calculate the mean bearing and mean elevation for each range, then to combine targets at the same distance. Considering that it is highly unlikely that both radars will give the same distance for a target,
partly due to errors in determining the range but also due to how the set-up is oriented, an overlap in range within a reasonable margin must be allowed.

Despite the fact that this method gives range, bearing and elevation to a target, there is a major drawback with this method, the process of getting these values removes the majority of the targets as seen in table 10.

The remaining targets is illustrated in figures 78 and 79, from the data it is known that the height for the overlapping points for the drop shaft spans from just above -0.5 metres to just under 3 metres, and for the slope the span is 0 to 2.5 metres.

Figure 78: Distance vs. lateral displacement for overlapping targets, drop shaft.
(a) Height between 0 to 1 metres.  
(b) Height between 1 to 2 metres.  
(c) Height between 2 to 3 metres.

Figure 79: Distance vs. lateral displacement for overlapping targets, slope.
4 DISCUSSION

4.1 CONCLUSIONS

The conclusions that can be drawn from the previous sections are as follows:

From section 3.1.1, in conjunction with section 3.1.4, the bearing range for small targets, such as humans, at a range of less than a metre is ±40˚ and at a distance of five metres the bearing range has decreased to ±30˚. The bearing range continues to decrease with the distance and at a distance of 13 metres it has gone to zero. Translated into Cartesian coordinates this gives that the radar lobe spans an approximate rectangle with side ±3.5 metres and a depth of 13 metres.

The radar lobe coverage stated above is valid for humans only, from section 3.1.3 the difference in detection ranges for a human and a metallic object can be observed. The lamp pole is clearly visible beyond the radars detection range for humans. The bearing deviation for the pole corresponds to the tabulated deviation in bearing. This gives that the radar lobe coverage for metallic objects are at least as good as for humans and depending on the size of the object probably better.

The theoretical and measured relation between distance and intensity for the reflected power of the transmitted power differs somewhat, as can be seen in sections 3.1.2, 3.1.5 and 3.1.6. The received intensity can be written on the form $I = a + b \cdot 10 \cdot \log(R)$, where $a$ is the the logarithm of the coefficients related to the antennas directive gain and radiation loss, the one way power loss to and from the target, the cross-section of the target and the wavelength of the radar. While $b$ is the coefficient of the range. How the coefficients differs with different targets is illustrated in table 11, it is apparent that human echoes has higher intensity but it decays rapidly with range, while for trees has lower reflectivity than humans while their coverage in height increases with the distance and thus increases the cross-section.

<table>
<thead>
<tr>
<th>Object</th>
<th>Radar 1 a</th>
<th>Radar 1 b</th>
<th>Radar 2 a</th>
<th>Radar 2 b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human</td>
<td>135.2</td>
<td>−5.76</td>
<td>128.4</td>
<td>−5.33</td>
</tr>
<tr>
<td>Birch</td>
<td>103.2</td>
<td>−3.44</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Spruce</td>
<td>105.9</td>
<td>−3.28</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 11: Coefficients for the logarithmic fit.

In section 3.1.7 the comparison between trees in a grove and a human showed that a human was clearly distinguishable from trees when comparing the intensity from trees and a human at the approximate same distance. The difference in intensity is roughly 30 dB from the peak value for the intensity of the different echoes.
From section 3.1.8 it is clear that with large number of measurement and small enough steps in elevation a more or less comprehensive mapping of the volume in front of the radar is possible.

From sections 3.2.1 and 3.2.4 it is evident that placing the radar in vertical orientation is good for detecting object like walls, this is valid even if the walls are oriented at an angle with respect to the sensor. The sensor in this orientation is not good at detecting slender objects, such as wires, oriented in the same direction as the radar.

From sections 3.2.2 and 3.2.5 and 3.2.6 it is evident that placing one radar in horizontal orientation and one the radar in vertical orientation is good for increasing the spatial coordinates for the targets, but unfortunately this decreases the number of targets.

From section 3.2.3 it is evident that placing the radar in horizontal orientation is good for detecting slender targets, such as wires, in vertical orientation and walls orthogonal to the radars transmission direction. The radar in this orientation is bad at detecting tunnel walls parallel with the direction of the beam, this might mainly depend on the large amount of targets directly ahead of the sensor, this has probably something to do with the algorithm the radar uses to prioritise the targets.

From all the measurements in the mine there is evidence that the radar waves has a high tendency to bounce on multiple surfaces and thus create false echoes or worse not properly detect targets. With this in mind, care should be taken when utilising the radars in an confined space, since the walls might behave as an waveguide.

The data sheet for the radar did not state the polarisation of the radar and inquiries to M/A-Com has, so far, yielded no information in the matter. Since there was no difference in the occurrence of multiple reflections when placing the radar in different orientations, thus circular polarisation is a highly plausible polarisation of the electromagnetic wave.

There are some minor differences of the properties between the two radars, such as the difference in detection of targets, this is probably due to the fact that both radars are prototype units, with this in mind the units are very potent in with respect to their size and yield.

When representing the data it is evident that to represent a three dimensional situation on a two dimensional display. Thus two ways was utilized, both with their respective inherent drawbacks; the contour plot and the incision plot.

The contour plot takes the target coordinates and extrapolates, in this case linearly, a surface spanned by the targets. The contour plot has the benefits to be easy to interpret at a quick glance, but the drawback here is that if there are multiple targets on the z-axis, they will be reduced to the mean of these points, in the case of outliers such as reflections from the ceiling the surface will
be deformed and no longer representative of the measured volume.

The incision plot does not process the the data, here an incision between two heights are made and all values within these values are plotted in a two dimensional plot, the drawback here is the number of plots required to accurately represent the volume. Reducing the distance of the incision by half gives a doubling of the number of plots.

As an attempt to increases the possibility to accurately position the targets spatially, both sensors were mounted orthogonal with respect to each other, this method as utilized in these experiments, has a major drawback and that was the large number of targets that was lost while extracting the positions with higher accuracy. A source of errors here is the accuracy in the alignment of the radars and the accuracy when rotating the set-up. To get more targets that overlap, one approach might be to take smaller steps in the rotation and also add some measurements at different angles of elevation.

A way to do this might be to let the horizontally oriented sensor sweep in the vertical direction, while at the same time the vertically oriented sensor scans in the horizontal direction. This would increase the volume of intersecting points, and would be a good set-up for a stationary situation, like measuring the inclination of a slope. Taking into account the time it took to make just a few measurements, to implement said changes would take a lot of time considering the time each measurement took and that the main bulk of the time went into the alignment of the radars.

As seen in sections 3.2.1 and 3.2.3 with the drop shaft, the orientation of the sensor is of some importance and so is the number of sampling directions. Combining data of this type would increase the area with high bearing accuracy and probably give a better image of the area in question, as an example measure the inclination of slopes.

Since the test made in the mine was made in a stationary and a low dust environment it is uncertain how the radar would perform in an environment where people and machinery moves around and no tests were performed in a dusty environment, so how the radar would perform under those circumstances is unknown.

4.2 RECOMMENDATIONS

While not knowing how the properties of the final product may differ from the properties of the prototypes, my belief is that the sensor would most probably be a powerful tool to assist a driver in both mine and forest. Whether it is good enough for a fully autonomous vehicle is uncertain, but it would probably be a good complement to a driver in a forest harvester or mine truck.

My recommendation is that for a forest harvester or other forest going vehicles a radar mounted horizontally would be enough to help while reversing the vehicle or traversing the arm of a harvester, if the radar is mounted to assist
while traversing the arm the reflection of the arm must be taken into consideration and so must the positioning of the sensor. One way of achieving this and build in some redundancy is by positioning on radar on each side of the arm. I would recommend at a height of approximately 1-1.2 metres, thus being able to detect humans.

For mine trucks I would recommend, if it is a dumper, a horizontally mounted radar to aid in the backing of the truck. Where to mount it on said truck I do not know, as with the forest harvester to mount it around 1 metre above ground would probably be the best, but consideration must be made to avoid that the view is obstructed by ore or that the unit is damaged otherwise.

To measure the inclination of slopes in the newly blasted areas a vertically mounted radar would suffice, but if mounted on a vertically oriented tilt cradle the measurements would be quicker and several sweeps might be done rapidly, and thus by interpolate the mean values for each angle of rotation increase the reliability of the measurements.

By complementing the set-up with a servo and gyroscope, the radar would be able to compensate for rough terrain, but simplicity has its benefits, since the more complex a set-up becomes the more things that might break down, considering the environment the machines operate in and in combination with the vibrations from the machines this might shorten the lifespan of the set-up. Thus my recommendation in this aspect is that the units should be mounted firmly to the body of the vehicle.
References


clear all;
close all;

% Declaration of initial constants
height=110;
disp(1)=-23.5;
disp(2)=12.5;
else(1)=0;
else(2)=0;

r1=0;
theta1=0;
I1=0;
phi1=0;

r2=0;
theta2=0;
I2=0;
phi2=0;

r1_temp=0;
theta1_temp=0;
I1_temp=0;
phi1_temp=0;

r2_temp=0;
theta2_temp=0;
I2_temp=0;
phi2_temp=0;

[r1,theta1,I1,phi1,r2,theta2,I2,phi2]=gbr_centre;
%
[r1_temp,theta1_temp,I1_temp,phi1_temp,r2_temp,theta2_temp,I2_temp,phi2_temp]=gbr_left_20deg;
%
[r1,theta1,I1,phi1]=merge_4arrays(r1,theta1,I1,phi1,r1_temp,theta1_temp,I1_temp,phi1_temp);
[r2,theta2,I2,phi2]=merge_4arrays(r2,theta2,I2,phi2,r2_temp,theta2_temp,I2_temp,phi2_temp);
%
[r1_temp,theta1_temp,I1_temp,phi1_temp,r2_temp,theta2_temp,I2_temp,phi2_temp]=gbr_left_50deg;
%
[r1,theta1,I1,phi1]=merge_4arrays(r1,theta1,I1,phi1,r1_temp,theta1_temp,I1_temp,phi1_temp);
[r2,theta2,I2,phi2]=merge_4arrays(r2,theta2,I2,phi2,r2_temp,theta2_temp,I2_temp,phi2_temp);
%
[r1_temp,theta1_temp,I1_temp,phi1_temp,r2_temp,theta2_temp,I2_temp,phi2_temp]=gbr_left_70deg;
%
[r1,theta1,I1,phi1]=merge_4arrays(r1,theta1,I1,phi1,r1_temp,theta1_temp,I1_temp,phi1_temp);
[r2,theta2,I2,phi2]=merge_4arrays(r2,theta2,I2,phi2,r2_temp,theta2_temp,I2_temp,phi2_temp);
%
[r1_temp,theta1_temp,I1_temp,phi1_temp,r2_temp,theta2_temp,I2_temp,phi2_temp]=gbr_right_20deg;
%
[r1,theta1,I1,phi1]=merge_4arrays(r1,theta1,I1,phi1,r1_temp,theta1_temp,I1_temp,phi1_temp);
[r2,theta2,I2,phi2]=merge_4arrays(r2,theta2,I2,phi2,r2_temp,theta2_temp,I2_temp,phi2_temp);
%
[r1_temp,theta1_temp,I1_temp,phi1_temp,r2_temp,theta2_temp,I2_temp,phi2_temp]=gbr_right_50deg;
%
[r1,theta1,I1,phi1]=merge_4arrays(r1,theta1,I1,phi1,r1_temp,theta1_temp,I1_temp,phi1_temp);
[r2,theta2,I2,phi2]=merge_4arrays(r2,theta2,I2,phi2,r2_temp,theta2_temp,I2_temp,phi2_temp);
%
[r1,theta1,I1,phi1]=vect_sort(r1,theta1,phi1,I1);
[r2,theta2,I2,phi2]=vect_sort(r2,theta2,phi2,I2);

%plotting(r1,theta1,phi1,I1,r2,theta2,phi2,height,disp);
save gbr_rv;

disp('Dekimashita!');

coord_transf.m

function [X,Y,Z]=coord_transf(r,theta,phi,height,disp)

[x,y,z] = sph2cart(phi*pi/180,theta*pi/180,r);
[m,n]=size(x);

x_diff=sin(phi*pi/180)*disp;
y_diff=cos(phi*pi/180)*disp;

x=x+x_diff;
y=y+y_diff;

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y=y+y_diff;

X=x;
Y=y;
Z=z;

horizontal.m

function horizontal(r1,x1,y1,z1,I1,theta1,phi1,r2,x2,y2,z2,I2,theta2,phi2,elev)
%phi = bearing
%theta = elevation
fs=25;
figure;
plot3(r1/100,lcm1,phi1,'.r');
xlabel('Intensity','FontSize',fs);
ylabel('Bearing','FontSize',fs);
ylabel('Range [m]','FontSize',fs);
axis([0 10 0 100 0 100]);
view([0 90]);
print -depsc -r300 S1_point_range_vs_int
figure;
plot3(I1,phi1,r1/100,'.r');
ylabel('Intensity','FontSize',fs);
zlabel('Bearing','FontSize',fs);
axis([0 130 0 50 0 130]);
view([90 270]);
print -depsc -r300 S1_point_phi_vs_int
figure;
plot3(r2/100,lcm2,phi2,'.b');
xlabel('Range [m]','FontSize',fs);
ylabel('Intensity','FontSize',fs);
axis([0 13 0 130 -100 100]);
view([0 90]);
print -depsc -r300 S2_point_range_vs_int
figure;
plot3(I2,phi2,r2/100,'.b');
xlabel('Intensity','FontSize',fs);
ylabel('Bearing','FontSize',fs);
axis([0 130 -50 50 0 130]);
view([90 270]);
print -depsc -r300 S2_point_phi_vs_int
close all;

[rtheta1_2, rphi1_2, rr1_mean, rr1_std, rr1_var, rr1_median, rI1_mean, rI1_std, rI1_var, rI1_median]=simplify(r1,phi1,theta1,I1,elev);
rtheta2_2, rphi2_2, rr2_mean, rr2_std, rr2_var, rr2_median, rI2_mean, rI2_std, rI2_var, rI2_median]=simplify(r2,phi2,theta2,I2,elev);

phi1_std=zeros(size(phi1_2));
phi2_std=zeros(size(phi2_2));
k5=find(phi1_2>=25 | phi1_2<=-25);
k6=find(phi2_2>=25 | phi2_2<=-25);
phi1_std(k5)=10;
phi2_std(k6)=10;
k5=find((phi1_2<25 & phi1_2>=5) | (phi1_2<=-5 & phi1_2>-25));
k6=find((phi2_2<25 & phi2_2>=5) | (phi2_2<=-5 & phi2_2>-25));
phi1_std(k5)=5;
phi2_std(k6)=5;
k5=find(phi1_2<5 & phi1_2>-5);
k6=find(phi2_2<5 & phi2_2>-5);
phi1_std(k5)=2;
phi2_std(k6)=2;
for i=1:14
k1=find(theta1_2 == elev(i));
k2=find(theta1 == elev(i));
k3=find(theta2_2 == elev(i));
k4=find(theta2 == elev(i));
if(min(size(k1))==0)
 figure;
 hold on;
 errorbar(r1_mean(k1)/100,phi1_2(k1),phi1_std(k1),'.r');
 plot(r1(k2)/100,lcm1(k2),'.k');
 end;
 errorbar(r2_mean(k2)/100,phi2_2(k2),phi2_std(k2),'.b');
 plot(r2(k4)/100,lcm2(k4),'.b');
 end;
 figure;
 set(gca,'LineWidth',2,'FontSize',fs-10);
 view([90 -90]);
function incision(x1,y1,z1,x2,y2,z2)
% ******************************************************
% function gives incisions in height between
% (z, z+dz), with dz set to 1 metre
% *
% calls to: -
% ******************************************************
fs=25;
max_z=max([max(z1) max(z2)])
min_z=min([min(z1) min(z2)])

k1=find(z1 < 0);
k2=find(z2 < 0);
figure;
hold on;
plot(x1(k1)/100,y1(k1)/100,'xk');
plot(x2(k2)/100,y2(k2)/100,'sb');
xlabel('X, distance','FontSize',fs)
ylabel('Y, lateral displacement','FontSize',fs)
set(gca,'LineWidth',2,'FontSize',fs-10);
hold off;
axis([0 11 -6 6]);
print('-depsc', '-r300', ['incision_height_1_radar_1_2']);
close all;

k1=find((z1 < 100)&(z1 >= 0));
k2=find((z2 < 100)&(z2 >= 0));
figure;
hold on;
plot(x1(k1)/100,y1(k1)/100,'xk');
plot(x2(k2)/100,y2(k2)/100,'sb');
xlabel('X, distance','FontSize',fs)
ylabel('Y, lateral displacement','FontSize',fs)
set(gca,'LineWidth',2,'FontSize',fs-10);
hold off;
axis([0 11 -6 6]);
print('-depsc', '-r300', ['incision_height_2_radar_1_2']);
close all;

k1=find((z1 < 200)&(z1 >= 100));
k2=find((z2 < 200)&(z2 >= 100));
figure;
hold on;
plot(x1(k1)/100,y1(k1)/100,'xk');
plot(x2(k2)/100,y2(k2)/100,'sb');
xlabel('X, distance','FontSize',fs)
ylabel('Y, lateral displacement','FontSize',fs)
set(gca,'LineWidth',2,'FontSize',fs-10);
hold off;
axis([0 11 -6 6]);
print('-depsc', '-r300', ['incision_height_3_radar_1_2']);
close all;

k1=find((z1 < 300)&(z1 >= 200));
k2=find((z2 < 300)&(z2 >= 200));
figure;
hold on;
plot(x1(k1)/100,y1(k1)/100,'xk');
plot(x2(k2)/100,y2(k2)/100,'sb');
xlabel('X, distance','FontSize',fs)
ylabel('Y, lateral displacement','FontSize',fs)
set(gca,'LineWidth',2,'FontSize',fs-10);
hold off;
axis([0 11 -6 6]);
print('-depsc', '-r300', ['incision_height_4_radar_1_2']);
close all;

k1=find((z1 < 300)&(z1 >= 300));
end
k2=find((z2 < 300) & (z2 >= 200));
figure;
hold on;
plot(x1(k1)/100,y1(k1)/100,'xk');
plot(x2(k2)/100,y2(k2)/100,'sb');
xlabel('X, distance','FontSize',fs);
ylabel('Y, lateral displacement','FontSize',fs);
set(gca,'LineWidth',2,'FontSize',fs-10);
hold off;
axis([0 11 -6 6]);
print('-depsc', '-r300', ['incision_height_4_radar_1_2']);
close all;

k1=find((z1 < 400) & (z1 >= 300));
k2=find((z2 < 400) & (z2 >= 300));
figure;
hold on;
plot(x1(k1)/100,y1(k1)/100,'xk');
plot(x2(k2)/100,y2(k2)/100,'sb');
xlabel('X, distance','FontSize',fs);
ylabel('Y, lateral displacement','FontSize',fs);
set(gca,'LineWidth',2,'FontSize',fs-10);
hold off;
axis([0 11 -6 6]);
print('-depsc', '-r300', ['incision_height_5_radar_1_2']);
close all;

k1=find((z1 < 500) & (z1 >= 400));
k2=find((z2 < 500) & (z2 >= 400));
figure;
hold on;
plot(x1(k1)/100,y1(k1)/100,'xk');
plot(x2(k2)/100,y2(k2)/100,'sb');
xlabel('X, distance','FontSize',fs);
ylabel('Y, lateral displacement','FontSize',fs);
set(gca,'LineWidth',2,'FontSize',fs-10);
hold off;
axis([0 11 -6 6]);
print('-depsc', '-r300', ['incision_height_6_radar_1_2']);
close all;

k1=find(z1 >= 500);
k2=find(z2 >= 500);
figure;
hold on;
plot(x1(k1)/100,y1(k1)/100,'xk');
plot(x2(k2)/100,y2(k2)/100,'sb');
xlabel('X, distance','FontSize',fs);
ylabel('Y, lateral displacement','FontSize',fs);
set(gca,'LineWidth',2,'FontSize',fs-10);
hold off;
axis([0 11 -6 6]);
print('-depsc', '-r300', ['incision_height_7_radar_1_2']);
close all;

k1=find(z1 < 800);
k2=find(z2 < 800);
figure;
hold on;
plot3(x1(k1)/100,y1(k1)/100,z1(k1)/100,'xk');
plot3(x2(k2)/100,y2(k2)/100,z2(k2)/100,'sb');
xlabel('X, distance','FontSize',fs);
zlabel('Z, height','FontSize',fs);
set(gca,'LineWidth',2,'FontSize',fs-10);
hold off;
view([0 0]);
print('-depsc', '-r300', ['incision_height_all_radar_1_2']);
close all;

merge_3arrays.m

function [A,B,C] = merge_3arrays(A1,B1,C1,A2,B2,C2)
% Merges array X2 to array X1 and outputs the array X

[n1,m1]=size(A1);
n2=size(A2);
for i=1:n2
    A(i+1:n1)=A2(i);
    B(i+1:n1)=B2(i);
end
merge_4arrays.m

function [A,B,C,D] = merge_4arrays(A1,B1,C1,D1,A2,B2,C2,D2)
% Merges array X2 to array X1 and outputs the array X
% All X1 arrays are of same size
[n1,m1]=size(A1);
% All X2 arrays are of same size
[n2,m2]=size(A2);
for i=1:n2
    A1(i+n1,1)=A2(i);
    B1(i+n1,1)=B2(i);
    C1(i+n1,1)=C2(i);
    D1(i+n1,1)=D2(i);
end
A=A1;
B=B1;
C=C1;
D=D1;

plot_mesh2.m

function plot_mesh2(x,y,z,I,c)
fs=25;
[X,Y] = meshgrid(0:5:900,-400:5:400);
height=600;

k=find(z < height);
Z4 = griddata(x(k),y(k),I(k),X,Y,'linear');
Z5 = griddata(x(k),y(k),z(k),X,Y,'linear');

figure;
[C1,h1] = contour(X/100,Y/100,Z4);
if(min(size(h1))~=0)
    clabel(C1,h1)
    xlabel('X, distance','FontSize',fs)
    ylabel('Y, latteral displacement','FontSize',fs)
    title(['Intensity contours'],'FontSize',fs);
    grid on;
    colormap hsv
    print('-depsc', '-r300', ['contour_intensity_mean_S',num2str(c)]);
end

figure;
[C2,h2] = contour(X/100,Y/100,Z5/100);
if(min(size(h2))~=0)
    clabel(C2,h2)
    xlabel('X, distance','FontSize',fs)
    ylabel('Y, latteral displacement','FontSize',fs)
    title(['Height contours'],'FontSize',fs);
    grid on;
    colormap hsv
    print('-depsc', '-r300', ['contour_height_mean_S',num2str(c)]);
end

close all

plotting.m

function plotting(r1,theta1,phi1,I1,r2,theta2,phi2,I2,height,displ)
% Only for vv
% phi=bearing
% theta=elevation
[x1,y1,z1]=coord_transf(r1,theta1,phi1,height,displ(1));
[x2,y2,z2]=coord_transf(r2,theta2,phi2,height,displ(2));
phi=[-60 -40 -20 0 20 40];
x1=round(x1);
y1=round(y1);
z1=round(z1);
x2=round(x2);
y2=round(y2);
z2=round(z2);

overlap(x1,y1,z1,x2,y2,z2,phi1,phi2,phi1_err,phi2_err,si_err,s)
vertical2(x1,y1,z1,theta1,phi1,r1,x2,y2,z2,theta2,phi2,phi1_err,phi2_err,si_err)
incision(x1,y1,r1,x2,y2,s)
vertical(x1,y1,z1,theta1,phi1,r1,x2,y2,z2,theta2,phi2)
% close all
% plotting(r1,theta1,phi1,r2,theta2,phi2,phi1_err,phi2_err,si_err)

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% close all
[phi1_2,theta1_2,r1_mean,r1_std,r1_var,r1_median,I1_mean,I1_std,I1_var,I1_median]=simplify(r1,theta1,phi1,I1,phi);
[phi2_2,theta2_2,r2_mean,r2_std,r2_var,r2_median,I2_mean,I2_std,I2_var,I2_median]=simplify(r2,theta2,phi2,I2,phi);
[x1_mean,y1_mean,z1_mean]=coord_transf(r1_mean,theta1_2,phi1_2,height,displ(1));
[x2_mean,y2_mean,z2_mean]=coord_transf(r2_mean,theta2_2,phi2_2,height,displ(2));
[x1_median,y1_median,z1_median]=coord_transf(r1_median,theta1_2,phi1_2,height,displ(1));
[x2_median,y2_median,z2_median]=coord_transf(r2_median,theta2_2,phi2_2,height,displ(2));

% overlap(x1_mean,y1_mean,z1_mean,I1_mean,r1_mean,r1_std,phi,phi1_2,1)
% close all
% overlap(x2_mean,y2_mean,z2_mean,I2_mean,r2_mean,r2_std,phi,phi2_2,2)
% close all
% plot_3d(x1,y1,z1)
% plot_3d(x2,y2,z2)
plot_mesh2(x1_mean,y1_mean,z1_mean,I1_mean,1);
plot_mesh2(x2_mean,y2_mean,z2_mean,I2_mean,2);

[x3,y3,z3,I3]=merge_4arrays(x1_median,y1_median,z1_median,I1_median,x2_median,y2_median,z2_median,I2_median);
[x4,y4,z4,I4]=merge_4arrays(x1_mean,y1_mean,z1_mean,I1_mean,x2_mean,y2_mean,z2_mean,I2_mean);
plot_mesh2(x4,y4,z4,I4,4);

plotting_hh.m
function plotting(r1,theta1,phi1,I1,r2,theta2,phi2,I2,height,displ)

% Phi=Bearing
% Theta=Elevation
% Only for hh

elev=[-16.5, -13, -9, -6, -3, 0, 4.5, 7.5, 10.5, 13.5, 16.5, 19.5, 22.5, 25, 27.5, 30, 32, 35, 37.5, 40, 42.5, 45, 47.5, 50]; %actual elevation
[x1,y1]=coord_transf(r1,phi1,theta1,height,displ(1));
[x2,y2]=coord_transf(r2,phi2,theta2,height,displ(2));

x1=round(x1);
y1=round(y1);
z1=round(z1);

x2=round(x2);
y2=round(y2);
z2=round(z2);

incision(x1,y1,z1,x2,y2,z2);
horizontal(r1,phi1,theta1,phi1,x1,y1,z1,x2,y2,z2,theta2,phi2,elev);

[theta1_2,phi1_2,r1_mean,r1_std,r1_var,r1_median,I1_mean,I1_std,I1_var,I1_median]=simplify(r1,theta1,phi1,I1,elev);
[theta2_2,phi2_2,r2_mean,r2_std,r2_var,r2_median,I2_mean,I2_std,I2_var,I2_median]=simplify(r2,theta2,phi2,I2,elev);

[x1_mean,y1_mean,z1_mean]=coord_transf(r1_mean,theta1_2,phi1_2,height,displ(1));
[x2_mean,y2_mean,z2_mean]=coord_transf(r2_mean,theta2_2,phi2_2,height,displ(2));

plot_mesh2(x1_mean,y1_mean,z1_mean,I1_mean,1);
plot_mesh2(x2_mean,y2_mean,z2_mean,I2_mean,2);

[x3,y3,z3,I3]=merge_4arrays(x1_median,y1_median,z1_median,I1_median,x2_median,y2_median,z2_median,I2_median);
[x4,y4,z4,I4]=merge_4arrays(x1_mean,y1_mean,z1_mean,I1_mean,x2_mean,y2_mean,z2_mean,I2_mean);
plot_mesh2(x4,y4,z4,I4,4);

plotting_hv.m
function plotting(r1,theta1,phi1,I1,r2,theta2,phi2,theta3,I2,height,displ)

%Phi=Bearing
%Theta=Elevation
% Only for hh

phi3=phi1+theta1;
theta3=theta1*0;

[x1,y1,z1]=coord_transf(r1,theta3,phi3,height,displ(1));
[x2,y2]=coord_transf(r2,phi2,theta2,height,displ(2));

phi=[-60 -40 -20 0 20 40];
incision(x1,y1,z1,x2,y2,z2);

horizontal(r1,phi1,theta1,phi1,x1,y1,z1,x2,y2,z2,theta2,phi2,elev);

[theta1_2,phi1_2,r1_mean,r1_std,r1_var,r1_median,I1_mean,I1_std,I1_var,I1_median]=simplify(r1,theta1,phi1,I1,elev);
[theta2_2,phi2,theta3_2,r2_mean,theta2_std,theta2_var,theta2_median,I2_mean,theta2_std,theta2_var,I2_median]=simplify(r2,theta2,phi2,theta3,I2,elev);

[x1_mean,y1_mean,z1_mean]=coord_transf(r1_mean,theta1_2,phi1_2,height,displ(1));
[x2_mean,y2_mean,z2_mean]=coord_transf(r2_mean,theta2_2,phi2_2,theta3_2,height,displ(2));

[x1_median,y1_median,z1_median]=coord_transf(r1_median,theta1_2,phi1_2,height,displ(1));
[x2_median,y2_median,z2_median]=coord_transf(r2_median,theta2_2,phi2_2,theta3_2,height,displ(2));

plot_mesh2(x1_mean,y1_mean,z1_mean,I1_mean,1);
plot_mesh2(x2_mean,y2_mean,z2_mean,I2_mean,2);

[x3,y3,z3,I3]=merge_4arrays(x1_median,y1_median,z1_median,I1_median,x2_median,y2_median,z2_median,I2_median);
[x4,y4,z4,I4]=merge_4arrays(x1_mean,y1_mean,z1_mean,I1_mean,x2_mean,y2_mean,z2_mean,I2_mean);

plot_mesh2(x4,y4,z4,I4,4);
plot_mesh2(x1,y1,z1,x2,y2,z2,20);

plotting_hv.m

function plotting(r1,theta1,phi1,I1,r2,theta2,phi2,theta3,I2,height,displ)

%Phi=Bearing
%Theta=Elevation
% Only for hv, not vv

% compensate for the fact that sensor 1 is in bearing increased and
% decreased with the rotation
phi3=phi1+theta1;
theta3=theta1*0;

[x1,y1]=coord_transf(r1,theta3,phi3,height,displ(1));
[x2,y2]=coord_transf(r2,phi2,theta2,height,displ(2));

[x1,y1,z1]=coord_transf(r1,theta3,phi3,theta2,height,displ(1));
[x2,y2,z2]=coord_transf(r2,phi2,theta2,theta3,height,displ(2));

incision(x1,y1,z1,x2,y2,z2);

x1=round(x1);
y1=round(y1);
x1=round(x1);

\[ x2=\text{round}(x2); \]
\[ y2=\text{round}(y2); \]
\[ z2=\text{round}(z2); \]
\[ \text{horizvert}(r1,x1,y1,z1,I1,\theta1,\phi1,r2,x2,y2,z2,I2,\theta2,\phi2,\phi,\theta3,\phi3); \]
\[ \text{close all} \]

\[ \phi1_2,\theta1_2,\text{mean}_\phi,\text{std}_\phi,\text{var}_\phi,\text{median}_\phi,\text{I1}_\text{mean},\text{I1}_\text{std},\text{I1}_\text{var},\text{I1}_\text{median}; \]
\[ \phi2_2,\theta2_2,\text{mean}_\phi,\text{std}_\phi,\text{var}_\phi,\text{median}_\phi,\text{I2}_\text{mean},\text{I2}_\text{std},\text{I2}_\text{var},\text{I2}_\text{median}; \]
\[ \text{incision}(x1,y1,z1,x2,y2,z2); \]
\[ x1=\text{round}(x1); \]
\[ y1=\text{round}(y1); \]
\[ z1=\text{round}(z1); \]
\[ x2=\text{round}(x2); \]
\[ y2=\text{round}(y2); \]
\[ z2=\text{round}(z2); \]
\[ \text{vertical}(r1,x1,y1,z1,\theta1,\phi1,r2,x2,y2,z2,\theta2,\phi2,\phi2,\phi); \]
\[ \text{close all} \]
\[ \text{plot_3d}(x1,y1,z1,\text{I1}); \]
\[ \text{plot_3d}(x2,y2,z2,\text{I2}); \]
\[ \text{plot_3d}(x3,y3,z3,\text{I3}); \]

function \text{plotting}(r1,\theta1,\phi1,r2,\theta2,\phi2,\theta3,\phi3,\text{displ})
% Only for hv, not vv
% phi=heading
% theta=elevation
\[ [x1,y1,z1]=\text{coord_transf}(r1,\theta1,\phi1,\text{displ}); \]
\[ [x2,y2,z2]=\text{coord_transf}(r2,\theta2,\phi2,\text{displ}); \]
\[ \text{incision}(x1,y1,z1,x2,y2,z2); \]
\[ x=\text{round}(x1); \]
\[ y=\text{round}(y1); \]
\[ z=\text{round}(z1); \]
\[ x=\text{round}(x2); \]
\[ y=\text{round}(y2); \]
\[ z=\text{round}(z2); \]
\[ \text{vertical}(r1,x1,y1,z1,\theta1,\phi1,r2,x2,y2,z2,\theta2,\phi2,\phi2,\phi); \]
\[ \text{close all} \]
\[ \text{plot_3d}(x1,y1,z1,\text{I1}); \]
\[ \text{plot_3d}(x2,y2,z2,\text{I2}); \]
\[ \text{plot_3d}(x3,y3,z3,\text{I3}); \]
% remove_zero_data(x1,y1,z1,I1,x2,y2,z2,I2)

function [r,theta,I] = remove_zero_data(r_temp,theta_temp,I_temp)

k=find(theta_temp ~= -128);
if n>0
    r=r_temp(k);
    theta=theta_temp(k);
    I=I_temp(k);
else
    r=r_temp;
    theta=theta_temp;
    I=I_temp;
end

% simplify(r,theta,phi,I)

function [PHI,THETA,R_MEAN,R_STD,R_VAR,R_MEDIAN,I_MEAN,I_STD,I_VAR,I_MEDIAN] = simplify(r,theta,phi,I,phi_val)

r_mean=[];
r_std=[];
r_var=[];
r_median=[];
I_mean=[];
I_std=[];
I_var=[];
I_median=[];
theta_trans=[];
phi_trans=[];

for i=1:max(size(phi_val))
    k=find(phi == phi_val(i));
    max_theta=max(theta(k));
    min_theta=min(theta(k));
    for theta_val=min_theta:theta_val:
        while (max_theta < max_theta)
            theta_val=min( theta( find( theta>max(theta_val) & phi == phi_val(i) ) ));
        end
        for r=1:max(size(theta_val))
            r_res=30;
            k2=find(r>=(dr-r_res) & r<dr & phi==phi_val(i));
            if (n>0 & m>0)
                l=find(theta==theta_val(i)) & r>=(dr-r_res) & r<dr & phi==phi_val(i));
                if (n>0 & m>0)
                    r_mean=r_mean mean(r(l));
                    r_std=r_std std(r(l));
                    r_var=r_var var(r(l));
                    r_median=r_median median(r(l));
                    I_mean=I_mean mean(I(l));
                    I_std=I_std std(I(l));
                    I_var=I_var var(I(l));
                    I_median=I_median median(I(l));
                    theta_trans=theta_trans theta_val(i));
                    phi_trans=phi_trans phi_val(i));
                end
            end
        end
    end
end

% slope_centre

[97]
function [R1,THETA1,INT1,PHI1,R2,THETA2,INT2,PHI2] = slope_centre

% Center view... 275 is 0 deg rotation
load slope275vv;

c = 0;

for sensor = 1:2
    r = 0;
    theta = 0;
    I = 0;
    for i = 1:10
        j = i - 1;
        target = ['MAT_SENSOR' int2str(sensor) '_TARGET' int2str(j)];
        T = eval(target);
        T = remove_zero_data(T(:,1), T(:,3), T(:,2));
    end
    r = remove_zero_data(r);
    theta = remove_zero_data(theta);
    I = remove_zero_data(I);
    r = ['r', int2str(sensor), ' = r;'];
    theta = ['theta', int2str(sensor), ' = theta;'];
    I = ['I', int2str(sensor), ' = I;'];
    eval(r);
    eval(theta);
    eval(I);
end

[m, n] = size(r1);
phi1 = ones(m, n) * c;

[m, n] = size(r2);
phi2 = ones(m, n) * c;

R1 = r1;
THETA1 = theta1;
INT1 = I1;
PHI1 = phi1;

R2 = r2;
THETA2 = theta2;
INT2 = I2;
PHI2 = phi2;

function [A, B, C, D] = vect_sort(a, b, c, d)

vect = [a, b, c, d];
[t, k] = sort(vect);
vect = vect(k(:,2),:);
[t, k] = sort(vect);
vect = vect(k(:,3),:);
A = vect(:,1);
B = vect(:,2);
C = vect(:,3);
D = vect(:,4);

function vertical(r1, x1, y1, z1, I1, theta1, phi1, r2, x2, y2, z2, I2, theta2, phi2, phi)

fs = 25;

h = figure;
plot3(r1/100, I1, theta1, '.r');
ylabel('Intensity', 'FontSize', fs);
axis([0 130 -50 50 0 13]);
set(gca, 'LineWidth', 2, 'FontSize', fs - 10);
view([90 270]);
print -depsc -r300 S1_point_theta_vs_int

h = figure;
plot3(I1, theta1, r1/100, '.r');
xlabel('Intensity', 'FontSize', fs);
ylabel('Elevation', 'FontSize', fs);
axis([-100 100 -100 100 0 13]);
set(gca, 'LineWidth', 2, 'FontSize', fs - 10);
view([90 270]);
print -depsc -r300 S1_point_range_vs_int

h = figure;
plot3(r1/100, I1, theta1, '.r');
ylabel('Intensity', 'FontSize', fs);
axis([0 130 -100 100 0 13]);
set(gca, 'LineWidth', 2, 'FontSize', fs - 10);
view([90 270]);
print -depsc -r300 S1_point_range_vs_int

h = figure;
plot3(r1/100, I1, theta1, '.r');
ylabel('Intensity', 'FontSize', fs);
axis([0 130 -100 100 0 13]);
set(gca, 'LineWidth', 2, 'FontSize', fs - 10);
view([90 270]);
print -depsc -r300 S1_point_theta_vs_int

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