Universidade de Brasília - UnB

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GPR APLICADO AO ESTUDO DE BIOMASSA DE RAÍZES

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DISSERTAÇÃO DE MESTRADO Nº 161

GPR APLICADO AO ESTUDO DE BIOMASSA DE RAÍZES

Amanda Almeida Rocha

Dissertação de Mestrado apresentada ao Programa de Pós-Graduação em Geociências Aplicadas e Geodinâmica do Instituto de Geociências da Universidade de Brasília para a obtenção do Título de Mestre em Geociências Aplicadas e Geodinâmica. Área de concentração: Geofísica Aplicada.

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FOLHA DE APROVAÇÃO

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"Mede o que é mensurável e torna mensurável o que não é."

(Galileu Galilei)

Aos meus pais, Ivana e Jeferson, às minhas irmãs,

Janaína e Mariana, e à querida Heather.

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1.1 CONTEXTO DA PESQUISA

Nas últimas décadas, ações antrópicas têm provocado uma série de mudanças climáticas com o aumento das atividades emissoras de gases de efeito estufa intensificada desde a Revolução Industrial com a queima de combustíveis fósseis (Houghton, 2003; Carvalho *et al.*, 2010).

O aumento na concentração de gases de efeito estufa tem sido o foco de diversas conferências e convenções internacionais como: UNFCCC (*United Nations Framework Convention on Climate Change*) em 1992 e o Protocolo de Kyoto em 1997, programa REDD++ em 2009, IPCC em 2014, o Acordo de Paris em 2015, entre outras. O principal objetivo é encontrar estratégias para redução de emissão de gases de efeito estufa para a atmosfera. Isto tem motivado a demanda de conhecimento sobre a capacidade de diferentes ecossistemas de captarem e fixarem carbono da atmosfera em sua biomassa.

Neste contexto as florestas são um importante provedor de serviço ambiental para mitigar as mudanças climáticas. O carbono fixado pelo reservatório da biomassa viva (acima e abaixo do solo) podem representar entre 70 a 95% do CO_2 sequestrado durante o crescimento de uma floresta tropical (CGEE, 2008), o resto é representado pela serrapilheira, madeira morta e carbono no solo.

Avaliar a distribuição de biomassa no planeta é importante para estimar os estoques de sequestro de carbono, para a modelagem de ciclos biogeoquímicos e para o entendimento dos efeitos históricos e impactos futuros de ações antrópicas. A biomassa em subsuperfície representa 40% da biomassa total do planeta e é estimada em 230 Gt C (Bar-On *et al.* 2018).

De acordo com Grace *et al.* (2006), a produtividade da biomassa abaixo do solo contida nas raízes de ecossistema de savanas é frequentemente subestimada devido a dificuldade de quantificar, desde que a metodologias destrutivas requerem uma grande quantidade de tempo e serviço, fazendo da atividade bastante onerosa.

Para Qureshi *et al.* (2012), a quantificação do estoque de carbono em florestas é uma tarefa desafiadora, que devido às metodologias usadas, envolvem um alto nível de incertezas e discrepâncias.

Uma alternativa ao método destrutivo é o método indireto usando equações alométricas para estimar a biomassa de raízes. Entretanto é raro na literatura trabalhos que tem ajustado modelos alométricos para obter biomassa de raízes de um ecossistema natural (Kuyah *et al.*, 2012; Koala *et al.*, 2017).

Como uma alternativa promissora para as técnicas indiretas, o radar de penetração do solo (GPR), um método geofísico para mapeamento do subsolo, tem sido estudado desde Hruska (1999) para o imageamento de biomassa subterrânea.

A técnica tem mostrado bons resultados no imageamento do comportamento de padrões de raízes e ainda está sendo estudado para ser estabelecido como uma metodologia tradicional (Butnor *et al.* 2001; Butnor *et al.* 2003; Butnor *et al.* 2005; Tanikawa *et al.*, 2013; Guo *et al.* 2015).

De acordo com Azevedo (2014), a estimativa da biomassa florestal representa um papel importante na tomada de decisão em diversas áreas, tais quais o manejo florestal e mudança climática. Assim estudos relacionados a quantificação, amostragem e modelagem da vegetação do Cerrado são cientificamente relevantes. Fornecem informação para definir políticas florestais, gestão dos recursos florestal e planejamento estratégico do uso e conservação de recursos florestais.

1.2 OBJETIVOS

O objetivo geral do estudo é propor um método não invasivo para a estimativa eficiente da biomassa abaixo do solo em ecossistemas naturais através do cálculo de volume com a análise de radargramas.

1.2.1 Objetivos específicos

O projeto pretende:

- Realizar modelagem numérica da onda eletromagnética na frequência de radar para imageamento de raízes;
- Analisar o padrão de reflexão das seções de GPR [TE] e [TM] para diferentes ângulos em um ambiente controlado;
- Avaliar as melhores frequências para o cálculo de biomassa em uma aquisição de dados de GPR;
- Estabelecer o valor de corte na seção envelope para o cálculo de biomassa;
- Estimar o volume verdadeiro da biomassa de raízes em um ecossistema natural através de radargramas e análise bio-estatística;

1.3 ESTRUTURA DA DISSERTAÇÃO

A presente dissertação está estruturada em 8 capítulos, buscando objetividade no conteúdo exposto.

Capítulo 1 - Introdução - é feita uma abordagem aos objetivos, justificativa, contexto da pesquisa e fundamentação teórica que são comuns aos cinco artigos apresentados nos capítulos seguintes.

Capítulo 2 - Artigo 1 - está organizado em formato de artigo entitulado "Root slope effect in GPR data with [TE] and [TM] polarization".

Capítulo 3 - Artigo 2 - está também organizado em formato de artigo entitulado "GPR as non-invasive method to study root biomass: case study of Cerrado - Brazil".

Finalmente, as principais conclusões e recomendações dos estudos conduzidos são apresentados no Capítulo 4. No capítulo 5 estão dispostas as referências bibliográficas.

1.4 FUNDAMENTAÇÃO TEÓRICA

O GPR (ground penetrating radar / radar de penetração do solo) é uma técnica geofísica que usa a reflexão e o espalhamento do sinal de ondas eletromagnéticas de alta frequência para mapear a subsuperfície. É frequentemente usado para investigações rasas não-destrutivas do subsolo.

O método de aquisição usado é o *common offset*, que consiste de transmissão de radiação de ondas EM para o subsolo por uma antena transmissora colocada na superfície. A propagação do sinal EM depende das propriedades elétricas dos materiais e da frequência do sinal transmitido, que são diretamente relacionados ao teor de água do solo (Annan, 1992).

Então, quanto maior o teor de água, maior a atenuação do sinal da onda EM. Variações das propriedades elétricas na subsuperfície fazem com que parte do sinal seja refletido (**Figura 1.1**). Ondas de radar refletidas e difratadas na subsuperfície são recebidas através da antena receptora.

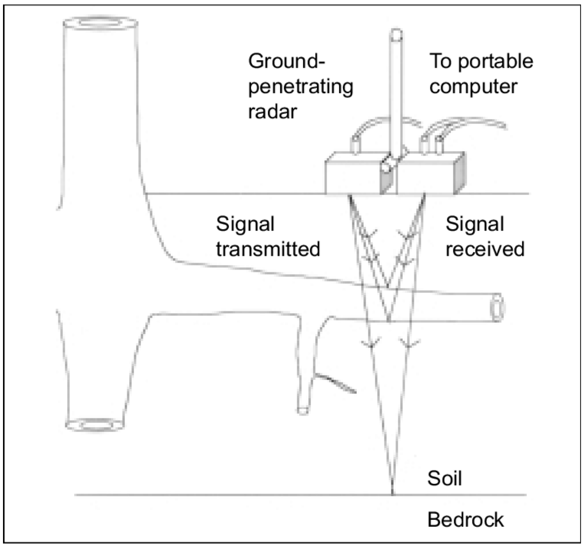

Figura 1.1 - Diagrama esquemático da metodologia GPR (Stokes *et al.*, 2002).

A profundidade de um objeto ou uma interface geradora de reflexão é dada pela seguinte relação:

$$D = \frac{V.t}{2}, (1)$$

onde 'D' é a profundidade, 'V' é a velocidade de propagação da onda EM no meio e 't' é o tempo de chegada da onda transmitida para o receptor.

No meio com baixa condutividade, a velocidade da onda EM pode ser estimada por:

$$V = \frac{c}{\sqrt{\varepsilon}}, (2)$$

onde c é a velocidade da luz e ε é a permitividade dielétrica.

1.4.1 - Equações de Maxwell

As equações de Maxwell descrevem matematicamente a física dos campos EM e as relações constitutivas quantificam propriedades dos materiais. Estas duas são a fundação para descrever quantitativamente o sinal do GPR (Jol, 2009).

Em termos matemáticos, os campos EM e suas relações são expressas a seguir:

$$\nabla \times \mathrm{E} = -\frac{\partial \mathrm{E}}{\partial \mathrm{t}} \qquad (3)$$

$$\nabla \times \mathrm{H} = \mathrm{J} + \frac{\partial \mathrm{D}}{\partial \mathrm{t}} \qquad (4)$$

$$\nabla . \mathrm{D} = \mathrm{q} \qquad (5)$$

$$\nabla . \mathrm{B} = 0 \qquad (6)$$

onde E é o vetor de força do campo elétrico (V/m); q é a densidade de carga elétrica (C/m³); B é o vetor de densidade de fluxo magnético (T); J é o vetor de densidade de corrente elétrica (A/m²); D é o vetor de deslocamento elétrico (C/m²); *t* é o tempo (s); e H é a intensidade do campo magnético (A/m).

As equações de Maxwell consistem na Lei de Faraday (3), Lei de Ampere (4), Lei de Gauss para eletricidade (5) e Lei de Gauss para o magnetismo (6).

A Lei de Faraday eq. (3), destaca o fato de que um campo magnético variável no tempo, aplicado perpendicularmente em um corpo condutor, provoca, neste, o movimento de cargas elétricas, gerando um campo elétrico paralelo ao deslocamento dessas cargas e ortogonal ao campo magnético variável aplicado.

A Lei de Ampére eq. (4), mostra que como um corpo condutor é impulsionado pela corrente variável, instantaneamente é gerado um campo magnético ao redor deste corpo.

Lei de Gauss para o campo elétrico, eq. (5), mostra que o fluxo elétrico para fora de uma superfície fechada é proporcional à carga total na superfície condutora, inclusive dentro de sua superfície fechada.

Lei de Gauss para campo magnético, eq. (6), mostra que para qualquer região fora de qualquer superfície fechada, o fluxo magnético será igual a zero, isto é, o fluxo magnético incidente no Pólo Sul será sempre igual ao fluxo magnético emitido pelo Pólo Norte. Assim, o campo magnético divergente sendo zero é o indicativo de que não há monopólos magnéticos.

1.4.2 - Equações constitutivas

Para o GPR, as propriedades elétricas e magnéticas são importantes. As equações constitutivas descrevem como elétrons, átomos e moléculas respondem à aplicação de um campo EM.

De acordo com Keller (1987), a ocorrência de um campo elétrico (E) em um terreno estimula o movimento de cargas elétricas em subsuperfície. Existem dois tipos de corrente: a corrente de condução e a corrente de deslocamento (**Figura 1.2**).

Quando um campo elétrico (E) é aplicado sobre um material, ele inicia a distribuição do momento dipolar, na qual a separação de cargas é descrita em termos da densidade do momento dipolar.

$$D = \varepsilon \, . \, E \quad (7)$$

A permissividade dielétrica ε caracteriza o deslocamento de carga restrito em uma estrutura de material à presença de um campo elétrico. O deslocamento de carga resulta em armazenamento de energia no material.

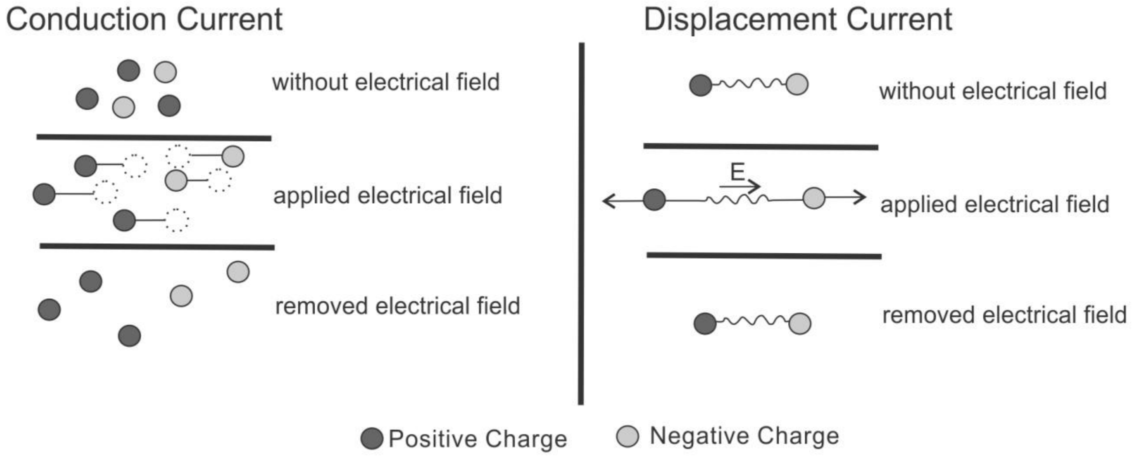

Figura 1.2 - Diagrama esquemático do efeito de presença do campo EM na distribuição de cargas em um corpo condutor: distribuição de cargas por condução e distribuição de cargas por deslocamento (Annan, 1996).

A ocorrência de um momento dipolar em um material está relacionada ao movimento de carga e, em seguida, há a ocorrência de dois tipos de correntes elétricas. A corrente de deslocamento ($\vec{J}_D$), que é dada pela variação da densidade do momento dipolar no tempo.

$$\vec{J}_D = \frac{d\vec{D}}{dt} \therefore \vec{J}_D = \frac{d\,(\varepsilon \cdot \vec{E})}{dt} \rightarrow \vec{J}_D = \varepsilon\,.\,\frac{d\vec{E}}{dt} \quad (8)$$

E a corrente de condução ($\vec{J}_C$), o produto entre a condutividade (σ), e o campo elétrico (E).

$$\vec{J}_C = \sigma.E \quad (9)$$

A corrente total ($\vec{J}_T$) que flui em um material natural é uma resposta para a aplicação do campo elétrico e a composição da corrente de deslocamento e da condução eq. (10):

$$\vec{J}_T = \varepsilon\,.\frac{d\vec{E}}{dt} + \sigma\,.\,\vec{E} \quad (10)$$

A terceira propriedade eletromagnética é a permeabilidade magnética (μ), uma medida da capacidade do momento dipolar presente nos átomos, quando submetido ao campo magnético externo, de se deslocar de sua orientação e alinhar-se com o campo aplicado.

A passagem da corrente elétrica no meio produz uma excitação magnética denominada campo magnético H, que origina uma indução magnética B, eq. (11), dada por:

$$B = \mu\ .\ H \quad (11)$$

1.4.3 - Propriedades da onda

Em estruturas com condutividade constante e permissividade dielétrica, existe uma freqüência de transição (Ft), onde $\vec{J}_C = \vec{J}_D$. Para a ocorrência de freqüências acima da freqüência de transição (Ft), a corrente de deslocamento ($\vec{J}_D$) é dominante (Annan, 1996). As correntes de deslocamento são caracterizadas por se propagarem como ondas com pouca ou nenhuma dispersão de freqüência angular de excitação (ϖ) dada por:

$$\varpi = \frac{\sigma}{\varepsilon} \quad (12)$$

Em um material simples, a freqüência de transição (Ft) é definida por eq. (13):

$$\mathrm{F_t} = \frac{\sigma}{2\pi\varepsilon} \quad (13)$$

As freqüências que ocorrem abaixo de Ft, a corrente de condução ($\vec{J}_C$) é dominante e a energia é difundida para o material.

Quando as freqüências são maiores que (Ft), a propagação de onda está relacionada à velocidade da onda (v) e atenuação da onda (α), como mostrado nas equações (2) e eq. (14):

$$v = \frac{c}{\sqrt{\varepsilon_r}}\,, \quad (2)$$

$$\alpha = \frac{\sigma}{2} . \sqrt{\frac{\mu}{\varepsilon}} \quad (14)$$

onde $\varepsilon_r = \frac{\varepsilon}{\varepsilon_0}$ = é a permitividade dielétrica relativa; (ε) é a permitividade dielétrica do material (F/m) e (ε_0) é a permitividade dielétrica do vácuo (8.854 x 10^{-12} F/m).

Esses dois parâmetros são diretamente influenciados pela permissividade dielétrica (ε_r), que atua na velocidade de propagação (v), e a condutividade elétrica (σ), que interfere na atenuação da onda (α) (Annan, 1996).

A **Figura 1.3** mostra que em altas frequências, acima de Ft, todos os componentes de frequência exibem a mesma velocidade e sofrem a mesma atenuação, correspondendo à faixa mais adequada para GPR (Annan, 1996).

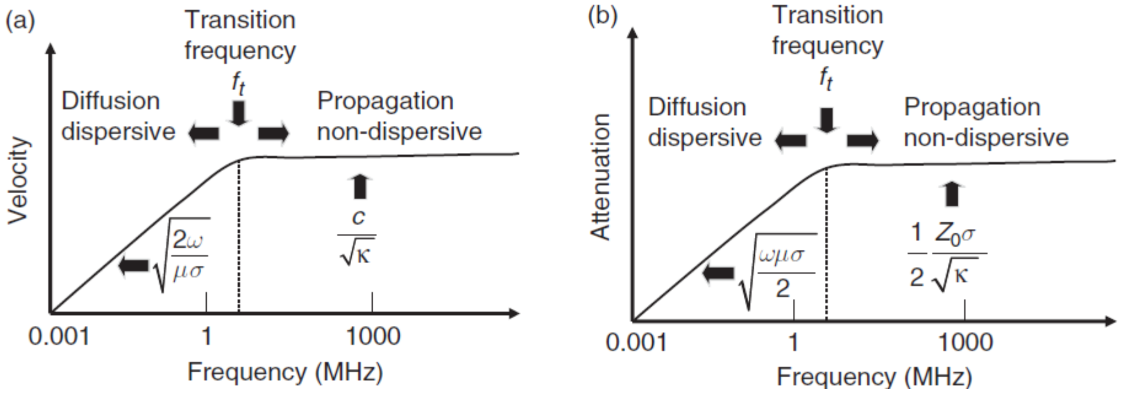

Figura 1.3 - Variação na velocidade e atenuação em um meio simples sem propriedades físicas dispersivas, c e Z_0 são a velocidade e a impedância do vácuo (Annan in Jol, 2009).

1.4.4 - Cone de transmissão

As ondas EM propagadas por GPR são emitidas em um cone ("cone de transmissão"), que se espalha com profundidade crescente abaixo da superfície (**Figura 1.4**). As dimensões do cone são determinadas pelas condições de subsuperfície encontradas pela freqüência da energia sendo transmitida para o solo, com energia de freqüência mais alta resultando em cones de transmissão mais estreitos, Dojack (2012):

$$A = \frac{\lambda}{4} + \frac{D}{\sqrt{\varepsilon+1}}, \quad (15)$$

onde A é a base do cone; λ é o comprimento de onda da frequência central do radar; D é a profundidade e ε é a permissividade dielétrica média.

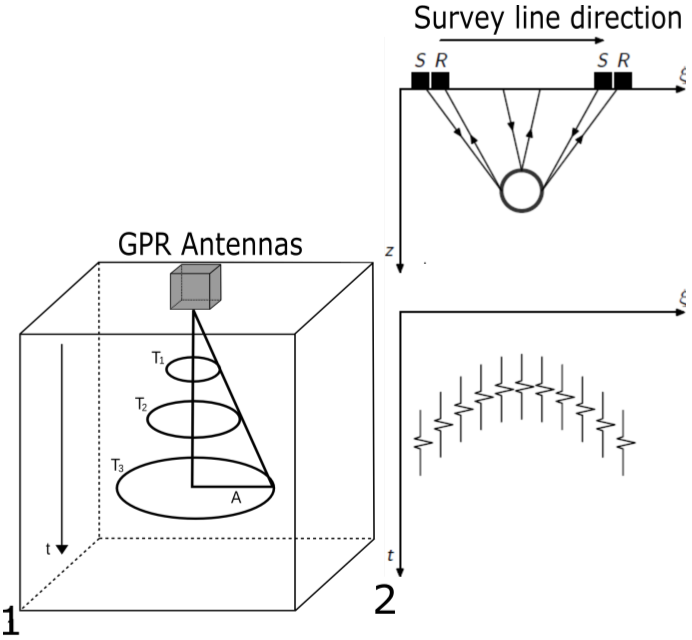

Figura 1.4 - 1) esquema de espalhamento cônico para GPR; 2) Aquisição de dados e modelo de velocidade.

1.4.5 - Reflexão

Quando as ondas EM encontram uma descontinuidade na subsuperfície com materiais de diferentes propriedades físicas e químicas, parte da onda é refletida fora do limite e de volta à superfície (Conyers, 2004).

A proporção e a direção dos EM refletidos dependem das propriedades do material e do formato do alvo dos quais são refletidos. Em uma superfície plana, o ângulo no qual a onda será refletida pode ser previsto com base na lei da reflexão:

$$\theta i = \theta r \quad (16)$$

onde θi é o ângulo de incidência e θr é o ângulo de reflexão.

A constante dielétrica e a condutividade elétrica são os parâmetros importantes que definem a propagação do sinal, Conyers & Goodman (1997). A intensidade das reflexões em uma interface entre dois materiais depende (Guo *et al.*, 2013, al-Hagrey 2007, Conyers & Goodman 1997):

$$R = \frac{\varepsilon_r - \varepsilon s}{\varepsilon_r + \varepsilon s} = \frac{Zs - Zr}{Zs + Zr}, \quad (17)$$

onde R é o coeficiente de reflexão na zona de fresnel, εr e εs são as constantes dielétricas da raiz e do solo, respectivamente; Vr é a velocidade de propagação da raiz e Vs é a velocidade de propagação do solo; Zs é a impedância do solo e Zr é a impedância da raiz.

O fator crítico é que um contraste de impedância EM deve existir para que haja uma resposta.

1.4.6 - Refração

A parte da onda EM que não é refletida nas descontinuidades subsuperficiais altera a velocidade, e ao fazê-lo é refratada ou curvada na interface, resultando em uma mudança na direção da onda através do solo (Conyers, 2004). O ângulo no qual a onda será refratada pode ser previsto com base na Lei de Refração de Snell:

$$\frac{\sin\theta 1}{\sin\theta 2} = \frac{V1}{V2} = \frac{N2}{N1}, \ (18)$$

onde θ é o ângulo de incidência (1) e refração (2), V é a velocidade e N é o índice de refração.

Quando v1> v2, o meio 2 tem um ângulo crítico além do qual a energia não pode se propagar do meio 1 para o 2. O ângulo crítico é determinado pela configuração de θ1 = 90°. O ângulo crítico desempenha um papel em muitas respostas GPR.

As ondas EM de vetor de campo são separadas em dois componentes independentes definidos pela orientação de campo em relação ao limite (**Figuras 1.5 e 1.6**). Os componentes são referidos como TE (campo elétrico transversal) e TM (campo magnético transversal).

O coeficiente de reflexão na zona de fresnel também pode ser descrito como:

$$R = \frac{Vs - Vr}{Vs + Vr} \quad (19)$$

A refração explica por que o cone de transmissão se torna cada vez mais estreito com a profundidade (Conyers, 2004).

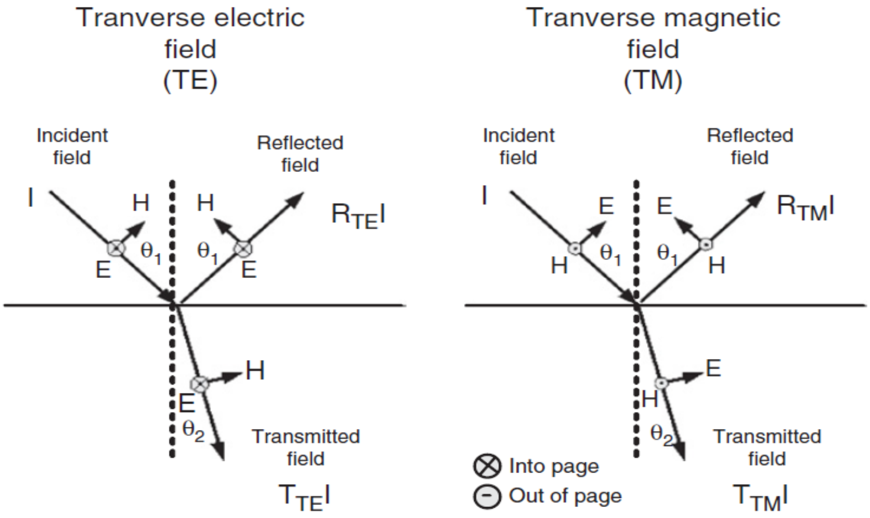

Figura 1.5 - Ondas eletromagnéticas são campos de ondas vetoriais transversais. Para qualquer direção de propagação, existem dois campos independentes. Para a interface planar, é tradição discutir as duas ondas, uma com o campo elétrico no plano de interface chamado TE, transversal elétrico, e outra com o vetor de campo magnético no plano de interface chamado TM, transversal magnético (Annan in Jol, 2009).

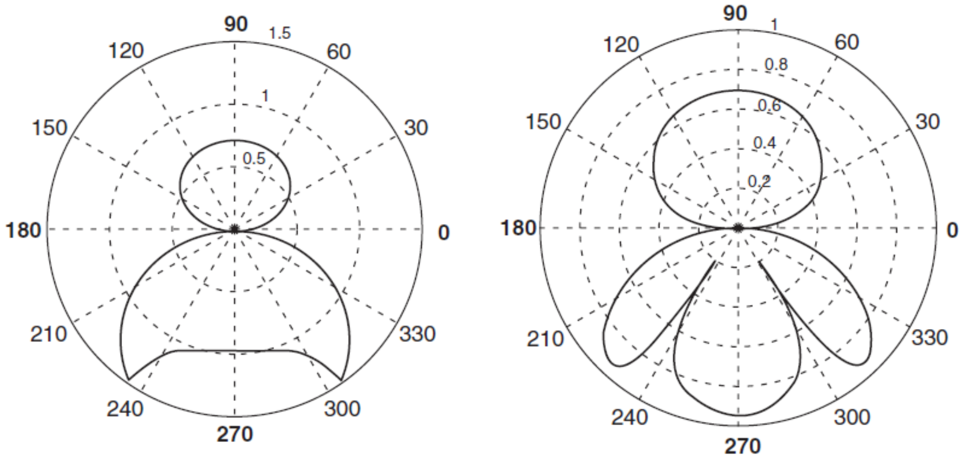

Figura 1.6 - Quando o dipolo está na superfície do solo, a diretividade é drasticamente alterada e depende da permissividade do solo. Os padrões TE e TM mostrados aqui são para permitividade do solo (Annan in Jol, 2009).

1.4.7 - Difração

Na física, "difração" refere-se à flexão de ondas ao redor de objetos, ou à propagação de ondas à medida que elas passam por aberturas estreitas. A difração pode ocorrer em torno de superfícies inclinadas ou verticais, resultando em aumento do tempo de viagem das ondas de radar e, portanto, distorção da profundidade, localização, tamanho e geometria do objeto (Conyers, 2004).

1.4.8 - Limites de resolução

A capacidade de resolução do GPR depende basicamente da frequência da antena usada, da profundidade do objeto alvo e da constante dielétrica do meio.

Os comprimentos de onda mais curtos das antenas de alta frequência central produzem um cone de transmissão mais estreito, que pode se concentrar em áreas menores e assim resolver características menores do que os cones de transmissão mais difundidos produzidos por antenas com baixas frequências centrais e comprimentos de onda maiores (Conyers 2004).

Em geral, a resolução máxima das características horizontais é aproximadamente equivalente à área de cobertura dada por Conyers & Goodman (1997):

$$\mathrm{A} = \frac{\lambda}{4} + \frac{D}{\sqrt{\varepsilon+1}}, \ (20)$$

onde A é a dimensão longa da pegada elíptica; λ é o comprimento de onda da frequência central do radar; D é a profundidade e ε é a permissividade dielétrica média.

A meta horizontal máxima resolúvel é equivalente a A, a dimensão longa da pegada (Conyers, 2004).

A resolução máxima das características verticais é aproximadamente equivalente ou maior que a metade do comprimento de onda (Neubauer *et al.* 2002). Interfaces horizontais empilhadas verticalmente devem ser separadas por pelo menos um comprimento de onda, caso sejam resolvidas (Conyers, 2004).

Quando o sinal GPR passa por um alvo menor que o limite de resolução, ocorre o fenômeno de espalhamento. A amplitude do sinal pode ser interpretada como o resultado do inteiro de superfície do alvo, que depende das dimensões em três direções.

Aqui é importante explicar que o GPR produz ondas EM em banda larga, de modo que frequências de meia a duas vezes a frequência central estão presentes (Annan 2009).

1.4.9 - Método das Diferenças Finitas no Domínio do Tempo

A equação do Método das Diferenças Finitas no Domínio do Tempo calcula o campo E_y^{n+1} com base no campo $H_x^{n+1/2}$. O mesmo procedimento é seguido pela expressão de cada componente do campo eletromagnético. Esta discretização para as equações de Maxwell constituem a base do algoritmo de Yee mostrado na **Figura 1.7**.

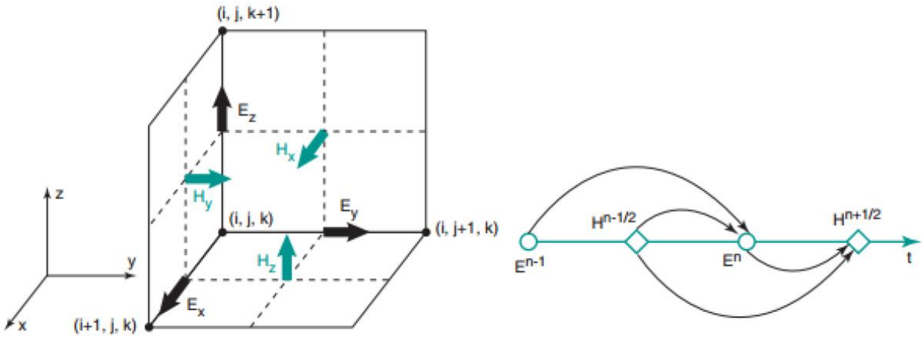

Figura 1.7 - Célula Yee com coordenadas cartesianas (Alsharadi *et al.* 2010).

Para o modo TE as equações 2D para FDTD se tornam:

$$\mathrm{H_x}\Big|_{\mathrm{i,j,k}}^{n+1/2} = \mathrm{H}_{\mathrm{i,j,k}}^{\mathrm{n}-1/2} + \frac{\Delta\mathrm{t}}{\mu_{\mathrm{i,j,k}}} . \frac{\mathrm{E}_y\big|_{\mathrm{i,j,k}+1/2}^{n} - \mathrm{E}_y\big|_{\mathrm{i,j,k}-1/2}}{\Delta z} \text{, (21)}$$

$$\mathrm{E_y}\Big|_{\mathrm{i,j,k}}^{n+1} = \left(\frac{1-\frac{\Delta \mathrm{t}.\sigma_{\mathrm{i,j,k}}}{2\varepsilon_{\mathrm{i,j,k}}}}{1-\frac{\Delta \mathrm{t}.\sigma_{\mathrm{i,j,k}}}{2\varepsilon_{\mathrm{i,j,k}}}}\right).\,\mathrm{E}_y\Big|_{\mathrm{i,j,k}}^{n} + \left(\frac{\frac{\Delta \mathrm{t}}{\varepsilon_{\mathrm{i,j,k}}}}{1+\frac{\Delta \mathrm{t}.\sigma_{\mathrm{i,j,k}}}{2\varepsilon_{\mathrm{i,j,k}}}}\right).\,\frac{\mathrm{H_x}\Big|_{\mathrm{i,j,k}+\frac{1}{2}}^{n+1/2} - \mathrm{H_x}\Big|_{\mathrm{i,j,k}-\frac{1}{2}}^{n+1/2}}{\Delta z}\,, \quad (22)$$

Então, os vetores espaciais (dx, dy, dz) e temporal (dt) discretizados representam um papel significativo, desde que eles são o mais próximo que um modelo de diferenças finitas no domínio do tempo pode chegar à representação real do problema.

1.4.10 - Processamento de sinal GPR

Os dados de GPR 2D adquiridos foram processados usando o software Reflex-Win v7.5 (Sandmeier, 2015). As principais etapas de processamento digital de sinal são mostrados na **Figura 1.8**. Estas etapas foram aplicadas aos dados para gerar o modelo de velocidade pelo empilhamento das amplitudes. Após a migração dos dados, o traço envelope foi usado para analisar a intensidade da amplitude. Fluxo de processamento similar foi previamente usado por Butnor *et al.* (2001), Tanikawa (2013) e Guo *et al.*(2013).

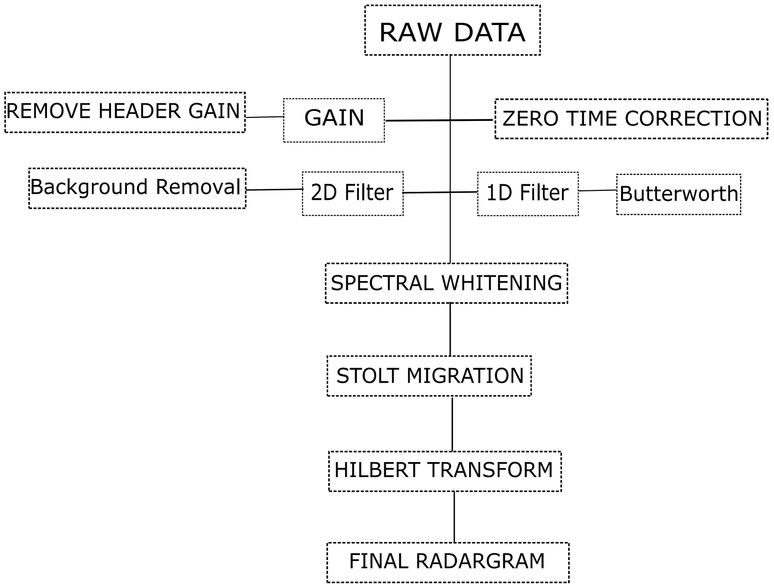

Figura 1.8 - Esquema do fluxo de processamento usado.

onde 1) Dados brutos

2) Remove header gain: os equipamentos da GSSI aplicam um ganho no sinal durante a aquisição de dados. Este ganho é removido para processar os dados brutos.

3) Zero time correction: O tempo de correção de tempo zero ou correção estática, busca eliminar o efeito da onda direta no solo. Este passo do processamento permite que o tempo zero correpondente a superfície onde a antena foi colocada, então cada estrutura identificada abaixo do solo tem seus valores de tempo duplo ajustadas (Jol, 2009).

Filtros são geralmente aplicados aos dados para remover ruídos e aprimorar a qualidade visual dos dados. Em geral, filtros básicos alteram os dados removendo, suprimindo ou aumentando o sinal de algumas frequências ou através de um número específico de traços no espaço ou amostras no tempo.

O filtros 1D são os mais básicos. Operam ao longo de cada traço individualmente, ou até mesmo universalmente através de todos os traços numa secção ou sobre um range selecionado de traços.

Os filtros espaciais 2D operam de modo similar aos filtros temporais, mas diferem pois operam através dos traços na distância em vez do tempo. Eles tendem a ter a forma de uma média simples ou filtros médios que abrangem um número definido de traços e são usados para enfatizar ou suprimir feições específicas na seção.

4) Band-pass Butterworth: Um filtro de passabanda ideal passa alguns ranges de frequências sem distorção e suprime todas as outras frequências. É uma combinação de ambos, filtros passa alta e passa baixa, uma função retângulo de frequência (**Figura 1.9**).

O filtro passabanda apropriado é o que o tempo de decaimento pode ser escolhido para ser razoável em combinação com um compromisso na forma do retângulo. O filtro Butterworth preenche estas necessidades.

Análise começa com uma equação que para a uma grande ordem de *n* é a equação de uma caixa:

$$\overline{\mathrm{B}(\omega)}\mathrm{B}(\omega) = \frac{1}{1+(\frac{\omega}{\omega 0})^{2n}} \quad , (23)$$

quando $|\omega| < \omega 0$, este espectro passa-baixa butterworth é sobre unidade. Quando $|\omega| > \omega 0$, o espectro cai rapidamente para zero. A magnitude $|\overline{\mathrm{B}(\omega)}|$ é plotada na **Figura 1.10** para vários valores de *n*.

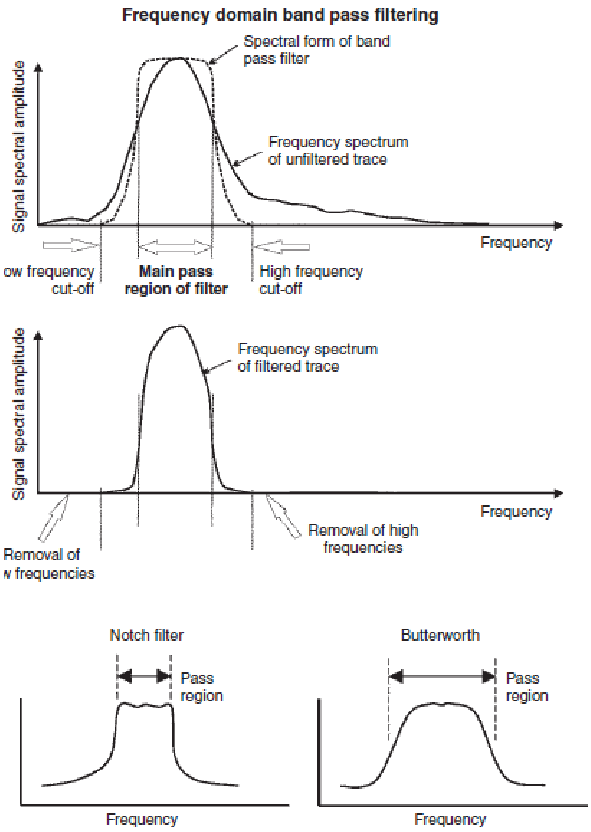

Figura 1.9 -Exemplo de filtro Butterworth.

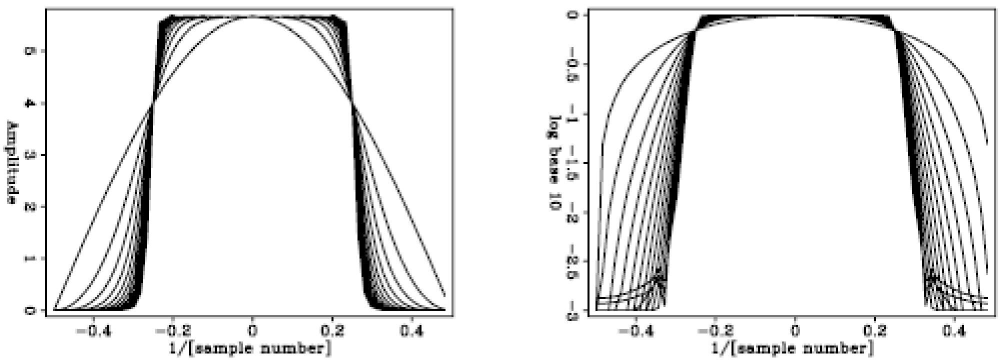

Figura 1.10 - Espectro do filtro butterworth de várias ordens *n*.

Para proceder é necessário expressar ω em termos de Z, onde Z = $e^{i\omega\Delta t}$. Então uma representação de tempo amostral de ω^2 = (i$\omega)(-i\omega)$ é:

$$\omega^2 = 4\,\frac{1-Z^{-1}}{1+Z^{-1}}\,\frac{1-Z}{1+Z}\ ,\ (24)$$

Substituindo equação (24) na equação (23) encontra-se:

$$\mathrm{B}\left(\frac{1}{Z}\right)\,\mathrm{B(Z)} = \frac{\mathrm{N(Z^{-1})N(Z)}}{\mathrm{D(Z^{-1})D(Z)}}\,,\ (25)$$

5) Background Removal: Este filtro espacial usa a média de todos os traços na seção e subtrai isto de cada traço. Remove ruídos de background e é bom para movimentos da antena. É um filtro muito útil para remover 'movimentos' nos dados mas pode remover também refletores retos. O uso de filtros de remoção de background são um passo chave no processamento e interpretação de dados de GPR em materiais de baixa perda (i.e., solos úmidos). Nestes ambientes, forte acoplamento de antenas no solo e camadas rasas, próximas a superfície, podem causar reverberação significante no sinal que podem mascarar sinais tardios.

6) Spectral Whitening: é o processo de fazer o espectro de magnitude uniforme. Isto faz com que o espectro de magnitude seja mais contínuo em vez de ther alguns *spikes* nas frequências, isto reduz a razão sinal-ruído (**Figura 1.11**).

O *spectral whitening* permite compensar para a atenuação da frequência com tempo. Isto também deconvolve parcialmente a fonte da forma de onda efetiva (Sandmeier, 2015). O aumento das altas frequências (naturalmente filtradas pela Terra) permitem ao intérprete resolver feições menores do que poderia se fosse observado naturalmente.

Se o dado é espectralmente balanceado ou se sua largura de banda de freqüência é estendida de alguma forma, os volumes resultantes podem levar a uma maior resolução vertical e lateral (Chopra & Marfut, 2016).

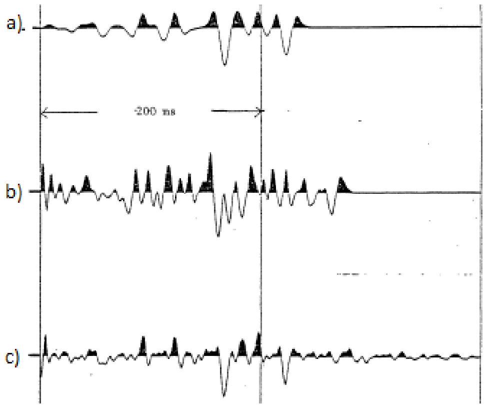

Figura 1.11 - Comparação do spectral whitening com deconvolução spiking quando a forma de onda de entrada é fase zero. a) Dado de entrada para os passos seguintes; b) resultado da deconvolução spiking; c) resultado do spectral whitening (Lee, 1986).

7) Stolt migration: Migração é geralmente usada para melhorar a resolução da seção e desenvolver imagens da superfície espacialmente mais realistas. Todos os métodos de migração atentam para reconstruir a seção GPR numa forma espacialmente acurada usando um modelo de velocidade da subsuperfície. Idealmente, a difração hiperbólica colapsará a um ponto de origem e refletores inclinados reposicionam-se a sua localização correta (**Figura 1.12**). O sucesso do processo de migração é altamente dependente da acurácia da análise de velocidade.

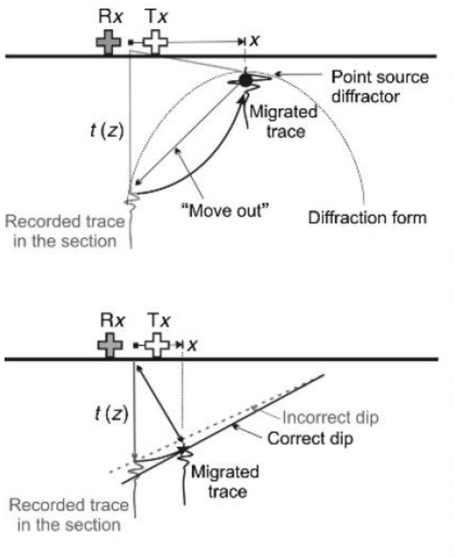

Figura 1.12 - Princípios metodológicos da migração (Jol, 2009).

8) Traço envelope / Transformada de Hilbert: A computação da parte imaginária não vista do sinal é conhecida como "Transformada de Hilbert". É uma análise de traço complexa usando fase instantânea, frequência e amplitude (Taner *et al.* 1978).

A transformada de Hilbert tradicional no domínio da frequência pode ser expressa (Claerbout, 2004):

$$\text{hi}\ (\omega) = \text{X}(\omega) \cdot \text{Sign}(\omega) \cdot \text{i}\ , \quad (26)$$

onde $\text{X}(\omega)$ é a transformada de Fourier de um dado de entrada x(t), hi (ω) é a transformada de Hilbert de x(t) no domínio da frequência, $\text{Sign}(\omega)$ é a função seno e i = $\sqrt{-1}$.

Aplicando a transformada inversa de Fourier a hi (ω) e estabelecendo t=0, obtém-se:

$$\text{hr}\ (0) = 2 * \sum_{\omega} \text{Re}[\text{X}(\omega) + \text{Re}[\text{X}(0)], \quad (27)$$

$$\text{hi}\ (0) = 2 * \sum_{\omega} \text{Im}[\text{X}(\omega)], \quad (28)$$

$$h(0) = hr(0) + i \cdot hi(0), \quad (29)$$

onde $\sum_{\omega}$ significa a soma sobre frequências positivas e hr(0) e hi(0) são as partes reais e imaginárias de um traço complexo h(0), respectivamente. Re e Im referem-se às partes real e imaginária de um valor complexo.

Um filtro que converte senos em cossenos é chamado "90º filtro de deslocamento de fase" ou "filtro de quadratura" (**Figura 1.13**). Mais especificamente, se a entrada é $\cos(\omega t + \varphi_1)$, então a saída deveria ser $\cos(\omega t + \varphi_1 + \pi/2)$, um exemplo é dado na **Figura 1.14**.

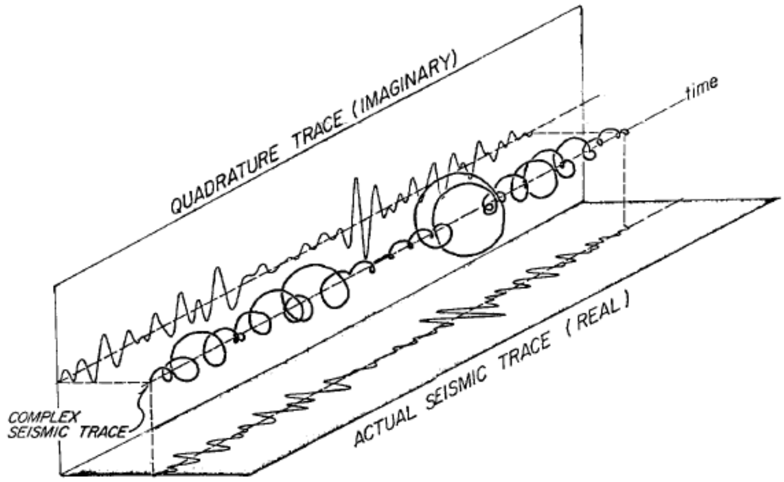

Figura 1.13 - Diagrama isométrico da porção de um traço sísmico (GPR) (Taner *et al.* 1978).

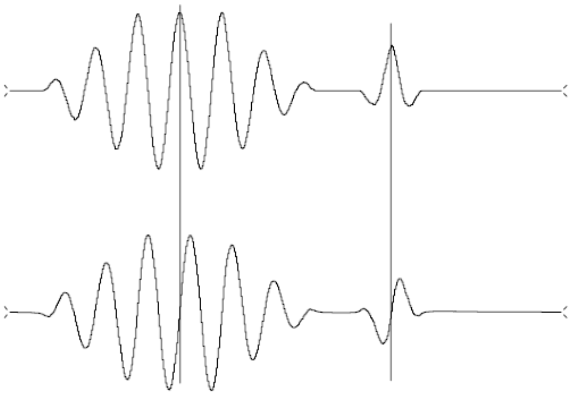

Figura 1.14 - Sinal de entrada (acima) filtrado com o filtrado de quadratura produz um sinal com deslocamento de fase (abaixo).

O filtro de quadratura é geralmente usado para fazer o envelope do sinal. A amplitude instantânea ou envelope é uma medida para intensidade da refletividade, que é proporcional a raiz quadrada da energia completa do sinal num instante do tempo.

O sinal envelope pode ser definido por:

$$\mathrm{e_t} = \sqrt{\mathrm{u_t^2 + v_t^2}}\ , \quad (30)$$

Alternativamente com o sinal analítico $\mathrm{g_t} = \mathrm{u_t} + \mathrm{i\,v_t}$, o envelope quadrado é: $\mathrm{e_t^2} = \mathrm{g_t\,g_t}$.

CAPÍTULO 2 – ARTIGO 1

ROOT SLOPE EFFECT IN GPR DATA WITH [TE] AND [TM] POLARIZATION

ABSTRACT

Trees are important functions in the ecosystem for being able to storage atmospheric CO_2 to increase its biomass. Roots are significant and indispensable for the ecosystem carbon budget, accounting for 20-40% of the total forest carbon storage. Traditional techniques used for forest engineers to quantify root biomass are destructive, laborious, and time demanding. Over the last decades, GPR has been studied to map efficiently coarse roots biomass, due to its non-destructive nature and fast data acquisition capability. Numerical modeling provides a faster alternative to study the limiting factors of GPR-based root investigation when compared to controlled experiments. Therefore the application of numerical modeling to understand the influences of limiting factors on both the detection and quantification of roots by GPR is promising. The controlled experiments have been mainly used for analyzing the GPR wave propagation and its interaction belowground. This work presents control measurements taken in a sandbox for examining the root slope effect in natural environments and shows the accuracy of numerical modeling satisfactorily using the software Reflexw and its feasibility in exploring the impacts of limiting factors on root diameter and root water content variation for the transverse electric field and the transverse magnetic field. The objective of this work is to analyze the signal amplitude for different root slopes. 2D GPR profiles were acquired for [TE] and [TM]. A new envelope index is successfully tested for estimation of amplitude area of different cross angles of the survey line.

Keywords: shallow geophysics, resolution limits, numerical modeling, sandbox, controlled environment, amplitude analysis.

2.1 - INTRODUCTION

GPR has been studied over the last decades to map efficiently coarse roots biomass, due to its non-destructive nature and fast data acquisition capability. GPR is a geophysical technique widely used for detecting materials within shallow subsurface (Conyers, 2004). It uses contrasts in reflected electromagnetic waves to map the subsoil.

Although the accuracy of root biomass estimation is still unsatisfactory because current models use information from reflective energy of each site-specific to calculate root biomass, it is necessary to understand better the various limiting factors to enhance the application of GPR.

The radar signal is significantly affected by many biotic factors (e.g. root diameter, root water content, roots spacing and root orientation) and abiotic variables (e.g. soil water content, soil texture, soil surface condition and antenna center frequency) (Barton and Montagu 2004; Dannoura *et al.* 2008; Hirano *et al.* 2009; Guo *et al.* 2013).

The depth of groundwave penetration decreased with increasing frequency and increased soil moisture, which affects εsoil and considerably changes the velocity model, according to Du & Rummel (1994).

The penetration depth is higher in dry soils and dry rocks, and considerably lower in moist and loamy soils, since both have high electrical conductivity (Wensink *et al.*, 1993).

Numerical modeling provides a faster alternative to study the limiting factors of GPR-based root investigation when compared to controlled experiments. Since all the variables in the simulation model can be precisely controlled, it is possible to differentiate and to detect the various limiting factors (Guo *et al.* 2013).

Therefore the application of numerical modeling to understand the influences of limiting factors on both the detection and quantification of roots by GPR is promising.

The controlled experimental studies produce an important understanding of how EM waves propagate beneath the ground surface. Previous work such as Leckebusch and Peikert (2001), Maciel *et al.* (2018) showed several measurements satisfactorily in a sandbox to examine the resolution of GPR data.

This work presents the control measurements taken in a sandbox with dimensions of 50cm (height) X 100cm (diameter) and 250 liters of volume (**Figure 2.1**). The samples used here are coarse roots (larger than 1cm), from different typical trees of Cerrado *sensu stricto* biome in Brazil.

The experiment was carried out varying the position of a cross angle in the x-direction for each survey line. The results show the transverse electric field (TE) and the transverse magnetic field (TM) for each angle specified.

It is important to understand the attenuation in amplitude area of different root slopes for mapping root biomass. This work successful tested a new index calculating the amplitude area of the envelope trace for each root sample.

2.2 - MATERIALS AND METHODS

The GPR (ground penetrating radar) is a geophysical technique which uses reflected or scattered signal of electromagnetic waves of high frequencies to map the subsurface. It is often used for non-destructive shallow investigations of subsoil.

The method used the common offset acquisition, which consists of the transmission of radiated EM waves to the subsoil by a transmitting antenna placed on the surface. The propagation of the EM signal depends on the electrical properties of the materials (such as dielectric constant of the soil and dielectric constant of the medium), on the target depth, and on the frequency of the transmitted signal, which is directly related to the soil water content (Annan, 1992). Thus, the higher the water content, the greater the attenuation of the EM wave signal. Variations of the electrical properties in subsurface cause part of the signal to be reflected. Radar waves reflected and diffracted in the subsurface are received through the receiving antenna.

Vector-field EM waves separate into two independent components defined by field orientation concerning the boundary. Components are referred to as the TE (transverse electric field) and TM (transverse magnetic field), each antenna dipole propagates differently below ground.

The fresnel reflection coefficient can be described as:

$$R = \frac{\varepsilon_r - \varepsilon s}{\varepsilon_r + \varepsilon s} = \frac{Zs - Zr}{Zs + Zr} = \frac{Vs - Vr}{Vs + Vr}, \quad (1)$$

2.2.1 - Resolution limits

The resolution capability of the GPR depends basically on the frequency of the antenna used, the depth of the target object, the dielectric constant of the medium, and the dielectric constant of the target.

The shorter wavelengths of high center frequency antennas produce a narrower cone of transmission, which can focus on smaller areas and thereby resolve smaller features than the more spread out transmission cones produced by antennas with low center frequencies and longer wavelengths (Conyers 2004).

Here it is important to explain that the GPR produces EM waves in broadband, such that frequencies from half to two times that of the center frequency are present (Annan 2009).

The maximum resolution of vertical features is roughly equivalent to or larger than half the wavelength (Neubauer *et al.* 2002). Vertically stacked horizontal interfaces must be separated by at least one wavelength if they are to be resolved (Conyers 2004).

Figure 2.1 represents the resolved limit (separated by one wavelength), the Rayleigh limit (separated by $\frac{1}{2}$ to $\frac{1}{8}$ wavelength) and the unresolved events (Kallweit & Wood, 1982).

The Rayleigh limit consists of the minimum separation for which two point sources can be distinguished.

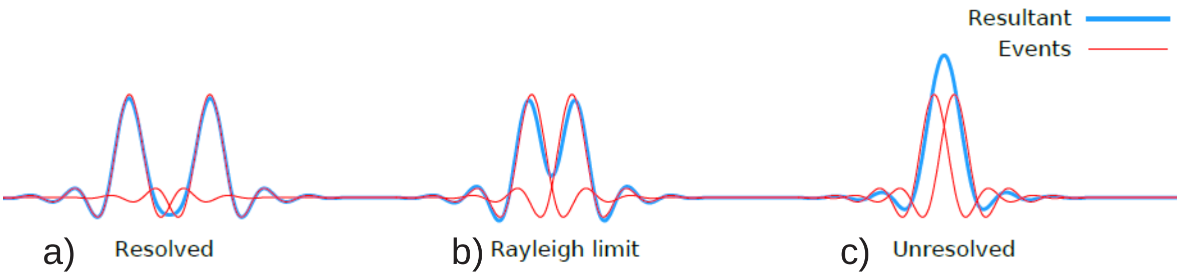

Figure 2.1: Schematic representation of resolution limits. a) Resolved limit; b) Rayleigh limit; c) Unresolved limit.

When there is a resolved signal amplitude is possible to estimate the reflection of the top and bottom of the root target efficiently through the GPR signal processing.

The signal amplitude can be interpreted as the result of the surface integer of the target, which depends on the dimensions in three directions.

The signal amplitude generated by the root target is equal to the summation of both top, and bottom reflections and its resolution limits vary with the diameter and dielectric constant of the root target.

The maximum resolution consists of the best approximation of the real diameter of target based on a specific environment condition (ε_{soil}) and root water content (ε_{root}).

When the GPR signal passes through a target smaller than the resolution limit, it occurs the scattering/diffraction phenomena. **Figure 2.1-c**), represents the unresolved limit, which the resultant underestimates the signal amplitude value for diffraction examples.

Higher water content in roots than in soil matrix can provide the necessary permittivity contrast, making root detection by GPR possible (Cui *et al.*, 2011). Dried roots are difficult to be detected by GPR. If the volumetric content of water by weight is less than 20%, detection becomes impossible, while roots with approximately 50% content are clearly identified (Hirano *et al.*, 2009).

The size of the final image generated by GPR relies on the top and bottom of reflections arrivals. Thus the dielectric constant of root and soil play an important role in defining the sample diameter value through the image.

Using the equations (2) and (3) for lossy dielectric medium and resolving for the maximum resolution:

$$V = \frac{c}{\sqrt{\varepsilon}} \quad (2)$$

$$\lambda = \frac{c}{f.\sqrt{\varepsilon_{soil}}} \quad (3)$$

The maximum resolution of vertical features is roughly equivalent to or larger than half the wavelength (Neubauer *et al.* 2002):

$$d > \frac{\lambda}{2} \quad (4)$$

Thus from equation (4), it is possible to visualize that the resolution limits of any target it is dependent on the wavelength, which varies with the central frequency of investigation and the dielectric constant of the medium (equation 3).

Figure 2.2 below shows the relationship between the wavelength and the central frequency investigation, the attenuation, and the skin depth for different soil velocities.

The most important factors that govern the propagation of an electromagnetic wave are the velocity (equation 2) and the attenuation (equation 5) (Stratton, 1941):

$$\alpha = \frac{\sigma}{2} \cdot \sqrt{\frac{\mu}{\varepsilon}} \quad (5)$$

For lossy dielectric medium $\mu = 1$, and $\sigma = 0.01$ for (for an oxidized soil case).

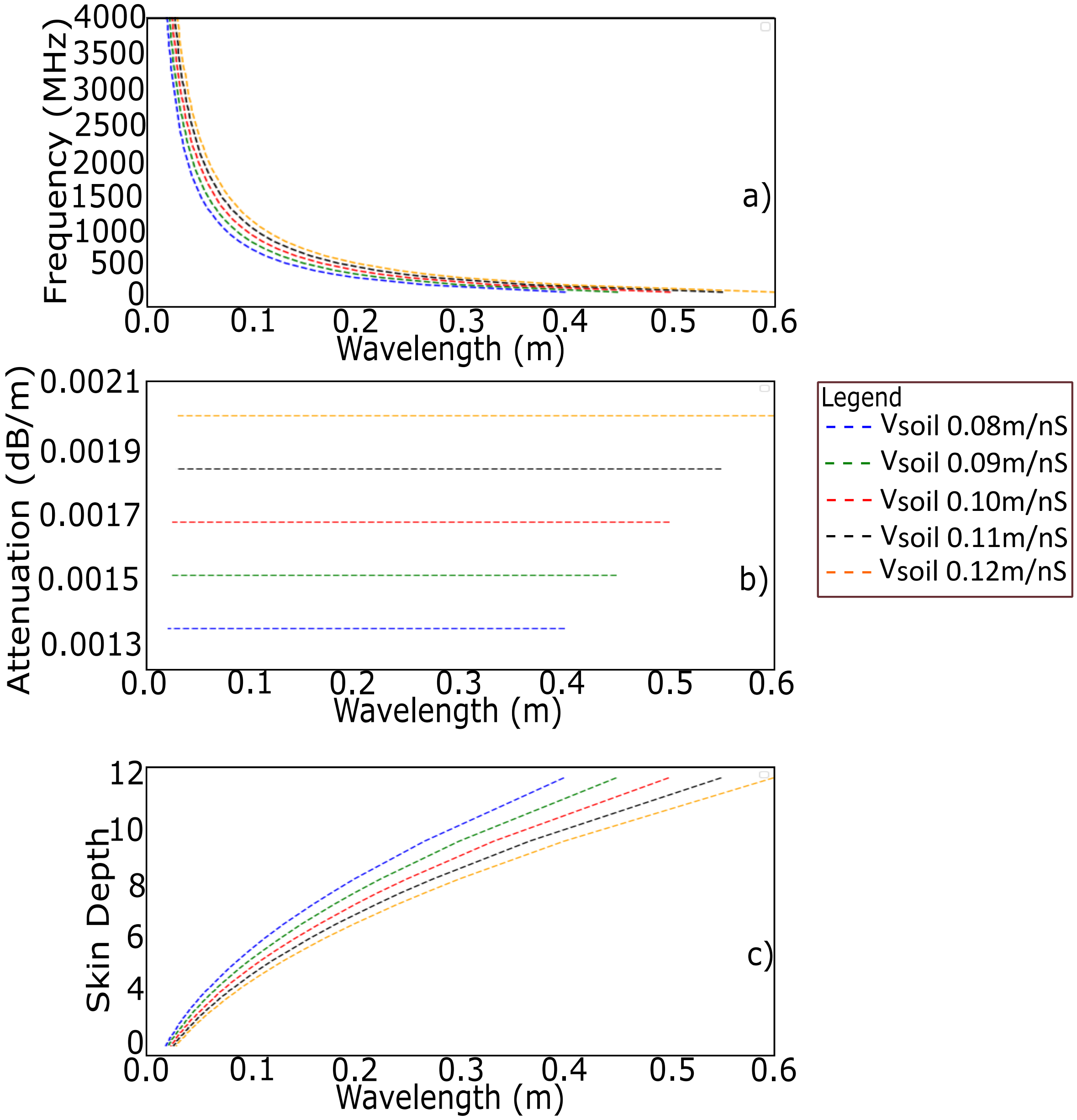

Figure 2.2: Plot of each soil velocity and the variation with wavelength and a) central frequency; b) attenuation; c) skin depth.

As predicted by equation 2 and 5, the attenuation varies with the dielectric constant of the medium. Different water content in the soil changes its velocity inversely proportional. **Figure 2.2-b)** shows that the attenuation is constant with the increasing of the wavelength and its value changes based on the medium velocity.

The amplitude of the electromagnetic fields decreases exponentially with increasing depth. The depth at which the field amplitude is reduced to e^{-1} is known as skin depth (δ). The δ is defined in equation (6):

$$\delta = \sqrt{\frac{2}{\omega\mu\varepsilon}} \quad (6)$$

For lossy dielectric medium $\mu = 1$, and $\omega = 2\pi f$.

Figure 2.2-c) shows that with the increase of skin depth, the wavelength also increases to propagate further deeply into the medium.

2.2.2 - Numerical modeling

The nature of the GPR forward problem can be classified as an initial value-open boundary problem. Then, to obtain a solution, one has to define an initial condition (i.e., frequency of the GPR transmitting antenna) and allow for the resulting fields to propagate through space, reaching – in theory – a zero value at infinity.

The specification of the source is required. Three main constants are used for both materials (in this case root and sand) to build numerical modeling in Reflexw: ε (dielectric permittivity); μ (magnetic permeability) and σ (electrical conductivity). The main parameters used to the model were established by al-Hagrey (2007), Annan (1992) and Torgonivkov (1992) in **Table 2.1**.

The finite-difference-time-domain method cannot assign the values of dx, dy, and dz independently, it is a conditionally stable numerical process. The stability condition is known as the CFL condition (Taflove, 1995) and is given by:

$$dt \leq \frac{1}{c\sqrt{\frac{1}{(dx)^2} + \frac{1}{(dy)^2} + \frac{1}{(dz)^2}}} \quad (7)$$

Where c is the speed of light. Hence, dt is bounded by the values of dx, dy, and dz. The stability condition for the 2D case is easily obtained by letting dz → ∞.

It is important to note that the spacial increment 'dx' is related to the minimum wavelength present in the medium (Taflove, 1995), this increment must be ten times smaller than the smallest wavelength existent in the system. Errors in the choice of the spacial and temporal parameters could bring on numerical dispersion (Sandmeier, 2015).

For the boundary conditions, it was established the parameter 'reflecting' for a 10 m distance borders, which means total reflection (rigid borders):

The antenna polarization used in the modeling were configured simulating the source transmitter with the dominant component Ey (Ey-Ey), transverse electric (TE), then the source used was the Ex component with the registration in (Ex-Ex), which represents the transverse magnetic (TM).

Simulating the reflections of the electromagnetic wave (Ey-Ey and Ex-Ex) by the surface of the reflector was used as the electromagnetic source the mode 'exploding reflector', which is characterized by the emission of the wavefront scattered directly by the target towards the surface (Yilmaz, 1987). In this procedure, the electromagnetic wave has only the outgoing time, although, in reality, the GPR reflected wave is recorded as a function of the double time. For adjusting the kinematics and the outgoing time to simulate a value equivalent to the double time, the velocity of the medium is divided by two (v/2) in this numerical modeling (Sandmeier, 2015).

For the numerical models studied, the dielectric constant of the soil was ε_{soil}= 15 (for an oxidized soil case). The central frequency of the antenna used was 2600 MHz. The average depth of the sample was 20cm. For the diameter variation results was fixed ε_{root}= 22 (saturated wood value) while for the dielectric constant variation results (ε_{root}) was fixed diameter of 5cm (thick/coarse root case). **Figure 2.2** exemplifies the general sample modeled.

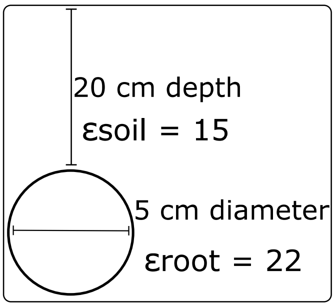

Figure 2.3: Schematic representation of a general sample modeled.

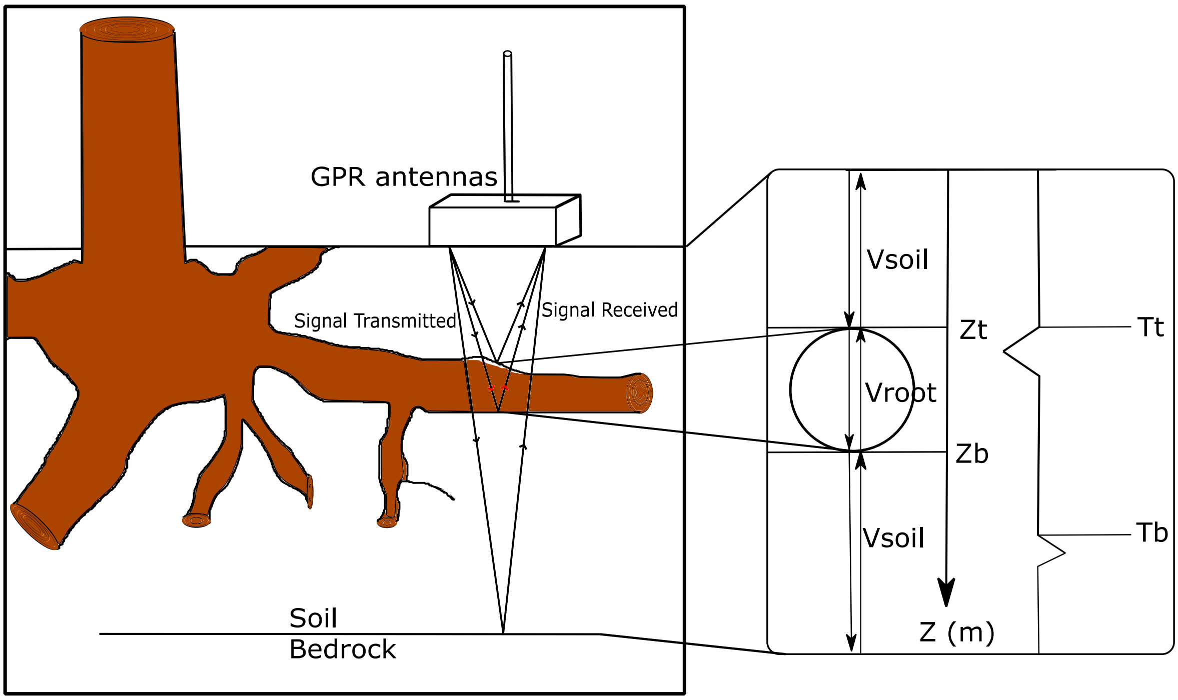

Figure 2.4: Schematic representation of electromagnetic wave interaction.

The results of the transverse electric and the transverse magnetic field of the numerical model are shown below in **Figure 2.5** for different root diameter (TE), in **Figure 2.6** for different root diameter (TM), in **Figure 2.7** for different root dielectric constant based in water content (TE) and in **Figure 2.8** for different root dielectric constant based in water content (TM).

From equation (7), the root has to have a larger diameter than 1.5 cm for resolving/quantifying the diameter in this experiment. **Figure 2.5-1a)-1b)** and **Figure 2.6-1a)-1b)** have smaller diameters than the quantifiable, so they represent diffractions examples, only the top reflection is visible. The **Figure 2.7-1a)-1b)-2a)-2b)** and **Figure 2.8-1a)-1b)-2a)-2b)** also represent diffractions examples, although it is possible to identify higher amplitude at unresolved limit (Kallweit & Wood, 1982).

The resolution limits, the attenuation and the amplitude decrease with the skin depth are the most important factors to define which parts of the image can be quantifiable (reflection events) or detectable (diffraction events).

The **Figure 2.7-1a), 1b), 2a), 2b)** and **Figure 2.8-1a), 1b), 2a), 2b)** have a phase inversion in comparison to the other examples. The reason is the lower ε_{root} [2 and 4.5] than the ε_{soil} [15] (for an oxidized soil case).

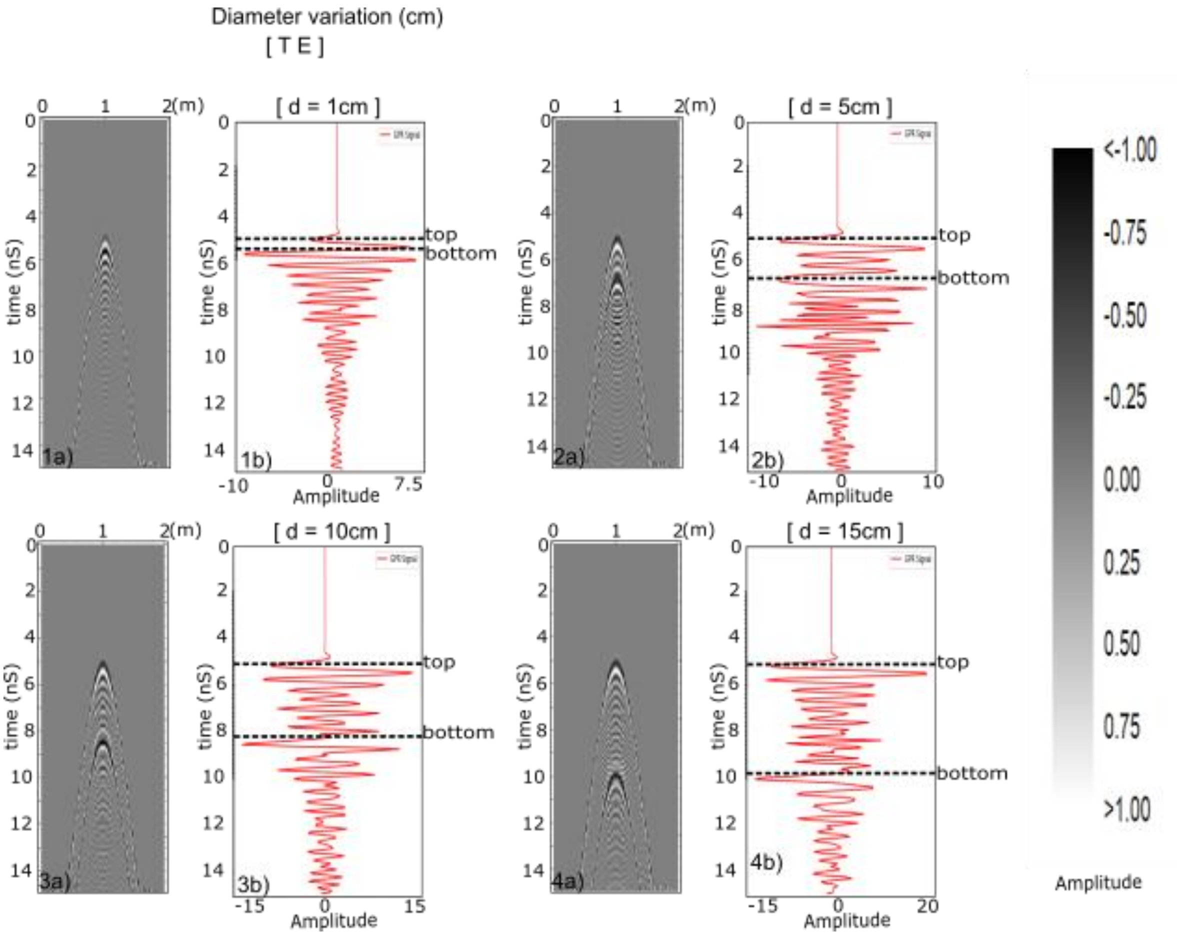

Figure 2.5 : Target diameter variation for the transverse electric field. 1a) Radargram of 1 cm diameter of root sample; 1b) Central trace radargram 1cm diameter of root sample; 2a) Radargram of 5 cm diameter of root sample; 2b) Central trace radargram 5 cm diameter of root sample; 3a) Radargram of 10 cm diameter of root sample; 3b) Central trace radargram 10 cm diameter of root sample; 4a) Radargram of 15 cm diameter of root sample; 4b) Central trace radargram 15 cm diameter of root sample.

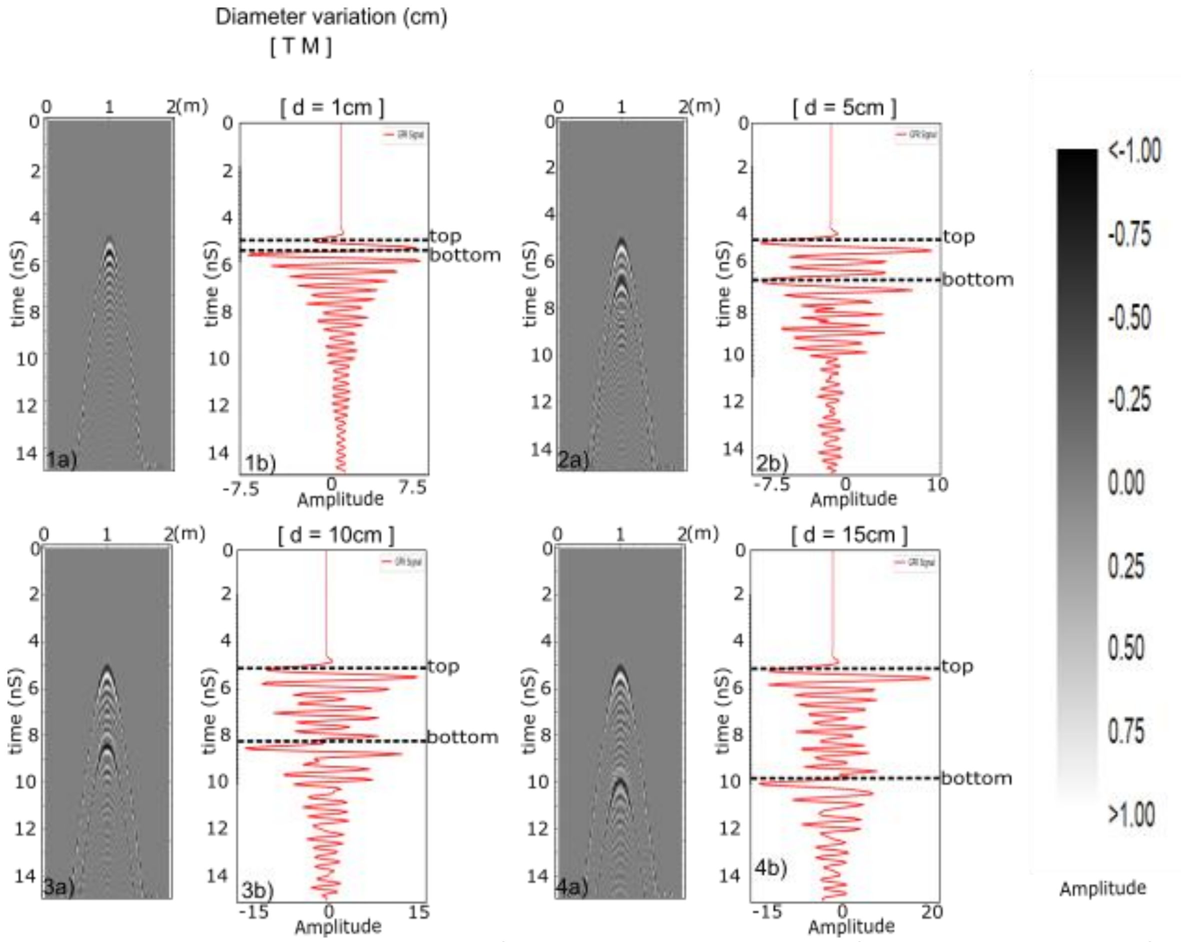

Figure 2.6: Target diameter variation for the transverse magnetic field. 1a) Radargram of 1 cm diameter of root sample; 1b) Central trace radargram 1cm diameter of root sample; 2a) Radargram of 5 cm diameter of root sample; 2b) Central trace radargram 5 cm diameter of root sample; 3a) Radargram of 10 cm diameter of root sample; 3b) Central trace radargram 10 cm diameter of root sample; 4a) Radargram of 15 cm diameter of root sample; 4b) Central trace radargram 15 cm diameter of root sample.

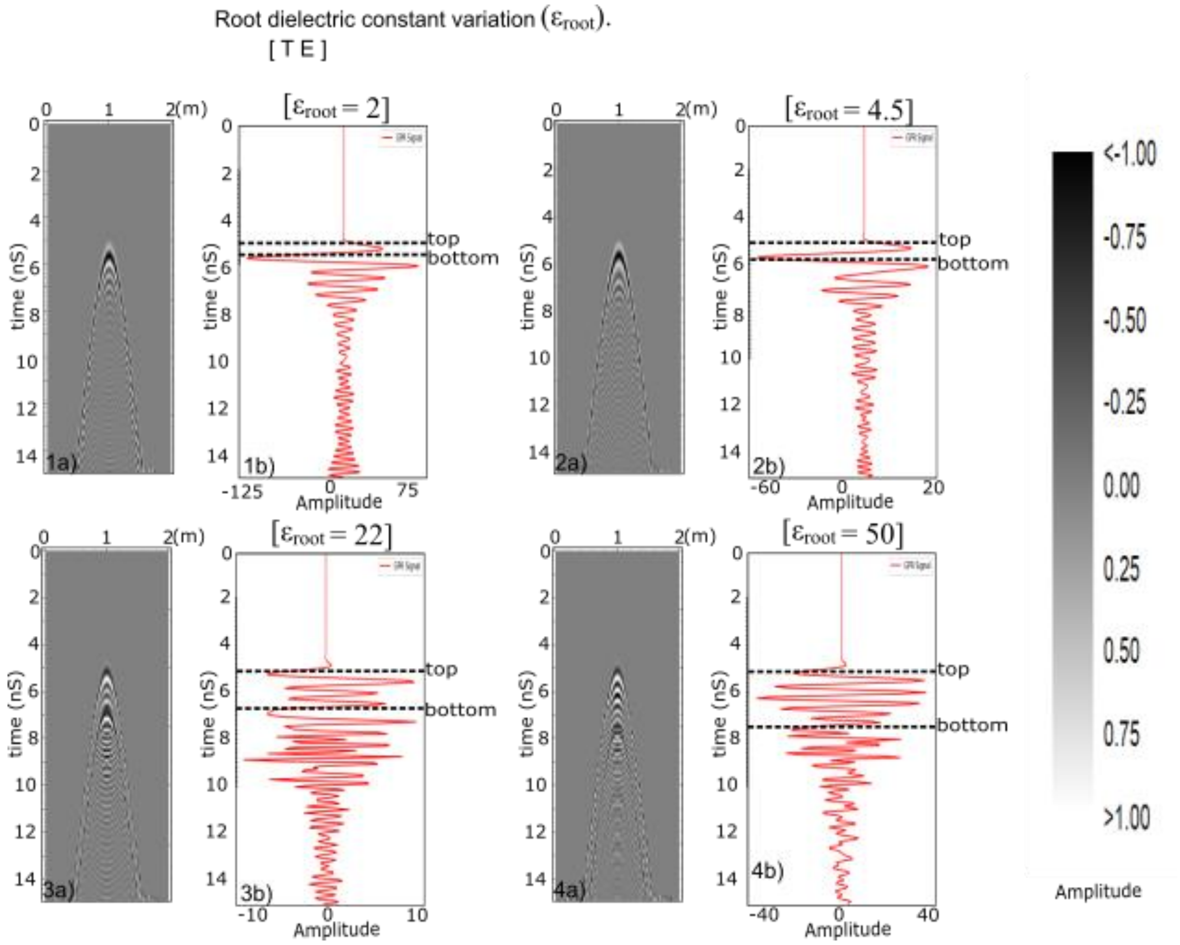

Figure 2.7: Target dielectric constant variation for the transverse electric field. 1a) Radargram of ε_{root} =2; 1b) Central trace radargram of ε_{root} = 2; 2a) Radargram of ε_{root} = 4.5; 2b) Central trace radargram of of ε_{root} = 4.5; 3a) Radargram of ε_{root} = 22; 3b) Central trace radargram of ε_{root} = 22; 4a) Radargram of ε_{root} = 50; 4b) Central trace radargram of ε_{root} = 50.

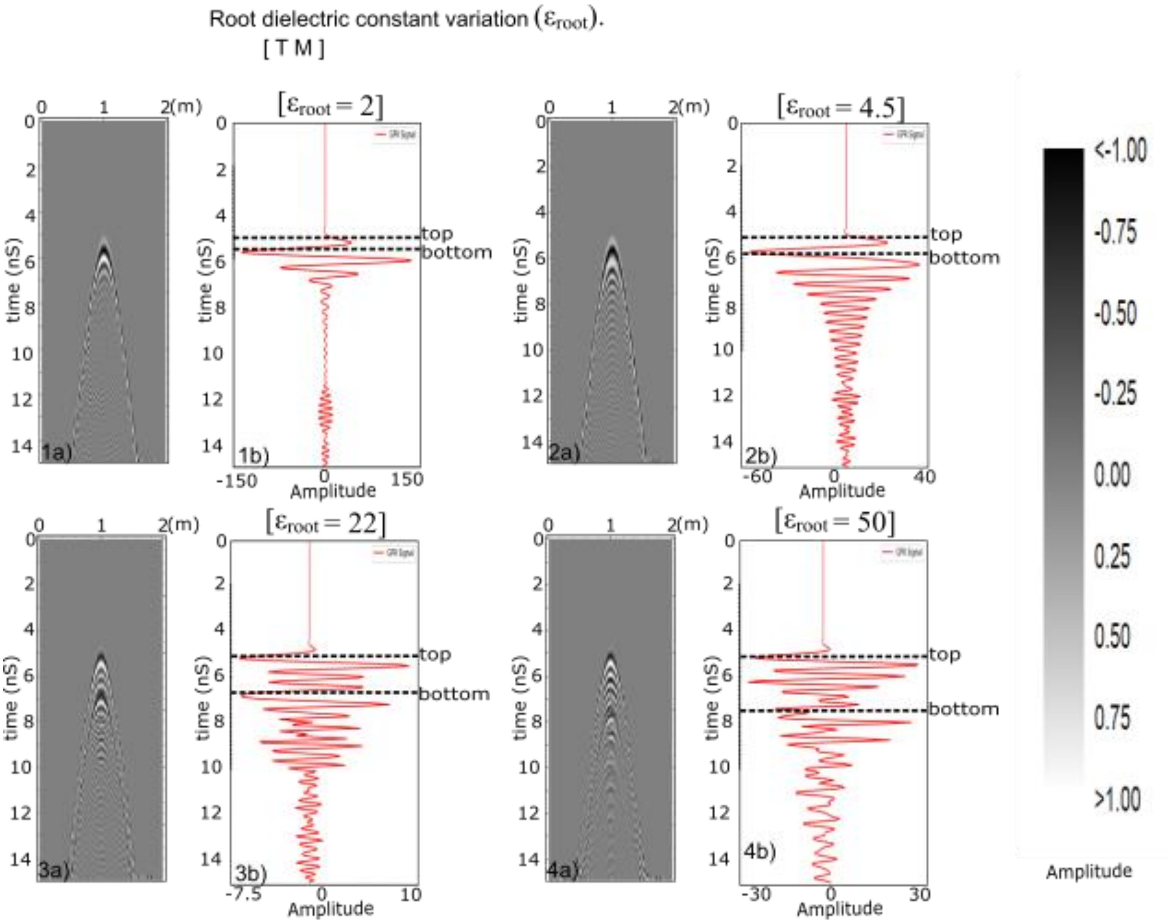

Figure 2.8: Target dielectric constant variation for the transverse magnetic field. 1a) Radargram of ε_{root} =2; 1b) Central trace radargram of ε_{root} = 2; 2a) Radargram of ε_{root} = 4.5; 2b) Central trace radargram of of ε_{root} = 4.5; 3a) Radargram of ε_{root} = 22; 3b) Central trace radargram of ε_{root} = 22; 4a) Radargram of ε_{root} = 50; 4b) Central trace radargram of ε_{root} = 50.

2.2.3 - Controlled experiment

Root detection and quantification are best when performed under favorable conditions, for example, in sandy soil (Butnor *et al.*, 2005). Soil characteristics have a great impact on the detection and quantification of coarse roots (Guo *et al.*, 2013). Large sandy soils are considered ideal for GPR surveys (Butnor *et al.* 2001, Butnor *et al.* 2005).

Due to the high dielectric constant of water compared to that of cellulose and air, the dielectric constant of the root is dominated by its water content (Guo *et al.* 2013; Al Hagrey 2007).

Other factors also have a direct influence on signal amplitude, such as the geometry of a target. The dimensions of roots used for this work is showed in **Table 2.1**. They have characterized as coarse roots (equal to or larger than 2mm), according to Silva (2007).

The root samples (**Figure 2.9**) were buried in the sandbox for data acquisition. The experiment consisted of analyzing the amplitude signal for different cross angles in the x-direction for each survey line (**Figure 2.10**).

Root	Length (cm)	Diameter (cm)	Depth (cm)
G(3,I)	10.5	3.5	11
G(1,II)	34	4	10
H(4,III)	22.5	2.5	10
H(2,II)	31.5	3	9-10
G(2,II)p	12	3.5	10

Table 2.1 - Root samples geometry and depth.

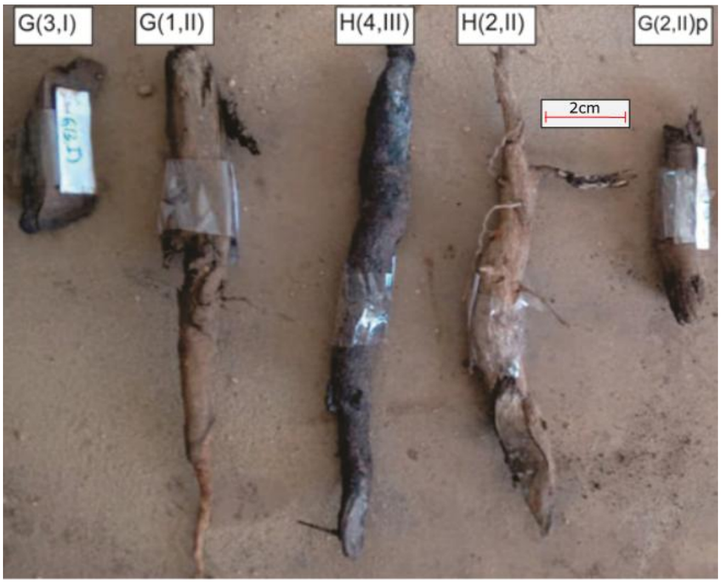

Figure 2.9 - Typical roots of Cerrado biome, samples used for data acquisition.

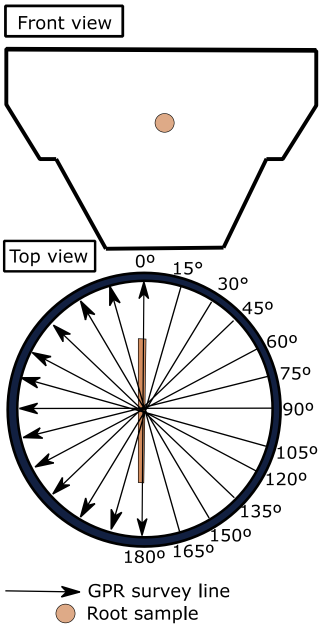

Figure 2.10 - Schematic view of data acquisition.

2.2.4 - Detection Range

According to Tanikawa *et al.* (2013) and Guo *et al.* (2015), the effective detection range for a cross angle of a target to GPR survey line is between 45º to 135º (**Figure 2.11**).

Equation (8) below express the minimum (eq. 9) and the maximum (eq. 10) A can be calculated for TE antenna polarization with various cross angles (x) of a survey line.

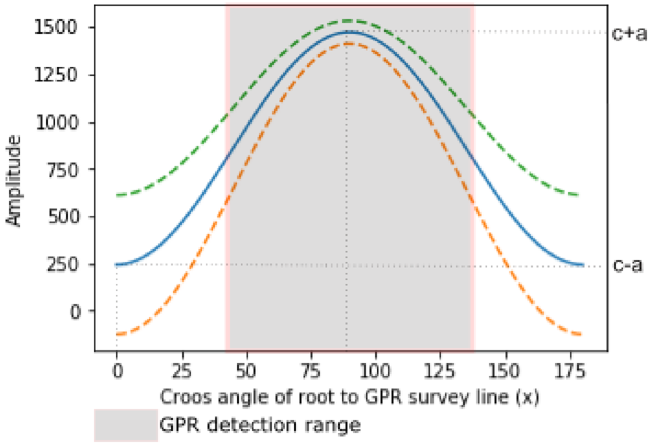

Figure 2.11 - Effective detection range for a cross angle of root to the GPR survey line with TE antenna polarization.

$$A(x) = - a \cos(2x) + c \quad (8)$$

$$A(0°) = c - a \quad (9)$$

$$A(90°) = c + a \quad (10)$$

For (TE) antennas polarization, when the survey line is orthogonal to the root orientation (x=90°), the polarization of the electromagnetic field is parallel to the long axis of a root branch. It allows the GPR to register the maximum reflection amplitude (Jol 2009, Wu *et al*. 2014b). However, when the survey line is parallel to root orientation (x=0°), the polarization of the electromagnetic field is orthogonal to root orientation. The GPR registers the minimum reflection amplitude.

For (TM) antennas polarization, when the survey line is orthogonal to the root orientation (x=90°), the polarization of the electromagnetic field is orthogonal to the long axis of a root branch. For this case, the GPR registers the minimum reflection amplitude (Jol 2009, Wu *et al*. 2014b). However, when the survey line is parallel to root orientation (x=0°), the polarization of the electromagnetic field is parallel to root orientation. It allows the GPR to register the maximum reflection amplitude.

The attenuation in amplitude area (A) caused by the cross angle (x) could be compensated by estimating A(90°) from multiple measured A(x), (Guo *et al.*, 2015).

2.3 - RESULTS AND DISCUSSION

The samples were buried in the sandbox at an average depth of 20cm. The central frequency of the antenna used for data acquisition was 2600 MHz. The data were processed using the software, Reflexw version 7.5 (Sandmeier, 2015). The processing flow (**Figure 2.12**) applied consisted on the header gain removal, static correction (zero time correction), background removal, time cut, spectral whitening, fk Stolt migration for v=0.17m/ns, Hilbert transform to envelope trace and final radargram.

The data was modeled using a script developed in Python v.3.7 (see Annex 1) for generating the final graphs.

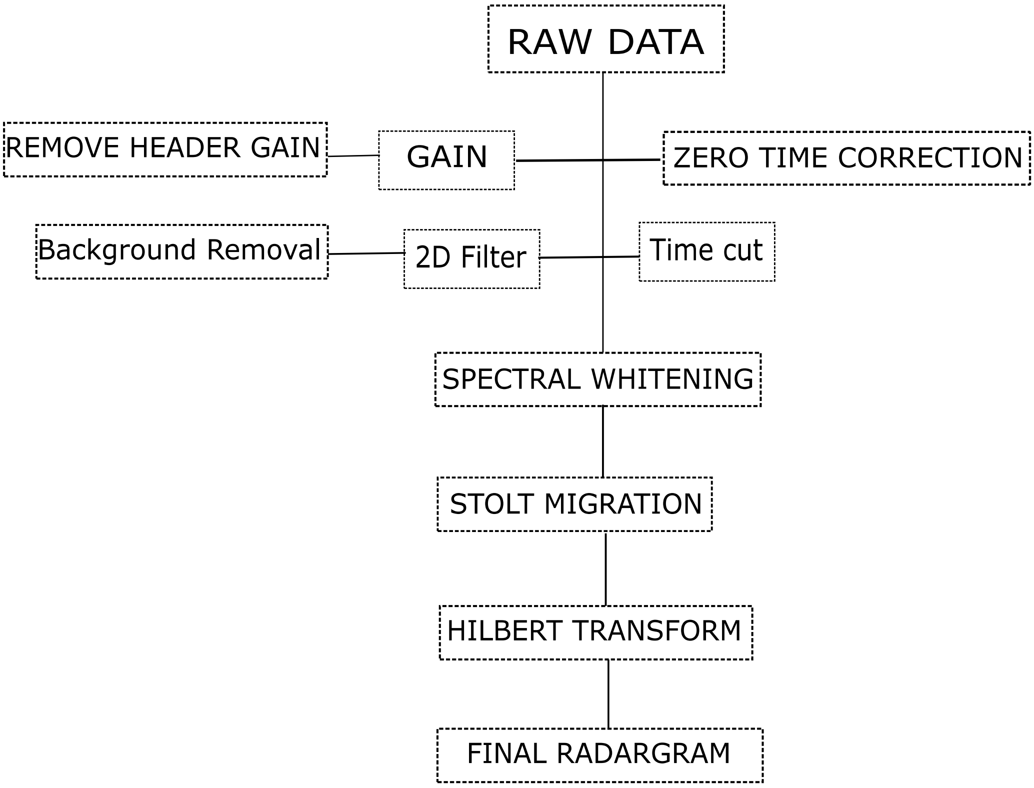

Figure 2.12 - Processing flow applied.

The results in **Figure 2.13- e)** shows a good correlation with 25% error of envelope index to the formula first predicted by Tanikawa *et al.* (2013). It is possible to visualize from **Figure 2.13 - d), i)** the amount of amplitude energy of the envelope trace for top and bottom root reflections. The samples were saturated in water for 24h before the data acquisition, then as the dielectric constant of the roots were high, the bottom root reflection is delayed about the top reflection allowing two separated picks visible in **Figure 2.13- c),h)**.

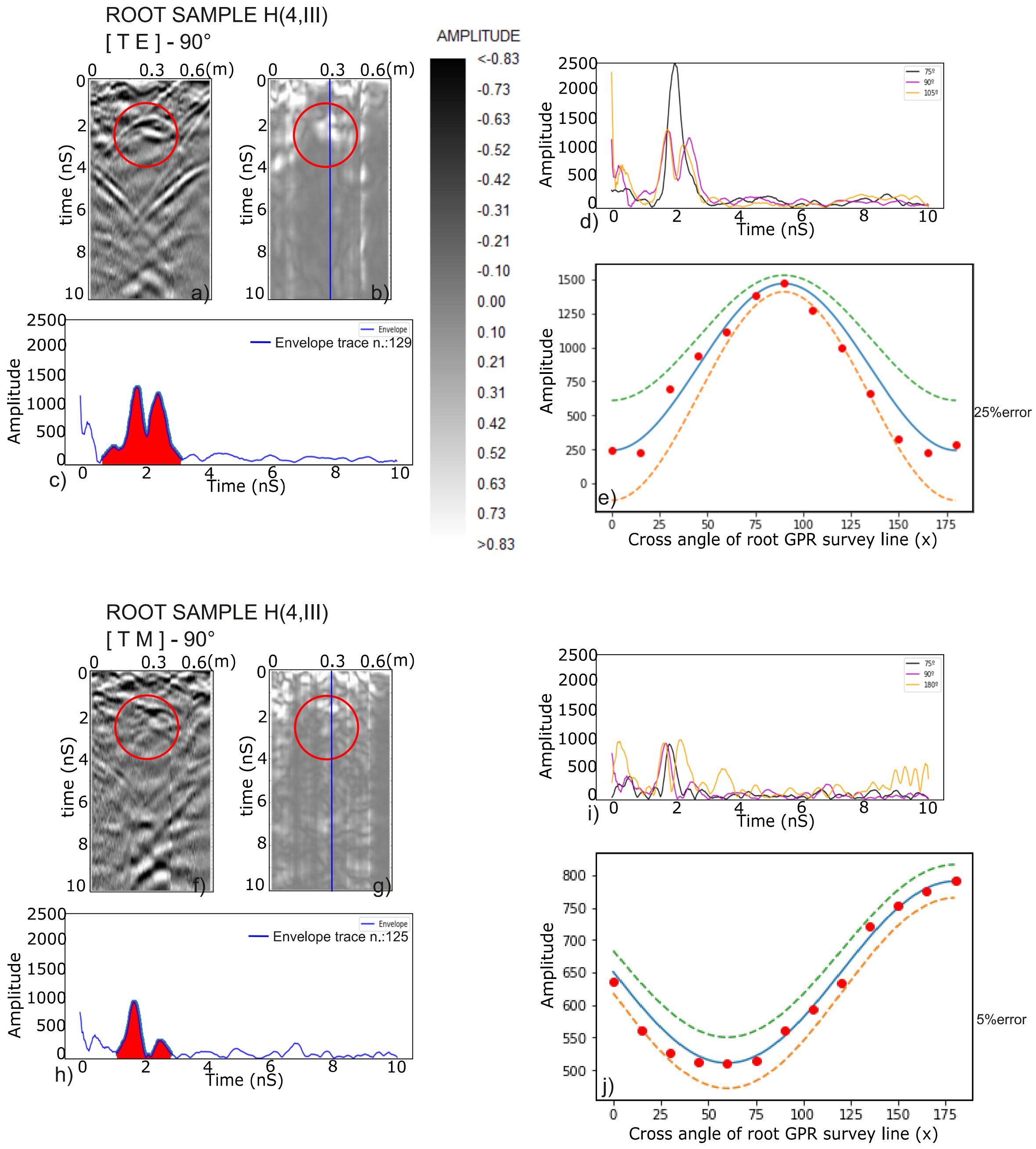

Figure 2.13- a) Radargram of background removal step for 90° TE; b) Final radargram for 90° TE; c) Amplitude area of envelope trace n.129 for 90° TE; d) Envelope trace of every cross angle for 90° TE; e) Correlation analysis for TE with Tanikawa *et al.* (2013) formula; f) Radargram of background removal step for 90° TM; g) Final radargram for 90° TM; h) Amplitude area of envelope trace n.125 for 90° TM; i) Envelope trace of every cross angle for 90° TM; j) Correlation analysis for TM with Tanikawa *et al.* (2013) formula.

Figure 2.13-a),f) show the radargram of background removal step for 90° TE and 90° TM. **Figure 2.13-b),g)** show the final radargram for 90° TE, and 90° TM. The value

for each sample displayed in **Figure 2.13-e),j)** are specified in **Table 2.2** for TE, and **Table 2.3** for TM.

Angle(x)	0	15	30	45	60	75	90	105	120	135	150	165	180
Envelope amplitude	243	223	695	936	1113	1380	1470	1275	998	664	327	223	287

Table 2.2 - Amplitude energy of envelope trace for each cross angle (x) for TE.

Angle(x)	0	15	30	45	60	75	90	105	120	135	150	165	180
Envelope amplitude	637	561	526	512	511	515	561	593	635	721	753	776	791

Table 2.3 - Amplitude energy of envelope trace for each cross angle (x) for TM.

The results in **Figure 2.13- j)** shows a good correlation with 5% error of the envelope index to the formula described by equation (5).

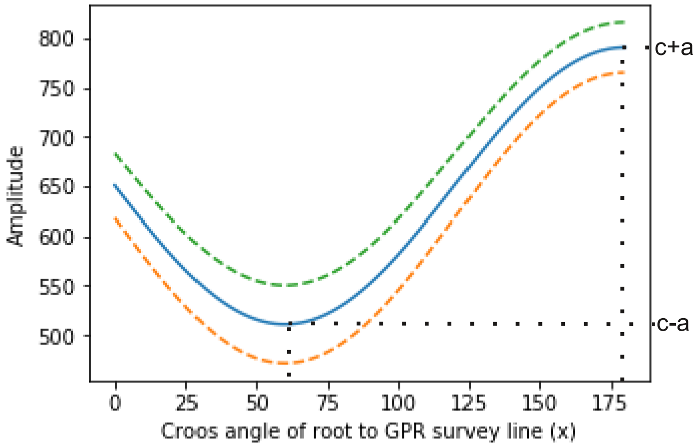

Figure 2.14 - Cross angle of root to GPR survey line with TM antenna polarization.

$$\mathbf{A(x) = - a \,.\, \sin\left(\tfrac{3}{2}x\right) + c \quad (11)}$$

$$A(180^{o}) = c + a \ (12)$$

$$A(60^{o}) = c - a \ (13)$$

The complemented results for generating the envelope amplitude index are shown by each cross angle in **Figure 2.15**, **Figure 2.16**, and **Figure 2.17** for TE and **Figure 2.18**, **Figure 2.19**, and **Figure 2.20** for TM.

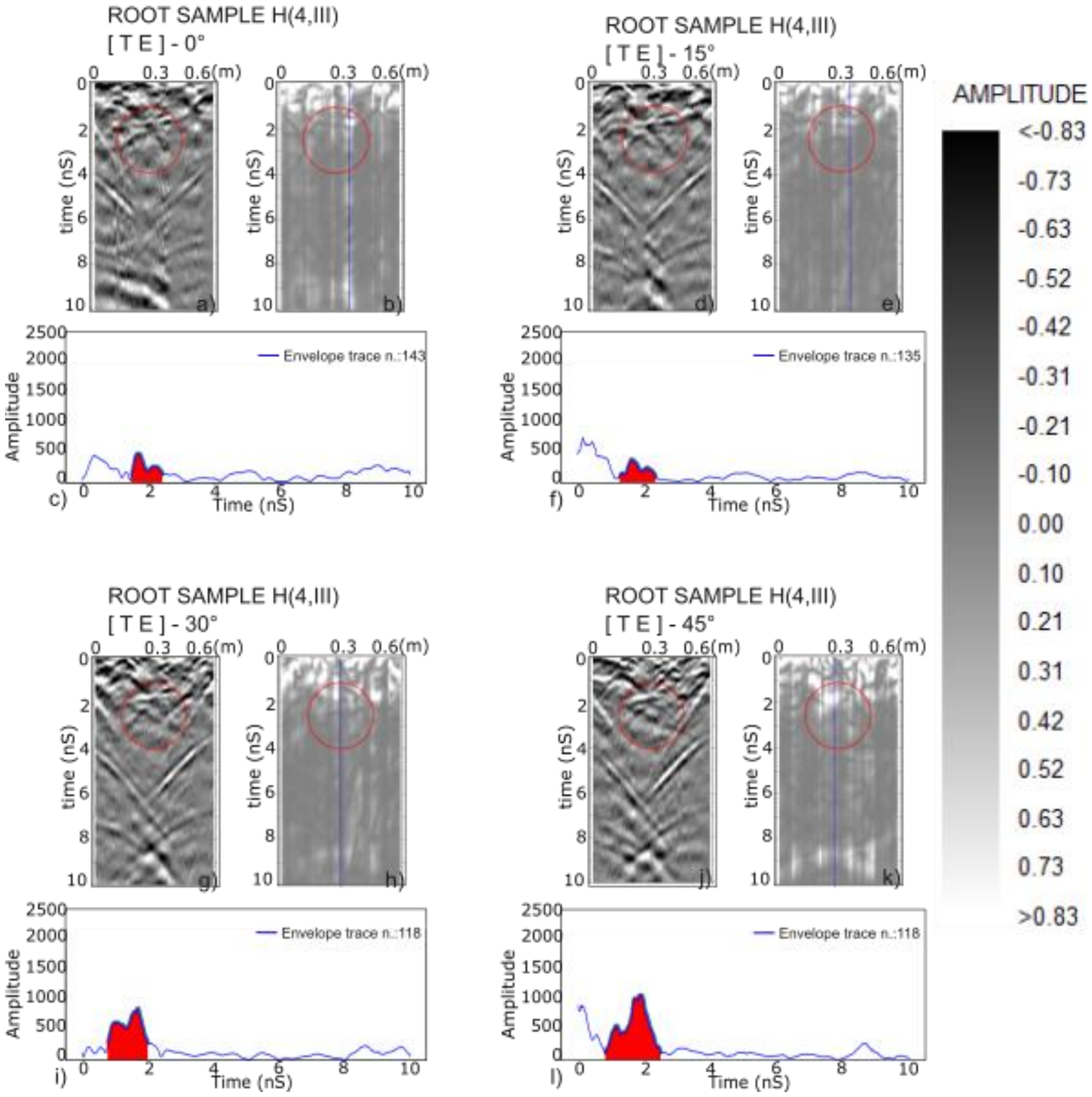

Figure 2.15 - Results for cross angle x=0° for TE a) Radargram of background removal step b) Final radargram c) Amplitude area of envelope trace. Results for cross angle x=15° for TE d) e) f). Results for cross angle x=30° for TE g) h) i). Results for cross angle x=45° for TE j) k) l).

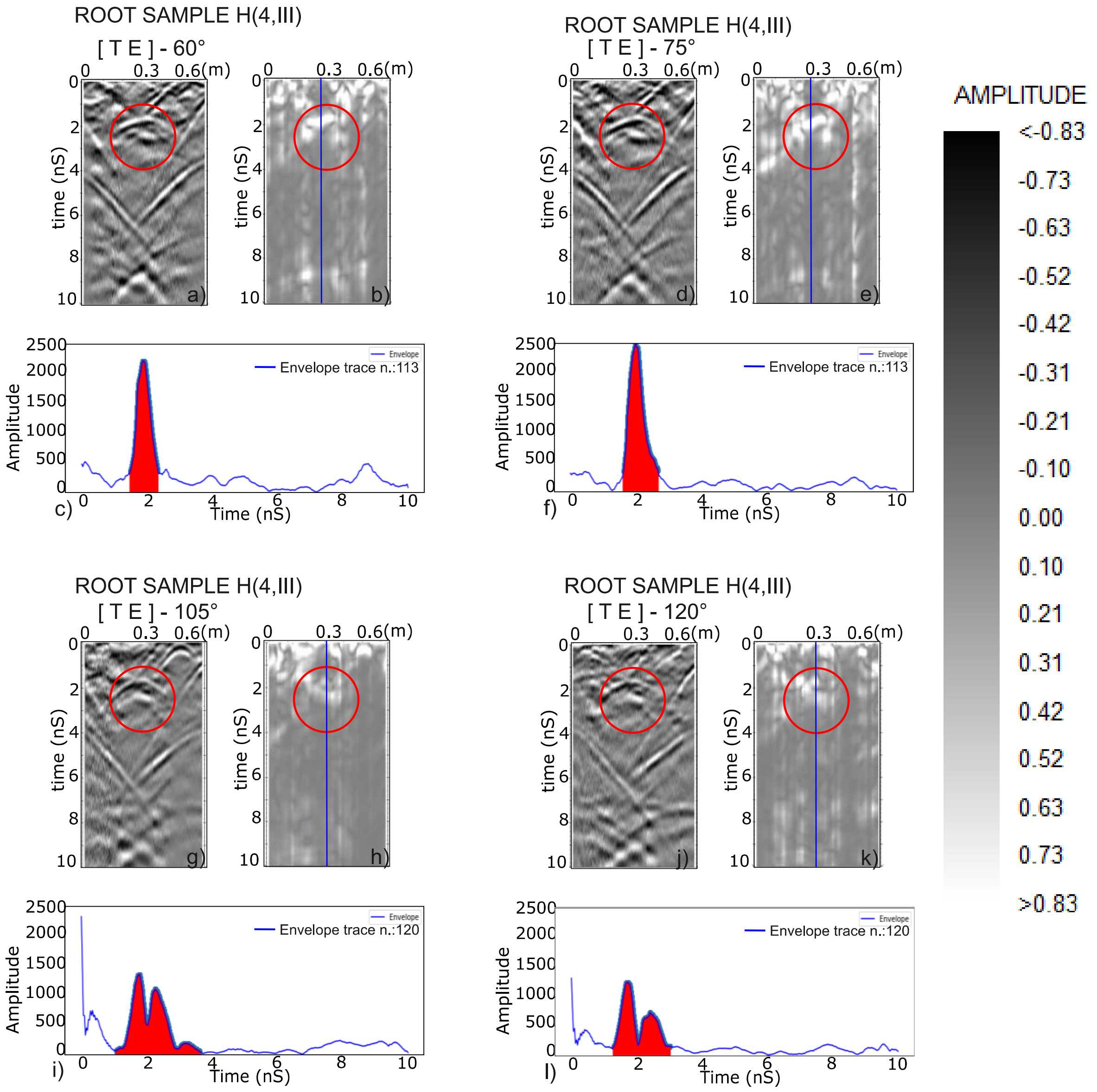

Figure 2.16 - Results for cross angle x=60° for TE a) Radargram of background removal step b) Final radargram c) Amplitude area of envelope trace. Results for cross angle x=75° for TE d) e) f). Results for cross angle x=105° for TE g) h) i). Results for cross angle x=120° for TE j) k) l).

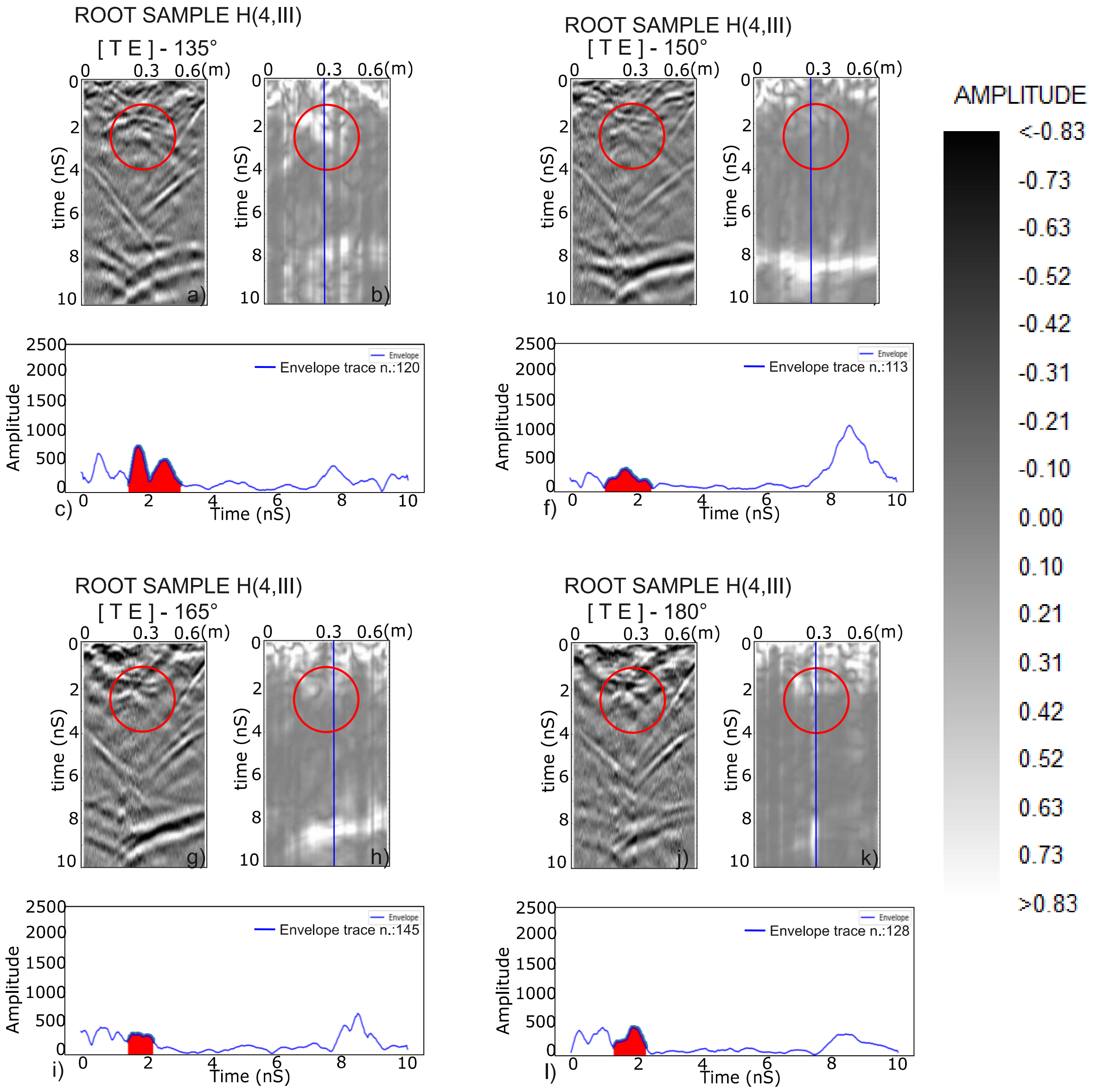

Figure 2.17 - Results for cross angle x=135° for TE a) Radargram of background removal step b) Final radargram c) Amplitude area of envelope trace. Results for cross angle x=150° for TE d) e) f). Results for cross angle x=165° for TE g) h) i). Results for cross angle x=180° for TE j) k) l).

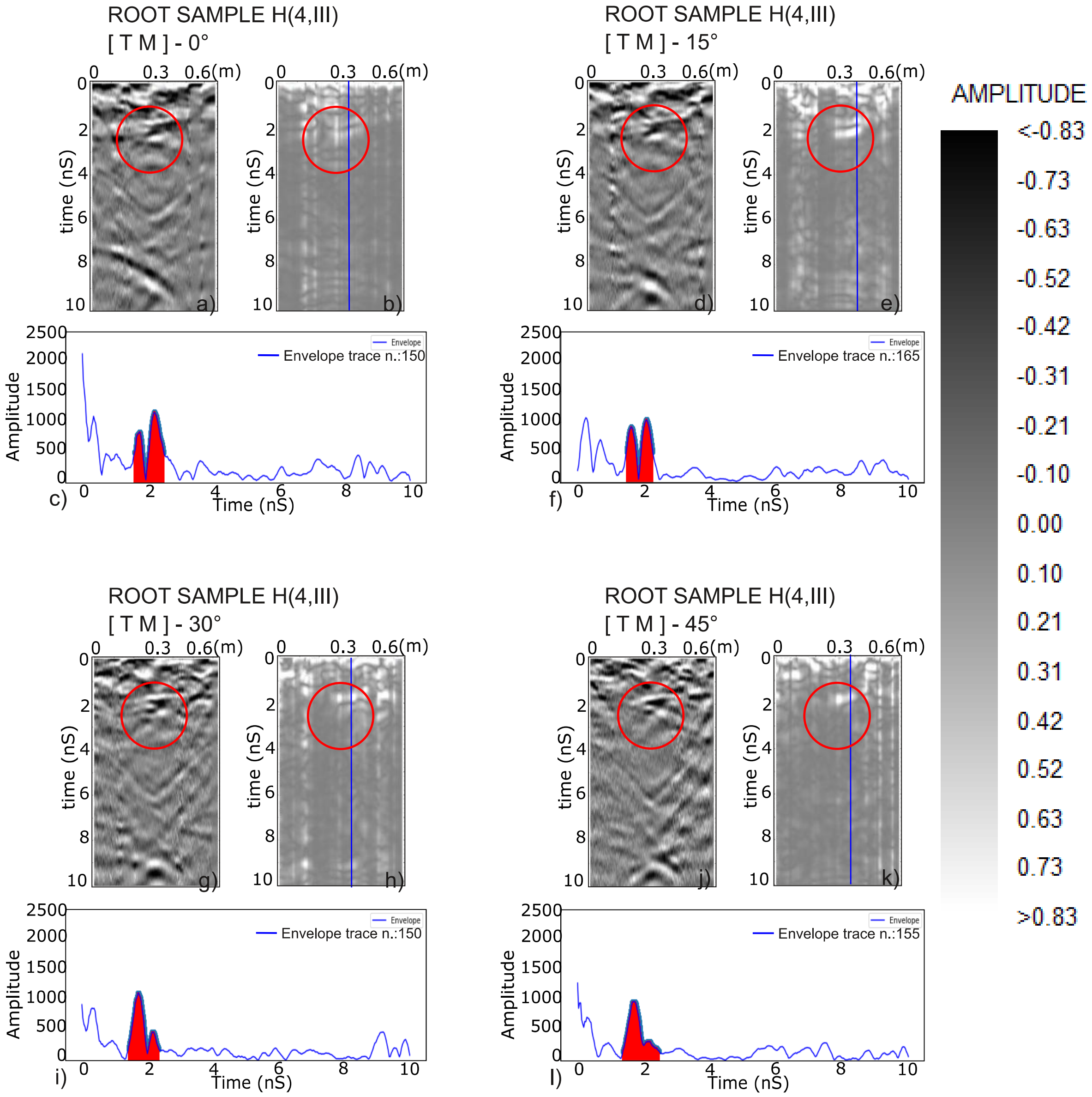

Figure 2.18 - Results for cross angle x=0° for TM a) Radargram of background removal step b) Final radargram c) Amplitude area of envelope trace. Results for cross angle x=15° for TM d) e) f). Results for cross angle x=30° for TM g) h) i). Results for cross angle x=45° for TM j) k) l).

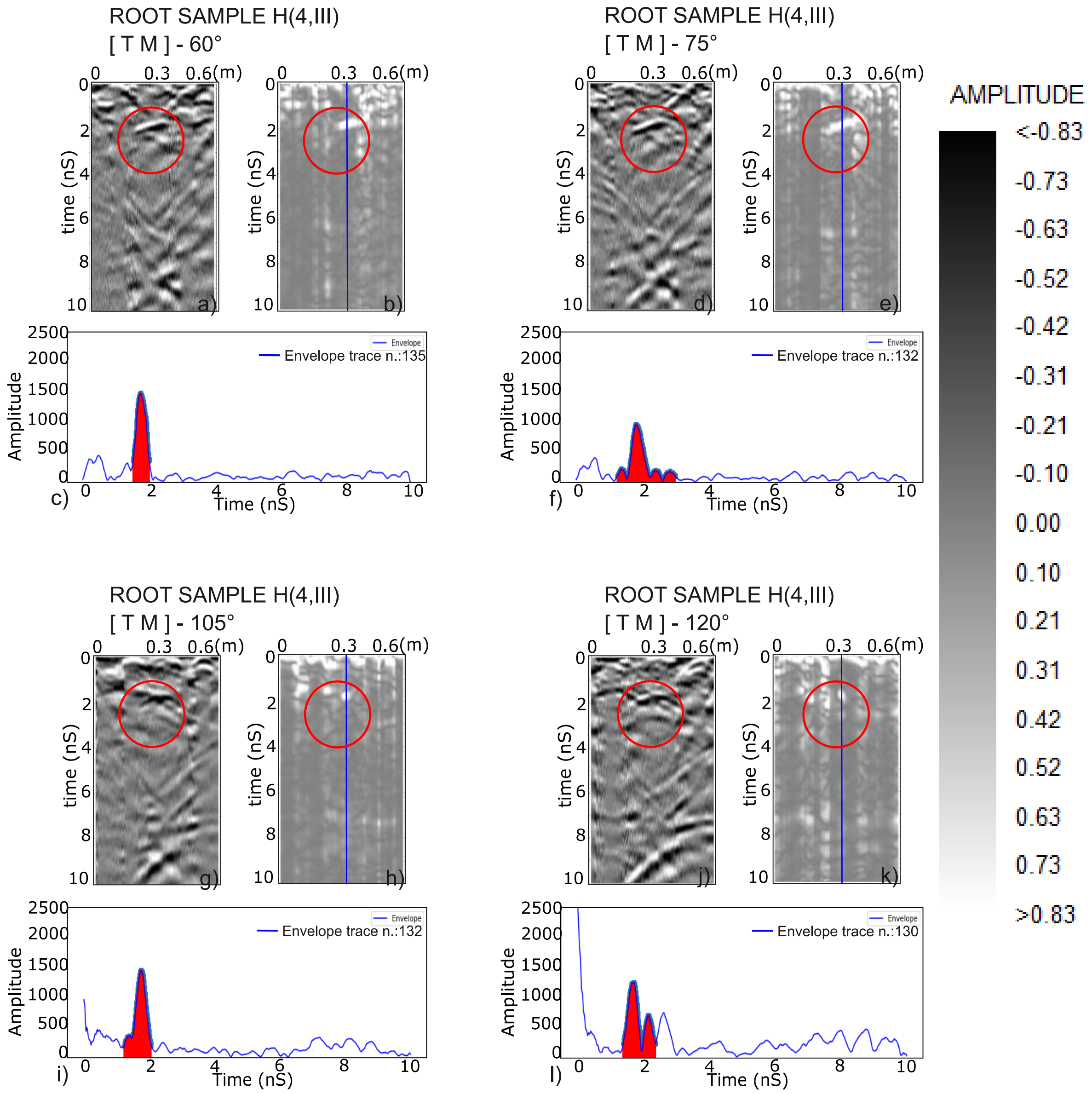

Figure 2.19 - Results for cross angle x=60° for TM a) Radargram of background removal step b) Final radargram c) Amplitude area of envelope trace. Results for cross angle x=75° for TM d) e) f). Results for cross angle x=105° for TM g) h) i). Results for cross angle x=120° for TM j) k) l).

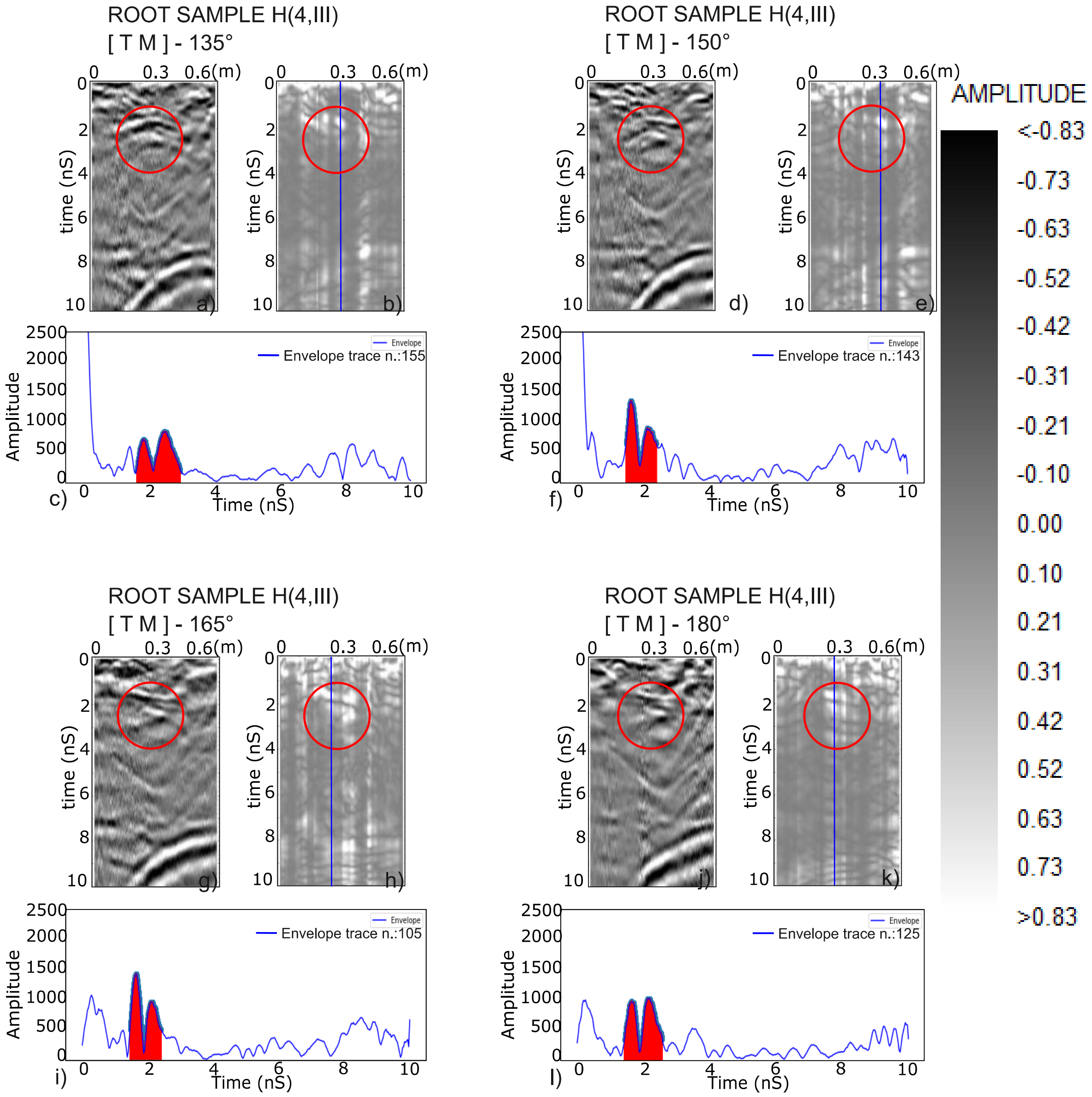

Figure 2.20 - Results for cross angle x=135° for TM a) Radargram of background removal step b) Final radargram c) Amplitude area of envelope trace. Results for cross angle x=150° for TM d) e) f). Results for cross angle x=165° for TM g) h) i). Results for cross angle x=180° for TM j) k) l).

2.4 - CONCLUSION

Through the numerical modeling experiment was possible to estimate the variables (target diameter, target depth, target dielectric constant, and the environment dielectric constant) to understand the electromagnetic wave propagation and interaction in the subsurface.

The understanding of the dielectric constant of the target plays a main role in finding the bottom reflection event of a root. It is difficult to estimate the right size of the event without the dielectric constant value, and also the maximum amplitude refers mainly only to part of the top root reflection, as shown in Tanikawa *et al.* (2013) study.

This work successful shows the envelope amplitude index for various cross angles (x) as predicted by equation (8). Also, the new data for the transverse magnetic field of polarization antenna fit the formula predicted in 2013. **Figure 2.13- e)** for the TE is an even function, as established by Eq. (8). **Figure 2.13- j)** for the TM it is possible to visualize an odd function. The equation established for the transverse magnetic field as a function of the envelope amplitude index for various cross angles (x) is predicted by equation (11).

Finding a faster solution for estimating the complete energy of full target reflection it is important to automate the volume estimation studies in future works. For this step, it is crucial to consider both top and bottom root reflections.

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- ANNEX I -

Python script developed for estimating the integer below a GPR trace

```
import numpy as np
import matplotlib.pyplot as plt
#from scipy.signal import hilbert

#OPEN FILE
x3,y3=np.loadtxt('VAR-X-H4III-90-TE-tr129-final.DAT',unpack=True)

#PARAMETERS
t=x3
y=y3-100 # auxiliar signal for finding zeros
dt = t[1]-t[0]
fs = 1/dt
fnew = 50*fs
dtnew = 1/fnew

#Resampling the auxiliar signal
tnew = np.arange(t[0],t[-1],1/fnew) # novos pontos da amostras
num_coeffs=len(t)
sm=0
for k in range(-num_coeffs,num_coeffs):
        sm+=y[k]*np.sinc( k - fs * tnew )

#Resampling the original signal
sm3=0
for k in range(-num_coeffs,num_coeffs):
        sm3+=y3[k]*np.sinc( k - fs * tnew )

#Finding zeros in auxiliar signal
Z=[] #amplitude (deve ser proximo de zero)
T=[] #tempo
K=[] #index
for k in np.arange(0,len(sm)-1,1):
        if sm[k]*sm[k+1]<0:
                Z.extend([sm[k+1]])
                T.extend([tnew[k+1]])
                K.extend([k])
print('K=',len(K))
print('y=',len(y))

#CALCULATE THE AREA in original signal
bmin=1 #bolinha inicial
bmax=2 #bolinha final
kmax=K[bmax]
kmin=K[bmin]
#n=kmax-kmin #numero de pontos no grid
```

```
S=0
Sabs=0

for l in range(kmin,kmax):
#	print(l)
	S+=sm3[l]*dtnew
	Sabs+=np.abs(sm3[l])*dtnew

print('Integral = ',S)
print('Integral absoluta = ',Sabs)
#tmin=tnew[K[bmin]]
#tmax=tnew[K[bmax]]
Tint=tnew[kmin:kmax]
Zint=sm3[kmin:kmax]

#print(len(Zint))
#print(len(Tint))

#PLOT GRAPH AMPLITUDE X TIME
fig=plt.figure(figsize=(10,20))
ax3=fig.add_subplot(511)
ax3.legend()
ax3.set_xlabel('Time (ns)')
ax3.set_ylabel('Amplitude')
plt.ylim([0,2500])

ax3.stem(Tint,Zint,'r')
ax3.plot(x3,y3,'b', label='Envelope')
#ax3.plot(tnew,sm,'xm') #plot resampled signal
#ax3.plot(x3,np.zeros(len(x3)),'k') #Black line axis t=0
#ax3.plot(T,Z,'o')
ax3.plot

ax3.legend()
plt.show()
```

CAPÍTULO 3 – ARTIGO 2

GPR AS NON-INVASIVE METHOD TO STUDY ROOT BIOMASS:

CASE STUDY OF CERRADO - BRAZIL

ABSTRACT

The reduction of greenhouse gases emission was the focus of several international conferences such as the Kyoto Protocol in 1997, REDD+ program in 2009, IPCC in 2014, the Paris Agreement in 2015, because of a series of global climate changes registered. In this scenario, the understanding of accumulation and fixation of atmospheric carbon realized by woody plants as part of its photosynthesis process has an important role in helping to mitigate the climatic change. The biome Cerrado and other savanna woodlands worldwide have a high proportion of below-ground biomass about above-ground biomass. There is still a relative lack of information on below-ground biomass in many ecosystems due to the difficulty of destructive technique, time laborious and expensive. The non-destructive methods currently used are the allometric equations. However, they are not well modeled yet for thick roots in tropical regions. The GPR (ground penetrating radar), as an alternative to the non-destructive methods for mapping root biomass, has been studied effectively and showing promising results. The object of this work is to verify the applicability of the GPR method to estimate root biomass in a natural ecosystem and compare the geophysical results to the traditional destructive technique results. The correlation results showed a strong relationship for each group (Pearson's coefficient greater than 60%) between root biomass from soil cores and estimated root biomass using GPR.

Keywords: Savanna woodland, below-ground, carbon stock, near surface geophysics.

3.1 - INTRODUCTION

Since the Industrial Revolution, the emission of greenhouse gases increased with the burning of fossil fuels. This increase led to a series of global climate changes due to anthropic actions in the last decades (Houghton 2003, Carvalho *et al.*, 2010; Bar-On *et al.* 2018).

The alarming increase in the concentration of greenhouse gases was the focus of several international conferences and conventions such a UNFCCC (United Nations Framework Convention on Climate Change) in 1992, the Kyoto Protocol in 1997, REDD+

program in 2009, IPCC in 2014, the Paris Agreement in 2015, among others. The main goal is to find strategies to reduce the emission of greenhouse gases to the atmosphere. Reducing the emission of greenhouse gases has motivated the knowledge demand about the capacity of different ecosystems to capture and fix atmospheric carbon in its biomass.

In this context, forests provide important environmental services to mitigate climate change. The carbon fixed by the living biomass reservoir (above and below-ground) can represent between 70 to 95% of the CO_2 sequestered during the growth of a tropical forest, the rest represents litter (layer of organic waste deposited in the forest soil); dead wood (dead trees and shrubs) and soil carbon (CGEE, 2008).

Assessing the distribution of biomass on the planet is important for estimating carbon sequestration stocks, for modeling biogeochemical cycles and for understanding the historical effects and future impacts of anthropogenic actions. Subsurface biomass accounts for 40% of the total biomass of the planet and is estimated at 230 Gt C (Bar-On *et al.*, 2018).

The below-ground biomass productivity contained in roots of savanna ecosystems is often underestimated due to the difficult to quantify (Grace *et al.* 2006, Miranda *et al.* 2014), since the destructive methodologies require a great amount of time and labor, making the activity quite costly.

Quantification of carbon stock in forests is a challenging task, which, due to the methodologies used, involves a high degree of uncertainty and discrepancies (Qureshi *et al.*, 2012).

Indirect methods using allometric equations to estimate root biomass are an alternative to the destructive method. However, it is rare in literature work that has adjusted allometric models to obtain the root biomass of natural ecosystems (Kuyah *et al.*, 2012; Koala *et al.*, 2017). In general, the estimation of below-ground biomass compartment is usually done by applying an expansion factor based on the ratio of below-ground biomass to above-ground biomass, known as root: shoot ratio (IPCC, 2006).

The geophysical technique to map the subsoil is another promising alternative to the indirect methods using allometric equations. The ground penetrating radar (GPR) has been studied since Hruska (1999) to image roots.

The GPR technique has shown great results on imaging the behavior of root patterns, and it is still being studied to settle as a traditional methodology (Butnor *et al.* 2001, Butnor *et al.* 2003, Butnor *et al.* 2005, Tanikawa *et al.*, 2013; Guo *et al.* 2015).

The Brazilian Cerrado is considered one of the 34 hotspots worldwide, one of the priority areas for nature conservation (Myers *et al.,* 2000 and Mittermeier *et al.*, 2005). However, land-use changes in Cerrado are occurring much faster than in other biomes. Approximately 50% of its original habitat had been converted into agricultural and livestock activities by 2010 (Roitman *et al.*, 2018).

The estimation of forest biomass plays a key role in decision-making in several areas, such as forest management and climate change. Thus studies related to modeling, sampling, and quantification of Cerrado vegetation are scientifically relevant (Azevedo, 2014). They provide information to define forest policies, forest management resources, and strategic planning to the use and conservation of forest resources. Because of its extensive area, data on this ecosystem is necessary for studies of productivity, energy analysis, and contributions of management practices to global carbon cycling (Abdala *et al.*, 1998).

The Cerrado vegetation covers approximately 2,000,000 km², 20% of the area of Brazil, in its various physiognomic forms (Abdala *et al.*, 1998). It is the second largest biome in South America exceeded only by the Amazon (MMA, 2007). Cerrado biome shows a large biological diversity, and its flora is composed by more than 12,000 species (Mendonça *et al.*, 2008), and around 40% of endemism (Klink & Machado, 2005).

One of the most typical characteristics of the Cerrado vegetation when compared to other tropical vegetation formation, is the high proportion of below-ground biomass about above-ground biomass (Castro, 1996; Haridasan, 2000).

The Cerrado biome is considered the largest neotropical savanna (Castro, 1996), and has a fundamental role in the global carbon cycle, acting as a huge assimilator and accumulator of carbon. The lack of related studies quantifying the total biomass in Cerrado compromises the understanding of CO_2 conversion process in the biome (Paiva *et al.* 2011).

The objective of this work is to verify the efficiency of the GPR method to estimate the below-ground biomass in the natural ecosystem of Cerrado in Brazil, using direct quantification and indirect estimation.

3.2 - MATERIALS AND METHODS

The ground penetrating radar (GPR) is a high-resolution geophysical method, which relies on the propagation and reflection of high-frequency electromagnetic waves. The GPR images below-ground structures related to changes in dielectric properties, such as roots or below-ground biomass.

The GPR data acquisition was carried out with a common spacing technique and central frequency antenna of 900 MHz. The equipment used was a GSSI SIR-3000.

The GPR profiles covered an area of 100 m² with the survey lines disposed of, as shown in **Figure 5.1**. The area was subdivided into four squares of 25 m². Each square was covered with 8 GPR profiles and 15 biomass samples. The total study consisted of 32 GPR profiles and 60 biomass samples.

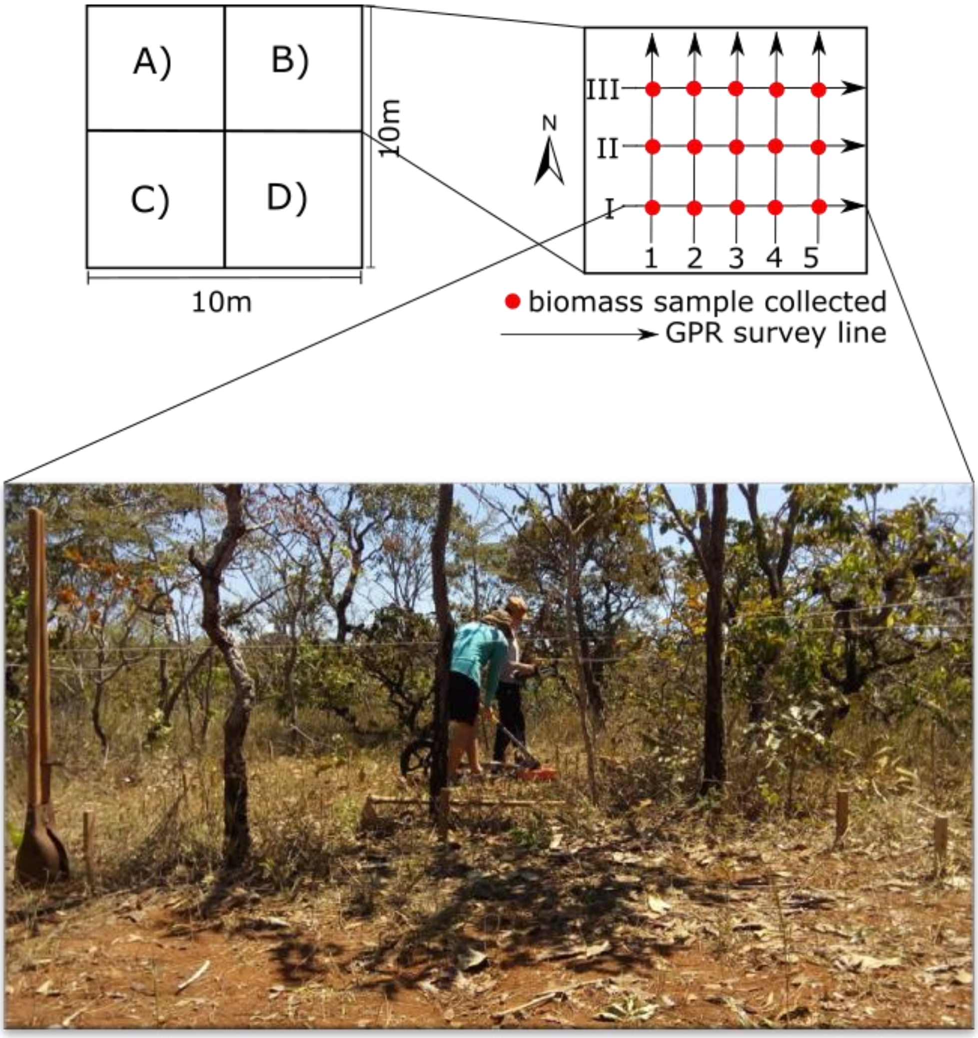

Figure 3.1 – GPR data acquisition, survey lines, and samples collected.

3.2.1 Site characterization

The most dominant savanna formation in the Cerrado biome is the cerrado *sensu stricto* (cerrado ss) with 70% of its extension (Eiten, 1972). According to Eiten (1972), this physiognomy is an herbaceous stratum, grasses, and woody, ranging from 3 to 5 meters tall, with a tree cover of 10 to 60% (Azevedo, 2014).

The Cerrado relief is generally quite flat or gently undulating, extending by immense plateaus. The altitude of 50% of its area is between 300 to 600 m above sea level, only 5.5% go beyond 900 m. The highest elevations are at the Chapada dos Veadeiros, which can reach 1676 m.

The climate predominant is the Tropical seasonal of dry winter. The average annual temperature is around 22-23ºC. The absolute monthly maximums can reach more than 40ºC, while the absolute minimum reaches values close to or below zero, in May, June, and July. It is common the occurrence of frost in Cerrado biome, in its southern portion. It is common the occurrence of fire in the biome during the dry season.

The average annual rainfall is between 1200 and 1800 mm in general. The average monthly rainfall presents a great seasonality, concentrating in the months of spring and summer (October to March), that is the rainy season. In the period from May to September, the monthly rainfall rates are greatly reduced, reaching zero (Coutinho, 2000).

The soil at the area studied is an oxidized soil (Red Latosoil-LV), which represents 39% of Federal District soils in Brazil (Reatto *et al.* 2004). The average dielectric constant of this soil is 14.67 (Coelho *et al.* 2006). The electromagnetic wave velocity for the first meter of this type of soils ranges from 0.06 m/nS to 0.13m/nS due to water content variation due to seasonality.

The studied area is located in a natural area for cerrado s*ensu stricto,* 300 m far from the University of Brasilia *Campus* Planaltina (FUP/UnB), as shown in **Figure 5.2**. The studied area presents fire scars and is a Cerrado open non-protected reserve of the Parque Ecológico Sucupira. The area chosen was the arboreal stratum sparse to medium; then the deforest was not necessary since the work did not have a deforestation license.

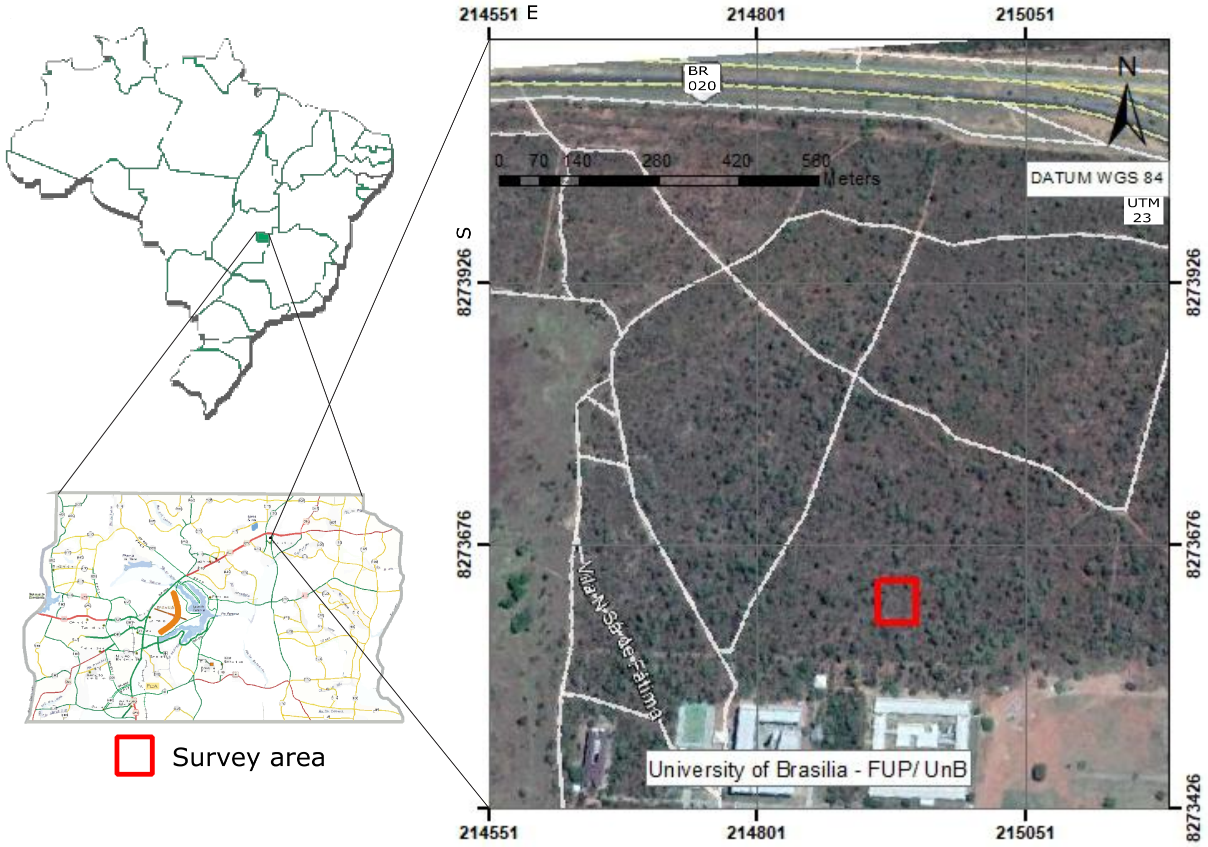

Figure 3.2 – Location of cerrado s*ensu stricto* studied area.

3.2.2 Biomass estimation - Above-ground

The above-ground biomass sample was based on the forest inventory carried out in the 100 m² plot. All trees with a base diameter (measured at 0.30 m height) larger than 5 cm were identified to species level and had their base diameter and height measured.

A floristic survey was carried out in the area. The objective of a floristic survey is to list the plant species that occur in a given area. Floristic studies in addition to generating information on classification and taxonomic distribution at the family and species level of a plant community can also provide information on ecological attributes of the species, such as formations of ecological groups, dispersion syndromes, phenology, and life forms, among others (Ratter *et al.* 2003).

This work compares two above-ground allometric equations. For Rezende *et al.* (2006), the estimate of dry biomass stock above-ground considers only the trunk and live trees. For Roitman *et al.* (2018) the estimate of dry biomass stock above-ground considers the trunk, live trees, thin branches, and leaves. Tree above-ground biomass was estimated using the equation (1) (Rezende *et al.*, 2006) and equation (2) (Roitman *et al.* 2018) both were developed for cerrado *sensu stricto* physiognomy.

$$TAGB\ (kg) = -0.49129+0.02912Db^2Ht \quad (1)$$

Where TAGB = tree above-ground biomass weight in kilograms (kg); Db = base diameter in centimeters (cm); Ht = height in meters (m).

$$TAGB\ (g) = 1.17\ [409.047\ .\ (v)^{0.976}] \quad (2)$$

Where TAGB = tree above-ground biomass weight in grams (g) ; v = volume (dm^3).

3.2.3 Biomass estimation - Below-ground

Among the destructive methods for below-ground biomass estimation are two widely used in studies of root biomass in different ecosystems: 1) excavation of the root systems of individual plants and (2) extraction of soil samples of known volume (Abdala *et al.*,1998).

The first is extremely laborious for large plants. On the other hand, the method of soil samples measures the root biomass and is more widely applicable, less destructive, and provides data on the root: shoot ratio for the ecosystem as a whole.

The main difficulty with the soil samples measures is that there is no pattern of survey methodology, as shown in **Table 5.1**. The works available in the literature for below-ground biomass estimation in cerrado *sensu stricto* physiognomy, present great variability of results due to different estimation techniques; different depths excavated; and different relations of the areas about the herbaceous stratum and the arboreal stratum. The great variability of results makes hard the comparison of the results for the root: shoot ratio (R:S). Although all the results present a higher proportion of below-ground biomass when compared to above-ground biomass.

State	Above-ground (Mg)	Below-ground (Mg)	R:S	Depth (cm)	References
DF	26	41.1	1.6	620	Abdala *et al.*(1998)
DF	12.8	46.6	3.6	200	Castro & Kauffman (1998)
DF	16.1	52.9	3.3	200	Castro & Kauffman (1998)
DF	16.1	36.8	2.3	50	Castro-Neves *et al.* (2007)
DF	17.2	39.7	2.3	50	Castro-Neves *et al.* (2007)
DF	18.2	41.9	2.3	50	Castro-Neves *et al.* (2007)
DF	23.8	45.5	1.9	50	Castro-Neves *et al.* (2007)
MG	19.6	30	1.5	200	Lilenfein & Wickle (2003)
MG	15.2	16.8	1.1	30	Miranda *et al.* (*unpublished*)
MG	16.7	19.3	1.2	30	Miranda *et al.* (*unpublished*)

Table 3.1 - Root: shoot ratio for cerrado *sensu stricto* physiognomy. Table adapted from Miranda *et al.* (2014).

This work used the GPR method, as shown in **Figure 3.1**. The crops of biomass samples collected were 60 in total, distributed for each area of 25m². The size of the crops was 25cm diameter X 40 cm in depth.

A forester engineer study (Azevedo, 2014) showed that for a cerrado s*ensu stricto* in a Federal District area was possible to infer that for the samples estimated 86% of the below-ground biomass were in the first 50cm depth. And also that the thick roots represented 67.1% of below-ground biomass. At field work was possible to estimate a 50cm depth for the soil horizon A, which had most of the organic matter and carbon concentration. Soil horizon B showed a different color and considerably less or none organic matter.

Figure 3.3 – a) Crops of biomass samples collected; b) stove model 032/1 from MARCONI; c) Analytical balance model Shimadzu Ay220.

After the field work steps the roots were separated from the soil using a sieve with 3mm mesh, classified according to their diameter into thick (> 10 mm), washed, and then weighed.

Roots samples were dried in an oven at 105 ± 2 ºC to obtain the dry biomass (**Figure 5.3**). The drying process was carried out in a laboratory oven with forced air circulation MARCONI model 032/1. Samples were weighed using the Shimadzu Ay220 analytical balance with an accuracy of 0.1 mg.

3.3 - RESULTS

The results obtained in this work are analyzed and exposed as follows.

3.3.1 - Above-ground biomass

The above-ground biomass also covers the floristics analysis exemplified in **Table 3.2**. According to Abdala *et al.* (1998), the AD (absolute density) is exemplified in equation (2); the RD is exemplified in equation (3); the AF is exemplified in equation (4), and RF is exemplified in equation (5).

$$\mathrm{AD} = \frac{n}{area\ (ha)}\ (2)$$

$$\mathrm{RD} = \frac{n}{N} \text{ x } 100\ (3)$$

$$\mathrm{AF} = \left(\frac{\mathrm{p}}{\mathrm{P}}\right) \text{ x } 100\ (4)$$

$$\mathrm{RF} = \frac{AF}{AFT} \text{ x } 100\ (5)$$

Where the AD (absolute density) considers the number o individuals per area (ha). The RD (relative density), where n numbers of individuals of each species and N the total number of individuals of all species. The AF (absolute frequency) is the relation between the number of quadrants that the species occurs (p) and the total number of quadrants (P). The RF (relative frequency) is the relation of the absolute frequency of the species (AF) and the sum of the absolute frequency of all species (AFT).

These data showed in **Table 3.1** represents the floristics in the area and is concordant to Françoso (2014) work, there exposes an RF of trees in cerrado *sensu stricto* area. Françoso (2014) shows a 62% of *Kielmeyera coriacea* relative frequency, 56% of *Caryocar brasiliense* relative frequency, 67% of *Byrsonima coccolobifolia* relative frequency, 67% of *Connarus suberosus* relative frequency, 65% of *Dimorphandra mollis* relative frequency, and the most abundant are the *Qualea grandiflora* 84% of relative frequency and *Qualea parviflora* 77% of relative frequency.

Specie Name	**A**	**B**	**C**	**D**	**TOTAL**	**AD**	**RD (%)**	**AF (%)**	**RF (%)**
Annona crassiflora	0	1	0	0	1	100	4.76	25	5.88
Byrsonima coccolobifolia	1	0	1	0	2	200	9.52	50	11.76
Byrsonima verbascifolia	0	0	0	2	2	200	9.52	25	5.88
Caryocar brasiliense	1	0	1	1	3	300	14.29	75	17.65
Connarus suberosum	0	0	1	0	1	100	4.76	25	5.88
Dimorphandra mollis	2	0	0	0	2	200	9.52	25	5.88
Erithroxylum suberosum	0	0	1	0	1	100	4.76	25	5.88
Kielmeyera coriacea	0	1	1	2	4	400	19.05	75	17.65
Ouratea hexasperma	0	2	0	0	2	200	9.52	25	5.88
Qualea grandiflora	0	1	0	0	1	100	4.76	25	5.88
Qualea parviflora	1	0	0	0	1	100	4.76	25	5.88
Salacia crassifolia	0	1	0	0	1	100	4.76	25	5.88
TOTAL	**5**	**6**	**5**	**5**	**21**				

Table 3.2 - Representation of floristics analysis in the studied area.

The result of the biomass amount was approximately **168 kg** (95% confidence interval = ± 3.29) for Roitman *et al.* (2018) and **130 kg** (95% confidence interval = ± 2.78) for Rezende *et al.*(2006) for tree above-ground biomass in 100 m² area as shown in **Table 3.3**, or **16.8 t/ha** and **13 t/ha**, respectively.

A	**Specie Name**	**Base diameter (cm)**	**Height (m)**	**P (kg) (Roitman *et al.*, 2018)**	**P (kg) (Rezende *et al.*, 2006)**
	Byrsonima coccolobifolia	6	2.5	3.13	2.13
	Caryocar brasiliense	6.8	2.2	3.55	2.47
	Dimorphandra mollis	5.5	3.1	3.25	2.24
	Dimorphandra mollis	5.4	2.9	2.93	1.97
	Qualea parviflora	7.5	3	5.85	4.42
B	*Annona crassiflora*	9	4	11.15	8.94
	Kielmeyera coriacea	9.5	2.5	7.85	6.08

	Qualea grandiflora	10	3.5	12.08	9.70
	Salacia crassifolia	9.4	2.2	6.78	5.17
	Ouratea hexasperma	15.5	2.6	21.71	17.70
	Ouratea hexasperma	18	2.5	28.18	23.10
C	*Byrsonima coccolobifolia*	6.3	2.1	2.91	1.94
	Caryocar brasiliense	5.8	2.7	3.15	2.15
	Connarus suberosum	7.5	3.2	6.23	4.75
	Erithroxylum suberosum	7	2	3.43	2.36
	Kielmeyera coriacea	7.9	2.5	5.43	4.05
D	*Byrsonima verbascifolia*	8	1.9	4.26	3.05
	Byrsonima verbascifolia	8.3	2.4	5.76	4.32
	Caryocar brasiliense	12.2	5	25.47	21.18
	Kielmeyera coriacea	5.4	1.5	1.54	0.78
	Kielmeyera coriacea	7	2	3.43	2.36
			TOTAL	**168.06**	**130.87**

Table 3.3 - Above-ground biomass estimation (trunk diamter > 5 cm).

3.3.2 - Below-ground biomass

As shown in **Figure 3.2** and **Figure 3.5,** the below-ground biomass was collected with a manual digger of 10cm diameter up until 40cm depth. After the field work, the root samples were conditioned in a tank of water until they reached saturation and constant mass, the saturated mass (*im*) was weighed (Barbosa e Ferreira, 2004). The samples were then dried in a stove until they get to their constant mass, determining their dried mass (*fm*). The mass is dried when the difference between two consecutive weighings with a difference of 24h was inferior of 1%.

The formula proposed by Smith (1954) calculates the basic density of samples:

$$\text{BD} = \frac{1}{\frac{im-fm}{fm}+\frac{1}{1.53}} \;\ldots..\; (6)$$

The result of the total biomass of thick roots was approximately **<u>2.4 kg</u>** (95% confidence interval = ± 0.04) up to a depth of 40cm in 100m² area as shown in **Table 3.4**, or **8.12 t/ha**. For a cerrado *sensu stricto* area, thick roots represent 43.87% up to 40 cm depth of the total amount of below-ground biomass (Abdala *et al.*, 1998). The total amount of below-ground biomass found for this work using this extrapolation is **18.42 t/ha**.

Sample	Wet weight (g)	Dry weight (g) - 48h -	BD
A(1,I)	366.58	141.82	0.45
A(2,I)	120.32	37.27	0.35
A(3,I)	90.65	29.10	0.36
A(4,I)	30.91	10.29	0.38
A(5,I)	25.25	8.35	0.37
A(1,II)	136.31	47.13	0.39
A(2,II)	94.81	29.15	0.34
A(3,II)	69.38	19.58	0.31
A(4,II)	32.77	10.13	0.35
A(5,II)	118.18	43.03	0.42
A(1,III)	146.86	48.37	0.37
A(2,III)	24.10	8.60	0.41
A(3,III)	23.21	8.78	0.44
A(4,III)	20.90	7.19	0.39
A(5,III)	54.51	18.48	0.38
B(1,I)	87.29	44.91	0.63
B(2,I)	21.81	14.29	0.85
B(3,I)	89.12	44.34	0.60
B(4,I)	124.02	52.93	0.50
B(5,I)	133.26	70.65	0.65
B(1,II)	74.36	38.28	0.63
B(2,II)	114.50	50.20	0.52
B(3,II)	32.50	18.86	0.73
B(4,II)	44.96	20.01	0.53
B(5,II)	147.32	73.66	0.60
B(1,III)	84.37	48.02	0.71
B(2,III)	52.62	23.89	0.54
B(3,III)	218.22	128.97	0.74
B(4,III)	64.74	33.41	0.63
B(5,III)	253.46	116.38	0.55
C(1,I)	115.75	28.38	0.27
C(2,I)	13.49	4.68	0.39
C(3,I)	36.40	12.33	0.38

C(4,I)	25.01	7.74	0.35
C(5,I)	166.85	55.98	0.38
C(1,II)	48.04	17.27	0.41
C(2,II)	19.19	5.87	0.34
C(3,II)	21.53	9.11	0.50
C(4,II)	306.70	122.39	0.46
C(5,II)	16.43	5.37	0.37
C(1,III)	60.82	23.19	0.44
C(2,III)	46.54	15.73	0.38
C(3,III)	17.78	5.88	0.37
C(4,III)	18.61	5.60	0.34
C(5,III)	78.85	28.08	0.41
D(1,I)	181.81	72.24	0.46
D(2,I)	167.67	71.54	0.50
D(3,I)	175.57	62.27	0.40
D(4,I)	31.07	11.35	0.42
D(5,I)	35.47	13.72	0.45
D(1,II)	187.30	73.59	0.45
D(2,II)	596.99	290.09	0.58
D(3,II)	103.14	47.23	0.54
D(4,II)	25.52	19.20	1.02
D(5,II)	25.49	10.01	0.45
D(1,III)	34.71	17.72	0.62
D(2,III)	138.16	56.23	0.47
D(3,III)	38.99	18.16	0.56
D(4,III)	47.49	2.48	0.05
D(5,III)	69.03	32.75	0.57
TOTAL=	**5747.68**	**2392.24**	

Table 3.4 - Results for thick roots as below-ground biomass.

For this work, the root: shoot ratio for total biomass below-ground estimated and the above-ground allometric equation of Roitman *et al.* (2018) is **1.1** and using the above-ground allometric equation of Rezende *et al.* (2006) is **1.4**. Both root: shoot ratios show the greater amount of the total below-ground biomass up to a depth of 40 cm in comparison to the total above-ground biomass.

If we consider only the thick roots up to a depth of 40 cm as below-ground biomass for root: shoot ratio is **0.48** using Roitman *et al.* (2018) for above-ground and is **0.62** using Rezende *et al.* (2006). Both root: shoot ratio shows that the investigation of thick roots up to a depth of 40 cm represents an average of 50% or higher in comparison to the total above-ground biomass (considering trees with a trunk diameter larger than 5 cm).

3.3.3 - 2D GPR

The GPR data were processed using the software Reflexw version 7.5 (Sandmeier, 2015). The processing flow (**Figure 3.4**) applied consisted on header gain removal, static correction (zero time correction), background removal, time cut, spectral whitening, Stolt migration, Hilbert transform to envelope trace and final radargram.

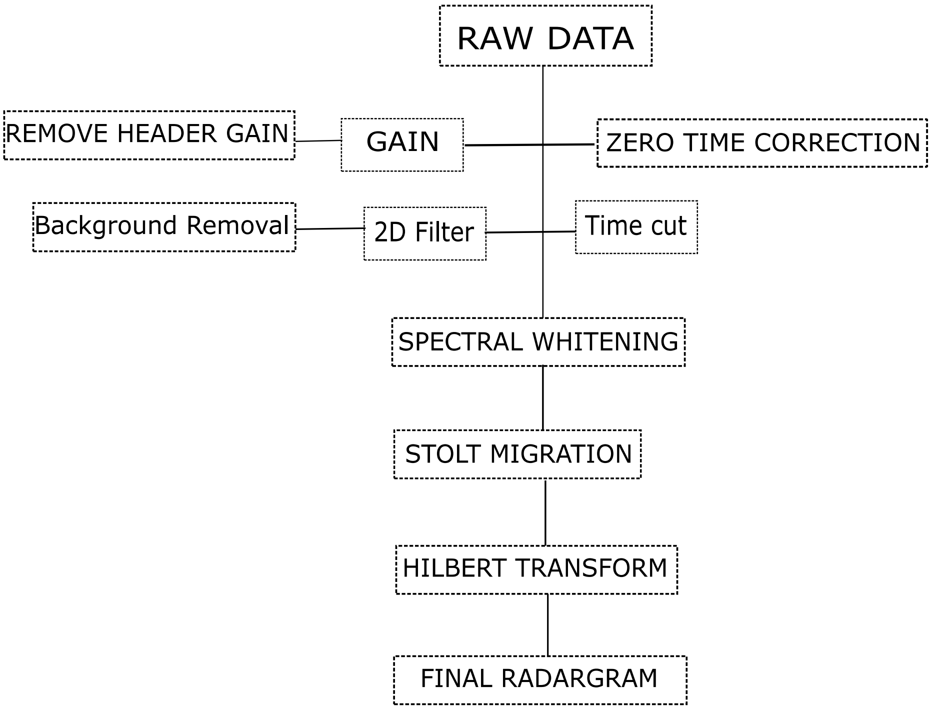

Figure 3.4 – GPR signal processing flow applied.

The results obtained with the shielded antennas with a central frequency of 900MHz allow the identification of hyperbolic diffractions related to the roots of trees. **Figures 3.5** and **3.6** exposes the results for GPR data.

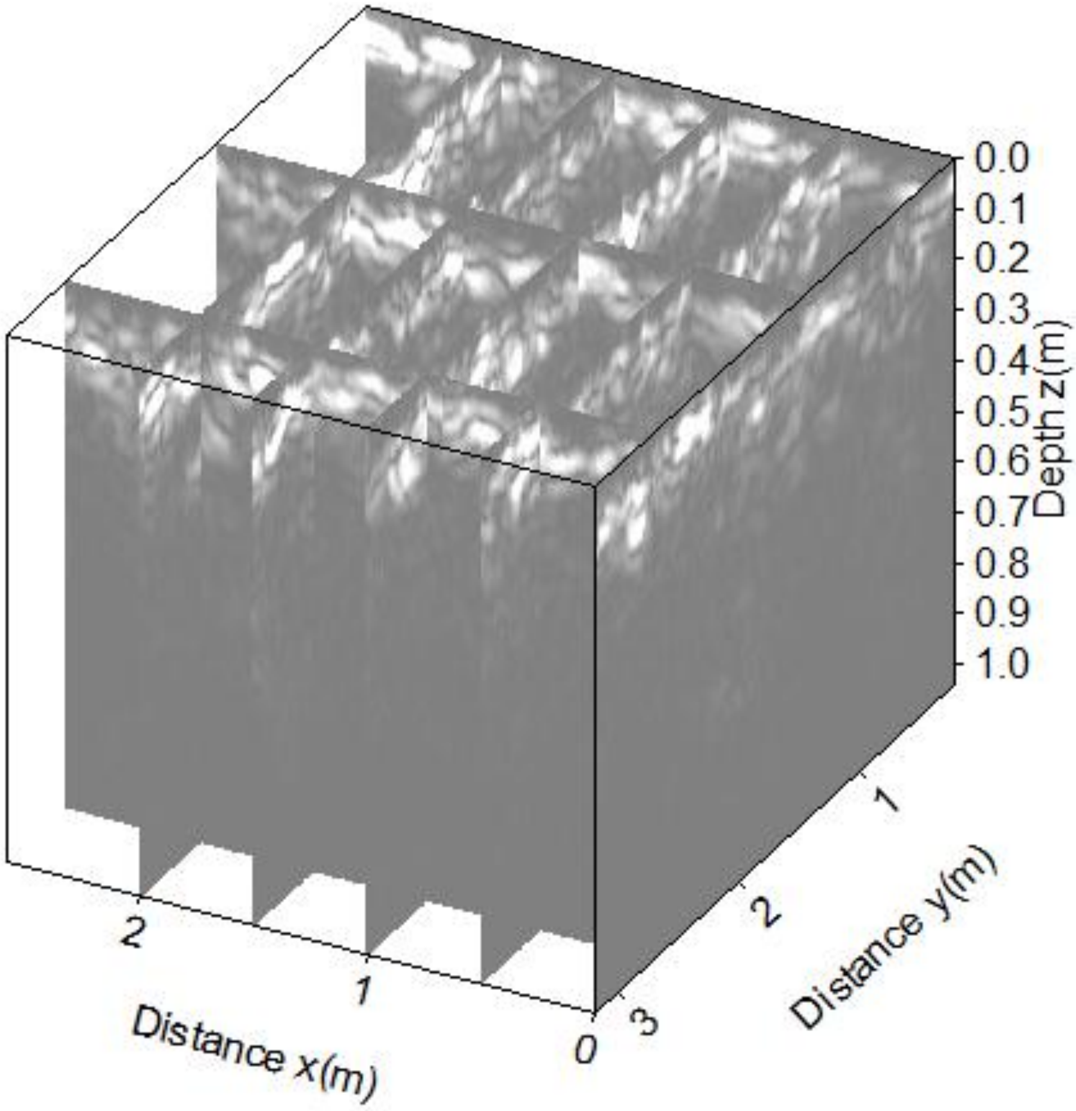

Figure 3.5 – Fence diagram of quadrant [B] with GPR survey profiles.

Since the maximum resolution of vertical features is roughly equivalent to or larger than half the wavelength, according to Neubauer *et al.* (2002). This vertical limit varies from $\frac{1}{2}$ to $\frac{1}{8}$Of wavelength, in some cases (Kallweit & Wood, 1982). For this study, the vertical limit range from 3 cm to 1 cm of wavelength. According to **Figure 3.6-c)-e)** it is possible to image thick/coarse roots of a cerrado *sensu stricto* due to the root-tangled pattern below-ground.

The below-ground biomass is a very porous target, considering the tangled pattern of different root diameters, such as fine (≤ 2 mm diameter), medium (from 2 mm to 1 cm diameter), thick (≥ 1 cm diameter). The high porosity causes the electromagnetic wave scattering and reduces the amplitude index.

As shown in **Figure 3.6-c)-d)-e)**, the tangled pattern scattered the wave energy reducing the amplitude index and consequently not considered in the binary image.

The GPR data was cut for the size of each core and generated a matrix of 26 traces in 25 cm and 91 samples in 40 cm depth to provide amplitude index information. The GPR-ascii matrix was then processed in a Python script developed (see Annex 1) for counting the number of pixels within a pre-established threshold range. **Figure 3.7** exemplifies the GPR image core and the binary image with related pixels within an amplitude threshold range established (1 for amplitudes ≥ 1500 and 0 for amplitudes < 1500).

The number of pixels in each core within the amplitude threshold range established for the GPR data was correlated with the root biomass dry weight per core. The data were divided into three groups, presenting individuals from all quadrants.

The separation in groups is necessary due to all the factors altering the amplitude intensity, such as the mean diameter, root dielectric constant, soil dielectric constant, porous tangled pattern, skin depth, growth angle variation, soil porosity.

The tangled pattern represents a very porous target, especially when formed by medium roots and fine roots, which causes greater scattering of the electromagnetic energy, reducing the intensity of the amplitude. For a cerrado *sensu stricto*, the thick roots represent 43.87%, while the average roots represent 16.13% and the fine roots represent 40% at a 40 cm depth (Abdala *et al.*, 1998). Thin and medium roots represent a greater amount than the thick roots when summed.

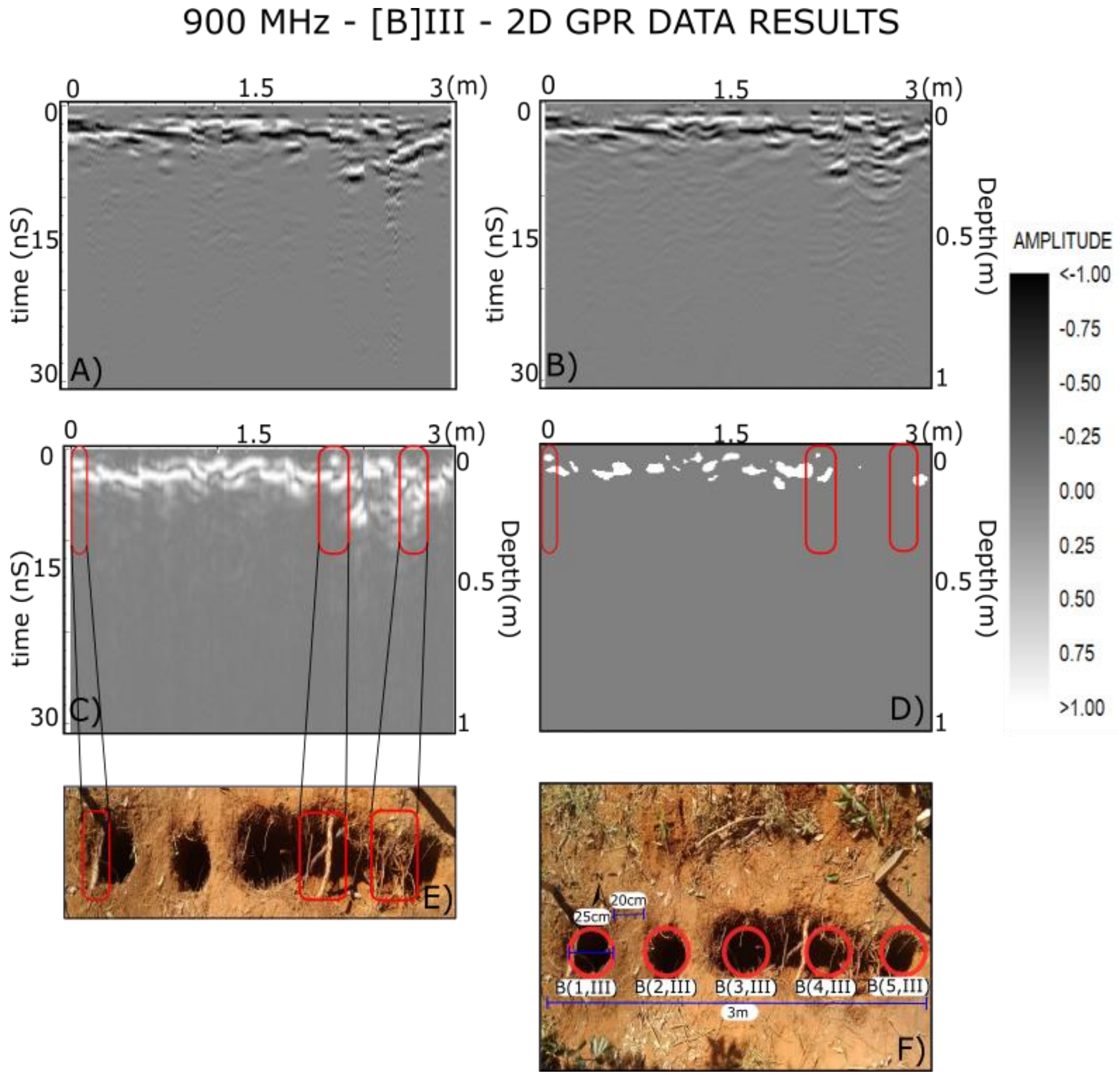

Figure 3.6 – GPR final radargram for [B]III survey line. A) spectral whitening; B) Stolt migration; C) Hilbert transform to envelope trace; D) Binary image with considered pixels within the amplitude threshold range (≥ 1500); E) Target behavior example; F) schematic representation of field work sampling.

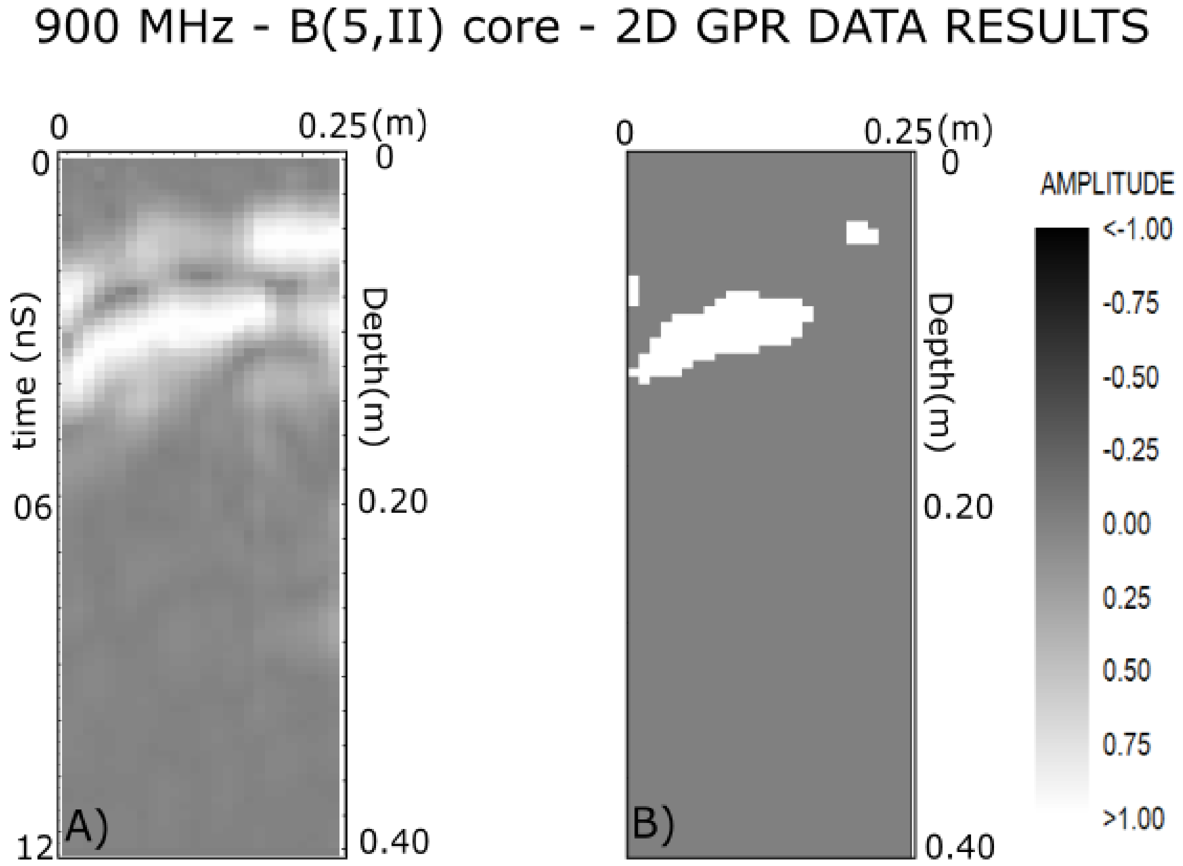

Figure 3.7 – Schematic representation of B(5, II) core. A) Final radargram GPR data of Hilbert Transform. B) Binary image with 113 considered pixels within an amplitude threshold range (≥ 1500).

Comparison between actual root biomass from soil core to root biomass from GPR was estimated using linear regression; Pearson's correlation; R^2; F test. The correlation results showed a strong relationship for each group (**Figure 3.8**) between root biomass from soil cores and estimated root biomass using GPR, within the amplitude threshold range (≥ 1500) with Pearson's coefficient greater than 60% for every case.

Simple and multiple linear and nonlinear regression have a long history as the fundamental tools used in developing statistical models (Draper and Smith,1981). The ordinary least squares (OLS) parameters are those that minimize the sum of squared residuals, which are the differences between observed values and predictions made by the model.

The most important assumptions in linear regression are (Weiskittel *et al.*, 2011): (1) correct specification of the relationship between independent and dependent variables (i.e. expected value of the error term is zero); (2) explanatory variables are without measurement error; (3) no perfect correlation exists between any linear combination of explanatory variables; and (4) model residuals are independent, have a constant variance (homoscedasticity), and are normally distributed.

Figure 3.8-a) represent the greater R^2, then the root biomass core (RBC) ≅ pixel GPR. The thick root-tangled pattern for this Group 1 model had *n* (sample size) equal to 19, medium porosity, low skin depth variation, cross-section angle variation ≅ 90°. **Figure 3.8-b)** represents the root biomass core (RBC) $<$ pixel GPR. The thick root-tangled pattern for this Group 2 model had *n* equal to 21, low porosity, low skin depth variation, cross-section angle variation ≅ 90°. **Figure 3.8-c)** represent the lower R^2, then the root biomass core (RBC) > pixel GPR. The thick root-tangled pattern for this Group 3 model had *n* equal to 18, high porosity and few thick roots, high skin depth variation, cross-section angle variations $<$ 90°. Group 3 was the only model which a normal distribution did not represent the residue. **Figure 3.9-3a-3b**, then it is not a reliable model. The high threshold range established let several cores with zero pixels, then it was not expected to be a reliable model. Only two cores were considered outliers A(2,III) and D(2,II).

In linear regression, the assumptions of the adjusted model must be validated so that the results are reliable. It is known as residual analysis a set of techniques used to investigate the suitability of a regression model based on residues. The basic idea of residual analysis is that if the model is appropriate, the residuals should reflect the properties imposed by the error term of the model.

The homoscedasticity is the term for the constant variance of experimental errors for distinct observations. The graph of fitted values versus residual values, **Figure 3.9-1a)-**

2a)-3a) verifies the homoscedasticity of the model. This graph is one of the main techniques used to verify the assumptions of the residues. If the points are randomly distributed around the 0, without any behavior or tendency, there are indications that the variance of the residues is homoscedastic.

Figure 3.9 represents the normality of residuals obtained through the R statistical software. The normality of residuals is an essential assumption for linear regression model to be reliable (Vanclay, 1994). The normal distribution is also known as Gaussian distribution; it is arguably the most important continuous distribution. The importance of a normal distribution is due to several factors, among them the central limit theorem, which is a fundamental result in practical and theoretical applications, since it guarantees that even if the data are not distributed according to a normal, the data average converges to a normal distribution as the number of data increases. Also, several practical studies have resulted in a normal distribution.

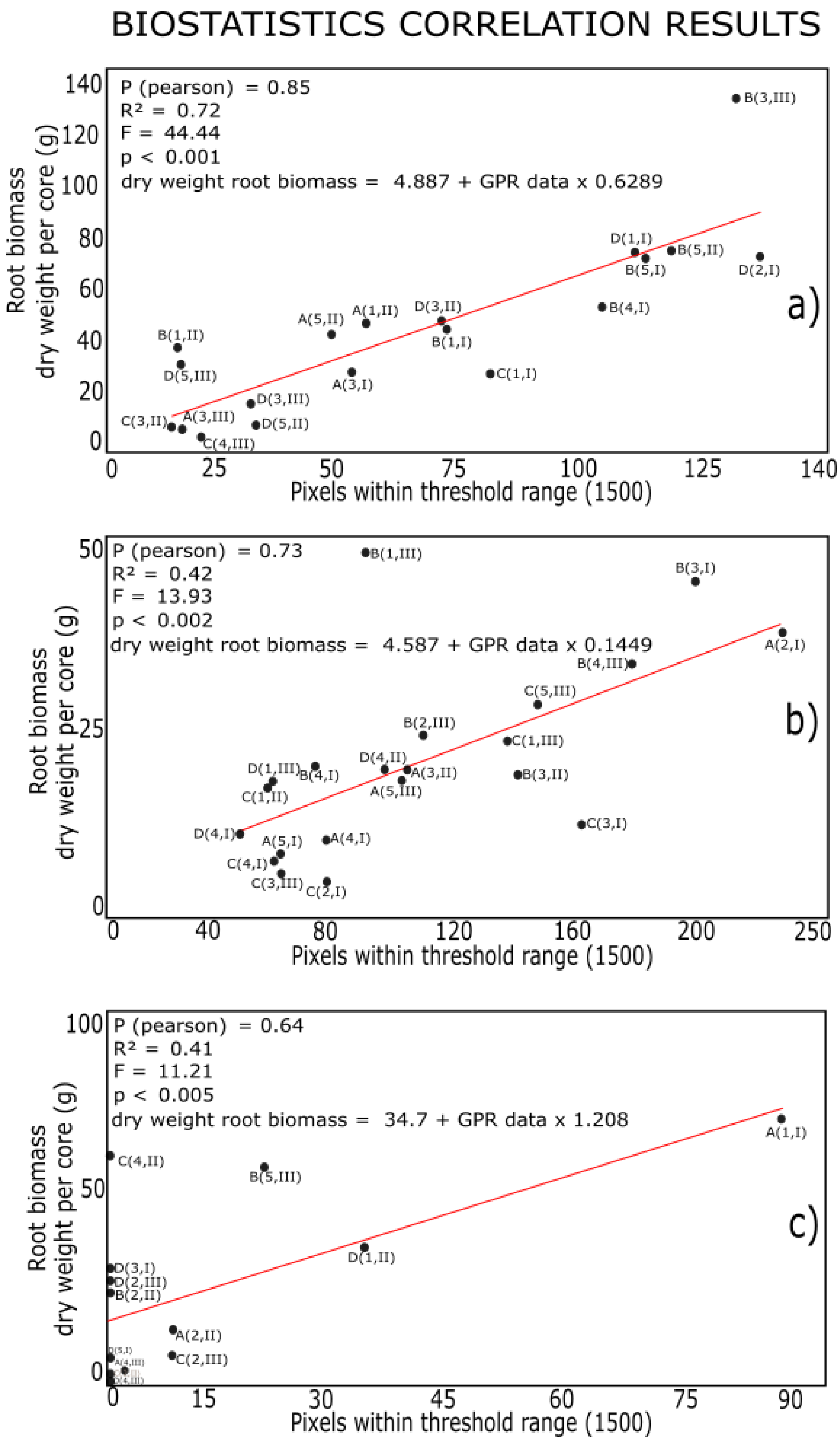

Figure 3.8 – Biostatistics: correlation results. a) Group 1; b) Group 2; c) Group 3.

The quantile is any separatrix that divides the frequency range of a sample into equal parts. The normal QQ-plot, **Figure 3.9-1b)-2b)-3b),** is a graphical method technique used to verify the adequacy of a given statistical model to the data. A perfect diagonal indicates perfect normality. Small deviations from diagonal are acceptable. Since the diagonal is not perfect, it is recommended to do another normality test.

The other normality test used for this work is the Shapiro-Wilk normality test (proposed in 1965), which is reliable for *n* (sample size) lower than 30, and it is based in the W statistics:

$$W = \frac{b^2}{\sum_{i=1}^{n}(x_i - \bar{x})^2} \quad (7)$$

where x_i are the values of ordered samples, b constant is determined for:

$$b = \begin{cases} \sum_{i=1}^{n/2}(a_{n-i+1} \times (x_{(n-i+1)} - x_{(i)}) \text{ if } n \text{ is even} \\ \sum_{i=1}^{(n+1)/2}(a_{n-i+1} \times (x_{(n-i+1)} - x_{(i)}) \text{ if } n \text{ is odd} \end{cases} \quad (8)$$

Where a_{n-i+1} are constants generated by the mean, variance, and covariance of ordered statistics of a sample with *n* size of a normal distribution and its values are available in the Shapiro-Wilk statistical table.

The significance level (α) is normally 0.05 to guarantee normal distribution. Confirming the affirmation that the sample comes from a normal population at the established significance level (α) in the Shapiro-Wilk table is when $W_{calculated} > W_{\alpha}$.

	NORMALITY TEST		
Group 1	Shapiro-Wilk	W = 0.90306	NORMAL
	p-value (α)	0.05528	
Group 2	Shapiro-Wilk	W = 0.86431	NOT NORMAL
	p-value(α)	0.007569	
Group 3	Shapiro-Wilk	W = 0.85316	NOT NORMAL
	p-value(α)	0.009503	

Table 3.5 - The Shapiro-Wilk normality test results.

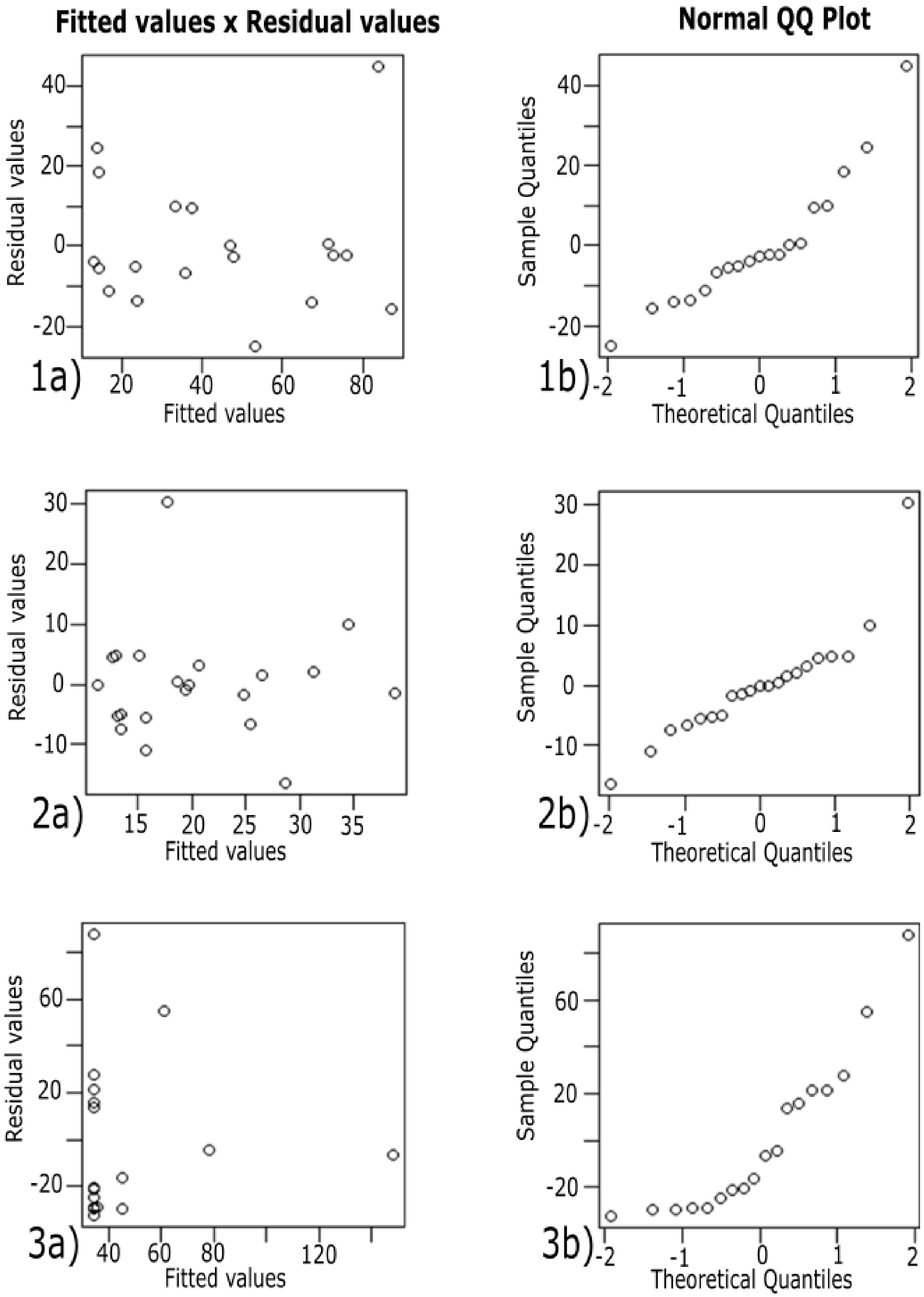

Figure 3.9 – The normality of the residuals. 1a) Fitted values x Residual values for Group 1; 1b) Normal QQ plot for Group 1; 2a) Fitted values x Residual values for Group 2; 2b) Normal QQ plot for Group 2; 3a) Fitted values x Residual values for Group 3; 3b) Normal QQ plot for Group 3.

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3.4 - CONCLUSION

This work shows that the GPR analysis for below-ground biomass estimation allows a good correlation with the traditional destructive biomass estimation technique. The main advantage of GPR when compared to the traditional destructive technique of root biomass estimation is the reduction of costs, short-term fieldwork, and minimum environmental impact.

Most of the biomass evidenced by the GPR data is stored in the first meters depth (Abdala *et al.*, 1998; Azevedo, 2014). The results classify the GPR as a good method to estimate the biomass of thick roots of cerrado sensu stricto indirectly.

The GPR central frequency of 900 MHz presents a better resolution for the first meters in comparison to the resolution of lower central frequencies antennas. Future work for investigating the first 40 cm depth with higher resolution antennas of central frequency from 1600 MHz to 2600 MHz is interesting for mapping better the tangled pattern of medium to fine roots (diameter smaller than 1 cm).

The understanding of the target as tangled roots is important. The target is very porous with random dispersion behavior. An important recommendation is to run the dielectric constant experiment for each crop sample of root biomass in a natural ecosystem. This experiment helps to estimate the amplitude index, which is intrinsic related to the real below-ground biomass.

The correlation results show a strong relationship between the GPR data and the actual root biomass per core. The amplitude data intensity changes with the root diameter, root dielectric constant, soil dielectric constant, root porous tangled pattern, skin depth, root growth angle variation. The amplitude index analysis would change drastically depending on the area.

Further work is necessary to analyze the amplitude variation with skin depth. Also, future work using the volume estimation from a 3D GPR image for a natural environment can improve the below-ground biomass estimation reducing the uncertainty of root growth angle variation.

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- ANNEX I -

Python script developed for counting the number of pixels within 2D GPR data

```
# -*- coding: utf-8 -*-
import numpy as np
import matplotlib.pyplot as plt
#OPEN FILE
[x1,b1,y1,z1]=np.loadtxt('B__II___-5.ASC',unpack=True)
print(len(x1))
print(len(b1))
print(len(y1))
print(len(z1))
p=0 #Count the amount of pixels within threshold
T=1500 #amplitude threshold range
Z1 = np.zeros(len(z1))
for k in range(0,len(Z1)):
        if z1[k]<T:
                Z1[k]=0
        else:
                Z1[k]=1
                p = p+1
dt=(12.3)/91 #dt=time(nS)/samples in each trace
print('The number of pixels within threshold this threshold range is ...:',p)
zz1 = np.reshape(z1,[26,91])
zz2 = np.transpose(zz1)
ZZ1 = np.reshape(Z1,[26,91])
ZZ2 = np.transpose(ZZ1)

#SAVE BINARY FILE IN TXT
np.savetxt('B__II___-5-saida.dat',(x1,b1,y1,Z1))

#PLOT GRAPH AMPLITUDE X TIME
fig=plt.figure(figsize=(10,40))
ax1=plt
ax1.subplot(211)
ax1.imshow(zz2,cmap='gray',clim=[-50,50])
ax1.colorbar()
ax2=plt
ax2.subplot(212)
ax2.imshow(ZZ2,cmap='gray',clim=[-1,1]) #Signal graphic representation
ax2.colorbar()
ax2.xticks(np.arange(0,2,13))
ax2.xlabel('(cm)')
plt.show()
```

CAPÍTULO 4 – CONCLUSÕES E RECOMENDAÇÕES

Esta dissertação apresenta uma revisão e soluções para a aplicação do GPR no mapeamento de biomassa de raízes. O GPR tem provado ser um valioso método não invasivo para detectar raízes grossas em baixa umidade e solos eletricamente resistivos. Contudo, os estudos para a detecção e quantificação de raízes grossas usando GPR ainda estão no início e nem todas as raízes ou condições do solo são adequados a esta técnica.

No Capítulo 2 foi exposto o impacto de fatores limitantes no diâmetro da raiz e na variação do teor de água da raiz para registros no campo elétrico transversal e o campo magnético transversal. O experimento de modelagem numérica mostrou resultados consistentes. Foi possível estimar as variáveis (diâmetro da raiz, profundidade da raiz, constante dielétrica da raiz e constante dielétrica do solo) para entender a propagação e interação da onda eletromagnética na subsuperfície.

Para aprimorar o desenvolvimento da pesquisa com modelagem numérica, é necessário o desenvolvimento de parâmetros físicos consistentes que levem em consideração todos os mecanismos físicos envolvidos neste imageamento. Um possível modelo conceitual unindo os índices de amplitude do GPR e relacionando-os com os parâmetros das raízes pode ser expresso como:

$$I = f(z_r, \theta_{xy}, \theta_{yz}, d_r, \rho_r, \phi_{er}, \varepsilon_r, \sigma_r, \phi_s, \varepsilon_s, \sigma_s, f_a);$$

onde z_r é a profundidade da raiz; θ_{xy} é a variação angular da raiz em xy (estudado no Capítulo 2); θ_{yz} é variação angular da raiz no plano yz (variação com a skin depth); d_r é o diâmetro da raiz; ρ_r é a densidade da raiz; ϕ_{er} é a porosidade do padrão emaranhado de raízes em levantamento em ecossistema natural; ε_r é a constante dielétrica da raiz; σ_r é a condutividade elétrica da raiz; ϕ_s é a porosidade do solo; ε_s é a constante dielétrica do solo; σ_s é a condutividade elétrica da raiz; e f_a é a frequência central da antena de GPR.

No Capítulo 2 também foi feita uma revisão da influência da variação do ângulo (θ_{xy}) de aquisição com o alvo com registro na transversal do campo elétrico e do campo magnético. A equação estabelecida para a variação (θ_{xy}) da transversal do campo magnético apresenta um período mais curto que a transversal do campo elétrico, podendo ser estudado posteriormente para verificar a diferença na precisão desses imageamentos.

Trabalhos futuros em ambiente controlado são necessários para avaliar a variação da amplitude do sinal com a variação angular de uma raiz no plano YZ (θ_{yz}), ou variação na skin depth.

Encontrar uma solução mais rápida para estimar a energia completa da reflexão do alvo (topo e base), com isso o script desenvolvido ajuda a calcular o índice de amplitude total para cada aquisição 2D. É importante automatizar os estudos de estimativa de volume em trabalhos futuros com desenvolvimento de softwares.

Para o melhor imageamento 3D em árvores individuais, é necessário estabelecer uma parametrização de aquisição e rotina de processamento digital de sinal que sejam as mais adequadas. Para o aprimoramento desta técnica de imageamento de indivíduo, a sugestão é que sejam analisados as diferenças na estimativa do volume final das imagens geradas com interpolação de perfis paralelos de GPR 2D e com interpolação de perfis concêntricos de GPR 2D.

No Capítulo 3, os resultados mostram a boa aplicabilidade do uso do GPR no imageamento de raízes grossas do bioma Cerrado, um dos principais biomas do mundo: que se destaca pela vasta biodiversidade e expressiva extensão territorial na América do Sul, ficando em segundo lugar, atrás apenas da Amazônia.

A análise da imagem do GPR para estimativa de biomassa abaixo do solo permite uma boa correlação com a técnica tradicional de estimativa de biomassa destrutiva para raízes grossas, apesar de alguns fatores limitantes na variação dos índices de amplitude.

As raízes grossas desempenham um papel crucial no crescimento das plantas; nutrição; acúmulo de biomassa; a arquitetura do sistema radicular e nos demais serviços ecossistêmicos.

Neste capítulo também é exposto um script capaz de automatizar a quantificação o número de pixels em uma imagem de GPR 2D para um dados valor de corte na amplitude (*threshold*).

Para o aprimoramento desta técnica de imageamento para este ecossistema natural, a sugestão é o uso fundamental de diferentes antenas de GPR com frequência central de 900 MHz a 2600 MHz para cada levantamento de dados.

A compreensão da constante dielétrica do alvo ao se considerar o padrão emaranhado de raízes também é fundamental para que haja uma melhoria no entendimento na variação dos índices de amplitude do sinal eletromagnético.

Por fim, a maior parte dos estudos publicados mostram a capacidade do GPR na detecção de biomassa abaixo do solo, e alguns trabalhos buscam a quantificação do valor da biomassa abaixo do solo através dos índices de amplitude.

Uma das sugestões para o desenvolvimento do uso desta metodologia para a quantificação de biomassa de raízes e sua parametrização é começar a analisar a amplitude do sinal para estimar o volume das raízes pelo radargrama. É necessário o desenvolvimento de software de pós-processamento, a fim de realizar demais ajustes no processamento de sinal para a maior precisão de estimativa de volume das raízes, de acordo com todos os parâmetros físicos envolvidos no sistema; como também, automatizar a estimativa de volume através da interpolação das imagens de GPR 2D pós-processadas.

CAPÍTULO 5 – REFERÊNCIAS

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