MAPAS DE VISIBILIDADE EM GRANDES TERRENOS REPRESENTADOS POR GRADES REGULARES

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MAPAS DE VISIBILIDADE EM GRANDES TERRENOS REPRESENTADOS POR GRADES REGULARES

Dissertação apresentada à Universidade Federal de Viçosa, como parte das exigências do Programa de Pós-Graduação em Ciência da Computação, para obtenção do título de *Magister Scientiae*.

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FERREIRA, Chaulio de Resende, M.Sc., Universidade Federal de Viçosa, fevereiro de 2014. **Mapas de visibilidade em grandes terrenos representados por grades regulares.** Orientador: Marcus Vinícius Alvim Andrade.

Uma operação muito comum em sistemas de informações geográficas (SIG) consiste no cálculo de *mapas de visibilidade*, ou *viewsheds*. Um mapa de visibilidade indica quais regiões de um terreno são visíveis a partir de um determinado ponto de observação, normalmente chamado de *observador*. Este trabalho apresenta dois novos algoritmos para cálculo de *viewshed* em grandes terrenos representados por grades regulares, ambos mais eficientes do que os demais encontrados em literatura. O primeiro algoritmo chama-se *TiledVS* e foi projeto especialmente para memória externa, ou seja, para reduzir o número de operações de entrada e saída (E/S) realizadas. Para isso, ele utiliza uma estrutura de dados denominada *TiledMatrix*, que subdivide o terreno em diversos blocos retangulares e gerencia os acessos aos dados de forma eficiente. De acordo com os resultados experimentais obtidos, este algoritmo é mais de 4 vezes mais rápido do que todos os outros encontrados em literatura. O segundo algoritmo é um algoritmo paralelo que utiliza o modelo de memória compartilhada (*OpenMP*). Este algoritmo subdivide o terreno em diversos setores em volta do observador, de modo que cada um destes setores possa ser processado de forma independente. Os resultados experimentais mostraram que com um computador com 4 *cores* é possível obter processamentos 4 vezes mais rápidos do que a versão sequencial do mesmo algoritmo. Já com um computador com 16 *cores*, foram obtidos processamentos até 12 vezes mais rápidos.

Abstract

FERREIRA, Chaulio de Resende, M.Sc., Universidade Federal de Viçosa, February, 2014. **Visibility maps on large terrain represented as regular square grids.** Adviser: Marcus Vinícius Alvim Andrade.

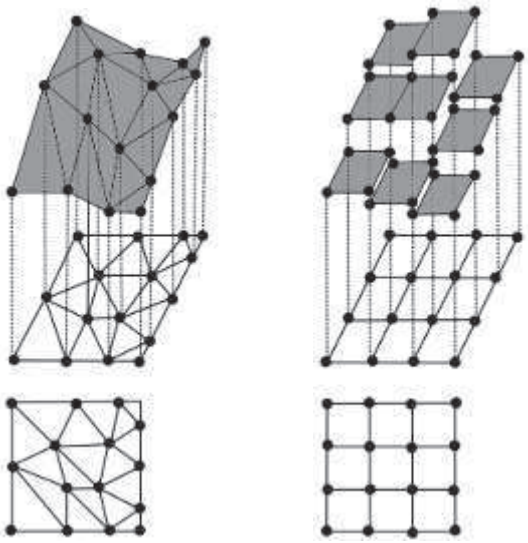
In geographical information science (GIS) it is usual to compute the *viewshed* of a given point on a terrain. This point is usually called *observer*, and its viewshed indicates which terrain regions are visible from it. In this work we present two novel algorithms for viewshed computation on large grid terrains, both more efficient than other approaches found in related work. The first algorithm is called *TiledVS*. It was specially designed for external memory processing, that is, it performs a smaller number of in/out (I/O) operations. To do that, it uses a special library called *TiledMatrix*, which subdivides the terrain into several rectangular blocks and efficiently manages the accesses to the terrain cells. According to our experimental results, *TiledVS* is more than 4 times faster than all other previous algorithms. The second one is a parallel algorithm that uses the shared memory model (OpenMP). It subdivides the terrain into several sectors around the observer, such that each sector may be processed independently. Our experimental results showed that, using a personal computer with 4 cores, it is possible to compute the viewshed 4 times faster than with the serial implementation of the same algorithm. Using a computer with 16 cores, we obtained up to 12 times speedups.

1. Introdução geral

Diversas aplicações em ciência da informação geoespacial (CIG) envolvem questões de visibilidade. Exemplos são: determinar o número mínimo de torres de celular necessárias para cobrir uma região [Ben-Moshe et al., 2002], otimizar o número e a posição de guardas para vigiar uma região [Bespamyatnikh et al., 2001], analisar as influências ambientais em preços de propriedades em um ambiente urbano [Lake et al., 1998], entre outras. Essas aplicações geralmente requerem o cálculo de *mapas de visibilidade*, ou *viewsheds*, de determinados pontos (chamados de *observadores*) em um terreno. Mais especificamente, o *viewshed* de um observador O indica quais regiões do terreno são visíveis a partir de O. Por exemplo, um observador pode representar uma torre de telefonia celular, enquanto seu *viewshed* representa as áreas do terreno onde espera-se que um usuário do serviço de telefonia consiga obter sinal diretamente a partir dessa torre. Neste trabalho, será analisado o problema de cálculo de mapas de visibilidade em grandes terrenos e serão propostos e avaliados algoritmos mais eficientes do que os encontrados atualmente na literatura.

Estas aplicações utilizam informações sobre o terreno, principalmente relacionadas à elevação de sua superfície, que geralmente são representadas por um modelo digital de terreno (MDT) Segundo Câmara et al. [2001], a aquisição de dados geográficos para a geração de MDTs pode ser feita através da amostragem de pontos espaçados de forma regular ou irregular. No caso de amostras irregularmente espaçadas, normalmente utilizam-se estruturas de dados de malha triangular, denominadas *triangulated irregular networks* (TINs). Já no caso de amostras regularmente espaçadas é possível utilizar estruturas de dados mais simples. Assim, normalmente são utilizadas grades regulares (*regular square grids* - RSGs), que consistem em matrizes que armazenam as elevações dos pontos amostrados. Estes dois formatos de MDT são ilustrados na Figura 1.1.

Neste trabalho foi utilizada a representação baseada em grades regulares, uma vez que esta é mais simples, mais fácil de ser analisada e atualmente existe uma grande quantidade de dados disponíveis neste formato. Além disso, os algoritmos propostos neste trabalho foram baseados em outros algoritmos que também trabalham com este formato. É importante ressaltar que a escolha de uma forma de representação específica não resulta em uma restrição relevante na prática, uma vez que existem métodos eficientes para a conversão entre as diversas formas de



(a) TIN. (b) RSG.

Figura 1.1: Modelos digitais de terreno.

representação [Li et al., 2005].

Entre os algoritmos para cálculo de *viewshed* em grades regulares, destacam-se o algoritmo *RFVS* [Franklin and Ray, 1994] e o proposto por Van Kreveld [1996], ambos muito eficientes. Além destes há ainda o clássico R3 [Shapira, 1990], menos eficiente, porém importante do ponto de vista teórico.

Os algoritmos *RFVS* e de Van Kreveld são muito eficientes, porém podem demandar um longo tempo de processamento dependendo das dimensões do terreno a ser processado. Por exemplo, os resultados apresentados no Capítulo 5 mostram que o algoritmo de Van Kreveld pode demorar mais de 20 minutos para processar um terreno de 3,35 GiB, mesmo utilizando-se um processador de última geração. É importante observar que atualmente, devido aos avanços tecnológicos no processo de coleta de dados baseados em sensoriamento remoto, há um enorme volume de dados de alta qualidade sobre a superfície terrestre representados na forma de grades regulares. Assim, os problemas envolvendo o processamento de terrenos frequentemente podem ser enquadrados na área de *big data*. Para esses problemas, torna-se necessário desenvolver novos métodos que possam processar grandes volumes de dados de forma eficiente. Em geral, o desenvolvimento destes métodos se baseia em duas estratégias: processamento em memória externa e processamento paralelo.

A primeira estratégia (processamento em memória externa) consiste em desenvolver algoritmos para processar terrenos maiores do que a memória interna (principal) do computador. Nesses casos, o número de operações de entrada/saída

(E/S) realizadas é tão grande que o tempo de processamento em CPU passa a ser praticamente insignificante. Assim, é importante o projeto de algoritmos que realizem menos acessos aos dados armazenados em memória externa (normalmente discos), visto que o estes acessos são da ordem de 10^6 vezes mais lento do que os acessos feitos à memória interna [Dementiev et al., 2005].

A segunda estratégia se baseia em desenvolver métodos paralelos para processar grandes volumes de dados. Esta estratégia tem atraído cada vez mais a atenção de vários pesquisadores, principalmente porque atualmente é possível adquirir, a um custo relativamente baixo, máquinas com grande capacidade computacional, isto é, com grande quantidade de memória interna e também vários núcleos de processamento paralelo.

Assim, neste trabalho serão apresentados dois algoritmos para cálculo de mapa de visibilidade, ou *viewshed*: um primeiro algoritmo, chamado *TiledVS*, para processamento em memória externa é descrito nos Capítulos 2, 3 e 4; e um segundo algoritmo, descrito no Capítulo 5, baseado em processamento paralelo. Conforme demonstrado pelos resultados experimentais apresentados, ambos são consideravelmente mais rápidos do que os algoritmos mais recentes e eficientes encontrados em literatura.

1.1 Objetivos

O objetivo geral deste trabalho foi o desenvolvimento de algoritmos mais eficientes para cálculo de *viewshed* considerando-se grandes volumes de dados. Para alcançar este objetivo geral, destacam-se alguns objetivos específicos que precisaram ser atingidos, como:

- Propor e implementar um algoritmo capaz de lidar com grandes terrenos armazenados em memória externa;
- Propor e implementar um algoritmo que utilize as modernas arquiteturas paralelas para realizar o processamento de forma mais eficiente;
- Realizar a análise de complexidade dos algoritmos desenvolvidos;
- Realizar revisão bibliográfica e avaliar experimentalmente os algoritmos desenvolvidos, comparando-os com outros métodos encontrados na literatura.

1.2 Resultados obtidos

Nos Capítulos de 2 a 5 são apresentados os artigos que descrevem os resultados obtidos neste trabalho. Mais especificamente, os Capítulos 2, 3 e 4 referem-se ao algoritmo desenvolvido para cálculo de *viewshed* em memória externa, denominado *TiledVS*, enquanto o Capítulo 5 apresenta o algoritmo desenvolvido para arquiteturas paralelas.

1.2.1 Algoritmo desenvolvido para memória externa

Os Capítulos 2, 3 e 4 apresentam o algoritmo *TiledVS*, desenvolvido para processar terrenos armazenados em memória externa de forma eficiente. Ele consiste em uma adaptação do algoritmo *RFVS*, proposto por Franklin and Ray [1994]. Para minimizar o número de operações de E/S realizadas durante o processamento, foi utilizada uma biblioteca denominada *TiledMatrix* [Silveira et al., 2013], capaz de armazenar e gerenciar grandes matrizes em memória externa de forma eficiente. Na prática, essa biblioteca gerencia os acessos aos dados em memória externa reorganizando-os de modo a realizar de forma eficiente os acessos aos dados que apresentem padrões de localidade espacial bidimensional. Os dados da matriz são subdivididos em blocos retangulares e as células de um mesmo bloco são armazenadas de forma contígua. Quando é necessário acessar uma dessas células, o bloco inteiro que a contém é copiado para a memória interna e nela continua armazenado por algum tempo. Assim, a memória interna é gerenciada como uma memória *cache* controlada pela aplicação que, diferentemente do sistema de paginação tradicional do sistema operacional, considera a localização bidimensional dos dados na matriz.

Uma primeira versão do método *TiledVS* é apresentada no Capítulo 2, onde é incluído o artigo "*Uma abordagem eficiente para o cálculo de* viewshed *em terrenos armazenados em memória externa*", apresentado no SEMISH 2012 (XXXIX Seminário Integrado de Software e Hardware) [Ferreira et al., 2012a]. Nesse artigo o novo algoritmo foi comparado experimentalmente com outro método para cálculo de *viewshed* em memória externa, também baseado no algoritmo *RFVS*: o método *EMViewshed* [Andrade et al., 2011]. Os resultados mostraram que o novo algoritmo conseguiu ser mais de 4 vezes mais rápido do que o *EMViewshed*. Além disso, nesse artigo foram realizados experimentos iniciais para tentar avaliar a influência dos tamanhos dos blocos utilizados na subdivisão da matriz feita pela *TiledMatrix*.

No Capítulo 3 é apresentado o artigo "*More efficient terrain viewshed computation on massive datasets using external memory*", apresentado no ACM SIGSPA-

TIAL 2012 (*20th International Conference on Advances in Geographic Information Systems*) [Ferreira et al., 2012b]. Nesse artigo o novo método *TiledVS* foi comparado também com outros algoritmos para cálculo de *viewshed* em memória externa propostos por Fishman et al. [2009] e, mais uma vez, mostrou-se mais eficiente do que todos eles. Nesse artigo também é apresentada uma análise formal do padrão de acesso utilizado pelo algoritmo e são estabelecidas algumas condições com relação ao tamanho dos blocos utilizados e da memória interna disponível de modo a garantir que o processamento seja sempre realizado de forma eficiente. Com essas condições, o algoritmo foi alterado para, com base nos parâmetros de entrada, estabelecer automaticamente o tamanho dos blocos utilizados durante o processamento, algo que anteriormente precisava ser escolhido explicitamente pelo usuário. Para finalizar, também foram incluídos experimentos para avaliar o comportamento do algoritmo em condições extremas como, por exemplo, o processamento de terrenos até 320 vezes maiores do que a memória interna disponível.

O Capítulo 4 apresenta o artigo "*A fast external memory algorithm for computing visibility on grid terrains*", submetido à revista ACM TSAS (*ACM Transactions on Spatial Algorithms and Systems*) [Ferreira et al., 2014]. Este artigo corresponde a uma versão estendida do artigo do Capítulo 3, onde foi utilizada uma estratégia de compressão de dados aliada à biblioteca *TiledMatrix* que conseguiu reduzir os tempos de processamento em até 42%. Mais especificamente, a biblioteca *TiledMatrix* passou a utilizar o algoritmo de compressão extremamente rápido LZ4 [Collet, 2012] para comprimir os dados de cada bloco antes de gravá-lo no disco, e também para descomprimi-los ao acessá-los novamente. Além disso foram feitas as análises de complexidade de E/S e de CPU do novo algoritmo, assim como alguns experimentos analisando a influência da compressão de dados sobre os tempos de processamento.

1.2.2 Algoritmo desenvolvido para arquiteturas paralelas

O Capítulo 5 apresenta o artigo "*A Parallel Sweep Line Algorithm for Visibility Computation*", que recebeu o prêmio de melhor artigo no GeoInfo 2013 (*XIV Brazilian Symposium on Geoinformatics*) [Ferreira et al., 2013].

Esse artigo descreve o algoritmo desenvolvido para cálculo de *viewshed* em arquiteturas paralelas, que foi baseado no algoritmo sequencial proposto por Van Kreveld [1996]. Para calcular o *viewshed* utilizando vários processadores paralelos, o algoritmo subdivide o terreno em diversos setores em volta do observador, de forma que cada um desses setores possa ser processado independentemente dos demais setores. Os resultados mostraram que, com 16 processadores paralelos, este algoritmo

foi até 12 vezes mais rápido do que sua versão sequencial. Como trabalho futuro, pretende-se melhorar o algoritmo e estender o artigo, visando sua submissão para uma revista da área.

2. Uma abordagem eficiente para o cálculo de viewshed em terrenos armazenados em memória externa[1]

Abstract

An important GIS application is computing the viewshed of a point on a DEM terrain, i.e. determining the visible region from this point. In some cases, it is not possible to process high resolution DEMs entirely in internal memory and, thus, it is important to develop algorithms to process such data in the external memory. This paper presents an efficient algorithm for handling huge terrains in external memory. As tests have shown, this new method is more efficient than other methods described in the literature.

Resumo

Uma importante aplicação em ciência da informação geoespacial (CIG) é o cálculo da região visível (viewshed) a partir de um determinado ponto em um terreno representado por um modelo digital de terreno (MDT). Muitas vezes, o processamento de MDTs de alta resolução não pode ser realizado em memória interna e, portanto, é importante o desenvolvimento de algoritmos para processar estes dados em memória secundária. Este trabalho apresenta um algoritmo para cálculo de viewshed que é capaz de lidar com grande volume de dados em memória externa de forma eficiente. Os testes realizados indicam que o método proposto é mais eficiente do que outros métodos descritos em literatura.

2.1 Introdução

Os recentes avanços tecnológicos em sensoriamento remoto têm produzido uma grande quantidade de dados de alta resolução sobre a superfície terrestre, o que

[1]Neste capítulo é apresentada uma primeira versão do método *TiledVS*. Nele está incluído o artigo "*Uma abordagem eficiente para o cálculo de* viewshed *em terrenos armazenados em memória externa*", apresentado no SEMISH 2012 (XXXIX Seminário Integrado de Software e Hardware) [Ferreira et al., 2012a].

tem aumentado a necessidade de se desenvolver novas técnicas em ciência da informação geoespacial (CIG) para lidar com este enorme volume de dados [Laurini and Thompson, 1992].

Uma forma muito utilizada para se representar a superfície da Terra de forma aproximada é através de um Modelo Digital de Terreno (MDT) que armazena as elevações de pontos amostrados sobre a superfície terrestre. Esses pontos podem ser amostrados de maneira irregular e ser armazenados como uma rede triangular irregular (TIN - *triangulated irregular network*) ou de maneira regular (RSG - *regular square grid*), sendo armazenados numa matriz [Felgueiras, 2001]. Neste trabalho será adotada a segunda forma de representação do MDT. Muitas vezes estas matrizes necessitam de mais espaço de armazenamento do que tem-se disponível na memória interna da maioria dos computadores atuais. Por exemplo, um terreno de $100km \times 100km$ mapeado com resolução de $1m$ resulta em 10^{10} pontos. Supondo que sejam utilizados 2 *bytes* para armazenar a elevação de cada ponto, são necessários mais de 18 GB para representar este terreno.

Desta forma, é importante o desenvolvimento de algoritmos específicos para processamento de dados armazenados em memória externa. Vale ressaltar que normalmente os algoritmos tradicionais de análise e processamento de dados geográficos buscam otimizar o tempo de processamento em CPU, sem grandes preocupações com o tempo de acesso à memória. Mas, por outro lado, o projeto e análise de algoritmos para memória externa devem focar-se em minimizar os acessos a disco, uma vez que estes são da ordem de 10^6 vezes mais lentos do que os acessos à memória interna [Dementiev et al., 2005].

Mais especificamente, algoritmos que processam dados em memória externa devem ser projetados e analisados considerando um modelo computacional que os avalie considerando as operações de transferência de dados em vez das operações de processamento interno. Um desses modelos, proposto por Aggarwal and Vitter [1988], determina a complexidade dos algoritmos com base no número de operações de E/S (entrada/saída) executadas. Este modelo será descrito com maiores detalhes na Seção 2.2.3.

Dentre as várias aplicações na área de CIG, há aquelas relacionadas a questões de visibilidade, como determinar o número mínimo de torres de celular necessárias para cobrir uma região [Ben-Moshe et al., 2002], otimizar o número e a posição de guardas para vigiar uma região [Bespamyatnikh et al., 2001], etc. Tais aplicações utilizam o conceito de observador e alvo: o observador tem o objetivo de visualizar (observar) outros objetos (os alvos) em um terreno, sendo que os observadores possuem um limite máximo para o alcance de sua visão, chamado de raio de interesse.

Por exemplo, uma torre de telefonia celular pode ser considerada um observador cujo raio de interesse corresponde ao alcance do sinal da torre e cujos alvos são os usuários do serviço de telefonia. A partir desse conceito, pode-se calcular o mapa de visibilidade (*viewshed*) de um ponto p do terreno, que indica a região do terreno que é visível por um observador posicionado em p. Há diversos métodos para cálculo de *viewshed* em memória interna, como os propostos por Franklin and Ray [1994] e Van Kreveld [1996]. Além disso, há também alguns métodos eficientes para processar terrenos armazenados em memória externa, como o método proposto por Haverkort and Zhuang [2007], que utiliza uma adaptação do método de Kreveld para memória externa e o método *EMViewshed* recentemente proposto por Andrade et al. [2011], descrito na seção 2.2.2, que é cerca de 6 vezes mais rápido do que o método proposto por Haverkort.

Este trabalho apresenta um novo método denominado *TiledVS*, que é cerca de 4 vezes mais eficiente do que o método *EMViewshed*. A idéia básica deste novo método consiste em adaptar o algoritmo proposto por Franklin and Ray [1994] alterando a forma como os dados em memória externa são acessados. Para isto, foi utilizada uma estrutura de dados que gerencia as transferências de dados entre as memórias interna e externa, buscando diminuir o número de acessos a disco. Maiores detalhes sobre esta estrutura encontram-se na seção 2.3 e os resultados dos testes da comparação deste novo método com o *EMViewshed* são apresentados na seção 2.5.

2.2 Referencial teórico

2.2.1 Visibilidade em terrenos

Um *terreno* corresponde a uma região da superfície da Terra cujo relevo é representado por uma Modelo Digital de Terreno (MDT) que pode ser representado por uma malha triangular irregular (*triangulated irregular network*, ou *TIN*), por linhas de contorno ou por uma matriz que contém elevações de pontos posicionados em intervalos regularmente espaçados. Devido à sua simplicidade e ao grande volume de dados disponíveis na forma matricial, esta é a representação utilizada nos algoritmos deste trabalho. É importante observar que há métodos eficientes para a conversão entre as diferentes formas de representação, e portanto, esta escolha não representa uma restrição relevante [Felgueiras, 2001].

Um *observador* é um ponto no espaço a partir do qual se deseja visualizar ou comunicar com outros pontos no espaço, chamados de *alvos*. As notações usuais

para um observador e um alvo são, respectivamente, O e T e estes pontos podem estar a certas alturas acima do terreno denotadas respectivamente por h_O e h_T. Os pontos do terreno verticalmente abaixo de de O e T são denominados pontos-base e são denotados por O_b e T_b, respectivamente.

O *raio de interesse*, ρ, de um observador O representa o alcance de sua visão, ou seja, o valor máximo da distância em que ele é capaz de enxergar ou se comunicar. Por conveniência, a distância entre um observador O e um alvo T é definida como a distância entre O_b e T_b.

Um alvo T é *visível* a partir um observador O se, e somente se, $|T_b - O_b| \leq \rho$ e não há nenhum ponto da superfície do terreno interceptando o segmento de reta $\overline{OT}$, que é chamado de *linha de visão*, ou *line of sight* (LOS). Um exemplo de cálculo de visibilidade é mostrado na Figura 2.1: o alvo T_1 é visível a partir de O, mas T_2 não é visível, pois $\overline{OT_2}$ é bloqueado por uma região do terreno.

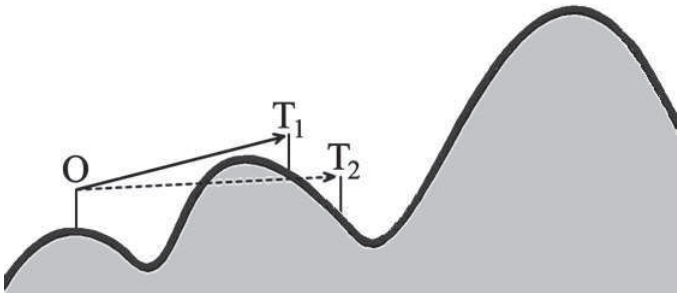


Figura 2.1: Cálculo da visibilidade em um corte vertical do terreno. O alvo T_1 é visível a partir de O e T_2 não é visível.

É importante ressaltar que a verificação de que a linha de visão intercepta ou não o terreno não é trivial. O problema é que a matriz de elevação contém informações somente sobre alguns pontos discretos do terreno, enquanto as linhas de visão são contínuas e geralmente passam entre pontos adjacentes, sem interceptá-los, o que muitas vezes requer um método de interpolação entre os pontos conhecidos [Magalhães et al., 2011].

O *viewshed* (ou mapa de visibilidade) de um observador O é o conjunto de pontos do terreno cujos alvos correspondentes são visíveis a partir de O.

2.2.2 Algoritmos para cálculo de *viewshed* em memória interna

Dados um terreno representado por uma matriz de elevação de dimensões $n \times n$, as coordenadas (x, y) do observador O, o seu raio de interesse ρ e as alturas h_O e h_T,

o objetivo de um algoritmo de cálculo do *viewshed* de O é determinar, para cada célula da matriz, se seu alvo correspondente é visível por O. Uma das maneiras de representar o *viewshed* calculado é utilizando uma matriz de bits com dimensões $n \times n$ onde um bit com valor 1 indica que o alvo T associado àquela célula do terreno é visível por O, enquanto um bit com valor 0 indica que T não é visível.

O algoritmo proposto neste trabalho para o cálculo do *viewshed* em grandes terrenos armazenados em memória externa é baseado no algoritmo para memória interna proposto por Franklin and Ray [1994], que será descrito de forma resumida a seguir.

Este algoritmo assume que todas as células são inicialmente não visíveis e realiza um processamento iterativo para determinar quais células são visíveis a partir de O. Primeiramente é definida uma região quadrangular S que envolva o círculo de raio ρ centrado em O (por exemplo, veja a figura 2.2a onde é mostrada esta região para $\rho = 4$). Daí, são traçados 8ρ segmentos de reta ligando O a cada uma das células na borda de S. Cada um destes segmentos define um corte vertical no terreno - a figura 2.2 exibe um exemplo desses segmentos e de um desses cortes.

O passo seguinte consiste em determinar quais células fazem parte de cada corte vertical. Para alguns casos, como os dos segmentos $\overline{OA}$ e $\overline{OE}$ mostrados na figura 2.2a, é fácil determinar estas células. No entanto, para a maioria dos segmentos essa determinação não é tão simples, como é o caso dos segmentos $\overline{OB}$, $\overline{OC}$ e $\overline{OD}$, onde é necessário determinar quais células são mais relevantes para cada segmento. Esse problema equivale à rasterização de segmentos e pode ser solucionado utilizando o algoritmo de Bresenham [1965], de modo que seja selecionada apenas uma célula para cada coordenada X ou Y (dependendo da inclinação do segmento).

Após a determinação das células de cada corte vertical, o próximo passo é percorrer estas células verificando quais são visíveis a partir de O. Seja um segmento composto pelas células $c_0, c_1, \cdots, c_k$, sendo que o observador está posicionado na célula c_0 e c_k é a última célula na região S dentro do raio de visão do observador. Então o processo consiste em inicialmente definir as células c_0 e c_1 como visíveis e inicializar μ, que armazena a maior inclinação de uma linha de visão já processada, com a inclinação da reta que passa pelos pontos c_0 e c_1. A partir daí, cada célula c_i é processada em ordem crescente de i, analisando-se a inclinação da reta que liga o observador ao alvo que está posicionado acima de c_i; se esta inclinação é maior ou igual a μ então a célula c_i é marcada como visível e μ é atualizado com o valor da inclinação da reta que passa por O e c_i.

Aplicando este algoritmo ao exemplo dado na figura 2.2b temos que os alvos posicionados acima dos pontos $0, 1, 2, 3$ e 7 são visíveis a partir do observador posi-

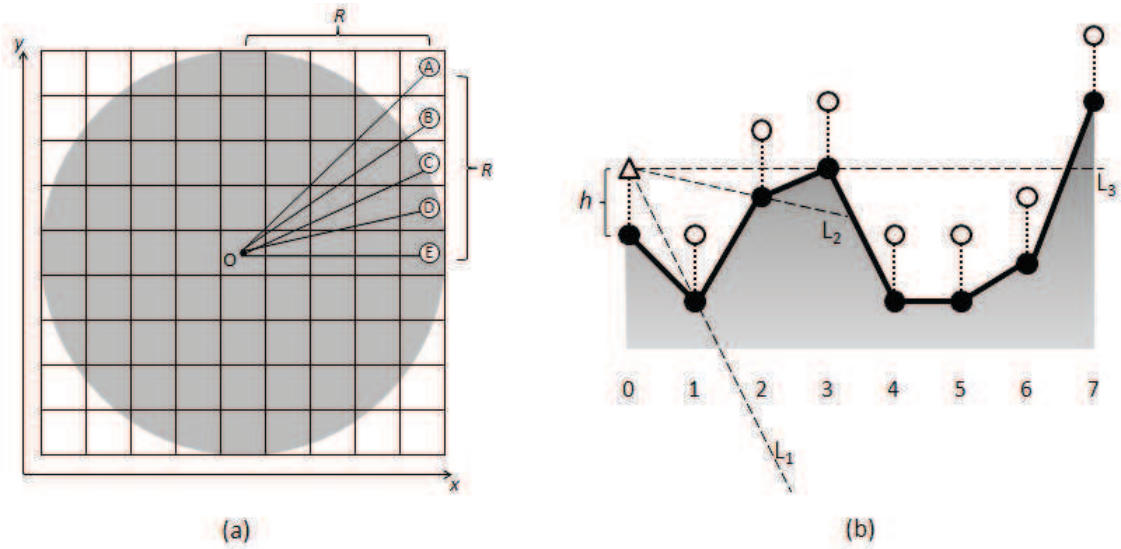


Figura 2.2: Algoritmo *RFVS*. a exemplos de segmentos em um terreno; (b) exemplo de um corte vertical definido por um segmento.

cionado acima do ponto 0 (representado por um triângulo) e os alvos posicionados acima dos pontos $4, 5$ e 6 não são visíveis.

2.2.3 Algoritmos eficientes para E/S

Durante o processamento de grande volume de dados, a transferência de dados entre a memória interna (mais rápida) e o armazenamento externo (mais lento) frequentemente torna-se o gargalo do processamento. Portanto, o projeto e análise de algoritmos usados para processar esses dados precisam ser feitos sob um modelo computacional que avalia as operações de entrada e saída (E/S). Um modelo frequentemente utilizado foi proposto por Aggarwal and Vitter [1988]. Nesse modelo, cada operação de E/S corresponde à transferência de um bloco de tamanho B entre a memória externa e a memória interna. O desempenho do algoritmo é determinado considerando-se o número de operações de E/S executadas.

A complexidade de um algoritmo é definida com base na complexidade de problemas fundamentais como varredura (*scan*) e ordenação (*sort*) de N elementos contíguos armazenados em memória externa. Se M é o tamanho da memória interna disponível, estas complexidades são definidas como:

$$scan\,(N) = \Theta\left(\frac{N}{B}\right) \quad \text{e} \quad sort\,(N) = \Theta\left(\frac{N}{B} log_{(\frac{M}{B})}\left(\frac{N}{B}\right)\right)$$

É importante salientar que normalmente $scan(N) < sort(N) << N$ e, então, um algoritmo que realiza $O(sort(N))$ operações de E/S é significantemente mais

eficiente do que um que realiza $O(N)$ operações. Assim, muitos algoritmos tentam reorganizar os dados na memória externa com o objetivo de diminuir o número de operações de E/S feitas.

2.2.4 O método *EMViewshed*

A estratégia proposta por Andrade et al. [2011] consiste em gerar e armazenar em memória externa uma lista com informações de todas as células do terreno e ordená-la de acordo com a ordem em que estas células serão processadas pelo algoritmo. Assim, o algoritmo pode percorrer esta lista sequencialmente, evitando acessos aleatórios à memória externa.

Mais especificamente, o algoritmo cria uma lista Q de pares (c, i), onde c é uma célula e i é um índice que indica "quando" c deveria ser processada. Isto é, se uma célula c está associada a um índice k, então c seria a k-ésima célula a ser processada.

Para determinar os índices é utilizado um processo similar ao descrito na seção 2.2.2, onde são traçadas diversas linhas de visão em sentido anti-horário, e as células recebem índices numerados de forma crescente em cada linha de visão. Uma mesma célula pode receber vários índices (e possuir várias cópias em Q) já que ela pode ser interceptada por múltiplas linhas de visão.

Depois de criada, a lista Q é ordenada usando os índices como chave de comparação, e então as células são processadas na ordem da lista ordenada por um algoritmo similar ao de memória interna que, neste caso, lê os dados de elevação diretamente de Q. Além disso, este algoritmo utiliza uma outra lista Q' onde as células visíveis são inseridas. Após o processamento de todas as células, Q' é ordenada lexicograficamente pelas coordenadas x e y e as células visíveis são armazenadas em um arquivo de saída, onde as posições visíveis são indicadas por 1 e as não visíveis por 0.

Um ganho de eficiência no processo é alcançado mantendo parte das matrizes em memória interna. As células que estão em memória interna não são inseridas em Q e Q' e, quando uma célula precisa ser processada, o algoritmo verifica se esta célula está na memória interna. Se estiver, ela é processada normalmente; caso contrário, ela é lida de Q.

Para analisar a complexidade deste algoritmo, é necessário utilizar um modelo como o descrito na Seção 2.2.3. Seja T o terreno representado por uma matriz de elevação de dimensões $n \times n$, ou seja, que contenha n^2 células. No primeiro passo do algoritmo, para ler as células do terreno e criar a lista Q, são realizadas $O(scan(\rho^2))$

operações de E/S. Neste passo, como mostrado na seção 2.2.2, o algoritmo traça 8ρ linhas de visão, cada uma contendo ρ células. Assim, a lista Q contém $O(\rho^2)$ elementos.

Em seguida esta lista é ordenada e então percorrida sequencialmente para se calcular a visibilidade das células, operações que apresentam complexidades $O(sort(\rho^2))$ e $O(scan(\rho^2))$, respectivamente.

Finalmente, a lista de pontos visíveis que contém, no máximo, $O(\rho^2)$ células é ordenada e o *viewshed* do terreno é gravado em disco, operações que apresentam complexidades $O(sort(\rho^2))$ e $O(scan(n^2))$, respectivamente. Como no pior caso $\rho = O(n)$, temos que a complexidade do algoritmo é:

$$O\left(sort\left(\rho^2\right)\right) = O\left(sort\left(n^2\right)\right) = O\left(\frac{n^2}{B} log_{\left(\frac{M}{B}\right)}\left(\frac{n^2}{B}\right)\right)$$

2.3 O método *TiledVS*

Ao analisar o algoritmo descrito na seção 2.3, pode-se perceber que o acesso às posições das matrizes apresenta um padrão radial, ou seja, as células são acessadas a partir daquela que contém o observador até cada célula que está no limite de seu raio de interesse, traçando diversas linhas de forma circular. Este padrão de acessos apresenta a propriedade de localidade de referência espacial: as células acessadas em um curto espaço de tempo estão, na maioria das vezes, próximas umas das outras na matriz. O problema é que, em geral, uma matriz bidimensional é armazenada de forma linear na memória e, por isso, muitas vezes células que são vizinhas na matriz ficam armazenadas em posições distantes umas das outras na memória. Como normalmente a localidade de referência espacial utilizada pela hierarquia de memória do computador é baseada no acesso sequencial [Patterson and Hennessy, 2008], esta forma de representação não tira proveito da localidade de referência espacial em termos bidimensionais, tornando o acesso ineficiente.

Para aproveitar a propriedade de localidade espacial e tentar diminuir o número de acessos a disco, este trabalho propõe um método denominado *TiledVS*, cuja estratégia consiste em adaptar o método *RFVS*, descrito na seção 2.2.2, de forma que todos acessos realizados às matrizes sejam gerenciados por uma estrutura de dados denominada *TiledMatrix* [Silveira et al., 2013], que é capaz de armazenar e gerenciar grandes matrizes em memória externa. Mais especificamente, um objeto do tipo *TiledMatrix* representa uma matriz que é dividida em blocos menores de dimensões fixas que são armazenados de forma sequencial em um arquivo na memó-

ria externa. Então, esta estrutura de dados gerencia a transferência de blocos entre as memórias interna e externa sempre que necessário. Em outras palavras, alguns blocos do terreno ficam armazenados em memória interna enquanto estiverem sendo processados, e podem voltar à memória externa quando não forem mais necessários, dando lugar a outros blocos. Desta forma, a estrutura de dados funciona como uma memória *cache* gerenciada pela aplicação, que busca predizer quais serão os próximos blocos do terreno a terem posições acessadas no processamento, mantendo-os na memória interna.

Uma questão importante a se considerar na implementação desta estrutura refere-se à política utilizada para determinar qual bloco será escolhido para ceder espaço a novos blocos. Neste trabalho utilizou-se a estratégia de retirar da memória interna aquele que está há mais tempo sem ser acessado pela aplicação. Em outras palavras, sempre que uma célula de um bloco é acessada, este bloco é marcado com um *timestamp*. Quando for necessário retirar um bloco da memória interna para carregar outro, será escolhido aquele que tiver o menor *timestamp*. Esta estratégia foi adotada baseado no fato de que há uma certa localidade no processamento das células pelo algoritmo. Isto é, se há um bloco que está há algum tempo sem ser acessado (nenhuma de suas células é processada) então há uma grande chance de que todas as células daquele bloco já tenham sido processadas e o bloco não precisará mais ser acessado.

Para ilustrar este processo, considere uma matriz que foi dividida em 5×5 blocos e uma memória interna capaz de armazenar no máximo 5 desses blocos. Suponha que em determinado momento do processamento os blocos de números 8, 9, 12, 13 e 14 estejam na memória interna, como mostrado na Figura 2.3a. Se for requisitado acesso a alguma célula que está contida em algum destes blocos, não será necessário buscá-la na memória externa, e o acesso será feito de forma mais eficiente. Por outro lado, se for requisitado acesso a alguma célula de outro bloco, diz-se que ocorreu uma *cache miss*, e esta célula deverá ser buscada na memória externa. Porém, por acreditar que logo em seguida serão requisitados acessos a outras células deste mesmo bloco, a estrutura de dados transfere e carrega para a memória interna o bloco inteiro que contêm a célula requisitada, substituindo um dos blocos que já estavam carregados. Considere, por exemplo, uma requisição de acesso a alguma célula do bloco 4, e que o bloco 14 é o que está há mais tempo sem ser acessado dentre aqueles carregados em memória interna e, portanto, é o que deverá ser substituído. Antes de realizar a substituição, é necessário verificar se alguma instrução de escrita foi executada no bloco 14 enquanto ele esteve em memória interna. Se sim, seus dados devem ser atualizados na memória externa.

Caso contrário não é necessário realizar esta atualização. Depois dessa verificação, o bloco 4 é copiado para a memória interna, resultando no estado representado na Figura 2.3b. Assim, para *cada cache miss* ocorrida, acontece exatamente um acesso de leitura e no máximo um acesso de escrita a um bloco na memória externa.

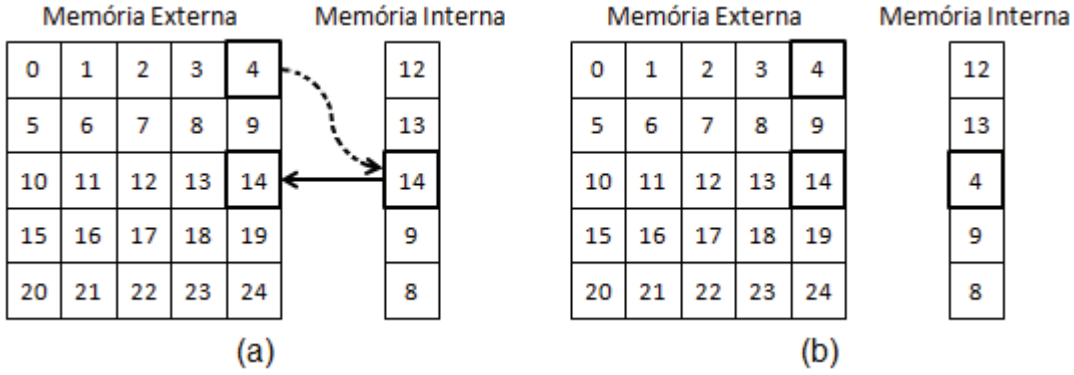


Figura 2.3: Transferências entre as memórias interna e externa gerenciadas pela classe *TiledMatrix*. Em (a), uma célula do bloco 4 é acessada e, como esse bloco não está na memória principal, ele é carregado, substituindo o bloco 14, que foi utilizado menos recentemente. A figura (b) apresenta o estado da memória interna após a troca do bloco 14 pelo bloco 4.

Além de tirar proveito de dados com localidade de referência espacial, outra grande vantagem de utilizar esta estrutura é que ela proporciona uma maior facilidade para a adaptação de algoritmos para memória interna já existentes, de modo que seus desempenhos considerando dados armazenados em memória externa sejam melhorados. Basicamente, é necessário somente substituir a utilização de matrizes tradicionais pela utilização da classe *TiledMatrix*. Desta forma, esta estratégia pode ser utilizada em diversas aplicações, não somente na área de CIG, mas sempre que forem utilizadas matrizes maiores do que o espaço disponível em memória interna e que o acesso às posições das matrizes apresente um padrão de localidade de referência espacial.

2.4 Complexidade do algoritmo

As dimensões dos blocos utilizados e o número máximo de blocos que a memória interna utilizada pode armazenar têm influência direta no desempenho do algoritmo. Considere, por exemplo, a inicialização da matriz de elevação, em que uma parte do terreno é carregada na estrutura *TiledMatrix*. Mais especificamente, nesta etapa são copiadas para a estrutura as células que estão contidas em um quadrado de

dimensões $(2\rho + 1) \times (2\rho + 1)$ com centro no observador O, onde ρ é o raio de interesse de O.

Por questões de eficiência, é importante que a memória interna disponível seja suficiente para armazenar no mínimo $\frac{2\rho+1}{t}$ blocos, onde t é a dimensão de cada lado dos blocos. Esta condição é necessária para que a inicialização da estrutura *TiledMatrix* possa ocorrer sem que seja necessário carregar um mesmo bloco mais de uma vez, ou seja, para que não ocorram *cache misses*. Para ilustrar a necessidade dessa condição, suponha que uma matriz de elevação de dimensões 50×50 seja armazenada em uma *TiledMatrix* M que a divide em blocos de dimensões 10×10 e que a memória interna comporte apenas 4 desses blocos. Note que, devido ao padrão que remove o bloco menos recentemente utilizado, quando os 10 últimos elementos da primeira linha da matriz forem copiados para M o bloco que contém os 10 primeiros elementos dessa linha deverá ser removido da memória interna. Porém, ao copiar os 10 primeiros elementos da próxima linha da matriz para M, esse bloco deverá voltar novamente para a memória interna. Esse padrão de acesso ocorrerá diversas vezes em todas as linhas de M e, assim, esse processo seria ineficiente. Portanto, para realizar a análise de complexidade do algoritmo, será suposto que o tamanho da memória interna atenda a esta restrição e, assim, cada bloco será carregado apenas uma vez durante a inicialização dessa estrutura de dados.

Como o algoritmo precisa carregar da matriz de elevação $(2\rho + 1) \times (2\rho + 1)$ células, a inicialização do algoritmo realiza $O(scan(\rho^2))$ operações de E/S.

Durante a etapa do algoritmo onde são traçadas diversas linhas de visão em sentido anti-horário para calcular o *viewshed* de O, também será necessário carregar cada bloco do terreno uma vez, com exceção dos blocos que contém simultaneamente células das primeiras e últimas linhas de visão a serem processadas, que precisarão ser carregados duas vezes. Como o número de células processadas é $O(\rho^2)$ e cada célula é transferida da memória externa no máximo duas vezes, esta etapa também é realizada em $O(scan(\rho^2))$ operações de E/S.

Depois de calculado, o *viewshed* é armazenado em um arquivo de saída com um *bit* para cada célula do terreno. Se o terreno tiver dimensões $n \times n$, serão efetuadas $O(scan(n^2))$ operações de E/S. Portanto, a complexidade do algoritmo *TiledVS* é:

$$O\left(scan\left(n^2\right)\right) = O\left(\frac{n^2}{B}\right)$$

2.5 Resultados

O método *TiledVS* foi implementado em C++ e compilado com o g++ 4.5.2. Optou-se por realizar os testes em um computador com pouca memória RAM para que fosse necessário realizar operações de processamento em memória externa mesmo para terrenos não tão grandes (como os com 10000^2 e 20000^2 células). Por isso, os testes foram executados em um PC Pentium 4 com 3.6GHz, 1GB de RAM, HD Sata de 160GB e 7200RPM. O sistema operacional utilizado foi o o Linux, distribuição Ubuntu 11.04 de 64bits. Dos 1024MB disponíveis em memória interna, foram utilizados 800MB para armazenar os dados, e os demais foram reservados para uso do sistema.

Os terrenos utilizados nos testes foram obtidos na página do *The Shuttle Radar Topography Mission* (SRTM) [Rabus et al., 2003]. Os dados correspondem a duas regiões distintas dos EUA amostradas em diferentes resoluções, gerando assim terrenos de diferentes tamanhos (10000^2, 20000^2, 30000^2, 40000^2 e 50000^2). Para cada tamanho de terreno, foi calculada a média do tempo necessário para processamento das duas regiões.

Em todos os testes foi considerado o pior caso, ou seja, o valor para o raio de interesse utilizado foi grande o suficiente para cobrir todo o terreno. Para avaliar a influência do número de pontos visíveis no tempo de execução, o observador foi posicionado em diferentes alturas acima do terreno (50 e 100 metros). Além disso, em todos os testes foi considerado que $h_O = h_T$, ou seja, os possíveis alvos estão posicionados à mesma altura que o observador. Os tempos de execução do método *TiledVS* foram comparados com os tempos do método *EMViewshed*, uma vez que este mostrou-se mais eficiente que os demais métodos encontrados em literatura [Andrade et al., 2011].

As Tabelas 2.1 e 2.2 mostram os tempos médios de execução, em segundos, necessários para processar cada um dos terrenos, utilizando o método *EMViewshed* (EMVS) e o método *TiledVS* considerando diferentes tamanhos de blocos (100^2, 250^2, 500^2, 1000^2, 2500^2 e 5000^2), sendo que a Tabela 2.1 refere-se aos testes com $h_O = h_T = 50$, enquanto a Tabela 2.2 refere-se aos testes com $h_O = h_T = 100$. A linha *Dim. Bl.* indica o tamanhos dos blocos utilizados, e a linha *# Bl.* indica o número máximo de blocos de cada tamanho que podem ser armazenados nos 800MB disponíveis na memória interna, ou seja, o tamanho da *cache* utilizada pela *TiledMatrix*.

Para cada tamanho de terreno, o tempo médio destacado em negrito indica o

Tabela 2.1: Tempos médios de execução, em segundos, para os métodos *EMViewshed* (EMVS) e *TiledVS*, considerando diferentes tamanhos de blocos e terrenos e altura de 50 metros. A linha *Dim. Bl.* indica as dimensões dos blocos utilizados, e a linha *# Bl.* indica o número máximo de blocos que podem ser armazenados na memória interna.

Tamanho do terreno (# células)	*TiledVS*						EMVS
	Dim. Bl.	100^2	250^2	500^2	1000^2	2500^2	5000^2	
	# Bl.	27962	4473	1118	279	44	11	
10000^2		58	57	57	58	63	60	**37**
20000^2		443	305	304	298	300	307	**220**
30000^2		1395	828	752	**729**	735	752	1465
40000^2		1772	1229	**1179**	1184	1185	1223	4709
50000^2		7717	2833	2417	2334	**2309**	2338	8988

Tabela 2.2: Tempos médios de execução, em segundos, para os métodos *EMViewshed* (EMVS) e *TiledVS*, considerando diferentes tamanhos de blocos e terrenos e altura de 100 metros. A linha *Dim. Bl.* indica as dimensões dos blocos utilizados, e a linha *# Bl.* indica o número máximo de blocos que podem ser armazenados na memória interna.

Tamanho do terreno (# células)	*TiledVS*						EMVS
	Dim. Bl.	100^2	250^2	500^2	1000^2	2500^2	5000^2	
	# Bl.	27962	4473	1118	279	44	11	
10000^2		64	64	63	65	65	65	**37**
20000^2		470	333	319	311	312	318	**234**
30000^2		1753	891	831	803	**784**	806	1502
40000^2		2148	1407	1303	1293	**1256**	1293	5530
50000^2		7570	2868	2437	2406	**2346**	2364	9839

método que apresentou o melhor desempenho. Os resultados mostram que, para os terrenos de dimensões 10000^2 e 20000^2, o método *EMViewshed* apresentou desempenho melhor do que o *TiledVS*, independentemente do tamanho dos blocos. Já para os terrenos de tamanhos 30000^2, 40000^2 e 50000^2, o método *TiledVS* mostrou-se mais rápido do que o *EMViewshed* para praticamente todos os testes realizados, com exceção do que utilizou blocos de tamanho 100^2 para processar o terreno de dimensões 30000^2 com altura de 100 metros.

É possível perceber que o tamanho dos blocos afeta diretamente o desempenho da estrutura *TiledMatrix*. Enquanto os testes com blocos de tamanho 100^2 apre-

sentaram os piores tempos, os testes com blocos de tamanho 500^2, 1000^2, e 2500^2 apresentaram os melhores tempos entre os tamanhos testados. Os gráficos da Figura 2.4 mostram os tempos de execução do *EMViewshed* e do *TiledVS* utilizando estes 3 tamanhos de blocos.

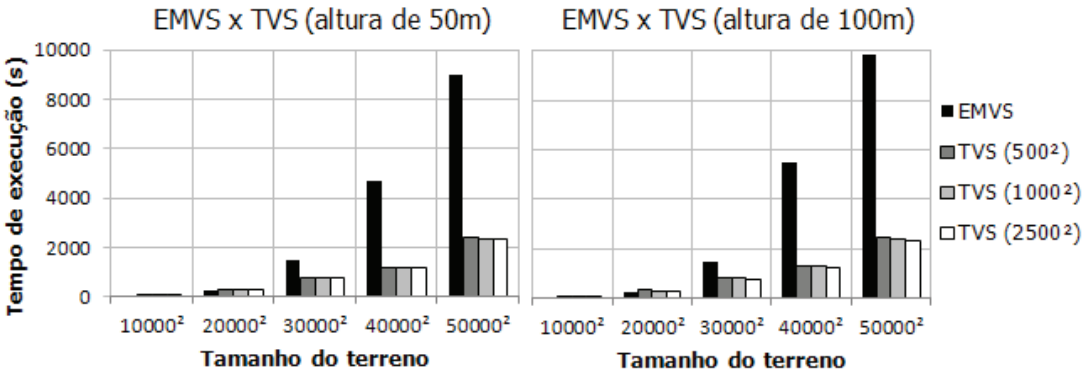


Figura 2.4: Tempos de execução do *EMViewshed* (EMVS) e do *TiledVS* (TVS) utilizando os 3 tamanhos de blocos com melhores desempenhos e alturas de 50 e 100 metros.

Com relação à variação nas alturas dos observadores e alvos, pode-se perceber que o número de observadores visíveis afeta o tempo de execução de ambos os métodos, uma vez que os tempos médios para os testes com altura de 100m são maiores do que os com altura de 50m. No entanto, este aumento foi consideravelmente maior para o método *EMViewshed* (11,1% em média) do que para o método *TiledVS* (4,7% em média).

2.6 Conclusões e trabalhos futuros

Neste trabalho foi apresentado o algoritmo *TiledVS* para cálculo de *viewshed* em terrenos armazenados em memória externa que mostrou-se até 4,4 vezes mais rápido do que o *EMViewshed*, proposto por Andrade et al. [2011], que era até então o método mais eficiente encontrado em literatura.

Além disso, a estratégia utilizada no método apresentado pode ser adaptada para outras aplicações que utilizem matrizes grandes armazenadas em memória externa. Como trabalhos futuros, propõe-se a utilização da classe *TiledMatrix* em outras aplicações com este perfil, assim como um estudo para avaliar a influência do tamanho dos blocos no desempenho do algoritmo e desenvolver uma estratégia para determinar automaticamente o tamanho mais adequado.

3. More efficient terrain viewshed computation on massive datasets using external memory[1]

Abstract

We present a better algorithm and implementation for external memory viewshed computation. It is about four times faster than the most recent and most efficient published methods. Ours is also much simpler. Since processing large datasets can take hours, this improvement is significant. To reduce the total number of I/O operations, our method is based on subdividing the terrain into blocks which are stored in a special data structure managed as a cache memory.

The viewshed is that region of the terrain that is visible by a fixed observer, who may be on or above the terrain. Its applications range from visual nuisance abatement to radio transmitter siting and surveillance.

3.1 Introduction

Terrain modeling has been widely used in Geographical Information Science (GIS) including applications in hydrology, visibility and routing. In visibility applications it is usual to compute which points can be viewed from a given point (the *observer*) and the region composed of such points, known as *viewshed* [Franklin and Ray, 1994]. Some applications include minimizing the number of cellular phone towers required to cover a region [Ben-Shimol et al., 2007], optimizing the number and position of guards to cover a region [Franklin and Vogt, 2006], etc.

There are various algorithms for viewshed computation but most of them were designed assuming that the terrain data fits in internal memory. However, the huge volume of high resolution terrestrial data available has become a challenge for GIS since the internal memory algorithms do not run well for such volume of data on most computers. Thus, it is important to optimize the massive data

[1]Neste capítulo é apresentado o artigo "*More efficient terrain viewshed computation on massive datasets using external memory*", apresentado no ACM SIGSPATIAL 2012 (*20th International Conference on Advances in Geographic Information Systems*) [Ferreira et al., 2012b].

processing algorithms simultaneously for computation and data movement between the external and internal memories since processing data in external memory takes much more time. That is, the algorithms for external memory should be designed (and analyzed) considering a computational model where the algorithm complexity is evaluated based on I/O operations. A model often used was proposed by Aggarwal and Vitter [1988] where an I/O operation is defined as the transfer of one disk block of size B between the external and internal memories and the performance is measured considering the number of such I/O operations. The internal computation time is assumed to be comparatively insignificant. An algorithm's complexity is related to the number of I/O operations performed by fundamental operations such as scanning or sorting N contiguous elements. Those are $scan(N) = \theta(N/B)$ and $sort(N) = \theta\left(\frac{N}{B}\log_{M/B}\frac{N}{B}\right)$ where M is the internal memory size.

This work presents an efficient algorithm, named *TiledVS*, to compute the viewshed of a point on terrains stored in external memory. The large number of disk accesses is optimized using a new library to manage the data swap between the external and internal memories. This new algorithm was compared against the most recent and most efficient published methods: *EMViewshed* [Andrade et al., 2011] and *io_radial2, io_radial3* and *io_centrifugal* [Fishman et al., 2009]. Our new method is much simpler and, also, the tests showed that it is more than four times faster than all of them. Since processing large datasets can take hours, this improvement is significant.

3.2 Definitions and related work

A *terrain* is a tridimensional surface τ where any vertical line intersects τ in at most one point. In this paper we will consider terrains represented by *regular square grids* (RSGs) since they use simpler data structures, i.e., matrices storing the elevations of regularly spaced positions of the terrain.

An *observer* is a point in the space from where the other terrain points (the *targets*) will be visualized. Both the observer and the targets can be at a given height above the terrain, respectively indicated by h_o and h_t. Usually, it is assumed that the observer has a range of vision ρ, the *radius of interest*, which means that the observer can see points at a given distance ρ. Thus, a target T is visible from O if and only if the distance of T from O is at most ρ and the straight line, the *line of sight*, from O to T is always strictly above the terrain. See Figure 3.1.

The *viewshed* of O corresponds to all points that can be seen by O. Since

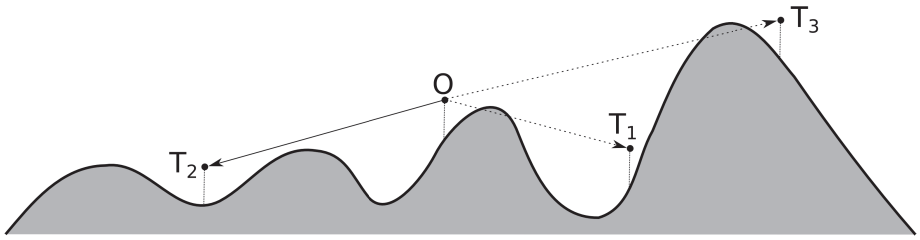


Figure 3.1: Target's visibility: T_1 and T_3 are not visible but T_2 is.

we are working with regular square grids, we represent a viewshed by a square $(2\rho+1) \times (2\rho+1)$ matrix of bits where 1 indicates that the corresponding point is visible and 0 is not. By definition, the observer is in the center of this matrix.

Earlier works have presented different methods for viewshed computation. Among the methods for RSG terrains, we can point out the one proposed by Van Kreveld [1996], and the one by Franklin et al., named *RFVS* [Franklin and Ray, 1994]. These two methods are very efficient and are particularly important in this context because they were used as the base for some very recent and efficient methods for the viewshed computation in external memory: Fishman et al. [2009] adapted Van Kreveld's method, and Andrade et al. [2011] adapted the *RFVS* method. This work also presents an IO-efficient adaptation of the *RFVS* method. Therefore, below we will give a short description of the *RFVS* method.

In that method, the terrain cells' visibility is computed along rays connecting the observer to all cells in the boundary of a square of side $2\rho+1$ centered at the observer where ρ is the radius of interest. That is, the algorithm creates a ray connecting the observer to a cell on the boundary of this square, and this ray is counterclockwise rotated around the observer following the cells in that boundary and the visibility of the cells in each ray is determined following the cells on the segment. Thus, suppose the segment is composed by cells $c_0, c_1, \cdots, c_k$ where c_0 is the observer's cell and c_k is a cell in the square boundary. Let α_i be the slope of the line connecting the observer to c_i and let μ be the highest slope among all lines already processed, that is, when processing cell c_i, $\mu = \max\{\alpha_1, \alpha_2, \cdots, \alpha_{i-1}\}$. Thus, the target on c_i is visible if and only if the slope of the line from O to the target above c_i is greater than μ. If yes, the corresponding cell in the viewshed matrix is set to 1; otherwise, to 0. Also, if $\alpha_i > \mu$ then μ is updated to α_i. We say that a cell c_i blocks the visibility of the target above c_j if cell c_i belongs to the segment $\overline{c_0 c_j}$ and α_i is greater or equal to the slope of the line connecting the observer to the target above c_j.

3.3 *TiledVS* method

As mentioned in section 3.2, the *RFVS* sweeps the terrain cells rotating a ray connecting the observer cell to a cell in the boundary of a bounding box and the cells' visibility is processed along this ray. Thus, the matrix access pattern presents a spatial locality of reference, that is, in a short time interval, the accessed cells are close in the matrix. However, this access pattern is not efficient in external memory since the cells which are close in the (bidimensional) matrix may not be stored close because, usually, a matrix is stored using a linear row-major order.

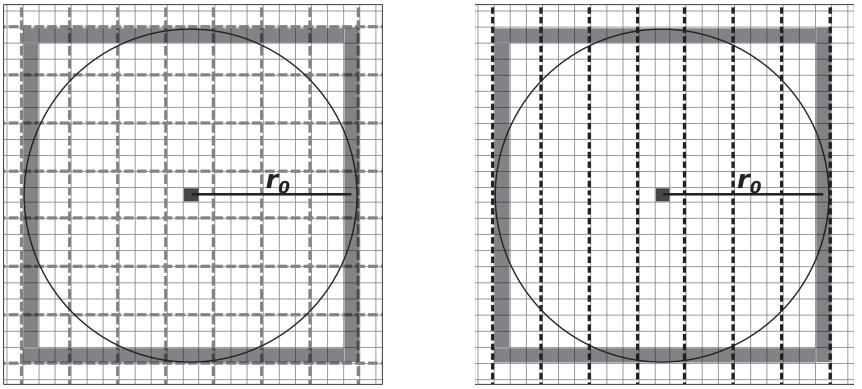
To reduce the number of non-sequential accesses, we present a new method, called *TiledVS*, where the basic idea is to adapt the *RFVS* algorithm to manage the access to the matrices stored in external memory using the library *TiledMatrix* [Silveira et al., 2013].

In brief, this library subdivides the matrix in small rectangular blocks (*tiles*) which are sequentially stored in the external memory. When a given cell needs to be accessed, the whole block containing that cell is loaded into the internal memory. The library keeps some of these blocks in the internal memory using a data structure, named *MemBlocks*, which is managed as a "cache memory" and the replacement policy adopted is based on *least recently used - LRU*. That is, when a block is accessed it is labeled with a *timestamp* and if it is necessary to load a new block into the cache (and there is no room for this block), the block with smaller *timestamp* is replaced with the new block. When a block is evicted, it is checked whether that block was updated (it is particularly important for the viewshed matrix); if any cell was updated then the block is written back to the disk.

Now, we will show that it is possible to define the *MemBlocks* size such that the adopted matrix partitioning associated with the *LRU* policy can be effective for the *RFVS* algorithm, that is, we will prove that this process will load a block in the cache, keep it there while it is accessed and it will be evicted only when it will be no longer needed.

In the following, we will suppose that the matrix partitioning creates square blocks with $\omega \times \omega$ cells and these blocks are grouped in vertical bands with ω columns of cells. See figure 3.2. And, given a ray r defined by the *RFVS* algorithm, without loss of generality, in the demonstrations below, we will consider rays whose slope is at most 45°. For rays with greater slope just replace rows with columns.

Lemma 3.3.1 *Any ray intersects at most* $\frac{\rho}{\omega} + 2$ *bands where* ρ *is the radius of interest (in number of terrain cells).*



(a) square blocks with 3×3 cells. (b) vertical bands with 3 columns.

Figure 3.2: Matrix partitioning.

Proof 3.3.2 *For the viewshed computation, the* RFVS *algorithm defines a square bounding box of side* $2\rho+1$ *with the observer on its center and creates rays connecting the observer to the center of the cells in the square border. Since any ray whose slope is at most* $45°$ *intersects* $\rho + 1$ *columns in this square, this ray intersects* $\lceil \frac{\rho+1}{\omega} \rceil + 1$ *vertical bands. The additional* $+1$ *is because the observer may not be in the central column of a band (notice that, if the observer in Figure 3.2b is moved one cell to the right, ray* r_0 *will cross the last band boundary and will intersect an aditional band). Since* $\lceil \frac{\rho+1}{\omega} \rceil = \lfloor \frac{\rho}{\omega} \rfloor + 1$ *then* $\lceil \frac{\rho+1}{\omega} \rceil + 1 \leq \frac{\rho}{\omega} + 2$.

Lemma 3.3.3 *Let* r_k *and* r_{k+1} *be two consecutive rays in the* RFVS *algorithm sweeping. Then these two rays intersect at most* $2\left(\frac{\rho}{\omega} + 2\right)$ *blocks.*

Proof 3.3.4 *Since the* RFVS *algorithm uses the Bresenham rasterization method, there is exactly one cell for each column intersected by a ray. Let* l_r *and* c_r *be respectively the number of rows and columns intersected by a ray* r*. As the ray slope is at most* $45°$ *then* $l_r \leq c_r$.

Given two consecutive rays r_k *and* r_{k+1}*, the vertical distance between them is at most one cell side - see Figure 3.3a. As, for each vertical band, they intersect* ω *columns, they can intersect at most* $\omega + 1$ *rows in that band. Thus, in each band, they can intersect at most two blocks (since the block height is* ω *rows). Therefore, from Lemma 3.3.1, rays* r_k *and* r_{k+1} *can intersect at most* $2\left(\frac{\rho}{\omega} + 2\right)$ *blocks.*

Lemma 3.3.5 *Let* r_0 *be the first ray in the sweeping sequence. Given a block* B *not intersected by* r_0*, let* r_k *and* r_{k+1} *be two consecutive rays. If* r_k *intersects* B *and* r_{k+1} *doesn't, then no other ray after* r_k *will intersect block* B.

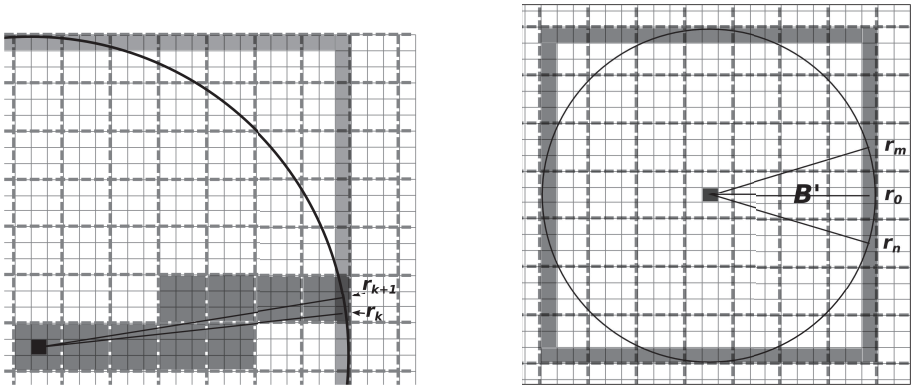
Proof 3.3.6 *It is straightforward from the fact that the algorithm uses a radial sweeping sequence and the blocks are convex. And it doesn't work for the blocks intersected by ray r_0 because, considering the radial sweeping, these blocks can be intersected again by the last rays. See Figure 3.3b.*

Theorem 3.3.7 *Given a block B not intersected by r_0, if the* MemBlocks *size (in number of blocks) is, at least, $2\left(\frac{\rho}{\omega}+2\right)$ then the* LRU *policy will evict block B from* MemBlocks *only if it is no longer needed.*

Proof 3.3.8 *Suppose that* MemBlocks *has $2\left(\frac{\rho}{\omega}+2\right)$ slots to store the blocks. Let r_k and r_{k+1} be two consecutive rays such that r_k intersects block B. At some point during the processing of ray r_k, block B will start to be processed and it is stored in the* MemBlocks *(if r_k is the first ray intersecting block B then B will be loaded in* MemBlocks*). Now, if ray r_{k+1} also intersects block B, this block needs to be processed again. But, the* MemBlocks *size is enough to avoid block B eviction because, let $B'_1, B'_2, \cdots, B'_j$ be the sequence of blocks that need to be processed among the twice processing of B, that is, it is the sequence of blocks to be processed after B in the ray r_k and before B in ray r_{k+1}. From lemma 3.3.3, $j \leq 2\left(\frac{\rho}{\omega}+2\right)$ and since B is not included in the sequence then $j < 2\left(\frac{\rho}{\omega}+2\right)$. Thus, if* MemBlocks *size is $2\left(\frac{\rho}{\omega}+2\right)$ then it has slots to store all blocks that need to be processed and B will not be evicted. In other words, the* LRU *policy will not evict block B because the distinct blocks that need to be accessed can be stored in* MemBlocks*.*

On the other hand, if ray r_{k+1} doesn't intersect block B then, from lemma 3.3.5, no other ray after r_k will intersect B and thus, it can be evicted since it is no longer needed. There is a special situation for the blocks intersected by r_0 because, after being evicted, they can be loaded again when processing the last rays. But notice that these blocks can be loaded at most twice. See Figure 3.3b where block B' is loaded in the processing of r_0, is evicted after the processing of r_m and it is loaded again when processing r_n.

It is possible to demonstrate that the *TiledVS* algorithm does $\theta(scan(N))$ I/O operations and takes $\theta(N)$ time to process a terrain with N cells considering that the memory can store $2\left(\frac{\rho}{\omega}+2\right)$ blocks. This complexity works even if the radius of interest ρ is large to cover the whole terrain.



(a) Blocks intersected by two consecutive rays

(b) Block B' is loaded because of ray r_0, is evicted after ray r_m and loaded again for ray r_n.

Figure 3.3: *TiledVS* algorithm.

3.4 Experimental Results

The *TiledVS* method was implemented in C++ and compiled with g++ 4.3.4. It was compared against the most efficient algorithms recently described in literature: *io-radial2, io-radial3* and *io-centrifugal*, proposed by Fishman et al. [2009], and *EMViewshed*, proposed by Andrade et al. [2011].

Lacking access to Fishman's programs, we compared our algorithm to his published results. We executed our algorithm using the same datasets and also a same platform as that one used by those authors, i.e. a computer with an Intel Core 2 Duo E7500 2.93GHz processor, 4GiB of RAM memory, and a 5400RPM SATA HD (Samsung HD103SI) which was rebooted with 512MiB RAM. The operational system used was Linux, Ubuntu 10.04 32bits distribution.

Our results are presented in Table 3.1 and Figure 3.4 where we reproduce the times presented in Fishman et al. [2009]. Notice that our algorithm is faster than the others in all situations and, on huge terrains, it is about 4 times faster. Also, the table includes the processing time of our algorithm on very huge terrains generated by interpolation of Region02.

We also compared our new algorithm *TiledVS* against our previous one *EMViewshed* [Andrade et al., 2011]. We used different datasets generated from two distinct USA regions sampled at different resolutions using 2 bytes per elevation value. The results are presented in Table 3.2. Note that our new algorithm *TiledVS* is about 7 times faster than our previous one.

Table 3.3 presents the *TiledVS* running time (in seconds) for different terrain

Table 3.1: Running time (seconds) for *io-radial2* (io-r2), *io-radial3* (io-r3), *io-centrifugal* (io-cent) and *TiledVS* with 512MiB RAM.

Dataset	Terrain size			*io-r2*	*io-r3*	*io-cent*	*TiledVS*
	cols	rows	GiB				
Cumberlands	8 704	7 673	0.25	72	104	35	17
USA DEM 6	13 500	18 200	0.92	2 804	458	115	85
USA DEM 2	11 000	25 500	1.04	1 883	735	121	98
Washington	31 866	33 454	3.97	13 780	3 008	676	386
SRTM1-reg03	50 401	43 201	8.11	37 982	6 644	2 845	994
SRTM1-reg04	82 801	36 001	11.10	—	8 834	5 341	1 347
SRTM1-reg04	68 401	111 601	28.44	—	26 193	12 186	5 034
Reg02 interp.	150 000	91 000	50.85	—	—	—	5 079
Reg02 interp.	200 000	122 000	90.89	—	—	—	12 642

sizes using only 128MiB and 512MiB of RAM. As can be noticed, our algorithm is scalable to data that is much bigger than the machine internal memory.

3.5 Conclusion

We presented a new algorithm for viewshed computation on huge grid terrains stored in external memory. Our new method uses a special data structure to manage the data transference between the internal and external memories reducing the number of I/O operations. For terrains with N cells, its I/O completixy is $\Theta(scan(N))$.

Table 3.2: Running time (seconds) for *EMViewshed* (EMVS) and *TiledVS* with 1024MiB RAM.

Size		EMVS	*TiledVS*
cols × rows	GiB		
30 000 × 30 000	1.68	727	256
40 000 × 40 000	2.98	3168	515
50 000 × 50 000	4.65	5701	812
60 000 × 60 000	6.71	8961	1265

The algorithm was compared against the most recent and efficient algorithms in the literature and, as the tests showed, it was faster than all others. In general, it was about 4 times faster and this improvement is significant because processing huge terrains can take hours. Also, it is much simpler.

Table 3.3: *TiledVS* running time (seconds) using a RAM memory with 128MiB and 512MiB.

Terrain Size				RAM Size	
cols	×	rows	GiB	128MiB	512MiB
37 000	×	37 000	5	634	604
52 000	×	52 000	10	1277	1168
73 500	×	73 500	20	3324	2708
104 000	×	104 000	40	7511	5612

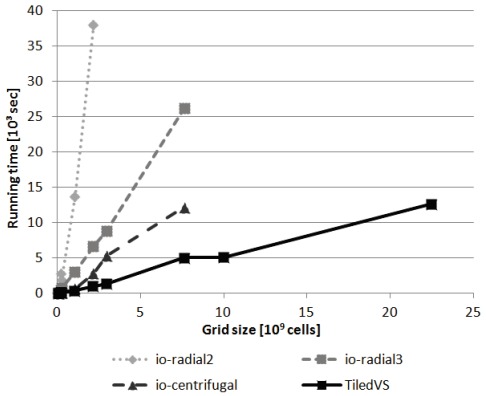


Figure 3.4: Comparing the running time of the four methods.

Addionally, the algorithm was able to process huge terrains using small RAM memory. For example, the viewshed of a terrain of size 40 GiB, using 128 MiB RAM was computed in 7511 seconds.

The algorithm souce code (in C++) is avalable and distributed under Creative Common GNU GPL license at `http://www.dpi.ufv.br/~marcus/TiledVS.htm`

4. A fast external memory algorithm for computing visibility on grid terrains[1]

Abstract

This paper presents a novel external memory algorithm for terrain viewshed computation that decreases the total number of I/O operations. The algorithm subdivides the terrain into blocks that are stored in a special data structure managed as a cache memory, combined with a fast lossless block compression algorithm that reduces the amount of data transfered between external and internal memories.

Computing the viewshed, i.e., the set of points visible from a given point on a terrain, is a widely used visibility application, but the amount of recently available high resolution terrestrial data overloads traditional internal memory algorithms.

Experimentally, our algorithm is about four times faster than the most recent and efficient published methods. This is significant since processing huge terrains is quite compute-intensive.

4.1 Introduction

One important component of terrain modeling in Geographical Information Science (GIS) is visibility, or line-of-sight, computation. That is, determining the *viewshed*, or set of *target* points that can be seen from a given *observer* point [Floriani et al., 1999; Franklin and Ray, 1994; Nagy, 1994]. Applications range from visual nuisance abatement to radio transmitter siting and surveillance, such as minimizing the number of cellular phone towers required to cover a region [Ben-Shimol et al., 2007; Camp et al., 1997; Bespamyatnikh et al., 2001], optimizing the number and position of guards to cover a region [Franklin and Vogt, 2006; Eidenbenz, 2002; Magalhães et al., 2011], analysing the influences on property prices in an urban environment [Lake et al., 1998] and optimizing path planning [Lee and Stucky, 1998]. Using the term *line of sight*, Champion and Lavery [2002] present other applications.

[1]Este capítulo apresenta o artigo "*A fast external memory algorithm for computing visibility on grid terrains*", submetido à revista ACM TSAS (*ACM Transactions on Spatial Algorithms and Systems*) [Ferreira et al., 2014].

There are various algorithms for viewshed computation. However most of them assume that the data fits in internal memory and thus can be processed with no access to external memory (except to load the data). Therefore, the recent increase in the volume of high resolution terrestrial data, too large for the internal memory of most computers, creates a challenge.

For example, NASA's Shuttle Radar Topography Mission (SRTM) 30 meter resolution terrain data occupies about 10 terabytes. Processing sub-meter resolution data, perhaps from LIDAR, will be an even greater challenge. Thus, it is important to optimize the massive data processing algorithms simultaneously for computation and data movement between the external and internal memories, since external memory accesses are about 10^6 times slower [Dementiev et al., 2005]. In this case, algorithms for external memory processing should be designed and implemented to minimize the number of I/O operations for moving data between main memory and disk.

The techniques developed for external memory algorithms are also relevant to GPU programming. A state-of-the-art NVIDIA Tesla K20x GPU accelerator [NVidia, 2012], announced in Nov 2012, has 6GB of memory and also can have data from the host's much larger memory transferred over. However it contains four different types of memory, with relative speeds ranging over a factor of 100. The fastest memory is the register bank, which is quite small, with only 65536 registers shared by all the threads in the block. Therefore, exploiting such GPUs to process current datasets requires good parallel algorithms that, similarly to external algorithms, optimize the movement of data across the layers of memory on a GPU.

So, external memory processing algorithms need to be designed under a machine model minimizing data transfer operations instead of CPU processing. A common model, proposed by Aggarwal and Vitter [1988], defines an I/O operation as the transfer of one disk block of size β between external and internal memories. The measure of performance is the number of such I/O operations. The internal computation time is assumed to be comparatively insignificant (within reasonable limits). It can be convenient to analyze an algorithm in comparison to the cost of a common lower level operation such as scanning or sorting N contiguous elements stored in external memory. Those are $scan(N) = \Theta(N/\beta)$ and $sort(N) = \Theta\left(\frac{N}{\beta}\log_{(M/\beta)}\frac{N}{\beta}\right)$, where M is the internal memory size.

This work presents *TiledVS*, an efficient method to compute the viewshed of a point on a terrain stored in external memory. *TiledVS* is an adaptation of *RFVS* an internal memory algorithm proposed by Franklin and Ray [1994]. It allows efficient manipulation of huge terrains (100 GiB or more). The large number

of disk accesses is optimized using a new library to manage the data swap between external and internal memories. When compared to the most recent and most efficient published methods (namely, *EMViewshed* proposed by Andrade et al. [2011]; and *io_radial2, io_radial3* and *io_centrifugal* proposed by Fishman et al. [2009]), *TiledVS* is much simpler and faster, experimentally, by a factor of four. Since processing large datasets can take hours, this improvement is significant.

4.2 Some definitions for the viewshed problem

In what follows, our region of interest is small compared to the radius of the earth, so that for this discussion the earth can be considered to be flat. There is a horizontal reference plane γ, a section of the geoid.

A *terrain* τ is a $2\frac{1}{2}$ dimensional surface where any vertical line intersects τ in at most one point. M_p is the projection of any point p onto γ. The terrain is usually represented approximately either by a *triangulated irregular network (TIN)* or a *regular square grid* (RSG) [Li et al., 2005; Floriani et al., 1999]. A TIN is a partition of the surface into planar triangles, i.e., a piecewise linear triangular spline, where the elevation of a point p is a bilinear interpolation onto γ of the elevations of the vertices of the triangle containing the projection of p. On the other hand, a DEM is simply a matrix storing the elevations of regularly spaced positions or posts, where the spacing may be either a constant number of meters or a constant angle in latitude and longitude. In this paper, we will use the DEM representation because of its simpler data structure, ease of analysis, and ability to represent discontinuities (cliffs) more naturally. Finally, there is a huge amount of data available as DEMs.

One objection to the DEM is that it uses too much space because it does not adapt to the varying information content of different regions of the terrain. However that could be handled by postprocessing with an adaptive compression technique, such as the on presented by Stookey et al. [2008]. In contrast, storing the topology in a TIN usually takes more space than it is required to store the elevations [Li et al., 2005], although tradeoffs between space and data structure complexity are possible.

An *observer* is a point in space from where other points (the *targets*) will be visualized. Both the observer and the targets can be at given heights above τ, respectively indicated by h_o and h_t. We often assume that the observer can only see targets whose distances from it are smaller than its *radius of interest*, ρ. Thus, a target T is visible from O if and only if the distance from O to T is at most ρ

and the straight line, the *line of sight*, from O to T is always strictly above τ; see Figure 4.1.

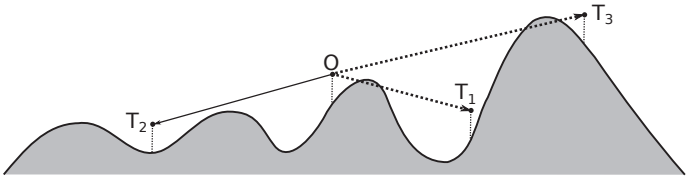


Figure 4.1: Targets' visibility: T_1 and T_3 are not visible but T_2 is.

The *viewshed* of O is the set of all terrain points vertically below targets that can be seen by O; formally,

$$viewshed(O) = \{p \in \tau \mid \text{the target above } p \text{ is visible from } O\}$$

with ρ implicit. The viewshed representation is a square $(2\rho + 1) \times (2\rho + 1)$ bitmap with the observer at the center.

Theoretically, determining whether a target T is visible from O requires verifying all points in the line of sight connecting O to T. But since τ is represented with a finite resolution, only points close to the rasterized line segment connecting the projections of O and T onto the horizontal plane will be verified. The visibility depends on the line segment rasterization method used (see Figure 4.2) and how the elevation is interpolated on those cells where the segment does not intersect the cell center.

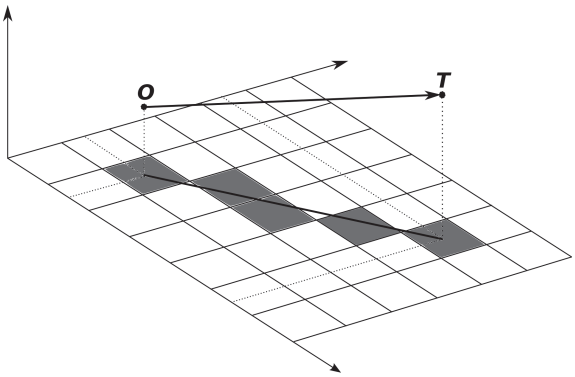


Figure 4.2: The rasterization of the line of sight projection.

Considering that there are many alternatives for these decisions, it is usual that different viewshed algorithms obtain slightly different results, depending on the choices made by the programmer while implementing the algorithm. In fact, Fisher [1993] stated that "the viewshed is a fundamentally uncertain phenomenon within a

GIS and is simply not repeatable across a spectrum of systems". Furthermore, since the terrain model only represents approximations of the real terrain's characteristics, the computed viewshed will also be an approximation whose accuracy is dependent on the terrain model's accuracy itself.

4.3 Related Work

4.3.1 Viewshed algorithms

Different terrain representations call for different algorithms. A TIN can be processed by the algorithms proposed by Cole and Sharir [1989] and Floriani and Magillo [2003]. For a DEM, we recommend [Van Kreveld, 1996] and *RFVS*, proposed and implemented by Franklin and Ray [1994]. These two algorithms are very efficient. Both have been recently extended to efficient external memory viewshed algorithms. Fishman et al. [2009] adapted Van Kreveld's and Andrade et al. [2011] adapted *RFVS*. (This paper's contribution is a new and more efficient adaptation of *RFVS*).

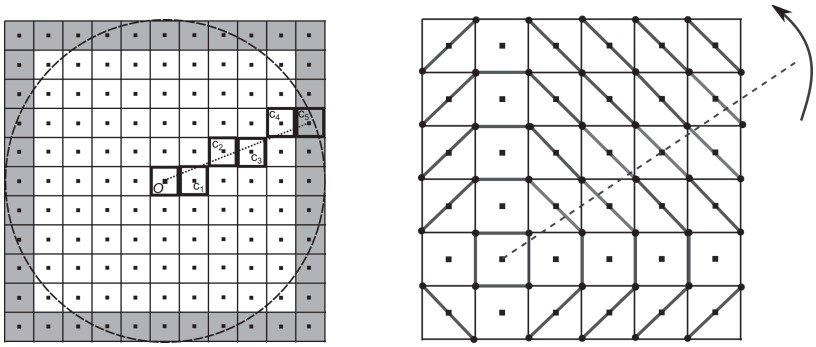
These two algorithms differ from each other not only on their efficiency, but also on the visibility models adopted. For instance, Van Kreveld's algorithm uses a center-of-cell to center-of-cell visibility, that is, a cell c is visible if and only if the ray connecting the observer (in the center of its cell) to the center of c does not intersect the terrain. On the other hand, *RFVS* uses a less restrictive approach where a cell c may be considered visible if its center is not visible but another part of c is.

Therefore, the viewsheds obtained by these methods may be different. Without knowing the application and having a model for the terrain's elevation between the known points, it is impossible to say which one is better. Some applications may prefer a viewshed biased in one direction or the other, while other may want to minimize error computed under some formal terrain model. For instance, the designer of a surveillance or a cellphone network may consider that duplicate coverage of some regions is preferable to no coverage and so would want to underestimate viewsheds.

Considering that both these algorithms have been recently adapted for efficient external memory processing, we will briefly describe them in the next sections.

4.3.1.1 The *RFVS* algorithm

RFVS [Franklin and Ray, 1994] is a fast algorithm that runs in $\Theta(n)$, where $n = \Theta(\rho^2)$. It computes the terrain cells' visibility along rays (line segments) connecting the observer (in the center of a cell) to the center of all cells in the boundary of a square bounding box of side $2\rho + 1$ centered at the observer (see Figure 4.3a).



(a) *RFVS* algorithm. (b) Van Kreveld's algorithm.

Figure 4.3: Viewshed algorithms.

RFVS creates a ray connecting the observer to a cell on the boundary of this square, and then rotates it counter-clockwise around the observer to follow along the boundary cells. The visibility of each ray's cells is determined by walking along the segment, which is rasterized following [Bresenham, 1965]. Suppose this segment is composed of cells $c_0, c_1, \cdots, c_k$ where c_0 is the observer's cell and c_k is a cell in the square boundary. Let α_i be the slope of the line connecting the observer to c_i. For each cell c_i, the algorithm compares α_i against all α_j with $0 < j < i$. If, for any such j, $\alpha_i \leq \alpha_j$, then c_i is not visible. Otherwise it is.

Formally, given a terrain τ represented by an elevation matrix $\mathcal{M}$, the observer position c_0 on τ, the radius of interest ρ, and h_o, the observer's height above the terrain, this algorithm computes the viewshed of O within a distance ρ of c_0, as follows:

1. Let c_0's coordinates be (x_0, y_0). Then the observer O will be at a distance h_o above cell (x_0, y_0) in $\mathcal{M}$.
2. Imagine a square of side $(2\rho + 1) \times (2\rho + 1)$ centered on (x_0, y_0).
3. Iterate through the cells p of the square's perimeter.
    a) For each p, run a straight line in $\mathcal{M}$ from (x_0, y_0) to (x_p, y_p).

b) Find the cells intersected by that line, perhaps using Bresenham. From c_0 to p, in that order, let them be $c_0, c_1, \cdots c_{k-1}, c_k = p$.

c) Let α_i be the slope of the line from O to c_i, that is,

$$\alpha_i = \frac{\zeta(c_i) - (\zeta(c_0) + h_o)}{dist(c_0, c_i)}$$

where $\zeta(c_0)$ and $\zeta(c_i)$ are, respectively, the elevation of cells c_0 and c_i and $dist(c_0, c_i)$ is the "distance" (in number of cells) between these two cells.

d) Let μ be the greatest slope seen so far along this line. Initialize $\mu = -\infty$.

e) Iterate along the line from c_0 to p.

i. For each cell c_i, compute α_i.

ii. If $\alpha_i > \mu$, then set c_i as visible in the viewshed (which is simply a $2\rho \times 2\rho$ bitmap) and update $\mu = \alpha_i$.

4.3.1.2 Van Kreveld's algorithm

Van Kreveld's algorithm [Van Kreveld, 1996] is another fast viewshed algorithm, which runs in $\Theta(n\ log\ n)$, also with $n = \Theta(\rho^2)$. Its basic idea is to rotate a sweep line around the observer and compute the visibility of each cell when the sweep line passes over its center (see Figure 4.3b). For that, it maintains a balanced binary tree (the *agenda*) that stores the slope of all cells currently being intersected by the sweep line, keyed by their distance from the observer. When this sweep line passes over the center of a cell c, the *agenda* is searched to check c's visibility. More specifically, this algorithm works as follows:

For each cell, it defines three types of events: *enter*, *center*, and *exit* events to indicate, respectively, when the sweep line starts to intersect the cell, passes over the cell center and stops to intersect the cell. The algorithm creates a list E containing these three types of events for all cells inside the region of interest. The events are then sorted according to their azimuth angle.

To compute the viewshed, the algorithm sweeps list E and for each event it decides what to do depending on the type of the event:

- If it is an *enter* event, the cell is inserted into the *agenda*.
- If it is a *center* event of cell c, the *agenda* is searched to check if it contains any cell that lies closer to the observer than c and has slope greater or equal

to the slope of the line of sight to c; if yes, then c is not visible, otherwise it is.

- If it is an *exit* event, the cell is removed from the *agenda*.

It is important to note that the *agenda* is implemented as a balanced binary tree, that performs insertions, removals and queries in $\Theta(log\ n)$, which keeps the algorithm efficiency in $\Theta(n\ log\ n)$.

4.3.2 External memory viewshed algorithms

4.3.2.1 EMViewshed

EMViewshed [Andrade et al., 2011] is an efficient external memory algorithm based on *RFVS*. It creates and stores in external memory a list with data about all terrain cells and sorts it according to the order that they will be processed by the *RFVS* algorithm. Thus, it can sweep that list sequentially, avoiding random accesses to external memory.

More specifically, it creates a list Q of pairs (c, k), where c is a terrain cell and k is an index that illustrates when c will be processed. That is, if there is a pair (c, k) in Q, then c will be the k-th cell to be processed. After creating Q, the algorithm sorts Q according to these k indices using an external memory sorting algorithm [Dementiev et al., 2005]. Then it sweeps Q to calculate the viewshed, making only sequential accesses to external memory, which guarantees the algorithm I/O efficiency.

Although EMViewshed is a fast I/O-efficient algorithm, our experiments in Section 4.6 show that our new algorithm is about 10 times faster than it.

4.3.2.2 Algorithms based on Van Kreveld's algorithm

Van Kreveld's method was adapted for external memory processing by various authors using different strategies: *ioviewshed* [Haverkort et al., 2007] creates a list of events and sorts it with an external memory sorting algorithm. These events are used to process the terrain with a sweep-line approach. This algorithm was renamed *io-radial1* in [Fishman et al., 2009] where the authors describe two other algorithms also based on Van Kreveld, *io-radial2* and *io-radial3*. They sweep the terrain by rotating a ray around the viewpoint while maintaining the terrain profile along the ray (similar to Van Kreveld). The difference between the two algorithms lies in the preprocessing step before sweeping the terrain. In *io-radial2*, the grid points are

sorted into concentric bands around the viewpoint, while *io-radial3*, the grid points are sorted into sectors around the viewpoint. Fishman et al. [2009] also described another algorithm, *io-centrifugal*, but it is not based on Van Kreveld. Instead, it sweeps the terrain centrifugally, growing a star-shaped region around the observer while maintaining an approximate visible horizon of the terrain within the swept region.

ioviewshed (or *io-radial1*) was implemented as an add-on in GRASS (versions 6.x/7.x), named *r.viewshed* [Toma et al., 2010]. As described in [Fishman et al., 2009], it is much slower than *io-radial2* and *io-radial3*, which is the fastest among these three methods but slower than *io-centrifugal*. Nonetheless, the tests in Section 4.6 show that the method described in this paper is about 8 times faster than *io-radial3* and 4 times faster than *io-centrifugal*.

4.4 *TiledVS* method

4.4.1 Algorithm description

In this section, we propose a new external memory viewshed algorithm based on an adaptation of *RFVS* algorithm.

As described in Section 4.3.1.1, *RFVS* sweeps the terrain cells by rotating a ray that connects the observer cell to the cells in the boundary of a square bounding box. The cells' visibility is processed along this ray. Thus the matrix access pattern presents a spatial locality of reference, that is, in a short time interval, the accessed cells are close in the matrix. However, cells that are close in this bidimensional matrix may not be close in memory because a matrix is usually stored using a linear row-major order, which is inefficient when using the external memory required by huge terrains.

To reduce the number of non-sequential accesses, we present *TiledVS*, a new method whose basic idea is to adapt *RFVS* to manage access to the matrices stored in external memory by using a special library, *TiledMatrix* [Silveira et al., 2013]. *TiledMatrix* subdivides the matrix into small rectangular blocks (*tiles*) that are stored in external memory; see Figure 4.4. To access a given cell, *TiledMatrix* copies the whole block containing that cell into internal memory.

To improve the matrix access efficiency, *TiledMatrix* keeps some of these blocks in internal memory. It uses a data structure named *MemBlocks*, which is an array of blocks managed as a cache memory using the least recently used (LRU) replacement policy. When a block is accessed it is labeled with a *timestamp*; and when it is

necessary to evict a block from the cache to load a new block, the block with the smallest *timestamp* is replaced with the new block. When a block is evicted, it is checked for whether it has been updated, and if so, it is written back to disk.

The blocks are stored in a file on disk. To reduce I/O, *TiledMatrix* uses the fast lossless compression algorithm LZ4 [Collet, 2012] to compress the blocks before writing to disk, and to uncompress them after reading. To simplify file management, each block's reserved space on the disk is the original uncompressed size. But when a block is transferred, only its compressed size (recorded in an auxiliary array) is transferred. As detailed in Section 4.6, our tests showed that compressing reduces the block size by 66%, on average, which reduces the amount of I/O by 2/3.

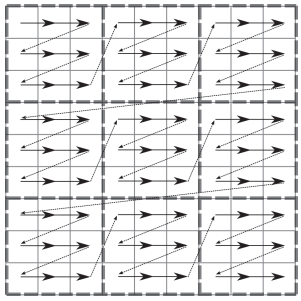


Figure 4.4: Partitioning the elevation matrix into blocks and reorganizing the cells in external memory to store the cells of each block in sequence. The arrows indicate the writing sequence.

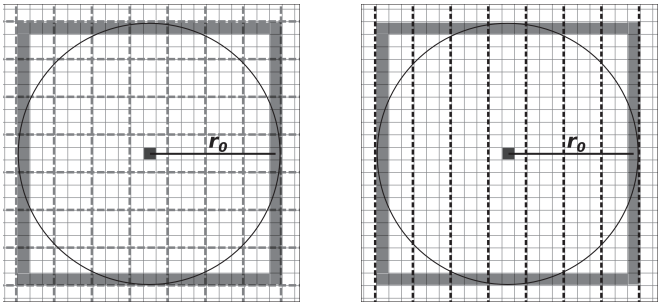
We will show that it is possible to define the *MemBlocks* size such that our matrix partitioning is very effective for *RFVS*. That is, we will prove that this process will load a block in the cache, keep it there while it is accessed and it will be evicted only when it will be no longer needed.

4.4.2 Demonstration of *TiledVS* effectiveness

In the following, suppose that the matrix partitioning creates square blocks (tiles) with $\omega \times \omega$ cells and these blocks are grouped in vertical bands with ω columns of cells; see Figure 4.5. Without loss of generality, consider only the rays in the first quadrant and whose slope is at most 45°, since the rest is obvious.

Lemma 4.4.1 *Any ray intersects at most* $\frac{\rho}{\omega} + 2$ *bands.*

Proof 4.4.2 *For the viewshed computation,* RFVS *defines a square bounding box of side* $2\rho + 1$ *with the observer on its center and creates rays connecting the observer to the center of the cells in the square border; see Figure 4.3a. Since any ray whose*



(a) Square blocks with 3×3 cells.

(b) Vertical bands with 3 columns. The radius of interest $\rho = 10$.

Figure 4.5: The terrain matrix partitioning.

slope is at most $45°$ *intersects at most* $\rho+1$ *columns in this square, this ray intersects at most* $\lceil \frac{\rho+1}{\omega} \rceil + 1$ *vertical bands. The additional* $+1$ *is because the observer may not be in the central column of a band (notice that, if the observer in Figure 4.5b is moved one cell to the right, ray* r_0 *will cross the last band boundary and will intersect an additional band). As shown by Graham et al. [1994],* $\lceil \frac{\rho+1}{\omega} \rceil = \lfloor \frac{\rho}{\omega} \rfloor + 1$*, then* $\lceil \frac{\rho+1}{\omega} \rceil + 1 \leq \frac{\rho}{\omega} + 2$*.*

Lemma 4.4.3 *Let* r_k *and* r_{k+1} *be two consecutive rays in the* RFVS *algorithm sweeping. Then these two rays intersect at most* $2\left(\frac{\rho}{\omega} + 2\right)$ *blocks.*

Proof 4.4.4 *Since* RFVS *uses Bresenham, exactly one cell in each column is intersected by a ray. Let* l_r *and* c_r *be respectively the number of rows and columns intersected by a ray* r*. As the ray slope is* $\leq 45°$ *then* $l_r \leq c_r$*.*

Given the two consecutive rays r_k *and* r_{k+1}*, the vertical distance between them is at most one cell side; see Figure 4.6. For each vertical band, both rays intersect* ω *columns, then they can intersect at most* $\omega + 1$ *rows in that band. Thus, in each band, the two rays can intersect at most two blocks (since the block height is* ω *rows). Therefore, from Lemma 4.4.1, rays* r_k *and* r_{k+1} *can not intersect more than* $2\left(\frac{\rho}{\omega} + 2\right)$ *blocks.*

Lemma 4.4.5 *Let* r_0 *be the first ray in the* RFVS *sweeping sequence, that is,* r_0 *is the horizontal ray connecting the observer to the center of the cell on the right boundary of the square; see Figure 4.5. Given a block* B *not intersected by* r_0*, let* r_k *and* r_{k+1} *be two consecutive rays. If* r_k *intersects* B *and* r_{k+1} *does not, then no other ray after* r_k *will intersect* B*.*

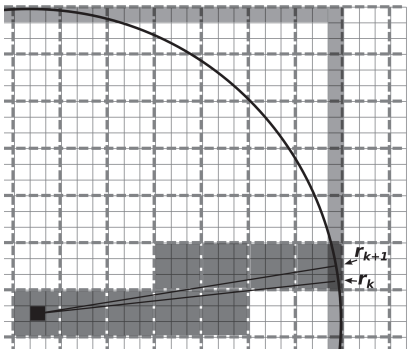


Figure 4.6: Blocks intersected by two consecutive rays.

Proof 4.4.6 *It is straightforward from the fact that the algorithm uses a radial sweeping sequence and the blocks are convex. The only exception is the set of blocks intersected by* r_0*; these blocks can be intersected again by the last rays; see Figure 4.7.*

Theorem 4.4.7 *Given a block* B *not intersected by* r_0*, if the number of blocks in* MemBlocks *is at least* $2\left(\frac{\rho}{\omega}+2\right)$ *then the* LRU *policy will evict block* B *from* MemBlocks *only if it is no longer needed.*

Proof 4.4.8 *Suppose that* MemBlocks *has* $2\left(\frac{\rho}{\omega}+2\right)$ *slots to store the blocks. Let* r_k *and* r_{k+1} *be two consecutive rays such that* r_k *intersects block* B*. Thus, at some point during the processing of ray* r_k*, block* B *will start to be accessed and will be stored in* MemBlocks *(if* r_k *is the first ray intersecting block* B *then* B *will be loaded into* MemBlocks*). Now, if ray* r_{k+1} *also intersects block* B*, this block needs to be acessed again. But, the* MemBlocks *size is enough to avoid block* B *eviction because, let* $B'_1, B'_2, \cdots, B'_j$ *be the sequence of blocks that need to be accessed among two consecutive processings of* B*, that is, it is the sequence of blocks to be accessed after* B *on ray* r_k *and before* B *on ray* r_{k+1}*. From Lemma 4.4.3,* $j \leq 2\left(\frac{\rho}{\omega}+2\right)$ *and since* B *is not included in the sequence then* $j < 2\left(\frac{\rho}{\omega}+2\right)$*. Thus, if* MemBlocks *size is at least* $2\left(\frac{\rho}{\omega}+2\right)$ *then it has enough slots to store* B *and all the blocks in this sequence, so* B *will not be evicted. In other words, in this case, the* LRU *policy will not evict block* B *because the distinct blocks that need to be accessed can be stored in* MemBlocks*.*

On the other hand, if ray r_{k+1} *does not intersect block* B *then, from Lemma 4.4.5, no other ray after* r_k *will intersect* B *and thus, it can be evicted since it is no longer needed.*

There is a special situation for the blocks intersected by r_0 *because, after being evicted, these blocks can be loaded again when processing the last rays. But, notice that these blocks can be loaded at most twice. See Figure 4.7 where block* B' *is loaded*

in the processing of ray r_0, is evicted after the processing of r_m and it is loaded again when processing ray r_n.

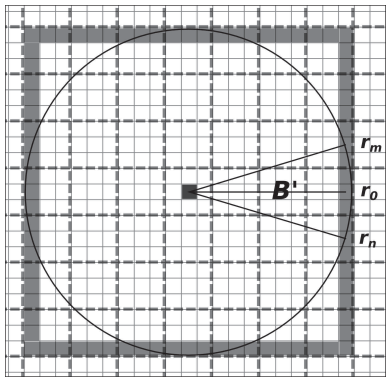


Figure 4.7: Block B' is loaded because of ray r_0, is evicted after r_m and loaded again for r_n.

4.5 *TiledVS* complexity

4.5.1 I/O complexity

TiledVS uses two external memory matrices: the elevation matrix *Elev* and the viewshed matrix V. Initially, *TiledVS* reads the terrain from the input file and initializes *Elev*. Then the two matrices are accessed during the viewshed computation and, finally, the matrix V is written to the output file.

From *RFVS*, the matrices' dimension is $(2\rho + 1) \times (2\rho + 1)$ and, supposing that the block's side is ω, each matrix will be divided into at most $\lceil \frac{2\rho+1}{\omega} \rceil^2$ blocks.

Assume that, for each matrix, it is created a *MemBlocks* with at least $2\left(\frac{\rho}{\omega} + 2\right)$ blocks, and that the block size is greater than the disk block transfer size.

In the first step, matrix *Elev* is initialized with the elevation values and is subdivided in blocks with $\omega \times \omega$ cells that are stored in external memory. Since the *MemBlocks* size is $2\left(\frac{\rho}{\omega} + 2\right)$ blocks, there are enough slots to store internally all the blocks in one matrix row. Thus, the *Elev* initialization, subdivision and writing is done step by step as follows: $\omega \times (2\rho + 1)$ cells, corresponding to $\lceil \frac{2\rho+1}{\omega} \rceil$ blocks, are read from the input file and are stored in *MemBlocks*, and then *MemBlocks* is swept, and each block stored in external memory. Thus, each step reads and writes $\lceil \frac{2\rho+1}{\omega} \rceil$ blocks from and to the external memory. Since the matrix *Elev* has $\lceil \frac{2\rho+1}{\omega} \rceil$ rows of blocks then the whole process reads and writes $\lceil \frac{2\rho+1}{\omega} \rceil^2$ blocks. Therefore, this first step does $\Theta(scan(\rho^2))$ I/O operations.

During the viewshed computation, as shown in Theorem 4.4.7, the blocks from the *Elev* matrix intersected by the first ray are loaded from the disk at most twice and all the other blocks are loaded once. Then, all $\lceil \frac{2\rho+1}{\omega} \rceil^2$ blocks of this matrix are loaded once and the $(\frac{\rho+1}{\omega} + 2)$ blocks intercepted by the first ray are loaded once more. And, at this step, the blocks of *Elev* do not need to be written back to disk because no value of this matrix has been changed. Therefore, for *Elev*, $\Theta((\rho/\omega)^2)$ blocks are read. For the viewshed matrix V, the blocks are accessed in the same order as for *Elev* and so the number of block reads for this matrix is the same as for *Elev*: $\Theta((\rho/\omega)^2)$. Additionally, the blocks of V may need to be written back to disk as the cells' visibility is computed. In the worst case when all blocks loaded in the internal memory are written back, there are $\Theta((\rho/\omega)^2)$ blocks written. In total, we have $\Theta((\rho/\omega)^2)$ I/O operations, or $\Theta(scan(\rho^2))$ as in the first step.

In the last step, matrix V is written in the disk. Again, since *MemBlocks* size is enough to store at least one row of blocks, this step can be done using a standard row-major sweep in V, leading to at most $\Theta((\rho/\omega)^2)$ blocks swapping which means $\Theta(scan(\rho^2))$ I/O operations.

Therefore, the I/O complexity of *TiledVS* is $\Theta(scan(\rho^2))$ which is equivalent to $\Theta(scan(n))$ considering a terrain with n cells and the radius of interest ρ big enough to cover the whole terrain.

Note that the *MemBlocks* size constraint is not too restrictive because it allows processing huge terrains in computers with very small internal memory. For example, with 512 MiB of RAM, it is possible to compute efficiently the viewshed for terrains with more than 300 GiB.

4.5.2 CPU complexity

The $(2\rho + 1) \times (2\rho + 1)$ square centered at the observer usually contains $(2\rho + 1)^2$ cells, with 8ρ perimeter cells. (The exception is that there are fewer cells when the observer is near the terrain border.) Since the algorithm works by shooting rays from the observer to the perimeter cells, it will shoot 8ρ rays, each one at most $\rho+1$ cells long. Therefore it will process at most $8\rho^2 + 8\rho$ cells. Since there are $(2\rho + 1)^2$ distinct cells, therefore on average, each cell will be processed $\frac{8\rho^2+8\rho}{(2\rho+1)^2} < 2$ times. That is, *TiledVS* is linear in the number of cells; for a terrain with n cells, it takes $\Theta(n)$ CPU time. Since each cell must be read, at least once, that is asymptotically optimal.

4.6 Experimental Results

TiledVS was implemented in C++ and compiled with g++ 4.3.4. It was compared against the most efficient recently published algorithms: *io-radial2, io-radial3* and *io-centrifugal*, proposed by Fishman et al. [2009], and *EMViewshed*, proposed by Andrade et al. [2011]. We also assessed its scalability, the influence of compressing the blocks and compared the *TiledMatrix* library with the Operating System (OS) Virtual Memory Manager (VMM). In all experiments, the running time includes the total time taken by the whole process, i.e.: loading the data, partitioning the grid, processing the terrain and writing the output file (the viewshed). Also, in all experiments, we chose the block sizes depending on the terrain dimensions and the memory size, such that MemBlocks was always at least as large as defined in Theorem 4.4.7, leading to efficient performances..

Our current results improve on [Ferreira et al., 2012b] by 30% to 40%, mostly because of the new fast lossless compression strategy. There are also smaller improvements such as using special buffer arrays for reading the input and writing the output.

4.6.1 Comparison with Fishman et al. algorithms

Lacking access to the programs used by Fishman et al. [2009], we compared our algorithm to their published results. We executed our algorithm using the same datasets and also a similar platform as the one used by those authors. That is, while they ran their experiments on HP 220 blade servers with an Intel Xeon 2.83GHz processor and a 5400RPM SATA hard drive, we used a computer with an Intel Core 2 Duo E7500 2.93GHz processor, 4GiB of RAM memory, and a 5400RPM SATA HD (Samsung HD103SI) which was rebooted with 512MiB RAM. The operational system used was Linux, Ubuntu 10.04 32 bits distribution. Although these two platforms are very similar, according to the benchmarks described in [Pasmark, 2013], our CPU is a little slower.

Our results are presented in Table 4.1, where we reproduce the values presented by Fishman et al. [2009] including an additional column *TiledVS* with the results from our algorithm. As it can be noticed, our algorithm is faster than the others in all situations and, in huge terrains, it is about 4 times faster (see the processing time for SRTM-region04). We also extended the table to include the processing time of our algorithm on very large terrains generated by interpolation of the Region02; see the last two rows.

The results from Table 4.1 are plotted in Figure 4.8, showing that the bigger the terrain, the better is our algorithm in comparison to the other methods.

Table 4.1: Running time (seconds) for *io-radial2* (io-r2), *io-radial3* (io-r3), *io-centrifugal* (io-cent) and *TiledVS* with 512MiB RAM.

Dataset	Terrain size			*io-r2*	*io-r3*	*io-cent*	*TiledVS*
	cols	rows	GiB				
Cumberlands	8 704	7 673	0.25	72	104	35	12
USA DEM 6	13 500	18 200	0.92	2 804	458	115	66
USA DEM 2	11 000	25 500	1.04	1 883	735	121	80
Washington	31 866	33 454	3.97	13 780	3 008	676	297
SRTM1-reg03	50 401	43 201	8.11	37 982	6 644	2 845	670
SRTM1-reg04	82 801	36 001	11.10	—	8 834	5 341	1 027
SRTM1-reg04	68 401	111 601	28.44	—	26 193	12 186	2 885
Reg02 interp.	150 000	91 000	50.85	—	—	—	5 198
Reg02 interp.	200 000	122 000	90.89	—	—	—	9 953

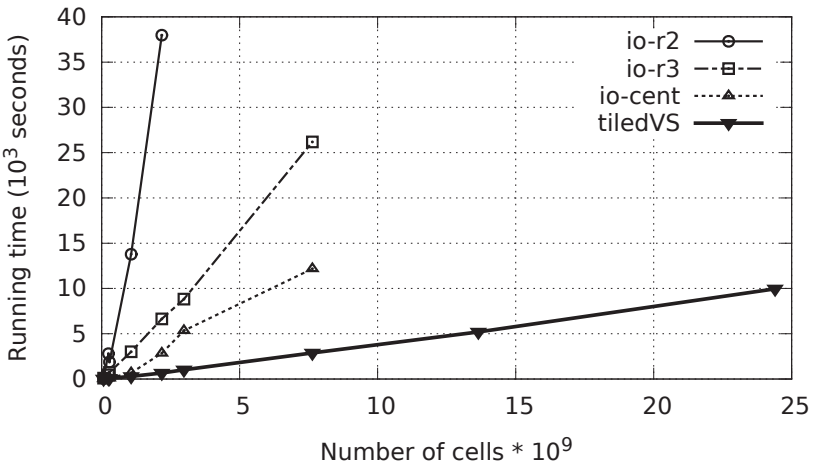


Figure 4.8: Comparing the running time of the four methods.

Figure 4.9 plots the number of cells processed per second versus the terrain size. Again, our algorithm presents a much better performance than the three others. All methods asymptotically process a constant number of cells per second, with ours being about 4 times faster than their fastest one.

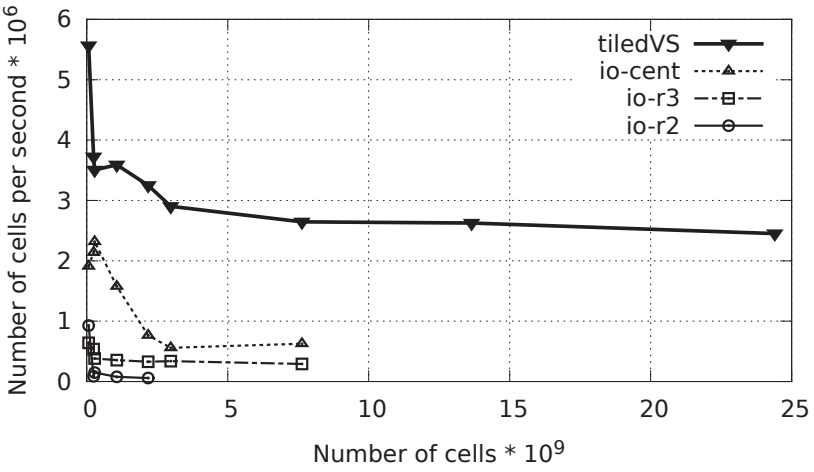


Figure 4.9: Number of cells processed per second by each method.

4.6.2 Comparison with *EMViewshed*

We also compared our new algorithm *TiledVS* against our previous one *EMViewshed* [Andrade et al., 2011]. We used some different datasets generated from two USA regions sampled at different resolutions using 2 bytes per elevation. The algorithms were executed five times on each terrain. The average time is presented in Table 4.2 and in Figure 4.10. Note that *TiledVS* is about 10 times faster than *EMViewshed*. In Table 4.2, the terrains were represented with 2 bytes per cell to match the *EMViewshed* implementation.

Table 4.2: Running time (seconds) for *EMViewshed* (EMVS) and *TiledVS* with 1024MiB RAM.

Terrain size cols × rows	GiB	*EMVS*	*TiledVS*
10 000 × 10 000	0.19	29	22
20 000 × 20 000	0.75	125	99
30 000 × 30 000	1.68	727	172
40 000 × 40 000	2.98	3 168	351
50 000 × 50 000	4.65	5 701	525
60 000 × 60 000	6.71	8 961	864

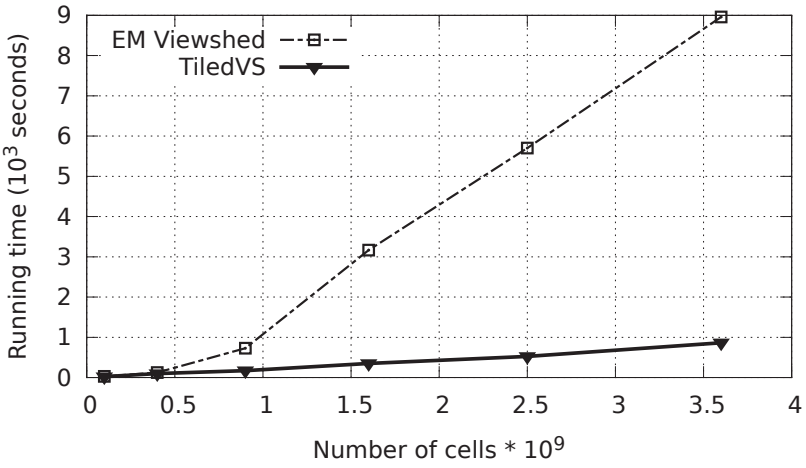


Figure 4.10: Running time of methods *EMViewshed* and *TiledVS*.

4.6.3 *TiledVS* scalability

Table 4.3 presents the *TiledVS* running time (in seconds) for different terrain sizes using small internal memory sizes: 128MiB and 512MiB. *TiledVS* scales to dataset sizes that are far too large to fit into internal memory. For example, it was able to compute the viewshed of a 40 GiB terrain, using only 128 MiB RAM, in 5740 seconds.

Table 4.3: *TiledVS* running time (seconds) with either 128MiB or 512MiB RAM.

Terrain size		RAM size	
cols×rows	GiB	128MiB	512MiB
37 000 × 37 000	5	369	339
52 000 × 52 000	10	862	721
73 500 × 73 500	20	2 287	1 735
104 000 × 104 000	40	5 740	3 548

4.6.4 The influence of compression

Several experiments concerning *TiledMatrix* performance have been conducted by Silveira et al. [2013], who showed how compressing the blocks reduces the amount of data that needs to be transferred to/from the disk, with only a small time penalty for

the compression. To test this on *TiledVS*, we tested *TiledMatrix* with compression enabled and then disabled — see Table 4.4 — with very favorable results. The terrain blocks compressed, on average, by a factor of 3. Also, the compression reduced, on average, the processing time by 37%.

Table 4.4: Running time (seconds) of *TiledVS* using *TiledMatrix* with compression enabled (w comp.) and disabled (w/o comp.).

Terrain size		*TiledVS*		*comp.*
cols × rows	GiB	*w comp.*	*w/o comp.*	*ratio*
10 000 × 10 000	0.37	26	33	2.7
20 000 × 20 000	1.49	109	155	2.8
30 000 × 30 000	3.36	249	345	3.0
40 000 × 40 000	5.96	454	638	3.1

4.6.5 *TiledMatrix* compared against the OS's Virtual Memory system

Since our method uses a straightforward implementation of the LRU caching strategy also used by many operating systems (OSs) such as Linux, one might suspect that similar running times could be obtained by reorganizing the data in blocks (as shown on Figure 4.4) and allowing the OS Virtual Memory Manager (*VMM*) to manage the block swapping. We tested this with an implementation (named *VMM_VS*) that subdivides and reorganizes the terrain matrix but does not manage the data accesses, letting the Linux *VMM* do that.

First, the terrain was subdivided in blocks with 1000×1000 cells and the execution time was compared using *VMM_VS* and *TiledVS* for a terrain with 30000^2 cells. In this test, *VMM_VS* processed the terrain in 3480 seconds while *TiledVS* executed in 249 seconds.

Considering that each *VMM* page has 4096 bytes, each block with 1000×1000 cells uses 977 different pages. Therefore, if the operating system loads a page containing a cell, there is no guarantee that all pages of this block will be loaded. On the other hand, to verify the *VMM_VS* performance when each block requires only one *VMM* page, the algorithms were tested using blocks with 32×32 cells, that is, each block had 4096 bytes. Also, the matrix was aligned to the *VMM* pages, such that each page contained exactly one entire block. In this case, *VMM_VS*

was faster and executed in 1203 seconds while the *TiledVS* execution time was 5338 seconds.

Silveira et al. [2013] showed that *TiledMatrix*'s performance decreases with small blocks, because transferring small bunches of data does not amortize the disk seek and latency times. When the block size is increased to 1000^2 cells, *TiledVS*'s performance improves, but the performance of *VMM_ VS* becomes worse since each block requires several pages, which are loaded separately by the *VMM*.

Fishman et al. [2009] obtained a similar result, concluding that, "one of our findings is that relying purely on *VMM*, even for a theoretically I/O-efficient data access, is slow", and "by telling the algorithms explicitly when to load a memory-size block (and not using the *VMM*), we obtained significant speedups (without sacrificing I/O-efficiency for the levels of caching of which the algorithm remained oblivious, and without sacrificing CPU-efficiency)."

4.7 Conclusion and future work

We have presented *TiledVS*, a new algorithm for viewshed computation on huge grid terrains stored in external memory, based on an adaptation of the internal memory algorithm *RFVS* [Franklin and Ray, 1994].

TiledVS uses a special data structure to manage the data transfer between internal and external memories, thereby reducing the number of I/O operations. For terrains with n cells, its I/O complexity is $\Theta(scan(n))$.

TiledVS was compared against the most recent and most efficient algorithms described in the literature, and shown to be faster than all the others, by about a factor of 4. This improvement is significant because processing huge terrains can take hours. Additionally, *TiledVS* is also much simpler.

TiledVS is able to process huge terrains using small amounts of internal memory (RAM). For example, the viewshed of a 40 GiB terrain GiB was computed in 5740 seconds, using 128 MiB RAM.

There are many possible avenues for future research, the most obvious to exploit parallelism, such as with Graphics Processing Units (GPUs). In order to make its results more widely useful, this paper has considered only CPUs. However, a roadmap for utilizing parallelism might proceed as follows. The initial step might be to use multi-core multi-threaded shared-memory Intel CPUs. One machine available to us allows 32 parallel threads by using dual 8 core Intel Xeon E5-2687W CPUs. OpenMP is an appropriate API. However this machine has so much memory

(128GB) that external algorithms are unnecessary. The next step would be to use the NVIDIA Tesla K20x GPU accelerator mentioned earlier, which has 2688 CUDA cores. Although each core has only about one tenth of the computing power of one Intel thread, there are a lot of them. The problem is that efficiently using them is not yet a totally solved problem. Nevertheless, we are pursuing this approach.

Our algorithm source code (in C++) is available, as open source code distributed under a Creative Common GNU GPL license, at *http://www.dpi.ufv.br/∼marcus/TiledVS.htm*

5. A parallel sweep line algorithm for visibility computation[1]

Abstract

Visibility map (or viewshed) computation is required for many GIS applications. As terrain data continue to become available at higher resolutions, there is a need for faster architectures and algorithms. Since the main improvements on modern processors come from multi-core architectures, parallel programming provides a promising means for developing faster algorithms. In this paper, we describe a new parallel algorithm, based on the model proposed by Van Kreveld [1996]. Our algorithm uses the shared memory model, which is relatively cheap and supported by most current processors. Experiments have shown that, with 16 parallel cores, it was up to 12 times faster than the serial implementation.

5.1 Introduction

An important group of Geographical Information Science (GIS) applications on terrains concerns visibility, i.e., determining the set of points on the terrain that are visible from some particular observer, which is usually located at some height above the terrain. This set of points is known as *viewshed* [Franklin and Ray, 1994] and its applications range from visual nuisance abatement to radio transmitter siting and surveillance, such as minimizing the number of cellular phone towers required to cover a region [Ben-Shimol et al., 2007], optimizing the number and position of guards to cover a region [Magalhães et al., 2011], analysing the influences on property prices in an urban environment [Lake et al., 1998] and optimizing path planning [Lee and Stucky, 1998]. Other applications are presented in Champion and Lavery [2002].

Since visibility computation is quite compute-intensive, the recent increase in the volume of high resolution terrestrial data brings a need for faster platforms and algorithms. Considering that some factors (such as processor sizes, transmission

[1]Este capítulo apresenta o artigo "*A Parallel Sweep Line Algorithm for Visibility Computation*", que recebeu o prêmio de melhor artigo no GeoInfo 2013 (*XIV Brazilian Symposium on Geoinformatics*) [Ferreira et al., 2013].

speeds and economic limitations) create practical limits and difficulties for building faster serial computers, the parallel computing paradigm has become a promising alternative for such computing-intensive applications [Barney et al., 2010]. Also, parallel architectures have recently become widely available at low costs. Thus, they have been applied in many domains of engineering and scientific computing, allowing researchers to solve bigger problems in feasible amounts of time.

In this paper, we present a new parallel algorithm for computing the viewshed of a given observer on a terrain. Our parallel algorithm is based on the (serial) sweep line algorithm firstly proposed by Van Kreveld [1996], which is described in Section 5.2.3.3. Comparing to the original algorithm, our new algorithm achieved speedup of up to 12 times using 16 parallel cores, and up to 3.9 times using four parallel cores.

5.2 Related work

5.2.1 Terrain representation

In what follows, our region of interest is small compared to the radius of the earth, thus, for this discussion the earth can be considered to be flat.

A *terrain* τ is a $2\frac{1}{2}$ dimensional surface where any vertical line intersects τ in at most one point. The terrain is usually represented approximately either by a *triangulated irregular network (TIN)* or a *regular square grid* (RSG) [Li et al., 2005]. A TIN is a partition of the surface into planar triangles, i.e., a piecewise linear triangular spline, where the elevation of a point p is a bilinear interpolation of the elevations of the vertices of the triangle containing the projection of p. On the other hand, a RSG is simply a matrix storing the elevations of regularly spaced positions or posts, where the spacing may be either a constant number of meters or a constant angle in latitude and longitude. In this paper, we will use the RSG representation because of its simpler data structure, ease of analysis, and ability to represent discontinuities (cliffs) more naturally. Finally, there is a huge amount of data available as RSGs.

5.2.2 The viewshed problem

An *observer* is a point in space from where other points (the *targets*) will be visualized. Both the observer and the targets can be at given heights above τ, respectively indicated by h_o and h_t. We often assume that the observer can see only targets that

are closer than the *radius of interest*, ρ. We say that all cells whose distance from O is at most ρ form the *region of interest* of O. A target T is visible from O if and only if the distance of T from O is, at most, ρ and the straight line, the *line of sight*, from O to T is always strictly above τ; see Figure 5.1.

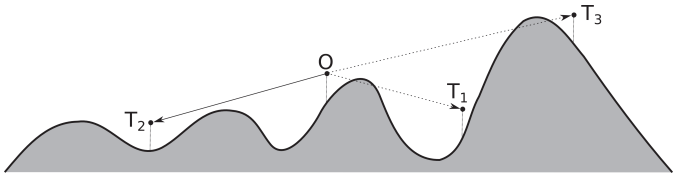


Figure 5.1: Targets' visibility: T_1 and T_3 are not visible but T_2 is.

The *viewshed* of O is the set of all terrain points vertically below targets that can be seen by O; formally,

$$viewshed(O) = \{p \in \tau \mid \text{the target above } p \text{ is visible from } O\}$$

with ρ implicit. The viewshed representation is a square $(2\rho + 1) \times (2\rho + 1)$ bitmap with the observer at the center.

Theoretically, determining whether a target T is visible from O requires verifying all points in the line of sight connecting O to T. But since τ is represented with a finite resolution, only points close to the rasterized line segment connecting the projections of O and T onto the horizontal plane will be verified. Which points those might be, is one difference between competing algorithms, as the ones we will describe in Section 5.2.3. The visibility depends on the line segment rasterization method used, see Figure 5.2, and how the elevation is interpolated on those cells where the segment does not intersect the cell center.

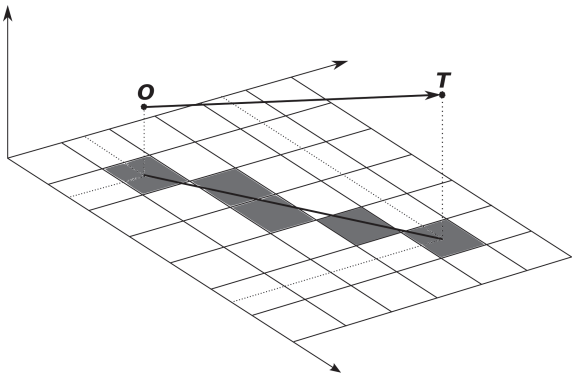


Figure 5.2: The rasterization of the line of sight projection.

The visibility of a target above a cell c_t can be determined by checking the slope of the line connecting O and T and the cells' elevation on the rasterized segment.

More precisely, suppose the segment is composed of cells $c_0, c_1, \cdots, c_t$ where c_0 and c_t correspond to the projections of O and T respectively. Let α_i be the slope of the line connecting O to c_i, that is,

$$\alpha_i = \frac{\zeta(c_i) - (\zeta(c_0) + h_o)}{dist(c_0, c_i)} \tag{5.1}$$

where $\zeta(c_0)$ and $\zeta(c_i)$ are, respectively, the elevation of cells c_0 and c_i and $dist(c_0, c_i)$ is the 'distance' (in number of cells) between these two cells. The target on c_t is visible if and only if the slope $\frac{\zeta(c_t)+h_t-(\zeta(c_0)+h_o)}{dist(c_0,c_t)}$ is greater than α_i for all $0 < i < t$. If yes, the corresponding cell in the viewshed matrix is set to 1; otherwise, to 0.

5.2.3 Viewshed algorithms

Different terrain representations call for different algorithms. A TIN can be processed by the algorithms proposed by Cole and Sharir [1989] and Floriani and Magillo [2003]. For a RSG, we can point out [Van Kreveld, 1996] and *RFVS* [Franklin and Ray, 1994], two very efficient algorithms. Another option for processing RSGs is the well-known R3 algorithm [Shapira, 1990]. Although this one is not as efficient as the other two, it has higher accuracy and may be suitable for small datasets.

These three algorithms differ from each other not only on their efficiency, but also on the visibility models adopted. For instance, R3 and Van Kreveld's algorithms use a center-of-cell to center-of-cell visibility, that is, a cell c is visible if and only if the ray connecting the observer (in the center of its cell) to the center of c does not intersect a cell blocking c. On the other hand, *RFVS* uses a less restrictive approach where a cell c may be considered visible if its center is not visible but another part of c is.

Therefore, the viewsheds obtained by these methods may be different. Without knowing the application and having a model for the terrain's elevation between the known points, it is impossible to say which one is better. Some applications may prefer a viewshed biased in one direction or the other, while others may want to minimize error computed under some formal terrain model. For instance, since Van Kreveld's algorithm presents a great tradeoff between efficiency and accuracy [Fishman et al., 2009], it may be indicated for applications that require a high degree of accuracy. On the other hand, if efficiency is more important than accuracy, the *RFVS* algorithm could be preferred.

Considering that each one of these algorithms might be suitable for different applications, we will describe them briefly in the next sections.

5.2.3.1 R3 algorithm

The R3 algorithm provides a straightforward method of determining the viewshed of a given observer O with a radius of interest ρ. Although it is considered to have great accuracy [Franklin et al., 1994], this algorithm runs in $\Theta(n^{\frac{3}{2}})$, where $n = \Theta(\rho^2)$. It works as follows: for each cell c inside the observer's region of interest, it uses the digital differential analyzer (DDA) [Maćiorov, 1964] to determine which cells the line of sight (from O to the center of c) intersects. Then, the visibility of c is determined by calculating the slope of all cells intersected by this line of sight, as described in Section 5.2.2. In this process, many rules to interpolate the elevation between adjacent posts may be used, such as average, linear, or nearest neighbour interpolations.

5.2.3.2 *RFVS* algorithm

RFVS [Franklin and Ray, 1994] is a fast approximation algorithm that runs in $\Theta(n)$. It computes the terrain cells' visibility along rays (line segments) connecting the observer (in the center of a cell) to the center of all cells in the boundary of a square of side $2\rho + 1$ centered at the observer (see Figure 5.3a). In each column, it tests the line of sight against the closest cell. Although a square was chosen for implementation simplicity, other shapes such as a circle would also work.

RFVS creates a ray connecting the observer to a cell on the boundary of this square, and then rotates it counter-clockwise around the observer to follow along the boundary cells (see Figure 5.3a). The visibility of each ray's cells is determined by walking along the segment, which is rasterized following Bresenham [1965]. Suppose the segment is composed of cells $c_0, c_1, \cdots, c_k$ where c_0 is the observer's cell and c_k is a cell in the square boundary. Let α_i be the slope of the line connecting the observer to c_i determined according to Equation (5.1) in Section 5.2.2. Let μ be the highest slope seen so far when processing c_i, i.e., $\mu = \max\{\alpha_1, \alpha_2, \cdots, \alpha_{i-1}\}$. The target above c_i is visible if and only if the slope $(\zeta(c_i) + h_t - (\zeta(c_0) + h_o))\,/dist(c_0, c_i)$ is greater than μ. If yes, the corresponding cell in the viewshed matrix is set to 1; otherwise, to 0. Also, if $\alpha_i > \mu$ then μ is updated to α_i. We say that a cell c_i blocks the visibility of the target above c_j if c_i belongs to the segment $\overline{c_0 c_j}$ and α_i is greater or equal to the slope of the line connecting the observer to the target above c_j.

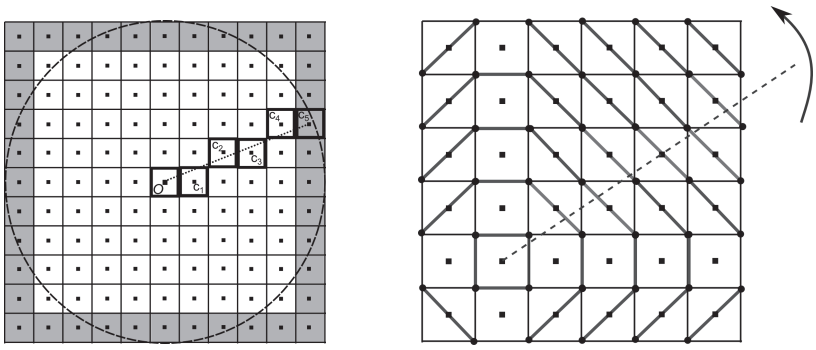
5.2.3.3 Van Kreveld's algorithm

Van Kreveld's algorithm [Van Kreveld, 1996] is another fast viewshed algorithm. According to Zhao et al. [2013], its accuracy is equivalent to the R3 algorithm's, while running in $\Theta(n\ log\ n)$. Its basic idea is to rotate a sweep line around the observer and compute the visibility of each cell when the sweep line passes over its center (see Figure 5.3b). For that, it maintains a balanced binary tree (the *agenda*) that stores the slope of all cells currently being intersected by the sweep line, keyed by their distance from the observer. When this sweep line passes over the center of a cell c, the *agenda* is searched to check c's visibility. More specifically, this algorithm works as follows:

For each cell, it defines three types of events: *enter*, *center*, and *exit* events to indicate, respectively, when the sweep line starts to intersect a cell, passes over the cell center and stops to intersect a cell. The algorithm creates a list E containing these three types of events for all cells inside the region of interest. The events are then sorted according to their azimuth angle.

To compute the viewshed, the algorithm sweeps the list E and for each event it decides what to do depending on the type of the event:

- If it is an *enter* event, the cell is inserted into the *agenda*.
- If it is an *center* event of cell c, the *agenda* is searched to check if it contains any cell that lies closer to the observer than c and has slope greater or equal to the slope of the line of sight to c; if yes, then c is not visible, otherwise it is.
- If it is an *exit* event, the cell is removed from the *agenda*.



(a) *RFVS* (b) Van Kreveld

Figure 5.3: Viewshed algorithms.

5.2.3.4 Parallel viewshed algorithms

Parallel computing has become a mainstream of scientific computing and recently some parallel algorithms for viewshed computation have been proposed. Zhao et al. [2013] proposed a parallel implementation of the R3 algorithm using Graphics Processing Units (GPUs). The *RFVS* algorithm was also adapted for parallel processing on GPUs by Osterman [2012]. Chao et al. [2011] proposed a different approach for parallel viewshed computation using a GPU, where the algorithm runs entirely within the GPUs visualization pipeline used to render 3D terrains. Mills et al. [1992]; Teng et al. [1993]; Gao et al. [2011]; Strnad [2011] Zhao et al. [2013] also discuss other parallel approaches.

However, we have not found any previous work proposing a parallel implementation of Van Kreveld's algorithm. In fact, Zhao et al. [2013] stated that "a high degree of sequential dependencies in Van Kreveld's algorithm makes it less suitable to exploit parallelism". In Section 5.3 we show how we have overcome this difficulty and describe our parallel implementation of Van Kreveld's sweep line algorithm.

5.2.4 Parallel programming models

There are several parallel programming models, such as distributed memory/message passing, shared memory, hybrid models, among others [Barney et al., 2010]. In this work, we used the shared memory model, where the main program creates a certain number of tasks (*threads*) that can be scheduled and carried out by the operating system concurrently. Each thread has local data, but the main program and all threads share a common address space, which can be read from and written to asynchronously. In order to control the concurrent access to shared resources, some mechanisms such as locks and semaphores may be used. An advantage of this model is that there is no need to specify explicitly the communication between threads, simplifying the development of parallel applications.

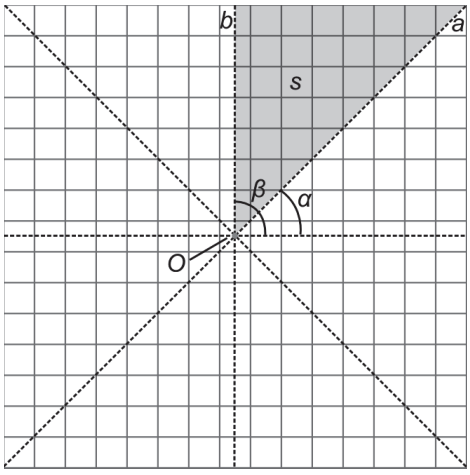
For the implementation of the algorithm, we used OpenMP (*Open Multi-Processing*) [Dagum and Menon, 1998], a portable parallel programming API designed for shared memory architectures. It is available for C++ and Fortran programming languages and consists of a set of compiler directives that can be added to serial programs to influence their run-time behaviour, making them parallel.

5.3 Our parallel sweep line algorithm

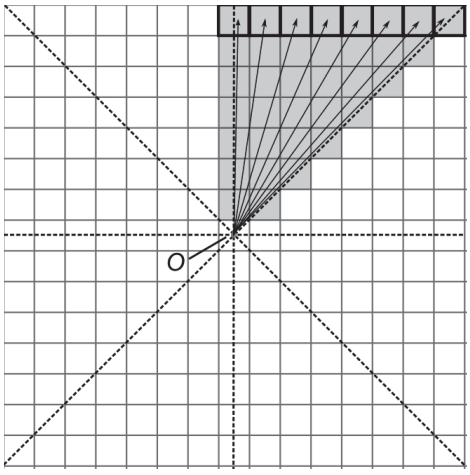
As described in Section 5.2.3.3, Van Kreveld's algorithm needs information about the cells intersected by the sweep line. It maintains these information by processing the *enter* and *exit* events to keep the *agenda* up to date as the sweep line rotates. Therefore, processing a *center* event is dependent upon all earlier *enter* and *exit* events.

In order to design a parallel implementation of this algorithm, this dependency had to be eliminated. We did that by subdividing the observer's region of interest into S sectors around the observer, O (see Figure 5.4a, where $S = 8$). Our idea is to process each one of these sectors independently using Van Kreveld's sweep line algorithm, such that it can be done in parallel.

More specifically, consider sector s defined by the interval $[\alpha, \beta)$, where α and β are azimuth angles. Let a and b be the line segments connecting O to the perimeter of its region of interest, with azimuth angles α and β, respectively (see Figure 5.4a). To process s, the algorithm creates rays connecting O to all cells on the perimeter of the region of interest that are between (or intersected by) a and b (see Figure 5.4b). These rays are rasterized using the DDA method [Maćiorov, 1964] and the events related to the intersected cells are inserted into s's own list of events, E_s. Since the grid cells are convex, this process inserts into E_s the events for all cells inside s or intersected by a or b. The inserted cells are shown in Figure 5.4b.



(a) Subdivision of the region of interest and the sector s, defined by the interval $[\alpha, \beta)$.



(b) The cells in the perimeter of the region of interest, the rays used to determine which cells are intersected by s and the cells inserted into E_s (shaded cells).

Figure 5.4: Sector definition.

Then, the algorithm sorts E_s by the events' azimuth angles and sweeps it in the same manner as Van Kreveld's algorithm. Note that, because we have distributed the events into different lists and each list contains all events that are relevant to its sector, each sector may be processed independently, each one with its own *agenda*. This allows a straightforward parallelization of such processing. Also, note that the events of a cell may be included in more than one sector's event list and therefore some cells may be processed twice. But that is not a problem, since this will happen only to a few cells, and it will not affect the resulting viewshed.

It is also important to note that our algorithm might be faster than the original one even with non-parallel architectures. For instance, we achieved up to 20% speedup using only one processor (see Section 5.4). This happens because both implementations have to sort their lists of events and, while the original (serial) algorithm sorts a list of size n, our algorithm sorts S lists of size about $\frac{n}{S}$. Since sorting can be done in $\Theta(n\ logn)$, the latter one is faster. In practice, we empirically concluded that, for a computer with N cores, using $S > N$ achieved better results than using $S = N$. This will be further discussed in Section 5.4, as long with our experimental results.

5.4 Experimental results

We implemented our algorithm in C++ using OpenMP. We also implemented the original (serial) Van Kreveld's algorithm in C++. Both algorithms were compiled with g++ 4.6.4 and optimization level -O3. Our experimental platform was a Dual Intel Xeon E5-2687 3.1GHz 8 core. The operational system was Ubuntu 12.04 LTS, Linux 3.5 Kernel.

The tests were done using six different terrains from SRTM datasets and, in all experiments, the observer was sited in the center of the terrain, with $h_O = 100$ meters and $h_T = 0$. The radius of interest, ρ, was set to be large enough to cover the whole terrain.

Another important parameter for our program is the number of sectors S into which the region of interest will be subdivided. Changing the number of sectors may significantly modify the algorithm's performance. Empirically, we determined that good results are achieved when the region is subdivided such that each sector contained about 40 cells from the perimeter of the region of interest, so we adopted that strategy. Other strategies for choosing the number of sectors should be further investigated and it could be an interesting topic for future work.

To evaluate our algorithm's performance, we compared it to the original (serial) algorithm. We ran several experiments limiting the number of parallel threads to the following values: 16, 8, 4, 2 and 1. The results are given in Table 5.1 and plotted in Figure 5.5a, where the times are given in seconds and refer just to the time needed to compute the viewshed. That is, we excluded the time taken to load the terrain data and to write the computed viewshed into disk, since it was insignificant (less than 1% of the total time in all cases). Also, the time represents the average time for five different runs of the same experiment.

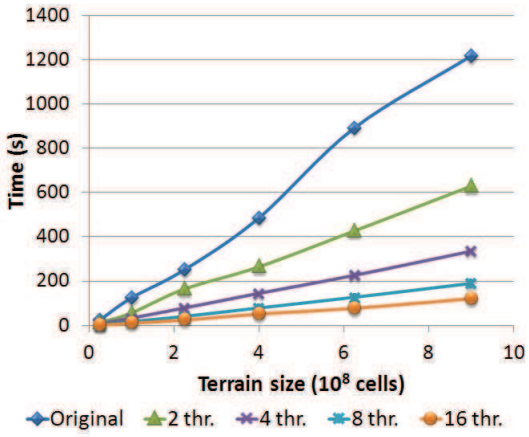
Table 5.1: Running times (in seconds) for the serial algorithm and the parallel algorithm with different number of threads.

Terrain size		Serial Alg.	Parallel Alg. Number of threads				
# cells	GiB		16	8	4	2	1
$5\,000^2$	0.09	24	2	4	7	13	23
$10\,000^2$	0.37	125	11	17	32	57	105
$15\,000^2$	0.83	252	25	41	78	165	246
$20\,000^2$	1.49	485	52	79	144	265	464
$25\,000^2$	2.33	891	78	128	226	427	740
$30\,000^2$	3.35	1 216	121	191	335	629	1 100

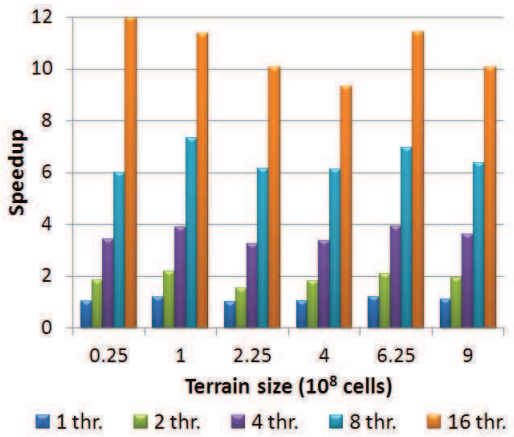
Table 5.2: Speedups achieved by our parallel algorithm, with different number of threads.

Terrain size		Parallel Alg. Number of threads				
# cells	GiB	16	8	4	2	1
$5\,000^2$	0.09	12.00	6.00	3.43	1.85	1.04
$10\,000^2$	0.37	11.36	7.35	3.91	2.19	1.19
$15\,000^2$	0.83	10.08	6.15	3.23	1.53	1.02
$20\,000^2$	1.49	9.33	6.14	3.37	1.83	1.05
$25\,000^2$	2.33	11.42	6.96	3.94	2.09	1.20
$30\,000^2$	3.35	10.05	6.37	3.63	1.93	1.11

We calculated our algorithm speedup compared to the original algorithm. The speedups are presented in Table 5.2 and plotted in Figure 5.5b. Our algorithm has shown very good performance, achieving up to 12 times speedup, when running 16 concurrent threads. It is also important to notice that with only four threads we achieved a speedup of 3.9 times for two terrains and more than 3 times for all



(a) Running times (in seconds) for the serial algorithm and the parallel algorithm with different number of threads



(b) Speedups achieved by our parallel algorithm, with different number of threads.

Figure 5.5: Experimental results.

other terrains. Considering that processors with four cores have become usual and relatively cheap nowadays, these improvements may be useful for real users with regular computers. Finally, as discussed in Section 5.3, the experiments with only one thread show that our strategy can be faster than the original program even with serial architectures.

5.5 Conclusions and future work

We proposed a new parallel sweep line algorithm for viewshed computation, based on an adaptation of Van Kreveld's algorithm. Compared to the original (serial) algorithm, we achieved speedup of up to 12 times with 16 concurrent threads, and up to 3.9 times using four threads. Even with a single thread, our algorithm was better than the original one, running up to 20% faster.

Compared to other parallel viewshed algorithms, ours seems to be the only to use Van Kreveld's model, which presents a great tradeoff between efficiency and accuracy [Fishman et al., 2009]. Also, most of them use other parallel models, such as distributed memory/message passing and general purpose GPU programming. On the other hand, ours uses the shared memory model, which is simpler, requires cheaper architectures and is supported by most current computers.

As future work, we can point out the development of other strategies for defining S, the number of sectors into which the region of interest is subdivided. We also intend to develop another adaptation of Van Kreveld's model using GPU

programming. Since GPU architectures are much more complex, this will not be a straightforward adaptation.

6. Conclusões gerais e trabalhos futuros

Neste trabalho foram apresentados dois algoritmos para cálculo de *viewshed* em grandes terrenos representados por grades regulares: um especialmente projetado para ser eficiente em terrenos maiores do que a memória interna disponível, e outro capaz de utilizar arquiteturas paralelas de forma eficiente. Como mostraram os resultados experimentais, ambos são mais eficientes do que algoritmos propostos anteriormente em literatura. Os ganhos (*speedups*) obtidos por estes dois algoritmos podem ser importantes para usuários de aplicações de visibilidade de duas diferentes maneiras: primeiramente, com um algoritmo mais rápido é possível avaliar regiões maiores em tempos razoáveis; além disso, também é possível avaliar uma determinada região com dados em alta resolução, gerando resultados cada vez mais precisos sem necessariamente aumentar o tempo de processamento.

Nos Capítulos de 2 a 4 foi apresentado o algoritmo para memória externa *TiledVS*. Este algoritmo consiste em uma adaptação do algoritmo *RFVS*, proposto por Franklin and Ray [1994]. Para diminuir o número de operações de E/S realizadas, é utilizada a biblioteca especial *TiledMatrix* [Silveira et al., 2013], que controla os acessos às matrizes armazenadas em memória externa de forma eficiente. Para isso, esta biblioteca reorganiza os dados da matriz em memória externa subdividindo-a em blocos retangulares que são armazenados de forma contígua. A memória interna é então gerenciada como uma memória *cache* gerenciada pela aplicação, que carrega estes blocos à medida que são requisitados acessos a suas células, descarregando, quando necessário, os blocos que estão a mais tempo sem ser acessados. Além disso, na versão mais recente deste algoritmo (descrita no Capítulo 4), é utilizada também uma estratégia de compressão rápida dos blocos, o que conseguiu diminuir os tempos de processamento em até 42%. Os resultados experimentais mostraram que este novo algoritmo é mais de 4 vezes mais rápido do que todos os demais algoritmos encontrados em literatura.

Com relação ao algoritmo *TiledVS*, propõe-se acelerar ainda mais o processamento através de algoritmos paralelos, possivelmente com a utilização de placas gráficas (GPUs). Uma primeira abordagem seria a paralelização do algoritmo de compressão utilizado pela *TiledMatrix*, para que esta compressão seja feita de forma ainda mais rápida. A segunda ideia seria a paralelização do processo de rotação da linha de visão utilizado pelo algoritmo *RFVS*. Esta segunda abordagem representa

uma tarefa bem mais complexa do que a primeira, uma vez que combinar processamento em memória externa com processamento paralelo não é trivial. Porém, como Zhao et al. [2013] mostraram recentemente, é possível alcançar bons resultados.

No Capítulo 5 foi proposto outro algoritmo para cálculo de *viewshed*, neste caso baseado em arquiteturas paralelas. O novo algoritmo utiliza o modelo de programação paralela de memória compartilhada (*OpenMP*), disponível na maioria das arquiteturas atuais, mesmo em computadores pessoais relativamente simples. O novo algoritmo subdivide o terreno em diversos setores em torno do observador e processa cada um destes setores de forma independente. Conforme mostrado pelos resultados experimentais, usando um computador com 4 *cores* pode-se obter resultados até 4 vezes mais rápidos do que o algoritmo convencional (isto é, sequencial). Além disso, com um computador com maior capacidade (por exemplo, com 16 *cores*), é possível obter processamentos até 12 vezes mais rápidos.

A intenção como trabalho futuro é adaptar este algoritmo utilizando programação em GPUs. Porém, esta adaptação não poderá ser feita forma direta, uma vez que a arquitetura das GPUs apresenta diversas diferenças com relação à arquitetura de um processador *multi-core*. Por exemplo, dentre as dificuldades que serão encontradas ao fazer esta adaptação, podemos citar o alto custo das operações de cópia de dados em uma GPU e a impossibilidade de utilizar ponteiros para implementar a árvore binária balanceada utilizada pelo algoritmo de Van Kreveld. Assim, esta tarefa exigirá um estudo mais detalhado da arquitetura das GPUs, que são mais complexas e contém diversas camadas de memória com diferentes características.

Referências Bibliográficas

Aggarwal, A. and Vitter, J. S. (1988). The input/output complexity of sorting and related problems. *Communications of the ACM*, 31(9):1116–1127.

Andrade, M. V. A., Magalhães, S. V. G., Magalhães, M. A., Franklin, W. R., and Cutler, B. M. (2011). Efficient viewshed computation on terrain in external memory. *Geoinformatica*, 15(2):381–397.

Barney, B. et al. (2010). Introduction to parallel computing. *Lawrence Livermore National Laboratory*, 6(13):10.

Ben-Moshe, B., Mitchell, J. S. B., Katz, M. J., and Nir, Y. (2002). Visibility preserving terrain simplification — an experimental study. In *Proceedings of ACM Symposium of Computational Geometry*, pages 303–311, Barcelona, Spain.

Ben-Shimol, Y., Ben-Moshe, B., Ben-Yehezkel, Y., Dvir, A., and Segal, M. (2007). Automated antenna positioning algorithms for wireless fixed-access networks. *Journal of Heuristics*, 13(3):243–263.

Bespamyatnikh, S., Chen, Z., Wang, K., and Zhu, B. (2001). On the planar two-watchtower problem. In *7th International Computing and Combinatorics Conference*, pages 121–130. Springer-Verlag London.

Bresenham, J. E. (1965). An incremental algorithm for digital plotting. *IBM Systems Journal*, 4(1):25–30.

Câmara, G., Davis, C., and Monteiro, A. M. (2001). *Introdução à Ciência da Geoinformação*. Instituto de Pesquisa Espacial- INPE, São Jose dos Campos, SP, Brasil,Disponivel em: http://www.dpi.inpe.br/gilberto/livro/introd/ — Acessado em 16 Novembro 2013.

Camp, R. J., Sinton, D. T., and Knight, R. L. (1997). Viewsheds: A complementary management approach to buffer zones. *Wildlife Society Bulletin*, 25(3):612–615.

Champion, D. C. and Lavery, J. E. (2002). Line of sight in natural terrain determined by L_1-spline and conventional methods. In *23rd Army Science Conference*, Orlando, Florida.

Chao, F., Chongjun, Y., Zhuo, C., Xiaojing, Y., and Hantao, G. (2011). Parallel algorithm for viewshed analysis on a modern GPU. *International Journal of Digital Earth*, 4(6):471–486.

Cole, R. and Sharir, M. (1989). Visibility problems for polyhedral terrains. *Journal of Symbolic Computation*, 7(1):11–30.

Collet, Y. (2012). Extremely fast compression algorithm. http://code.google.com/p/lz4/.

Dagum, L. and Menon, R. (1998). Openmp: an industry standard api for shared-memory programming. *Computational Science & Engineering, IEEE*, 5(1):46–55.

Dementiev, R., Kettner, L., and Sanders, P. (2005). Stxxl : Standard template library for xxl data sets. Technical report, Fakultät für Informatik, Universität Karlsruhe. http://stxxl.sourceforge.net/ — Acessado em 01 Dezembro 2013).

Eidenbenz, S. (2002). Approximation algorithms for terrain guarding. *Information Processing Letters*, 82(2):99–105.

Felgueiras, C. A. (2001). Modelagem numérica de terreno. In G. Câmara, C. Davis, A. M. V. M., editor, *Introdução à Ciência da Geoinformação*, volume 1. INPE.

Ferreira, C. R., Andrade, M. V., Magalhaes, S. V., and Franklin, W. R. (2014). A fast external memory algorithm for computing visibility on grid terrains. *Submitted for publication. ACM Transactions on Spatial Algorithms and Systems.*

Ferreira, C. R., Andrade, M. V. A., Magalhães, S. V. G., and Pompermayer, A. M. (2012a). Uma abordagem eficiente para o cálculo de viewshed em terrenos armazenados em memória externa. In *XXXIX Seminário Integrado de Software e Hardware (SEMISH 2012).*

Ferreira, C. R., Andrade, M. V. A., Magalhães, S. V. G., Franklin, W. R., and Pena, G. C. (2013). A parallel sweep line algorithm for visibility computation. In *GeoInfo 2013 - XIV Brazilian Symposium on Geoinformatics*, pages 85–96.

Ferreira, C. R., Magalhães, S. V. G., Andrade, M. V. A., Franklin, W. R., and Pompermayer, A. M. (2012b). More efficient terrain viewshed computation on massive datasets using external memory. In *Proceedings of the 20th International Conference on Advances in Geographic Information Systems*, SIGSPATIAL '12, pages 494–497, New York, NY, USA. ACM.

Fisher, P. F. (1993). Algorithm and implementation uncertainty in viewshed analysis. *International Journal of Geographical Information Science*, 7(4):331–347.

Fishman, J., Haverkort, H. J., and Toma, L. (2009). Improved visibility computation on massive grid terrains. In Wolfson, O., Agrawal, D., and Lu, C.-T., editors, *GIS*, pages 121–130. ACM.

Floriani, L. D. and Magillo, P. (2003). Algorithms for visibility computation on terrains: a survey. *Environment and Planning B: Planning and Design*, 30(5):709–728.

Floriani, L. D., Puppo, E., and Magillo, P. (1999). Applications of computational geometry to geographic information systems. In J. R. Sack, J. U., editor, *Handbook of Computational Geometry*, pages 303–311. Elsevier Science.

Franklin, W. R. and Ray, C. (1994). Higher is not necessarily better: Visibility algorithms and experiments. In Waugh, T. C. and Healey, R. G., editors, *Advances in GIS Research: Sixth International Symposium on Spatial Data Handling*, pages 751–770, Edinburgh. Taylor & Francis.

Franklin, W. R., Ray, C. K., Randolph, P. W., Clark, L., Ray, K., and Mehta, P. S. (1994). Geometric algorithms for siting of air defense missile batteries.

Franklin, W. R. and Vogt, C. (2006). Tradeoffs when multiple observer siting on large terrain cells. In Riedl, A., Kainz, W., and Elmes, G., editors, *Progress in Spatial Data Handling: 12th international symposium on spatial data handling*, pages 845–861, Vienna. Springer. ISBN 978-3-540-35588-5.

Gao, Y., Yu, H., Liu, Y., Liu, Y., Liu, M., and Zhao, Y. (2011). Optimization for viewshed analysis on GPU. In *Geoinformatics, 2011 19th International Conference on*, pages 1–5. IEEE.

Graham, R. L., Knuth, D. E., and Patashnik, O. (1994). *Concrete Mathematics: A Foundation for Computer Science*. Addison-Wesley Longman Publishing Co., Inc., Boston, MA, USA, 2nd edition.

Haverkort, H. and Zhuang, Y. (2007). Computing visibility on terrains in external memory. In *Proceedings of the Ninth Workshop on Algorithm Engineering and Experiments / Workshop on Analytic Algorithms and Combinatorics (ALENEX/ANALCO)*.

Haverkort, H. J., Toma, L., and Zhuang, Y. (2007). Computing visibility on terrains in external memory. In *ALENEX*.

Lake, I. R., Lovett, A. A., Bateman, I. J., and Langford, I. H. (1998). Modelling environmental influences on property prices in an urban environment. *Computers, Environment and Urban Systems*, 22(2):121–136.

Laurini, R. and Thompson, D. (1992). *Fundamentals of Spatial Information Systems*. Academic Press.

Lee, J. and Stucky, D. (1998). On applying viewshed analysis for determining least-cost paths on digital elevation models. *International Journal of Geographical Information Science*, 12(8):891–905.

Li, Z., Zhu, Q., and Gold, C. (2005). *Digital Terrain Modeling — principles and methodology*. CRC Press.

Maćiorov, F. (1964). *Electronic digital integrating computers: digital differential analyzers*. Iliffe Books (London and New York).

Magalhães, S. V. G., Andrade, M. V. A., and Franklin, W. R. (2011). Multiple observer siting in huge terrains stored in external memory. *International Journal of Computer Information Systems and Industrial Management (IJCISIM)*, 3.

Mills, K., Fox, G., and Heimbach, R. (1992). Implementing an intervisibility analysis model on a parallel computing system. *Computers & Geosciences*, 18(8):1047–1054.

Nagy, G. (1994). Terrain visibility. *Computers and Graphics*, 18(6):763–773.

NVidia (2012). Tesla GPU high performance computing for servers. Available from: http://www.nvidia.com/object/tesla-servers.html.

Osterman, A. (2012). Implementation of the r.cuda.los module in the open source grass gis by using parallel computation on the NVIDIA CUDA graphic cards. *ELEKTROTEHNIËĞSKI VESTNIK*, 79(1-2):19–24.

Pasmark (2013). Cpu benchmark. http://www.cpubenchmark.net/.

Patterson, D. A. and Hennessy, J. L. (2008). *Computer Organization and Design, Fourth Edition, Fourth Edition: The Hardware/Software Interface (The Morgan Kaufmann Series in Computer Architecture and Design)*. Morgan Kaufmann Publishers Inc., San Francisco, CA, USA, 4th edition.

Rabus, B., Eineder, M., Roth, A., and Bamler, R. (2003). *The Shuttle Radar Topography Mission (SRTM)*. http://www2.jpl.nasa.gov/srtm/ — Acessado em 14 Janeiro 2014.

Shapira, A. (1990). Visibility and terrain labeling. *Master's thesis, Rensselaer Polytechnic Institute*.

Silveira, J. A., Magalhães, S. V. G., Andrade, M. V. A., and Conceição, V. S. (2013). A library to support the development of applications that process huge matrices in external memory. In *Proceedings of 15th International Conference on Enterprise Information Systems (ICEIS)*, pages 305–310, Angers, France.

Stookey, J., Xie, Z., Cutler, B., Franklin, W. R., Tracy, D. M., and Andrade, M. V. (2008). Parallel ODETLAP for terrain compression and reconstruction. In Aref, W. G. et al., editors, *16th ACM SIGSPATIAL International Conference on Advances in Geographic Information Systems (ACM GIS 2008)*, Irvine CA.

Strnad, D. (2011). Parallel terrain visibility calculation on the graphics processing unit. *Concurrency and Computation: Practice and Experience*, 23(18):2452–2462.

Teng, Y. A., Dementhon, D., and Davis, L. S. (1993). Region-to-region visibility analysis using data parallel machines. *Concurrency: Practice and Experience*, 5(5):379–406.

Toma, L., Zhuang, Y., and Richard, W. (2010). r.viewshed. https://trac.osgeo.org//grass/browser/grass-addons/raster/r.viewshed?rev=45442.

Van Kreveld, M. (1996). Variations on sweep algorithms: efficient computation of extended viewsheds and class intervals. In *Proceedings of the Symposium on Spatial Data Handling*, pages 15–27.

Zhao, Y., Padmanabhan, A., and Wang, S. (2013). A parallel computing approach to viewshed analysis of large terrain data using graphics processing units. *International Journal of Geographical Information Science*, 27(2):363–384.