Earth Rendering With Qt3D

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Generating the Earth

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What do we need?
Generating the Earth Ellipsoid
Coordinates Systems

- **Geographic Coordinates**
  - Latitude, Longitude, Height → Geodetic

- **Cartesian Coordinates (using the WGS84 coordinate system)**
  - $x, y, z$ relative to the center of the earth
  - Defines earth ellipsoid radii
    - (6 378 137km, 6 356 752.3km, 6 378 137km)

- **Projected Coordinates**
  - Mercator projection (usually on WGS84 ellipsoid) for 2D Maps
Earth Ellipsoid

- Various techniques to create a sphere
  - Geographic Grid Tessellation
    - Result in non uniform tile size but maps easily with imagery
  - Cube Map Tessellation
    - Non uniform tile size but better than the geographic grid, doesn’t map straightaway with imagery
  - Tetrahedron, Octahedron Tessellation
    - Uniform tile size, doesn’t map straightaway with imagery

- We want lots of details, lots of vertices
- But the GPU cannot contain it all at the same time
Cube Map Tessellation

- Generate a sphere from a cube
- Subdivision becomes easy
- Cube → Sphere
  - Starting from a unit cube (-1, 1)
  - We normalize each vertex
- Sphere → Ellipsoid
  - We multiply the normalized vertex by the WGS84 radius
    (6 378 137 m, 6 356 752.3 m, 6 378 137 m)
- Area of each subdivision doesn’t vary much
  - Not as good as Tetrahedron tessellation though
- Maps well to cubemap texturing
Handling Level of Details

- We want to model earth from space as well as on surface
  - Large Range of Values (km → m)
  - Too much data to be rendered at once
    - Doesn’t fit in RAM
    - GPU not powerful enough
    - Not enough disk space
- We need an acceleration structure
  - Divide the world into areas
  - QuadTree, Octree
Adaptative LOD

- We want to subdivide our ellipsoid so that we can have more nodes on the areas we are looking at
  - Our cube/sphere is composed of 6 faces
    - Each face has a root node
    - Each node contains 4 corners
  - For a given node at level n
  - Check if node should be split
    - If yes:
      - subdivide the node into 4 children of level n + 1 and recurse
    - If no:
      - If node is not a leaf, recursively merge it’s children
      - If visible, append to the list of nodes to render
When should a node be split?

- When the following conditions are met:
  - When its size is larger than a threshold value
    - Project into screen space and compare size with target tile size (256 x 256)
  - When it’s visible
When is a node visible?

- When the following conditions are met:
  - It is a leaf node
  - Not culled by the camera (within the view frustum)
  - Not too far from the camera
    - node’s distance to camera < camera’s distance to earth center
      - If we assume earth center is (0, 0, 0)
        - |node center – camera| < |(0, 0, 0) -camera|
        - |node center – camera| < | -camera|
  - Has its face normal facing us ( \( \overrightarrow{\text{viewVector}} \cdot \overrightarrow{\text{normal}} > 0 \) )
Adding details with imagery tiles
Imagery

- For each geometric tile we need to find the matching imagery tiles
- Various providers
  - Bing Map
  - Google Map
  - Open Street Map
  - ArcGis
  - ...
- Various types of layers
  - Satellite
  - Map
  - Heat
  - ...
Imagery Layers

- Most imagery layers are provided in Web Mercator projection
- Web Mercator assumes the Earth is a sphere, but we used an Ellipsoid
  - We need to reproject (let's keep that for later)
- Most imagery tiles are accessed using “slippy map” addressing
  - http://someMapLayerProvider/zoom/x/y.png
  - Zoom is usually between 0 and 18
    - At zoom 0, 1 tile covers the whole world
    - At zoom 1, 4 tiles cover the whole world
    - At zoom n, $2^{(2n)}$ tiles cover the whole world
  - X goes from 0 to $2^{zoom} - 1 \rightarrow 0$ is $-180^\circ$, $2^{zoom} - 1$ is $180^\circ$
  - Y goes from 0 to $2^{zoom} - 1 \rightarrow 0$ is $-85.0511^\circ$, $2^{zoom} - 1$ is $85.0511^\circ$
Mapping Imagery Tiles to Geometric Tiles

- A geometric tiles may map to several imagery tiles
- For each geometric tile we need to:
  - Find which imagery tiles are required
  - Load the imagery tiles as textures
  - Map these textures on the geometric tile’s vertices
Find the Imagery tiles covering a geometric tile

- For each corner of the geometric tile:
  - Retrieve geographic coordinates (lat, lon)
- Retrieve
  - minimum longitude, latitude (lonMin, latMin)
  - maximum longitude latitude (lonMax, latMax)
- Given a zoom level, convert
  - (lonMax, latMax) → toSlippyTileId (xMax, yMax)
  - (lonMin, latMin) → toSlippyTileId (xMin, yMin)
- We can then compute the number of tiles
  \((xMax - xMin + 1) \times (yMax - yMin + 1)\)
Mapping Imagery Tiles to Geometric Tiles

- Given the Imagery Tiles required to cover a Geometric Tile
- We then compute the
  - Offset in X and Y
  - The minimum and maximum extent of the tile
  - Its scale (node level / tile level)
- At render time, for each geometric tile we provide the GPU with the associated mapping for up to 4 imagery tiles

```
struct TextureInfo
{
    vec4 layerScaleOffsets[4];
    vec4 extentMinMax[4];
};
```
Vector Format Tiles

• Advantages
  – Less data to transmit (binary, json, xml)
  – Finer granularity: select only features you need

• Disadvantages
  – Requires polygon assembly and triangulation
  – More preprocessing overhead

• Rendering:
  – Option 1: Assemble polygons, triangulate and convert to VBO
  – Option 2: Render polygons into Texture
    • Allows to threat these tiles just like Imagery tiles

• Mapzen also provides tiles in vector format
Terrain Elevation
Terrain

- Elevation is provided through elevation textures
  - Mapzen provides elevation tiles
    - www.mapzen.com
- Reuses the same mapping as for imagery tiles
- Elevation tiles are used as heightmaps to displace vertices of geometric terrain tiles
  - Can be done in the Vertex Shader on the GPU
Mapzen Elevation Formats

- 4 formats available
  - Terrarium (.png)
  - Normal (.png)
  - GeoTIFF (.tif)
  - Skadi (.hgt)

- Terrarium
  - PNG tiles
  - 256x256 pixels
  - 32 768 offsets split into red, green blue channels
  - Red and green represent 16 bits of integer
  - Blue represents 8 bits of fraction
  - Height = (red * 256 + green + blue / 256) – 32768
  - Range of elevations span from (-11 000 to 8 900 meters) → (rgb(85, 8, 0) to rgb(162, 198, 0))
Even more details

- We displace the height of each vertex of a geometric tile using the heightmap
  - But wait!!! We only have 4 vertices per tile :(  
- We could subdivide more and regroup all the vertices
- Or we could tessellate on the GPU
  - Each geometric tile is initially composed of 4 vertices
  - We can use a tessellation shader to increase that directly on the GPU
    - Each outer edge is subdivided 8 times
    - Each inner edge is subdivided 8 times
    - \( \rightarrow 64 \) quads per tile \( \rightarrow 256 \) vertices
In practice
Drawing
Drawing

- How many draw calls do we need?
  - One per geometric tile?
  - One per imagery tile?
  - Or maybe one draw call is enough?
Drawing

- **Option 1**
  - 1 draw call to render the whole scene

- **Option 2**
  - 1) 1 draw call to render the Cube with the textures applied on each face into a CubeMap texture
  - 2) 1 draw call to render the Sphere (looking up textures into the CubeMap is easy)
  - Probably costlier on the GPU than option 1

- Both options have low driver overhead
Building data to be Rendered

- **Vertex Data (Geometric Tiles)**
  - OpenGL VBO built with Qt3DRender::QBuffer, Qt3DRender::QAttribute
  - For each renderable tile, retrieve its 4 corners and append them a QVector<QVector3D>
    - Perform conversion so that vertex is relative to eye (see vertex precision issues)
    - Set the resulting data array on the Qt3DRender::QBuffer with setdata()

- **Texture Data (Elevation and Imagery)**
  - Texture2DArray with Qt3DRender::QTexture2DArray and Qt3DRender::QTextureImage
    - Allows to group up to 2048 images within a single texture
    - This allows to draw up to 2048 different texture images with a single draw call

- **Mapping between Geometric Tiles and Imagery Tiles**
  - Uniform Buffer Object
    - Array of structs on GPU memory that can be accessed by shaders
    - Can easily be done by setting a Qt3DRender::QBuffer on a Qt3DRender::QParameter
  - For each tile vertex we associate an index
    - We then use the index to lookup values into the Uniform Buffer Object within our shaders
• Precision Issues

• The GPU is good at handling single-precision floats
  – Given the range of values we are working with, single-precision is not enough

• Vertex
  • Causes Jitter

• Depth
  • Causes Z-Fighting
Vertex Precision: Rendering relative to the eye

- Compute world vertex position on the CPU using doubles
- Before uploading the vertices to the GPU
  - Retrieve the eye position $E$
  - Transform vertex $V$ so that it is relative to the eye: $V_{\text{rel}} = V - E$
  - $V_{\text{rel}}$ can be converted to a single precision float with a minimal loss of precision
- At render time
  - Transform the ViewMatrix into a ViewMatrix relative to the eye (removing the translation vector)
    
    ```
    mat4 viewMatrixRTE = viewMatrix;
    viewMatrixRTE[3] = vec4(0.0, 0.0, 0.0, viewMatrix[3][3]);
    ```
  - Perform usual model view projection transformation using viewMatrixRTE
    
    ```
    gl_Position = projectionMatrix * viewMatrixRTE * vec4(position, 1.0);
    ```
Working around Depth Precision

- We only have 24 bits to store depth values
- Depth is $1/z$
  - As $z$ increases, precision decreases
  - We have less precision for values which are far away
- We can work around that by adapting near and far plane of frustum
- Or we could use a Logarithmic Depth Buffer
  - Allows a better control of the distribution of depth values
Camera Zoom

- Sequence of step
- Each step the distance is half what it was at step \( n - 1 \)
- Stop when reaching the surface
Code

- Code is available at https://github.com/KDAB/qt3d-examples
- About 1500 LOC of C++ and 500 LOC of QML
- Scripts to download tiles provided
  - You just need to register for a free Mapzen account
Possible Improvements

- Work out texture mapping
- Use a dedicated Qt3D aspect to perform the cube map generation and imagery tile selection
- Perform smarter tessellation on the GPU instead of the fixed number of subdivisions for inner and outer edges
- Fill cracks between tiles
- Use remote loading of textures (should already be possible but not tested)
- Load textures across several frames (right now it loads everything for the frame)
- Better heuristics to predict which tiles to load
- Fine tune tile culling
Suggested Readings

- 3D Engine Design for Virtual Globes by Patrick Cozzi and Kevin Ring
- Rendering the Whole Wide World on the World Wide Web by Kevin Ring
- Rendering Massive Terrains using Chunked Level of Detail Control by Thatcher Ulrich
- Depth Precision Visualized by Nathan Reed
  - https://developer.nvidia.com/content/depth-precision-visualized
Thank you