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Survey Paper

A Survey of Digital Earth ☆

Ali Mahdavi-Amiri *,1, Troy Alderson 2, Faramarz Samavati 3

Department of Computer Science, University of Calgary, 2500 University Drive, N.W. Calgary, Alberta, Canada T2N 1N4

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ABSTRACT

The creation of a digital representation of the Earth and its associated data is a complex and difficult task. The incredible size of geospatial data and differences between data sets pose challenges related to big data, data creation, and data integration. Advances in globe representation and visualization have made use of Discrete Global Grid Systems (DGGSs) that discretize the globe into a set of cells to which data are assigned. DGGSs are well studied and important in the GIS, OGC, and Digital Earth communities but have not been well-introduced to the computer graphics community. In this paper, we provide an overview of DGGSs and their use in digitally representing the Earth, describe several current Digital Earth systems and their methods of Earth representation, and list a number of applications of Digital Earths with related works. Moreover, we discuss the key research areas and related papers from computer graphics that are useful for a Digital Earth system, such as advanced techniques for geospatial data creation and representation.

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1. Introduction

Over the past three decades, the field of computer graphics has experienced significant research and technical advancements, which have revolutionized application areas such as the film and video game industries. Inspired by this success, Thomas Funkhouser, in his visionary talk at the SIGGRAPH 2014 achievement award session, encouraged computer graphics experts to expand the scope of this field to new real-life application areas [1]. We focus on one such application, the Digital Earth, which is a disruptive approach to the methods of geospatial analysis and visualization currently employed within the field of GIS that uses a virtual (3D) representation of the globe as a reference model for geospatial data.

The Earth is immense, and data about the Earth is similarly immense. The field of GIS exists to gather, integrate, process, visualize and distribute this data, traditionally performed by individual GIS experts. Several petabytes of geospatial data occupy GIS servers around the world, and more continues to be generated every day.

Geospatial data is typically found in one of three forms: raster data (e.g. satellite imagery), feature data (e.g. road networks and nation boundaries, usually represented as vector data), and 3D geometry. The resolution and size of these data are usually quite high, depending on the data capture technologies used, and are constantly growing as such technologies improve.

One of the main challenges faced by GIS experts is that of data integration. These geospatial data are gathered and processed by disparate organizations and stored in various file formats at different resolutions. The traditional model of GIS, in which GIS experts clean, process, integrate, and distribute the data, is unsustainable in the face of the ever increasing flow of data.

Furthermore, even after the data are integrated, their traditional representation as layers of 2D maps presents difficulties in analyzing and understanding these data. While cartography is an old and studied field, human intuitions on distance and area break down in the face of areal distortions inherent in any projection of the Earth to a 2D cartographic map, especially for non-experts. Such maps offer a flat view of the 3D globe and do not take advantage of the possibilities for the interactive 3D exploration of the Earth that may be easily accomplished with modern graphics applications.

Moving to a 3D representation of the Earth for integration, analysis, and visualization can help address these issues, despite the fact that the non-Euclidean nature of the Earth's spherical surface presents its own challenges. One such representation that has emerged to facilitate solutions to data integration and analysis is that of the Digital Earth (aka the Digital or Virtual Globe). In a Digital Earth system, data are assigned to locations on the 3D Earth

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* Corresponding author.
E-mail addresses: amahdavi@ucalgary.ca (A. Mahdavi-Amiri), tfalders@ucalgary.ca (T. Alderson), samavati@ucalgary.ca (F. Samavati).
[1] Tel.: +1 403 220 7691 2.
[2] Tel.: +1 403 220 7693 3.
[3] Tel.: +1 403 210 9454; fax: +1 403 284 4707.

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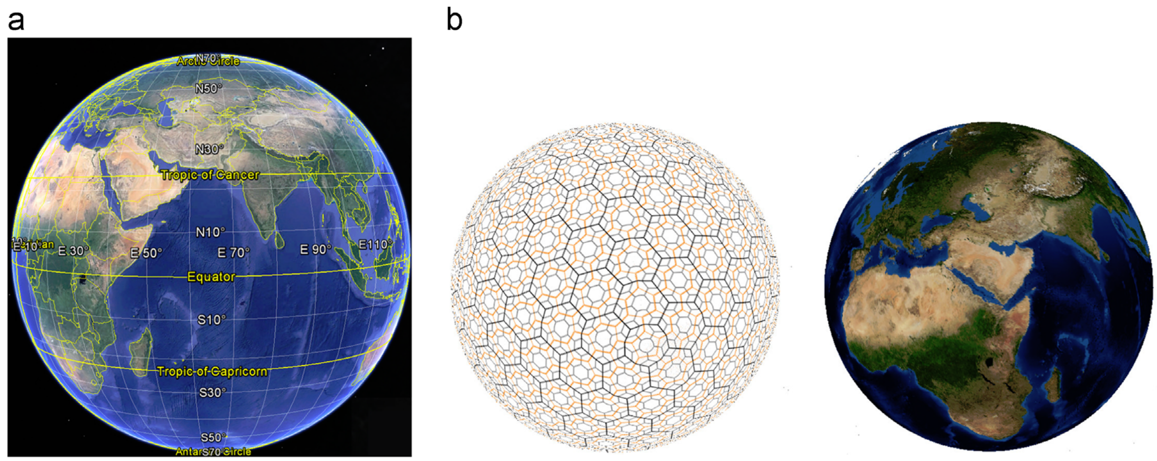

Fig. 1. The Earth can be discretized into cells using, e.g., (a) latitude/longitude parametrization (image taken from Google Earth [5]), or (b) a refined polyhedron projected to the sphere (image taken from the PYXIS Innovation Inc. framework [6], used with permission).

(typically approximated using either a sphere or, for more accuracy, an ellipsoid) through one of a variety of techniques.

In most cases, data are assigned to the cells of an underlying discretization of the Earth (see Fig. 1). Each cell represents a particular region and receives a unique index (or address), which can be used for fast data access and/or hierarchical or adjacency queries. While alternatives to discretization are possible, grappling with the non-Euclidean geometry of the Earth's surface is a non-trivial task. Examples of discretization approaches include Voronoi cells or latitude/longitude grids [2–4].

One of the advantages of latitude/longitude cells over Voronoi cells is that the cells are mostly *regular* (i.e. they have a grid-like structure), simplifying adjacency and hierarchical queries substantially. Discretizations of the Earth into a multiresolution hierarchy of indexed (mostly) regular cells are known as Discrete Global Grid Systems (DGGSs) and form the backbone of the state-of-the-art in Digital Earth systems. To further simplify such queries, most DGGSs aim for uniform, equal-area cells and are typically constructed via an initial discretization into planar cells that are then refined by some refinement method and projected onto the spherical Earth.

DGGSs may be characterized according to the shapes of the cells and their initial structure, the refinements applied to these cells, the projection method that maps points on a planar map to and from the spherical Earth, and the indexing method used to refer to these cells. We present in this paper a survey of DGGSs as characterized by these factors, in addition to a brief overview of the state-of-the-art Digital Earth software currently in use and applications of globe representation and visualization, for use by both the computer graphics and GIS communities.

The survey is organized as follows. In Section 2, we review the data types typically encountered in a Digital Earth setting, alongside relevant research and survey papers that deal with using, managing, and creating such data sets. The various types of DGGSs and their components are discussed in Section 3, followed by an overview of existing and well-known Digital Earth systems and each's underlying globe representation in Section 4. Finally, we mention some of the important applications of the Digital Earth in the modern age in Section 5 and conclude in Section 6.

2. Data types

Various types of geospatial data sets are visualized, analyzed, and combined on a Digital Earth. Although these data sets generally fall into a small number of type categories, there exist a plethora of file formats used to describe and store them (see [7]), data acquisition techniques used to generate them, and organizations that collect and catalog them. Each category of data type is a field of research unto itself and each has been studied in several works within the literature.

One of the main challenges that all Digital Earth systems face is the sheer immensity of the amount of data available. These data sets, which are not small in general, are captured over time and regularly kept for posterity. Petabytes worth of geospatial data already exist, and this amount grows every day at an increasing rate due to improving fidelity in data capture technologies. Appropriate methods (e.g. multiresolution representations) are needed to handle such large volumes of data and are well-studied topics for each data type.

In the following section, we present a glimpse of the important related works that study these data sets and their applications more comprehensively. We give partial focus to fundamentals such as multiresolution representations and visualization rather than data processing and analysis, which are generally application-dependent.

2.1. Imagery data sets

Geospatial imagery data sets, typically categorized into aerial or satellite photographs, are very useful for the visualization and analysis of locations. They are often used as textures for the cells of the discretized Earth at multiple resolutions, but can also be used for analysis or to provide interesting views of the Earth (e.g. spherical panoramic views).

Aerial photographs are photographs taken from aircraft such as helicopters and balloons, that do not have a fixed support on the Earth, while satellite photographs are taken by satellites. Aerial images generally benefit from higher resolution and image quality in comparison to satellite images, but are subject to air traffic and other restrictions, while satellites are operational throughout the year and can frequently re-visit locations for time-lapse captures [8].

On the Digital Earth, multiple images of a single region can exist from different times, at different scales, under different projections, with different spatial extents and orientations, and with different viewpoints and lighting; and providing a meaningful connection between these images has become an important subject of research [9] (see Fig. 2(a) and (b)). One powerful tool for image representation at multiple scales is the mip-map — a pyramidal structure consisting of progressively lower resolution versions of a given image [10] — which has been used in [11] to

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