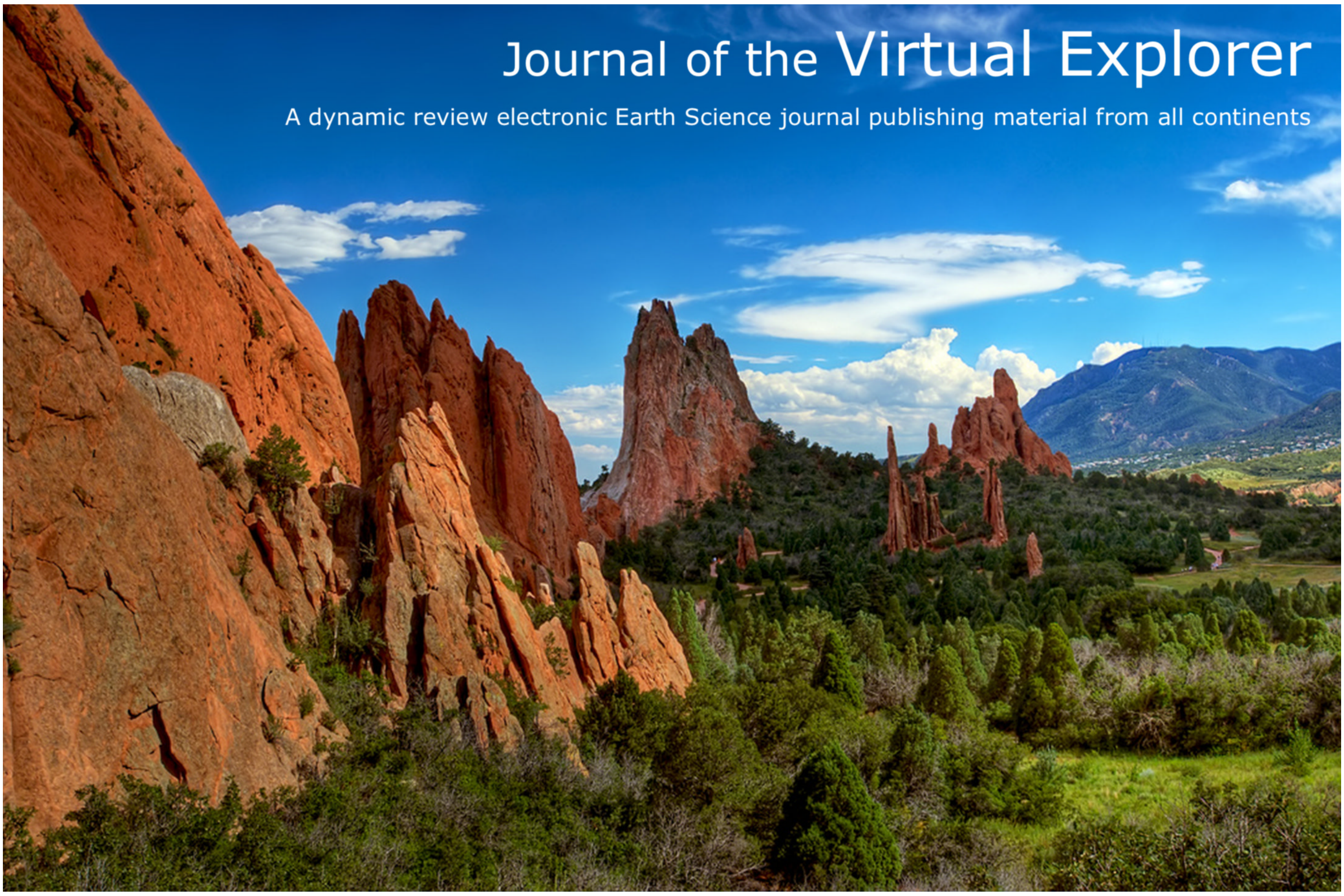

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Abstract: In order to augment the research and public outreach value of NASA Earth Science data, the Goddard Earth Science Data and Information Center (GES DISC) uses Google Earth as one of its geospatial visualization methods. Google Earth supports both two-dimensional flat data and three-dimensional data which include the vertical dimension in the atmosphere. Possible general solutions to visualizing these kinds of scientific data are proposed and illustrated in details. Several results derived from the GES-DISC Interactive Online Visualization ANd aNalysis Infrastructure (Giovanni) have been rendered in Google Earth. A new method is proposed here using vertical satellite data to render vertical orbit curtains in Google Earth. This capability improves awareness of NASA scientific data among Google Earth users, including the general public. The availability of multiple scientific results in Google Earth enables easy and convenient synergistic research on a virtual platform, advancing collaborative and globalized scientific research.

http://virtualexplorer.com.au/article/2008/194/geospatial-data-using-google-earth

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Introduction

The GES DISC, located at Goddard Space Flight Center in Greenbelt, Maryland, is one of several NASA Earth Science data archive centers, primarily archives satellite data related to precipitation, hydrology (Nadeau, *et al.* 2006), hurricanes, atmospheric chemistry, and atmospheric dynamics. It aims to maximize use of satellite data from numerous satellites and field programs.

Scientists at the GES DISC are familiar with the recent advent of "virtual globes", such as NASA World Wind (NASA 2008a), Google Earth (Google 2008), Microsoft Virtual Earth (Microsoft 2008), ArcExplorer (ESRI 2008), and others. These virtual globes can integrate satellite imagery, aerial photography, and digital maps and present a three-dimensional interactive representation of data on a global scale.. Especially, "NASA has released World Wind as an open source program to improve its quality through peer review, maximize awareness and impact of NASA research, and increase dissemination of World Wind in support of NASA's mission" (NASA 2008a). It provides, in default, lots of NASA Earth science data from such missions as Landsat 7, the Shuttle Radar Topography Mission, and the Moderate-resolution Imaging Spectroradiometer (MODIS). However, better support for Keyhole Markup Language (KML) makes Google Earth very popular and widely accepted by professionals and public. For this reason, Google Earth was selected to augment the value of geospatial data at NASA GES DISC. Virtual globe systems can be used to discover, add, and share information about any subject in the world that has a geospatial element (Nature 2006). These systems also enable researchers to conveniently collaborate and share their research projects and results. There is renewed hope that every sort of information on the state of the planet, from the levels of toxic chemicals to the incidence of disease will become available to all with a few moves of the mouse (Butler 2006). With the emergence of Web 2.0 and 3.0, research and applications are moving from local machine-based environments to online web-based platforms. Thus, virtual globes are recognized as an important trend in geoscience research and applications.

For the last few years, virtual globes, notably Google Earth, have been used for research and applications in areas such as global climate change (Burek, *et al.* 2007), weather forecasting (Travis, *et al.* 2006), natural disasters, conservation of the environment (NIEES 2006), travel, nature, people and culture, history illustration, presidential elections, avian flu (Nature 2006), online game, *etc.* Most applications involve flat geospatial data and socio-economic data. They are displayed in a virtual globe using geographic elements. The hurricane portal (Leptoukh 2006), implemented and maintained by the GES DISC, uses data derived from NASA remote-sensing instruments to study and visualize hurricanes. More descriptions for other researches and literatures can be found in 'Related research and discussion' section of the paper.

In this paper, several solutions are proposed to augment the value of distributed geospatial data based on Google Earth. These solutions cover most of current available methods used in Google Earth for two-dimensional (2D) and three-dimensional (3D) geospatial data. In particular, a new method is proposed here to render vertical geospatial data into vertical orbit curtains in Google Earth. The resultant orbit curtains make vertical geospatial data viewable, transparently or opaquely, in Google Earth. Using our method, 3D geospatial data can be combined and compared with other simultaneously displayed data to facilitate scientific research, create new insights, and improve public understanding of our planet.. Vertical geospatial data derived from satellite CloudSat, Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO), and the Aqua and 2D flat geospatial data from Tropical Rainfall Measurements Mission (TRMM) and Aqua satellite are rendered in Google Earth to provide a basis for synergistic research of Earth science.

NASA GES Satellite Data

The Earth Observing System is a major component of NASA's Earth-Sun System Missions. The mission has three components: a. a coordinated series of polar-orbiting and low inclination satellites for long-term global observations of the Earth's biosphere, including the land surface, atmosphere, oceans; b. a data system supporting them; and c. a science component. The 2D and 3D geospatial imagery at the GES DISC are being integrated into Google Earth to augment their scientific value.

Two-dimensional flat satellite data

Currently, 2D flat satellite data from TRMM and Aqua satellites separately are integrated into Google Earth for synergistic visualization and research.

On TRMM, there are five instruments on the satellite (NASA 2007a): a Precipitation Radar device, a Microwave Imager, a Visible Infrared Scanner, a Cloud and Earth Radiant Energy measuring device, and a Lightning Imager. Data from these instruments are processed for rendering on Google Earth. The core geophysical parameters represented in the data include rain rate; rain frequency; mean surface rainfall; rain rate probability distribution; cloud liquid water; rain water, and so on. The temporal range of the data products is from December 1997 to present. The spatial range covers all longitudes but emphasis is mainly on latitudes between 40°N and 40°S (NASA 2007b).

The Aqua spacecraft detects water in all its forms -- liquid, solid, and vapor -- throughout the atmosphere and both on and near the earth's surface. The Atmospheric Infrared Sounder (AIRS) instrument on Aqua produces global coverage data twice daily that describes atmospheric temperature and humidity, land and sea surface temperatures, clouds, and radioactive energy flux (Pagano 2003). The gridded level 3 daily and monthly standard products are processed and visualized by Google Earth. The described physical parameters include total integrated column cloud liquid water; total integrated column ozone burden; surface air temperature; surface skin temperature; mean surface pressure; outgoing long-wave radiation flux; and combined cloud top temperature.

In addition to the above, Ozone Monitoring Instrument data from Aura, MODIS data from Terra and Aqua, and Advanced Microwave Scanning Radiometer data from Aqua are analyzed, processed and served via (Giovanni 2007b) and finally visualized in Google Earth. User can specify spatial and temporal range, physical parameters, plots methods, *etc.*

Three-dimensional vertical satellite data

Four kinds of 3D satellite data are rendered in Google Earth for synergistic scientific research: CloudSat, CALIPSO, AIRS and MODIS-Aqua data. All data are first processed through Giovanni version 3 system (Giovanni 2007a) , then visualized as an orbit curtain in Google Earth.

The CloudSat satellite, which was launched by NASA on April 28, 2006, and which has been collecting data since June 2, 2006, records vertical profiles of clouds. The profiles provide a 3D view of the vertical structure of clouds from the top of the atmosphere to the surface and the radar observations are processed into estimates of water and ice content with 500m vertical resolution (Partain 2006). The data are made available in the format of Hierarchical Data Format for Earth Observation System (HDF-EOS).

The CALIPSO satellite employs an innovative set of instruments to explore our atmosphere and to study the aerosols and thin clouds that play a major role in regulating earth's weather, climate, and air quality. It collects data about the vertical structure of clouds and aerosols unavailable from other earth-observing satellites. CALIPSO globally surveys the vertical distribution of aerosols and clouds in the atmosphere, and optical and physical properties of aerosols and clouds (NASA 2005). On CALIPSO, there are loaded three co-aligned, near-nadir viewing instruments: a 2-wavelength polarization-sensitive lidar, an imaging infrared radiometer, and a high-resolution wide field camera. The lidar profiles provide information on the vertical distribution of aerosols and clouds, cloud particle phase, and classification of aerosol size (NASA 2006).

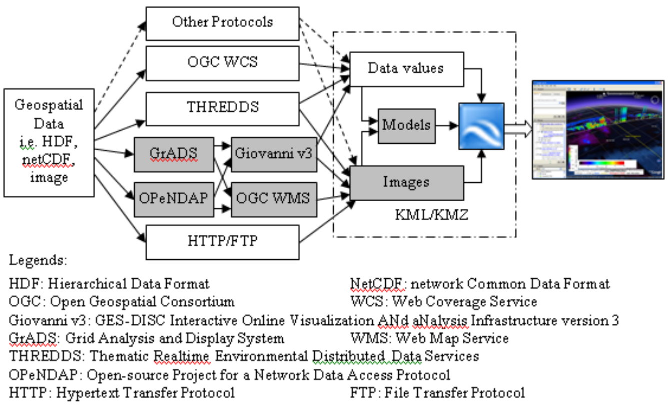
AIRS and MODIS-Aqua also provides vertical profiles of quantities such as atmospheric temperature, H_2O saturation, and of H2O vapor. AIRS measurements of the Earth's atmosphere and surface allow scientists to improve weather predictions and observe changes in Earth's climate. Much of the data from MODIS includes 3D features of the land, oceans, and atmosphere, which will improve our understanding of dynamics global processes (NASA 2007c).

Data organization, serving and visualization in Google Earth

KML is an XML-compliant markup language, invented by a company called Keyhole Inc. that was later acquired by Google Inc. It can be used to represent, organize, store, manage, serve and visualize 2D and 3D geospatial data in geographic browsers such as Google Earth, Google Maps, Google Mobile, World Wind and Virtual Earth. Non-expert users can easily publish their geospatial data using KML in Google Earth. Data can also be streamed continuously from a server.

The KML language permits the user to plot points, lines, and polygons, and to superimpose images on the screen or on or above the ground. Data may be linked to remote servers and textual descriptors may be added. All geospatial data, regardless of form (point, line strings, polygons, geometries, images, and 3D models), always have corresponding longitude, latitude and altitude information. KML tags, such as scale, tilt, heading, and style, can make the view of geospatial data more specific. KML also provides time features, such as TimeSpan and TimeStamp, which are very important for visualization of a massive historical archive of geospatial data. Geospatial data can be nicely organized via specific tags in KML files (Google 2007a). Figure 1 illustrates how to utilize general and scientific specific data access protocols to represent, store, serve and visualize the geospatial data in Google Earth via KML/KMZ files.

Figure 1. Visualizing geospatial data in Google Earth



Serving and visualizing geospatial data in Google Earth via KML/KMZ files

Basically, KML provides three kinds of methods for visualizing data in Google Earth.

Directly using geospatial data values in KML files and rendering them in Google Earth

In this method, such KML tags as Point, LineString, LinearRing, Polygon, MultiGeometry play important roles. Geospatial data can be accessed by some scientific data specific protocols, such as Web Coverage Service (WCS) from Open Geospatial Consortium, Inc. (OGC), Thematic Realtime Environmental Distributed Data Services, NASA GES DISC Giovanni v3, and others. The scietific data values are read into the KML file as the values of the KML tags and its properties. Finally, the scietific data are visualized in Google Earth via the KML file.

Using images of geospatial data

Geospatial data are first rendered in standard image formats - png, jpeg, gif, *etc.* Then, images are stored in KML files in standard web address or local path. Such tags as PhotoOverlay, ScreenOverlay, and GroundOverlay are used to access the above files. The Google Earth application can display such images with features (e.g location, or transparency) specified in KML. Images can be remotely provided through HTTP/FTP protocol or HTTP/FTP-based OGC Web Map Service (WMS) or Giovanni v3, *etc.* Scientific data relating to planet Earth may be accessed via other protocols that are generally used only by scientists, *e.g.*. the Grid Analysis and Display System (GrADS) (Doty 1995) and Open-source Network for a Data Access Protocol (OPeNDAP) (OPeNDAP 2007). This solution is currently used by the GES DISC for integrating 2D AIRS and TRMM data into Google Earth (Figure 1). It is also used to produce images for creating the orbit curtain models of CloudSat, CALIPSO, MODIS-Aqua, and AIRS vertical data.

Using models in KML files

The Google Earth application can display 3D Collada models (*http://www.khronos.org/collada/*). Collada is the name of an XML-compatible file type especially used for modeling 3D objects. So, 3D and 4D data sets can be prepared for viewing in Google Earth via using the SketchUp tools (Google 2007) which exports Collada files. Both numeric data and graphic images can be imported into Collada models via the above two methods. The model template is created via Google's SketchUp tool. This method is used to create the orbit curtain of the vertical data of CloudSat, CALIPSO, AIRS, and MODIS-Aqua.

Folder, Document, Placemark and NetworkLink tags are used to organize and manage the geospatial data. Their attributes are used to describe datasets, offer download addresses, and introduce data-related issues. The shadowed elements of the diagram in Figure 1 are the solutions used by the GES DISC. These solutions embrace Earth science specific protocols and services for access to, processing Earth science data and visualizing them in Google Earth

GES DISC Data Processing

In order to visualize 2D geospatial satellite data and analyze output results in Google Earth, data access and processing services are used to pre-process the data into images or user required format. The results from those services are then integrated and visualized in Google Earth.

Uniform serving of and access to data products

OPeNDAP simplifies scientific data networking, allowing uniform and simplified access to remotely-sited data. OPeNDAP servers can make data from any server appear local -- regardless of data type, storage location, storage format, or user's visualization package. Existing, well-known data analysis and visualization applications such as Matlab and Interface Definition Language can be easily transformed into clients to interact with OPeNDAP server. The server consists mainly of an OPeNDAP Light Front Server and Back End Server (OPeNDAP 2007). GrADS is another kind of interactive software tool for easy access, processing, and visualization of scientific data related to the Earth. It handles datasets in a four-dimensional data environment (longitude, latitude, vertical level, and time). GrADS can process many kinds of data formats, including binary, GRIdded Binary, and HDF (Doty 1995)

Both GrADS and OPeNDAP are used at GES DISC to serve vast volumes of Earth science data distributed among different data servers. The data include TRMM, AIRS, MODIS-Aqua, MODIS-Terra, *etc.* GrADS mainly serves data in binary format. Most data in HDF format are served through uniform OPeNDAP interfaces that can be remotely accessed by any client or user requests.

Uniform processing geospatial data

Figure 1 shows several solutions that can be used to visualize geospatial data in Google Earth. OGC WCS and WMS standard specifications have been widely followed, developed and applied in geoscience communities. WCS provides the getCoverage interface for accessing user required data that can be output to KML files. WMS provides the getMap interface for outputting user required data in the desired image format, such as png, jpeg, and gif. Output images can be embedded into a KML file and visualized in Google Earth.

WMS has been implemented and used by many academic, non-profit, governmental, and commercial organizations. WMS has lots of versions because implementations vary widely. Most WMS implementations are free of charge and open source for future development and improvement according to users' specific requirements. One of the most popular and stable WMS is from the University of Minnesota. It is called MapServer and is being maintained by a growing number of developers (nearing 20) from around the world, and is being supported by a diverse group of organizations that fund enhancements and maintenance (MapServer 2007).

The GES DISC has selected MapServer to customize and visualize geospatial data. MapServer can access up to 60 different data formats via the geospatial data abstract library, one of whose features is the capability to create a virtual file format where different data-related options can be specified. The MapServer can access a SQL database, such as PostGreSQL, or MySQL, whose records point to local virtual files. Inside the virtual file is geospatial information, warping information, a color bar, and an OPeNDAP link. MapServer uses this information to render the data. Once all user-required layers have been processed and overlain, the resulting image is sent back to the OGC-compliant client or to any Web browser for display.

Figure 2. Dataflow diagram for user customizable visualization of data through OPeNDAP

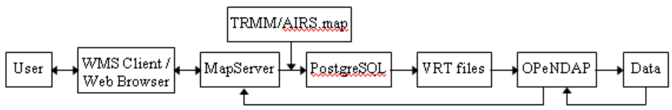


Figure 2 is the data flow diagram for transparent, uniform access to vast volumes of distributed, heterogeneous geospatial resources, with the results returned to the user in an image format through OPeNDAP and MapServer. The advantage of this approach is that the data and computational servers are totally separated. The data server can be freely archived and managed without any concerns about processing services served through OPeNDAP. The computational server can freely access and retrieve user-required data and process these data through a uniform URL interface.

Visualization of 2D data products in Google Earth

Any path followed in Figure 1 will allow users to customize, visualize, and display distributed and heterogeneous geospatial data in Google Earth. At GES DISC, the shadowed paths in Figure 1 are used. Several kinds of 2D data are made available in Google Earth, including Level 3 monthly, daily and 3-hour TRMM, monthly and daily AIRS, monthly MODIS-Terra and MODIS-Aqua, and monthly Polarization & Anisotropy of Reflectances for

Atmospheric Sciences coupled with Observations from a Lidar, and others.

KML files are used as the intermediate media to visualize the aforementioned available images or data in Google Earth. Those images or data are produced on-the-fly via WMS/Giovanni 3 rendering the data that are served through OPeNDAP/GrADS. Table 1 is a KML file for TRMM data inside which a WMS request is embedded. When the user opens the KML file in Google Earth, a WMS request is sent to the WMS server and an image is returned to the Google Earth for display. The KML <LookAt> tag defines how Google Earth displays the image to the user. The KML <href> tag is a WMS request that is necessary for WMS to acquire and process the data and includes all user-provided parameters. The KML <LatLonBox> tag defines the size of the image that will be displayed. Because all TRMM data are global for the tropical and subtropical regions, they cover 40°N to 40°S of latitude and 180°E to 180°W of longitude.

Table 1 - KML file for integrating TRMM 3A12 data produ

```
<kml xmlns="http://earth.google.com/kml/2.0">
   <Folder>
   <name>NASA TRMM_3A12_V6 2000-07-01</name><desc
   <LookAt>
     <longitude>-92.5813388657719</longitude>
     <latitude>26.80481483728439</latitude>
      <range>8000000.0</range>
      <tilt>0.0</tilt>
     <heading>0.0</heading>
   </LookAt>
     <Document>
       <name>TRMM V6 Data</name><description>…</description>
       <GroundOverlay>
         <name>2000-07-01</name>
         <Icon>
           <href><![CDATA[http://g0dup05u.ecs.nasa.gov/cgi-bin/wms_ogc?SERVICE=WMS&
      VERSION=1.1.1&REQUEST=Getmap&layers=bluemarble,TRMM_3A12_V6_MONTHLY_surfrain
      &BBOX=-180,-50,180,50&TIME=2000-07-01&format=png&transparent=true&WIDTH=1500 &
      HEIGHT=800]]> </href>
         </Icon>
         <LatLonBox>
           <north>50</north>
           <south>-50</south>
           <east>180</east>
           <west>-180</west>
         </LatLonBox>
         <TimeStamp>
           <when>2000-07-01</when>
         </TimeStamp>
       </GroundOverlay>
     </Document>
    ……
   </Folder>
 </kml>
```

Figure 3. TRMM 3A12 data in Google Earth

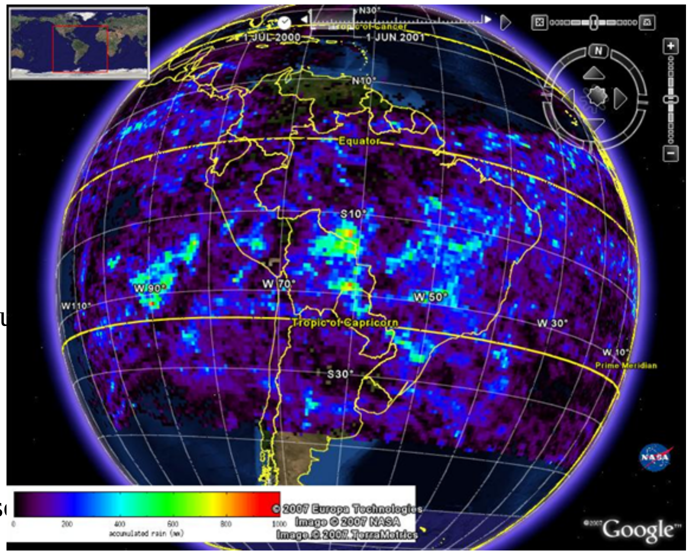


Figure 3 is the TRMM 3A12 0.5˚ x 0.5˚ gridded monthly product that is integrated into Google Earth via the above KML file. The image product consists of mean 2A12 data, calculated vertical hydrometeorological profiles, and mean surface rainfall.

Processing geospatial vertical data

The A-Train is a succession of seven U.S. and international sun-synchronous orbit satellites. The A-Train orbital configuration enables synergistic scientific measurement using data from several different satellites (Vicente 2006). The vertical geospatial data from the “A-Train” constellation satellites CloudSat, CALIPSO, and Aqua (mainly MODIS and AIRS products) are being processed with a new approach that is different from the one processing 2D data. Vertical atmospheric data includes cloud characteristics in radar reflectivity, received echo power, cloud/aerosol classification, dew point temperatures, saturation mass mixing ratios, vapor mass mixing ratios, and atmospheric temperatures. These vertical data are considerably different from 2D data.

GES DISC Giovanni online visualization and analysis system

GES DISC has facilitated pure and applied research by applying cutting-edge information technology to the development of new tools and data services. Giovanni is one such tool that has gained considerable popularity. It continues to evolve in response to science research and application needs (Giovanni 2007a). It is a Web-based interactive data analysis and visualization tool, used primarily for exploring NASA atmospheric and precipitation datasets. With the rapidly increasing volume of archived atmospheric and precipitation data from NASA missions, Giovanni enables users easily to manipulate data and facilitate scientific discovery (Chen, *et al.* 2008).

The earlier Giovanni Version 2 (G2) (Giovanni 2007a) provides capabilities including area plots, time plots, Hovmöller plots, two parameter inter-comparisons, two parameter plots, temporal correlation maps, *etc.* All those capabilities can be applied to most NASA atmospheric and precipitation data. Giovanni Version 3 (G3) (Giovanni 2007b) offers many new and more advanced functions, such as vertical data profiling, vertical cross-sections, and zonal averaging. The newest function in G3 is producing multi-instrument vertical plots beneath the A-Train orbit track. G3 provides a useful platform for the utilization of both 2D and 3D geospatial data.

G3 uses a service- and workflow-oriented asynchronous architecture. FTP, HTTP-based scientific data networking software, such as OPeNDAP and GrADS Data Server, are used to enable G3 to access and transfer local and remote scientific data online. Service-oriented architecture requires that all data processing and rendering be implemented through standard Web services. The workflow-oriented management system enables users to easily create, modify, and save their own workflows. This asynchronicity guarantees that more complex processing without the limitation of HTTP time-outs is possible, and that Web services in a process can run in parallel. Finally, G3 is intrinsically extensible, scalable, and easy to work with (Giovanni 2007b).

Image curtain of vertical data from Giovanni 3

The A-Train Data Depot is the first instance of the use of G3 for processing and analyzing geospatial data derived from the A-Train satellite constellation (Kempler, *et al.* 2006). The data can be combined to address scientific problems more comprehensively than is possible with data from any single satellite dataset (Vicente, *et al.* 2006). At present, vertical data from three of the seven satellites in the A-train – CloudSat, CALIPSO, and Aqua – are processed using G3 and integrated together in Google Earth.

Users can launch a G3 web-based graphical user interface to input spatial and temporal criteria to produce a curtain plot image. The interface lists all available parameters that users can customize to their specific requirements. When the user selects the input parameters from the interface, the user interface software creates an XML representation of the inputs, and initiates execution of the appropriate workflow. For the asynchronous case, when the workflow processing is complete, the URL of the resultant product (usually an image) is available. When the processing is fast and appears to be synchronous, the result will be directly returned to the user, usually via the Web browser (Berrick, *et al.* 2006).

The following geospatial vertical data are processed in G3 to be rendered into the curtain plot, to reveal different physical phenomena with different physical parameters:

1. The standard level 1B data product (version 008) from CloudSat for vertical profiles of clouds, which indicates such cloud characteristics as reflectivity and Received Echo Powers (CloudSat 2007).
2. The standard level 2B data product from CloudSat for vertical profiles of ice water content and liquid water content CloudSat 2007).
3. Lidar Level 2 Vertical Feature Mask (version 001) data products from CALIPSO for high-resolution vertical profiles of clouds and aerosols, which can be used to classify clouds and aerosols and to distinguish ice and water phases.
4. AIRS and MODIS vertical data from Aqua for vertical profiles of atmospheric temperature, H_2O temperature, and H_2O vapor

Figure 4. Image curtain of vertical data from CALIPSO in G3

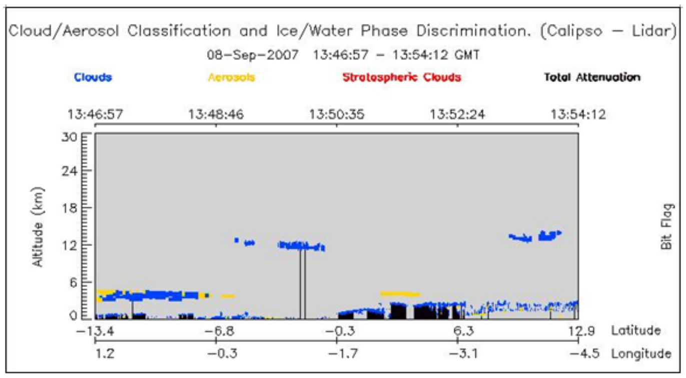
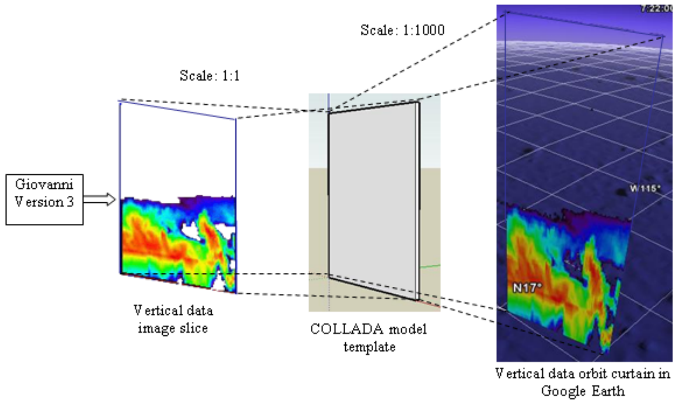


Figure 5. Rendering the orbit curtain from vertical data



A Perl script automatically acquires the vertical data image curtain. First, the script produces the requested parameters file in XML format for the temporal range selected and inputted by the user. In the parameters file, the temporal range and the specific satellite orbit model are used to calculate the spatial range. Other parameters depend on the relevant physical variable, *e.g.*. Radar Reflectivity or Received Echo Powers. Second, the parameters file is used to invoke a workflow from G3 to transparently access the vertical data. Finally, a series of procedures such as sub-setting, extracting, scaling, stitching, and plotting are used to process the data to output the curtain plot image (Chen, *et al.* 2008). Figure 4 shows a curtain plot for Cloud/Aerosol Classification and Ice/Water Phase Discrimination from CALIPSO in A-Train system

Formation and visualization of a vertical data orbit Curtain Plot in Google Earth

Google Inc. provides a 3D tool named SketchUp (Google 2007b). SketchUp is used to save a Collada model, which defines a 3D model that can be imported into Google Earth for visualization. Collada is for establishing an open, standard, XML-based Digital Asset schema for interactive 3D applications (Barnes 2006). Here, its real 3D features are used to represent geospatial vertical data

Figure 5 illustrates the rendering procedure of an orbit curtain for vertical data in Google Earth. The image curtain output is produced using G3 and chopped into small size image slices. The Collada model's template is created via SketchUp. The image slices are applied to the model template to form a series of Collada models. In order to assemble those 3D models accurately along the satellite orbit track in Google Earth, the coordinate system of SketchUp (x, y, z) must be mapped to that of Google Earth (Longitude, Latitude, Altitude). The model template has an x value, z value, and approximately (but not exactly) zero y value, which makes the model 3D, but it looks like a thin curtain. The model's x-z plane is textured with the transparent vertical data image slice. The 3D model can be finally exported out as a KML Zipped (KMZ) file, which is supported in Google Earth. The KMZ file zips all related files required for visualizing this model in Google Earth. It usually includes, at the minimum, a KML file, image file(s), model file(s), and a texture file. The KML file determines the spatial coordinates, the level of zooming out, and the number of degrees of rotation needed to accurately visualize each model along the satellite orbit track to form the orbit curtain in Google Earth. The Texture file determines the images used as texture for models.

Table 2 - A COLLADA model example that defines 3D model a

```
<?xml version="1.0" encoding="utf-8"?>
<COLLADA xmlns="http://www.collada.org/2005/11/COLLADA
   <library_images>
         <image id="cloudsat_data-image" name="cloudsat_data
            <init_from>../images/20070820_19_007.png</init_f
```

```
    </image>
  </library_images>
  ……
  <library_geometries>
   <geometry id="mesh1-geometry" name="mesh1-geometry">
    <mesh>
     <source id="mesh1-geometry-position">
      <float_array id="mesh1-geometry-position-array" count="12">0 0 0 109.5 0 0 -2.548 0 28 0 12 0 300</float_array>
     </source>
     ……
     <triangles material="cloudsat_data" count="4">
      <input semantic="VERTEX" source="#mesh1-geometry-vertex" offset="0"/>
      <input semantic="NORMAL" source="#mesh1-geometry-normal" offset="1"/>
      <input semantic="TEXCOORD" source="#mesh1-geometry-uv" offset="2" set="0"/>
          <p>0 0 0 1 0 1 2 0 2 0 1 0 2 1 2 1 1 1 3 0 3 2 0 2 1 0 1 3 1 3 1 1 0 0 2</p>
     </triangles>
   </mesh></geometry></library_geometries>
  ……
</COLLADA>
```

The spatial coordinates for each model are calculated from the satellite orbit model and the orbit time in the form of year, month, day, hour, minute, and second (Durden, *et al.* 2004). Considering the rendering speed and accuracy of the orbit curtain in Google Earth, 10 seconds is selected as the minimum temporal range whose corresponding spatial range is represented by each model. The corresponding spatial range (about 67.7km) serves as a reference for determining the x value of the Collada model. The zoom scale in the x and z directions, is calculated from the x and z sizes, respectively, of the model and the real size represented by the model in Google Earth. The rotation degree of the model is derived from the coordinates of two endpoints of the orbit represented by the model. The detailed calculation formulas are available in Chen, *et al.* (2008). Table 3 is part of the KML codes for one image slice on the orbit track. It shows geospatial coordinates, rotation degree, and the scale of zoom-out for the 3D model.

Table 3 - Example of KML codes for one slice of image curtain

```
  <Placemark>
    <name>HourSlice_20070820_19_007</name>
    <description><![CDATA[]]></description>
    <Style id='default'></Style>
    <Model>
      <altitudeMode>clampToGround</altitudeMode>
      <Location>
        <longitude> 90.10498000</longitude>
        <latitude> -39.09050700</latitude>
        <altitude>0.000000</altitude>
      </Location>
      <Orientation>
        <heading>-103.548000</heading>
        <tilt>0.000000</tilt>
        <roll>0.000000</roll>
      </Orientation>
      <Scale>
        <x>1003</x>
        <y>1</y>
        <z>1.2002</z>
      </Scale>
      <Link>
        <href>models/20070820_19_007.dae</href>
      </Link>
    </Model>
  </Placemark>
```

This solution accurately places vertical image slices along the orbit track in Google Earth. Figure 6 shows part of the orbit curtain for cloud reflectivity (dBZ) from the CloudSat satellite. This vertical data orbit curtain function has been closely integrated into the Giovanni A-Train operation system. Users can directly download the KMZ file after they view the image curtain in their Web browser and open it as a curtain plot to overlay with any other scientific products in Google Earth.

Figure 6. The orbit curtain of CloudSat (radar reflectivity - dBZ) in Google Earth

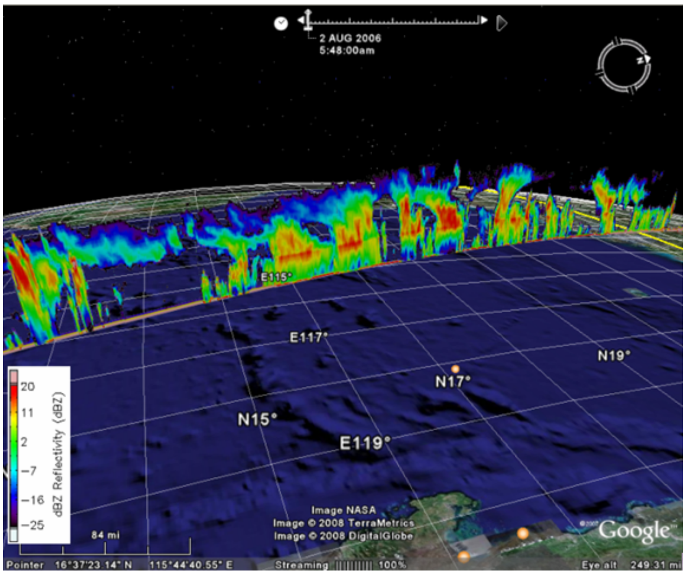
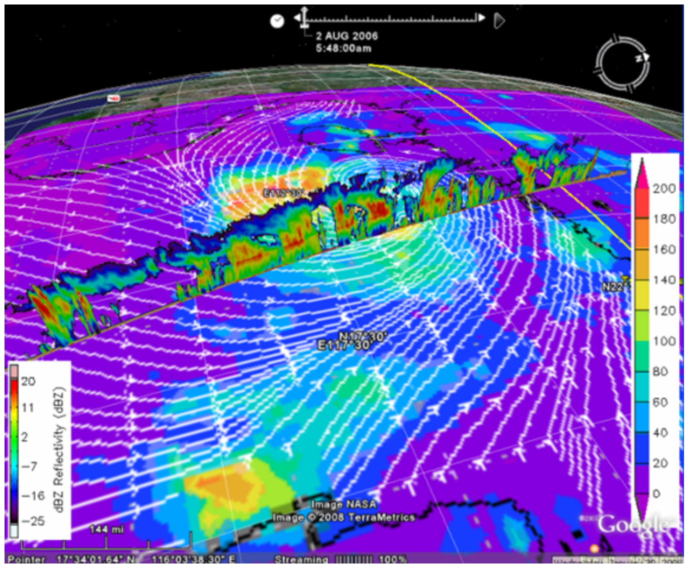


Figure 7. Integration of CloudSat vertical data with typhoon Prapiroon on 02 August, 2008 from TRMM



Scientific research of synergistic analysis and application in Google Earth

Figure 7 integrates data for the typhoon Prapiroon on August 2nd, 2006 from the TRMM satellite and from the CloudSat satellite. On this date, the typhoon was located over the South China sea and the CloudSat parameter shown is the dBZ reflectivity. The heights of the highest clouds are ~15 kms and substantial convective activity can be seen within the vertical structure of the typhoon. The 3B42 daily TRMM data is showing the rainfall rate and QuikSCAT data showing the wind in the area of typhoon. The integration clearly shows the relationship and interaction of typhoon, rainfall, cloud, and wind. Scientists use such results to forecast weather and disasters, analyze climate change, report air quality, and carry out other atmospheric-related scientific research. It can also help general users to comprehend relationships among rainfall, cloud, and wind.

A real-time weather forecast can be implemented in Google Earth and shown on the Earth's surface. Professionals can utilize the existing landmarks, road signs, and political boundaries in Google Earth to accurately judge the location of thunderstorms or sandstorms to refine forecasts or advance research. With the wide and increasing utilization of high resolution Google Earth images in scientific communities and public discourse, such scientific research and applications become more interesting and practical. As concern about global climate and environment change becomes more serious, scientists, decision-makers, and policy-makers must be increasingly concerned about the regional environment and the occurrence of sudden natural disasters. This methodology allows scientists to easily integrate socio-economic data and information with geospatial data to enable improved decision-making during crises, exemplified by hurricane forecast and rescue operations. Based on Google Earth, all past and near-real-time data and information about the atmosphere, sea and rainfall from satellites and ground stations can be integrated for decision-making agencies and individuals. Any available or possible information related to rescue tools, search plans, agents, and volunteers can be dynamically and interactively put together via geospatial position in Google Earth for timely rescue and help.

Related research and discussion

Displays of 2D flat data using Google Earth are widely used for geospatially related data from satellite, aerial and ground stations. The best example of displaying 2D geospatial data is Google Earth itself. GES DISC is one of a few pioneer organizations using online geospatial data access and processing services, such as OGC WMS, WCS, and G3, to display 2D meteorological data and their analysis results in Google Earth, enhancing the value of geospatial data. In particular, OPeNDAP and GrADS protocols are used to ubiquitously provide online geospatial data to analysis and processing services, which further process data in the manner requested by the user.

In addition to the solution to visualizing vertical geospatial data in Google Earth described above, there are two other solutions for rendering a 3D orbit curtain in Google Earth: The first one is directly to process geospatial data values to produce a KML file that creates a flat curtain in Google Earth. The curtain is made from many vertical small rectangles over the surface of the Google Earth. At the highest resolution, the length of each rectangle represents the distance the satellite travels in 5 seconds. The problem with this method is that the rendering speed is very slow if the curtain resolution is as good as the one from our proposed solution, but if the rendering speed is faster, the curtain resolution and quality are not good enough for scientific research and applications. So, our approach is fast, of high resolution and high quality. The second solution is to first design the orbit model, then, project geospatial data onto the model using SketchUp's "texture" feature. This method is used for creating the orbit of planet Saturn. The orbit of Saturn completely covers the virtual globe from Google Earth. When zooming in, the orbit of Saturn is not visible on the high-resolution surface of Google Earth. It is not suitable for displaying high-resolution geospatial data over Google Earth surface through this kind of orbit model. Moreover, the orbit of Saturn uses one generalized image stripe repeatedly as the texture of the Saturn 3D orbit model (Barnabu 2006). However, the curtain images from NASA satellites vary greatly. So, this solution is not suitable for visualizing vertical geospatial data in Google Earth.

Geens (2006) first suggested displaying vertical data in Google Earth. But the description about how to display the vertical data is rough, and the position where the image is placed in Google Earth is not accurate. No systematic and scientific procedures are related to the calculation of the position, scale, and rotation degree of a 3D data model along with the satellite orbit in Google Earth. Yamagishi *et al.* (2006) provided a tool to convert a seismic tomography model into KML files. The KML file used the first method discussed above. The latitude, longitude, and altitude data are provided using a seismic model for rendering the flat rectangle to represent the geospatial data in Google Earth.

Our solution makes image products at GES DISC available beyond the scientific and research communities. Thus, the virtual globe Google Earth can be used with these products for national public applications with societal benefits. Virtual globes are becoming the next generation framework for sharing data, information and knowledge, collaborating in scientific research, and visualizing education in many disciplines.

It is worthy mentioning that KML 2.2 (Beta) directly supports vertical images in Google Earth via a new tag named 'PhotoOverlay' (Google 2007a). It can directly and vertically display images on the surface of the Google Earth. We tried to use it to render the vertical data in Google Earth. However, the following issues were encountered:

1. Small-scale photographs are acceptably rendered. However, when large-scale images are displayed, one end of the image is on land, but the other end rises into the sky.
2. It is not easy to control the scale and rotation degree relative to satellite orbit.
3. Only one side of the image is viewable, no matter how you rotate the globe. But, our current Collada model can display both sides of the vertical image data.

Conclusions and future work

Our general solutions to visualizing both 2D flat data and 3D vertical data in Google Earth enhance the usefulness of geospatial satellite data at GES DISC. 2D geospatial data are accessed and processed into images through standard protocols, such as OPeNDAP, OGC WMS, and directly offered to Google Earth with proper control parameters for visualization. The most important feature of the solutions is that diverse data access and processing are transparent and independent of platform, data format, and application requirements.

An innovative solution is proposed to render 3D geospatial data profiles into vertical orbit curtains by following the Collada and KML standards and visualized in Google Earth. A new curtain model for specific physical phenomena is proposed based on satellite orbit parameters. The key merit of the solution is the ability to reveal new information and knowledge that would otherwise have been hidden by visualizing and comparing diverse simultaneous geospatial data from different data resources in a unified platform – virtual globes. Successful implementations have been released online and can be accessed at the website *http://disc.sci.gsfc.nasa.gov/googleearth/*. These general solutions can be applied to most geospatial data to integrate them into Google Earth for collaborative and synergistic scientific research and applications.

In the near future, more vertical data will be overlaid on one orbit curtain to compare and visualize different physical parameters from the A-Train constellation and other satellites. Currently, vertical data profiles for different kinds of physical parameters from CloudSat, CALIPSO, AIRS, and MODIS-Aqua are transparently integrated on one orbit curtain. Each kind of implemented data product is given an online available KMZ example in Table 4. Interested readers can download and view them in Google Earth. More examples and an online access system are available at *http://disc.sci.gsfc.nasa.gov/googleearth/*.

Table 4. KMZ examples of NASA GES DISC 2D and 3D geospatial data products

2D AIRS	*http://disc.sci.gsfc.nasa.gov/googleearth/examples/AIRS-AIRX3STD-2007-07-29_CldTopTemp.kml*; (combined cloud top temperature (Kelvin))
2D TRMM	*http://disc.sci.gsfc.nasa.gov/googleearth/examples/TRMM-3A12-2000-07-01-.kmz*; (0.5 x 0.5 degree gridded monthly product comprised of mean 2A12 data and mean surface rainfall (mm))
3D MODIS/Aqua	*http://disc.sci.gsfc.nasa.gov/googleearth/examples/20070223_12_TP.kmz*; (atmospheric temperature (Kelvin))
3D CloudSat	*http://disc.sci.gsfc.nasa.gov/googleearth/examples/20070223_12_dBZ.kmz*; (cloud radar reflectivity (dBZ))
3D CALIPSO	*http://disc.sci.gsfc.nasa.gov/googleearth/examples/20070223_12_calipso.kmz*; (cloud/aerosol classification (Vertical Feature Mask))

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Glossary

AIRS: Atmospheric Infrared Sounder
CALIPSO: Cloud-Aerosol Lidar and Infrared Pathfinder Satellite
Collada: the COLLAborative Design Activity
DISC: Data and Information Service Center

EOS: Earth Observation System
G2: Giovanni Version 2
G3: Giovanni Version 3
GES: Goddard Earth Science
GES DISC: Goddard Earth Science Data and Information Services Center
Giovanni: GES-DISC Interactive Online Visualization ANd aNalysis Infrastructure
GrADS: Grid Analysis and Display System
HDF: Hierarchical Data Format
KML: Keyhole Markup Language
KMZ: KML Zipped file
MODIS: MODerate-resolution Imaging Spectraradiometer
OGC: Open Geospatial Consortium, Inc.
OPeNDAP: Open-source Project for for a Network Data Access P
TRMM: Tropical Rainfall Measurements Mission
WMS: Web Map Service
WCS: Web Coverage Service
WFS: Web Feature Service

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