CloudSat Reflectivity Data Visualization Inside Hurricanes

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Abstract – Animations and other outreach products have been created and released to the public quickly after the CloudSat spacecraft flew over hurricanes. The automated script scans through the CloudSat quicklook data to find significant atmospheric moisture content. Once such a region is found, data from multiple sources is combined to produce the data products and the animations. KMZ products are quickly generated from the quicklook data for viewing in Google Earth and other tools. Animations are also generated to show the atmospheric moisture data in context with the storm cloud imagery. Global images from GOES satellites are shown to give context. The visualization provides better understanding of the interior of the hurricane storm clouds, which is difficult to observe directly. The automated process creates the finished animation in the High Definition (HD) video format for quick release to the media and public.

Keywords: CloudSat, visualization, hurricanes, Google Earth

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1. INTRODUCTION

As an addition to the NASA's A-Train constellation to observe the weather on earth, CloudSat was launched on April 28, 2006 from Vandenberg Air Force Base. Its purpose is to provide the detailed measurements of the vertical structures of clouds and the vertical profiles of cloud liquid water and ice content. The quicklook images of the observed data have been available to the public on the project's website.[1] A new software script has been set up to automatically generate easy-to-understand animations, by combining the CloudSat quicklook data with the infra-red cloud images by the GOES satellite.

The animations are rendered in full HD video format, which is compatible with the current broadcasting television standard, within a few hours after the CloudSat quicklook images become available on the website.

2. CLOUD PROFILING RADAR (CPR)

2.1 CloudSat Mission

CloudSat was selected as a NASA Earth System Science Pathfinder satellite mission to provide observations necessary to advance our understanding of cloud abundance, distribution, structure, and radiative properties.

CloudSat was co-launched with the CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations) satellite aboard a Delta II rocket. In a series of maneuvers, CloudSat and CALIPSO joined three satellites already in orbit (Aqua, PARASOL, and Aura) to form a constellation of satellites known as the A-Train on 1 June 2006. The satellites fly in a nearly circular orbit with an equatorial altitude of approximately 705 km. The orbit is sun-synchronous, maintaining a roughly fixed angle between the orbital plane and the mean solar meridian. CloudSat maintains a close formation with Aqua and a particularly close formation with CALIPSO, providing near-simultaneous and collocated observations with the instruments on these two platforms.

2.2 CloudSat Instrument

Since 2006, CloudSat has flown the first satellite-based millimeter-wavelength cloud radar—a radar that is more than 1000 times more sensitive than existing weather radars. Unlike ground-based weather radars that use centimeter wavelengths to detect raindrop-sized particles, CloudSat's Cloud-Profiling Radar allows the detection of the much smaller particles of liquid water and ice that constitute the large cloud masses that make our weather.

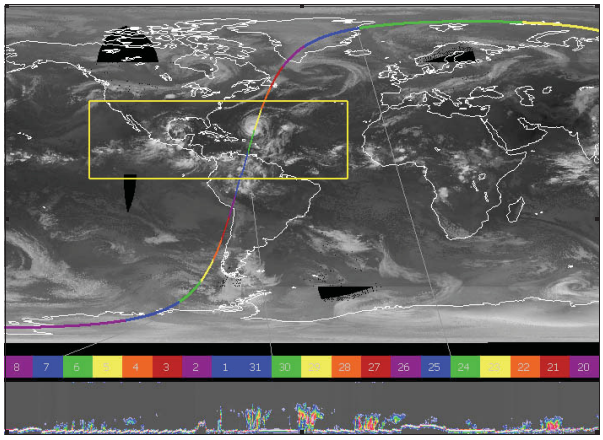

Figure 1 - CloudSat orbit on September 18, 2010. CloudSat flew over Hurricane Igor to the east of Florida, while flying from over Greenland to South America. The yellow box indicates a typical "storm search" area.

2.3 Data Description

The primary CloudSat data used for the browse and animation product generation is the quicklook product. These quicklook products are images showing the atmospheric moisture content profiles with predefined colormaps applied. The A-Train satellites complete an orbit approximately every 90 minutes and CloudSat products for all orbits on a given day are archived together within a directory. Each orbit is divided into 31 granules, each representing about 3 minutes of orbital motion or about 11.6 degrees of arc or about 700 nautical miles of ground track. Thus, a pass over a storm will typically occupy

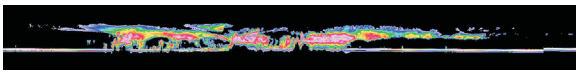

Figure 2 - Quicklook image of the reflectivity data acquired by the CPR while flying over Hurricane Igor

one or two adjacent granules. Figure 1 illustrates an orbit that passed over Hurricane Igor in September of 2010. Figure 2 illustrates a composite of two adjacent granules (numbers 29 and 30 in Figure 1) containing the path through Igor. More information on the CloudSat mission can be found in the work by Vane and Stephens[2] and project materials[3].

3. BROWSE PRODUCT (GOOGLE EARTH)

3.1 Description

The Google Earth browse product is a rapidly generated, zipped file containing all the necessary data for display in the Google Earth application. The methodology used to generate them is based strongly on the work of Chen, et al[4]. These browse products are generated in approximately 30 seconds and posted to a web site for download.

Google Earth accepts files in the Keyhole Markup Language (KML) format for describing features relative to the Earth. Since the browse products also contain image files for the profile data as well as globe overlays, all the data files are combined into a compressed file, using the zip utility, called a KMZ file. This file is the product posted on the website.

Each browse product is generated by a set of scripts and utilities beginning with the specification of the latitude and longitude and name of a specific storm. Typically the latitude and longitude will identify the current location of the eye of a hurricane. An optional time may be specified that identifies the UTC time at which the storm eye was located at the specified latitude and longitude. The script then downloads available data and produces the KMZ file.

The procedure for creating the KMZ file is as follows:
1) Download TLE orbital description file for specified time
2) Determine closest approach to specified location
3) Download adjacent granules for closest approach
4) Crop granule images to remove ground effect noise
5) Slice images into narrow vertical sections
6) Make images transparent if no moisture content
7) Create collada file for each vertical strip
8) Reference each collada file in master KML file
9) Add marker for storm center
10) Add description of orbital path
11) Optionally add GOES image of storm
12) Compress (zip) all files and images into KMZ file
13) Post the KMZ file on a website for perusal

Figure 3 shows the result of running the process on a CloudSat pass over Igor on September 16, 2010, as displayed in Google Earth. The resulting KMZ file is just over 85KB, with most products between 55KB and 100KB. These products download rapidly for perusal by science team members and the public.

Due to the motion of a storm, it is possible that determining the closest approach by the CloudSat CPR is not useful enough to be of interest. In fact, the instrument might never pass over the storm if its path moves it away from the spacecraft's track. Thus, a different approach to this problem was taken for the animation products, described in the next section.

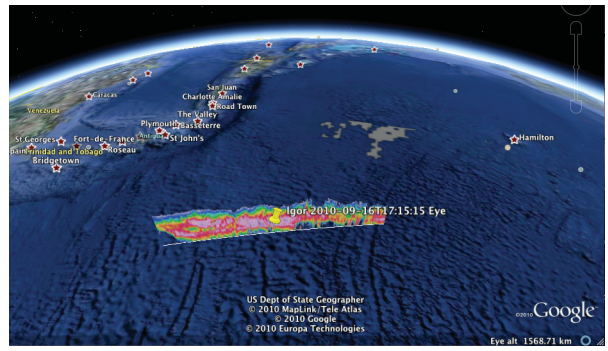

Figure 3 - A CloudSat profile in Google Earth of Hurricane Igor on September 16, 2010

4. ANIMATION PRODUCT

4.1 Creating the Animation Product

The CloudSat data represents the moisture inside of the clouds, which is not visible from outside. In order to present the data in the appropriate context, an automated script creates animations to show the global cloud motion, the three-dimensional shape of the cloud surrounding the data, and then the data itself.

For creating the animation products, a different algorithm was implemented for selecting appropriate passes of interest. Rather than utilizing predefined locations of storms, the algorithm searches the quicklook products for images showing a relatively large moisture content that are located within a pre-defined storm search area, as illustrated in Figure 1. This methodology avoids issues such as missing or delayed data products and timing issues between storm motion and data collection. Rather than only processing "best" passes, it generates products for all "interesting" data.

The procedure for creating the animation product is as follows:
1) Run the script with a time period to search for storms and generate animations
2) Download the TLE orbital description file for the specified time period
3) Determine the time segment when the CloudSat spacecraft flew over the specified storm search area (Figure 1)
4) Download the latest quicklook images that cover the time period
5) Search for a significant storm within the images
6) Determine the start time, end time, and mid-point of the path over the storm
7) Determine the latitude and longitude of the mid-point using the TLE orbital description
8) Search and download the highest resolution GOES image that covers the specified location, and was imaged within one hour of the pass
9) Cut out a circular area of the downloaded GOES image around the midpoint of the pass
10) From the image, create a three-dimensional mesh representing the cloud top
11) Map the image to the mesh
12) Download GOES full disk images of the previous 72 hours at 3-hour intervals for global cloud motion
13) Determine the locations of all active hurricane centers and place a marker at those locations
14) Define camera motion
15) Render animation frames

16) Make a movie file from the rendered frames with timestamp and legend overlay
17) Send out an email notification that an animation has been rendered

Once the script is started, steps 2 through 17 are repeated until all passes by the spacecraft over the search area during the entire time period have been processed. Some of the key steps are explained further in the following sections.

4.2 CloudSat Orbit Determination
The CloudSat project's website publishes the CloudSat orbit in two-line element (TLE) format. Using the TLE files, the script finds a path in the specified region, defined by the east / west longitudes and north / south latitudes of the storm search area. The NAIF SPICE [5] toolkit is used to interpret the TLE and to determine the latitude and longitude of the spacecraft.

4.3 CloudSat Quicklook image
If the CloudSat path is within storm search area, the corresponding reflectivity quicklook image granules are downloaded, which is a similar step used by the browse product generation process. The downloaded granules are merged to form one large tile, then cropped from the starting time to the end time. The image is then examined to find any significant storm within it. A program adds density values in each column of the image. If the sum is over a predefined threshold value, the column is marked as "wet." If a series of "wet" columns are detected, it is determined to be a storm. Start time, end time, as well as the mid-point of the CloudSat path for the detected storm are calculated. The latitude and longitude are calculated using the two-line element data.

4.4 Creating a mesh model from GOES image
Once the location of a storm is determined from the quicklook image, the script searches for the most recent, highest resolution GOES image. Figure 4 is a full disk GOES-East image with hurricane "Igor" clearly visible in the frame.

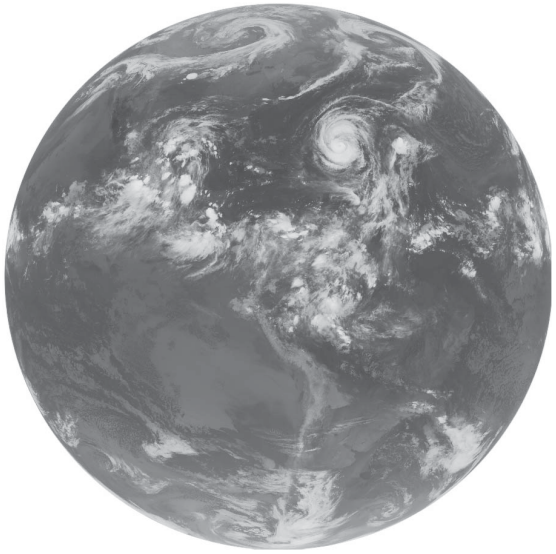

Figure 4 - IR-4 Image from GOES-East Satellite on September 18, 2010.
Hurricane Igor is visible to the east of Florida.

In the IR-4 image, the DN value of each pixel has a strong correlation to the height of the cloud. This channel, also called brightness temperature, is brighter for colder temperatures. Since colder air is generally at a higher altitude, and the ground and ocean are generally above the air temperature, the colder parts of the image generally represent the cloud tops. If the DN value of the pixel is above a threshold value, the pixel is considered to be the cloud top, and the height is estimated from the value. Values below the threshold are considered ground or water and are masked out via the use of transparency.

The GOES image file is accompanied by a 'nav' file, which lists the latitude and longitude coordinate for each pixel of the image. Using the latitude and longitude coordinate from the 'nav' file, as well as the height from the image, the cartesian coordinate of the pixel can be calculated. By connecting the adjacent pixels, a mesh of triangular polygons is created to represent the cloud top of the storm. Each vertex of the mesh includes the texture-mapping coordinate (u, v) to drape the GOES image over the mesh, and to apply the transparency map. Figure 5 illustrates the resulting 3D polygon mesh model of the cloud tops with transparency where the cloud is thin or nonexistent.

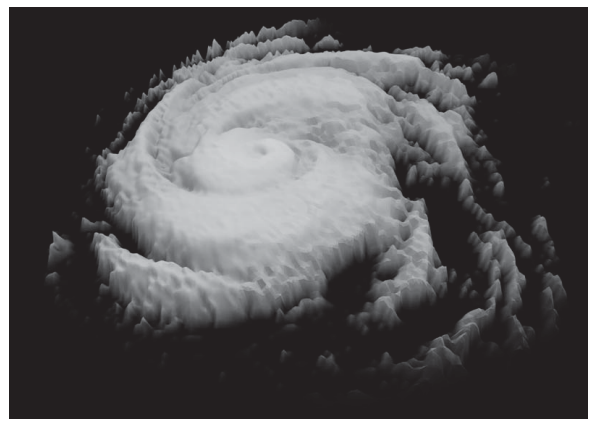

Figure 5 - 3D shape model of Hurricane Igor created from GOES IR-4 image.

4.5 Global cloud motion as context
To highlight the storm in a context of global cloud motion, full disk IR-4 images by the GOES satellite are displayed. It represents the cloud motion during 72-hour period prior to the CloudSat observation of the storm. GOES full disk images are posted on the web every three hours. Therefore, 24 images are flipped to show the 72-hour sequence at the beginning of the animation.

4.6 Tracking the center of the storms
During the hurricane season, National Hurricane Center (NHC) issues information of the active storms in the Atlantic and east Pacific regions. The script automatically interprets these announcements by downloading the source text of the web page and parsing it to determine the current location of the storm. An icon is overlaid on the storm clouds to indicate the center of the storm.

4.7 Setting the Camera Motion
The camera motion is automatically set by the script to view the 72 hours of global cloud motion from zenith at the beginning, then to smoothly change the camera position to

show the CloudSat spacecraft icon passing over the hurricane, while the quicklook image is revealed from right to left. The early camera view allows the viewer to understand the location of the storm in a global context, and to understand how the storm has moved in the past three days. The camera motion allows the viewer to then visualize the storm cloud shape and size relative to the earth. Then the right to left image exposure allows the viewer to connect spacecraft motion and cloud shape to the revealed data and time.

4.8 Rendering Animation Frames
After the script has acquired the data, the movie frames are rendered using a commercial off-the-shelf (COTS) animation rendering software. For a typical 25 to 30 seconds of animation, it takes a little more than an hour to render the whole sequence in full HDTV resolution (1920x1080, 29.97 interlaced) using a single desktop computer. Since the rendering is done frame-by-frame, the production time can be reduced by rendering in parallel using multiple computers.

4.9 Compositing Animation with Timestamp and Legend
The timestamp movie file to indicate the date and time is rendered separately. The frames of the timestamp movie contain only the timestamps displayed in the upper-left corner in sync with the spacecraft position. After the rendering is finished, the main movie frames, the timestamp movie, and the reflectivity color scale are composited by COTS software, as seen in Figure 6. The final movie output is a full HD resolution animation file, which is ready for playback or copy to a tape. A smaller size movie is created from the full HD resolution movie, also. The reduced size movie can be posted to a website or broadcast via email.

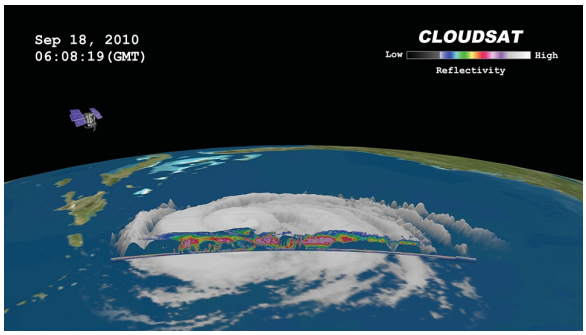

Figure 6 - Final composited frame

4.10 Automated Notification
For each CloudSat path that crosses the search area, the script determines if there was a storm cloud or not. If a storm was found, the entire animation is rendered. The small size movie file created from the full HD movie is sent by email as an attachment to a list of pre-registered recipients for immediate notification. The email contains other metadata information, such as location of the storm and date/time.

If no storm was found, only the still images of the first and last frame of the animation are rendered and attached to the message to notify that there was no storm in the path. The movie and images in a message can be viewed not only on a desktop and laptop computers, but also on handheld mobile smart phones. Because of the time sensitive nature of the hurricane observations, this automated notification to the mobile phones is essential to the release of the animations to the media and to the public in a timely manner.

5. CONCLUSION

This work has demonstrated a methodology to automatically generate interesting outreach products in various formats for satellite data. In particular, the outreach products for CloudSat overflights of hurricanes and other large storms provide useful glimpses into the inner workings of such storms. These products are generated automatically as standard mission data products are generated, with no operator input. The products include Google Earth browse products for interactive exploration and High-Definition video animation products for media use. Automated notification of product generation puts the data products in the hands of people who are able to choose the appropriate dissemination outlets.

6. FUTURE WORK

The current version of the product generation tools is limited to using the IR-4 channel from the GOES-East and GOES-West satellites, allowing product generation for the western Atlantic, eastern Pacific, and the North and South American continental masses only. Future work would extend these tools to incorporate METEOSAT and other meteorological satellite data to provide products for other parts of the world.

Another desired product would be three-dimensional (3D) video products for display on new 3D-capable video displays. This would require additional rendering time, about double the current time, as well as experimentation into appropriate parallax and eyepoint separation for optimal viewing.

ACKNOWLEDGEMENTS

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