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13.2 REVISTING 3D STEREO SATELLITE IMAGE DISPLAYS

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1. Introduction

This past spring, a super salesperson convinced my Department Chairman that “students learn better in 3D”. The Department Chair bought a 3D projector system which uses the technology currently available in 3D TVs. The projector uses shutter glasses which turn on and off for the right and left images. After delivery of the system, the Chair then expected the faculty to start using the new 3D projector for class presentations, not realizing that the infrastructure for 3D presentations is not yet very mature. However, the 3D “fad” may be more than a passing craze. I checked at a local TV store and the sales person said that over half of the larger TV sold were 3D TVs. Even without 3D shows, the 3D TVs are sharper for normal shows because of the high 120 or 240 Hz refresh rates. Hence an infrastructure of 3D TVs are going into homes, which opens a potential market for original 3D presentations. Since weather is naturally a 3D phenomenon, it makes sense to think about development of 3D data sets for future 3D weather presentations.

2. 3D Developments from 30 Years Ago-True Stereo

The use of 3D weather displays is a case of déjà vu. Around 30 years ago, there was a flurry of development activities using binocular 3D technology. In the Feb. 1981 issue Bulletin of the AMS (BAMS), Fritz Hasler of NASA Goddard Space Flight Center had a cover article on stereographic images generated from two GOES satellites. Figure 1 shows the BAMS cover. This image required red/cyan glasses with the red on the right. (Note current red/cyan glasses have the red on the left so to view figure 1 turn your glasses backwards.) The two

GOES images were remapped into a common projection. One of the resultant remapped images was projected through a red filter and the other through a green/blue (cyan) filter. The colored glasses allows for one eye to see the east image and the other to see the west. The remapping algorithm would calculate the latitude/longitude of the ray going from the satellite to the surface of the Earth. If the cloud was above the surface of the Earth, the computed latitude/longitude would be displaced east or west of the true location.

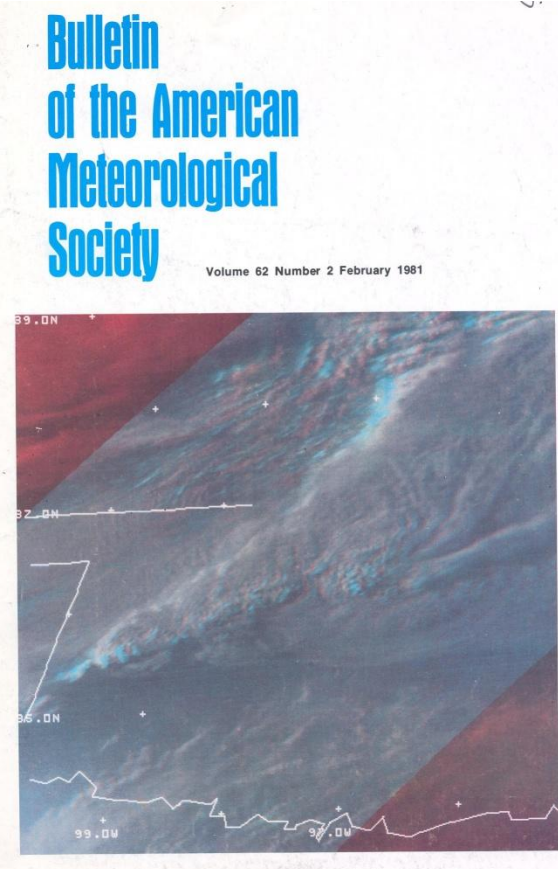


Figure 1. The February 1981 cover of the Bulletin of the AMS showing a true 3D satellite image of a severe storm in the Midwest. The 3D image was generated by remapping GOES-east and west images into a common projection. (Hasler , 1981)

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The higher the cloud, the more the remapping software would generate east/west displacements due to parallax. While true stereo pairs could be generated from the two GOES satellites, the technique never became widespread. In order to generate a stereo pair, both satellites need to scan the same location at the same time. During the 1980's, the satellite scanning schedules had a 15 minute displacement in start times for the images. Only during rapid scan operations during severe weather outbreaks would it be possible to time match images. The second problem with the true stereo was that the field of view of both satellites needed to overlap. This was possible only in the Midwest sections of the US.

3. 3D Developments from 30 Years Ago-Artificial Stereo

The limitations of the true 3D stereo satellite images led to the development of artificial stereo techniques. The infrared temperature was used to generate a parallax shift of the images. The colder the temperature, the bigger the parallax shifts of the pixels. Fritz Hasler had another 3D cover image of the July 1981 issue of BAMS. Figure 2 shows this BAMS issue with the 3D image of Hurricane Allen on the cover. In the same article, 3D displays of meteorological fields were also demonstrated. The purpose of the 3D displays was to provide an intuitive representation of the cloud height and meteorological fields. The primary drawback (other than having to wear colored glasses) of the artificial stereo satellite images was that the sensed infrared temperature is not always the true temperature. This caused thin cirrus clouds to look too low. The colored glasses used to separate the two colored images into a left and right eye also had the disadvantage of limiting color images. The technique worked well for black and white images, such as satellite images, but had major problems with varied graphical colors used for weather displays.

Back in the early 1980's I was excited about the possibilities of 3D displays, but the 3D "fad" did not withstand the test of time. When I went to my first job at the National Weather Service, I put some of my 3D software on the computer to show the forecasters. They were underwhelmed. Their comment was "I don't need funny glasses to tell how high a cloud is. I can tell just by looking at the infrared image." So I put my funny glasses in the bottom of my file cabinet, and 30 years later, they were still there.

While the binocular 3D display developments for weather data largely stopped by the mid 1980's, development efforts for perspective 3D continued. Bill Hibbard of the University of Wisconsin-Madison developed an interactive volumetric perspective display capability called Vis5D. The Vis5D source code was made freely available over the internet, and it formed the basis for other interactive perspective rendering displays, including the IDV software package available from the Unidata program and the Mcidas-V available from the University of Wisconsin. The fast rendering of the displays allows the user to change their viewing angle which provides three dimensional information on the relative height of the object being viewed.



Figure 2. The July 1981 cover of the Bulletin of the AMS showing an artificial stereo image of Hurricane Allen. The parallax is generated by shifting the visible image according to the infrared temperature. Use red/cyan glasses with the red lens on the right to view the image. (Hasler, et.al., 1981)

4. Today's 3D Satellite Data -True Stereo

In addition to the development of 3D TV display systems, many of the original problems of the 3D images of 30 years ago are no longer as serious as previously. The true 3D images generated by remapping GOES-east and west images can now be done routinely. The change of offset 30 minute scans of the satellites to routine 15 minute scans for both satellites has eliminated most of the timing problems. Also the availability of fast remapping algorithms has allowed for real time production of parallax image pairs. The web site http://wx.erau.edu/erau_sat/ has true 3D visible images over the Midwest. The GOES-east and west CONUS data sets are remapped to a rectilinear projection (equal lat/lon coordinates) centered at KMSF, KICT, KPIR, KABQ, KDEN, AND KCOD locations. The remapped resolution is 1.5 km with an image size of 900x1200 pixels. The nighttime portion of these images uses the 3.9-11 micron difference to generate a pseudo visible image at night. Figure 3 shows an example of a true 3D image displayed in anaglyph form for red/cyan glasses. The generation software also makes left/right pair images for use in 3D TV displays.

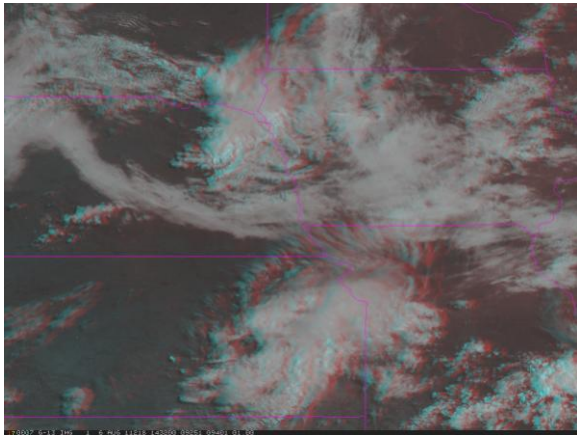


Figure 3. Example of true 3D visible images generated from remapped GOES-east and west images on August 6, 2011 at 14:30 UTC. These true 3D images are routinely available from http://wx.erau.edu/erau_sat/ for the Midwest US. The anaglyph glasses required for these have the red lens on the left and the cyan lens on the right.

5. Today's 3D Satellite Data – Artificial Stereo

The artificial stereo processing of Hasler, et.al. used the original image as one of the left/right pairs, and generated the other using the IR temperature to shift the original image. One of the problems with this method is what to use to fill in the hidden low clouds after a shift. For instance, the left side of a high cloud will shift right several pixels. In a true stereo shift, the satellite on the left will be able to see the low clouds under the higher clouds, but the artificial stereo does not know what is under the cloud. The normal way to handle this problem is to keep the high cloud values over the holes, which causes some image distortion of the resultant product. In the current processing two shifted images are generated. Left and right shifted images are generated, rather than one large shift. By splitting the shifts into a left and right component, the filled holes are half the size of the total shift, which reduces the image distortion. However the problem of filling the holes caused by the shifts limits the amount of apparent depth of the images. If one makes a huge shift (to make the clouds jump out of the screen a large amount) the distortion of the filled holes becomes noticeable. Hence the 3D images available at http://wx.erau.edu/erau_sat/ are configured to show clouds as one would see them from a spacecraft high above the clouds, rather than from an airplane flying among the clouds. The maximum shift for the 3D image generation is an input parameter and was arbitrarily set to generate the vertical image displacement similar to that generated by the true 3D images.

The IR temperature is not a linear function of cloud height. Rather than use the cloud top temperature directly for the calculation of the shifts, the current processing converts the IR temperature into cloud heights in meters. The conversion of IR temperature to cloud height requires knowledge of the temperature structure of the atmosphere for every pixel of the satellite data. Rather than use more accurate current observational or model data, the processing uses a climatological sounding function based on date and latitude. The advantage of the climatological sounding is that all the points are in data statements and the resulting calculations are very fast. For most situations, this climatological sounding conversion works well. However, unusually cold surface weather can cause low clouds to appear higher than they should be.

The conversion of IR radiances into cloud top temperature uses the assumption that the cloud is a blackbody. While the blackbody assumption is valid for large, thick clouds, thin or small clouds will violate this assumption and appear too low. Cirrus clouds in particular are a problem and appear too low. The true 3D stereo images do not suffer from the blackbody assumption, so the true 3D images can be used to judge how large the height errors are. Measuring the IR temperature of cloud elements with the correct apparent height and other clouds with too low apparent heights showed cloud top temperatures to be 20 to 30 degrees C. too warm. The problem is illustrated in figures 4a and 4b. Figure 4a shows the true stereo image which shows all the clouds being at the same height. Figure 4b is the artificial stereo showing the clouds to be at different heights.

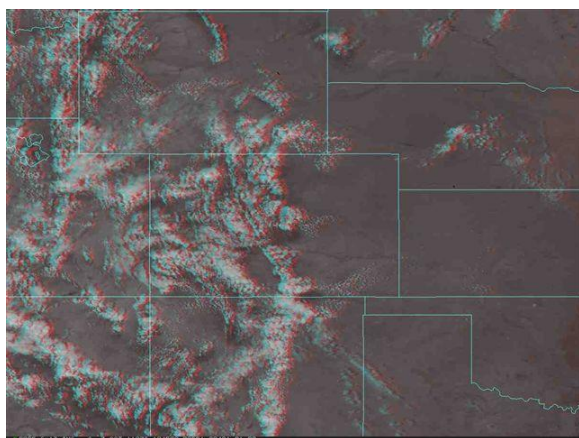


Figure 4a. True 3D showing clouds to be at same height.

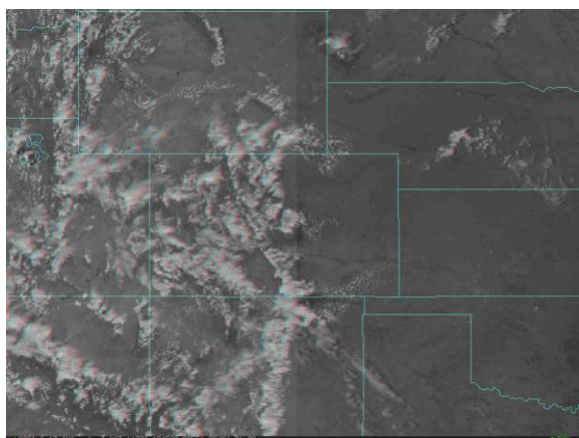


Figure 4b. Artificial 3D showing the clouds to be at different heights. The thin clouds are not blackbody radiators, so the IR temperature is too warm making some clouds appear too low.

6. Cloud Height Correction

The problems in computing cloud heights illustrated by figure 4.a & 4.b are caused by thin clouds transmitting radiation emitted from lower in the atmosphere through the cloud. The resultant IR temperature then is warmer than the true cloud top temperature. Several techniques have been developed previously to deal with this problem for the height assignment of cloud tracked winds. A CO₂ slicing technique (Menzel et. al 1983) used a CO₂ channel in conjunction with the 11 micron channel and a clear sky radiance to calculate the cloud top pressure for thin cirrus cloud tracers. While this technique can be applied to areas covered by the GOES and MSG satellites, it cannot be applied worldwide on all the geostationary weather satellites. Another cirrus cloud height technique (Szejwach 1982) was based on the 11 micron and 6.5 micron water vapor channels where several pixels viewing different cloud amounts were extrapolated to the correct cloud height. While this technique works for cloud tracked winds, it cannot determine a unique height for each pixel.

For this application, a different method was developed for approximating the height of thin cirrus clouds for each pixel. The method first identifies thin cirrus clouds and then utilizes the black body temperature of the water vapor channel rather than the IR channel to determine the cloud temperature/height. Since the underlying radiating surface for the water vapor channel is higher in the atmosphere than the underlying radiating surface for the 11 micron channel, the water vapor cirrus temperature should be more correct than the IR temperature. The algorithm for identification of the cirrus clouds is to first perform a high pass filter on both the IR and water vapor images. The current high pass filter consists of computing a running mean of 300 pixels and taking the difference between the pixel value at the center of the running mean and the average value. Pixel difference values which are less than zero are set to zero, so the high pass filter only contain values for clouds which are colder than the running average. In addition to the high pass values for both the IR and water vapor channels, a running standard deviation (within a 12 pixel window) is computed. The cirrus detection requires that both the IR and water vapor channel contains a high pass value and the IR standard deviation has some value. If the cirrus detection algorithm is positive, then the IR pixel value is replaced with the water vapor pixel value. Figure 5 shows the result of the cirrus filter. Figure 5a is the IR

image, figure 5b is the water vapor, and figure 5c are the pixels identified as cirrus which subsequently had the IR values replaced with the water vapor value.

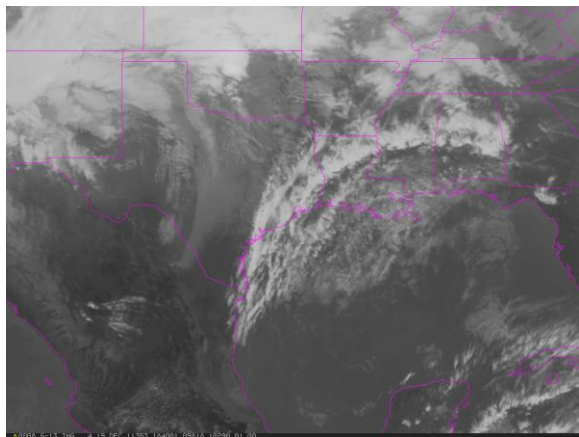


Figure 5a showing the original IR image.

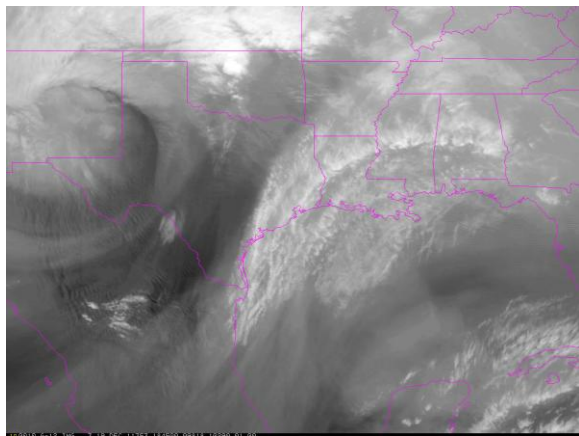


Figure 5b showing the water vapor image of 5a.

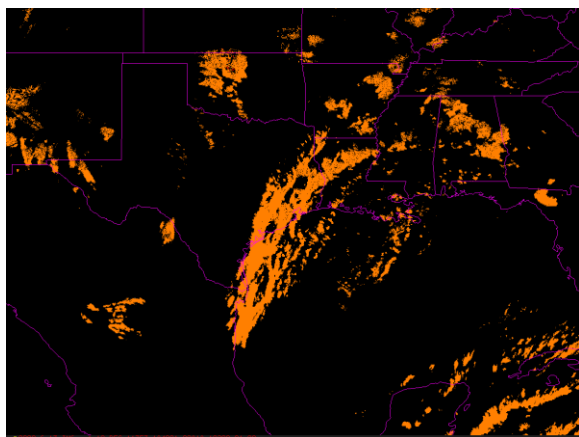


Figure 5c. The pixels identified as being cirrus which resulted in the IR pixel value being replaced by the water vapor pixel value.

Note how the cirrus clouds are identified, but the solid clouds are not.

While this cirrus cloud identifier algorithm improves the cloud height assignment, it is not perfect. Very thin cirrus clouds are sometimes not cold enough to be colder than the running average IR value. Another noted problem is that cirrus clouds that occur in a dry slot of the water vapor frequently are assigned a height which is too low since the underlying water vapor temperatures are warm. The other noted problem of the technique is that cirrus clouds to the east of a large cold cloud mass are not identified since the running average to the left have such cold values.

7. Applications

The 3D products have been routinely generated for the past few months. These include true 3D day/night visible images for the Midwest, synthetic 3D day/night visible, IR convective diagnostic, and Water Vapor images for 1 km sectors over the eastern $\frac{3}{4}$ of the US, and 4 km day/night visible sectors for the Western Hemisphere. The red/cyan anaglyph images have been posted to the web at http://wx.erau.edu/erau_sat and are publically available. The left/right image pairs have been made available internally for the 3D projection TV in the Weather Lab. While the 3D effect is noticeable using the red/cyan glasses, the 3D projection TV display is impressive. However to use the 3D projector, one has to turn off the overhead florescent lights because of the interference of the 60 Hertz light cycle with the 120 Hertz 3D glasses.

The question of the utility of the true 3D vs. the synthetic 3D showed a bias toward the synthetic 3D images. The true 3D images suffered from the pixel size of the original satellite images allowing only a limited range of vertical displacements. The synthetic 3D images allowed for a sharper image with better vertical displacement as well as being available anywhere. The true 3D images proved useful only as a ground truth for the impact of the IR temperature correction described in section 6. Users tended to go to the synthetic 3D image for viewing weather situations.

So back to the original premise which stated “students learn better in 3D”. The students are very enthusiastic about the 3D satellite images. Some of the enthusiasm is most likely due to the novelty of the presentation, but I believe that the 3D display does provide insight lacking in other traditional displays. The 3D displays have the most impact when there are

multiple layer clouds. The 3D displays helps the student understand which cloud are high and which are low and the relationship of the different flow patterns at the different levels. Figure 6 shows an image from October 9, 2011 at 17Z of a storm off the Florida coast. There was deep convection northeast of Miami, and the beginnings of a low level circulation east of the Miami area. The 3D TV display has also been useful for a Synoptic Analysis class recently which illustrated isentropic flow. The 3D satellite pictures clearly showed the clouds rising as the flow moved north with the warm advection.

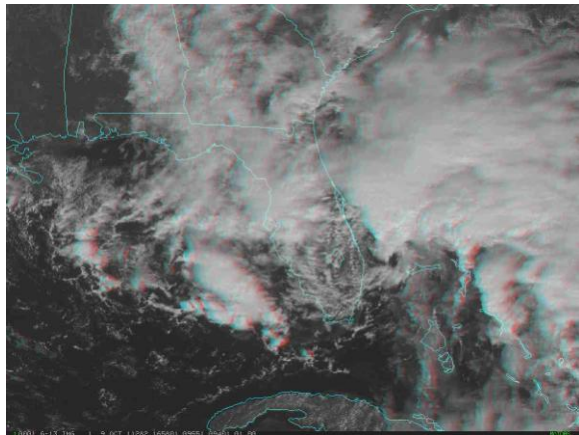


Figure 6 Disturbance off the Florida coast on Oct. 9, 2011 at 17Z. Animation of the images showed a low level closed circulation developing east of Miami.

The second concern about 3D technology was the view of the forecaster that "I don't need funny glasses to know how high a cloud is". I have been looking at the clouds on a daily basis with the red/cyan anaglyph glasses to get an impression of do they help me as a meteorologist to understand the weather. I keep a set of glasses at my computer at home as well as in the office. The biggest benefit is when there are multiple layers of clouds, such as a tropical disturbance. It is easier to see the low level circulation with the 3D glasses as opposed to the normal visible images. Another benefit which I had not expected is minor variations in height for oceanic cellular convection. There appears to be an organization of some of these clouds being slightly higher than others. As these clouds drifted over land the ASOS observations showed them to be around 2,000 feet higher than the other clouds. The slight height differences are not obvious from visual inspection of the IR or visible images, but show up nicely with the 3D. So the final conclusion I have is that the 3D technology has a future in meteorology. Future developments at ERAU will include expanding the satellite processing to the

entire global data set. Also we anticipate development activities using 3D graphic displays. The IDV software does have a 3D binocular 3D display capability which we have started to experiment with. We want to try combining the 3D satellite displays with 3D weather graphics.

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