Satellite Observations of the Elephant Butte Reservoir in New Mexico (USA)

Max P. Bleiweiss(1), Thomas Schmugge(2), William L. Stein(3)

(1) Dept. of Entomology, Plant Pathology & Weed Science, New Mexico State Univ.
PO Box 30003, MSC 3BE, Las Cruces, New Mexico 88003 USA
mbleiwei@taipan.nmsu.edu

(2) College of Agriculture, New Mexico State University
PO Box 30003, MSC 3AG, Las Cruces, New Mexico 88003 USA
schmugge@nmsu.edu

(3) Physical Science Laboratory, New Mexico State University
PO Box 30002, Las Cruces, New Mexico 88003 USA,
wstein@psl.nmsu.edu

ABSTRACT

Since the launch of NASA’s Terra satellite in December 1999, the Advanced Spaceborne Thermal Emission and Reflection (ASTER) instrument has made a number of observations of the Elephant Butte Reservoir. The first observations were in June 2000 and the most recent were in October 2007. This period includes the recent drought conditions and the earlier full water conditions. The area of the reservoir was estimated for each of these scenes and compared with known water levels. The ASTER observations include both the visible reflectance and the thermal infrared emission (surface temperature). Both spectral regions can provide good contrast between the water and the surrounding land. This contrast makes the area estimation straightforward.

INTRODUCTION

For many reservoirs there are considerable fluctuations in levels as water is drawn down for irrigation purposes. We present satellite observations of changes in the surface water area as evidence of this drawdown. Since the launch of NASA’s Terra satellite in December 1999, ASTER has made more than 30 observations of the Elephant Butte Reservoir located on the Rio Grande in central New Mexico, USA including night-time observations. The first observations were in June 2000 and continue to the present. This period includes low water levels resulting from the recent drought conditions and the earlier full high water conditions in 2000, resulting in a 25m change in water level. This change indicated a reduction of the water storage by more than half. The area of the reservoir was estimated for each of these scenes and compared with known water levels. Both visible reflectance and the thermal infrared data were used. These spectral regions provide good contrasts between water and surrounding land which makes the area estimation straightforward. A large range in surface water area was observed from 30,000 km² to more than 75,000 km². An approximately linear relation between area and water level was found.

Satellite sensors measure reflected and emitted radiation from the earth’s surface and atmosphere including clouds. Different land surface types (water, soil, vegetation) emit and reflect differently as a function of radiation wavelength. The portions of the electromagnetic spectrum that are commonly used in satellite remote sensing span the range from the blue part of the visible spectrum through the infrared portion to radio wavelengths. Spatial resolution varies with the “best” or, higher spatial detail, seen at visible wavelengths and lesser detail as one goes to longer wavelengths. An exception is the use of active remote sensing at radio wavelengths using synthetic aperture radar (SAR) where spatial resolution can be a few meters. A plot of reflectance with wavelength for a few common land surface types is shown in Fig. 1.

The ASTER sensor makes multispectral observations in three wavelength regions – visible to near IR (VNIR), shortwave IR (SWIR), and the thermal IR (TIR). The main characteristics of the ASTER sensor are:

- 3 bands in VNIR region with 15m spatial resolution
- Acquiring stereoscopic data on a single orbit
- 6 bands in SWIR region with 30m spatial resolution
- 5 bands in TIR region with 90m spatial
We make use of all these characteristics in the study reported here. The specific spectral ranges covered by each of the bands that the ASTER sensor uses are given in Table 1. The stereoscopic capability (band 3N and 3B) allows for the creation of a digital elevation model (DEM) from a scene – this was created for the Elephant Butte scene from July 7, 2004. The Terra satellite is in a sun-synchronous orbit whose equatorial overpass time (local) is 10:30 am which means that, nominally, observations are made on a daily basis in the morning and again at night, 12 hours later. The visible through shortwave IR bands are only usable in daytime (because they measure reflected solar radiation) while the mid-IR and far-IR (or thermal IR) bands can be used during both daylight and nighttime (because they measure emitted thermal radiation). The global coverage by ASTER is limited by several factors. Among these are the very high data rates as well as limited field of view. ASTER has limited capability for pointing off-nadir but its field of view only 60 x 60 km. The MODIS sensor on board the same satellite, Terra, for example, scans a swath that is 2330 km wide which is why it is able to make “daily” measurements. ASTER observations are on an “on-demand” basis and limited to about 650 scenes per day [1].

Parameters that can be derived from the observations of the ASTER sensor and are used in this study include (but are not limited to) the following: Normalized Difference Vegetation Index (NDVI) – a measure of green biomass, Land Surface Temperature (LST) (and water temperature), Short Wave Albedo (shortA), and Reflectance for a given channel (bands 3 and 4, in this study). Examples of most of these products for the reservoir are presented in Fig. 2.

DATA PROCESSING

The ASTER data that we used were provided by the Land Processes Distributed Active Archive Center (LPDAAC – http://edcdaac.usgs.gov/main.asp) and consisted of the following products:

- AST_05 – Surface Emissivity
- AST_07 – Surface Reflectance (VNIR, SWIR)
- AST_08 – Surface Kinetic Temperature
- AST_09 – Surface Radiance (VNIR, SWIR)
- AST_09T – Surface Radiance (TIR)
- AST_14 – DEM

We have these data for more than 30 observations between June 2000 and October 2007. Not all dates were processed through to final products for a variety of reasons that consist primarily in difficulties in differentiating the land surface from the water surface. The details of these difficulties will be discussed later. Ancillary to this estimation of area is an interest in the elevation contours of the reservoir – if we knew the elevation contour for a particular water level, we could also determine the area from that information.
Table 1. ASTER band designations and spectral ranges [1].

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Band No.</th>
<th>Spectral Range (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VNIR</td>
<td>1</td>
<td>0.52-0.60</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.63-0.69</td>
</tr>
<tr>
<td></td>
<td>3N</td>
<td>0.78-0.86</td>
</tr>
<tr>
<td></td>
<td>3B</td>
<td>0.78-0.86</td>
</tr>
<tr>
<td>SWIR</td>
<td>4</td>
<td>1.60-1.70</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>2.145-2.185</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>2.185-2.225</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>2.235-2.285</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>2.295-2.365</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>2.360-2.430</td>
</tr>
<tr>
<td>TIR</td>
<td>10</td>
<td>8.125-8.475</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>8.475-8.825</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>8.925-9.275</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>10.25-10.95</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>10.95-11.65</td>
</tr>
</tbody>
</table>

Preliminary Processing

The 60 x 60 km ASTER scenes needed to be rotated to true North and subsetted to the area of interest (a region 9.1 km by 23.9 km that contains the lower/main part of the reservoir) to make the subsequent processing more efficient. The subsetting was such that the resulting images include the reservoir from approximately Hellion’s Canyon near the “Narrows” to just south of the southern most extent of the reservoir (which is actually a bit farther south than the dam). In addition, all basic parameters were resampled to 15m to be compatible with the VNIR data – one could argue that, perhaps, it would be better or even more proper to resample to the 90m of the TIR data. An ASTER scene prior to resampling, rotation and subsetting is 4980 pixels wide and 4200 pixels high. The resultant rotated and subsetted scene is 605 pixels by 1595 pixels. The remote sensing software package ENVI®, by Research Systems, Inc., and its many tools was used for all processing described here.

For the creation of the various products to be used in the analysis, different algorithms were required. These are given below:

- Short wave albedo (shortA) [2]:
  \[
  \text{shortA} = 0.484 \rho_1 + 0.335 \rho_3 - 0.324 \rho_5 + 0.551 \rho_6 + 0.305 \rho_8 - 0.367 \rho_9 - 0.0015
  \] (1)
  
  where \( \rho_i \) is the reflectance in band \( i \).

- Land surface temperature (LST): (used as received from the LPDAAC after the above processing)
- Band 3 and 4 surface reflectance: (used as received from the LPDAAC after the above processing)
- NDVI:
  \[
  \text{NDVI} = \frac{\rho_3 - \rho_2}{\rho_3 + \rho_2}
  \] (2)

As part of this investigation, we also considered two other parameter but they did not show any promise. The first was emissivity and the second was nighttime LST.
Fig. 2. Examples of four products used in the estimation of area for Elephant Butte Reservoir from the observations of June 10, 2000. The products are, from left to right, Band4, LST, NDVI, and shortA.

Classification of Images

In order to determine the water and non-water pixels in an objective manner, some sort of classification scheme needs to be used. For our purposes here, it was decided to use a “density slice”. Basically, this type of classification examines the range of the data and separates the data into, initially, some default number of equally spaced ranges of data values. This is shown graphically in Fig. 3 where a histogram of data values is shown and the delineation of the various “slices”, or ranges, is shown. Once a density slice image was created, visual inspection determined whether the data were useful for further analysis – if there were no obvious discrimination between the water and surrounding land, then that image was discarded and a different product or date was chosen. This process was carried out for all of the dates for which we had data. The four parameters that were used initially were NDVI, LST, shortA, and band4. And later, band 3 was also included in the processing. Future work will also make a more detailed analysis of the emissivity and other individual bands. Once a “good” slice was obtained, the ranges (or slices) were reduced to two: one with water and one with no water. This was accomplished in an interactive way that was somewhat subjective; however, some care was taken to not “fix” the process – pixels were assigned to where water was expected to be as long as that “class”, or color, did not appear elsewhere in the image. In other words, adjacent classes were merged or subclasses were created from neighboring classes and merged until, for the most part, the “water” class was confined to the expected reservoir area.

Results of Area Measurements

Once the classification was completed, the density slice map was converted to a “class” map whereby each color is assigned a classification number (1, 2, etc.) that is unique for each color in the image. This class map was then processed to arrive at a total number of pixels that were in the class “water”. The results from this processing are given as a graph of elevation versus area in Fig. 4. One date, November 28, 2004 allowed no determination of area to be made from any of the parameters. A simple regression analysis yields an $R^2=0.98$ which indicates, for this reservoir, a linear relationship over most of the depth range. However, there may be a slight difference between the upper levels and lower levels which would indicate a difference in the slope of the reservoir sides – possibly more sediment at the bottom with a more shallow slope.
Fig. 3. Graphical description of the density slice process. The distribution of the histogram of grey levels in an image (in this case LST) into equal size bins as is the case for the initial application of the Density Slice Algorithm. This “unsupervised classification” is manipulated (or supervised) to arrive at a binomial distribution of levels to arrive at a discrimination between land and water.

Fig. 4. Plot of area versus elevation, or reservoir level, in meters referenced to the Bureaus of Reclamation (BoR) datum, for Elephant Butte Reservoir within the region considered in this study. For water levels above approximately 1338 m, the reservoir extends beyond the region of interest so that the true area is not determined.
Fig. 5. Gray scale image of the ASTER DEM (left) from July 7, 2004 and, for comparison, the color IR image for the same scene (right). The contour level of 1327.6 m (white) seems to capture the boundary between the black area that is given as zero in the DEM and the “gray” regions which show the topography of the surrounding terrain. In other words, the ASTER DEM seems to have done a good job of providing a height measurement for Elephant Butte Reservoir.

Determination Of The Elevation Of Lake/Reservoir Surface

As part of the determination of area, we also studied topographic maps and other elevation data for comparison to the imagery. These consisted of USGS topographic maps, a DEM that we had requested from the LPDAAC, and a bathymetric chart (fishing map). The spillway elevation is 4407 ft with the US Bureau of Reclamation (BoR) datum and 4450 from the US Geological Survey (USGS) datum (NAD 27 and, apparently, WGS 84) – a 43 ft difference. These correspond to 1343.25 m, 1356.36 m, and 13.11 m, respectively. A gray scale image of the DEM from the ASTER scene is shown in Fig. 5 along with the ASTER color IR image from the same date. The green line on the DEM image is a contour level drawn at 1327.6 m – the approximate level of the reservoir on July 7, 2004 as given in the Bureau of Reclamation record of reservoir levels. They report, on midnight, for the 6th, 7th, and 8th of July a level of 4312.40 ft, 4312.94 ft, and 4312.48 ft, respectively. An elevation of 1327.6 m corresponds to an elevation of 4355.75 ft which is 4312.75 ft plus 43 ft. The ASTER DEM is at a spatial resolution of 30m and, as a result, some of the detail seen in the 15m color IR is missing from the DEM. Because of the abrupt change from whatever level is represented at the reservoir boundary to the zero as given by the DEM at the water surface, it is difficult to establish a definitive value for the ASTER DEM estimate of lake level – the “edge” pixels are not all at some level but vary considerably. The reason that the water level is shown as zero is that the water is relatively flat and the parallax required for stereoscopic analysis is missing. Regardless, choice of an approximate contour to surround the “zero” region does yield a good estimate of lake elevation.

DEM results from another spaceborne sensor, the Shuttle Radar Topography Mission (SRTM), were also investigated. SRTM was flown on a NASA Shuttle mission (11 - 22 February 2000). Details of the mission can be found at http://www2.jpl.nasa.gov/srtm/. These data are available in a variety of formats – the one chosen here is the 30m data in Worldwide Reference System (WRS)-2 tiles -- and from different agencies and locations. The source of our data was the Global Land Cover Facility (GLCF) at the University of Maryland (http://esip.umiacs.umd.edu/index.shtml). The WRS-2 tiles correspond to the same path/row scene labeling scheme that is used for Landsat TM and ETM+ data. As Elephant Butte Reservoir is in the left side of one scene (p33r37) and the right side of another (p34r37), both scenes were processed. Out of curiosity, once the two DEMs were subsetted, a difference image was created – the difference, one would think, would be zero (or, at least, very close to zero). Apparently, the processing of the SRTM data is such
that there is a difference of the order of 5 to 10 meters at any given location that appears to be due to slight differences in registration between the two scenes. A figure showing the a gray scale image for the DEM from p33r37 overlaid with a contour at 1351 m does not render with sufficient clarity to be used as a grayscale image in this paper. This level is an average from a portion of the DEM located over the open water. Unlike the ASTER DEM, the SRTM DEM does show a level for the water; however, there is considerable “noise” in an overlaid contour. Using a region of approximately 3.48 km$^2$ about mid-way in the image and “on the water”, for the p34r37 scene, we get a mean value of 1350.9 m for the water level (WGS-84). During this time, the BoR records show a level of 4391 ft (BoR datum) or 1338 m while 1351 m is approximately 4432 ft; a difference of 41 ft (Recall that the difference between WGS-84 and BoR datum is 43 ft with the BoR level being the lower of the two.). So, the real difference between the SRTM DEM measurement and the reported water level is 0.6 m (2 ft).

**DISCUSSION**

One of the reasons for conducting the research reported here is to determine algorithms that may be used for measuring flood inundation areas. The other, more obvious use, is in remotely monitoring of lake/reservoir levels or the detection of ponds that may be used as surrogates for rainfall detection in regions without gauges. The ASTER sensor seems to have sufficient spectral coverage to allow the classification of water covered areas. The results reported here are for a “simple” case of a lake/reservoir where there are no buildings or trees rising above the water level as would be the case in a flooded region. Problems that we encountered, which made an automatic classification impossible with our technique, were the presence of clouds, shadows, variation in water color (variable turbidity) and disturbed water surface from wind variability. In addition, during some periods of the year, there was little or no difference between land and water temperatures. Perhaps, a more sophisticated approach would allow autonomous classification with similar results. Because of this, the research reported here is work in progress as we attempt more analyses.

**Acknowledgement**

This research was carried out partially under the auspices of the Rio Grande Basin Initiative, a grant from the National Geospatial-Intelligence Agency (NGA), and through the funding of the NMSU College of Agriculture and Home Economics Gerald Thomas Chair in Water Resource Research. The Global Land Cover Facility (GLCF) at the University of Maryland was the source of the SRTM data. The Land Processes Distributed Active Archive of the EROS Data Center, USGS was the provider of the ASTER data.

**References**
