Validation Snow Extent Product from MODIS Data

(Final Report)

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1. Introduction

The objective of this investigation is to validate snow covered area mapping algorithm developed by MODIS science team and to assist monitoring of snow processes over alpine watersheds scale to regional and global scales.

For climatic, hydrological, and snow hazard investigations, the areas covered by snow is one of the most important parameters. Seasonally snow covered areas of the Earth's mountain ranges are important components in the global hydrologic cycle. Monitoring the extent of the seasonal snow cover and the accumulation and ablation zones of glaciers is essential for understanding of the global hydrologic cycle, one of the objectives in the study of the Earth. They account for a significant fraction of the Earth's fresh water supply. Seasonal snow cover is the major source of the fresh water supply over wide areas of the mid-latitudes. In the western U.S., for example, about 80 per cent of the total runoff comes from melting snow. Measurement of the amount of water stored in the snow pack and forecasting the rate of melt are thus essential for managing the water supply and flood control systems. At the mesoscale, the atmosphere and the underlying surface represent a coupled system. Snow and soil properties determine the runoff production in response to atmospheric precipitation, and the presence of snow modifies fluxes of radiation, moisture, heat, and momentum into the atmosphere that affect the atmospheric circulation. Both factors are highly relevant to regional weather, water supply and flood forecasting, and are substantially affected by complex topography. Therefore, the spatial and temporal distribution of snow cover area is a crucial input to models of hydrology and climate in alpine and other seasonally snow covered areas.

The spatial distribution of snow cover is mainly described as a function of elevation in a mountain area. It is generally varies from a full or large fraction to a small fraction as elevation decrease. In addition to elevation, snow spatial distribution is modified by the surface orientation, and the intensity and direction of wind. To evaluate the impact of snow mapping accuracy on hydrological applications, we performed a simulation study with snow cover as an input of the snow-melt runoff model. The simulation was performed using the data on March 15, 1989. The study site was divided into three elevation zones. Snow-covered area was obtained from TM imagery and considered as a ground truth reference. Percent cover of 97%, 72%, and 46% was used for high middle, and low elevation zones, respectively. The runoff prediction on March 30, without introducing any error in snow cover, was 40.3 m^3s^{-1}. In order to test the sensitivity of the snow-melt runoff model to input of snow-covered area, each test run was performed with all parameters fixed except that a relative error in snow covered area at each elevation zone was introduced. Figure 1 shows the sensitivity of snow-melt runoff to snow mapping accuracy at different elevation zones. The x-axis represents the relative error in percent of snow cover in a given elevation zone. The y-axis is the corresponding predicted snow-melt runoff in m^3s^{-1}. The solid, dot, and dash lines represent those predictions at low, middle, and high elevation zones, respectively. The accuracy of snow-covered area in high elevation zones has a little impact on snow-runoff predication as clearly indicated by the dashed line: because of a low temperature condition during the time of simulation runs, snow did not melt and contribute to runoff. On the other hand, the major contribution of runoff was from the low and middle elevation zones. The error in the input snow covered area will result in a great error in snow-melt runoff prediction. This simulation indicates that snow cover identification is not only important in terms of estimating its total snow covered area in a drainage basin but also requires acknowledge of where snow is distributed in a drainage basin.

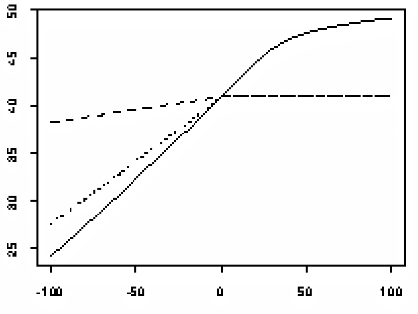


Figure 1. *Effects of snow mapping accuracy on snow-melt predication at different elevation zones. The x-axis represents the relative error in percent of snow cover in a given elevation zone. The y-axis is the corresponding predicated snow-melt runoff in* m^3s^{-1}*. The solid, dot, and dash lines represent those predictions at low, middle, and high elevation zones, respectively.*

In an attempt to develop or verify a snow-mapping algorithm, a common problem is lack of sufficient ground truth data. Most snow mapping algorithms were developed and validated with only limited “user-supplied” ground truth data that covers only a very small portion of snow-covered environmental conditions. This type of technique can not provide any information on evaluation of the algorithm performance and assessment of the accuracy of classification results where the ground truth was not available. It is clear that the key to validation of the MODIS snow extent product is to obtain a sufficient amount of ground truth data that covers different background targets, terrain, atmosphere, solar and sensor viewing geometry.

The ground truth of snow-covered area through this validation project has been obtained by high resolution image data - digitized VNIR color photo (1.5 – 4 m), ASTER (15m and 30m), and ETM+ (30m). For a large portion, especially in alpine regions, these ground truth data are represented in terms of a snow fraction cover at each MODIS 500 m pixel resolution. On the other hand, the MODIS snow-mapping algorithm is a binary classification technique, i.e., a pixel is identified either as snow or not-snow. This difference has resulted in a difficulty for quantitative comparison of the above two results. Our validation has been performed under two concepts for accuracy assessment based on the applications that use snow covered area as the model input for 1) **climatic study** - snow covered area is evaluated in terms of total snow cover at different scales or a grid ranging from 10 km x 10 km to 50 km x 50 km for variety of the regional to global scale GCM input. 2) **Hydrological study** - snow classification is evaluated at MODIS pixel scale – 500 m x 500 m.

The project has two phases. Phase I - pre-launch validation, our study mainly focused on 1) validation - using the high resolution VNIR color photo derived ground truth and simulated MODIS image data from Airborne (AVIRIS) data, and 2) examining and developing the techniques to obtain the ground truth by using satellite ASTER and TM image data. Phase II – after-launch validation, we validated MODIS snow mapping algorithm using ASTER and EMT+ image data.

2. Validation Using AVIRIS simulated MODIS data

2.1 Technical Approach

The ground truth data is a key to any algorithm development and validation. We used the digitized high resolution VNIR color photo that is taken simultaneously with AVIRIS image data on ER-2. It covers about 15 km x 15 km. This film, originally referred to as camouflage-detection film, differs from conventional color film because its emulsion layers are sensitive to green, red, and near-infrared radiation (0.5 μm to 0.9 μm). With a yellow filter to absorb the blue light, this film provides sharp images and penetrates haze at high altitudes. The color infrared photo can be digitized to a three-band digital image with a pixel resolution from 1 to 4 m. Meanwhile, MODIS, ASTER, and TM image data can be simulated with or without the atmospheric corrected AVIRIS reflectance image by using each sensor's spectral and spatial response functions. The snow mapping algorithms were then performed. The effect of atmosphere on MODIS algorithm performance can be then evaluated by comparison above two type of input data – the planetary and surface reflectences. In contrast with other techniques, such as low elevation aerial photo, the advantages of using color infrared photo are 1) the color infrared photo and airborne image data are taken simultaneously; 2) similar solar illumination and sensor viewing geometry since the instruments are on the same platform; and 3) covers large area.

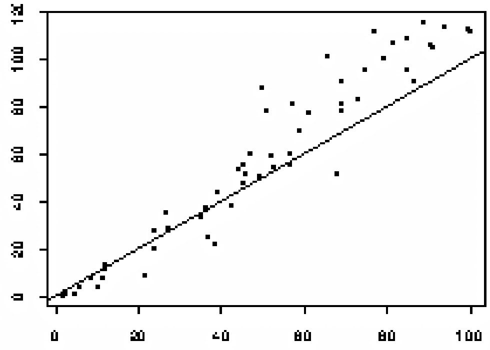
Thus, we can access large amounts of ground truth data of snow-covered areas and validate the accuracy of the snow mapping algorithm under a variety of viewing and illuminations, land cover types, atmospheric and terrain conditions.

We have collected 367 AVIRIS scenes with snow cover over different regions in North America Since 1994. They cover a wide range of solar illumination, atmospheric, terrain, and snow conditions. Our evaluation was performed on 67 AVIRIS scenes with VNIR color photos available. These data acquired over the Sierra Nevada and South Cascades Mountain Ranges represent the environment of common alpine regions and were obtained from April to July, during snow melting season.

2.2 Validation and Analyses

The validation was performed on 1) the total snow fraction at AVIRIS scene scale, i.e., about 10 km by 12 km, and 2) the pixel-based validation. The former represents the case for climatic studies where we are only interested in the snow fraction in a grid but do not care where and how they are distributed inside a grid, such as GCM input. The latter represents the case for hydrological studies where we need information not only on the total snow covered area but also on where they are distributed.

Figure 2 shows the total snow covered area derived from the photo as x-axis compared with that estimated by the MODIS algorithm as y-axis using 67 simulated MODIS data from AVIRIS scenes. The left side is that derived using the simulated MODIS surface reflectance data or atmospheric corrected image data. It has an overall accuracy of 21.9 km^2 and a maximum error of 58.3 km^2. The right side is that derived from the simulated MODIS planetary reflectance or without atmospheric correction. The overall accuracy is 14.6 km^2 with a maximum error of 37.9 km^2, for which the corresponding fraction covers in a scene are 12.1 % and 31.6 %, respectively. In both cases, the MODIS algorithm performed well at small fraction ranges. At large fraction range, its estimation has larger error with over-estimation in the most of the cases. As we noticed that a better accuracy was obtained from the simulated MODIS data without atmospheric correction. This is because MODIS snow mapping algorithm was developed from TM data without atmospheric correction – the planetary reflectance at top of atmosphere. It is well known that the surface reflectance of a high reflectance target is larger than its planetary reflectance and that surface reflectance of a very low reflectance target is smaller than its planetary reflectance due to atmospheric effects. At visible bands, snow surface reflectance is larger than its planetary reflectance. At short wave infrared bands, however, snow is a high absorber and has very low reflectance. Its surface reflectance is generally smaller than its planetary reflectance. This differences result in NDSI, that MODIS snow mapping algorithm is mainly based on, measurement obtained from the atmospherically corrected surface reflectance is higher than that derived from the planetary reflectance measurements. Therefore, it generally over-estimates snow cover when using the atmospherically corrected MODIS image data. Moreover, the MODIS algorithm performed quite well in overall in estimating total snow covered area at a grid scale of AVIRIS scene coverage even in the alpine regions.



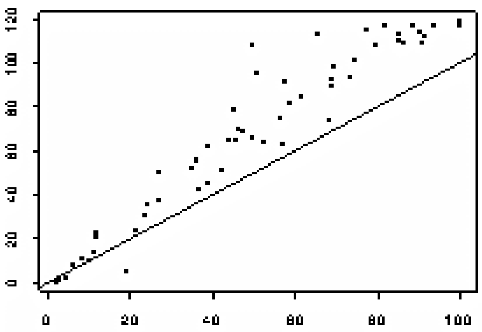


Figure 2. *Comparison of the high resolution VNIR color photo derived snow covered area in km*^{2} *as x-axis with that derived from the simulated MODIS image data by AVIRIS with the planetary reflectance on left and the atmospheric corrected surface reflectance on right.*

Figure 3 shows a histogram of the Root Mean Square Error (RMSE) from each scene by means of the pixel-based comparison. That is, each RMSE value was obtained by evaluating every pixel in a simulated MODIS scene. The overall RMSE for all scenes is 25.1 %. In most of the cases, the RMSE for each scene ranges from 20 % to 30 %. A good binary snow classification algorithm classifies a pixel as the snow when snow fraction is greater than 50 % and as snow-free when it is less than 50 %; the RMSE from a scene will be around 25 %. Under this condition, the error might be canceled out if the error were randomly or uniformly distributed. As a result, the MODIS algorithm gives quite accurate results in terms of estimating total snow covered area in a scene. Thus, it indicates that MODIS algorithm is a good binary snow mapping classifier.

However, we can see a large range of RMSE with a maximum 49.5 % in the right side of Figure 3, which indicates the effects of different background gargets on the algorithm performance. The large errors were mainly found in the patched snow distribution and forested regions. The large range RMSE also indicates that we need a large amount of ground truth data for validation. In other words, it requires a large sample to infer the correct conclusion.

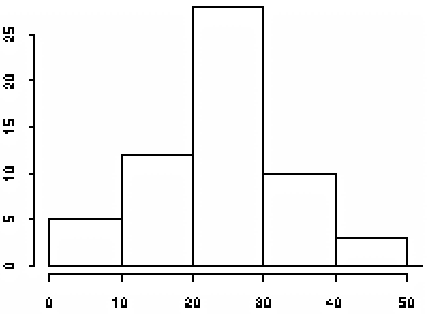


Figure 3. *RMSE in % from each scene in term of pixel based comparison.*

A common problem with a binary classifier under effects of "mixed" pixel is that the probability of a pixel to be classified as snow is proportional to snow fraction in a pixel. The more snow cover is in a pixel, the more likely it will be classified as snow. The spatial distribution of snow cover in a mountain area depends upon elevation, surface orientation, and the intensity and direction of wind. It is, in general, characterized as full, large fraction, and small fraction at high, middle, and low elevation zones. To demonstrate the effect of such a snow distribution on MODIS algorithm performance, we show Figure 4. They are snow cover image estimated with the MODIS algorithm on left, snow fraction image from the color photo in middle, and the difference between these two maps on right at MODIS 500m pixel resolution. The brightness in the difference image ranges from – 90% (black color) to 53% (white color). It represents an over-estimation (black) or under-estimation (white color) of snow cover fraction in % at that pixel. The gray color indicates that there is no difference between these two. There is no significant difference at the regions near the center of the ice field or at high elevations where the pixels are fully or near fully covered by snow. Going from high elevation to low elevation (or departing from the center ice field), the brightness in the difference image becomes darker, indicating the algorithm over-estimate snow cover in these regions. At low elevation or near the edges of ice fields, the brightness suddenly changed from black to white indicating under-estimation in these regions. It is clear that both over- or under-estimations are caused by the "mixed pixel" problem. As discussed sensitivity of snow distribution to snow melting predication and shown in Figure 1, under-estimating snow cover especially at low elevation may result in a significant error in snow melting predication. For hydrological applications, therefore, it requires much more accurate snow cover information.

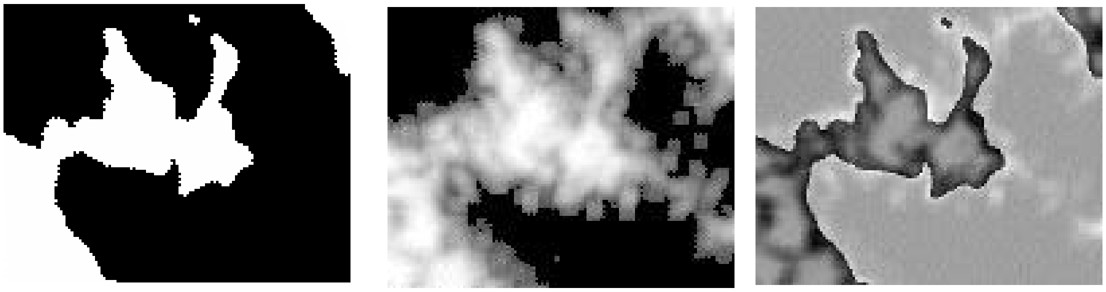


Figure 4. *The MODIS derived snow map on left, snow map from photo in middle, and the difference on right.*

To further evaluate the effect of characteristics in snow spatial distribution, two simulated MODIS images were selected with one representing a continue snow distribution case and the other representing a patched snow distribution case. We evaluated the MODIS algorithm performance using these two images at different scales as shown in Figure 5. Y-axis is the relative error in %between the snow cover derived from VNIR color photo and that derived from simulated images using MODIS algorithm and x-axis is the resolution scale of the simulated images. It clearly indicates that snow spatial distribution has significant impact on the accuracy of the MODIS algorithm. For the patched snow distribution case, the accuracy decreases as the resolution decreases due to "mixed pixel" problem. For the continue snow distribution case, however, the pixel resolution has a little in impact within the range of our simulations.

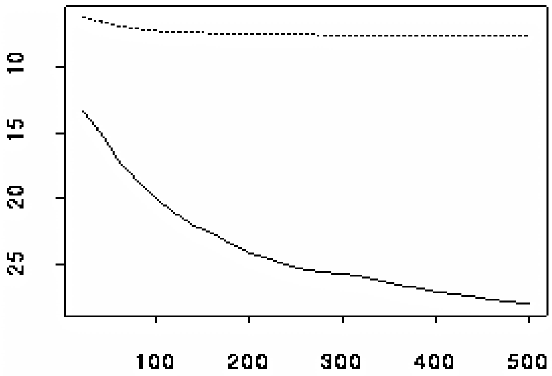


Figure 5. *Effect of the characteristics of snow spatial distribution on MODIS algorithm performance at different resolution scale.*

3. Assessments of Ground Truth Accuracies Derived from ASTER and TM Using AVIRIS Simulated Data

We investigated the techniques to derive ground truth by using ASTER and TM so that the after-launch validation can be carried out with sufficient image data at different environmental conditions. This is because the RMSE in pixel-based validation had large variations as shown in Figure 3 and the limited airborne campaigns as we expected during after-launch validation. For this task, we have evaluated two major techniques based on the classification concept: 1) evaluating the current available classification algorithms and 2) using the spectral unmixing technique.

3.1 Evaluation of the Available Classification Algorithms

To evaluate the feasibility of the current available classification techniques to obtaining the ground truth of snow covered area using high resolution image data (ASTER and TM), we performed 1) MODIS algorithm (1996), 2) Rosenthal and Dozier's regression tree algorithm (1996), and 3) a binary classification algorithm that uses only three of ASTER's 15m visible-near-infrared bands. The evaluation was carried out by first classifying the pixels at ASTER or TM, both simulated using AVIRIS, resolution scales, i.e., 15m or 30m. Then the classification results were re-sampled to MODIS 500m resolution in order to evaluate the pixel-based comparison. Meanwhile, the total snow covered area or percent of snow cover in each scene was also calculated. Similarly, the corresponding snow cover ground truth derived at AVIRIS resolution scale from high resolution VNIR color photos was re-sampled to MODIS 500m pixel resolution. The evaluation is based the comparison of above two results. Table below shows the RMSE of the overall and maximum errors in % from 67 AVIRIS simulated scenes. The second and third columns represent the comparison for overall and maximum errors in % of estimating the total snow-covered fraction of the AVIRIS coverage. The last two columns are for the pixel-based comparison, also in %.

	Percent Snow of cover		**Pixel Based Comparison**	
	Overall	*Max.*	*Overall*	*Max.*
MODIS	7.4	20.2	15.6	30.4
Rosenthal's	6.7	22.2	14.2	28.8
ASTER	4.8	12.6	12.6	22.5

Table 1. Validation of the current available TM and ASTER algorithms from 67 AVIRIS simulated scenes.

In comparing the MODIS algorithm performance at TM 30 m and MODIS 500 m resolution scales, the accuracy in both estimation of total snow-covered fraction for a scene and the pixel-based comparison is significantly improved because the effects of the "mixed" pixel problem have been greatly reduced. A slightly better result than the MODIS algorithm was obtained from Rosenthal's algorithm. However, this algorithm was developed from TM data at Sierra Nevada areas and a larger portion of the AVIRIS data used in this evaluation was from this site. Therefore, we conclude that both algorithms have similar accuracy in terms of using TM to derive the snow covered fraction and pixel based ground truth at MODIS 500 m resolution scale. Furthermore, the most accurate results can be obtained by using ASTER's three 15m visible and near-infrared bands, largely due to a better spatial resolution than TM data.

3.2 Development of Unsupervised Unmixing Technique for ASTER

The surface reflectance, such as derived from atmospheric corrected AVIRIS, MODIS and ASTER, is usually a function of local solar illumination angle, surface orientation, and sensor viewing geometry. Terrain has a great impact on the imaged pixel size. In alpine regions, the great variations in elevation and surface orientation from pixel to pixel consistently result in a great variation in the derived surface apparent reflectance. This variation due to topographic effects unrelated to the spectral reflection properties of surface cover type has great impact on classification accuracy and on spectral linear unmixing technique.

Linear spectral unmixing techniques have been applied to snow-covered area classifications. The major difference in these studies is the techniques for selecting spectral endmembers. Our analyses of terrain effects on spectral unmixing indicate that each current technique for selecting the reference spectral endmembers has its own advantages and disadvantages under mountainous areas.

1. Scene-selected spectral endmembers by either manually averaging from training sites or by using convex geometry technique
    - Advantages: less sensitive to system noise, error in atmospheric correction, local spectral endmembers
    - Disadvantages: terrain and illumination effect in the selected endmembers
2. Spectral library by either field measurements or model simulation
    - Advantages: the normalization can be used to reduce terrain effect
    - Disadvantages: limited available data, affected by system noise, illumination, and difference between model predictions and measurements

By taking advantage of each approach, we developed a technique for automatic selection of local reference spectral endmembers for ASTER. The results indicate that the linear unmixing technique can provide a more accurate snow mapping method. However, this technique is the computationally intensive and may not be suitable for analyzing large data volumes [4]. The reason why we selected ASTER rather than TM for our linear unmixing technique development was that TM has saturation problem at its visible bands. Our spectral library derived from AVIRIS image data does not reflect this problem. For ASTER, there are three gain settings. The saturation problem could be avoid if the low gain were acquired.

4. After-Launch Validation Using ASTER and ETM+

4.1 Data Collection, Quality, and Processing

During after-launch validation, ASTER and ETM+ data with simultaneous MODIS surface reflectance image data have been collected with a total of 28 scenes in different regions to derive ground truth for validation of MODIS snow mapping algorithm. They are all cloud-free. Table 2 summarize the ASTER and ETM+ data used in after-launch validation.

Data		Date	Longtitude	Latitude	Location
ASTER L2	3	2000-11-04	-110.85	45.05	Yellowstone (Mo)
		2000-11-07	-120.65	38.72	Placerville (CA)
		2000-11-13	-109.89	43.48	Fish Creek Park (WY)
ASTER L1B	3	2000-11-13	-109.71	44.01	Fall Creek (WY)
		2000-11-14	-95.98	43.48	Little rock (IA)
		2000-11-14	-96.15	42.95	Mauria (IA)
ETM+	3	2000-12-02	-118.98	37.46	Sierra magret Lake (CA)
		2000-12-28	-118.98	37.46	Sierra magret Lake (CA)
		2001-01-03	-118.98	37.46	Sierra magret Lake (CA)
ASTER L1A	19	2000-12-01	-106.45	40.11	Kremmling(CO)
		2000-12-01	-106.63	39.58	Fulford (CO)
		2000-12-01	-106.81	39.05	Hayden Park (CO)
		2000-12-01	-106.97	38.75	Flat Top (CO)
		2000-12-01	-104.61	43.90	Sheep Cayon Creek (WY)
		2000-12-01	-105.40	41.91	Rock River (WY)
		2001-01-02	-106.74	40.99	Davis Peak (CO)
		2001-01-02	-106.91	40.46	Co-creek (CO)
		2001-01-02	-107.08	39.94	Dome peak(C)
		2001-01-25	-105.74	46.70	Kiney NW (MT)
		2001-01-25	-109.52	35.64	Ganado (AZ)
		2001-01-28	-117.42	37.85	Paymaster Ridge (NV)
		2001-01-28	-117.56	37.34	Tule Cayon (NV)
		2001-01-28	-117.78	36.82	Lower warm Spring (CA)
		2001-02-05	-123.84	50.29	Canada
		2001-02-07	-121.98	49.83	Canada
		2001-02-07	-121.95	48.81	Mt Barker (WA)
		2001-02-20	-114.27	48.55	Whitefish range (MT)
		2001-02-20	-113.66	47.88	Swan Peak (MT)

Table 2. ASTER and ETM+ data used in validation.

In order to validate MODIS snow mapping algorithm with ASTER and EMT+ derived ground truth, the co-registration of MODIS image data to ASTER and ETM+ image data is required. The technique we used is the splint-window auto-correlation technique. We first converted MODIS coordinates (Lat/Lon) to ASTER and EMT+ coordinates (UTM) and then re-sampled to 450m resolution by the bi-linear re-sampling. A sub-image winder with the distinguished geometric and spectral characteristics such as the corner of an island in a lake, mountain ridge with shadow, … The sub-image has widow size at least 3 x 3 from MODIS image data. The corresponding sub-image from ASTER or ETM+ was first re-sampled to MODIS resolution with moving window method. Then the auto-correlation value was calculated for ASTER or ETM+ data at each widow. In this way, the control points on both images can be selected by finding the maximum auto-correlation value from each moving windows. Then, the re-sampled MODIS image data (450m) can be co-registered to ASTER or ETM+ image data.

It has been recognized that TM and ETM+ image data have saturation problem in their visible channels over snow cover. For ASTER, however, it has three sensor gain control level – high, normal, and low gains. It was assumed that there would not be any saturation problem at its visible bands over snow cover if the low gain were selected. This is major reason why we were developing the unmixing method for using ASTER data during pre-launch validation phase. Unfortunately, ASTER data has been processed by the Japanese team in Japan. All our collected ASTER data were processed with the high gain that had the lowest irradiance setting and they all have saturation problem in its visible bands (band 1 and 2). Therefore, the linear unmixing technique we developed in pre-launch validation phase can not be applied.

A supervised maximum likelihood classifier with carefully selected training sites in each scene was used to obtain the high resolution snow covered area maps from ASTER (15m) and EMT+ (30m) image data. The classification results were also checked with USGS land use and land cover maps and compared with MODIS algorithm performed at ASTER and ETM+ data. There is almost no difference in classified results between this two classifiers. For our supervised classifier, five input measurements were selected:

- Reflectance of the visible band (ASTER band 1 or EMT+ band 2): It has good separation of snow with others and can be used to identify possible snow in solar shadow,
- Short wave infrared band (ASTER band 8 or EMT+ band 7): It can be used to identify bare surface with others,
- NIR band (ASTER band 3 or ETM+ band 4): Separate water with others,
- NDSI: Separate snow with others,
- NDVI: Identify vegetated surfaces.

Notice that ASTER’s short infrared bands were re-sampled to 15 m from 30 m in order to generate high resolution snow map. The average error of this technique in comparison with the snow covered area derived from the high resolution VNIR color photo is about 5 % at 10 km x 12 km scale.

4.2 Results

Similar to pre-launch validation, we validate the MODIS snow algorithm under two concepts: 1) the accuracy of snow covered area at a given scale for climatic studies, and 2) the pixel based accuracy for hydrological studies.

For the first task, we performed comparison of snow covered area at different scales since the different GCM models use different input scales. This was done by dividing snow covered maps obtained from each ASTER, ETM+, and MODIS scene into sub-images with the scales at 10 km x 10 km, 20 km x 20 km, 30 km x 30 km, 40 km x 40 km, 50 km x 50 km, respectively. The total snow cover within a scene of ASTER or EMT+ (ASTER - 60 km x 60 km and EMT+ - 185 km x 185 km) was also calculated. Figure 6 shows the comparison of the total snow covered area with unit of 100 km^2 that estimated from ASTER and ETM+ as x-axis and that from estimated from MODIS as y-axis with (A) to (F) represents the results at above each scale, respectively. From Figure 6 (A) to (F), we can see that the MODIS derived snow cover area at 10 km x 10 km scale has largest variations or the relative errors. As the scale increased to 20 km x 20 km, the relative error becomes stabilized. This is because the larger the area is the more possibility that the classification error will be cancelled out. Table 3 shows the overall RMSE of both the absolute error in unit of 100 km^2 and the relative error in % at each scale. The relative error is an essential indicator for the confidence of MODIS derived snow cover as an input for GCMs. the absolute error in estimation of total snow covered area increases as the corresponding scale increases. The opposite is true for the relative error.

Unit km^2	10x10	20x20	30x30	40x40	50x50	scene
Absolute Error in 100 km^2	0.12	0.43	0.79	1.13	1.97	3.43
Relative Error in %	26	20	20	18	13	15

Table 3. The RMSE of absolute and relative errors at different scales.

In overall, MODIS algorithm performed quiet well at small snow cover cases. For large snow cover cases, the accuracy decreases with an over-estimation for the most of the cases. We believe that it is mainly resulted from effects of atmospheric conditions. MODIS data that we used is the atmospherically corrected surface reflectance. This problem has been recognized in our pre-launch validation.

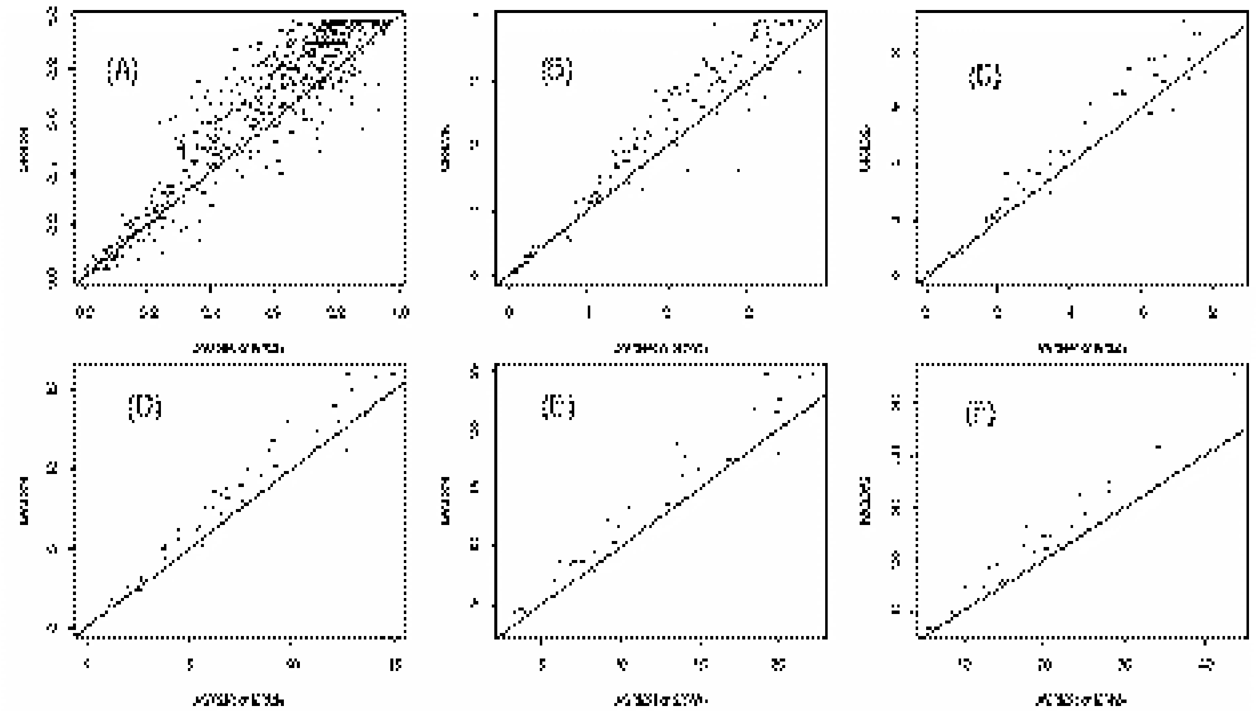


Figure 6. *Comparison total snow cover estimated using ASTER and ETM+ with MODIS at different spatial scales.*

In addition, we found that MODIS algorithm under-estimates snow cover mainly under two cases – thin snow cover and snow in dense forest. The later has been well understood and documented by MODIS team and will not be discussed here. For thin snow cover, the snow surface reflectance can be much smaller than that of thick snow at visible bands due to the significant penetration. The underlay surface reflectance has a great impact on the snow surface reflectance. At short wave infrared bands, there is a little difference in snow surface reflectance because of small penetration depth at those wavelengths. As a result, the NDSI measurements are smaller from thin snow cover than that from thick snow cover. Notice that the NDSI value of thin snow cover is at low end of its value range for a snow covered pixel. With further present of "mixed pixel problem" at MODIS 500m pixel resolution that further decreases the NDSI value, MODIS algorithm may classify the thin snow covered pixels as non-snow and result in an under-estimation of snow cover. This problem is not significant when we derived snow cover using ASTER and ETM+ image data. The thin snow covered regions can be identified using MODIS algorithm using high resolution ASTER and ETM+ image data but they were classified as non-snow when using MODIS image data.

For the second task, the pixel based comparison was performed. Figure 7 shows the histogram of the absolute RMSE in % obtained from each scene. The average of the error is 32 %. It is very similar to our pre-launch airborne data validation results with about 25 % RMSE. The difference was mainly caused by the effect of atmospheric conditions.

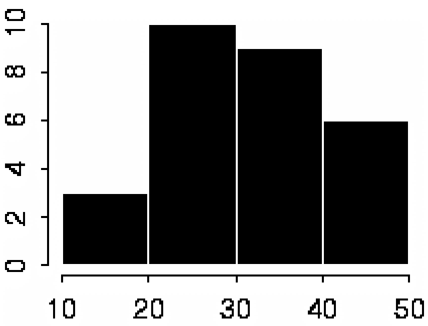


Figure 7. *Pixel based validation of RMSE from each ASTER and EMT+ scene.*

5. Summary

During this project, we have carried out validations with AVIRIS simulated MODIS in pre-launch phase and MODIS image data in after-launch phase. In using the airborne data validation, we used the digitized high resolution VNIR color photo (1m-4m) to obtain the ground truth data of snow cover [1-2]. Meanwhile the MODIS, ASTER, and TM image data were simulated using AVIRIS image data with the considerations of the point spread and spectral response functions of a given sensor [2]. The validation was performed with 67 AVIRIS scenes over the Sierra Nevada and South Cascades Mountain Ranges representing the environments of common alpine regions. They mainly represented the characteristics of spatial distribution of snow cover during snow melting season (April to July) in alpine regions. The 28 ASTER and ETM+ scenes were used for the after-launch validation. They mainly represented snow distribution during snow accumulation season (Dec. and Jan.) in alpine regions. Due to the complexity of the Earth's surface, the largest errors of the MODIS algorithm are expected to occur mainly in rugged alpine and forest regions. Our validation was performed from data representing alpine environments with one of the worst conditions for the MODIS snow-mapping algorithm.

The validation was performed under two concepts:

1) **Total snow fraction at different scales ranging from 10 km x 10 km to 50 km x 50 km**: It represents the concept of climatic application where we are only interested in the snow fraction of a grid, such as GCM input. The errors, when using the surface reflectance measurements, are with an average of 18.2 % and 26 % at the scale about 10 km x 10 km in comparison with the ground truth derived from the high resolution VNIR color photo and ASTER and EMT+ image data, respectively. A better accuracy would be expected if the planetary reflectance measurements were used. In the airborne data validation, the average error was 12.1 % at 10 km x 12 km scale. We also noticed that the error variation was stabilized at the scales 20 km x 20 km or larger. This type of accuracy is much better than the current techniques that are used to generate snow-covered area as the GCM input, such as that obtained using passive microwave sensors. Therefore, we expect that MODIS's snow mapping algorithm provides a reliable snow extent input for climatic studies.

2) **The pixel-based validation:** It represents the concept of the hydrological applications that snow cover information is needed not only with its total snow cover but also with

> where snow distributed in a drainage basin. The errors of the pixel-based comparison are 25.1 % and 31 % for AVIRIS simulated MODIS and MODIS data, respectively. Due to the complexity of natural earth surfaces, it has been recognized that a binary classifier is always affected by the "mixed" pixel problem when it is applied to moderate or coarse resolution image data. The probability that a pixel will be classified as snow is proportional to snow fraction in a pixel. As a result, the common problem with a binary classifier in snow mapping is that it will over- and under-estimate snow covers for high fraction and low fraction of snow cover in a pixel, respectively. The sensitivity test indicates that this type of error could have a significant impact on the snow melting predications. Therefore, a further improvement of MODIS snow mapping accuracy is needed for hydrological applications.

Through validation of the snow mapping algorithm developed by the MODIS team under different snow, surrounding targets, terrain, solar and sensor viewing conditions, the confidence of the snow covered area product for the user community can be established. MODIS snow products provide a reliable snow extent input for climatic studies. However, the accuracy needs to be further improved for hydrological applications. The major errors occur in the dense forested regions where MODIS sensor has its limitation due to solar illumination or sensor viewing angles – either sensor can not “see” or the snow signal is too weak to be detected. In addition, MODIS algorithm also poorly identify where snow cover is thin and mixed with other targets.

Publications

[1] J. Shi and Z. Li, Validation of MODIS snow mapping algorithm using AVIRIS image and Near-infrared color photo, in *Proceedings of SPIE'98*, Ed. Robert O. Green and Qingxi Tong, The International Society for Optical Engineering, vol. 3502, pp. 243-250, Beijing, Sept. 1998

[2] Z. Li and J. Shi, Establishment of a database for development and validation of snow mapping algorithms, to be published in *Proceedings of Fourth Remote Sensing in Hydrology*, Santa Fe, Nov. 1998

[3] J. Shi, Estimation of Snow Fraction Using AVIRIS Simulated ASTER Image Data, to be published in *Proceedings of Eighth Airborne Geoscience AVIRIS Workshop*, Ed. Robert O. Green, Feb. 1999

[4] J. Shi, Snow Fraction Estimation in Alpine Regions Using AVIRIS Simulated ASTER Image Data, to be published in *Proceedings of IGARSS'99*, Hamburg, Germany, June, 1999