On-Orbit Vicarious Calibration of GOSAT Satellite

Victor Gandarillas
Mentor: Carol J. Bruegge
Jet Propulsion Laboratory, California Institute of Technology
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Abstract

NASA and other space agencies take measurements from space for earth science. The Greenhouse Gases Observing Satellite (GOSAT) is one such earth science mission launched in January of 2009 by the Japanese Aerospace Exploration Agency (JAXA). This sensor measures the amount of carbon dioxide and methane in the atmosphere in order to improve our understanding of global warming.

All on-orbit sensors degrade with time, meaning the signal from the sensors is lower with time for a constant amount of light hitting them. On-orbit calibration accounts for this degradation and allows scientific products to be returned without loss of accuracy, correcting for this change in time.

This paper discusses the on-orbit calibration of the GOSAT science instruments using surface reflectance data from the desert playa in Railroad Valley, NV (RRV).

Introduction

In the traditional on-orbit approach, people have used desert playas as a reference for reflectance properties to compare to sensor data. Desert playas are preferable to other areas because they provide a large, flat, homogeneous surface that reflects light in all directions more or less equally.

The Jet Propulsion Laboratory (JPL) and the University of Arizona use the RRV playa for Vicarious Calibration (VC) of various satellites. In our campaign, we took spectroscopic measurements of the RRV playa using a Spectralon panel as our reflectance reference. The objective was to use these reflectance measurements as a validation of the GOSAT data product. The figures below (Figures 1 & 2) show examples of Analytical Spectral Devices (ASD) data collection and surface reflectance results at RRV. The ASD is a field spectrometer that, when referenced to a reflectance standard, can be used to measure reflectance in the 350 to 2500 nm wavelength range. Data are taken at 1 nm sample steps.

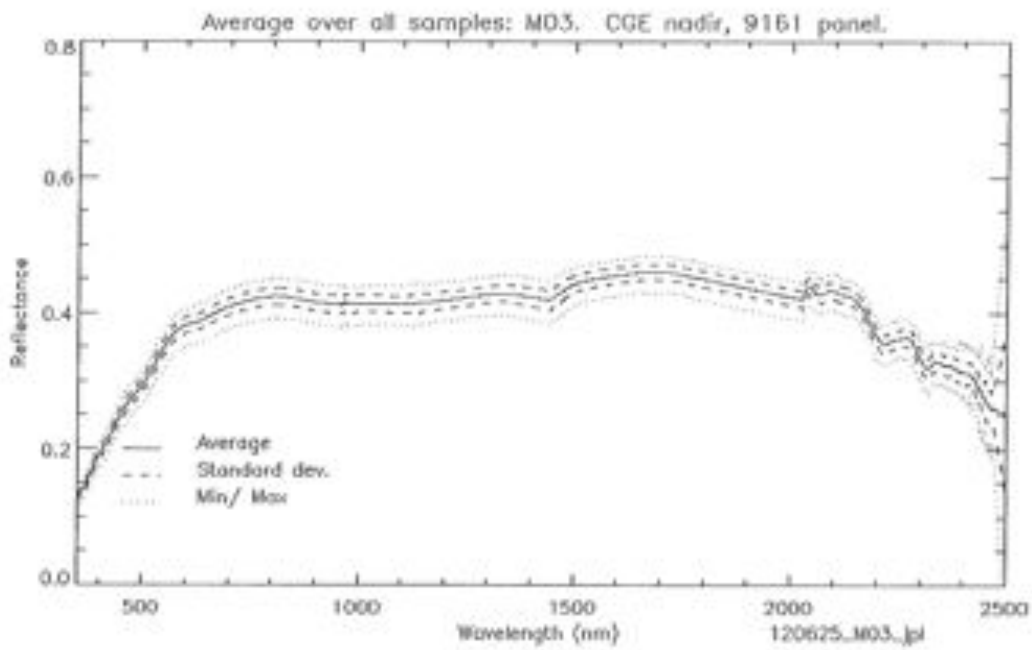

Figure 1 – Reflectance versus wavelength

Figure 1 shows the average of 180 individual reflectance samples taken at one RRV test site on one day. Also shown is the standard deviation (dashed line) and the maximum and minimum reflectance (dotted line). From this figure, it is evident that the range of reflectances at the test site is on the order of 4%. Figure 2 shows individual samples used to derive the site average. Data are plotted at the oxygen (760 nm), weak CO2 (1620 nm), and strong CO2 (2000 nm) wavelengths; the same bands measured by GOSAT.

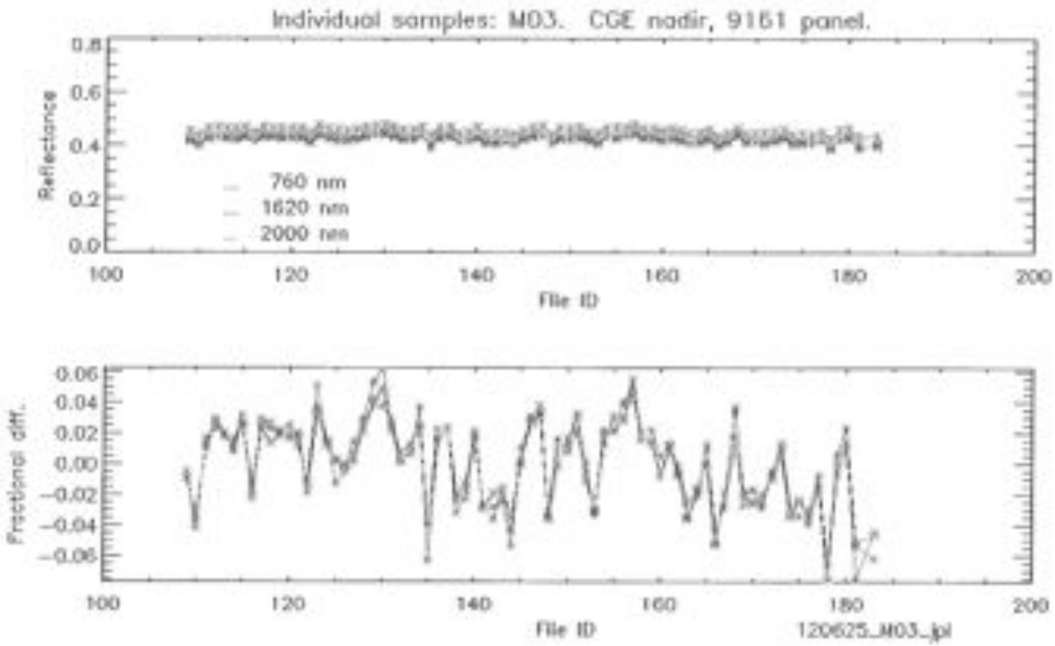

Figure 2 – Reflectance uniformity, sample to sample

Summary of Field Work

Reflectance measurements were taken at a number of 500 m test sites. In addition to measuring surface reflectance, the JAXA team and JPL team had Microtops sensors, a Cimel sensor, and radiosondes to measure atmospheric data (aerosol column amount, temperature, humidity, pressure, winds). Off-nadir reflectance ratios were calculated based on the JPL measurements of the test sites, and a spatial scale factor was developed from MODIS data to compare these measurements to GOSAT data. This data was used as input to a radiative transfer code to model how much light hits GOSAT, thus validating GOSAT measurements.

The field campaign lasted from 25 June – 2 July 2012. While GOSAT passed over Nevada, the JPL team took measurements with the ASD spectrometer from three angles: nadir, 20 deg from the east, and 30 deg from the west around three automated sites and one not. With data taken at different angles, we can look at bidirectional reflectance differences from site to site. Figure 3 shows the track around an automated ASD test site.

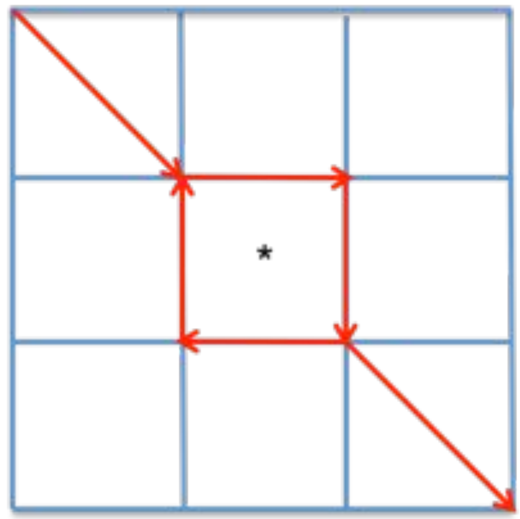

Figure 3 – Walking track (denoted by red arrows) around automated ASD site (denoted by an asterisk)

Using MODIS Data

The MODerate resolution Imaging Spectroradiometer (MODIS), a separate instrument, takes images of large areas, including the RRV playa where GOSAT is pointing. GOSAT pixels correspond to a 10 km footprint at nadir. We wish to know the mean surface reflectance within this area. Because we cannot measure the entire 10 km area, we measured the reflectance of the playa in 500x500 m areas around a number of test sites. Upon returning from RRV, work was performed to compare reflectance data from a MODIS pixel coincident with the GOSAT footprint. MODIS was chosen because of the accessibility of its data and the amount of information it contains for a larger number of wavelengths. Each pixel corresponds to an area of 500 m, the same size as the area measured using the ASD spectrometer at the test sites.

Taking an average of the reflectance of the MODIS pixels coincident with the GOSAT footprint, and computing a ratio of that value to the reflectance value of each individual pixel corresponding to the test sites, the mean surface reflectance within a GOSAT footprint was computed. The relation between surface reflectance and top of atmosphere reflectance for MODIS and GOSAT is given in Equation 1.

$$\rho_{GOSAT} = \frac{L_{GOSAT}}{L_{site}} \rho_{site} \qquad (1)$$

where ρ_{GOSAT} is the surface reflectance within the GOSAT footprint, ρ_{site} is the reflectance of the ASD site, L_{GOSAT} is the radiance within the GOSAT footprint measured by MODIS, and L_{site} is the radiance of the MODIS pixel coincident with the test site.

Since we could not take measurements of the entire 500x500m area, we walked across one grid, around the perimeter of the 167x167m ASD site, and across the way (diagonally) of the rest of the 500x500m area. 500x500m areas were chosen to match the size of a MODIS pixel. MODIS data was used to develop a spatial scale factor to compare GOSAT data to the handheld measurements.

GOSAT Flight Path

There are two off-nadir overpasses GOSAT makes over RRV. Figure 4 shows the trajectories of these overpasses (Kuze et al.).

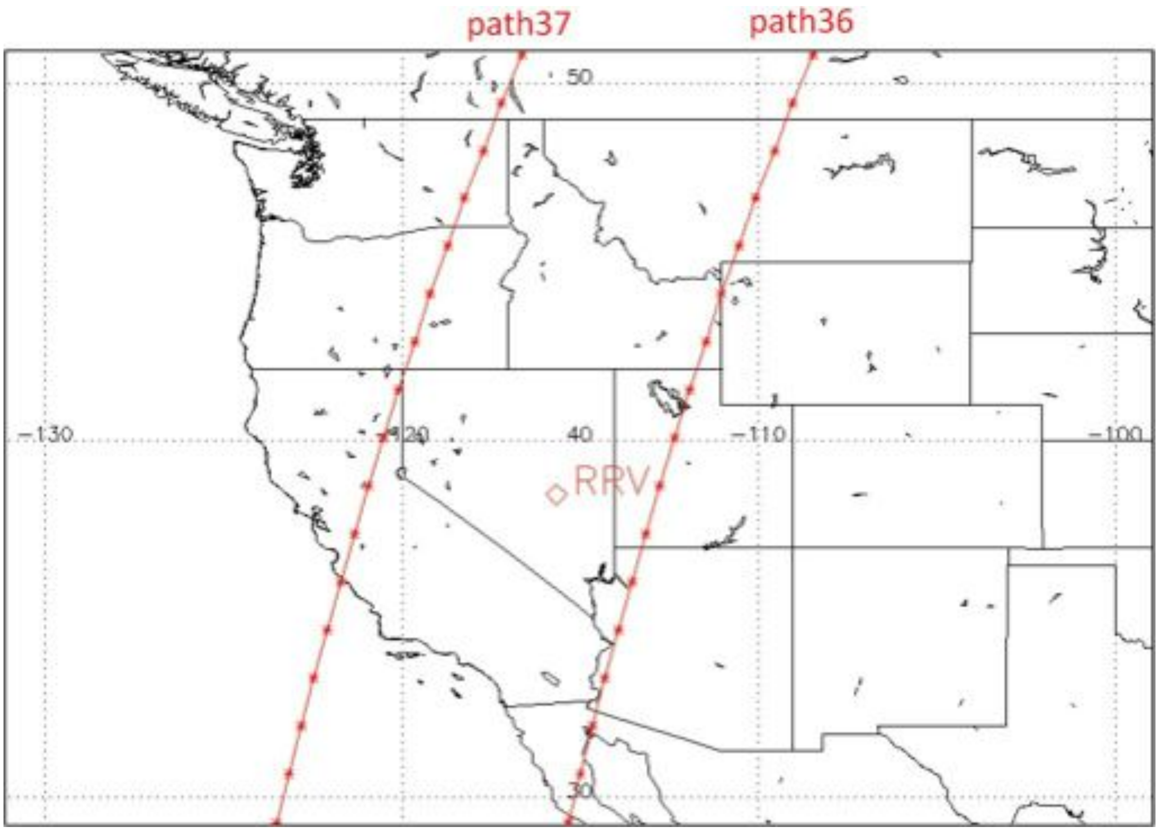

Figure 4 – GOSAT path 36 and path 37 overpasses

When GOSAT flies path 37, it views RRV at approximately 33.0 deg from the west, and 19.9 deg from the east when flying path 36 (Figure 5, Kuze, et al.).

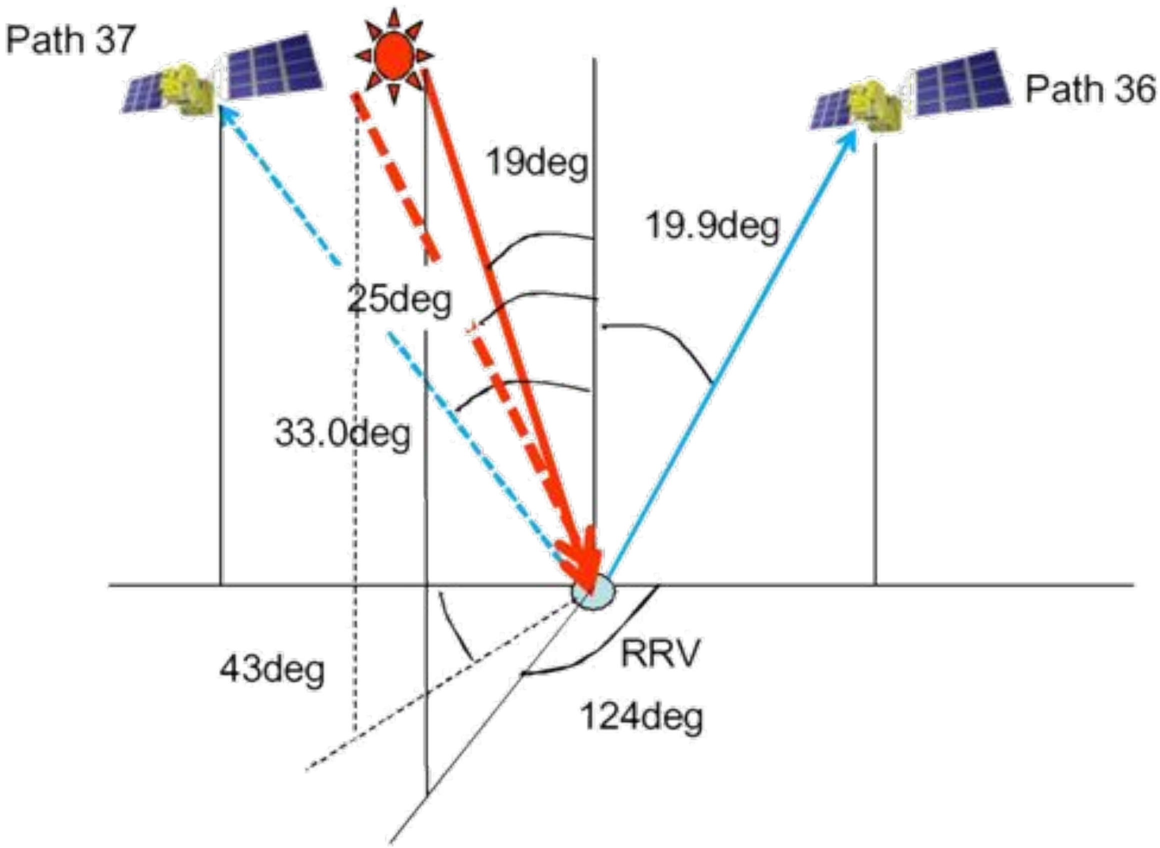

Figure 5 – Schematic of north-facing view of GOSAT overpass view angles for path 36 and path 37.

Actual viewing angles were 19.97 deg from the east and 32.83 deg from the west for path 36 and 37, respectively. The JPL team took reflectance measurements from nadir, 20 deg from the east, and 30 deg from the west. This is different from the way the JAXA team took measurements because they only took nadir data. Using data from a nadir perspective is simpler; it represents an ideal view angle from GOSAT; simplifies how they mount their hardware to their cart (Figure 6), making their measurements easily repeatable; and data taken at nadir can be used any day for any overpass because the surface does not change much due to minimal weather effects.

Figure 6 – GOSAT team member taking ASD data adjacent to automated test site sensors

Data Analysis

The objective of the data analysis discussed in this paper was to compare the MODIS reflectance data corresponding to the GOSAT footprint to the MODIS data for the ASD site. Equation 1 defines the representative surface reflectance for GOSAT based on applying the scale factor from MODIS data to the surface reflectance measurements taken during the RRV campaign.

The scale factor is the ratio of the radiance measured within the GOSAT footprint by MODIS to the radiance measurement of the MODIS pixel that coincides with the ASD site to which the scale factor is being applied.

Discussion of Scale Factor Code

The GOSAT footprint is circular when GOSAT is in the nadir-viewing angle. The footprint is elongated approximately in the east-west direction to an ellipse for other viewing angles. The major axis of the ellipse is not necessarily perpendicular to the local meridian (Figure 7).

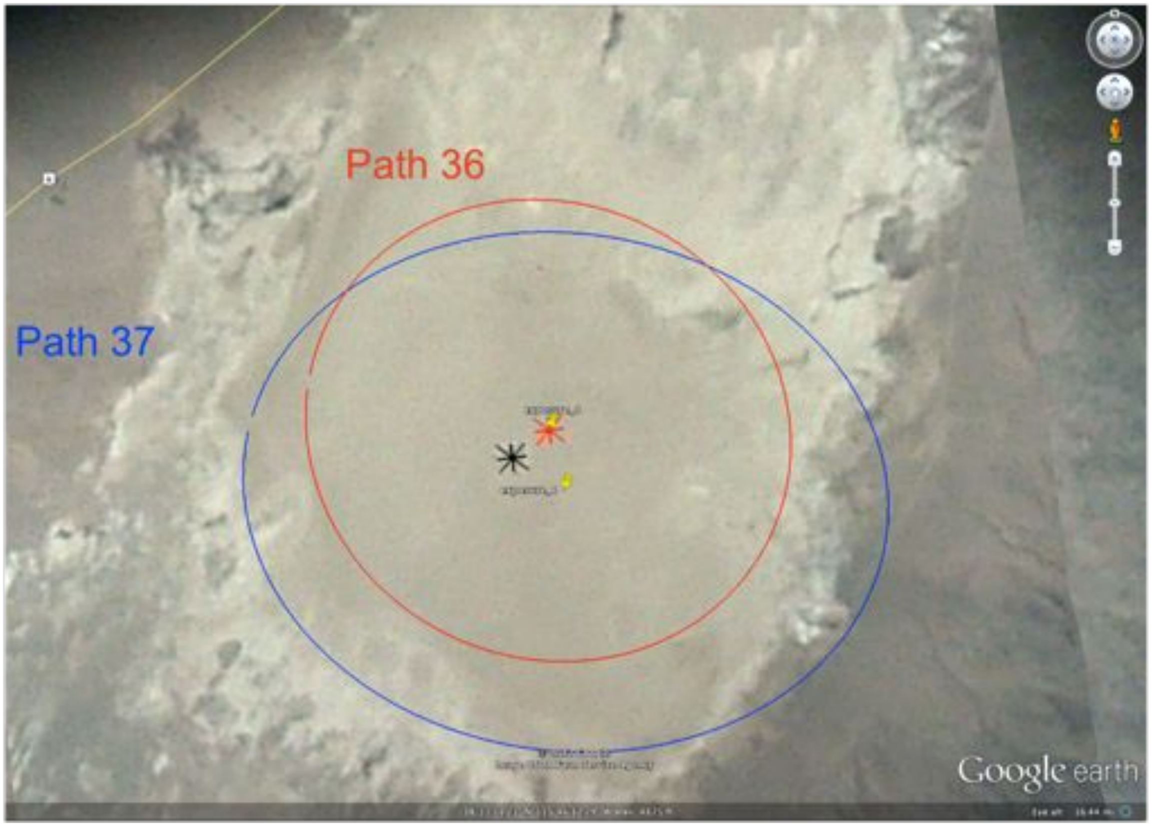

Figure 7 – GOSAT footprint projections based on points provided by JAXA

An algorithm was developed to develop the scale factor shown in Equation 1. As stated earlier, the objective of this algorithm was to compare the MODIS reflectance data corresponding to the GOSAT footprint to the MODIS data for the ASD site in order to develop a scale factor for each test site. In order to do this, an ellipse was defined corresponding to the GOSAT footprint. At nadir, the GOSAT footprint is circular, but for paths 36 and 37, the projection becomes an ellipse of varying eccentricity.

Based on these ellipses, the algorithm extracts MODIS pixels whose centers lie within the GOSAT footprint (Figure 8) and takes an average of their radiance values.

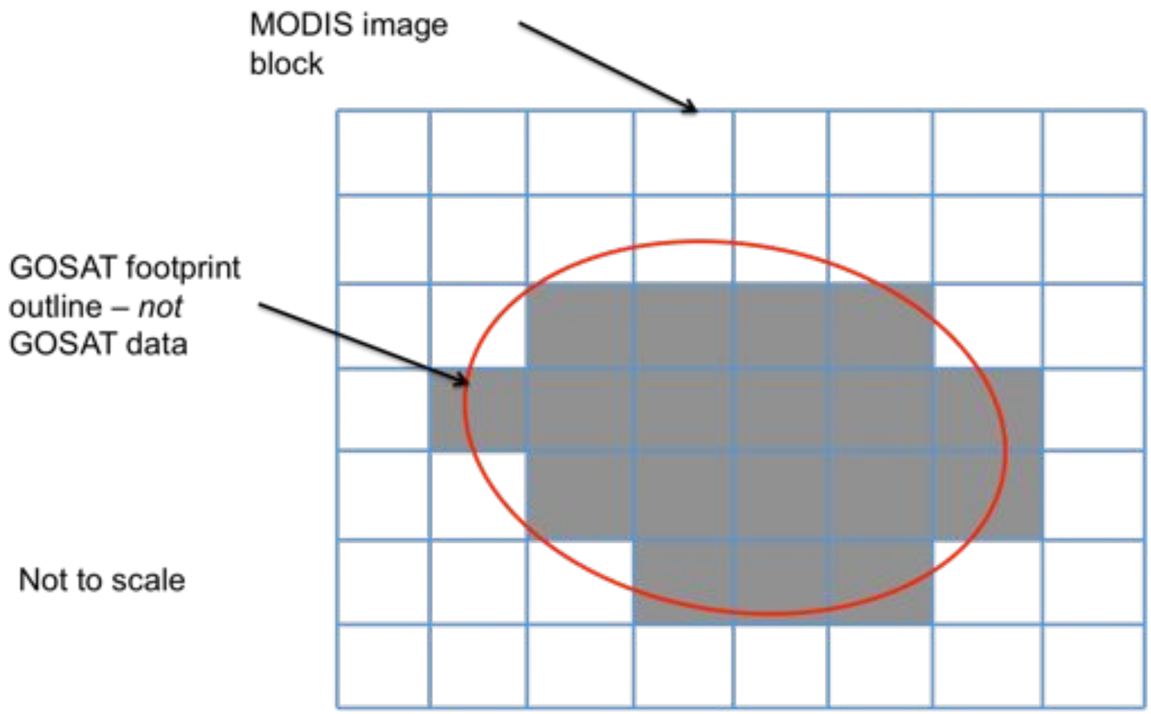

Figure 8 – Schematic of GOSAT footprint projection superimposed over MODIS image block showing pixels used for radiance average

It then finds the pixel whose latitude and longitude are the smallest distance (using a distance on sphere formula) from the ASD site for which the scale factor is being calculated (Figure 9).

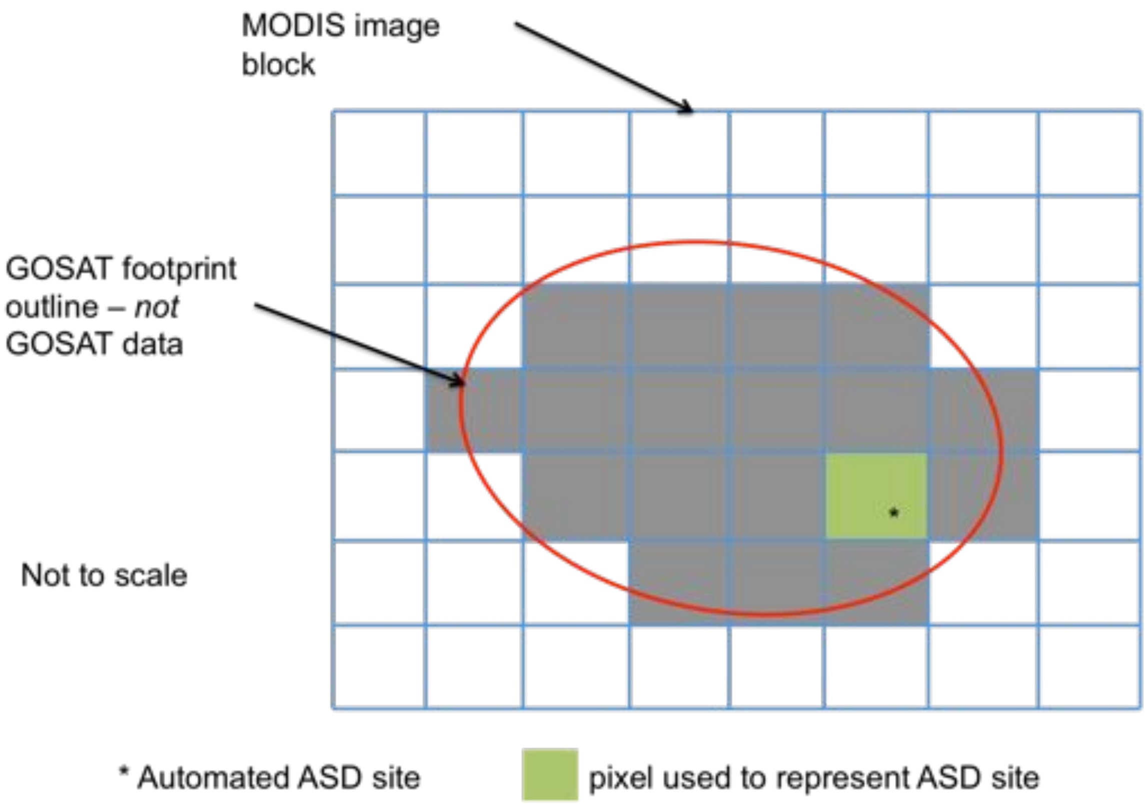

Figure 9 – Previous schematic showing selection of MODIS pixel closest to corresponding ASD site.

The scale factor calculated for each test site is then input to the Orbiting Carbon Observatory (OCO) radiative transfer code. OCO is a JPL satellite under development that will also measure the amount of carbon in the atmosphere.

Image Processing

GOSAT takes a single set of data for the three wavelengths it measures for a circular footprint when viewing from nadir view angle. As mentioned above, however, GOSAT only flies paths 36 and 37 (~19.9 and 33.0 deg, respectively) at RRV. The JAXA team provided a set of points defining the elliptical footprints. The semi-major and semi-minor axes were derived from these points and input into the equation of a rotated ellipse (Equation 2).

$$\frac{x^2\cos^2\phi + 2xy\sin\phi\cos\phi + y^2\sin^2\phi}{a^2} + \frac{x^2\sin^2\phi - 2xy\sin\phi\cos\phi + y^2\cos^2\phi}{b^2} \le 1 \tag{2}$$

This takes into account rotations of the instrument about the line of sight relative to the MODIS image block reference frame. The points selected by the code to determine the semi-major and semi-minor axes were placed on a map and compared to the images supplied by the JAXA team in Google Earth (Figure 10).

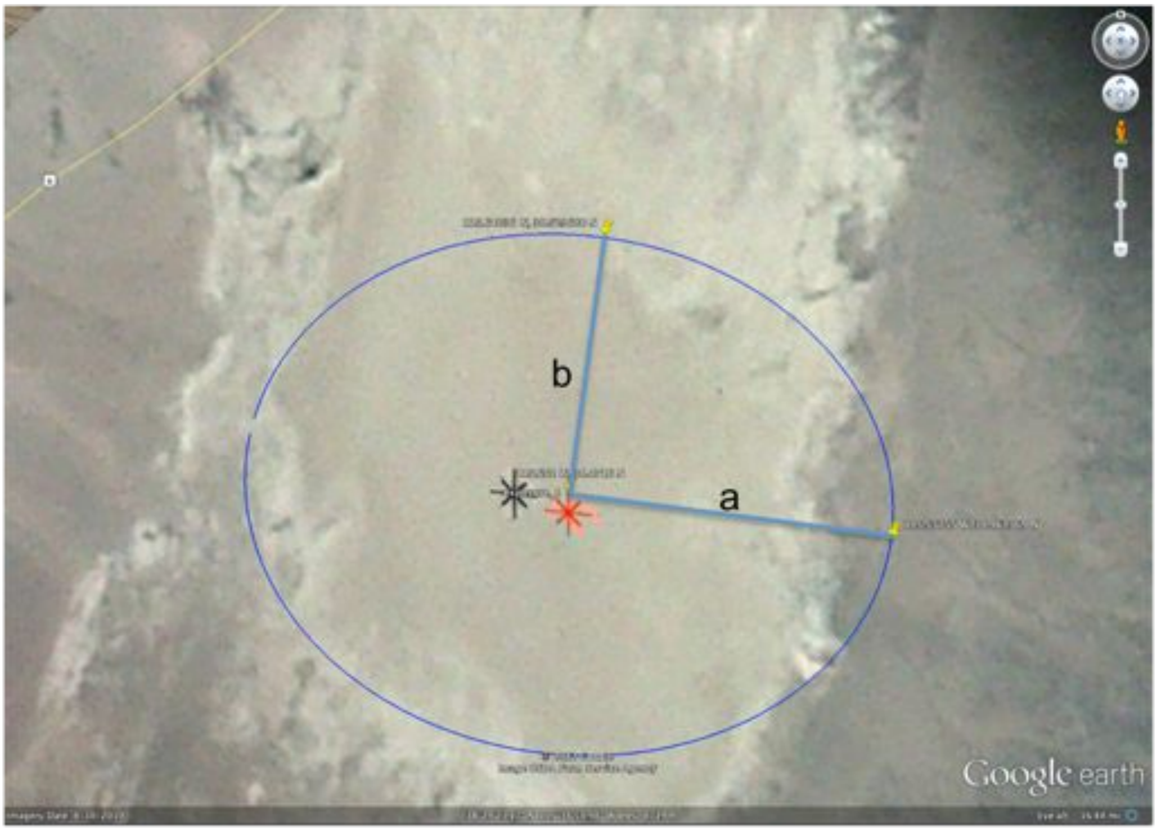

Figure 10 – Major and minor semi-axes superimposed onto path 37

Images of the MODIS blocks corresponding to the GOSAT footprints for paths 36 and 37 were also used for validation (Figure 11).

Path 36 Path 37

Figure 11 – Images of MODIS blocks within GOSAT footprint projection used for validation

The output of the scale-factor algorithm for site M20, path 37 is shown in Table 1.

Table 1 – Scale factor circled in scale factor algorithm output for site M20, path 37. Only the ratio for band 4 was used in this program.

M20, Path 37

	Band 1	Band 2	Band 3	Band 4
MODIS radiance:	158.4475	177.1597	167.2223	117.7603
eq. reflectance:	0.2470	0.2995	0.3281	0.3738
area average:	158.8245	177.2673	167.4984	118.0839
stdev:	0.3908	0.6847	0.8716	0.4034
% stdev:	0.2460	0.3862	0.5204	0.3417
min rad:	158.4475	176.3466	166.4072	117.7113
max rad:	159.2700	177.8771	168.3792	118.4664
ellipse avg:	0.2523	0.3025	0.3281	0.3781
ellipse stddev:	0.0208	0.0242	0.0255	0.0275
GOSAT-to-ASD reflectance:	1.0211	1.0097	1.0000	1.0115

These values were input to the Orbiting Carbon Observatory (OCO) radiative transfer code to generate calibration factors for the GOSAT data based on each site (Table 2). The first column shows the dates where reflectance measurements were taken at the RRV playa, the second column shows the test site for which each scale factor was calculated, and the third column shows the scale factor for each site. Calibration factors from the OCO radiative transfer code are shown in the right column for oxygen (ABO2), weak CO2 (WCO2), and strong CO2 (SCO2). The OCO radiative transfer code also generated bidirectional reflectance factors (BRF), shown in the fourth column.

Table 2 – Table of GOSAT calibration factors based on scale factors ("GOSAT/ASD ratio" column) and reflectance data taken for each site during that GOSAT overpass date/path

GOSAT Overpass Date/ Path	ASD site	GOSAT /ASD ratio	BRF (off-nadir/nadir reflectance)	Ratio Slope of ratio ABO2, WCO2, SCO2
June 25-P36	M03	1.0189	0.94	0.986, 0.924, 0.949 0.328 0.399 -0.260
June 26-P37	L08	1.0413	1.06	Sounding id update needed
June 28-P36	H14	0.9977	0.94	0.966, 0.913, 0.930 -0.645 0.438 -0.256
June 29-P37	M20	1.0115	1.06	1.069, 1.014, 1.045 0.060 0.434 -0.434
July 1-P36	L04	1.0064	0.94	0.982, 0.936, 0.954 0.488 0.427 -0.256
July 2-P37	MODIS	0.9912	1.06	1.041, 0.988, 0.991 0.653 0.491 -0.307

Scale factors were based on 28 June 2012 MODIS data and were applied to the reflectance data taken at the sites shown above on the respective dates.

Time-series of MODIS Data

Daily reflectance values for M03, M20, and H14 sites were used in determining homogeneity of RRV playa. Each reflectance value corresponds to one of three GOSAT bands. There was a maximum deviation of 8% of any value from the average of the measurements of all three sites for any point in time. Large day-to-day differences can be attributed to changing view angle. The time-series show consistency among test sites for a given day (Figures 12-15).

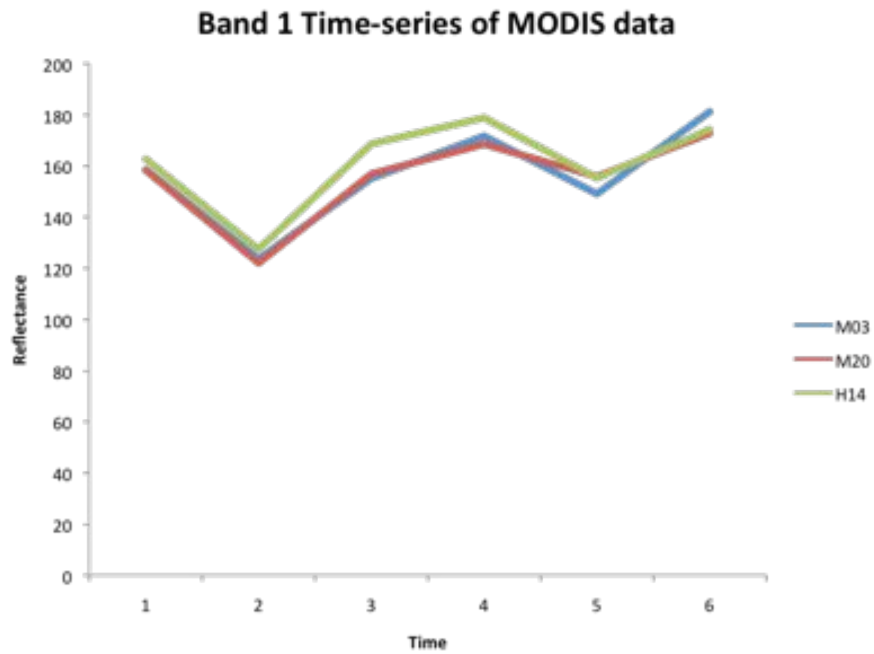

Figure 12 – Band 1 time-series showing reflectance values of M03, M20, and H14 sites

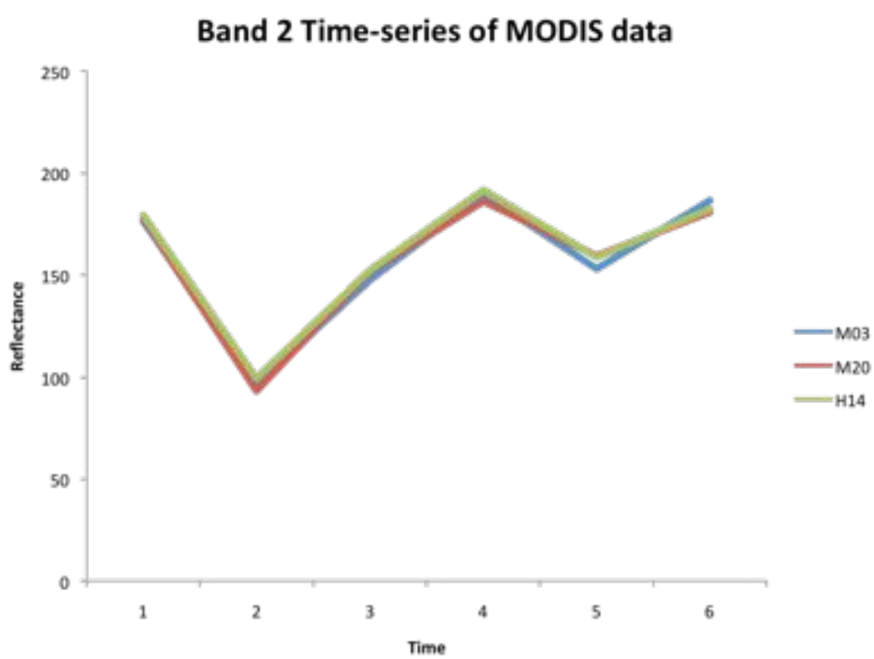

Figure 13 – Band 2 time-series showing reflectance values of M03, M20, and H14 sites

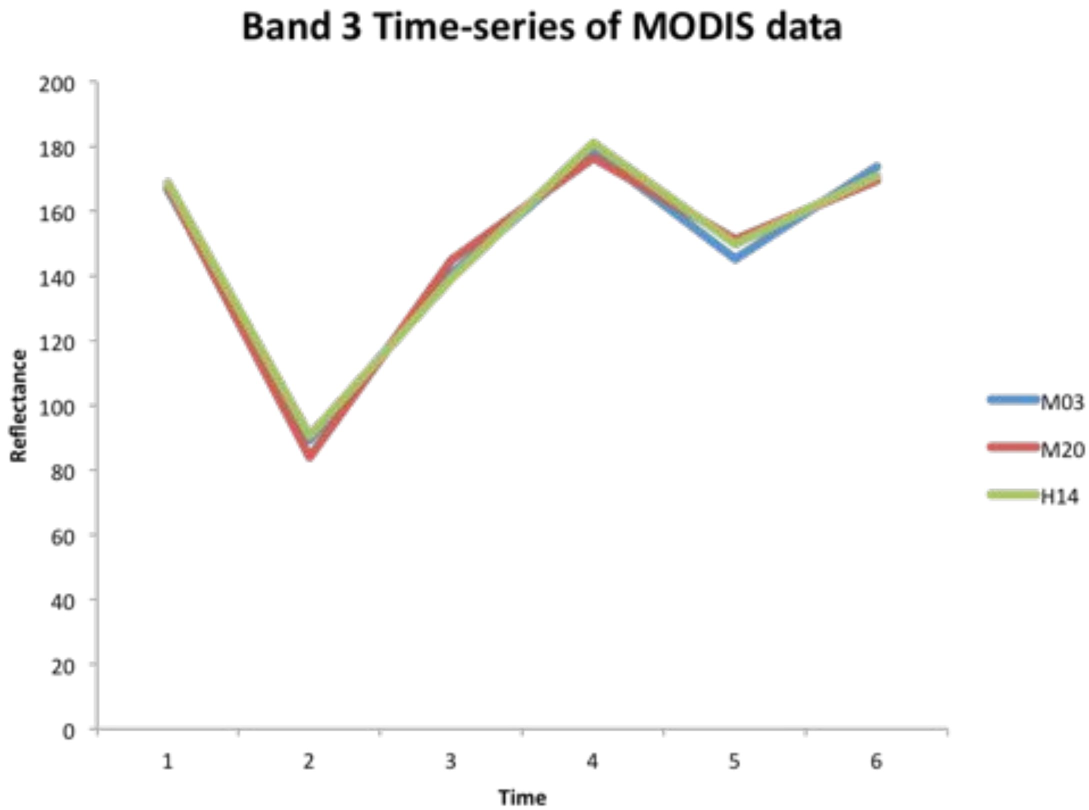

Figure 14 – Band 3 time-series showing reflectance values of M03, M20, and H14 sites

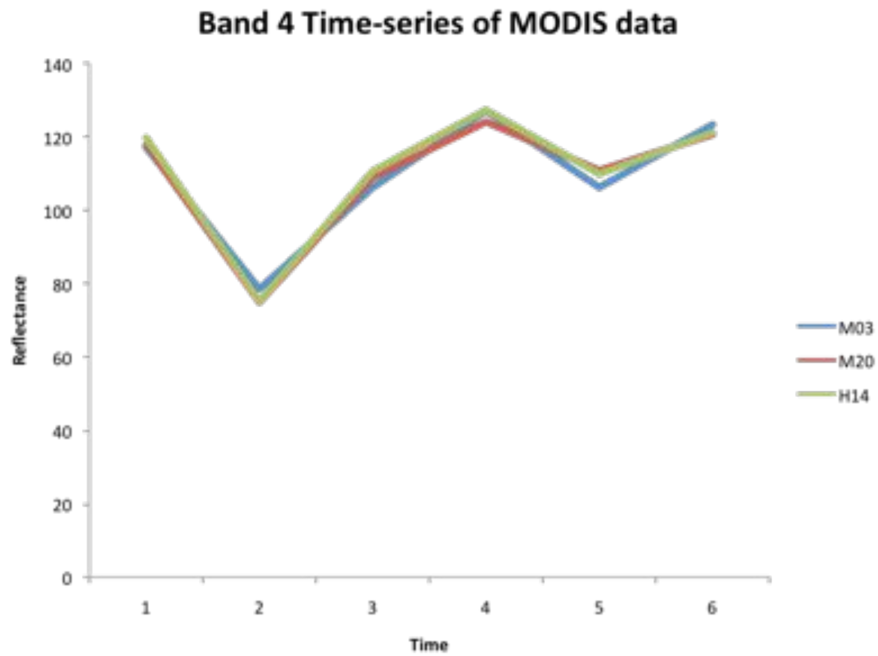

Figure 15 – Band 4 time-series showing reflectance values of M03, M20, and H14 sites

Conclusion

MODIS data shows RRV is a reflectively homogeneous surface over a 10 km area, making it suitable for GOSAT calibration. MODIS data needs to be selected for constant view angles in order to be used to determine surface reflectance changes with time. Since MODIS viewing angle cycles every 16 days, and the RRV campaign lasted only 10 days, data could not be selected for this paper to show changes in reflectance values for GOSAT bands.

Follow-up Work

A more accurate value for the radiance values of the test sites could be derived from MODIS data products by taking a weighted average of the pixels surrounding the test site instead of just using the value of the nearest pixel to the site (Figure 16).

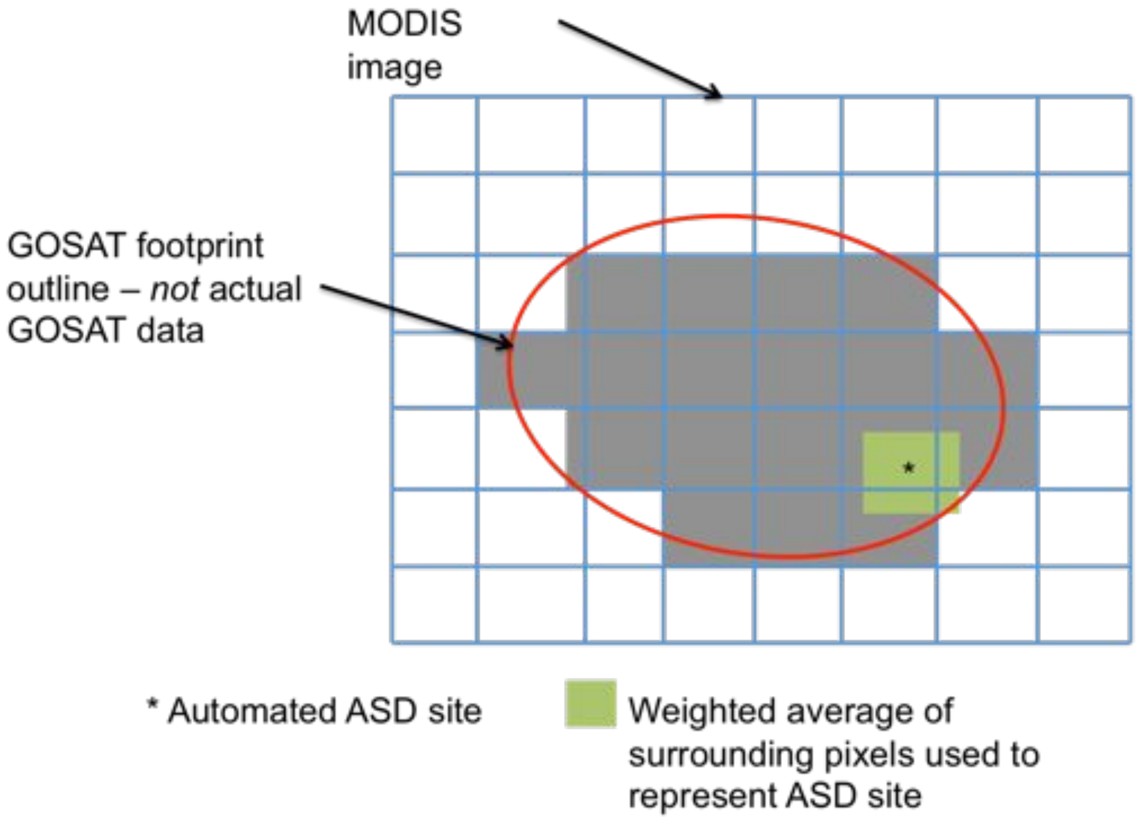

Figure 16 – Schematic of weighted average of MODIS pixels surrounding ASD site with GOSAT ellipse superimposed over MODIS image block

This work has started, but was not completed at the time of writing this paper.

References

A. Kuze, et al., "Vicarious Calibration of the GOSAT Sensors Using the Railroad Valley Desert Playa," IEEE Transactions on Geoscience and Remote Sensing, vol. 49, no. 5, pp 1781-93, May 2011.

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