APPLICATION OF GLOBAL HIGH-RESOLUTION DEM IN THE OCO MISSION

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ABSTRACT:

The Orbiting Carbon Observatory (OCO), scheduled for launch in December 2008, will make the first space-based measurements of atmospheric CO_2 with the precision, spatial and temporal resolution needed to characterize CO_2 sources and sinks on regional spatial scales and seasonal to interannual time scales. Variations in surface topography have a direct impact on the retrieval of the column-averaged CO_2 dry air mole fraction, X_{CO2}, since elevation changes of ~25 meters are equivalent to the 1 ppm X_{CO2} measurement precision sought by OCO. The OCO Level 1B Geolocation process uses a global high-resolution digital elevation model (DEM) dataset to geo-register OCO soundings on the Earth surface. Topographic characteristics (slope, roughness, etc) influence the quality of the X_{co2} retrieval. This paper describes the challenge of applying a high-resolution, high vertical precision, and globally distributed DEM in an automated ground geolocation processing. In this processing, an OCO sounding is first geo-registered to the Earth geoid surface, then to a relatively coarse topography represented by the 30 arc-second EOS/AM1 DEM, and finally to a fine topography at the 3 arc-second. The primary source of the high-resolution DEM dataset is the Shuttle Radar Topography Mission (SRTM) DEM, supplemented by other ancillary DEM data sources. An automated production software system has been built within the OCO ground data processing system to generate the geolocation data, and tested with simulated OCO data and the high-resolution DEM data.

1. INTRODUCTION

1.1 Background

Carbon dioxide (CO_2) is the principal anthropogenic greenhouse gas. Measurements from a global network stations over the past 40 years indicate that the annul increase of CO_2 in the atmosphere varies dramatically from year to year. Though it is known that biosphere and oceans are absorbing almost half of the carbon that has been emitted into the atmosphere, the nature and the geographic distribution of the sinks that absorb half of the human generated CO_2 are still ambiguous [Bousquet, *et. al*, 2000]. The ability to predict the location and the efficiency of the CO_2 sinks and sources is critical to accurate estimates of the future global carbon cycle and climate change.

The Orbiting Carbon Observatory (OCO) is a NASA Earth System Science Pathfinder mission specifically designed to yield measurements of the column-averaged CO_2 dry air mole fraction, X_{co2}, from space with a precision better than 1 part per million (ppm). OCO will make the first space-based measurements of atmospheric CO_2 with the precision, spatial and temporal resolution needed to characterize CO_2 sources and sinks on regional spatial scales and seasonal to interannual time scales. OCO data will provide valuable insight into the nature and geographic distribution of land and ocean carbon sinks [Crisp, D., *et. al*, 2004].

1.2 The OCO Measurement and Topography

OCO is scheduled to launch on December 2008. Once on orbit, OCO will fly at the head of the Earth Observing System Afternoon Constellation (A-Train) [The Earth Science Enterprise Series, 2003] a polar, sun-synchronous orbit with a nominal ascending node crossing at 13:26 local solar time (LST). This orbit provides global observations on a 16-day/233-orbit repeat cycle. The nominal mission duration is two years.

The OCO science payload is a single instrument consisting of three high-resolution grating spectrometers: the 1.61 μm weak CO_2 band, the 2.06 μm strong CO_2 band, and the 0.76μm O_2 A-band. Simultaneous, boresighted observations of sunlight reflected from the Earth's surface in these three bands constitute a single *sounding*. OCO will collect science observations in Nadir, Glint, and Target modes when the spacecraft is on the day-side of the orbit. In the Nadir mode the instrument boresight points to the sub-spacecraft point on the surface. In Glint mode the boresight points at the point where sunlight is spectacularly reflected from the surface, the glint spot. In Target mode the boresight is locked onto a specific surface location during the spacecraft overflight.

An OCO sounding has a typical footprint of 1.29 km in the cross-track direction and 2.25 km in the along-track direction in nadir observations. OCO records up to eight cross-track soundings at three Hz. A *frame* includes all cross-track soundings recorded during each 333 msec integration period. Precise collocation of a sounding from three OCO spectra is important for accurate X_{CO2} retrievals since the algorithms depend on a number of factors such as the presence of cloud and aerosols, surface pressure, and topography. Combination of three OCO bands can effectively detect cloud and relevant aerosol signatures when three bands are collocated. Both surface pressure and inhomogeneous scenes are closely related to the surface topography, including surface type, surface elevation, and variations in surface elevations. The 1ppm retrieval accuracy requires knowledge on the surface elevation to be at a precision of 25 meters or better.

1.3 Ground Data Processing

The OCO Level 1B processing automatically performs radiometric calibration and geometric registration of OCO instrument data. The geo-registered, calibrated radiances will be stored in the OCO Level 1B products, accessible from the Physical Oceanography Data Active Archive Centre (PO,DAAC). All soundings in the Level 1B product shall also contain sounding surface characteristics. This requires use of high-resolution, high vertical precision, and globally distributed digital elevation model (DEM). The OCO Geolocation Product Generation Executable (PGE) is designed and implemented to generate the geolocation parameters in the Level 1B product.

2. GEOLOCATION OVERVIEW

2.1 Instrument Geometry

The OCO mission and measurement strategy have been described in detail elsewhere [Crisp *et al.*, 2004; Miller *et al.*, 2007]. The instrument consists of three spectrometers for the designated weak CO_2 band, strong CO_2 band, and O_2 A-band, respectively. The input signal coming through the OCO telescope is redirected to each spectrometer, passing through a thin slit, and recorded on the focal plane of the spectrometer. The active focal plane contains about 160 spatial pixels and 1016 spectral pixels. In any science mode such as nadir, glint, or target mode, the instrument reads out focal plane in samples. Each sample contains about 20 spatial pixels. Though the instrument slits are very thin and the instantaneous field of view (IFOV) cross a slit is only 68m projected on the ground, the rolling focal plane read out causes a footprint about 2.25km in the along-track direction. Figure 1 illustrates a segment of OCO ground track.

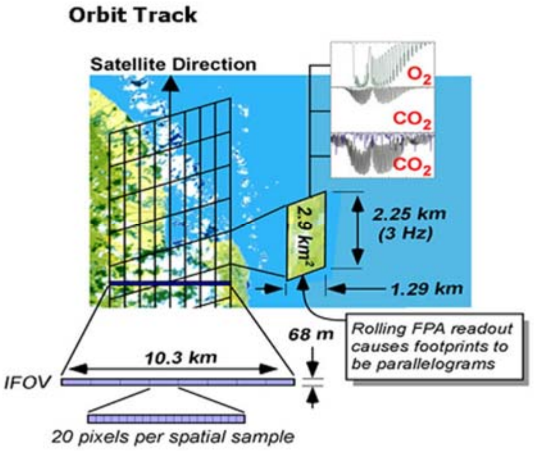

Figure 1 OCO ground track and field of view. The IFOV contains eight footprints in this diagram. Footprints are not rectangular because of the timing of the focal plane read out.

2.2 Sounding Geometry

Sounding geolocation is defined as the intersection of the collocated instrument line-of-sign (LOS) with the topographic surface. Both solar azimuth and zenith angles and instrument LOS azimuth and zenith angles defined at the geolocation are valuable knowledge for derivation of surface bi-directional reflectance. The topographic variation or roughness of a sounding field of view (FOV) is characterized by the standard deviation of elevations within the sounding FOV. Surface orientation aspect and slope angles are also important parameters, particularly in the case that the three spectrometers are not perfectly boresighted. An important a prior knowledge to the Level 2 X_{co2} retrieval is the overlapping percentage of all three OCO footprints on the ground. More details regarding geometric parameters in the OCO Level 1B product are defined in the reference [Weiss, *et. al*, 2007].

2.3 Algorithm Overview

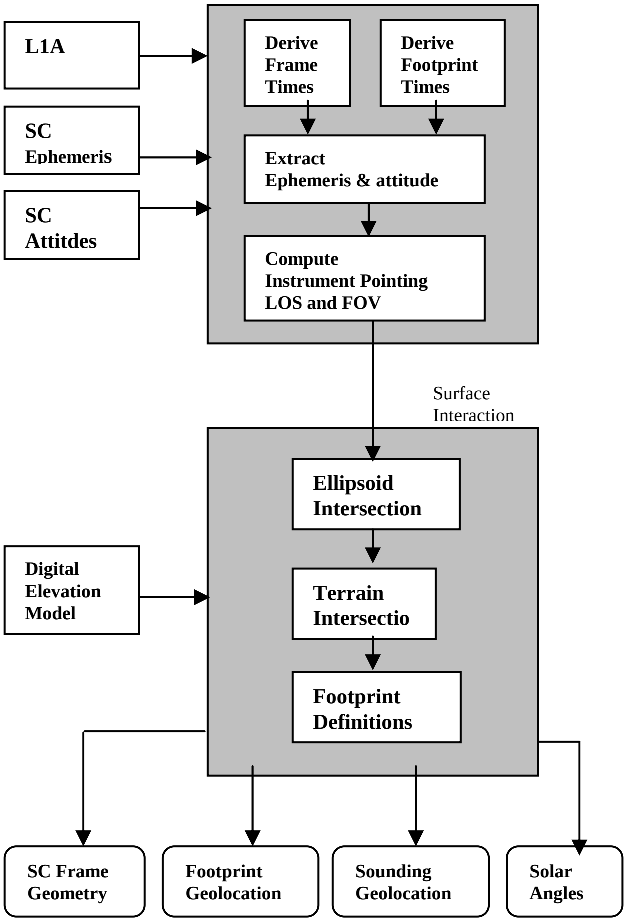

Figure 2 Geolocation Algorithm Overview

The geometric parameters for OCO frames and soundings are determined by the ground data production software, the Geolocation PGE. The Geolocation PGE operates in the OCO process control system (PCS) that manages the automatic production of OCO products upon the arrival of instrument telemetry. The Geolocation PGE combines Level 1A instrument data with spacecraft ephemeris and attitude to derive instrument pointing at the frame and individual footprint times. The PGE then computes the intersection of the look vectors of the instrument LOS and FOV corners with the Earth surface. Figure 2 illustrates an overview of the geolocation algorithm. Due to the rolling focal plane read out, each footprint within a frame is imaged at different times. The Earth surface is first represented by the WGS84 ellipsoid, then by the geoid with undulations.

With a seed point on the Earth geoid, the local surface terrain can be extracted for a ray casting intersection. After all three footprints are defined, a sounding is combined.

3. DEM APPLICATION

3.1 DEM Requirements

The main challenge of the OCO geolocation comes from the requirement of applying global high-resolution DEM in the automated geolocation process. Even though there are only 233 OCO orbit paths and OCO cross-track data swath is only about 10 km wide, half of the OCO science data are planned to be taken in Glint mode. Seasonal variation of sun glint prevents precalculation of fixed sun-glint ground tracks. Therefore, the DEM data need to be available *globally*. The global DEM applied in the OCO mission must also have a *vertical precision* of 25 meters or better (i.e. ±12.5 meters) since uncertainties in surface elevation flow directly into uncertainties in the inferred surface pressure and hence uncertainties in X_{CO2}. The column CO_2 retrieval is also sensitive to inhomogeneous surface topography. Fine details regarding surface roughness and orientation need to be derived from a *high horizontal resolution* DEM. The Level 2 retrieval also requires basic knowledge of surface type, such as land or water. And finally, the OCO mission is a fund-capped mission. The limitation upon resources in terms of both personnel and machine power demands the application of a globally distributed, high-resolution, high vertical precision DEM to be at low cost and efficient.

3.2 EOS/AM1 DEM

The first global DEM data set acquired by the OCO project is part of the Earth Observation System (EOS) Science Data Production (SDP) Toolkit, created in 1999 at the Jet Propulsion Laboratory (JPL). It is also called the EOS /AM1 DEM or Terra DEM [The NASA/EOS DEM SWG, 1999]. The EOS/AM1 DEM was originally created to meet the needs of various EOS/AM instruments. The GTOPO30 DEM produced by the United States Geological Survey (USGS) Earth Resource Observation System (EROS) Data Centre (EDC) was ultimately selected as the Terra DEM. The 30 arc-second (~900m) EOS/AM1 DEM dataset is available globally and includes the following data layers:

- elevation,
- standard deviation of elevation,
- slope gradient,
- standard deviation of slope,
- slope aspect,
- land water mask,
- geoid

The primary source of this global DEM is the Digital Terrain Elevation Data (DTED). Accuracy analyses of the data set indicate an overall 70~80m root mean square error for the 30 arc-second dataset. At the 30 arc-second resolution, the data set is accessible to the general public. In fact, the SDP Toolkit provides seamless access routines to all data layers.

The EOS/AM1 DEM was selected by the OCO project as its baseline DEM because of its global coverage, multiple data layers that meet OCO's requirements, as well as the available seamless access tools. However, the 30 arc-second resolution is too coarse relative to the OCO footprint. Particularly, the vertical accuracy does not meet the OCO requirements, so an effort was undertaken to locate possible EOS/AM1 DEM alternatives.

3.3 SRTM DEM

The Shuttle Radar Topography Mission (SRTM) DEM was the natural next choice for the OCO project. The elevation data obtained by the SRTM on a near-global scale in 2000 generated the most complete high-resolution digital topographic database of the Earth. The 3 arc-second SRTM is globally available within +/- 60° latitude. The vertical accuracy as shown in Table 1 meets the OCO requirements [Rodriguez, et. al, 2005]. However, with an inclination angle of 98°, the OCO spacecraft takes data beyond the +/-60° latitude coverage of the SRTM range. Modelling of sources and sinks of the global carbon cycle requires knowledge on the quantity and distribution of column CO2 at both the extreme high and low latitudes.

	Africa	Australia	Eurasia	Islands	N.A	S.A
Absolute Geolocation Error	11.9	7.2	8.8	9	12.6	9
Absolute Height Error	5.6	6	6.2	8	9	6.2
Relative Height Error	9.8	4.7	8.7	6.2	7	5.5

Table 1. SRTM DEM Performance Report

3.4 The OCO DEM

To satisfy the OCO project's science requirements for high resolution DEM, the OCO project is using a modified SRTM 3 arc-second (~90m) DEM. The SRTM data are divided into one by one degree latitude and longitude tiles in geographic projection (equal intervals of latitude and longitude). File names refer to the centre latitude and centre longitude of the lower left corner of the dataset or tile. For example, for file N37W105, the lower left corner of the dataset is at 37° North latitude and 105° West longitude. SRTM files contain 1201 lines and 1201 samples. Height values are signed two byte integers.

For the purposes of automatic processing on a global scale, voids and missing SRTM elevation data were filled with DTED Level 1 or GTOPO30 data and converted to the same resolution and format as the SRTM dataset. This provides OCO with not only the optimal DEM quality but also a uniform dataset which simplifies the Geolocation PGE dramatically.

Below South 60° of the SRTM data coverage is the Antarctic. For this part of the world, the Radarsat Antarctica Mapping Project (RAMP) 1km DEM Version 2 dataset [Jezek, et. al, 2002] from the National Snow and Ice Data Center (NSIDC) is used. This data was converted to the 3 arc-second scale for compatibility with the SRTM data. Vertical accuracy of the RAMP Antarctic DEM is ± 100 meters over rugged mountainous areas, ± 15 meters for steeply sloped coastal regions, ± 1 meter on the ice shelves, ± 7.5 meters for the gently sloping interior ice sheet, and ± 17.5 meters for the relatively rough and steeply sloped portions of the ice sheet perimeter. The OCO ground track reaches as low as about 81° South. The candidate soundings for Xco2 retrieval are on flat reagions with gental slopes. At such conditions, the vertical accuracy of the RAMP data set is sufficient for the OCO project.

All combined, there are a total of 25,738 1°x1° global high resolution DEM cells assembleed for use in the OCO geolocation process. When high resolution data is not necessary, the EOS/AM1 DEM will be used.

3.5 DEM Application Strategy

Applying automatic geolocation with such a large number of high-resolution DEM files could be a very expensive process. Based on the specific need of the OCO mission that the geolocation process shall identify candidate soundings with homogeneous and near flat surface environment, the Geolocation PGE approaches with a coarse to fine scheme.

For a given footprint, the approximate geolocation on the Earth's surface is defined by the intersection of the footprint LOS look vector with the geoid surface. Because the geoid is relatively flat locally, a step by step ray casting is replaced with a one-step intersection of the LOS with a pseudo Earth ellipsoid at the local geoid height relative to the WGS84 ellipsoid. Tests indicated virtually no error was introduced by this simplification.

Based on the first approximate geolocation, the next step is to determine if the footprint would be excluded from the Level 2 X_{co2} retrieval according to the EOS/AM1 DEM. First, a ray casting intersection is applied to intersect the LOS with the EOS/AM1 DEM to get geolocation at the EOS/AM1 surface. Next, the following conditions are evaluated:

- if the land water mask indicates that the OCO footprint around the geolocation is ocean,
- if the standard deviation at the geolocation exceed a predefined threshold,
- if the surface slope at the geolocation exceed a predefined threshold.

Test thresholds are configurable and adjustable in both pre-flight and in-flight situations. In the case where the ocean evaluation is true, the Geolocation PGE would define the footprint at the geoid. If either one of the last two conditions returns true, it means the footprint is obviously in a rugged mountainous area or a steep slope according to the 30 arc-second data layers from the EOS/AM1 DEM. The Geolocation PGE would define the footprint according to the EOS/AM1 DEM in such a case. Otherwise, the footprint would be defined according to the high-resolution DEM. Once the local DEM surface is selected, the Geolocation PGE performs ray casting to intersect the footprint LOS look vector with the local DEM to get the geolocation. After geolocation, ray-casting intersection will be applied again to intersect the look vectors of the four corners of the FOV with the DEM to define the surface footprint.

3.6 Footprint Terrain Characteristics

OCO footprints are geo-registered to both the geoid and the topographic surface. Footprint terrain characteristics are defined based on the DEM. When the EOS/AM1 DEM is applied, the *footprint altitude, footprint roughness, footprint aspect, footprint slope, and footprint slope error* are the average of the corresponding data layers of all 30 arc-second pixels within the footprint polygon. A *Footprint land water flag* is derived based on the land water mask of the DEM data with four possible values: LAND, OCEAN, INLAND WATER, MIXED. *Footprint altitude error* is the vertical accuracy derived from the EOS/AM1 DEM quality assessment metadata, which is reported in one by one degree resolution.

When the high-resolution DEM is applied, all footprint surface parameters are derived except the *footprint land water flag*, which is always defined according to the EOS/AM1 DEM. The *footprint altitude* is the averaged surface elevations of all 3 arc-second pixels within the footprint polygon. The *footprint roughness* is the standard deviation of the surface elevations of all pixels within the footprint polygon. The *footprint aspect* and *footprint slope* are defined from the same algorithm adopted by the NASA/EOS DEM Science Working Group in the derivation of the 30 arc-second surface slope gradient data layer of the EOS/AM1 DEM. Basically the footprint polygon is further divided into evenly spaced 3 x 3 boxes. The footprint surface angles are derived from the averaged elevations within these 3 x 3 boxes using the ArcInfo algorithm [Horn, 1980]. Similarly, the *footprint slope error* is obtained by further deriving surface slopes within each of the above 3 x 3 boxes and calculating the standard deviation of all nine slopes. *Footprint altitude accuracy* is defined roughly according to the vertical accuracy of the source data, such as Table 1 for the SRTM DEM.

3.7 Sounding Terrain Characteristics

An OCO footprint is a polygon defined by its four corner geolocations. To determine footprint overlaps, the algorithm defines a rectangle that covers the maximum extent of all three footprints in both the north-south and east-west directions. The rectangle is then divided into a number of evenly spaced grids in both directions.

The algorithm then counts the grids that are covered by any of the three footprints that contribute to a sounding, as well as the number of grids that are covered by the region where all three footprints overlap. If the centre of a grid is within a polygon that represents any one of the three footprints, that grid contributes to the total overall count. If the centre of a grid is within all three polygons that represent all three footprints, then that grid contributes to the overlap count. The parameter *sounding overlap* is the ratio of the overlap count to the total overall count measured in percent. Obviously, the finer the grid resolution, the better the overlap accuracy would be. For example, if the rectangle is divided into 30 by 30 grids, then the overlap area error could not be better than 1/900 or 0.1%.

A similar algorithm is applied for the elements that provide the overlap between two of the three footprints within a sounding. *Sounding overlap o2 weak co2*, *sounding overlap weak co2 strong co2*, or *sounding overlap strong co2 o2* is the ratio of the overlap count to the overall count of the two relevant bands measured in percent. The name of the element depends, of course, on which two footprints are being compared.

Sounding geolocation is represented at the sounding time. The parameter *sounding time* is the average of three *footprint times* derived according to the OCO science telemetry. Nominally all three footprint times should coincide. If there exists any difference among the three footprint times and the difference between any two footprint times is larger than a predefined threshold, a quality flag will indicate a timing problem.

The geolocation parameters *sounding latitude geoid* and *sounding longitude geoid* are the average of the corresponding *footprint latitude geoid* and *footprint longitude geoid*, respectively. Similarly *sounding latitude* and *sounding longitude* are the average of the corresponding *footprint latitude* and *footprint longitude*, respectively. If the distance between the geolocations of any pair of the footprints that comprise a sounding is larger than a predefined threshold, a quality flag will indicate a collocation problem.

Other sounding parameters include angle parameters *sounding azimuth*, *sounding zenith*, *sounding solar azimuth*, and *sounding solar zenith*, and surface parameter *sounding altitude*, *sounding altitude error*, *sounding slope*, *sounding slope error*, *sounding aspect*, and *sounding surface roughness*. The algorithm views a sounding as the union of all three footprints and therefore defines these sounding parameters as the average of the corresponding footprint parameters.

4. EXPERIMENTS AND RESULTS

4.1 Geolocation Software

The geolocation software is object-oriented and implemented with the c++ programming language. It contains several components such as *coordinate systems*, *instrument pointing*, *orbit data handling*, *DEM manipulations*, *space to surface intersection*, etc. Many of these components are heritage software developed from previous Earth missions. Reuse of the heritage design and software significantly sped up the development of the Geolocation PGE, which is critical to a cost-constrained mission like OCO. The PGE can be run either in the OCO automatic PCS environment or stand alone. The Level 1B product is output in the Hierarchical Data Format (HDF).

A seamless access tool was built to access the high-resolution DEM. The PGE keeps a few high-resolution data tiles on the buffer storage of the DEM reader to avoid repeated IO processing. The active buffer in the DEM object is built around predicated geolocation. Should the surface intersection detect the geolocation is moving out of the coverage of the active buffer, the PGE would request the DEM reader to roll the active buffer along with the ground track. Separate objects of EOS/AM1 DEM and high-resolution DEM are created. Each of them rolls along the ground track independently as requested by the algorithm.

4.2 Global Maps

The OCO instrument can gather as many as 74,000 soundings on the sunlit side of any nadir orbit. It is important to understand how much retrieval that the OCO mission can expect from the measurement of a 16 day repeat cycle, given the fact that the X_{co2} retrieval is very sensitive to rugged topography and steep slopes. A set of global maps were derived based on the 30 arc-second EOS/AM1 data layers. In Figure 3, the percentage of the Earth's surface where either the *30* arc-second standard deviation of elevation exceeds *16* meters, or the *30* arc-second surface slope exceeds *5* degrees are mapped. The percentage is computed for every *2 x 2* square degrees. Table 2 shows the mean and standard deviation of the grid percentage with surface roughness or slope over the above thresholds, listed by continent. Both the figure and the table support that the OCO should have sufficient global coverage with dense sampling. But a challenge remains over Asia where over half of the land has surface roughness and slopes that are over the test thresholds. Overall, the global percentage of grids that exceeds the threshold is about 15%.

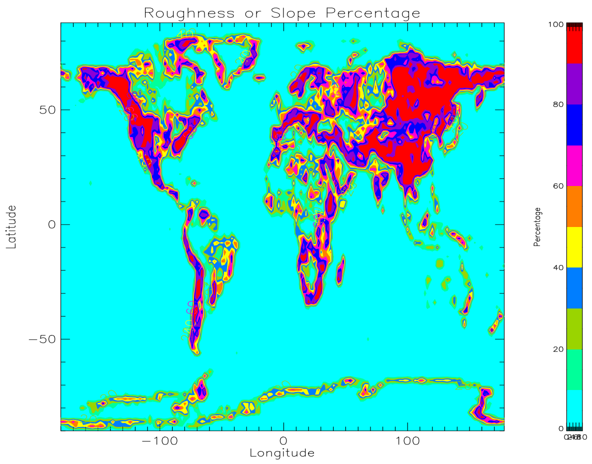

Figure 3. Global map of percentage of surface roughness or slope.

Continents	Mean	Standard Deviation
Antarctica	11	19
North America	41	32
South America	34	29
Australia	11	17
Africa	37	30
Europe	48	31
Asia	57	35
Global	15	25

Table 2 Mean and standard deviation of the grid percentage with surface roughness or slope over test thresholds, listed by continent

4.3 Data Simulation

In order to test the Geolocation PGE, the L1A instrument product was reverse engineered from simulated OCO radiances. The Ephemeris product was simulated using existing orbit data from EOS spacecrafts such as Terra or Aura that share the same A-Train. The OCO instrument pointing was controlled by spacecraft manoeuvre and the attitude data was simulated according to instrument pointing at the science mode.

4.4 Geolocation with Simulated Data

The first revision of the Geolocation PGE was implemented and tested with simulated inputs. The test demonstrated that using a global high-resolution DEM could be a very costly process. A coarse-to-file strategy is necessary to zoom into the Earth surface. With the coarse-to-fine approach, the PGE takes about two seconds to process an ocean frame, about eight seconds to process a frame with footprints on a rugged surface or a steep slope, and about 50 seconds to process a frame with footprints on the high-resolution DEM surface. Performance analyses indicate that the cost is closely related to the surface intersection and high-resolution raster data manipulation. The higher the vertical accuracy in the local DEM, the more steps are required to precisely land the ray casting on the surface. The higher the resolution in the raster DEM, the more searches are required to define a polygon in the data. There are some additional performance improvements that could be applied, but the overall processing time will still depend upon how much high-resolution DEM will be applied. Table 1 indicates that this is about 15% of the Earth's surface. The PGE keeps a list of frames that are precisely geolocated onto the high-resolution DEM, a list of frames that are geolocated onto the EOS/AM1 DEM, and the rest of the frames that are on the geoid. The limited test conducted with the simulated inputs agrees with the estimate of the global map and suggests a good distribution of potential CO_2 retrieval. Once OCO is in orbit, the distribution of candidate soundings that are registered on the high-resolution DEM as well as on the geoid over a repeat cycle can be plotted globally.

5. CONCLUSION

With the ever growing need in the understanding of our home planet, the integration of digital topography into remote sensing of the Earth environment becomes more critical. The challenge of employing global digital topography in the automatic data reduction of the OCO mission is driven by its need of global geolocation at high vertical precision as well as high horizontal resolution. Acquiring a global DEM data set at the right high-resolution and high vertical precision was one of the first challenges to the OCO mission, and has been shown to be valuable in the automatic data reduction of satellite measurements. The OCO Geolocation software relies on two sets of DEM data, the EOS/AM1 DEM at 30 arc-seconds resolution and the primary SRTM high-resolution DEM at 3 arc-seconds resolution, to geo-register OCO soundings on the Earth's topography and derive sounding surface terrain characteristics. The coarse-to-fine approach is robust enough to access and intersect with the right topography model as it is needed. The experiments also demonstrated that the application of global high-resolution is still expensive given the current implementation. Further optimization and evaluation of the software for generating OCO soundings is expected in the future.

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