Development and Test of a Raster Scanning Laser Altimeter for High Resolution Airborne Measurements of Topography

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INTRODUCTION

The RAster SCanning Airborne Laser (RASCAL) sensor was developed in 1995 at the Goddard Space Flight Center for airborne mapping of surface topography. RASCAL is a second generation laser altimeter with application to both Earth (airborne) and planetary surface (space-based) topography measurement. It differs from earlier nadir-profiling laser altimeters (ref.1) by a two-order of magnitude increase in pulse repetition rate and provision for a near-contiguous scan pattern. It was operated in a NASA airborne remote sensing program in California in September 1995 where it's ability to produce a high-resolution (better than 2 m spatial resolution) three-dimensional image of topography was demonstrated. The design and operational use of the RASCAL sensor are presented below, along with sample data sets that demonstrate its ability to map surface elevation at the sub-meter level of accuracy.

INSTRUMENT AND MISSION DESCRIPTION

The principal of operation of RASCAL is the time-of-flight measurement of 10 nsec wide laser pulses, each of 150 μJ pulse energy, from which the range (i.e. distance) from aircraft to ground can be determined. Optical pulses at 523 nm wavelength are generated by a Nd:YLF Q-switched diode-pumped frequency-doubled laser transmitter and directed at the Earth's surface by a rotating scan mirror. The pulses are then received by a 12.5 cm diam. telescope that is co-located with the laser in the RASCAL sensor, detected by a nsec-response photomultiplier tube, and processed on-board by timing and energy measurement electronics in a microprocessor-controlled data system. The size of each RASCAL laser footprint on the surface is determined by the aircraft height above ground level and laser divergence, and is nominally maintained at 1 m in diameter. To date, the RASCAL instrument has been operated on the NASA Wallops Flight Facility T-39 twin-turbo jet aircraft (N425NA) using a nominal straight-and-level flight pattern with a ground-speed of 100 m/sec at an altitude of 500 m above ground level. Airborne operation of RASCAL at 5,000 laser pulses-per-sec produces a nominal 100 m wide swath of topographic data with 1.67 m along-track and across-track (i.e. spatial) resolution between each measurement footprint. The primary data generated by RASCAL are time-interval-unit (TIU) measurements of the round-trip travel time of each laser pulse between a zero reference surface in the instrument and the Earth's surface. Additionally, the apparent surface reflectivity (i.e. detected pulse energy) of each laser pulse is recorded. Pulse energy data are used to correct the time-interval data for time-walk effects resulting from surface reflectance variability, on the threshold detecting algorithm of the instrument. The RASCAL time-of-flight data must also be corrected for output beam angle, sensor pointing attitude, and the global positioning system (GPS) derived trajectory of the T-39 airborne platform in order to derive accurate values (i.e. geo-referenced values) for the Earth surface elevation and spatial position of each sensor footprint.

Fig. 1 is a block diagram of the RASCAL sensor. Shown are details of the raster scan generator which is based on a 45-sector polygon-shaped aluminum scan mirror. This device was specially fabricated by Lincoln Laser Corp., by means of a diamond-turning process that produced close tolerances for the mirror surface quality of each sector and sub-mrad accuracy in scan pattern generation. The laser transmitter is a diode-pumped Nd:YLF laser (TFR Model from Spectra Physics, Inc.). This frequency doubled laser pulses at 523 nm wavelength producing a visible, mm-size beam with a two-dimensional gaussian intensity cross-section and a 2 mrad divergence. The 15 cm diameter polygon scan mirror, which is mounted with its rotation axis parallel to the aircraft flight direction, directs this high repetition-rate pulsed laser beam across the ground track of

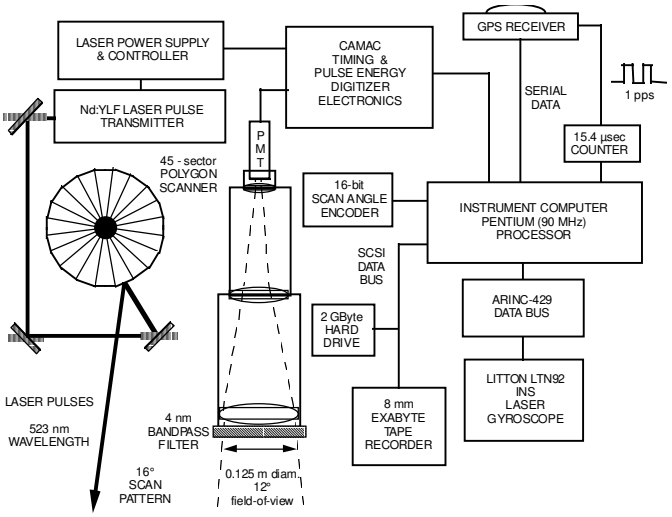

Figure 1 - Block Diagram of the RASCAL altimeter

the aircraft in a raster pattern. Note that the transition between sectors causes an abrupt retrace (i.e. reset) of the scan pattern. The rotation speed of the mirror is servo-controlled and can be fixed to a constant rate. A rotation of 80 rpm creates the contiguous scan pattern for the current platform. At this speed, the mirror produces 60 scans per sec (45 faces multiplied by 80 rpm) to produce the desired across-track pattern. Ground tests showed that laser spots were stable to approximately 1/4 of a spot diameter in pointing angle from the RASCAL sensor and the scan speed was stable to better than 1%. The 45 sectors in the polygon scan mirror each occupy an 8 degree sector of the scan mirror and produce a 16 degree scan pattern by angle-doubling of the reflected laser beam. The RASCAL telescope is a custom-designed refractive optical system based on stock, spherical-surface lenses that focus a 12 degree field-of-view onto a 20 mm diameter blur circle where the photomultiplier tube photocathode is located. A 4 nm bandpass filter covers the entire telescope entrance aperture and provides some degree of rejection of solar background irradiance. The telescope field-of-view was set less than the scan pattern in order to eliminate, by truncation, those laser pulses that reflect from edges of each scan mirror sector. The effective scan pattern is a ± 6 degree swath (i.e., 0.2 radian) that is centered on the aircraft roll axis and consists of 3,600 laser pulses for topography measurements per second. This pattern nominally results in a 60 by 60 grid of measurements that is 100 m square.

The timing and pulse energy digitization electronics of RASCAL are contained in a CAMAC (IEEE 583 Bus) crate along with various supporting electronics consisting of a real-time clock, range-gate, and power supply modules. The time-interval-unit that is the heart of the RASCAL data is a LeCroy, Inc., Model 4204 time-to-digital converter which has 0.15625 nsec timing resolution. These CAMAC electronics are controlled by a custom C-language program running on a 90 MHz Pentium processor. The flight software fires the laser under external trigger control and then reads the TIU and pulse energy data for each laser pulse. Time basis is provided by the 1 Hz signal generated by the GPS receiver. Ancillary data on the polygon scan mirror position are derived from a BEI Motion Systems Co. 16-bit shaft angle encoder and the aircraft roll, pitch, and heading angles from a Litton LTN92 laser gyroscope inertial navigation system (INS) and are read at a rate of 100 measurements per sec by the flight software. Status information and small subsets of data are interleaved to the screen during data collection for quality assurance.

A typical, T-39 airborne science flight of RASCAL spans 2.5 hours of data operations and produces approximately 15 million laser pulse measurements of surface topography. The record from each flight comprises approximately 700 megabytes of range-to-the-surface, pulse energy, GPS, and pointing angle data. Each mission includes deliberate measurements of instrument pointing angle biases. For these measurements the T-39 aircraft is flown in a series of deliberate banking and pitching maneuvers over bodies of water to produce a data record with a wide variety of laser pulse incident angles over a locally-horizontal surface. Pointing angle data collected from a laser gyroscope system mounted on the instrument platform are used in data analysis to compute the pointing biases which reproduce a flat surface from the ranging data. End-to-end length calibration of the ranging data for each flight is accomplished by two passes (in opposite directions) over the ground-based GPS reference station in which the X-Y location of the GPS antenna and its surface elevation appear in the altimetery data. In addition, intersecting passes over the topography of the science flight lines are typically flown to provide self-consistency tests of the data within each flight mission and among all flight missions over the same terrain. Within three hours of landing from each flight mission, all flight and ground data are backed-up on hard drives and data tapes, a GPS trajectory of the aircraft position at 500 msec intervals with ~ 50 cm accuracy is produced, and laser altimeter data quality is assessed. Post flight data analysis takes place over the next few months. In this phase, instrument range and pointing angle biases are combined with a 5 cm-quality GPS trajectory of the aircraft derived from precision orbits for the GPS spacecraft. The end goal of measurements, calibrations, and analysis is sub-10 cm vertical accuracy in geo-referenced topographical data for each RASCAL sensor pulse on the Earth's surface. The final data products are the latitude, longitude, and surface elevation of each laser pulse which constitute digital elevation maps of the scientific study sites.

DATA ANALYSIS METHODOLOGY

The final data product of surface elevation for individual laser pulse measurements requires many steps of data analysis. A suite of Interactive Data Language (IDL) routines were developed for processing laser altimetery data in a UNIX environment on a SUN Sparc 10 workstation. These routines were developed for other laser altimeters and only slight modifications were required for RASCAL's scanning system. Supplemental routines were written to accommodate some of the unique features of the scanning system. There are several steps involved in processing the data.

Determination of biases for pointing angle data and the range data must be done before processing can begin and are the first steps in data analysis. The aircraft, laser gyroscope angle measurements are re-sampled, to match the laser pulse rate, from the smoothed (i.e. filtered) set of 100 samples-per-sec of the INS data record. The INS data are also time shifted to compensate for transport delay from the INS to the data system. The digital encoder's position as a function of time is converted to an output beam angle. These angles are similarly interpolated from the 100 sample-per-sec record of the encoder and inserted into the data structure as a roll bias for each pulse. The aircraft GPS trajectory, which is available only at 2 Hz, is then fit with a cubic-spline to provide a smoothly varying position for the aircraft as a function of time that can be re-sampled for each laser pulse. The next step is application of a range calibration to each laser pulse. Range calibration information is generated in ground testing by operating RASCAL with its scanner stopped over a short (~ 50 m) horizontal path, measuring range as a function of pulse energy, and then measuring the calibration range with a steel tape and a static GPS survey. From these ground-based data a look up table of range vs. pulse energy is created to compensate for time-walk due to variable pulse rise times affecting the threshold detecting range measurement. The range correction is then applied in the data analysis to each laser pulse. A key aspect of this procedure is determining the exact distance between the RASCAL scan mirror surface, which is used as a zero-range reference surface, and the calibration target. Finally, all laser pulse data are passed through a pulse energy filter to eliminate laser pulses with too low or too high pulse energy. The high and low limits are set based on quality of the range calibration. Both high (i.e. saturated) and very low energy laser pulses have excessive (> 20 cm) range errors.

After all data are prepared and filtered, the geo-referencing of each remaining laser pulse proceeds by translation and rotation in a matrix formulation. This procedure is derived from the method of Vaughn et al (ref. 2) and was converted into an IDL procedure. Geo-referencing involves rotation through angular offsets between INS and scanner reference frames, vector displacement of the laser output point to the GPS antenna element, and translation by the RASCAL range measurement to the Earth's surface. All angle biases are taken into consideration when calculating these rotations. The end result is a latitude, longitude and elevation of each valid range measurement in the reference frame that the GPS trajectory was processed. Typically this is the (World Geodedic System) WGS-84 reference ellipsoid.

OPERATIONS COMPLETED AND EXAMPLES

The RASCAL instrument completed its first operational science deployment during October 1995 in eastern and southern California. During a two week period, the RASCAL instrument was shipped to Los Angeles by air cargo, hand carried to Bishop, CA, incorporated into the Wallops Flight Facility T-39 aircraft (N425NA), and employed in two campaigns of science investigations comprising 7 separate flight missions. The first series of flights (5) were conducted from the Bishop Airport over volcanic terrain of Long Valley Caldera and a wide variety of landforms within the Death Valley National Monument. The second series of science flights (2) were conducted from Edwards Air Force Base over terrain along the San Andreas fault and related faults at the southern end of the San Joaquin Valley. These science application data sets will be the subject of future presentations and journal manuscripts. In our current program of data analysis we are verifying the data analysis methodology described herein and investigating data quality. To those ends, we provide examples of data acquired at Bishop, CA and the NASA Dryden Flight Research Center (DFRC) at Edwards Airforce Base, CA.

Fig. 2 is an image of topographic data collected during a RASCAL flight mission on October 13, 1995 over the hangars and support buildings of DFRC. The data show the main hangar complex at DFRC, cars parked around the various buildings, and the concrete ramp area adjacent to the hangars. The RASCAL surface elevation data in this figure were smoothed in IDL by triangulation, gridding and linear surface fitting of all valid measurements. Close examination at the pixel level of these data revealed that part of our ground-based GPS antenna was measured. This permitted us to positively identify the GPS base station antenna at the point indicated by the arrow head in Fig. 2. The RASCAL measurements at this point were a mean surface elevation of 665.30 m (WGS-84 ellipsoidal height), a latitude of North 39.949444140 deg., and a longitude of East 242.11390015 deg. The measured elevation was computed from 10 pixel values of the concrete ramp surrounding the GPS antenna base. These data compare to the following values for the Defense Mapping Agency marker # 1381 GSS, which was embedded in the concrete ramp at the plumb line location of our GPS antenna. It's postion is reported to be North 34.94944147 deg. longitude, East 242.1139071 deg. latitude and an elevation of 665.073

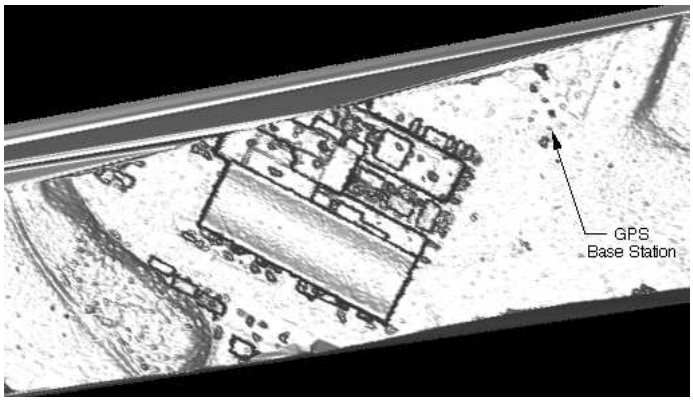

Figure 2 - GPS Ground Station and DFRC Hangars

m. The difference of the measured surface and known location of the area indicate an elevation bias of ~ 25 cm with peak to peak spreading of the elevation values of 10 cm. The spatial measurement determines the location of the antenna to less than 0.5 m. This is an end-to-end verification of RASCAL airborne topography measurement accuracy. A second pass over the same site shortly after this measurement, as well as an additional pass on October 11, 1996 gave similar results.

Fig. 3 presents a gridded digital elevation model (DEM) with 1 m pixels produced from RASCAL data over Lake Crowley Reservoir northwest of Bishop, CA along the Owens River. This image is a composite of six parallel passes flown at an offset of ~ 100 m to create a larger DEM of the area. There are 450,000 topographic measurements in this scene and shading is based on surface elevation. Note the Lake Crowley Dam at the center of the scene. It is a concrete dam with an earthen rampart and service roads on the downstream face. There are some artifacts present in the data (e.g. triangular wedges in the water surface behind the dam) that are produced as the IDL fitting program acts to join data points where there are gaps within a single scan (i.e. pass) or between adjacent scans. This figure serves to demonstrate the high-resolution topography mapping ability of the RASCAL instrument and provides a indication of work to be done to verify the vertical and horizontal positioning of RASCAL data sets over topographic features. We are now in the process of comparing RASCAL data of the water level and Lake Crowley dam structure to independent field measurements with water-level gauges and geodetic surveys.

CONCLUSION

The specific goal of RASCAL airborne laser altimeter operations was the acquisition of geodetic-quality DEM data of sub meter vertical resolution over sets of kilometer length scale, dynamic topography. This development was

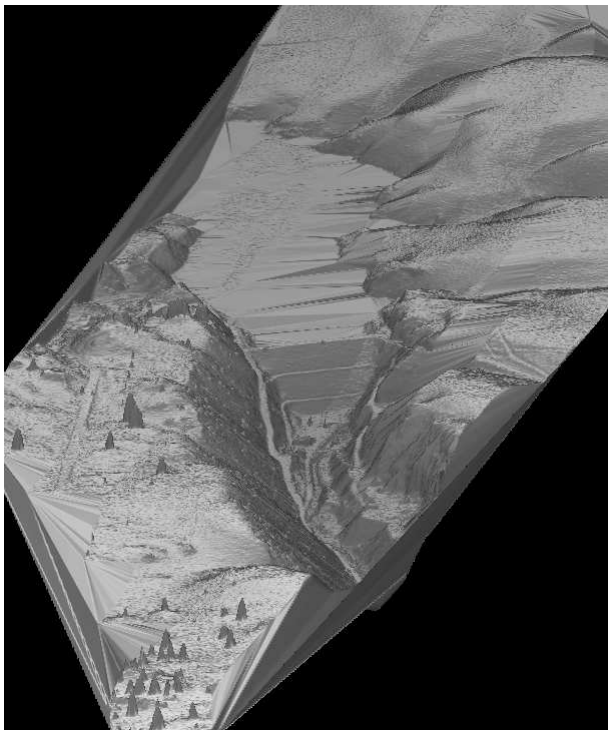

Figure 3 - Lake Crowley Dam and Surroundings

sponsored by the NASA Planetary Program and the Topography and Surface Change Program as a pathfinder investigation for future, NASA space-based topography missions. The initial development of the RASCAL sensor and demonstration of its science measurement potential are complete. The RASCAL instrument worked very well in seven flight missions flown in the fall of 1995 in California and demonstrated a new capability for high-resolution, high-accuracy topography mapping. A data analysis system is also in place to produce georeferenced data products consisting of high accuracy surface elevation from the RASCAL airborne data set. The first steps have been taken to verify the geodetic accuracy of the RASCAL scan observations, and they indicate the sub-meter level-of-performance.

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