SHUTTLE RADAR TOPOGRAPHY MISSION: AN INNOVATIVE APPROACH TO SHUTTLE ORBITAL CONTROL

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ABSTRACT

On February 11, 2000, the space shuttle Endeavour lifted off to tackle an ambitious mission: make the most comprehensive map ever of planet Earth. The successful 11-day Shuttle Radar Topography Mission (SRTM) produced the most complete terrain map of the world. Radar inteferometry was used to derive surface elevation by calculating the differences between measurements taken from slightly different locations.

The payload consisted of a main antenna and an electronics package in the shuttle's payload bay with an outboard antenna at the end of a 200-foot mast extended once the shuttle is in orbit.

Maintaining the planned orbital profile was crucial to guarantee complete coverage of the entire land coverage with no gaps between radar swaths. Orbital maintenance was accomplished during trim maneuvers executed approximately once per day. Maneuver design was constrained significantly by the presence of the delicate 200-foot mast. During the flight, seven trim burns were performed using a "fly-cast" maneuver which required a set of precisely timed pulses to minimize loading on the mast. All maneuvers were successful and kept the orbit within required limits.

Extensive interaction with the Johnson Space Center Flight Dynamics Office ensured proper design and execution of the orbital control.

1. INTRODUCTION

Shuttle Radar Laboratory (SRL) as predecessor

Synthetic Aperture Radar (SIR-C/X -SAR) was a cooperative space shuttle program between the National Aeronautics and Space Administration (NASA), the German Space Agency (DARA), and the Italian Space Agency (ASI). The main objective of the mission was to use L, C and X-Band Synthetic Aperture Radar on board the Space Shuttle to scan the Earth allowing detailed observations at any time, regardless of weather or sunlight conditions. The data collected during the mission are still used by the international scientific community to better understand the global environment and how it is changing.

The first SIR-C/X-SAR mission, called SRL-1, was flown aboard STS-59 in April 1994. The second mission, called SRL-2, took place in October 1994 with the same payload aboard STS-68 to acquire images of the same area of the first flight to compare them [1]. Another great success of the SIR-C/X-SAR mission was to test a new image elaboration technique known as interferometry. By exploiting separate passages of the antenna over nearly the same area with the same geometry, a DEM (Digital Elevation Model) of the observed areas was obtained. These results were achieved because of the extremely precise control of the Shuttle orbit during the second flight which was able to simulate a single flight carrying two antennas slightly displaced in space. The excellent results from these missions opened the door to the SRTM mission

2. MISSION DESIGN

2.1 *Project Objectives and Organization*

The Shuttle Radar Topography Mission (SRTM) is a joint project of the National Imagery and Mapping Agency (NIMA), the National Aeronautics and Space Administration (NASA),

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and the German and Italian space agencies to map the world in three dimensions.

Using the Spaceborne Imaging Radar (SIR-C) and X-Band Synthetic Aperture Radar (X-SAR) hardware that flew twice on Space Shuttle Endeavour in 1994, SRTM collected the following:

- Data that will be used to generate a digital topographic map of 80 percent of Earth's land surface (everything between 60 degrees north and 56 degrees south latitude), with data points spaced every 1 arcsecond of latitude and longitude (approximately 30 meters). The data will meet Interferometric Terrain Height Data (ITHD)-2 specifications (30 m x 30 m spatial sampling with ≤16 m absolute vertical height accuracy, ≤ 10 m relative vertical height accuracy and ≤20 m absolute horizontal circular accuracy). All accuracies are quoted at the 90% level, consistent with National Map Accuracy Standards.
- Data sufficient to produce a rectified, terrain-corrected, C-band (5.6 centimeters wavelength) radar image mosaic of 80 percent of Earth's land surface also at 30 meter resolution.

Additions that were made to the SIR-C hardware to create SRTM, a fixed-baseline interferometer optimized for day/night, all-weather topographic mapping, included:

- A 60-meter-long, deployable mast derived from space station designs.
- Additional C-band and X-band antennas located at the end of the mast.
- Avionics for attitude and orbit determination.

The X-band interferometer was built and supplied by the German and Italian space agencies. Data processing is in progress and should require 18 months total. The resulting digital topographic map will form a homogeneous data set referenced to a uniform global geodetic datum.

Data formats will be compatible with standard software and terrain analysis programs, tailored to the needs of the civil, military, and scientific user communities.

Analysts will use the SRTM data to generate 3–D topographic maps called digital elevation models for studies of flooding, erosion, land-slide hazards, earthquakes, ecological zones, weather forecasts, and climate change. The data's military applications include mission planning and rehearsal, modeling, and simulation. Other possible uses include optimizing locations for cellular phone towers and improving topographic maps for backpackers, firefighters, and geologists.

Data from the SRTM mission will be made available to these users in accordance with release guidelines mutually developed by NIMA and NASA.

2.2 *Orbit Design*

In order to match the mission requirements and to comply with the Shuttle operational constraints, the optimal orbit selected was circular, 57 deg inclined with a mean altitude of 233.1 Km [2]. In fact such an orbit, which repeats the ground track in 9.8 days after 159 orbits, allowed the C-band radar to cover completely the surface of the Earth between approximately +/- 60 deg of latitude. With the nominal orbit, the radar swath was predicted to have only 7 Km of overlap (measured across the swath) with a ground track spacing of 252 km at the equator.

It is well known that several perturbations affect the motion of a satellite orbiting around the Earth. For the above orbit, the main perturbation was the atmospheric drag which, along with the effects of the Shuttle Reaction Control System (RCS) for maintaining the orbiter attitude with the mast deployed, represented the largest uncertainty in predicting the Shuttle orbit evolution during the SRTM mission. Other perturbations like the Earth's gravitational field, the solar-lunar effect, solar radiation pressure, etc. are much better known and can be precisely modeled in the orbit propagator.

Pre-mission simulations had shown that the expected orbit decay due to the atmospheric drag was about 1.5 km/day. Such decay would have caused the violation of the node location constraint in about 24 hours. Therefore periodic orbit maintenance maneuvers (Trim Burns) at that frequency had to be planned in order to control the orbit to avoid violation of this fundamental mission constraint.

2.3 *Requirements and Constraints*

The design of the maneuver strategy has been extremely demanding and challenging because of:

- unpredictability of the perturbation to the orbit caused by the RCS (Shuttle had never flown before in the complex structural and dynamical configuration determined by the presence of the 60 meter mast and outboard antenna);
- uncertainty in the actual atmospheric drag during the flight;
- tight constraints on the maneuver execution placement (TIG) which was desired by the customer to occur only when Shuttle was flying over the ocean in order not to lose ground coverage. This parameter was strongly impacting the orbit eccentricity control and consequently the instantaneous altitude constrained by the radar performance;
- additional timing constraints to place maneuvers during one ground operations shift which was staffed with the personnel required to perform the maneuvers, AND placement near the astronaut crew handovers when both crews were awake and could assist in troubleshooting;
- total duration of the maneuver (about 40 min) which restricted enormously the opportunities for performing the maneuvers;
- radar swath overlap determined not only by orbit dynamics, but also by the radar functional characteristics which could change during the mission;
- a very limited RCS propellant budget.

For the above an unusual approach to the Shuttle orbital control strategy was followed.

First, a burn technique to avoid unacceptable stress to the mast structure during the orbital maneuvers was studied. The “fly-cast” burn technique was proposed by JPL structural engineers as a way to minimize loads on the mast during PRCS burns. It consists in a series of precisely-timed pulses to “stop” the mast at its rebound position for the main portion of the burn, minimizing overshoot and misalignment of the outboard antenna from excessive motion. This technique requires pulses to be performed at an interval equal to a fraction of the mast natural frequency.

Second, for Shuttle missions the customer defines the orbital requirement for fulfilling the objectives of the mission and the JSC Flight Dynamics Officer (FDO) is in charge of planning and conducting the flight operations in order to comply with the customer requirements.

For SRTM the swath overlap requirement couldn’t be specified as pure orbit dynamics characteristics, therefore FDO and the SRTM Mission Planners needed to work tightly together before and during the mission execution.

The nominal plan for controlling the orbit is summarized in Fig. 1 where the predicted mean altitude is plotted vs. time. It can be seen that nine periodic trim burns for raising the altitude were planned approximately every 24 hours.

In Tab. 1 the detailed nominal sequence of the trim burns is given.

Maneuver #	Time from launch (day/h:m)	ΔV (m/s)
TRIM-1	1/2:33	1.1
TRIM-2	2/13:24	1.1
TRIM-3	3/13:39	1.0
TRIM-4	4/12:57	1.0
TRIM-5	5/13:12	1.0
TRIM-6	6/12:29	1.0
TRIM-7	7/12:47	1.0
TRIM-8	8/12:02	1.1
TRIM-9	9/12:21	1.0

Tab. 1 – Pre.mission trim burn plan

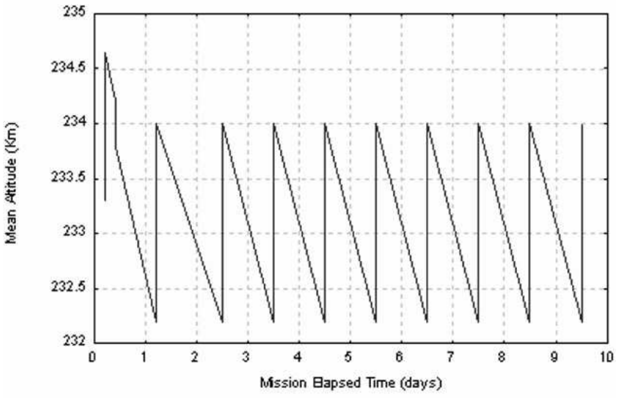

Fig. 1 – Mean altitude nominal profile

In addition to the maneuvers listed, a couple of orbit adjustment (OA-1 and OA-2) and two test RCS firings were included in the plan during the check-out phase, in order to refine the orbit after the STS main engine cut-off and for checking the mast structural behavior after deployment.

3. MISSION OPERATIONS

3.1 *Planning Resources & Interactions*

During the flight, the SRTM orbit planners used a software package developed specifically for SRTM to receive state vectors, propagate them to form ephemeris files for the orbiter, and analyze those ephemeris files versus the orbit requirements to plan and execute maneuvers.

While many approaches were considered in developing the planning resources, it became clear once interactions with the JSC Flight Dynamics Officers were underway that consistency of data between the two teams and clarity of communication was paramount. For this reason, special care was taken on the SRTM side to design plots in concert with the JSC team which illustrated the same data in the same units. In addition, the SRTM propagator used by the orbit planners was carefully calibrated to bring it in alignment with the JSC orbit propagator to ensure consistency. With the complexity and large number of constraints on the maneuver design, confusion from mismatched software, data formats, or units would have slowed down the process considerably and likely have made the problem intractable.

During the flight, plots of mean altitude (a measure of orbital energy), orbital radius (to assess orbital eccentricity and pass-to-pass variation), and node crossing location (plotted both in time and by physical location) were generated by both teams and examined in the control centers to determine the health of the orbit.

Once a rough estimate for the upcoming maneuver time was determined, a preflight-generated “quiet periods” document which was generated by the SRTM orbit planners and distributed to both teams was consulted. This document was produced to illustrate long ocean passes in which maneuvers could be placed to minimize impact on data acquisition.

From this, the maneuver (and a highly desired backup window, preferably on the next orbit) was scheduled and then simulated by both teams in software to determine the ΔV necessary to put the orbit back on track.

Both teams then worked together to finalize the maneuver plan. At approximately 3 hours before the maneuver time, planning was completed and information on the maneuver distributed throughout the control centers. Once the maneuver was complete, JSC provided prompt performance results to confirm that the maneuver executed as planned.

3.2 *Trim RE-planning and Performances*

One of the main concerns before the flight was the uncertainty in the on-orbit drag which could have had a severe impact on the trim burn sequence if it varied significantly from predictions. Fortunately, the orbital decay measured from the beginning of the flight was very close to the predictions and only minor adjustments were made to the nominal plan during the first half of the mission [Ref. 3].

Everything went as planned and the only refinements needed during the trim re-planning were the TIG (Time of Ignition) and the ΔV. Trims 1, 2, 4, 5 were postponed by one revolution in order to minimize the ground track deviation from the baseline.

The sequence of Trim 6, 7, 8 and 9 was completely reworked during the mission because of the failure of the cold-gas thruster mounted at the tip of the mast. This thruster was developed to help counteract large gravity gradient torques on the orbiter due to the specific orientation required to point the antennas. Unfortunately the thruster stopped working early in the mission and the Shuttle used up much more propellant than planned for attitude control, reducing the amount of propellant available for orbit maintenance.

In order to complete the mapping with the reduced propellant availability, the shuttle navigators and the SRTM mission planners worked-out a new maneuver sequence from trim 6. The plan was to delete trim 8 and 9, to increase the delta-v of trim 6 and 7, and to postpone trim 7 by about 12 hours. With this sequence, even some violation of the ground track constraint was expected. However, the exact phasing and choice of ΔV were creative enough to open up no gaps between radar swaths. Therefore, it was possible to successfully complete the mapping operations.

The actual trim burn sequence with the deviations from the target delta-Vs recomputed during the replanning activities, is reported in Tab. 2.

The ground track deviation (triangle marked line) from the baseline (continuous line) is shown in Fig. 2

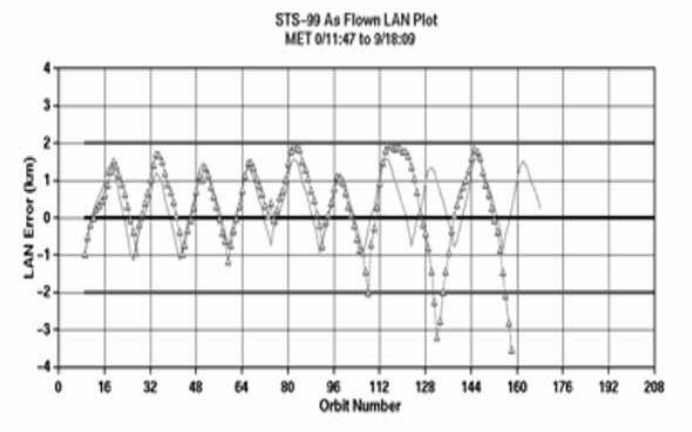

Fig. 2 – Ground track deviation

4. RESULTS

4.1 *The accuracy achieved*

The Shuttle Endeavour launch occurred nominally and the first measurements of the orbit indicated that the altitude was slightly higher than expected. The two orbit adjustment opportunities scheduled in the pre-mission plan were used to reduce the altitude and to optimize the eccentricity for the beginning of the mapping operations.

Man. #	TIG	Delta-V	
		Target	Actual
TRIM-1	1/14:00	1.10	1.13
TRIM-2	2/14:53	1.16	1.20
TRIM-3	3/13:39	1.13	1.17
TRIM-4	4/14:23	0.88	0.92
TRIM-5	5/14:26	0.90	0.95
TRIM-6	6/13:56	1.16	1.22
TRIM-7	8/02:53	1.55	1.56
TRIM-8	(deleted)		
TRIM-9	(deleted)		

Tab. –2 Actual trim burn sequence

As mentioned earlier the only anomaly experienced was the failure of the cold gas thruster which impacted only on the propellant margins forcing to adopt a maneuver plan for the second part of the flight substantially different from the baseline.

The post-flight analysis performed by the Shuttle Navigators [3], indicated that the average delta-V error for all the seven Trim Burns was 0.04 m/sec posigrade with a standard deviation of 0.01 m/sec. The total ΔV error including the attitude flip maneuver necessary to get the burning attitude and the subsequent maneuver to return to the mapping attitude, was about 0.02 m/sec retrograde. It is clear that the two 180 deg. reorientation maneuvers reduced the orbit energy, canceling the small excess of ΔV of the trim burns.

The extremely satisfactory accuracy of the orbit control allowed precise ground track and radius control as well, resulting in a radar swath placement without any coverage gap as desired.

Even the intentionally introduced violations of the node location after trim-5, to cope with the reduced availability of propellant, did not cause any gap in the coverage, demonstrating an excellent performance of not only the SRTM hardware and electronics, but the payload and planning teams as well.

4.2 *The coverage obtained*

During the 11-day flight, the SRTM system executed 765 data takes, collecting over 12 terabytes of data (8.6 terabytes for C-band, 3.4 terabytes for X) on 330 high-density tapes stored on board the shuttle (this data volume is approximately equivalent to the U.S. Library of Congress).

With the successfully deployed 60 meter mast, the Shuttle and SRTM payload created the largest rigid structure ever flown in space and the world's first spaceborne single-pass interferometer at C-band and X-band frequencies.

Of the target land mass between ±60° latitude, 99.96% of it was imaged at least once, totaling over 119 million square kilometers. In addition, 94.6% of the target land was imaged at least twice. The only regions not imaged during the mission were located within the continental United States, where 30 meter resolution topography data already exists and is managed by the U. S. Geological Survey. Figure 3 illustrates the coverage obtained.

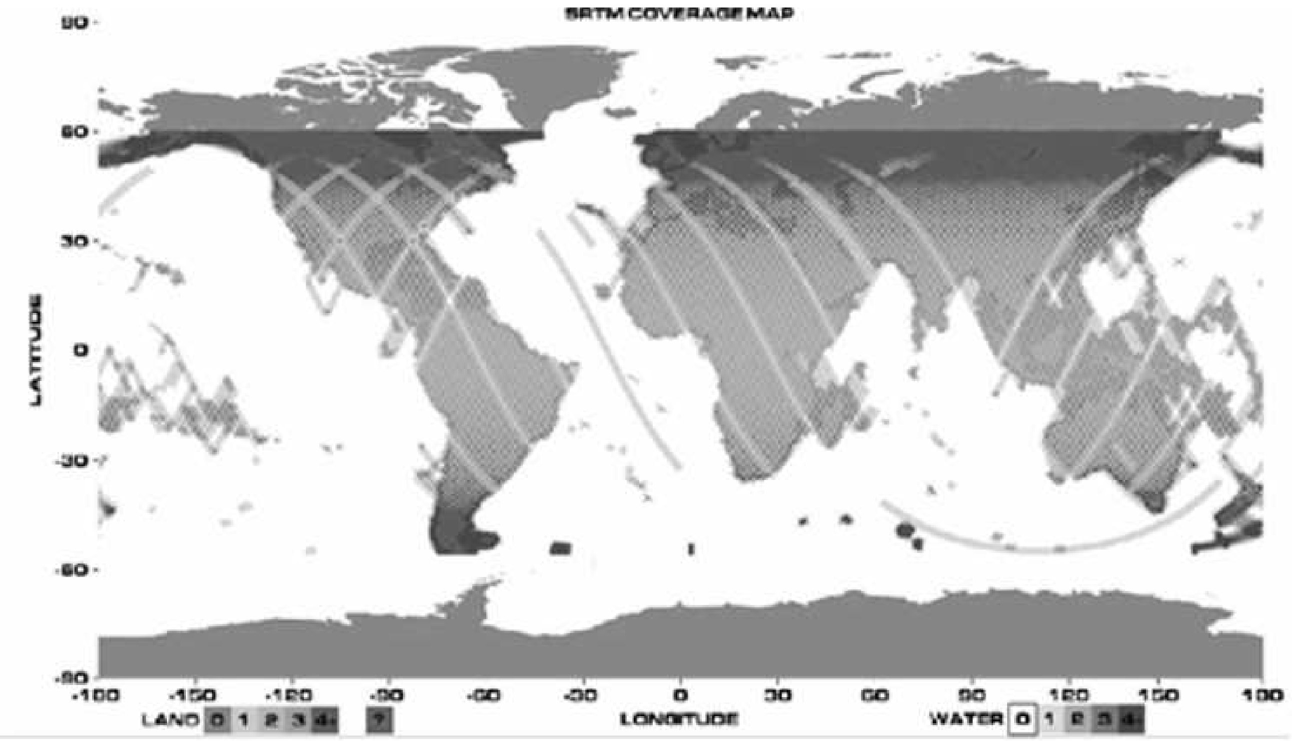

Fig. 3 – Coverage Map

REFERENCES

[1]"*X-SAR Program: Orbit Planning and Control During the Development Phase and Mission Operations (Shuttle Flights STS-59 and STS-69)*", A. Foni, CNUCE Internal Report C95-14, May 1995, CNUCE, Pisa, Italy

[2] "*SRTM Mission Planning – Detailed Design Document*", D. Seal, JPL D-15448, NASA/JPL, Pasadena, California, USA

[3]"*Precise Trajectory Control of the Shuttle Radar Topography Mission*", J. Chris Edelen, AIAA Conference, August 2000, Denver, Colorado, USA