Apr 26th, 4:00 PM

# Paper Session II-C - Optical Alignment Measurements of Space Shuttle Tiles

Rebecca L. Welling
*Lockheed Research and Development Division, Lockheed Missiles and Space Company*

Rick A. Williams
*Lockheed Research and Development Division, Lockheed Missiles and Space Company*

Edward D. Huber
*Lockheed Research and Development Division, Lockheed Missiles and Space Company*

# OPTICAL ALIGNMENT MEASUREMENTS OF SPACE SHUTTLE TILES

REBECCA L. WELLING
RICK A. WILLIAMS
EDWARD D. HUBER

LOCKHEED RESEARCH AND DEVELOPMENT DIVISION
LOCKHEED MISSILES AND SPACE COMPANY
3251 HANOVER STREET
PALO ALTO, CA 94304

## INTRODUCTION

The Space Shuttles are serviced and maintained by the Lockheed Space Operations Company (LSOC) at the Kennedy Space Center in Florida. The tiles which act as a heat shield during Shuttle re-entry into the earth's atmosphere, are a major part of the Shuttle servicing efforts. One very tedious and labor intensive task is the alignment measurement of these tiles. Alignment measurements include measuring the gaps, or separation between two adjacent tiles, and measuring the steps, or the height differences between adjacent tiles.

Traditional methods of measurement required two mechanical tools to separately measure steps and gaps. Plastic feeler gauges were used for gap measurements and dial-indicator trammel tools were used to measure steps. The Lockheed Research And Development Division (R&DD) in Palo Alto, CA developed and built the hand-held optical tool, the Lockheed Laser Tool (LLT), that is currently being used to measure tile steps and gaps. The LLT measures both steps and gaps simultaneously, replacing both mechanical tools.

Integration of the LLT into the Shuttle servicing environment and the formal certification and acceptance of its use was an important milestone for state-of-the-art technology being utilized to improve and maintain Shuttle processing flow. This was an iterative process during a six month period in 1988. Direct feedback from Shuttle operations/engineering helped refine the user-interface and became a critical contribution to the success of the program.

The system hardware includes:
- The hand-held instrument which is used to image the tile surface,
- A mobile cart-mounted work station with
  - A portable Personal Computer (PC) which processes the tile data captured by the instrument and computes the measurements,
  - A color monitor for remote viewing of the tile data as it is captured and processed by the system,
  - A printer which outputs the measurement results that have been stored by the computer.

Advantages of the LLT include:
- Measurement time has been reduced by a minimum factor of 4 because two tools were replaced by one, and data recording is automated where it was previously hand recorded.
- Repeatability and reliability have vastly improved because.the human no longer makes critical decisions about the values measured by the instrument used.

- Quality assurance/control has improved because data acquisition and display is automated with automated checks. Monitoring capabilities are possible that were impossible with previous methods, including the ability to verify whether a measurement was made relative to air flow and forward/aft positioning of the vehicle.

## PROBLEM STATEMENT

In order to maintain an efficient aerodynamic Shuttle surface the 30,000 ceramic tiles that protect the vehicles during re-entry must be well aligned. Step and gap measurements determine this relative tile alignment. As shown in Figure 1, step refers to the height difference between adjacent tiles. An even matching of tile heights (zero step) is desired. Gap refers to the spacing between adjacent tiles, also shown in Figure 1. Spacing between tiles is incorporated by design to provide for expansion and contraction of the vehicle. This spacing must be closely controlled to prevent hot gases from flowing between tiles and damaging the vehicle body.

Before the LLT was available for use, step and gap measurements were made using two different mechanical methods; plastic feeler gauges were used to measure gap spacings, and dial-indicator trammel tools were used to measure step heights. The process was extremely laborious because of the large number of locations requiring measurements on a given tile (around 24 locations per tile times 2 tools = 48 measurement locations per tile). In addition, all measured values had to be recorded by hand.

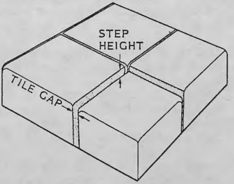


Figure 1. Schematic Of Step Heights And Gaps

Because the LLT measures both steps and gaps simultaneously replacing two tools with one, it directly reduces the number of measurements required by half. Other features make the system even faster yet, and in addition, make the overall process smoother and more reliable and subject to automated monitoring for quality control. This is achieved in part by pre-entering data set information of desired locations and utilizing data base systems to store and output data in the appropriate format and having color screen viewing of data capture and processing.

## SYSTEM DESIGN REQUIREMENTS

System design requirements were derived through an iterative process that included on-site discussions with KSC engineers/operators, and progress review meetings of prototype developments at Lockheed R&DD.

Several broad requirements were identified and used to govern the selection of the technical approach. These include:

- Improve reliability, safety, accuracy and time of process flow.
- Provide real-time access to inspection status.
- Design equipment that functions well in continuously changing shop environments.
- Demonstrate concept feasibility through prototype development.
- Develop equipment components that adapt easily for automation.
- Provide growth capabilities to solve other Shuttle problems.

The specific requirements can be divided into two categories, usage requirements and measurement requirements.

Usage Requirements:

The usage requirements define the environment or application needs of the user. For a step/gap measurement system these were defined to include:

1. hand-held,
2. light weight ( 2 lbs. to 3 lbs.),
3. insensitive to vibration or motion of the user's hand,
4. provide adequate viewing or visibility for precise measurement alignment
5. provide feedback to the user to assure that proper and accurate measurements are made,
6. portable for KSC OPF usage, safety and logistics requirements.

Measurement Requirements:

Measurement requirements provide a specific description of the measurements to be made. This includes not only the accuracy, precision and range requirements, but also includes a description of precisely what is to be measured and how the measurement is to be made and interpreted for the specific application. Step and gap measurement requirements are summarized as follows:

| | RANGE | ACCURACY | LOCATION |
|---|---|---|---|
| STEP | 0.0-0.5 IN | +/-0.003 IN. | 0.09-0.25 IN. FROM TILE GAP EDGE |
| GAP | 0.0-0.410 IN. | +/-0.003 IN. | AT RADIUS TANGENT OF BEVELED EDGES BETWEEN ADJACENT TILES |

Additional measurement requirements include a complete listing and description of types of step and gap configurations that must be measured. These include:

1. Types of tile materials: black tile (HRSI), white tile (LRSI), gray panels (RCC);
2. Types of gap filler materials: none (an empty gap or space between tiles), AMES gap filler (thin multiple leaves), pillow or pad gap filler (thick rounded material) and thermal barriers (larger formed, padded material;
3. Tile damage repair sites: ceramic repairs(gray), RTV repairs (black or white);

4. Tile surface blemishes: tile usage and aging (a lightening or graying of black tile); tile edge scorching (showing as slightly roughened or raised edges with a gray to white coloring; other cosmetic features including tile label lettering or RTV and gap filler burn markings.

The usage and measurement requirements combined to produce several unique features and problems that are peculiar to the optical inspection task. The data processing software was designed to handle the following:

- user interaction and variability;
- variability of tile step/gap configuration;
- variability of surface reflectivity.

One of our primary goals during development of the LLT was to ensure that the step and gap measurements provided by the instrument were completely correct. In order to safeguard against the delivery of incorrect data, the software was designed to consider each of the above possible sources of variability or error.

User Interaction And Variability:
Since the step/gap data are acquired from a hand-held, human-operated tool, human variability and error had to be considered. The following types of errors in operating procedure are detected and indicated on the operator's screen:

- the laser was not turned on
- the tool was not positioned on a measurement site
- tool alignment was outside of allowable limits

Variability Of Step/Gap Configurations:
Each tile provides a unique measurement configuration with respect to the LLT.

Tile variations: The shape of the tile edges as seen by the laser line are unique. Tile edges are designed to have a radius of curvature of 0.060", but manufacture and wear generate cases of near square edges to radii exceeding 0.250". The profile of the tile surface near the edge may be flat, sloped, or variable due to excessive heating or repairs.

Gap fillers: The gap between tiles may be filled by one of several types of filler material. One type (Ames gap filler) is made from multiple layers of material 0.015" thick. The layers sometimes become separated after the gap filler has undergone excessive heating and when imaged with the LLT could be mistaken by the software for tile-to-tile gaps. Other types of gap filler (thermal barrier, pillow/pad) are highly reflective (generating an Excessively wide laser line) and may protrude from the gap occluding the tile edge.

Tile/Gap-filler interface: When tiles have been flown with gap filler, excessive heat will have caused the gap filler material to burn and either scorch the tile surface or actually fuse to the tile.

Angled gaps: Some step/gap configurations consist of tiles with gap walls that are not perpendicular to the tile surface. These angled gaps require a separate software algorithm for gap measurement.

Variability Of Surface Reflectivity:
Several types of surface contaminants that are peculiar to the Shuttle tile environment cause extreme surface reflectivity variations which in turn reduce the accuracy of step and gap measurements.

Tile repair sites: Minor tile damage sites are repaired with a grey-colored material. When repairs are made on tile edges, direct effects on gap measurement accuracy are seen.

RTV residues: Gap fillers are held in place by an RTV glue which is highly reflective. RTV residues most often occur inside the gap near the tile edge, exactly the location at which gap measurements are made.

## TECHNICAL APPROACH

The approach to evolving the concept and design of the LLT included extensive contact with KSC engineers/operators to obtain and define the requirements. A broad survey of technology was performed to obtain the most suitable technical approach.

Fringe-line projection was selected as the best optical approach because the laser lines can be regulated as a strobe making the data capture insensitive to vibration or motion. In addition, projection offers high accuracy and high reliability because of hardware simplicity. It readily adapts to a hand-held design due to lightweight components and insensitivity to vibration.

The LLT instrument design utilizes a high resolution CCD array (512 x 480 pixels) camera in conjunction with a low powered laser diode line projector to simultaneously measure both the tile step and gap. This is accomplished by projecting the laser line onto adjacent tiles and across the gap at the location to be measured. The laser line is projected onto the tile at a 45 degree angle while the camera views the scene at normal incidence. The camera thus views the laser line as it crosses the adjacent tiles from a perspective angle. Software algorithms interpret the laser imaged data at the appropriate tile locations and computes step and gap values.

## SYSTEM DESCRIPTION

Based on the requirements described above the system was designed for use by technicians in a continuously changing shop environment where the Shuttles are serviced between flights.

Hardware:
System hardware components are categorized into two basic units, a hand-held instrument and a cart-mounted workstation.

Hand-Held Instrument

The instrument has three basic parts:

1. A handle grip with a trigger and two thumb buttons for system control and operation;

2. The instrument head which contains a low power laser diode line projector and a small, light-weight, solid state camera,
3. A small (2x2 in.) video monitor.
   The instrument head and video monitor are hinged or swivel mounted to the handle grip to facilitate hand-held operation over a wide variety of accessibility and alignment situations. Padded contact feet are provided on the front of the unit as an alignment aid to stabilize the instrument for ease of use.

   An important feature of the LLT is that all system controls and operation can be managed from the instrument itself. See Figure 2. The thumb button on the right and the fore finger trigger operate as computer-mouse signals. The thumb button clicks through the menu options which are shown on the display screen. Once an option has been selected the trigger implements that menu selection. The thumb button on the left controls the laser. When the button is depressed and held down the laser is on. When the button is released the laser is off. To take a picture of the projected light, the trigger is squeezed while the laser is on.


Figure 2. Operator Controls At Instrument

Mobile Cart-Mounted Work Station

The workstation consists of a small PC computer, a color video monitor and a printer. The work station is connected to the measurement instrument by a 35 ft. cable or umbilical.

The LLT is activated or initialized at the computer. Operational or measurement modes are selected from the menus. Tile data set information (such as tile numbers) are entered by filling in prepared data sheets which appear on the computer screen.

When step and gap measurements are made, operational control is transferred from the computer to the hand-held instrument. Menus that appear on the small monitor screen are used by the operator and provide complete control of the measurement process, with complete independence from the work station. The larger color monitor at the work station replicates the information which appears on the small hand-held unit. This provides an opportunity for both quality control and engineering to observe in real-time and review the measurement process in detail.

Software:
The role of the software is to provide user control of the instrument, control of the electronic interfaces between the sensor and the computer, calculation of step and gap values, and display and storage of step and gap information for identified tile part numbers.

Menus and Data Displays

The Main Menu is shown in Figure 3: Selections 1 through 3 allow the user to set up data files Selection 4 is used to verify that the step/gap calibration is within allowable limits. Selections 5 and 6 set the system into measurement mode for black or white tiles. In the measurement mode, control of the Step/Gap system is transferred to the menu displayed on the hand-held instrument monitor (see Figure 4) which is operated by using two buttons and a trigger on the handle. Selection 7 allows the user to print copies of the data sheets formatted to conform with existing LSOC operating procedures.

```
        Lockheed R&DD Step/Gap Sensor System
►(1)......Setup Corner Step & Gap Test
 (2)......Setup Midpoint Step & Gap Test
 (3)......Setup Statistical Step & Gap Test
 (4)......Verify Calibration
 (5)......Measure HRSI (Black) Tile
 (6)......Measure LRSI (White) Tile
 (7)......Print Data Sheet
 <ESC>....Exit to DOS
  Enter Selection:
```

Figure 3. Main Computer Menu


Figure 4. Instrument Menu

Data Processing and Error Checking

The goal of the data processing software is to calculate the step and gap measurements as specified in LSOC Engineering documentation. The step and gap processing occurs in three main steps as outlined in the following three subparagraphs.

1. Determine Gap Location

The captured video image consists of 480 data rows each consisting of 512 pixels. (Figure 5 is a grey-scale reproduction of an unprocessed, captured video image showing the general form of the laser stripe.) The software first processes the entire image to determine the location of the laser stripe within the image.

If the laser stripe intensity is within allowable limits, the software then determines the location of the gap within the image.

Error checking:
i. The "Laser off" message is displayed if no laser stripe is present;
ii. The "Background" message is displayed if too much light is present in the image for accurate processing to occur.
iii. The "Can't Calc Gap" message is displayed if the location of the gap cannot be determined from the image data.

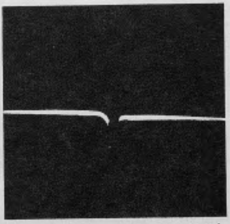

Figure 5. Grey Scale Of Captured Laser Line

2. Calculate Step

The value of the step is calculated by determining the average height of the tile surfaces. The tile height is measured at a location that is between 0.150 in. and 0.250 in. to the left and to the right of the gap. The rectangular boxes drawn in Figure 6 on either side of the gap indicate where step measurements are made. Within the boxed area, a linear fit is made to the surface profile determined from the laser stripe.

Error Checking:
The "Can't Calc Step" message is displayed if any portion of the data required for the step calculation are out of limits.

3. Calculate Gap

Two gap algorithms are utilized, one for standard tile-to-tile gaps and one for tile-to-RCC or RCC-to-RCC gaps where severely angled gap walls are present (see Figure 6).

Tile-to-tile gaps:
The software first measures the radius of the tile edges on both sides of the gap. Radii from a maximum of 0.090 in. to a minimum of .006 in. can be measured. If the radius exceeds .090 in., the gap measurement is made at a poin 0.090 in. down from the tile surface. If the radius is less than 0.006 in., the radius tangent point is assumed be at the tile surface. The radius tangent point is determined for both tile edges as the point where the laser line disappears down into the gap vertical bars in indicate gap measurement).

Error Checking:
The "Can't calc gap" message is displayed if the software is unable to make an accurate gap calculation

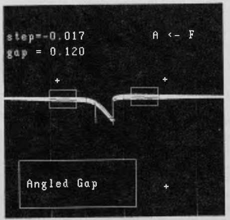


Figure 6. Processed Data For Angled Gap

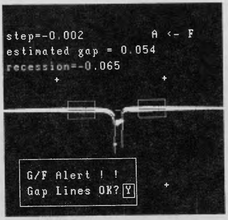


Figure 7. Processed Data For Gap With Recessed Gap Filler

Angled Gaps:
The software first determines if an angled gap wall is visible in the image. If an angled gap wall is found, a linear fit is made to the laser stripe illuminating the gap wall. The standard radius tangent algorithm is used for the opposing tile edge. The width of the gap is determined from the distance between the line representing the angled gap wall and the radius tangent of the other tile edge.

Error Checking:
i. The "Can't calc gap" message is displayed if the software is unable to make an accurate gap calculation
ii. The "Angled Gap" message is displayed to indicate that the angled gap algorithm was used to determine gap calculation

4. Calculate Gap Filler Recession/Protrusion

If the operator indicates that gap filler is present in the gap, the program will measure the recession (distance below) or protrusion (distance above) from the tile surface (refer to Figure 7).

The software first profiles the gap filler between the left and right tile edges and determines the highest point on the profile. Gap filler recession/protrusion is calculated as the distance and the highest point on the gap filler profile.

Error Checking:
i. The "GF Alert" message is displayed if gap filler is within about 0.10 in. of either tile surface. In addition, the operator must confirm visually that the gap has been correctly located and measured (see Figure 7).

ii. The "Gap Filler" message is displayed if gap filler is recessed or protruding more than about 0.10 in.

## SHOP INTEGRATION AND CERTIFICATION PROCESS

Development of the LLT system adhered to a plan that showed technical feasibility and demonstrated system capability following a 3 month effort. The demonstration featured a shop-usable prototype system measuring tile steps and gaps on Shuttle Columbia at KSC in March 1988. A baseline software package was utilized to measure cleaned black tile with no presence of gap filler.

Results from this initial on-site demonstration included the desire to place the tool into immediate use at KSC to help meet scheduled launch dates. Efforts were made to approve the instrument for vehicle use on tile conditions that fit the initial prototype design. Tools used on the vehicles to establish flight readiness data must be approved by Rockwell/JSC in addition to LSOC/KSC. Decisions were made to postpone use of the tool for flight support until the software development was complete to handle all of the varying tile conditions described in the requirements section and until a formal certification team could be assembled, test procedures defined, and evaluations completed. This process equated to a six month transition effort to integrate the system into KSC operations and certify it for use as support equipment for manned space-flight hardware. Part of this effort included multiple iterations of on-site testing where requirements for test were continually defined.

Two complete systems were delivered in September 1988 along with the necessary documentation including training and operating manuals. A certification letter was signed by JSC level 2 management on September 29, 1988.

## SYSTEM UPGRADES

The LLT uses a single laser to project a line of light captured by the camera, thereby measuring the step and the gap at a single location. An upgraded system is under development that will project multiple lines of light in perpendicular directions to make multiple measurements at tile intersections simultaneously. This tool will reduce the number of measurements required of the technician by a factor of 3 to 4. It will probably improve the speed of data collection by a factor of 4 over the current LLT.