Non destructive mechanical tests of the GLAST silicon tracker.

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Abstract
For the GLAST tracker 373 composite trays have been produced. To qualify each single tray for the space use, a non destructive test based on the Electronic Speckle Pattern Interferometry, has been developed. The ESPI is introduced and the results of the GLAST tracker tests are presented.
Agenda

• Short introduction to the ESPI technique
• Short description of the Large Area Telescope of the GLAST mission
• Dynamical ESPI acceptance test of the flight trays of the GLAST tracker
• Static ESPI acceptance test of the flight trays of the GLAST tracker
• Dynamical ESPI test on a Silicon Surface
• A Failure analysis case: the Engineering Model Tracker Tower test
• ESPI Overviews
• Conclusions
The ESPI concept

When the coherent light from a laser illuminates a rough object (roughness > \( \lambda \)), you can observe a curious granular appearance.

The scattered light from a rough object detected by a screen, is the sum of the light scattered by each point \( P_i \) of the surface of the object. Each contribution sums over with a random phase due to the different light paths. The result is a random variation in space of the detected light intensity. This variation is called SPECKLE effect. If the object moves a new speckle pattern will appear on the screen.

The SPECKLE INTERFEROMETRY

A Michelson arrangement of out-of-plane displacement is a sensitive speckle pattern correlation interferometry. Using the complex notation

\[ U_1 = u_1 \exp i\Psi_1 \]
\[ U_2 = u_2 \exp i\Psi_2 \]
\[ A_1 = I_1 + I_2 + \sqrt{I_1 I_2} \cos \Psi \]
\[ I_1 = U_1 U_1^* \]
\[ I_2 = U_2 U_2^* \]
\[ \Psi = \Psi_1 - \Psi_2 \]

If the object 1 is moved by \( \delta z \)

\[ A_2 = I_1 + I_2 + \sqrt{I_1 I_2} \cos(\Psi + 4\pi\delta z / \lambda) \]

The movement of the two objects causes a phase shift proportional to the object displacement. In the Electronic Speckle Pattern Interferometry the images are recorded by a CCD camera and the \( \delta z \) displacement is computed from comparison of \( A_1 \) and \( A_2 \).
The ESPI setup, for the modal analysis

In this presentation we assume $\alpha$ and $\beta \sim 0$
Formulas

The basic equation that describes the light propagation is

\[ I(t, x) = I \cos(2\pi ft + 2\pi x / \lambda + \phi) \]

\[ I = \text{amplitude} \]
\[ T = \text{period} \]
\[ f = \text{frequency} = 1/T \]
\[ \omega = \text{phase speed} = 2\pi f \]
\[ \lambda = \text{wavelength} = c/T \]
\[ \phi = \text{phase} \]

The beam reaching the CCD in a point \( x, y \), is the sum of the reference beam \( I_R \) with the beam reflected from the object \( I_O \).

\[ I(x, y, t) = I_R \cos(2\pi ft + \phi_R) + I_O \cos(2\pi ft + \phi_O) \]

The light sensors (the CCD of the photo camera) are sensitive to \( I^2 \) and they integrate the signal over times much greater than \( T \).

\[ I^2(x, y, t) = I_R^2 \cos^2(2\pi ft + \phi_R) + I_O^2 \cos^2(2\pi ft + \phi_O) + 2I_RI_O \cos(2\pi ft + \phi_R) \cos(2\pi ft + \phi_O) \]

After integration over the time

\[ \bar{I}^2(x, y) = \frac{1}{2} I_R^2 + \frac{1}{2} I_O^2 + I_RI_O \cos(\phi_O - \phi_R) \]

Interference part
The system takes 4 pictures with 4 displacements of the piezoelectric mirror so that the phase of the reference beam is shifted of the angle $0,1/2\pi,\pi,3/2\pi$. The object does not move in the time needed to acquire 4 frames.

Using the relations

\[
\begin{align*}
\sin(\phi+1/2\pi) &= \cos\phi \\
\cos(\phi+1/2\pi) &= -\sin\phi \\
\sin(\phi+\pi) &= -\sin\phi \\
\cos(\phi+\pi) &= -\cos\phi \\
\sin(\phi+3/2\pi) &= -\cos\phi \\
\cos(\phi+3/2\pi) &= \sin\phi
\end{align*}
\]

\[
I_0^2 = \frac{1}{2} I_R^2 + \frac{1}{2} I_O^2 + IRIO \cos(\phi_R - \phi_O)
\]

\[
I_{\pi/2}^2 = \frac{1}{2} I_R^2 + \frac{1}{2} I_O^2 + IRIO \cos(\phi_R - \phi_O + \pi / 2) = \frac{1}{2} I_R^2 + \frac{1}{2} I_O^2 - IRIO \sin(\phi_R - \phi_O)
\]

\[
I_{\pi}^2 = \frac{1}{2} I_R^2 + \frac{1}{2} I_O^2 + IRIO \cos(\phi_R - \phi_O + \pi) = \frac{1}{2} I_R^2 + \frac{1}{2} I_O^2 - IRIO \cos(\phi_R - \phi_O)
\]

\[
I_{3\pi/2}^2 = \frac{1}{2} I_R^2 + \frac{1}{2} I_O^2 + IRIO \cos(\phi_R - \phi_O + 3\pi / 2) = \frac{1}{2} I_R^2 + \frac{1}{2} I_O^2 + IRIO \sin(\phi_R - \phi_O)
\]

\[
\frac{I_{3\pi/2}^2 - I_{\pi/2}^2}{I_0^2 - I_{\pi}^2} = \frac{\sin(\phi_R - \phi_O)}{\cos(\phi_R - \phi_O)} = \tan\phi
\]

\[
\phi = \arctan \frac{I_{3\pi/2}^2 - I_{\pi/2}^2}{I_0^2 - I_{\pi}^2}, \phi \in [0,2\pi]
\]
Static test spatial resolution

The map of the phase $\phi(x,y) \in [0,2\pi]$ is calculated before and after the displacement. The phase differences correspond to the relative movements of the object in the direction of the beam.

Because the phase is defined modulo $2\pi$, fringes will appear. Each fringe corresponds to a relative shift of $\lambda/2 = 266\text{nm}$.

In principle it is possible to measure shifts with higher resolution and a positive sign of the phase shifts corresponds to an increase of the distance of the object from the camera.
ESPI Dynamic test

The object is supposed to move with an harmonic motion \( \delta(t) = a \cdot \cos(\omega_M t) \)

Two snapshots with phase shifts 0 and \( \pi \) are taken.

The difference of the 2 snapshots identify the interference part:

\[
D = 2 I_R I_0 \cos(\phi_R - \phi_O - \frac{4\pi a}{\lambda} \cos(\omega_M t))
\]

The integration of this formula over a period \( 2\pi/\omega \) gives

\[
\bar{D} = 2 I_R I_0 \cos(\Delta \phi) J_0 \left( \frac{4\pi a}{\lambda} \right)
\]

\( J_0 \) is the 0 order Bessel function shown in the graph. It is a quasi-periodic function that leads to the formation of fringes. The number of fringes is proportional to the semi-amplitude \( a \) of the movement.

\begin{itemize}
\end{itemize}
GLAST LAT Project

Short Introduction to the Large Area Telescope of the GLAST Mission
The GLAST Observatory

GLAST LAT Project

Gamma Ray Burst Monitor (GBM)
Large Area Telescope (LAT)

Launch Vehicle: Delta II – 2920-10H
Launch Location: Kennedy Space Center
Orbit Altitude: 575 Km
Orbit Inclination: 28.5 degrees
Orbit Period: 95 Minutes
Orientation: +X to the Sun
Launch Date: September 2007

A NASA mission with the responsibility of the construction of the principal instrument held by High Energy Physics Institutes

20/10/2005
Riccardo Bagagli INFN-Pisa
"Joint Adventure" between HEP and Astrophysics

P.I. Peter Michelson SLAC

- **U.S.A.** (NASA, DOE)
  - SU, SLAC, GSFC, NRL, OSU, UCSC, SSU, UW, TAMUK

- **JAPAN**
  - Tokyo, Hiroshima, ICRR, ISAS

- **Italy**
  - INFN (Bari, Padova, Perugia, Pisa, Roma 2, Trieste, Udine)
  - ASI

- **France**
  - CEA (Saclay)
  - CNES
  - IN2P3

- **Sweden**
  - KTH
  - Stockholm U.
GLAST LAT Project

GLAST science – the sky above 100 MeV

An observatory with a very large photon energy. From 20 Mev to 1 Tev, detecting the most energetic events of the universe

- unidentified sources
- sky map
- pulsar
- Gamma Ray Bursts
- solar flares
- Active Galactic Nuclei
- Super Nova Remnants and Cosmic Rays acceleration
- dark matter

<table>
<thead>
<tr>
<th>0.01 GeV</th>
<th>0.1 GeV</th>
<th>1 GeV</th>
<th>10 GeV</th>
<th>100 GeV</th>
<th>1 TeV</th>
</tr>
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</table>
Pair production is the dominant photon interaction above 10 MeV:
\[ E_\gamma \rightarrow m_{e^+}c^2 + m_{e^-}c^2 \]

**GLAST Concept**
- Low profile for wide f.o.v.
- Segmented anti-shield to minimize self-veto at high E.
- Finely segmented calorimeter for enhanced background rejection and shower leakage correction.
- High-efficiency, precise track detectors located close to the conversions foils to minimize multiple-scattering errors.
- Modular, redundant design.
- No consumables.
- Low power consumption (580 W)
Overview of LAT

**Precision Si-strip Tracker (TKR)**
- 18 XY tracking planes
- Single-sided silicon strip detectors
- 228 µm pitch, $8.8 \times 10^5$ channels
- Measure the photon direction

**Segmented Anticoincidence Detector (ACD)**
- 89 plastic scintillator tiles surrounding the TKR towers
- Reject background of charged cosmic rays
- Removes self-veto effects at high energy

**Hodoscopic CsI Calorimeter (CAL)**
- Array of 1536 CsI(Tl) crystals in 8 layers
- 6.1 $\times 10^4$ channels
- Measure the photon energy, image the shower

**LAT:**
- 4 x 4 modular array
- 3000 kg, 650 W

**Electronics & Flying Software**
**Data Acquisition System**
GLAST LAT Project

Tracker Production Overview

The Tower is very complex device, an high modularity is required, the modules are:

<table>
<thead>
<tr>
<th>Module Structure Components</th>
<th>SSD Procurement, Testing</th>
<th>SSD Ladder Assembly</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLAC: Ti parts, thermal straps, fasteners. Italy (Plyform): Sidewalls</td>
<td>SLAC, Japan, Italy (HPK)</td>
<td>Italy (G&amp;A, Mipot)</td>
</tr>
</tbody>
</table>

Tracker Module Assembly and Test

- Italy (Alenia Spazio)

Electronics Fabrication, burn-in, & Test

- UCSC, SLAC (Teledyne)

- SLAC: CC, bias circuits, thick W, Al cores

- Composite Panel, Converters, and Bias Circuits
  - Italy (Plyform): fabrication

Readout Cables

- UCSC, SLAC (Parlex)

- 2592

- 10,368

- 648=1Mch

- 342

- 18
The tray panel has a “stiffness driven design” and it is an entirely bonded structure, the acceptance NDI tests are:

1. The panel first resonance frequency has to be above a limit value that guarantees the requested panel design stiffness
2. If any, local defects at bonding interfaces have to be detected

For these purposes we have developed and qualified a workmanship acceptance test based on the ESPI, which is able to measure the resonance frequencies and to identify the local defects of the GLAST Tracker composite panels. To qualify this test we have performed FEM analysis of the trays to study:

1. The modal analysis of the trays
2. The out of plane displacements of local defects under thermal or dynamic loads, in order to evaluate the defects detection capability of the system

To experimentally validate the ESPI technique:

1. We have tested on a classical vibe facility a tray and we have compared the results with the ESPI modal analysis
2. We have built a tray with known defects and we have verified the capabilities to detect the defects with dynamic and static ESPI

The trays for the flight production have been finally tested and the results are presented.
The tray is the “building block” of the tracker. We had to face a large production: 370 trays to be produced and tested. Need of an NDI test that is:

- Fast
- Reliable
- Sensitive to small area defects

The “bare” tray is tested with ESPI before assembling the very expensive payload parts (SSD and electronics) and in order to have the best monitoring of the structural parts and all the bonding interfaces.
Modal analysis of a bare tray, evaluation of the panel stiffness: 1\textsuperscript{st} mode FEM analysis

The trays must be stiff enough to avoid the silicon-silicon impact of consecutive trays during the launch and the vibe tests: \textbf{2 mm separation!}. This requirement puts a threshold on the first mode frequency of the tray at the payload level. We have performed an FEM analysis to predict the relative frequency modes of the trays at the bare panel level (without payload)

\[ F_{\text{1mode}} = 1299 \text{Hz} \]
Modal analysis of a bare tray: 2\textsuperscript{nd} mode FEM analysis

$F_{2\text{mode}} = 2449\text{Hz}$
ESPI modal analysis: bare Mid trays results

Tray MID 1\textsuperscript{st} mode 1319Hz

Tray MID 2\textsuperscript{nd} mode 2430Hz
Vibe Test Modal analysis:
Tray (with payload) on the shaker

The item is fixed to the shaker table. The dynamic performance of the item is measured before and after a random vibe spectrum and according to the NASA GEVS.

Test configuration set-up. The labels TP5 (three-axial) and TP6 (mono-axial) indicate the three-axial accelerometers that measure the response of the tray.

Sine sweep response for the tray GLAST TG03, measured with the accelerometer placed in the center of the tray:
INFORMATION IN 1 POINT ONLY

White noise and random vibration responses up to qualification level.

Riccardo Bagagli INFN-I
TG07: Bare Panel + W + Bias Plane (payload)
The plot shows two peaks: @817 Hz and @1866 Hz
The more energetic one is supposed to be the first resonance mode, the second one should be investigated

TG07 - Sine Seep (20-2000 Hz)
TG07 panel + W + Bias Plane:
The maximum number of fringes is detected at the same resonance frequency (817 Hz) measured with the accelerometer on the vibe facility.

The shape observed is in agreement with the first mode shape found with the FEM simulation at payload level.
ESPI modal analysis: second peak identification

TG07 panel + W + Bias Plane:
Close to the second peak measured under the vibe test, the ESPI test (@1860 Hz) identifies a particular shape.

ESPI test identifies the same resonance frequencies like a classical sine sweep test on a vibe facility and provides the detailed shapes of the resonance mode. ESPI test does not expose the object to any relevant mechanical load.
GLAST results: Dynamic ESPI

All the 373 bare trays produced have been tested with the dynamic ESPI to detect the first resonance mode. This test guarantees the main mechanical performance of the bare tray assembly (face-sheets+honeycomb+closeouts+relative gluing). The frequency limits defined for the trays at the bare panel level (see table for MIN frequencies) take in consideration the worst contributions coming from all the sub-assembly parts (dimension, mass, mechanical properties, bonding process). These min values are anyway 40% higher than the design Specs. This frequency guarantees that the stiffness of the tray is enough to avoid any contact between the ladders surfaces on consecutive trays during vibe tests and launch. Each tray has been tested twice, with the top and bottom face of the tray exposed to the laser light. The difference between the 2 values is a measurement of the frequency resolution of the system:

\[
(\frac{\Delta f}{f})_{\text{max}} = 1.5\%, \quad (\frac{\Delta f}{f})_{\text{rms}} = 0.6\%
\]

As shown by the table, no tray has been rejected.

<table>
<thead>
<tr>
<th>tray type</th>
<th>produced trays</th>
<th>measured $f$ (Hz)</th>
<th>required minimal $f$ (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>mean</td>
<td>st.dev</td>
</tr>
<tr>
<td>top</td>
<td>19</td>
<td>1317</td>
<td>30</td>
</tr>
<tr>
<td>mid &amp; light</td>
<td>257</td>
<td>1291</td>
<td>42</td>
</tr>
<tr>
<td>heavy</td>
<td>78</td>
<td>1258</td>
<td>55</td>
</tr>
<tr>
<td>bottom</td>
<td>19</td>
<td>1437</td>
<td>41</td>
</tr>
</tbody>
</table>
Visualization of small defects with thermal loads: FEM temperature map

Temperature distribution of a heated tray ($\Delta T=10^\circ\text{C}$) in presence of a honeycomb – face sheet delamination. The debonded area does not exchange heat with the honeycomb with a correspondent $5^\circ\text{C}$ increase of the temperature of the face-sheet. In the same area the honeycomb’s temperature remains stable.
GLAST LAT Project

Visualization of small defects with thermal loads: FEM deformation map

The thermal anomaly induces a few $\mu$m out of plane local deformation of the face-sheet.
Visualization of small defects with dynamic loads:
FEM modal analysis of the honeycomb–face-sheet defect

The debonded area has proper resonance modes at high frequencies
ESPI experimental validation

To check the ESPI capabilities to detect small area defects, we have built a tray with known defects:

- Ply-Ply debonding
- Facesheet-Honeycomb debonding
- Honeycomb crash
- Facesheet-closeout debonding
Defected tray construction

Defects Insertion:

- Ply-Ply
- HONEYCOMB-SKIN
- CLOSEOUT-SKIN
- CELL-CRASHING
Defects detection with static ESPI 1

**STATIC ESPi:**
Thermal Loads

Honeycomb – Skin debonding
Defects detection with static ESPI 2

ESPI: Thermal Loads

Honeycomb crash
Defects detection with static ESPI 3

ESPI: Thermal Loads

facesheet - Closeout debonding
Local defects: Static and Dynamic ESPI test results of trays with face sheet - honeycomb debondings

Both faces of the trays have been exposed to a heat source (an alogen lamp, $\Delta T=+10^\circ C$). The phase shift maps are collected showing the deformation of the tray during the cooling. Irregularities of the fringes detect debonded zones. These debonded areas are visible in the dynamic ESPI too, with their own vibe modes. 6 of the 373 produced bare trays have been rejected.

MID041 static ESPI

MID041 dynamic ESPI 1934Hz
Local defects: Static ESPI test results of trays with **face-sheet - closeouts debondings**

These trays have been recovered injecting adhesive under the face-sheets borders

The high sensitivity to the small defects led the GLAST collaboration to use the ESPI test in substitution of the more common vibe test for the workmanship acceptance test of the flight mechanical trays. No failure induced by bare tray defects have been detected during the subsequent environmental tests (TVAC + VIBE) of the 17 flight towers we have built.
Dynamical ESPI test on a silicon surface:
Assembled Silicon Ladders on tray first resonance mode search

This picture shows the modal analysis performed on a tray with the silicon detectors bonded over the tray itself. The detectors are arranged in four independent ladders that cover the entire tray surface, and in the picture are aligned vertically. 2443 Hz is the same resonance frequency of all the four ladder.

The ladder main resonance mode has been found well over the test frequency range 20-2000Hz. Now we know the ladder resonance frequency and that it can be not observed during the vibe-test.
A FAILURE ANALYSIS CASE:
E.S.P.I. Engineering Model Tower Tests
Dynamic test on the GLAST tracker tower

The GLAST tower is a stack of 19 trays held together by 4 carbon fiber sidewalls. The bottom tray has carbon fiber closeout with Ti corner reinforcements and is connected to the satellite by means of 8 Ti flexures (mechanical link) and by 4 Cu thermal straps (thermal link).

**The mechanical link was the more challenging mechanical part under the stresses induced by the vibe test.**
Environmental tests on EM Tower

Vibration tests sequence:
✓ Sinusoidal and random vibrations +
  low level sweeps for resonance
  frequency search.

Alcatel Alenia Space shaker
Alenia: Environmental tests on EM tower

Vibe tests failure:

- Abrupt shift in the first normal mode: 130 to 80 Hz
- Serious failure on the structural integrity was speculated, the test had to be stopped and the damage had to be identified
- The preliminary inspection showed some loss of torque in the bolts at the connection between grid simulator and tower, but any other not visible damage or defect had to be considered.
- To re-torque the bolts and run a low level frequency search was not allowed until the right failure cause was identified
- The tower had to be removed from the shaker and shipped back to Pisa
The modal analysis of the Engineering Model tower has been studied with the ESPI in the INFN-Pisa lab. The first mode frequency is very sensitive to the constraint of the tower over the bench. It was very important to reproduce the constraint condition of the tower on the shaker, WE WANTED TO TEST THAT BY RE-TORQUEING THE BOLTS, THE SHIFT IN FREQUENCY COULD BE RECOVERED, IMPLYING NO FAILURE WITHIN THE TOWER
E.S.P.I. TEST: -X SIDE

The tower has been tested on a vibe test and with the ESPI system. The main mode frequencies were again well in agreement. The tower has been proved still undamaged after the resonance shift, thus the failure was limited to the interface only.
E.S.P.I. Overview

The test on a small area of about 5cm X 5cm instead of 36,8 cm X 36,8 cm, shows an increase in image resolution. The tray observed in a random small area shows detailed out of plane displacement induced by the cell, the honeycomb hexagonal pattern is clearly visible, eventual irregular shapes of the honeycomb cells can be detected.
E.S.P.I. Overview

Real-time image of pressing with the finger on the tray.

Is it possible to see the face sheet displacement driven by the honeycomb constrain pattern. At a bigger level a displacement envelope can be seen, with two fronts (blue lines).
Conclusions

• The ESPI test of all the GLAST trays has been concluded (373 trays).
• The technique has been successfully used to qualify the Engineering Model mechanics (tower, tray with payload) and as workmanship screening during the production of the flight bare trays.
• No large scale defects have been observed (no tray with first mode frequency below threshold).
• Small scale defects have been detected (face-sheet to honeycomb debonding with tray rejection, face-sheet to closeout debonding with tray repair). These defects have no impact on the main frequency value and on its stability during a random vibe test and could not be detected with the more common vibe test with accelerometers.
• No failure induced by bare tray defects have been detected during the subsequent environmental tests (TVAC + VIBE) of the 17 flight towers we have built.