Design and performance of µ-Spec, an ultra-compact high-sensitivity far-infrared spectrometer for SPICA

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Introduction

The design optimization of Micro-Spec (µ-Spec), a low-resolution far-infrared spectrometer for the SPace Infrared telescope for Cosmology and Astrophysics, SPICA, in terms of size and optical performance is presented. The method is based on the 2D

Motivation

Far-infrared spectroscopy represents a powerful tool to probe a wide range of environments in the universe. Infrared instruments are uniquely able to observe astrophysical processes deep within dusty regions and provide key information on the early steps of the universe.

Figure 1: A single µ-Spec module has a sensitivity orders of magnitude better than its predecessors, while covering the full spectral range simultaneously. A spectrometer with ~100 modules would have a remarkable mapping speed.

With its much higher sensitivity (Figure 1), µ-Spec will open new areas of discovery to the scientific community as no previous instruments have done before.

Objectives

Design, optimize, integrate, and test the µ-Spec module. This project spurs innovation in both areas of:

TECHNOLOGY - The dramatic size reduction will result in higher sensitivity

The long-wavelength capability of SPICA will be improved

SCIENCE - Further our understanding of the evolution of the universe, looking at:

• Physical processes in the early universe (p-Re), such as the role of H$_2$ in the formation of the earliest stars in the universe at very low metallicity

• Growth of structure and evolution of galaxies: merger rates and black-hole accretion rates across cosmic time

• Interstellar medium and physical/chemical processes in the Milky Way through HD0 detection in protoplanetary disks

• Comets in the solar system for tracking their content of H$_2$O, PAHs (poly aromatic hydrocarbons), mineralogy.

Methods and Analysis

Figure 2. Layout of the µ-Spec module. The power is coupled into the instrument using a broadband antenna (left). It is then transmitted through a low-loss superconducting transmission line to a divider and a phase delay network, which creates a retardation across the input to multimode region (in light blue). The feed horns will radiate a converging circular wave, which will concentrate the power along the focal surface, with different wavelengths at different locations. The outputs are connected to a bank of order-sorting filters to disentangle the various orders.

µ-Spec thus differs from similar technologies.

• In a Rowland spectrometer the required phase retardation is generated by reflection from the grating grooves [1-3].

• In Z-Spec propagation occurs in parallel-plate waveguides [4].

• Bootlace lenses are a one-dimensional analogues of Z-Spec [5-7].

Figure 3. A Rowland spectrometer (a), Z-Spec (b), and a bootlace lens (c).

Table 1: Spectrometer design parameters for the test configuration selected to fit 4 spectrometers in a 4"-diameter silicon wafer, each in a 1"x1" region. Although this choice is not optimal, it enables several designs to be studied and the development of the required fabrication process.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum beamsize</td>
<td>450 GHz</td>
</tr>
<tr>
<td>Maximum frequency</td>
<td>650 GHz</td>
</tr>
<tr>
<td>Minimum wavelength in Si</td>
<td>$\lambda_S = 105$ μm</td>
</tr>
<tr>
<td>Maximum wavelength in Si</td>
<td>$\lambda_S = 105$ μm</td>
</tr>
<tr>
<td>Blaze point wavelength in Si</td>
<td>$\lambda_b = 156$ μm</td>
</tr>
<tr>
<td>Antenna spacing or array peak</td>
<td>$p = 179$ μm</td>
</tr>
<tr>
<td>Antenna spacing in wavelengths</td>
<td>$\frac{\lambda_b}{\lambda_S} = 1.56$</td>
</tr>
<tr>
<td>Antenna center-to-center spacing</td>
<td>$\frac{\lambda_b}{\lambda_S} = 1.56$</td>
</tr>
<tr>
<td>Number of emitters</td>
<td>$N_e = 65$</td>
</tr>
<tr>
<td>Number of receivers</td>
<td>$N_r = 47$</td>
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<tr>
<td>Resolving power</td>
<td>$R = 85$</td>
</tr>
<tr>
<td>Multidisc radius</td>
<td>$R = 2.15$ cm</td>
</tr>
</tbody>
</table>

Parameters to optimize:

- Location of the emitter antennae ($x_i, y_i$)
- Delay line network phase correction ($t_i$)
- Blaze angle ($\theta_b$)
- Stigmatic correctors
- Emissors on a CR or close to it ($x_b, y_b$)
- Emissors directed to the center of the focal plane

Method and constraints used:

- Minimization of light path in a 2-D region through the goal attainment method of Gembicki [8]
- 3 stigmatic objectives
- Emissors on a CR or close to it ($x_b, y_b$)
- Emissors directed to the center of the focal plane

Figure 4. Overall design. The grating (black solid line) corresponds to a circle with a radius of 2.5 cm.

Figure 7. Power distribution (in Watt) in the multimode region at a frequency of 450 GHz. The first-order peak is visible at an angle $\theta_{10}^*$, the second-order diffraction peak at $8^\circ$ (defined in Figure 4).

Results

Figure 5. Rotated close-up on the emitter side, where the facets (red lines and dots) appear to be tangent to a common curve well approximated by a 2R circle (black solid line) and shifted 15 μm downward to account for the finite-element phase center correction of the E-field coming out from the feed horns.

Figure 8. Divergence angle (deg): Angular Half Power Width (HFW) is defined by the angle ($\theta_{hfa}$) calculated as $\theta_{hfa} = \text{arccos}(\frac{d_R}{2D})$

Figure 6. Beam pattern distribution over each feed horn. The curve represents the normalized E-field amplitude as a function of the feed horn angular aperture.

Figure 9. Beam pattern distribution over each feed horn.

Conclusions

Main results:

- Proof-of-concept demonstrated
- Power conservation achieved
- In this design configuration, throughput 30%
- Second-order diffraction peak
- Power absorbed by the dark walls

Removal of the second-order peak:

- Decreasing the radius by 16%
- Reducing the spacing between receivers

Overall efficiency improvement:

- Increasing the number of receivers by 18
- Reducing the spacing between receivers
- Maximum throughput thus achievable equal to 87%

- Narrowing the beam width would further increase the throughput.

References


Acknowledgments

I would like to acknowledge S. H. Moseley, PI of this project; E. J. Wollack, W.-C. Huang, and T. R. Stevenson for their contribution to the analysis efforts; and W.-T. Hsieh in her management role. This research is a collaborative effort between NASA and the Japanese Aerospace Exploration Agency (JAXA).

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