Superconducting Integrated Terahertz Spectrometer for Atmosphere Monitoring and Radio Astronomy

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in collaboration with

*SRON Netherlands Institute for Space Research, the Netherlands*
Superconducting Integrated Terahertz Spectrometer for Atmosphere Monitoring and Radio Astronomy

Outline

• Superconducting Integrated Receiver (SIR)
• Flux Flow Oscillator (FFO) for the SIR
• TErahertz LImb Sounder (TELIS) project
• TELIS SIR channel: design and performance
• First TELIS flight
• Future SIR applications
• Conclusion
Superconducting Integrated Receiver (SIR) with phase-locked FFO

4 K dewar

SIR chip

SIS mixer

Harmonic mixer

FFO as LO 500-650 GHz

HEMT

Reference 20 GHz

IF Processor & Digital Auto Correlator

Computer controlled data acquisition system

Electronics FFO, SIS, HM control

PLL

LSU

4 GHz

400 MHz reference

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Internal part of the SIR Microcircuit

Double-slot (dipole) twin SIS – 0.8 μm²

HM – 1.0 μm²

Nb-AlOₓ-Nb, Nb-AlN-NbN; Jc = 5 - 10 kA/cm²

Optionally: SIS – Jc = 8 kA/cm²; FFO + HM = 4 kA/cm²

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Nb-AlOx-Nb and Nb-AlN-NbN FFO for SIR

400 GHz

Frequency Tuning

700 GHz

JSC, $V_B = V_g/3$
Nb-AIN-NbN SIS pumped by FFO; FFO frequency tuning

HD13-09#26 (Vg=3.7mV, Rn=21 Ohm)

SIS Current (mkA)

SIS Voltage (mV)

FFO Frequency:
- 0 GHz
- 400 GHz
- 500 GHz
- 600 GHz
- 700 GHz

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Nb-AlN-NbN SIS pumped by FFO; FFO power tuning (f = 500 GHz)
Experimental Data vs. Symmetrized Data for FFO Frequency (GHz)
Frequency dependence of the FFO: Nb-AlOx-Nb and Nb-AlN-NbN circuits

![Graph showing frequency dependence of FFO currents and linewidths for different materials.](image)
FL and PL spectra of the FFO:
frequency 605 GHz; LW = 1.7 MHz; SR = 92%
Development of the Integrated Spectrometer for TELIS (TErahertz LImb Sounder)

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TELIS (Terahertz Limb Sounder)

**TELIS Objectives:**
- Measure many species for atmospheric science: ClO, BrO, O₃, HCl, HOCl, etc;
  - Chemistry, Transport, Climate
- Serve as a test platform for new sensors
- Serve as validation tool for future satellite missions
- Three independent frequency channels, cryogenic heterodyne receivers:
  - 500 GHz by RAL
  - 500-650 GHz by SRON-IREE
  - 1.8 THz by DLR (PI)

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SIR Mixer Block with Shields
Noise Temperature of the Flight SIR (DSB)

(T4m-093-05f, 17-Dec-2007)

Water line
557 GHz
SIR Noise Temperature on Intermediate Frequency and SIS Bias

(T4m-093-05f, 14-Dec-2007)

Data

YIG-filter's frequency (GHz)

(T4m-093-05f, 30-Mar-2008)

Receiver Noise Temperature (K)

SIS Bias (mV)
SIR Stability: Allan variance test

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Deconvolved spectrum of the OCS emission lines at a gas pressure 2.6 mBar.
LO frequency 601 GHz.

Two strong lines are saturated; weaker lines are not saturated isotopes.
The lines are detected, one in the LSB, the other one in the USB.
Amplitude and phase APB of the SIR with cold optics

Amplitude

Phase

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SIR for TELIS – remote operation

FFO frequency of about 500 GHz

(T4m-093#05m, 16-Nov-2007) SIS Ic(H)
# TELIS-SIR Main Parameters

(parameters determined by digital correlator are in parentheses)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input frequency range, GHz</td>
<td>500 – 650 ГГц</td>
</tr>
<tr>
<td>Minimum noise temperature in the range (DSB), K</td>
<td>120 К</td>
</tr>
<tr>
<td>Output IF range, GHz</td>
<td>4-8 (5-7) ГГц</td>
</tr>
<tr>
<td>Spectral resolution, MHz</td>
<td>&lt; 1 (2) МГц</td>
</tr>
<tr>
<td>LO frequency net, MHz</td>
<td>&lt; 300 МГц</td>
</tr>
<tr>
<td>Dissipated power at 4.2 K stage, mW</td>
<td>&lt; 30 мВт</td>
</tr>
<tr>
<td>Operation temperature, K</td>
<td>&lt; 4.5 К</td>
</tr>
</tbody>
</table>
TELIS (Terahertz Limb Sounder)

TELIS-MIPAS at Esrange, Sweden; March 2009
Balloon size: 400 000 m3; Payload weight: 1 200 kg
Altitude: 40 km (max); Duration: 12 hours
Flight trajectory (predicted)

Flight profile (actual)

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Frequencies and substances selected for the first TELIS flight

<table>
<thead>
<tr>
<th>##</th>
<th>FFO Frequency, GHz</th>
<th>Substances (High priority)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>495.04</td>
<td>H$_2^{18}$O</td>
</tr>
<tr>
<td>2</td>
<td>496.88</td>
<td>HDO</td>
</tr>
<tr>
<td>3</td>
<td>505.6</td>
<td>BrO ($\Delta T = 0.3$ K !!)</td>
</tr>
<tr>
<td>4</td>
<td>507.28</td>
<td>ClO</td>
</tr>
<tr>
<td>5</td>
<td>515.25</td>
<td>O$_2$ /pointing /pressure</td>
</tr>
<tr>
<td>6</td>
<td>519.25</td>
<td>BrO ($\Delta T = 0.3$ K !!)</td>
</tr>
<tr>
<td>7</td>
<td>607.78</td>
<td>O$_3$ isotopes</td>
</tr>
<tr>
<td>8</td>
<td>619.1</td>
<td>HCl (HOCl, ClO)</td>
</tr>
</tbody>
</table>
Spectra measured at limb-sounding

FFO Freq = 495 GHz
Orbit – 30 km;
Increment – 1.5 km,
Tangent: 10.5 – 30 km
45 degrees up

O$_3$

Down-converted Frequency, GHz
CIO line over time (FFO = 495 GHz)

Sunrise 5h08

O₃  CIO  O₃

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Back to the Earth…

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30-cm POrtable Submillimeter Telescope (POST)
Purple Mountain Observatory; Nanjing.
Site: Delingha of Qinghai province (altitude ~3200 m)

Frequency - 345 GHz
Tr (DSB) < 100 K
Spectral resolution < 1 MHz

2-stage GM type;
cooling capacity – 0.1 W;
compressor – 42 kg;
power consumption - 1.2 kW
ESPRIT – Exploratory Submm Space Radio-Interferometric Telescope

- Telescope sizes \( \sim 3.5 \) meter; off-axis
- Number of elements \( N = 6 \) (15 baselines)
- Projected baselines \( 200 - 1000 \) meter
- Frequencies:
  - Spots in the range \( 0.5 - 6 \) THz
- Front Ends - (0.5 – 1.5 THz):
  - SIS mixers, multiplier LO / SIR = FFO + SIS + HM
  - (1.5 – 6 THz) HEB mixers, QCL as LO
- System temperature \( < 1000 \) K
- IF bandwidth \( > 4 \) GHz (goal 8 GHz)

The six elements of ESPRIT in an Ariane 5

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“Millimetron” – Russian Space Agency ( > 2017)
12 m cryogenic mirror; \( \lambda = 0.01 - 20 \text{ mm} \).

Ground-space interferometer
Medical applications

Non-invasive medical diagnostics based on analysis of exhaled air

- human exhalation contains up to 600 volatile compounds
- some of them can be used as markers of diseases

- **CO** Blood disease, asthma, oxidative stress
- **NO** Diseases of respiratory tract, oncology
- **NH₃** Diseases of gastro-enteric tract, liver, kidney
- **CH₄** Malabsorption of hydrocarbons
- **CS₂** Markers of coronary arteries diseases, schizophrenia
- **H₂O₂** Radiation injury, asthma

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Gas Spectra Detection by FFTS

\[ \text{NH}_3 \text{ - 572.498 GHz} \]

Transmission

Frequency (GHz)

- P = 1 mBar
- 0.4 mBar
- 0.1 mBar
- 0.02 mBar
- 0.002 mBar

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Gas Spectra Detection - 2

PLL + mod. + sweep. → IF processor, Computer

Gunn 112-116 GHz → x5 → gas cell → SIR

SIR control

Intensity (mV)

-1500 -1000 -500 0 500 1000 1500

Frequency (GHz)

572,485 572,490 572,495 572,500 572,505 572,510

NH₃ (p = 5×10⁻³ mbar)

Intensity (mV)

-150 -100 -50 0 50 100 150

Frequency (GHz)

571,110 571,115 571,120 571,125 571,130

OSC (p = 2×10⁻³ mbar)

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Conclusion

- Concept of the **Phase-locked SIR** is developed and proven.
- **Nb-AlN-NbN** FFOs and SIRs have been successfully implemented.
- New generation of the SIR with PL FFO for **TELIS** has been developed showing a possibility to achieve all **TELIS** requirements: Frequency range 500 – 650 GHz; Noise temperature < 150 K; IF bandwidth 4 - 8 GHz; Spectral resolution better 1 MHz; Beam Pattern - FWHM = 3 deg, with sidelobes < - 17 dB.
- Procedure for **remote SIR operation** has been developed and experimentally proven.
- **TELIS flight** has been completed in March 2009 (Kiruna, Sweden).
- Future space and ground-base missions are under consideration.
- **SIR Technology** is mature enough for both future space missions and non-invasive medical diagnostic.