Introduction to IR detectors

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07.28. 2020
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- Thermal detectors
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Introduction
IR Electromagnetic spectrum

<table>
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<tr>
<th>Region</th>
<th>Range (μm)</th>
<th>Range (nm)</th>
<th>Group frequency region</th>
<th>Fingerprint region</th>
</tr>
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<tbody>
<tr>
<td>Near IR</td>
<td>0.7 – 1.4</td>
<td>700 – 2,500</td>
<td>14,286 – 4,000 cm⁻¹</td>
<td></td>
</tr>
<tr>
<td>Short-wavelength IR</td>
<td>1.4 – 3.0</td>
<td>2,500 – 6,897</td>
<td>4,000 – 1,450 cm⁻¹</td>
<td></td>
</tr>
<tr>
<td>Mid-wavelength IR</td>
<td>3.0 – 8.0</td>
<td>6,897 – 25,000</td>
<td>1,450 – 400 cm⁻¹</td>
<td></td>
</tr>
<tr>
<td>Far-wavelength IR</td>
<td>8.0 – 1.0 mm</td>
<td>25,000 – 1,000,000</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Atmospheric Absorption of IR

- Absorption and scattering affect the passage of IR through the Earth’s atmosphere.
- Two broadly defined atmospheric “windows” of relatively high transmittance (low absorption) are between 3 - 5 \(\mu m\) and 8 - 14 \(\mu m\).
Black body

Peak emission at environmental temperatures is in the $8 \mu m - 12 \mu m$ range. This range is important in thermal imaging.
Why is IR important?

1. We can detect and study structures and processes that are effectively invisible in the optical range.

Source: https://asd.gsfc.nasa.gov/archive/mwmw/mmw_sci.html
Why is IR important?

2. We can see and detect objects in the absence of visible light: thermal imaging.

Source: https://www.atncorp.com
Why is IR important?

3. We can probe the human body.

Why is IR important?

4. We can probe molecules: e.g., Fourier-transform infrared spectroscopy
IR detection and detectors

1. Detection of IR radiation is inherently more difficult than detection of visible light.
2. The challenge has spawned many innovative techniques and the development of materials.
3. IR detectors can be roughly divided into two classes: thermal and photonic.
Types of IR detectors: thermal sensors

Thermal sensors experience a temperature change due to absorption of radiation. The change in temperature is converted to electrical signal.
## Thermal Sensors

<table>
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<th>Sensor</th>
<th>What changes or what is measured?</th>
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</thead>
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<tr>
<td>Bolometer</td>
<td>Change in electrical conductivity</td>
</tr>
<tr>
<td>Thermopile</td>
<td>Voltage is generated at the junction of different materials</td>
</tr>
<tr>
<td>Pyroelectric</td>
<td>Change in electrical polarization</td>
</tr>
</tbody>
</table>
In a photon detector, the interaction of photons with charge carriers in the detector lead directly to the formation of the electrical signal. A photodiode and avalanche photodiode are two well-known examples of photon detectors.
Absorption coefficients of select materials

The choice of the material for the photon sensor will depend on the wavelength of the measured radiation.
Responsivity

\[ R = \frac{i_S}{\Phi(\lambda)\Delta\lambda} \]  
(nearly monochromatic)

- **\( R \)** – Responsivity \((A/W)\)
- **\( \Phi(\lambda) \)** – Spectral radiant incident power \((W/m)\)
- **\( \Phi(\lambda)\Delta\lambda \)** – Incident power \((W)\)
- **\( i_S \)** – Output current \((A)\)
Noise equivalent power, $NEP$

$NEP = \frac{i_n}{R}$

Noise equivalent power ($NEP$) is the incident power of the detector generating a signal output equal to the $rms$ noise output. Alternatively, the $NEP$ is the light level that produces a signal-to-noise ratio ($S/N$) of 1.
Detectivity and Specific Detectivity

\[ D = \frac{1}{NEP} \]  
(Detectivity)

\[ D^* = D(A_d\Delta f)^{1/2} = \frac{(A_d\Delta f)^{1/2}}{NEP} \]  
(Specific detectivity)
Comments on Specific Detectivity, $D^*$

1. Specific detectivity is a figure of merit used to compare performance of photodetectors of the same class. It is defined as a reciprocal of the detector’s NEP normalized to unit area and unit bandwidth.

2. The logic of the above equation: $NEP$ is proportional to $\sqrt{i_d^2}$ but $i_d$ is proportional to $\sqrt{A\Delta f}$ (the first dependence is due to the fact that the dark current $I_d$ is proportional to the area $A$), so $NEP$ is proportional to $\sqrt{A\Delta f}$. Therefore, multiplying the inverse of $NEP$ by $\sqrt{A\Delta f}$ removes the dependence on the area and bandwidth.
3. Specific detectivity can be a complicated function of wavelength, temperature, bias, and other parameters. There is no single equation for $D^*$ for all of the detectors.

4. Specific detectivity is commonly given for IR detectors in the form of a plot as a function of wavelength.
Specific detectivity for different classes of detectors

- Photonic (photovoltaic)
- Photonic (photoconductive)
- Thermal detectors
Thermal detectors
Thermal Detectors: Principle

![Diagram of thermal detector components]

\[ \Phi = \Phi_0 e^{i\omega t} \]  
(Assumed form of radiant power)

\[ \Delta T = \frac{\varepsilon \Phi_0}{\sqrt{G_{th}^2 + \omega^2 C_{th}^2}} \]  
(Change in temperature due to incident radiant power)

\[ \tau_{th} = \frac{C_{th}}{G_{th}} \]  
(Characteristic response time)

- \( \Phi_0 \) – Heat capacity of the detector
- \( G_{th} \) – Thermal conductance to the heat sink

Source: "Infrared Detectors", 2\textsuperscript{nd} edition, Antoni Rogalski
Thermal detector: equivalent thermal circuit

\[ P \rightarrow C_{th} \rightarrow \frac{1}{G_{th}} \rightarrow T_d \]

- \( P \) – dissipated power (heat)
- \( T_d \) – temperature increase of the detector
- \( \frac{1}{G_{th}} \) – thermal resistance
Thermal detectors: bolometer (thermistor)
Bolometer: thermo-resistance in a metal

\[ i_{\text{cold}} > i_{\text{hot}} \]

\[ \alpha \equiv \frac{1}{R} \frac{dR}{dT} \quad \text{(coefficient of resistivity)} \]

\[ \rho(T) = \rho(T_0)(1 + \alpha \Delta T) \]

for metals \( \alpha > 0 \)
Bolometer: thermo-resistance in a semiconductor

In a semiconductor, resistivity increases exponentially with temperature.

\[ \rho \propto e^{\frac{2kT}{E_g}} \]

\[ i_{\text{cold}} < i_{\text{hot}} \]
Resistance versus temperature for different materials

- Superconductor
- Metal
- Semiconductor
Bolometer

Cross-section of a bolometer (single cell)

IR

Radiation absorbing layer

contact

insulating layer

active (sensitive) layer

substrate/support

contact

$R = R(T)$

equivalent circuit
Bolometer: detection circuit

\[ \nu(t) = V \frac{R_l}{R_l + R_b} \]

Concern: since the current is not constant, Joule heating in the bolometer is not constant either.
Bolometer: detection circuit

\[ \nu(t) = IR_b \]

Concern: Joule’s heating goes up as one increases \( I \) to boost the value of \( \nu(t) \).
Imaging with bolometer(s)

Benefits of a bolometer

1. Operates at room temperature
2. Can detect both ionizing particles and light (all wavelengths)
3. Efficient in energy resolution and sensitivity, albeit slow
Thermal detectors: thermopiles
Seebeck effect

If $T_1 = T_2$, $V = 0$ Volts

If $T_1 \neq T_2$, $V \neq 0$ Volts
Understanding Seebeck effect (metal)

\[ V_{th} \]

“hot” \hspace{1cm} “cold”
Understanding Seebeck effect (semiconductor)

\[
\begin{align*}
N \text{-type semiconductor} & \quad \text{positive ions (donor atoms)} \\
& \quad \text{electrons} \\
& \quad \text{“hot”} \\
& \quad v_{th} \\
& \quad \text{“cold”} \\
\end{align*}
\]

\[
\begin{align*}
P \text{-type semiconductor} & \quad \text{negative ions (acceptor atoms)} \\
& \quad \text{holes} \\
& \quad \text{“hot”} \\
& \quad v_{th} \\
& \quad \text{“cold”} \\
\end{align*}
\]
Thermocouple

\[ V_{th} = \alpha_{S,AB} \Delta T \]
Thermopile

\[ V = 3v_{th} \]

\[ V = \gamma T \]

equivalent circuit
Thermopile

Example of Hamamatsu thermopile T11361 series

### Electrical and optical characteristics (Ta=25 °C)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Condition</th>
<th>T11361-01</th>
<th>T11361-05</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photosensitivity</td>
<td>S</td>
<td>1 Hz, 500 K</td>
<td>40</td>
<td>50</td>
<td>60</td>
</tr>
<tr>
<td>Element resistance</td>
<td>Re</td>
<td></td>
<td>100</td>
<td>125</td>
<td>150</td>
</tr>
<tr>
<td>Noise equivalent power</td>
<td>NEP</td>
<td>Johnson noise</td>
<td>-</td>
<td>45</td>
<td>50</td>
</tr>
<tr>
<td>Detectivity</td>
<td>D*</td>
<td>0.9 × 10⁶, 0.9 × 10⁶, 0.9 × 10⁶</td>
<td>9 × 10⁶, 9 × 10⁶, 9 × 10⁶</td>
<td>cm Hz¹/²/W</td>
<td></td>
</tr>
<tr>
<td>Rise time</td>
<td>tr</td>
<td>0 to 63%</td>
<td>-</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>Temperature coefficient of element resistance</td>
<td>TCR</td>
<td>±0.1</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Field of view</td>
<td>FOV</td>
<td>90</td>
<td>-</td>
<td>-</td>
<td>90</td>
</tr>
<tr>
<td>Thermistor resistance</td>
<td>Rth</td>
<td>9 to 11</td>
<td>9</td>
<td>10</td>
<td>11</td>
</tr>
<tr>
<td>Constant B</td>
<td>B</td>
<td>25/75 °C</td>
<td>3800</td>
<td>3900</td>
<td>4000</td>
</tr>
</tbody>
</table>
Benefits of a thermopile

1. Inexpensive, simple in construction, and rugged. Often used as temperature sensors.
2. Can be made very small and inserted in difficult-to-access places.
3. Can be used to measure wide range of temperatures.
Thermal detectors: pyroelectric detectors
Pyroelectric crystal, such as Tourmaline, at temperature $T$ and cut so that the intrinsic polarization $\vec{P}$ is in the vertical direction.
Pyroelectricity

When temperature of the crystal changes (increases), the polarization decreases, and current flows though the ammeter until a new equilibrium is reached.
Equivalent circuit

\[ I(t) = p \frac{dT}{dt} \]
A pyroelectric sensor can detect temperature changes on the order of $\mu K$. 
Benefits of pyroelectric IR detector

1. Sensitivity over a very large spectral bandwidth
2. Sensitivity over a very wide temperature range – from a few degrees kelvin to hundreds, depending on pyroelectric material
3. Low power requirement
4. Fast response
5. Low-cost manufacture from inexpensive material

Imaging with pyroelectric sensors

A ferroelectric-hybrid focal-plane device comprises a lens, usually made of germanium to block visible light, and an array of individual ferroelectric elements that are each bonded by tiny balls of solder to elements from a silicon multiplexer. The incident IR radiation must be periodically blocked, here by a chopper, to ensure that a temperature variation is measured.

Imaging with pyroelectric sensors

Pyroelectric imaging. These images were taken using a ferroelectric-hybrid focal-plane array (top) having 256 × 128 pixels (courtesy of DERA Malvern, Crown © 1989 and 1998) and a micromachined thin-film array (bottom) with 320 × 240 pixels (courtesy of Raytheon Commercial Electronics). Lighter colors correspond to warmer temperatures.

Frequency response of thermal detectors

Adapted from “Photodetectors: Devices, Circuits, and Applications” by Silvano Donati (Fig. 6-4)
Takeaways

1. Thermal IR detectors operate at room (or ambient) temperature.
2. They have a very broad spectral response.
3. They are inexpensive and simple to use.
4. They can be used in imaging.
5. They are generally slower and have lower $D^*$ compared to photonic devices.
Photon detectors (brief overview)
Types of excitation in a semiconductor

- **Intrinsic**: $h\nu > E_g$
- **Extrinsic**: $h\nu > E_d$
- **Free carrier**
# Types of IR photodetectors

<table>
<thead>
<tr>
<th>Type</th>
<th>Detector</th>
<th>Spectral response (µm)</th>
<th>Operating temperature (K)</th>
<th>$D^*(cm\cdot Hz^{1/2}/W)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal type</td>
<td>Thermocouple · Thermopile Bolometer · Pneumatic cell · Pyroelectric detector</td>
<td>Depends on window material</td>
<td>300</td>
<td>$D^*(λ,10,1) = 6 \times 10^8$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>300</td>
<td>$D^*(λ,10,1) = 1 \times 10^8$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>300</td>
<td>$D^*(λ,10,1) = 1 \times 10^8$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>300</td>
<td>$D^*(λ,10,1) = 2 \times 10^8$</td>
</tr>
<tr>
<td>Intrinsic type</td>
<td>PbS</td>
<td>1 to 3.6</td>
<td>300</td>
<td>$D^*(500,600,1) = 1 \times 10^9$</td>
</tr>
<tr>
<td></td>
<td>PbSe</td>
<td>1.5 to 5.8</td>
<td>300</td>
<td>$D^*(500,600,1) = 1 \times 10^9$</td>
</tr>
<tr>
<td></td>
<td>InSb</td>
<td>2 to 5</td>
<td>300</td>
<td>$D^*(500,1200,1) = 2 \times 10^9$</td>
</tr>
<tr>
<td></td>
<td>HgCdTe</td>
<td>2 to 16</td>
<td>300</td>
<td>$D^*(500,1000,1) = 1 \times 10^{10}$</td>
</tr>
<tr>
<td>Photovoltaic type</td>
<td>Ge</td>
<td>0.8 to 1.8</td>
<td>300</td>
<td>$D^*(1.0) = 1 \times 10^{11}$</td>
</tr>
<tr>
<td></td>
<td>InGaAs</td>
<td>0.7 to 1.7</td>
<td>300</td>
<td>$D^*(1.0) = 5 \times 10^{10}$</td>
</tr>
<tr>
<td></td>
<td>ErInGaAs</td>
<td>1.2 to 2.55</td>
<td>263</td>
<td>$D^*(1.0) = 2 \times 10^4$</td>
</tr>
<tr>
<td></td>
<td>InAs</td>
<td>1 to 3.1</td>
<td>77</td>
<td>$D^*(500,1200,1) = 1 \times 10^{10}$</td>
</tr>
<tr>
<td></td>
<td>InSb</td>
<td>1 to 5.5</td>
<td>77</td>
<td>$D^*(500,1200,1) = 2 \times 10^{10}$</td>
</tr>
<tr>
<td></td>
<td>HgCdTe</td>
<td>2 to 16</td>
<td>77</td>
<td>$D^*(500,1000,1) = 1 \times 10^{10}$</td>
</tr>
<tr>
<td>Extrinsic type</td>
<td>Ge:Au</td>
<td>1 to 10</td>
<td>77</td>
<td>$D^*(500,600,1) = 1 \times 10^{11}$</td>
</tr>
<tr>
<td></td>
<td>Ge: Hg</td>
<td>2 to 14</td>
<td>4.2</td>
<td>$D^*(500,600,1) = 8 \times 10^9$</td>
</tr>
<tr>
<td></td>
<td>Ge: Cu</td>
<td>2 to 30</td>
<td>4.2</td>
<td>$D^*(500,600,1) = 5 \times 10^9$</td>
</tr>
<tr>
<td></td>
<td>Ge: Zn</td>
<td>2 to 40</td>
<td>4.2</td>
<td>$D^*(500,600,1) = 5 \times 10^9$</td>
</tr>
<tr>
<td></td>
<td>Si: Ga</td>
<td>1 to 17</td>
<td>4.2</td>
<td>$D^*(500,600,1) = 5 \times 10^9$</td>
</tr>
<tr>
<td></td>
<td>Si: As</td>
<td>1 to 23</td>
<td>4.2</td>
<td>$D^*(500,600,1) = 5 \times 10^9$</td>
</tr>
</tbody>
</table>
Photovoltaic: PIN photodiode (e.g., InGaAs)

Spectral response of InGaAs photodiodes ranges from 0.5 – 2.6 μm
Bandgap energy of InGaAs

Relative concentrations of In, Ga, and As determine the bandgap energy and, thus, spectral response.
Equivalent circuit

Photodiode

$I_{ph} = \sigma P$

$R_{sh} –$ Shunt resistance

$R_S –$ Series resistance

$C_J –$ Junction capacitance

$R_L –$ Load resistance

$V_B –$ Bias voltage source

$I_{ph} –$ Photocurrent
Example of InGaAs photodiode specific detectivity as a function of wavelength. Note how the detectivity improves as temperature decreases.
Frequency response

Terminal capacitance and detection electronics determine the frequency response. Note how terminal capacitance increases with active area.
Shunt resistance versus temperature

Shunt resistance decreases with increasing temperature.
Detection circuit

1. Bandwidth increases with $V_B$
2. Linear response but dynamic range limited by amplifier saturation
3. Dark current
4. At high-frequency operation, the TIA may exhibit gain peaking and instabilities.

This is one of the most popular configurations.
Photoconductive (intrinsic)
Photoconductive (extrinsic)

These detectors are operated at low temperatures.
Specific detectivity

Note how $D^*$ increases with decreasing temperature and how the peak wavelength increases.
Both $R$ and $D^*$ are function of modulation frequency. As the plot shows, chopping the incident DC radiation improves $S/N$. 
Detectivities of photonic IR detectors

![Graph showing detectivities of photonic IR detectors across different wavelengths for various materials such as InGaAs, PbS, InAs, InSb, and MCT. The graph plots detectivity ($D^*$) in units of cm$^{-1}$·√Hz/W against wavelength in micrometers.]
Photon drag IR detectors

heavily doped semiconductor (n or p type)
Photon drag detector by Hamamatsu

Active material: germanium

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Condition</th>
<th>Min.</th>
<th>Typ.</th>
<th>Max.</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photosensitivity</td>
<td>S</td>
<td>$\lambda=10.6$ μm</td>
<td>-</td>
<td>1.2</td>
<td>-</td>
<td>mV/kW</td>
</tr>
<tr>
<td>Rise time</td>
<td>tr</td>
<td>10 to 90%</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>ns</td>
</tr>
<tr>
<td>Noise equivalent power</td>
<td>NEP</td>
<td>$\lambda=10.6$ μm</td>
<td>-</td>
<td>$4 \times 10^3$</td>
<td>-</td>
<td>W/Hz$^{1/2}$</td>
</tr>
<tr>
<td>Output impedance</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>50</td>
<td>-</td>
<td>Ω</td>
</tr>
</tbody>
</table>

Used for $CO_2$ laser detection
Takeaways

1. Photonic IR detectors offer larger $D^*$ compared to thermal IR detectors.
2. Photovoltaic detectors tend to have the largest values of $D^*$ but also the narrowest spectral response.
3. Photonic detectors need to be cooled, in some cases to a temperature as low as about 4 K.
4. Photonic IR detectors can be used in image arrays.
What IR detector should I use in my application?

The selection process is based on the following considerations:

1. Wavelength: longer the wavelength, fewer the choices.
2. Incident power: affects needed $D^*$. Typically, larger $D^*$ implies a higher cost.
3. Characteristics of the incident IR radiation: collimated, diffuse, DC, pulse, modulated
4. Does my application allow cooling?
5. Cost

The selection process can vary from trivially simple to quite complex involving tradeoffs. Contact HAMAMATSU for assistance and guidance.
Join Us for 10 Weeks of FREE Photonics Webinars (17 Topics)

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<th>Talk #1 Date</th>
<th>Talk #2 Date</th>
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<td>Introduction to Photodetectors</td>
<td>2</td>
<td>26-May-20</td>
<td>28-May-20</td>
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<tr>
<td>2</td>
<td>Emerging Applications - LiDAR &amp; Flow Cytometry</td>
<td>2</td>
<td>2-Jun-20</td>
<td>4-Jun-20</td>
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<tr>
<td>3</td>
<td>Understanding Spectrometer</td>
<td>2</td>
<td>9-Jun-20</td>
<td>11-Jun-20</td>
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<td></td>
<td><strong>1 Weeks Break</strong></td>
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<tr>
<td>4</td>
<td>Specialty Products – Introduction to Light Sources &amp; X-Ray</td>
<td>2</td>
<td>23-Jun-20</td>
<td>25-Jun-20</td>
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<td>5</td>
<td>Introduction to Image Sensors</td>
<td>2</td>
<td>30-Jun-20</td>
<td>02-Jul-20</td>
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<td><strong>1 Weeks Break</strong></td>
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<td>Specialty Products – Laser Driven Light Sources</td>
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<td>7</td>
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<td>21-Jul-20</td>
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<td>8</td>
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<td>28-Jul-20</td>
<td>30-Jul-20</td>
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<td><strong>1 Weeks Break</strong></td>
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<td>9</td>
<td>Photon Counting Detectors – SiPM and SPAD</td>
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<td>10</td>
<td>Using SNR Simulation to Select a Photodetector</td>
<td>1</td>
<td>18-Aug-20</td>
<td></td>
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Thank you for listening

Contact information:

piatek@njit.edu