CSIR

Defence, Peace, Safety and Security

Pyradi: an open-source toolkit for infrared calculation and data processing

SPIE S+D 8543-19

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Willers, Willers, Santos,
van der Merwe, Calitz, de Waal & Mudau

Infrared Data Analysis

Who has done infrared measurement data analysis?

You will understand the next slide….

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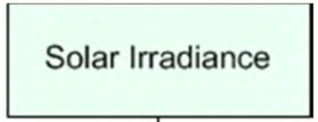
Infrared Data Analysis

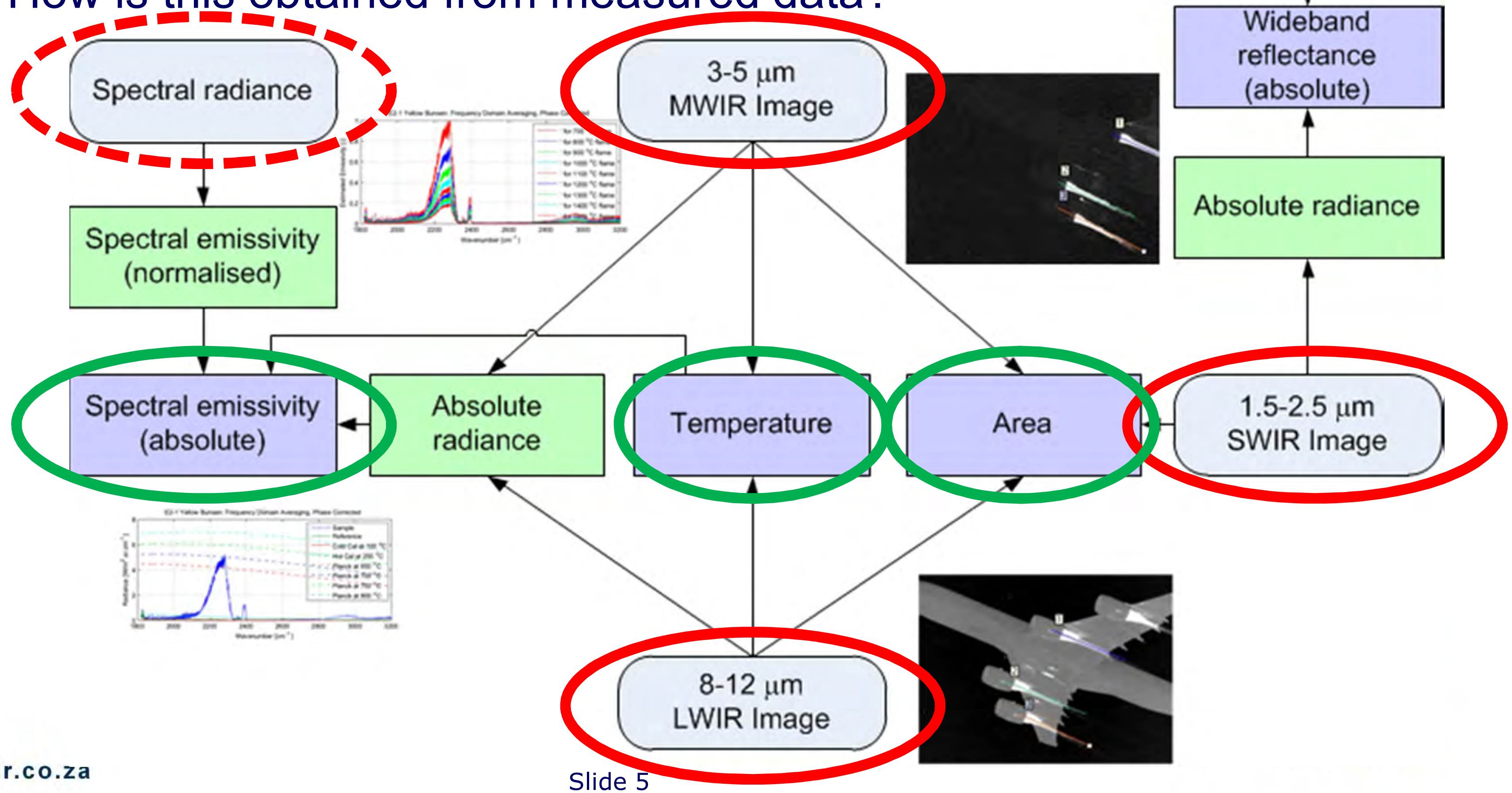
Signatures From Measurements

Main focus of infrared target modelling:

- temperature
- spectral emissivity
- area

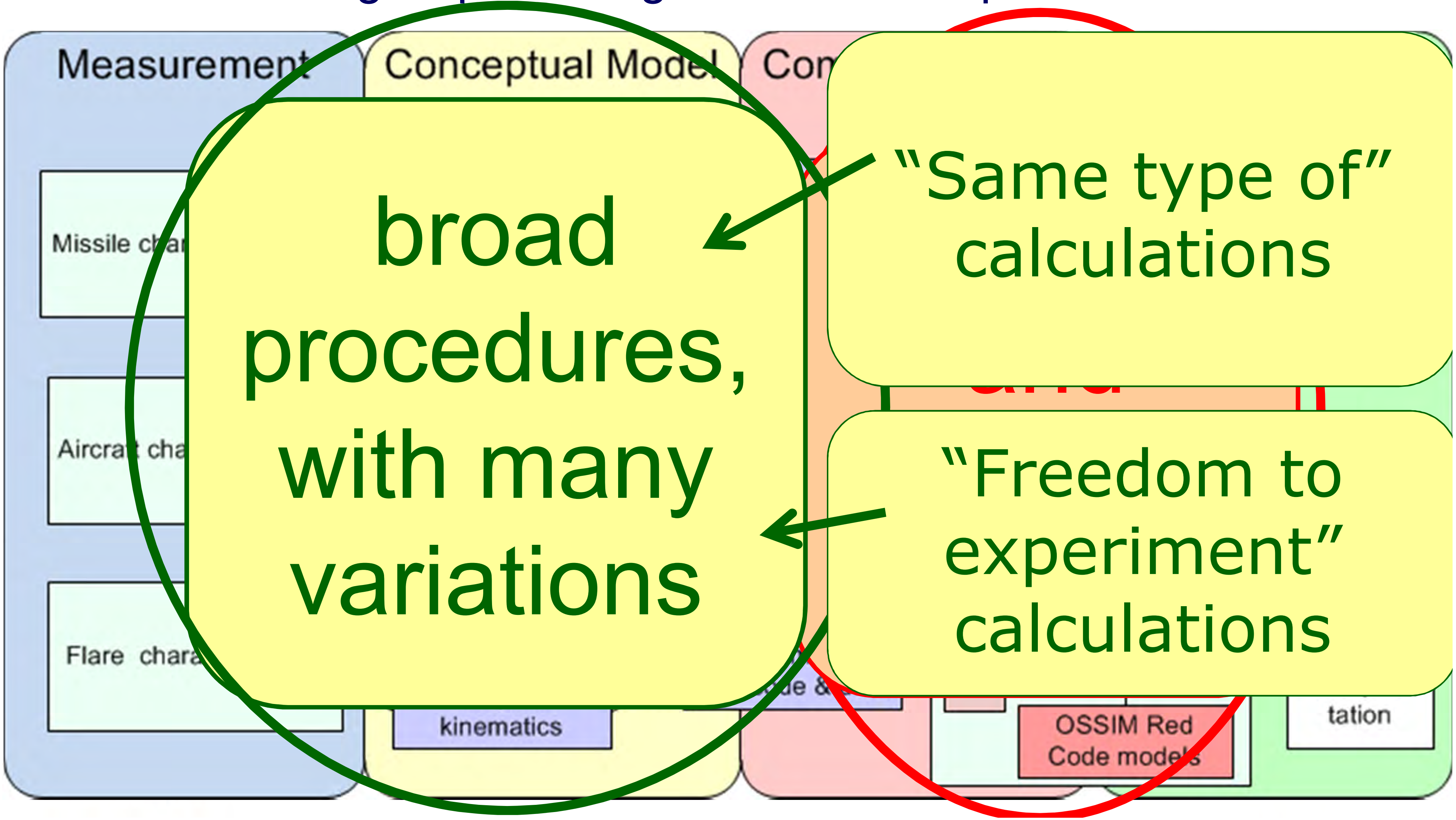
How is this obtained from measured data?





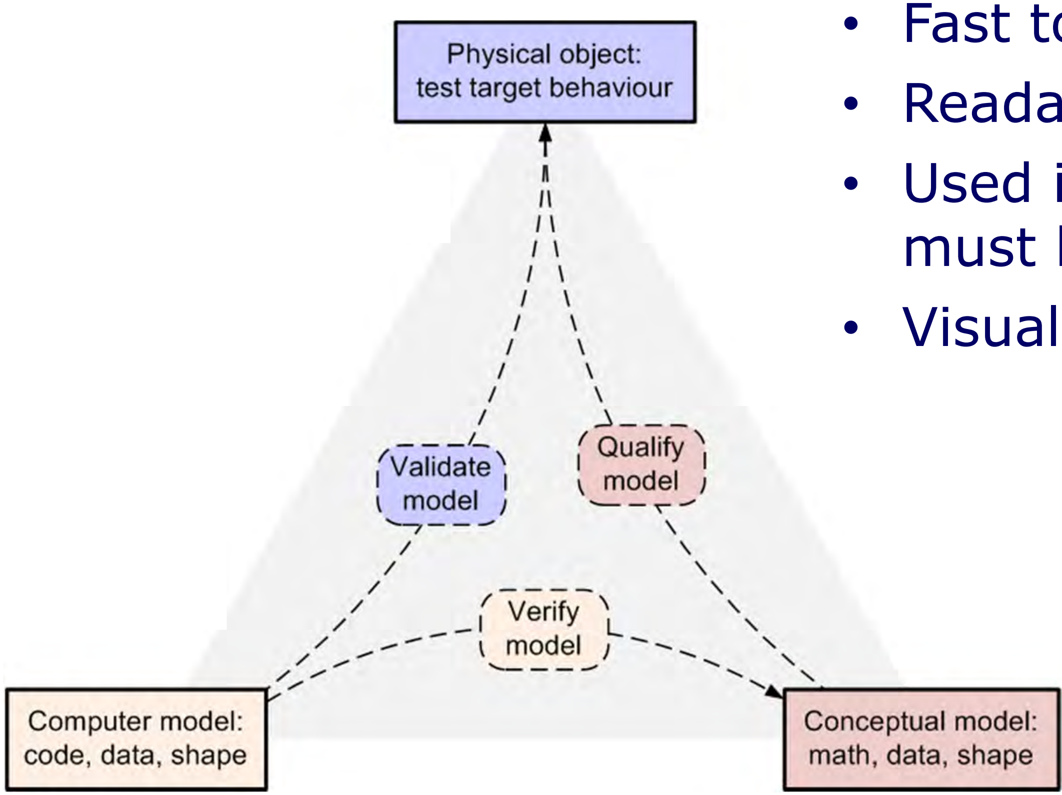
From Measurements to Results

Model building requires huge amount of repetitive calculation



Vital to Insight!

Key Requirements



- Easy to use.
- Fast to prototype.
- Readable, uncluttered code.
- Used in validation/verification: must be a well-tested library.
- Visualisation is critical!

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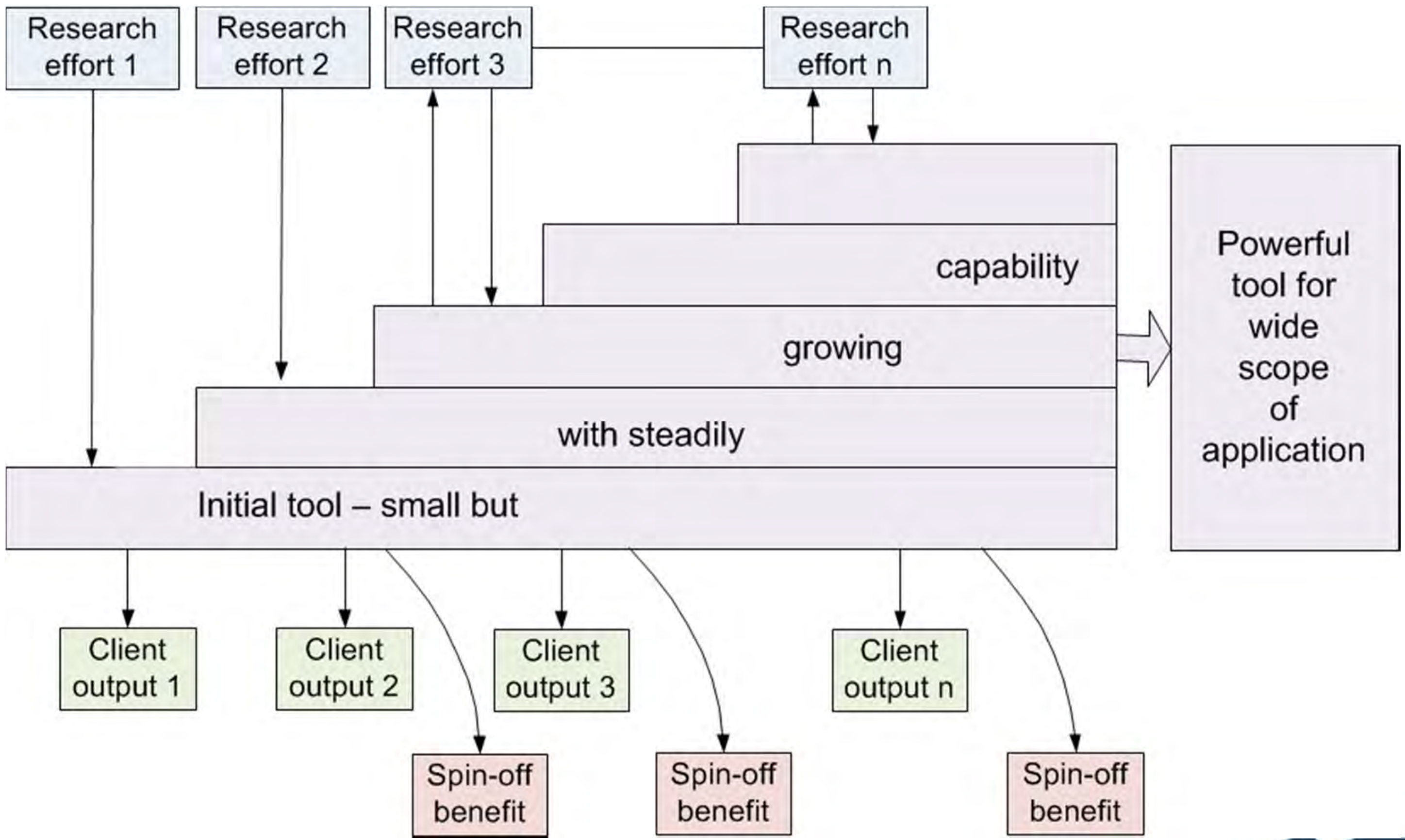
pyradi

Focussed on electro-optics calculations.

The toolkit covers

- models of physical concepts,
- mathematical operation,
- data manipulation, and
- graphical visualisation.

Cumulative Development



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Scripting Language

Matlab vs Python.

Extensive experience with both languages.

Python won:

- General purpose, mainstream, language.
- A more powerful and productive language.
- Many extensions in very many application areas.
- Numpy & Scipy equal to Matlab for scientific work.
- Superior visualisation & graphics tools.
- Easy to learn & very strong open source support.
- Zero acquisition cost & low usage cost.
- Negative: no Simulink, fewer toolboxes.

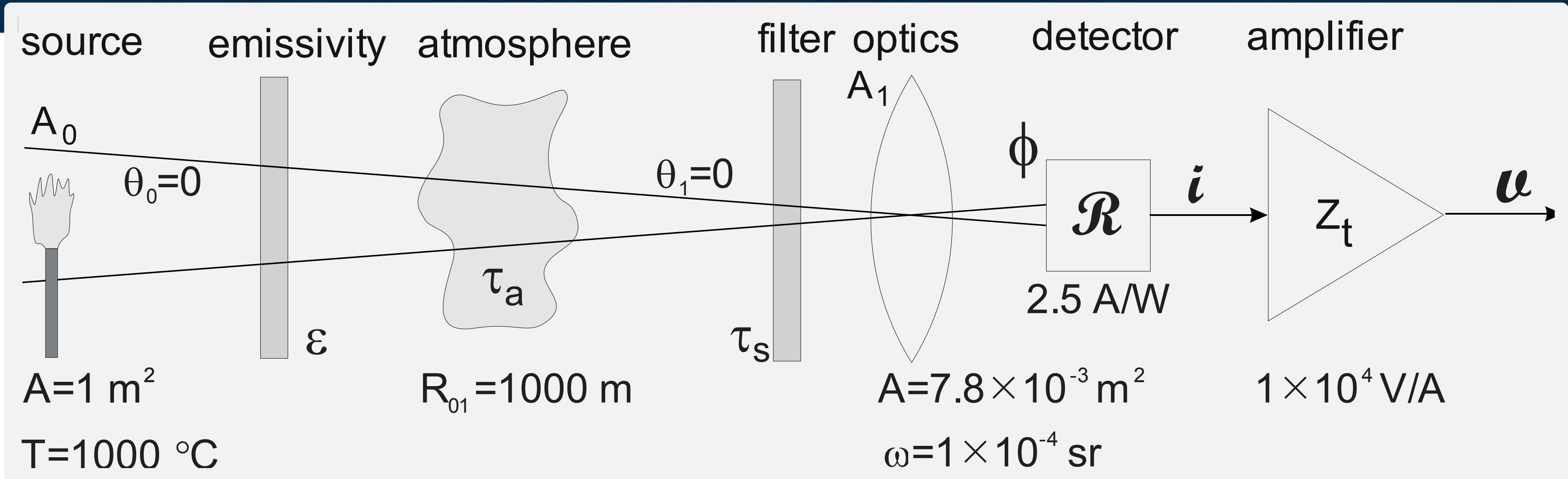
Unix Tool Philosophy

Write programs that do one thing and do it well.

Write programs to work together.

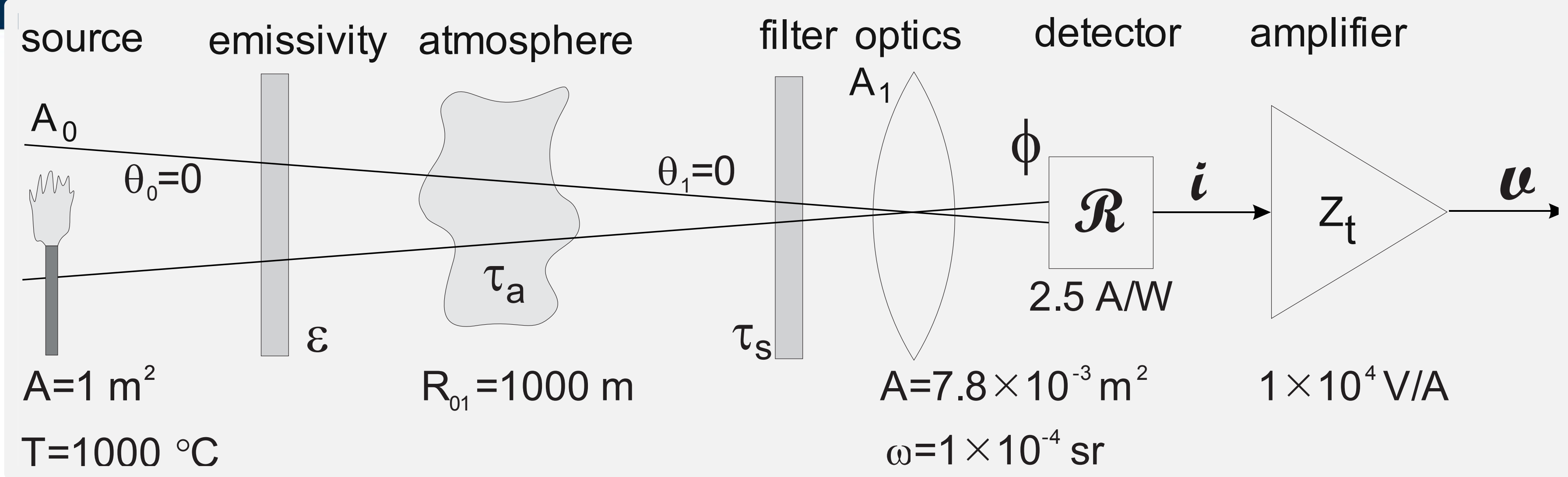
- Simple parts connected by clean interfaces.
- Clarity in coding.
- Write big programs putting together building blocks.
- Programmer time is expensive; conserve it.
- Quick prototyping before polishing.
- Design for the future, because it will be here sooner than you think.

Example: Flame Detection



Detect the presence or absence of a flame, through the atmosphere in 3-5 μm band.

Example: Flame Detection



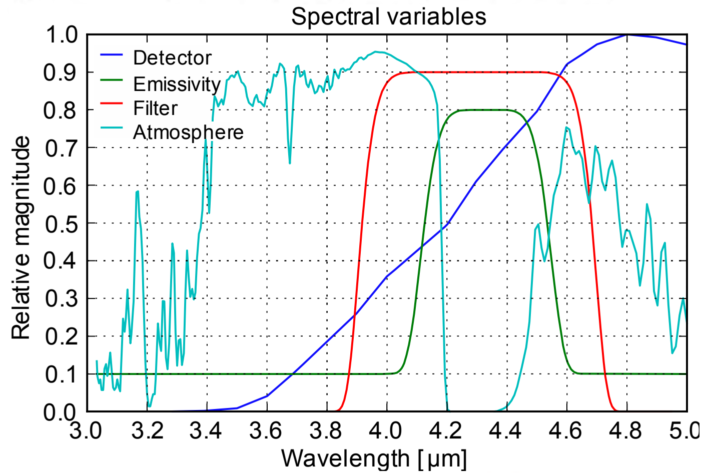
Signal from the flame:

$$v = Z_t \int_{A_0} \int_{A_1} \frac{1}{r_{01}^2} \int_0^\infty \epsilon_\lambda L_\lambda(T, A_0) \tau_{a\lambda} \tau_{s\lambda}(A_1) \mathcal{R}_\lambda \, d\lambda \, d(\cos\theta_0 A_0) \, d(\cos\theta_1 A_1).$$

Signal from the atmospheric radiance:

$$v = Z_t \omega_{\text{optics}} A_{\text{optics}} \int_0^\infty L_{\text{path}\lambda} \tau_{s\lambda} \mathcal{R}_\lambda \, d\lambda,$$

Modtran spectral transmittance & path radiance



Solution Page 1 of 2

```
#load atmospheric transmittance from file created in Modtran in wavenumbers
# the transmittance is specified in the wavenumber domain with
# 5 cm-1 intervals, but we want to work in wavelength with 2.5 cm-1
waven = numpy.arange(2000.0,  3300.0,  2.5).reshape(-1, 1)
wavel= ryutils.convertSpectralDomain(waven,  type='nw')

#remove comment lines, and scale path radiance from W/cm2.sr.cm-1  to W/m2.sr.cm-
1
tauA = ryfiles.loadColumnTextFile('data/path1kmflamesensor.txt',
        [1],abscissaOut=waven,  comment='%')
lpathwn = ryfiles.loadColumnTextFile('data/pathspaceflamesensor.txt',
        [9],abscissaOut=waven,  ordinateScale=1.0e4,  comment='%')

#convert path radiance spectral density from 1/cm^-1 to 1/um, at the sample
#wavenumber points
(dum, lpathwl) = ryutils.convertSpectralDensity(waven,  lpathwn, type='nw')

#load the detector file in wavelengths, and interpolate on required values
detR = ryfiles.loadColumnTextFile('data/detectorflamesensor.txt',
       [1],abscissaOut=wavel,  comment='%')

#construct the flame emissivity from parameters
emis = ryutils.sfilter(wavel,center=4.33, width=0.45, exponent=6, taupass=0.8,
         taustop=0.1 )
#construct the sensor filter from parameters
sfilter = ryutils.sfilter(wavel,center=4.3, width=0.8, exponent=12,
          taupass=0.9, taustop=0.0001)
```

Only two pages

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Solution Page 2 of 2

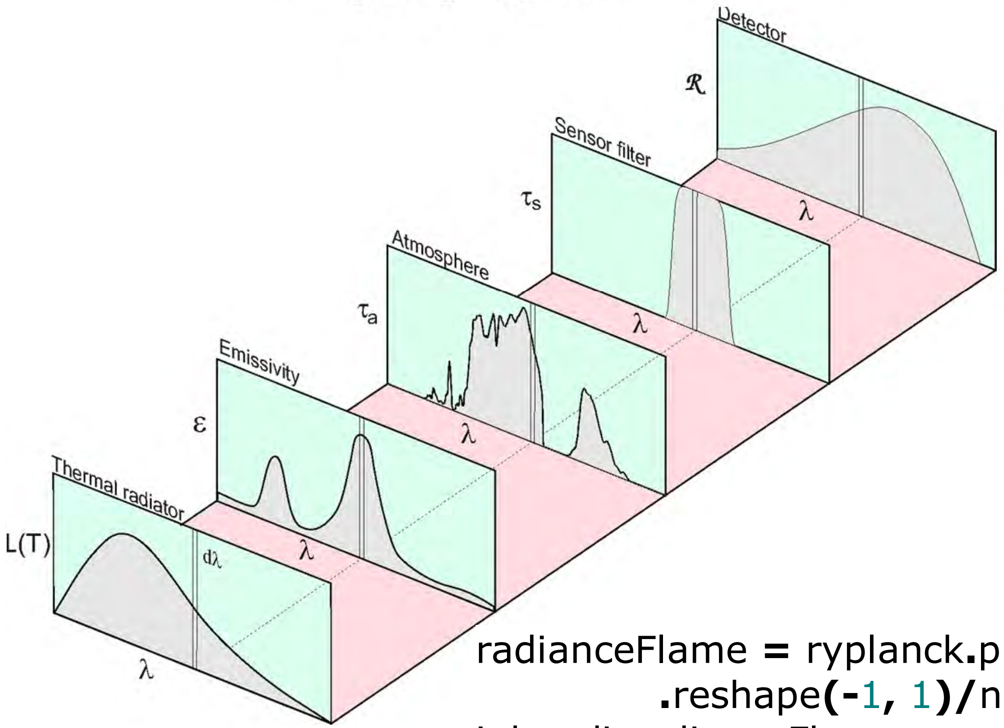
```
# define sensor scalar parameters
opticsArea=7.8e-3 # optical aperture area [m2]
opticsFOV=1.0e-4 # sensor field of view [sr]
transZ=1.0e4 # amplifier transimpedance gain [V/A]
responsivity=2.5 # detector peak responsivity =A/W]

# define the  flame properties
flameTemperature = 1000+273.16    # temperature in [K]
flameArea = 1  # in [m2]
distance = 1000  # [m]
fill = (flameArea /distance**2) /  opticsFOV # how much of FOV is filled
fill = 1 if fill > 1 else fill # limit target solid angle to sensor FOV

# flame get spectral radiance in  W/m^2.sr.cm-1
radianceFlame = ryplanck.planck(waven, flameTemperature,  type='en')\
           .reshape(-1, 1)/numpy.pi
inbandirradianceFlame = radianceFlame * detR * tauA * emis * sfilter *\
           fill * opticsFOV
totalirradianceFlame = numpy.trapz(inbandirradianceFlame.reshape(-1, 1),
          waven, axis=0)[0]
signalFlame = totalirradianceFlame *transZ*responsivity *opticsArea

# now do path
inbandirradiancePath =  lpathwn * detR * sfilter * opticsFOV
totalirradiancePath = numpy.trapz(inbandirradiancePath.reshape(-1, 1),waven, axis=0)[0]
signalPath = totalirradiancePath * transZ*responsivity *opticsArea
```

The code is:

- Compact
- Clean
- Intuitive

Multi-spectral Calculations

$$v = Z_t \int_{A_0} \int_{A_1} \frac{1}{r_{01}^2} \int_0^\infty \epsilon_\lambda L_\lambda(T, A_0) \tau_{a\lambda} \tau_{s\lambda}(A_1) \mathcal{R}_\lambda \, d\lambda \, d(\cos\theta_0 A_0) \, d(\cos\theta_1 A_1).$$

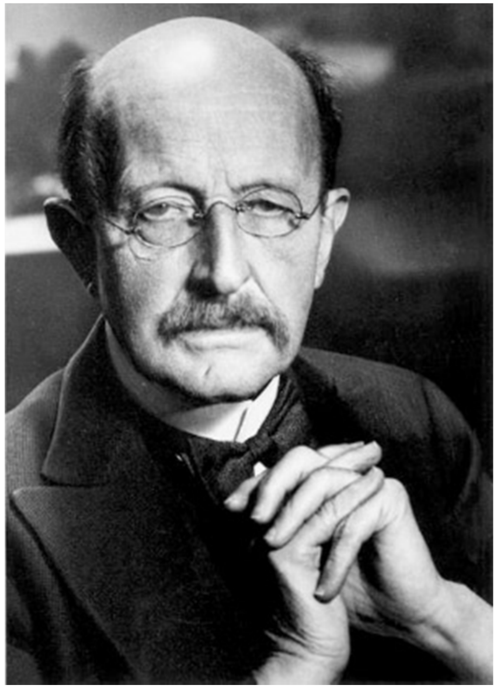


- Spectral variables are vectors.
- Calculate irradiance at each wavelength 'bin' by vector element-wise multiplication.
- Add flux at all wavelengths.

```
radianceFlame = ryplanck.planck(waven, flameTemperature,  type='en')\
            .reshape(-1, 1)/numpy.pi
inbandirradianceFlame = radianceFlame* emis* tauA  * sfilter * detR *\
            opticsFOV
totalirradianceFlame = numpy.trapz(inbandirradianceFlame.reshape(-1, 1),
            waven, axis=0)[0]
signalFlame = totalirradianceFlame *transZ*responsivity *opticsArea
```

Planck's Law

$$M_{e\lambda}(T) = \frac{2\pi h c^2}{\lambda^5 \left(e^{\frac{hc}{\lambda kT}} - 1\right)}$$

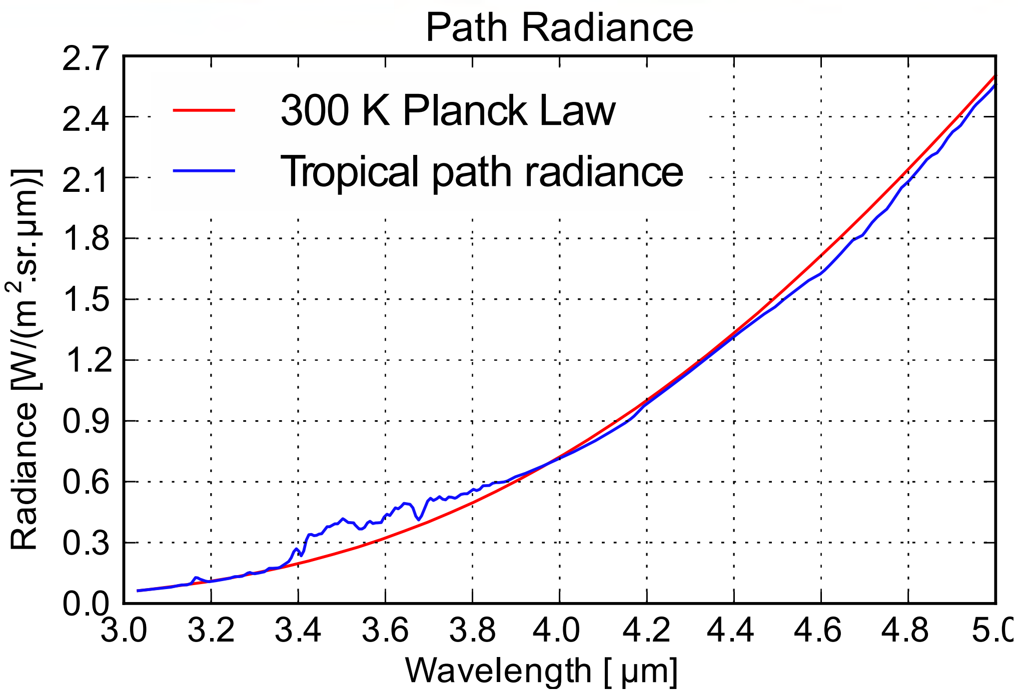


Pyradi provides functions for Planck Law emittance, as well as Planck Law temperature derivative in terms of:

[W] or [q/s] and [μm, cm^{-1}, Hz].

```
Mel = planck(wl, temperature[0], type='el') # [W/(m$^2$.$\mu$m)]
Mql = planck(wl, temperature[0], type='ql') # [q/(s.m$^2$.$\mu$m)]
Men = planck(n, temperature[0], type='en')  # [W/(m$^2$.cm$^{-1}$)]

Mqn = dplanck(n, temperature[0], type='qn')  # [q/(s.m$^2$.cm$^{-1}$.K)]
Mef = dplanck(f, temperature[0], type='ef')  # [W/(m$^2$.Hz.K)]
Mqf = dplanck(f, temperature[0], type='qf')  # [q/(s.m$^2$.Hz.K)]
```

Visualising Path Radiance



Flame sensor path:

- Horizontal path to space.
- Notice correspondence.
- Visualisation important!

```
#check path radiance against Planck's Law for atmo temperature
LbbTropical = ryplanck.planck(wavel, 273+27, type='el').reshape(-1, 1)/numpy.pi
plot1.plot(2, wavel, LbbTropical, plotCol=['r'], label=['300 K Planck Law'])
plot1.plot(2, wavel, lpathwl, plotCol=['b'], label=['Tropical path radiance'])
currentP = plot1.getSubPlot(2)
currentP.set_xlabel('Wavelength [$\mu$m]')
currentP.set_ylabel('Radiance [W/(m$^2$.sr.$\mu$m)]')
currentP.set_title('Path Radiance')
```

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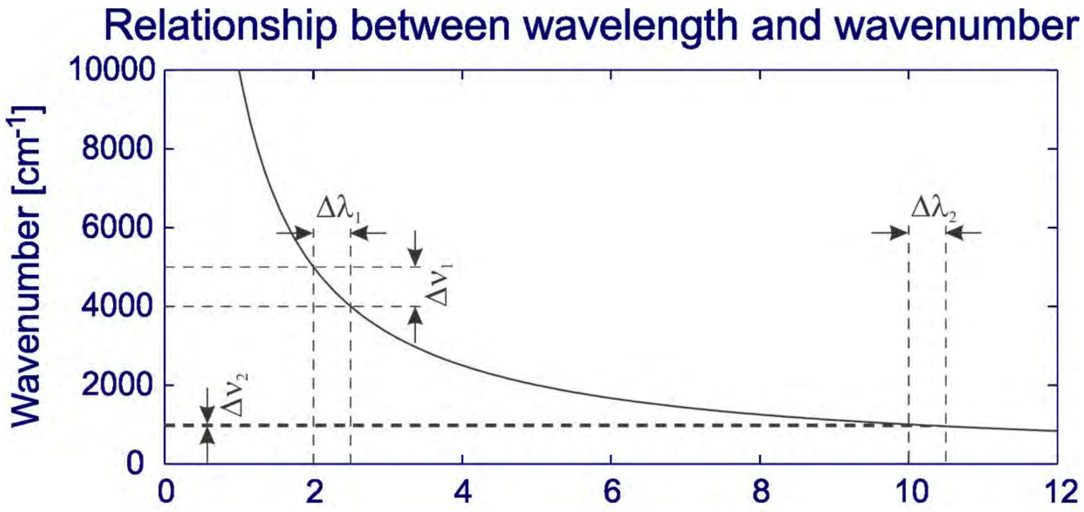
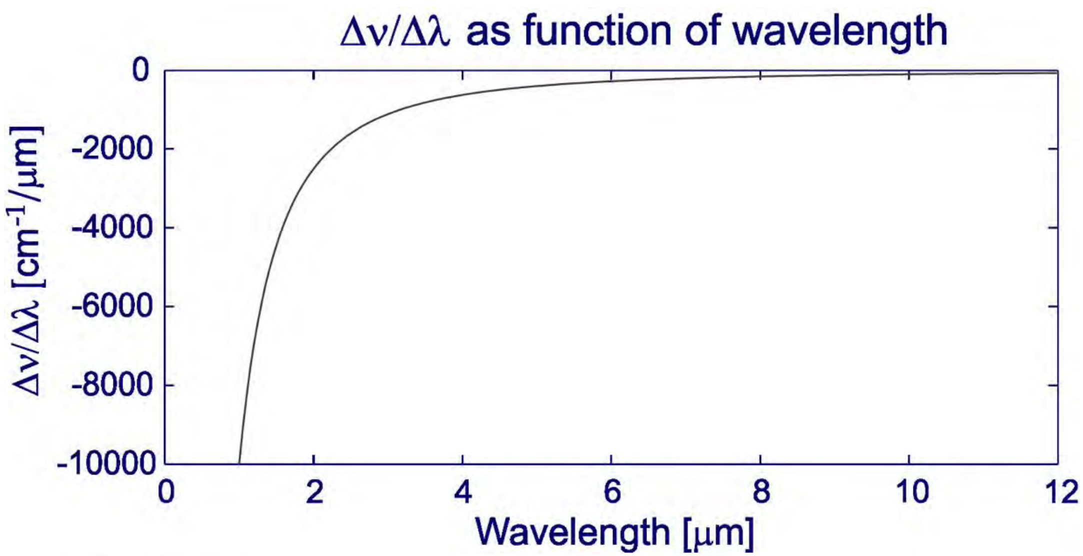
Wavelength and Wavenumber





Wavenumber is given by

$$\nu = 10^4/\lambda$$

where λ is in units of μm.

The conversion of a spectral quantity requires the derivative, as follows:

$$d\nu = \frac{-10^4}{\lambda^2} d\lambda = \frac{\nu^2}{-10^4} d\lambda$$

$$dL_\nu = dL_\lambda \frac{\lambda^2}{10^4} = dL_\lambda \frac{10^4}{\nu^2}$$

Pyradi converts between spectral variables:

[μm, cm^{-1}, Hz],

as well as spectral densities:

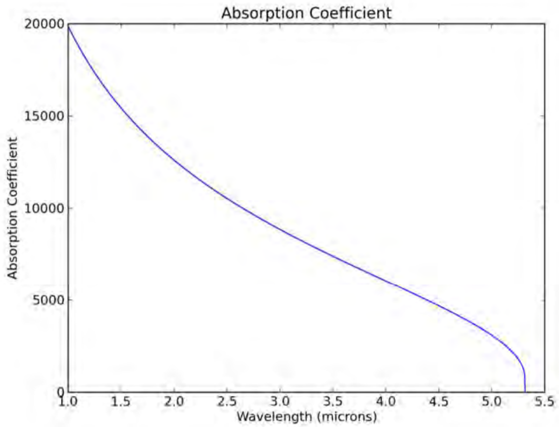
[W/($m^2\cdot\mu$m)],

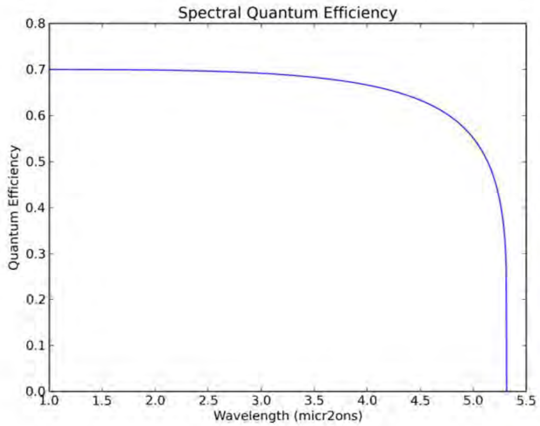
[W/($m^2\cdot$cm-1)],

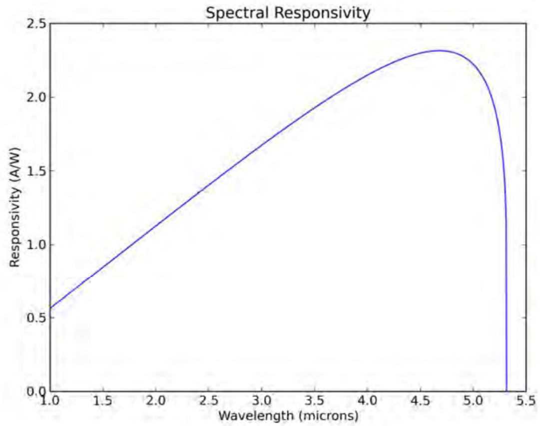
[W/($m^2\cdot$Hz)].

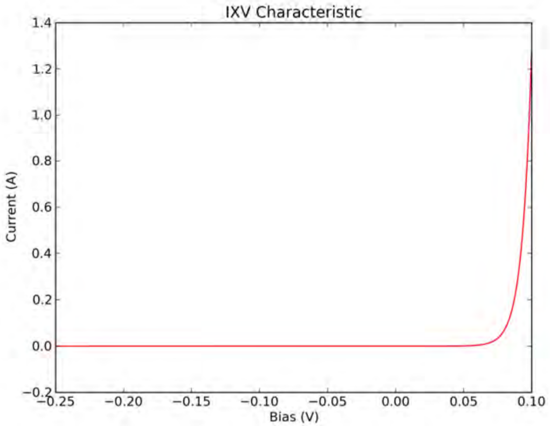
Detector Modelling

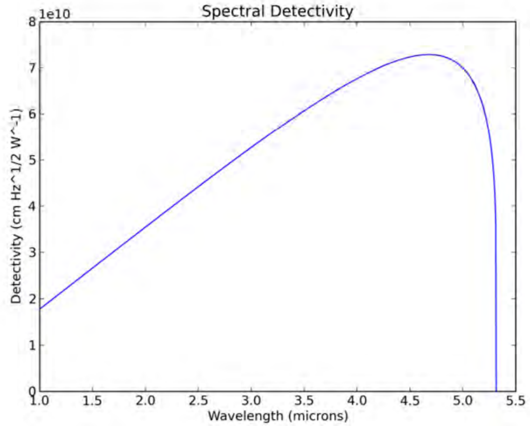
Detector model, based on first principles physics.
Example shown is for InSb detector.



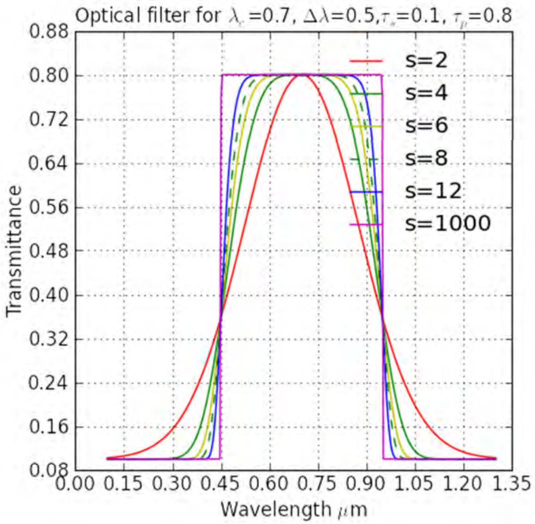


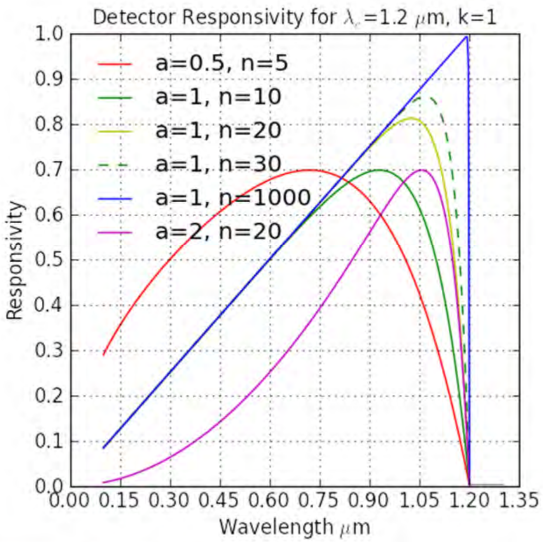


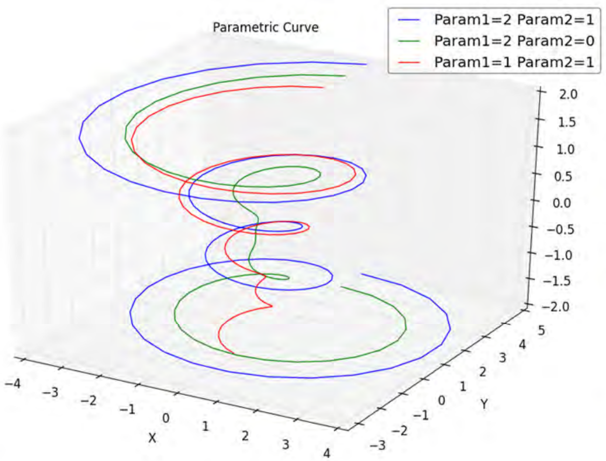




Utility Functions

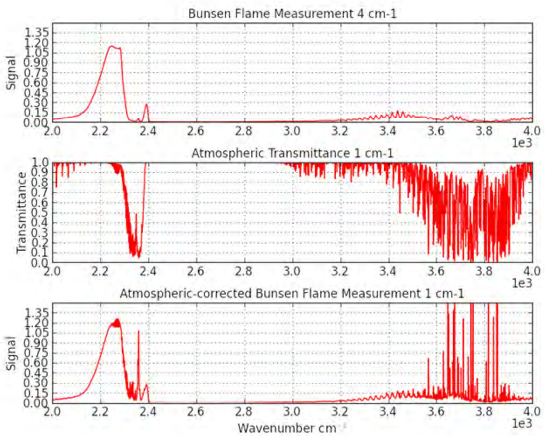


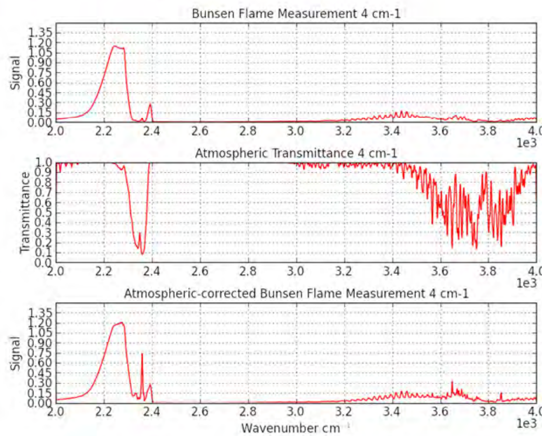




General purpose models:

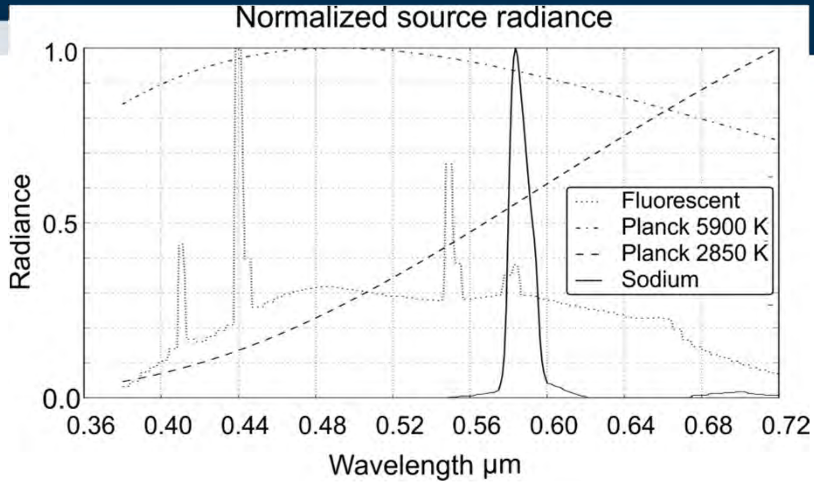
- Spectral filter shapes.
- Photon detector shapes.
- Spectral convolution.
- Effective value normalisation.
- Various 2-D & 3-D plotting functions.

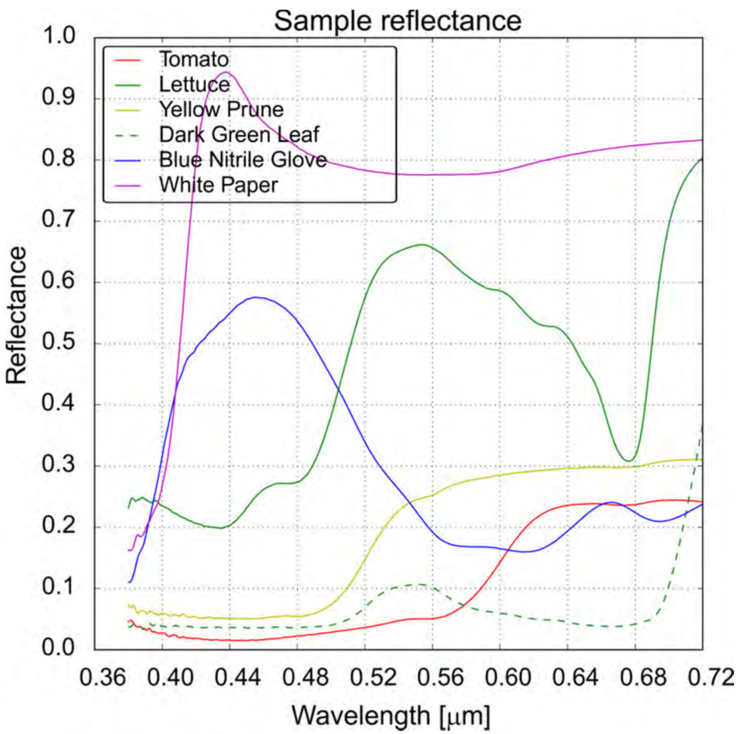


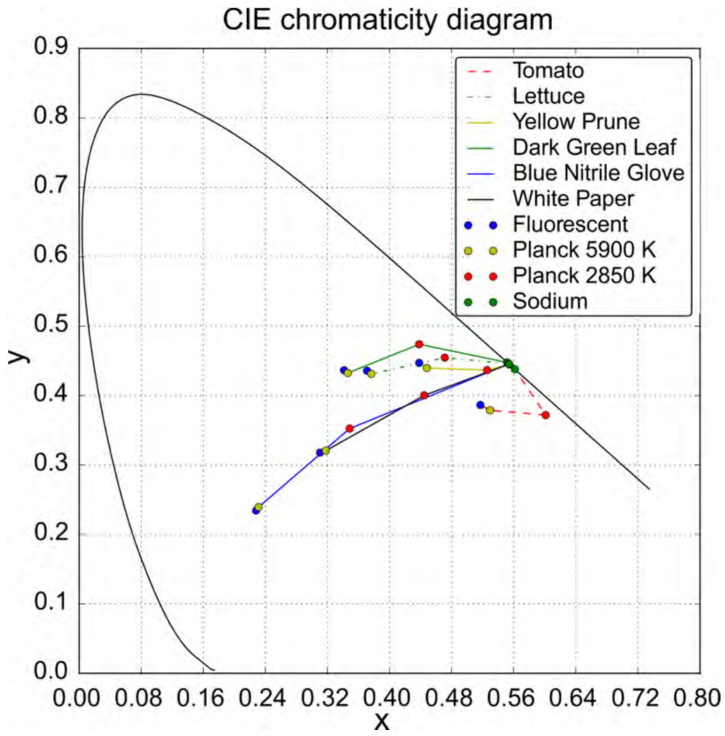


Chromaticity Coordinates

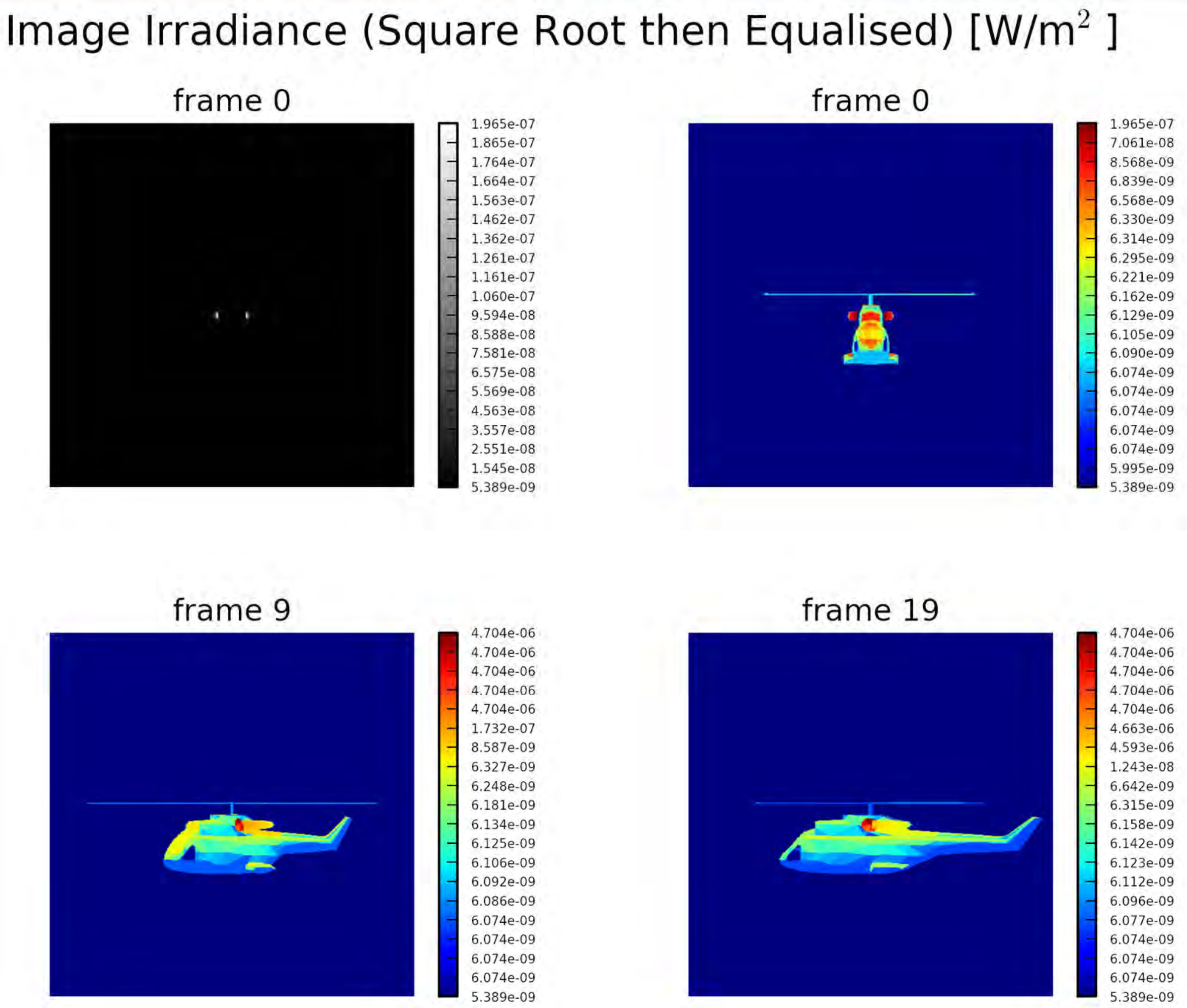
Basic functionality for CIE-1931 coordinate calculation for spectral source radiance and sample reflectance







Histogram Equalisation



Reading Data Files

- Binary raw image files: select frames, size & data type.

```
imagefile = 'data/sample.ulong'
rows = 100
cols = 100
vartype = numpy.uint32
framesToLoad =  [1, 3, 5, 7]
frames, img = readRawFrames(imagefile, rows, cols, vartype, framesToLoad)
```

- FLIR Inc (CEDIP) *.ptw image files: select frames.

```
ptwfile  = 'data/PyradiSampleMWIR.ptw'
header = readPTWHeader(ptwfile)
#loading sequence of frames
framesToLoad = [3,4,10]
data = getPTWFrames (header, framesToLoad)
```

(Instrument calibration scaling still to follow).

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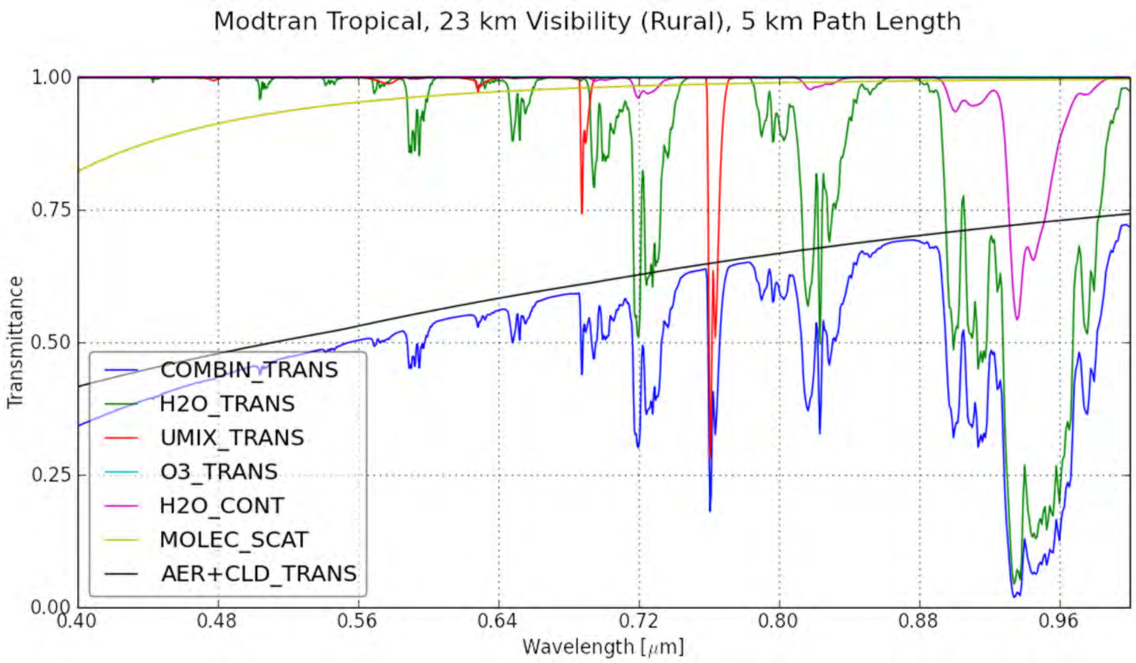
Read Modtran tape7 Files

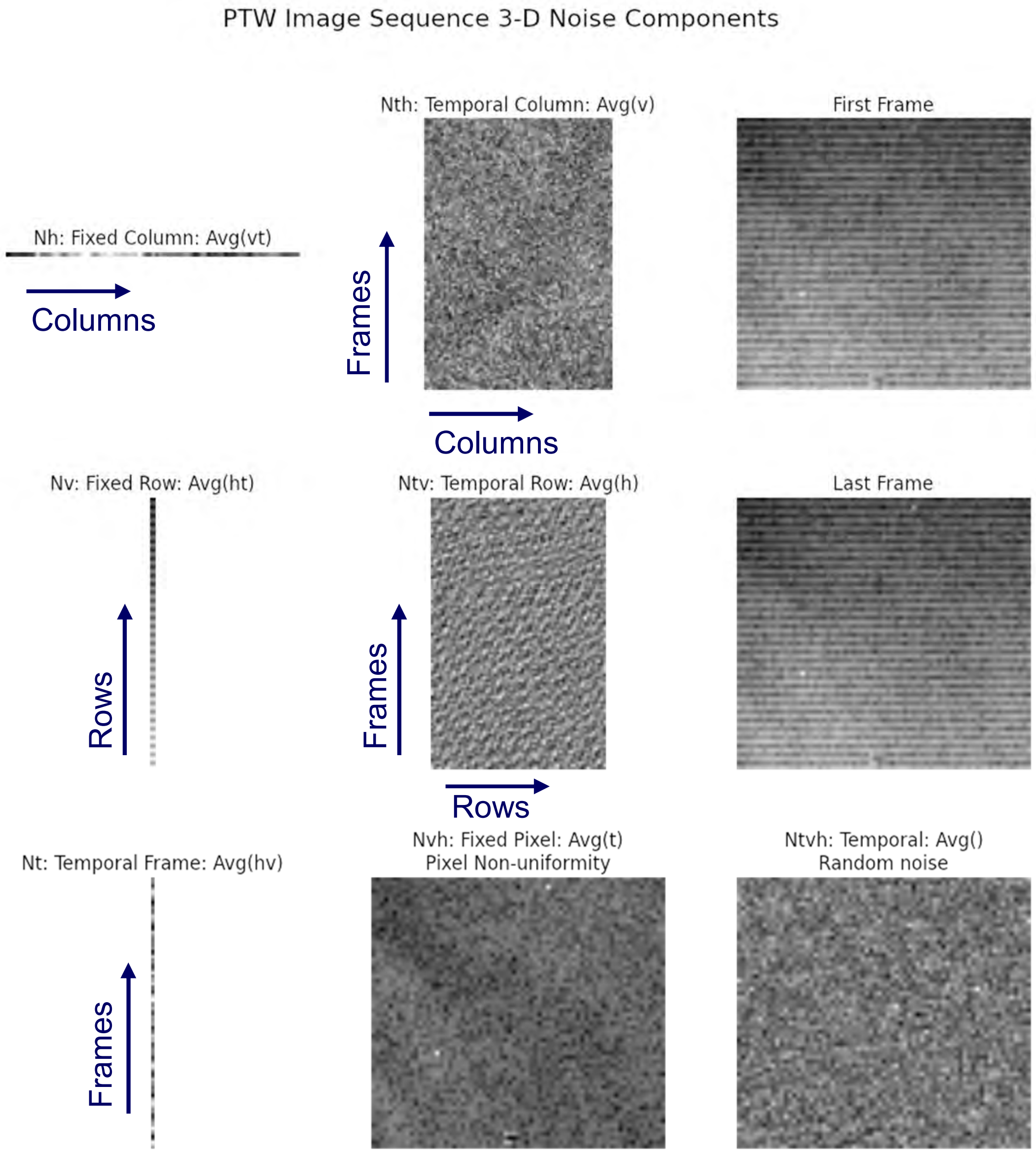
```
colSelect =  ['FREQ_CM-1', 'COMBIN_TRANS', 'H2O_TRANS', 'UMIX_TRANS', \
             'O3_TRANS', 'H2O_CONT', 'MOLEC_SCAT', 'AER+CLD_TRANS']
tape7= loadtape7("data/tape7VISNIR5kmTrop23Vis", colSelect )

wavelen = ryutils.convertSpectralDomain(tape7[:,0],  type='nl')
mT = ryplot.Plotter(1, 1, 1,"Modtran Tropical, 23 km Visibility (Rural)"\
             + ", 5 km Path Length",figsize=(12,6))
mT.plot(1, wavelen, tape7[:,1:], "","Wavelength [$\mu$m]", "Transmittance",
             label=colSelect[1:],legendAlpha=0.5, pltaxis=[0.4,1, 0, 1],
             maxNX=10, maxNY=4, powerLimits = [-4,  4, -5, 5])
mT.saveFig('ModtranPlot.png')
```

- Select columns by header title.
- Supports all four IEMSCT file variants.



3-D Noise Analysis



3-D noise analysis of image sequences.

- Averages and filters along frames, rows and columns.
- Isolates individual noise causes.

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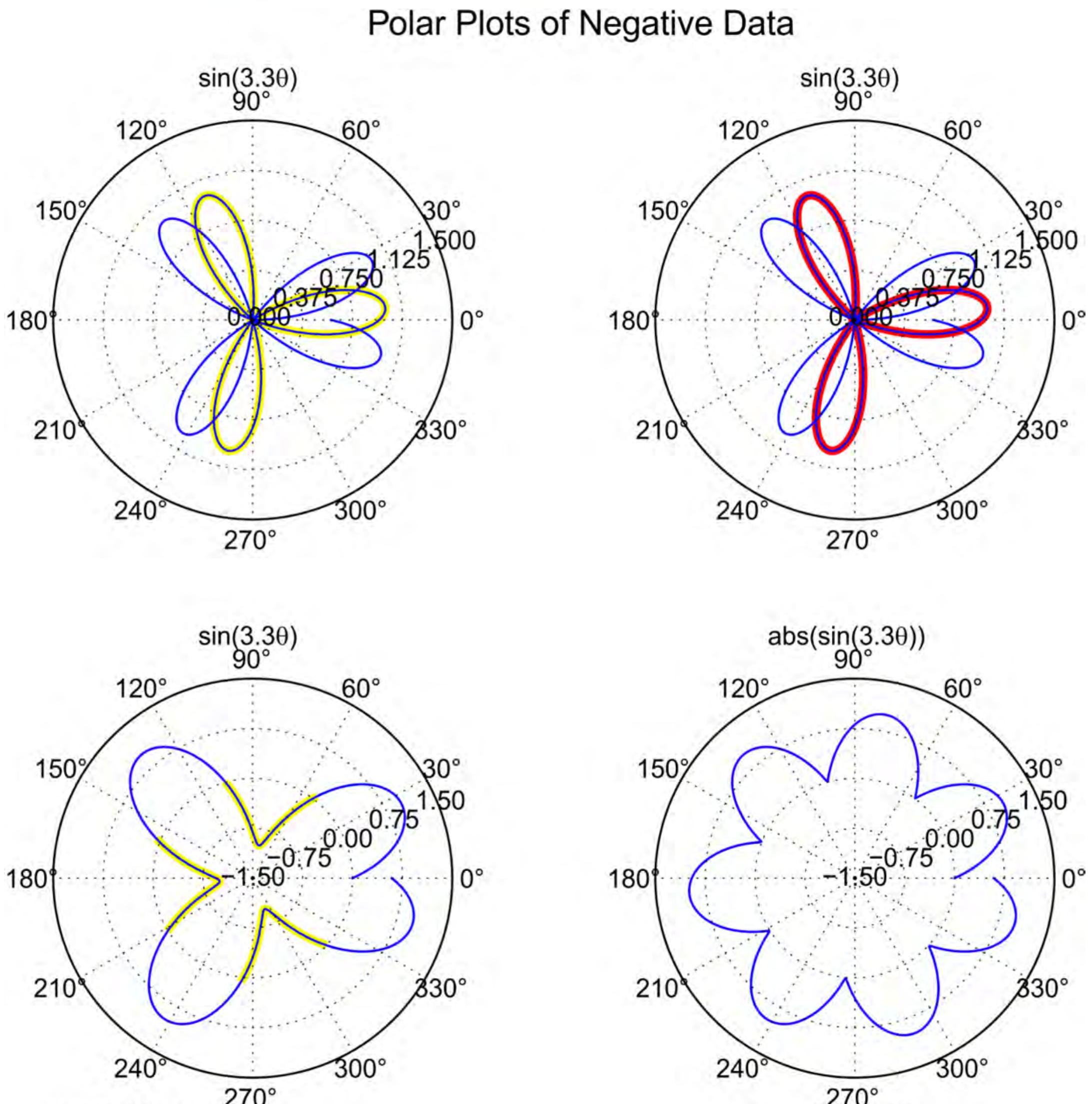
Polar Plots



- -1 is a π phase shift: plot on ‘other’ side.
- Confuse direction with magnitude!
- Two options:
  - Highlight negative.
  - Zero not in centre.

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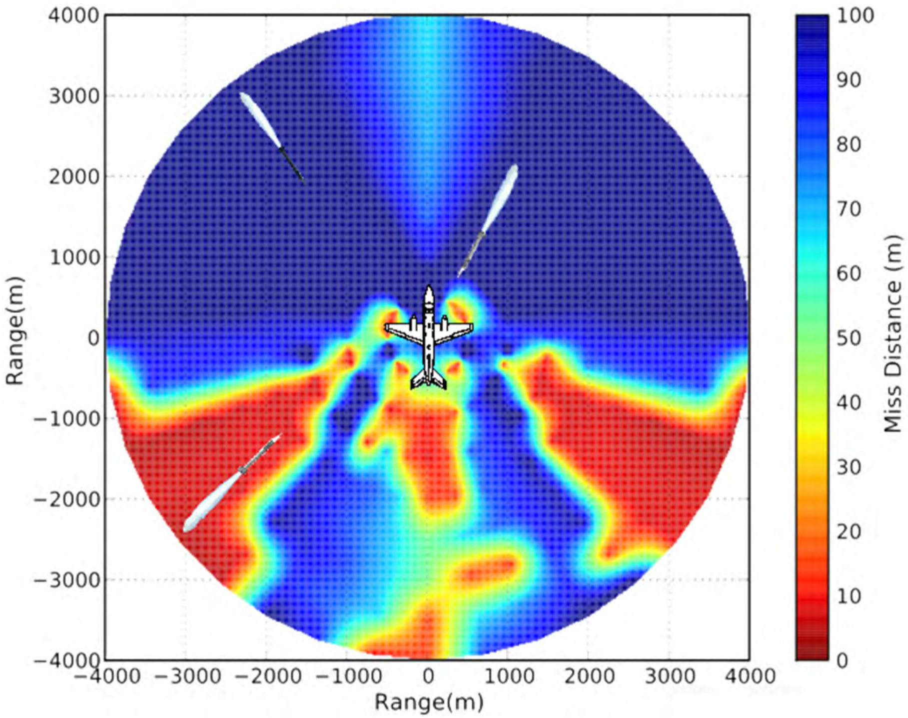
Aircraft Vulnerability

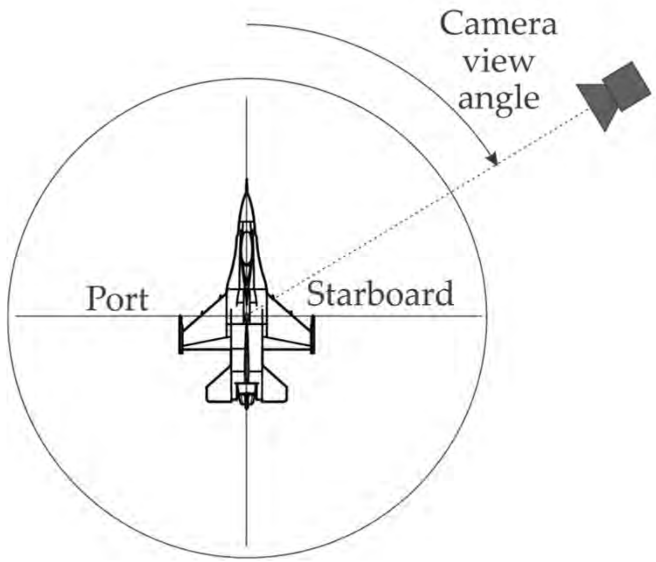
Missiles launched from red position are kills.

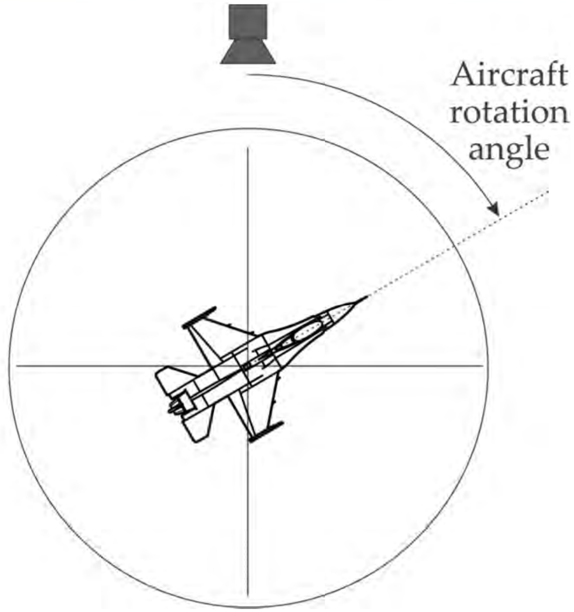
- Why are countermeasures not effective?
- Investigate Jam / Signal ratios.
- Investigate geometry: aircraft fuselage obscuration.
- Investigate angular 3-D signatures.



Welcome to the haunted house of 3-D signatures!

Two 3-D Scenarios

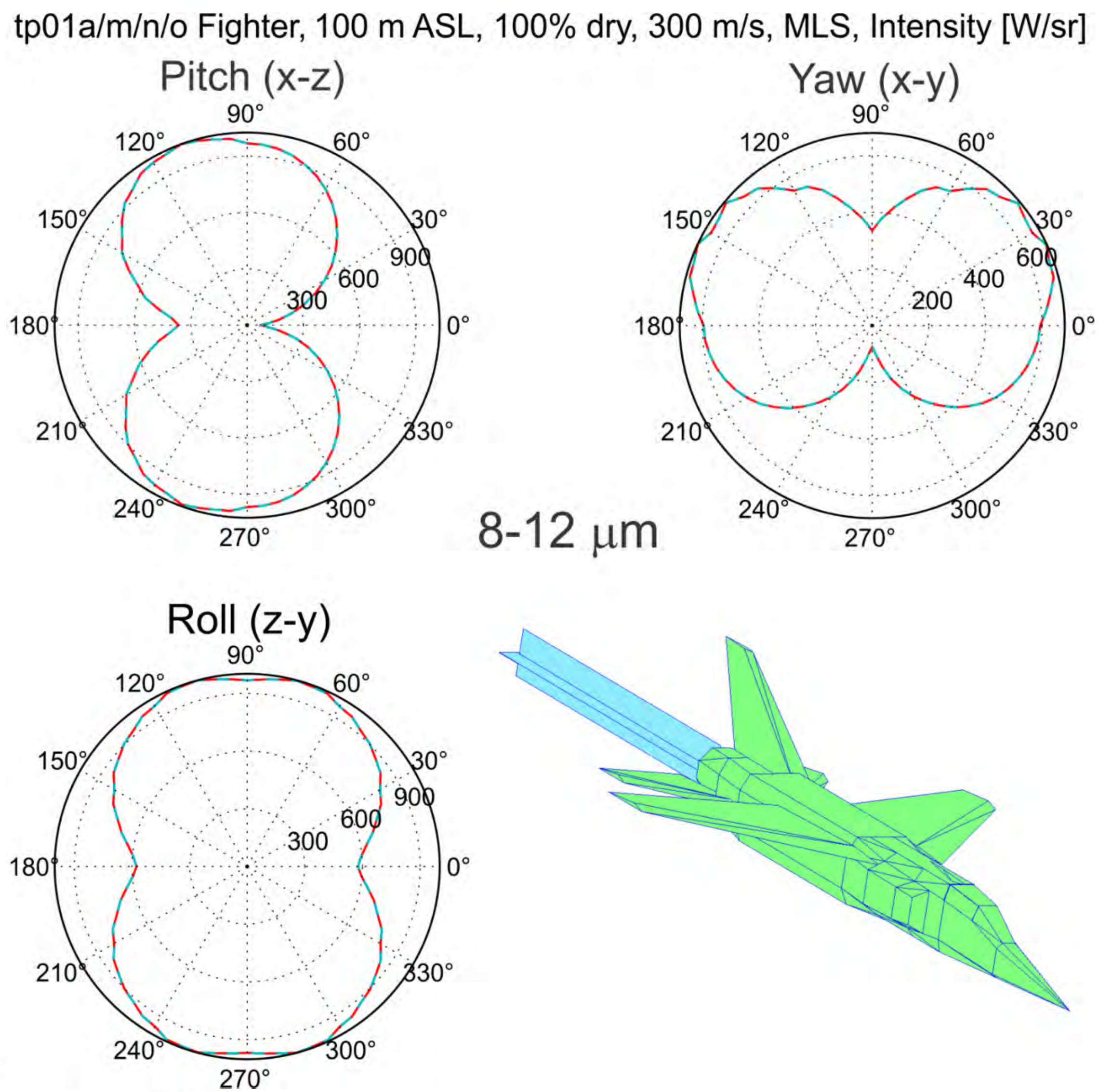




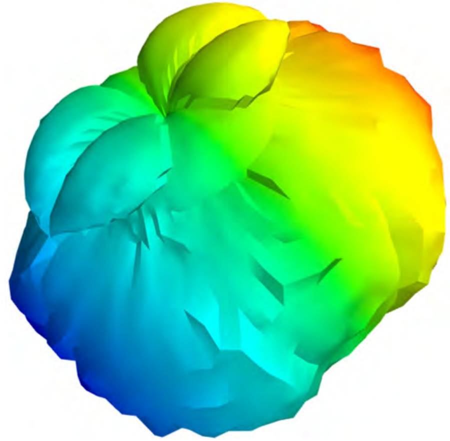
- Stationary target.
- Orbiting camera.
- Varying background.
- Stable sun position.

- Stationary camera.
- Rotating target.
- Varying sun position.
- Stable background.

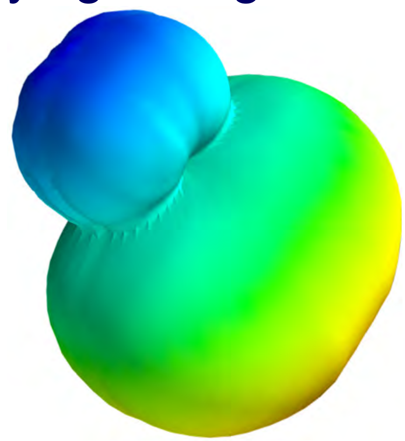
Intensity Polar Plots 8-12 μm



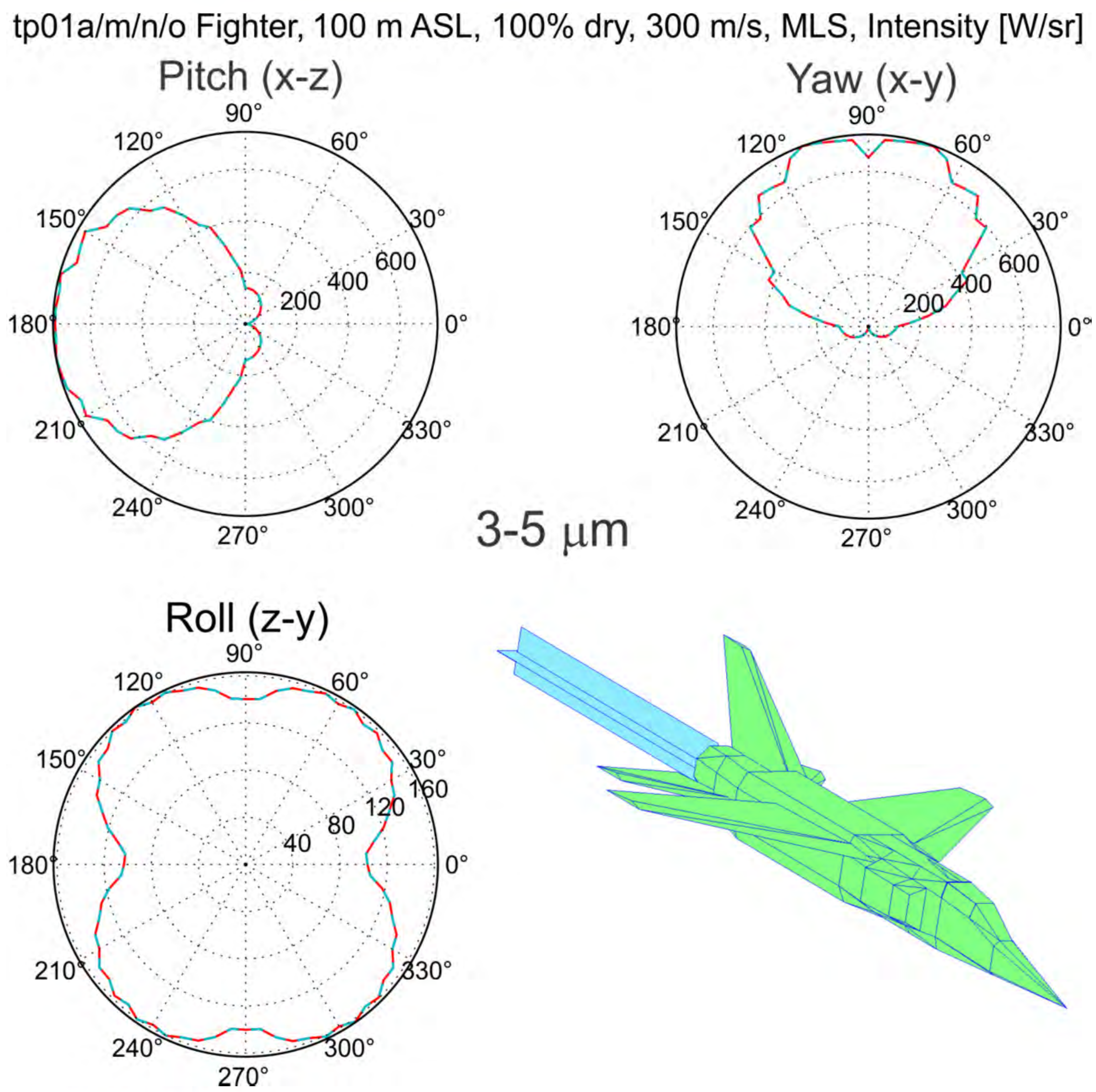
Rotating target:
constant background



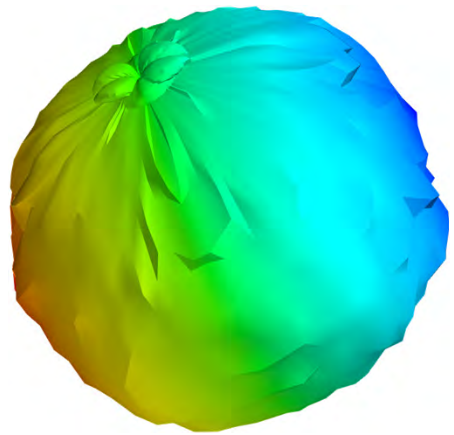
Orbiting sensor:
varying background



Intensity Polar Plots 3-5 μm

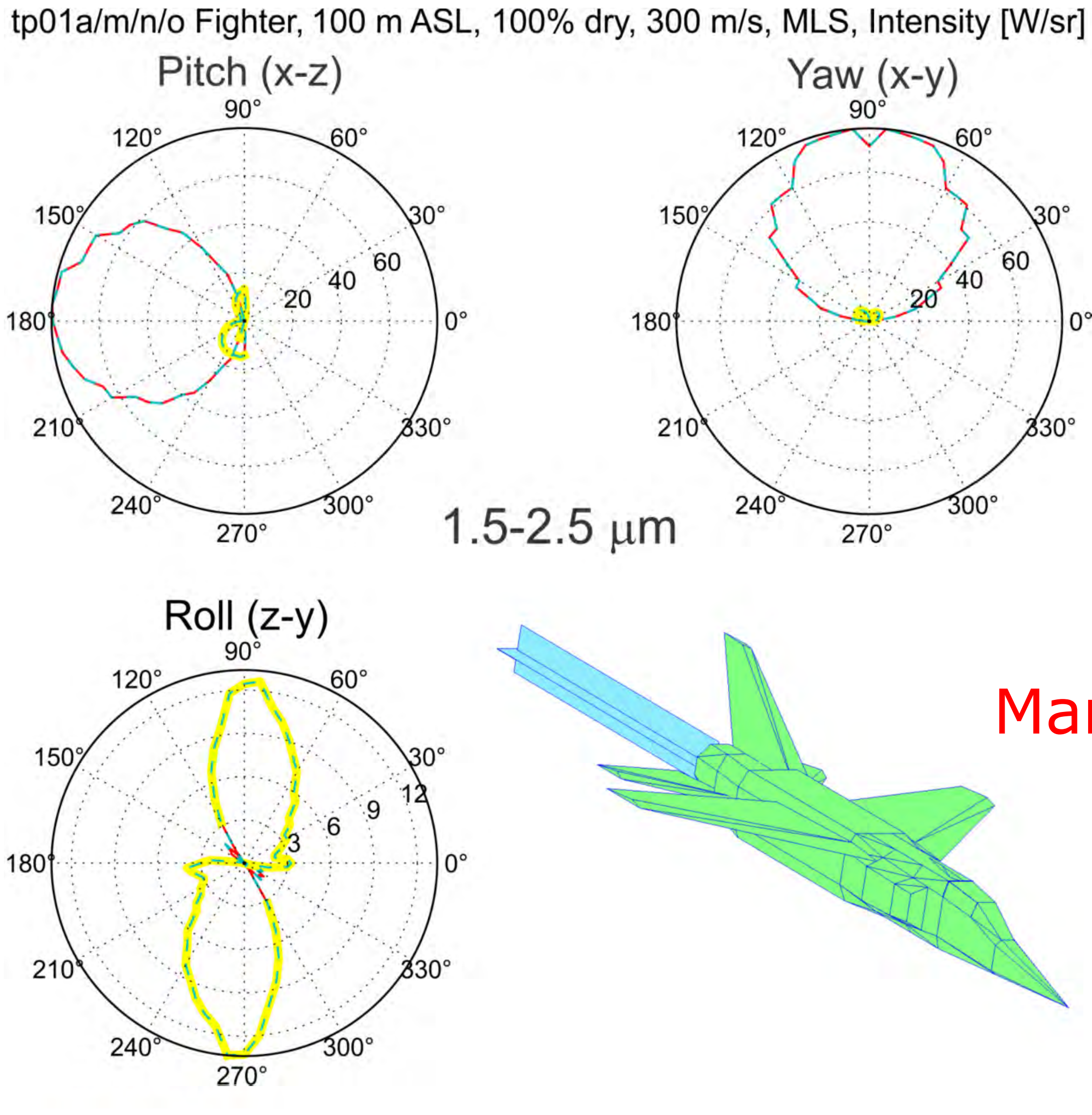


Rotating target:
constant background

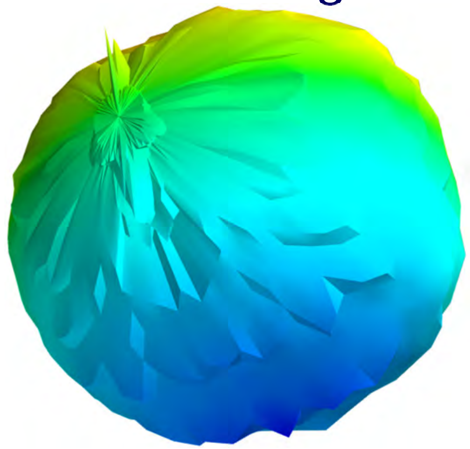


Orbiting sensor:
varying background

Intensity Polar Plots 1.5-2.5 μm

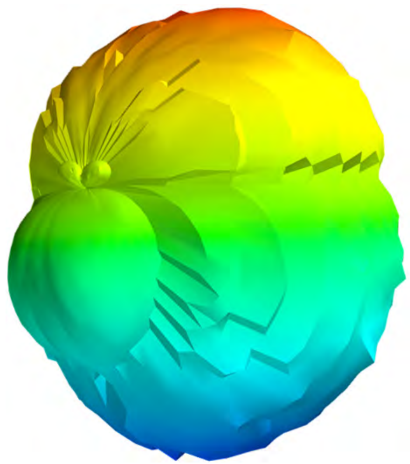


Rotating target:
constant background

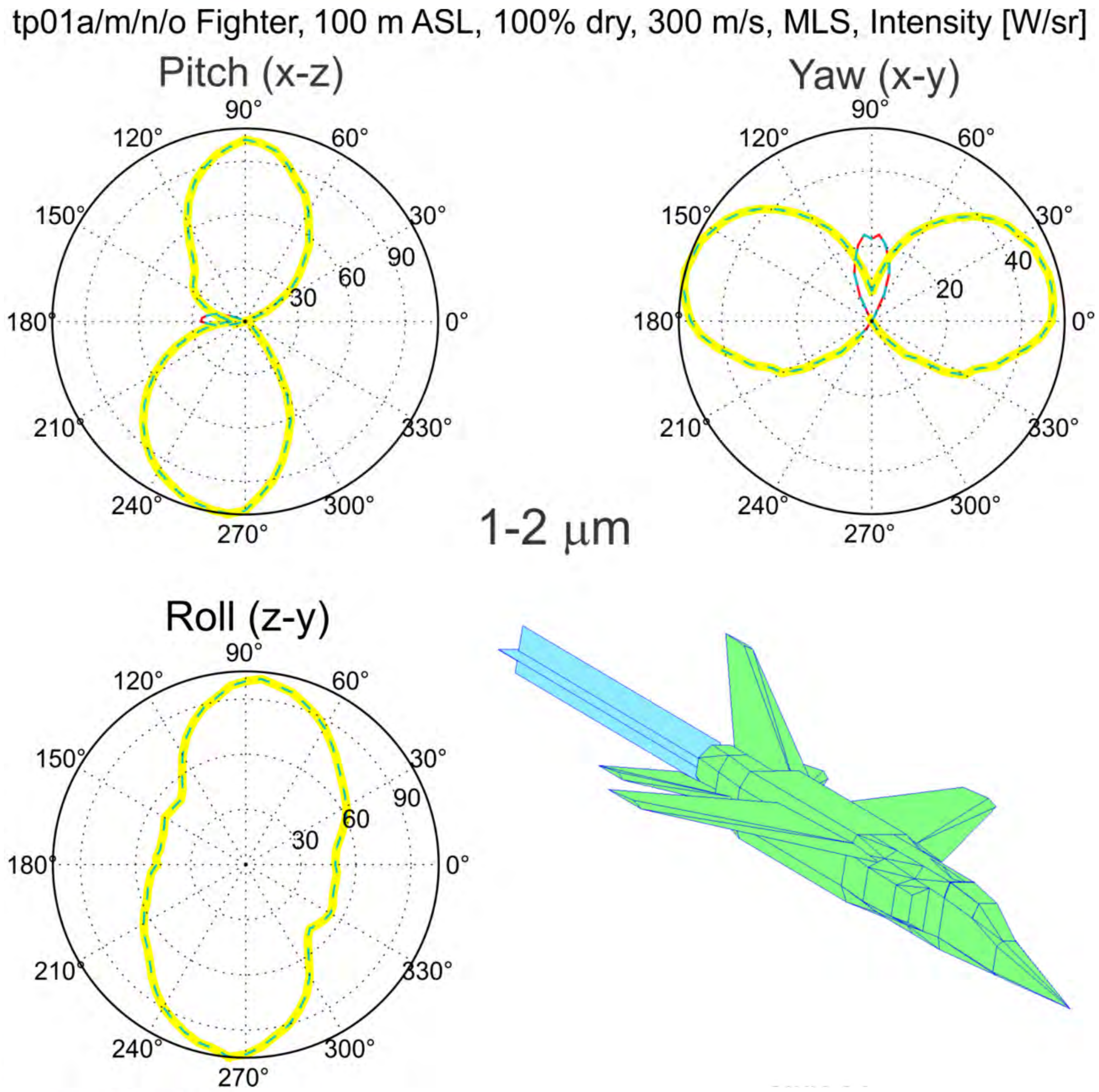


Orbiting sensor:
varying background

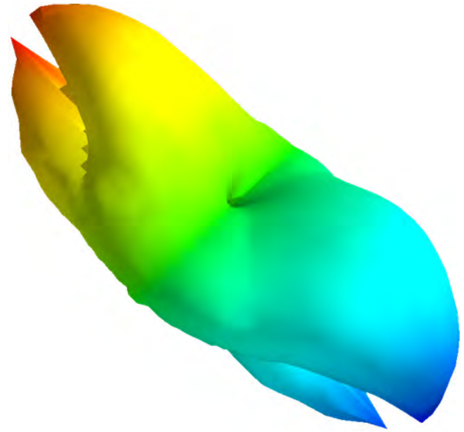
Mario!



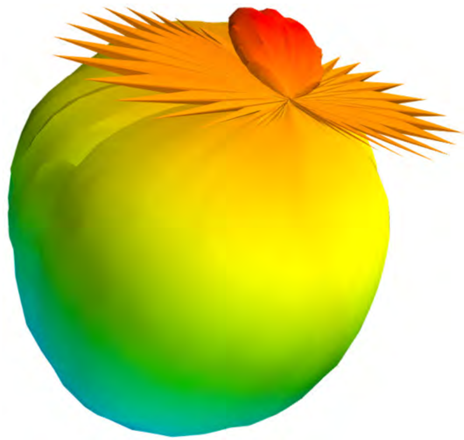
Intensity Polar Plots 1-2 μm



Rotating target:
constant background

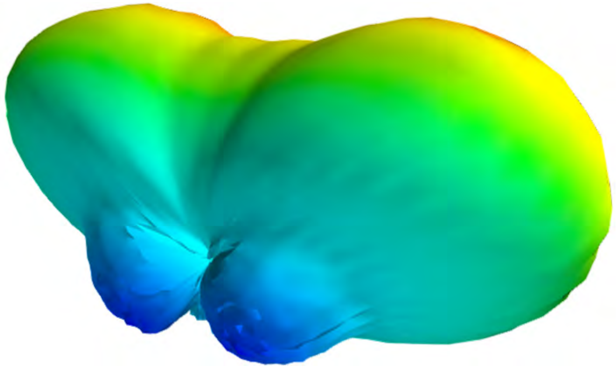


Orbiting sensor:
varying background

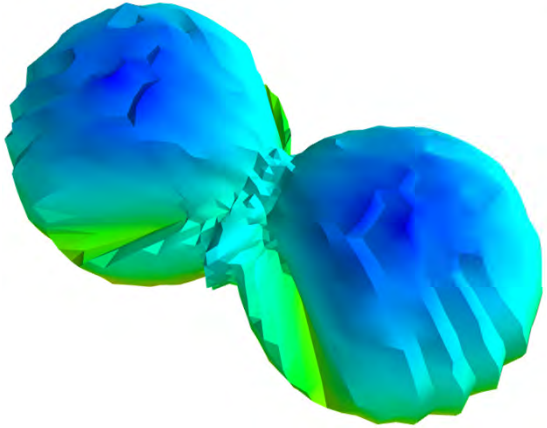


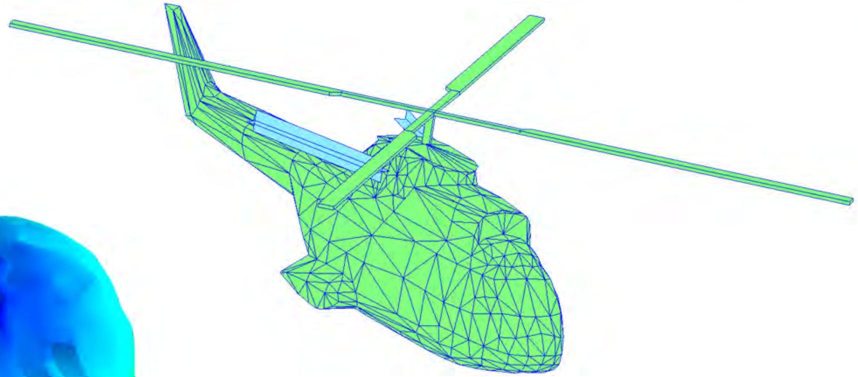
Puma Helicopter Model

8-12 μm



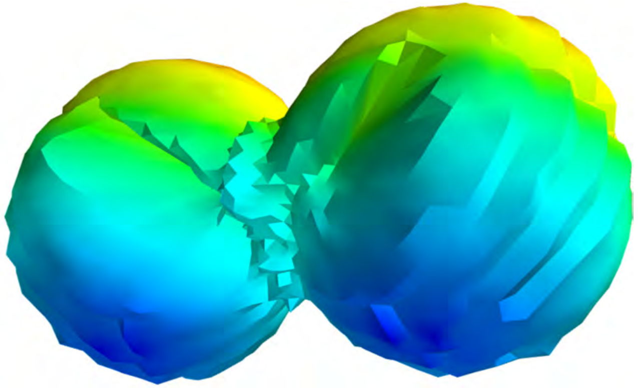
3-5 μm



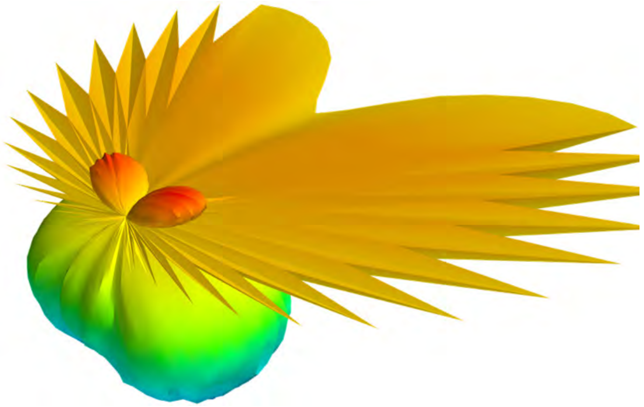


Orbiting sensor:
varying background

1.5-2.5 μm



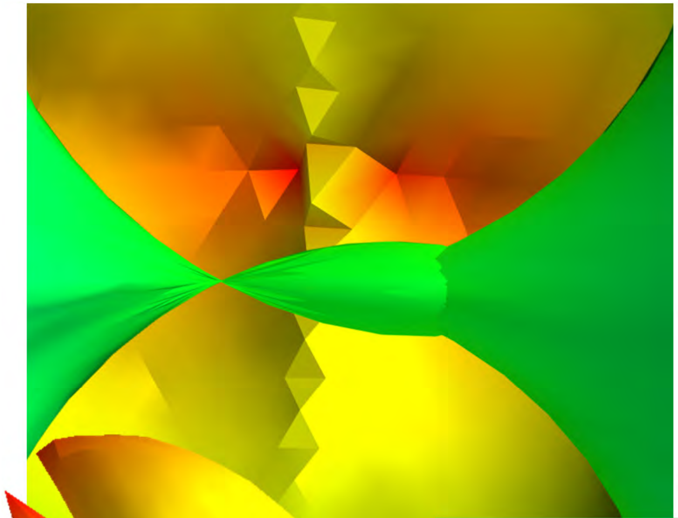
1-2 μm

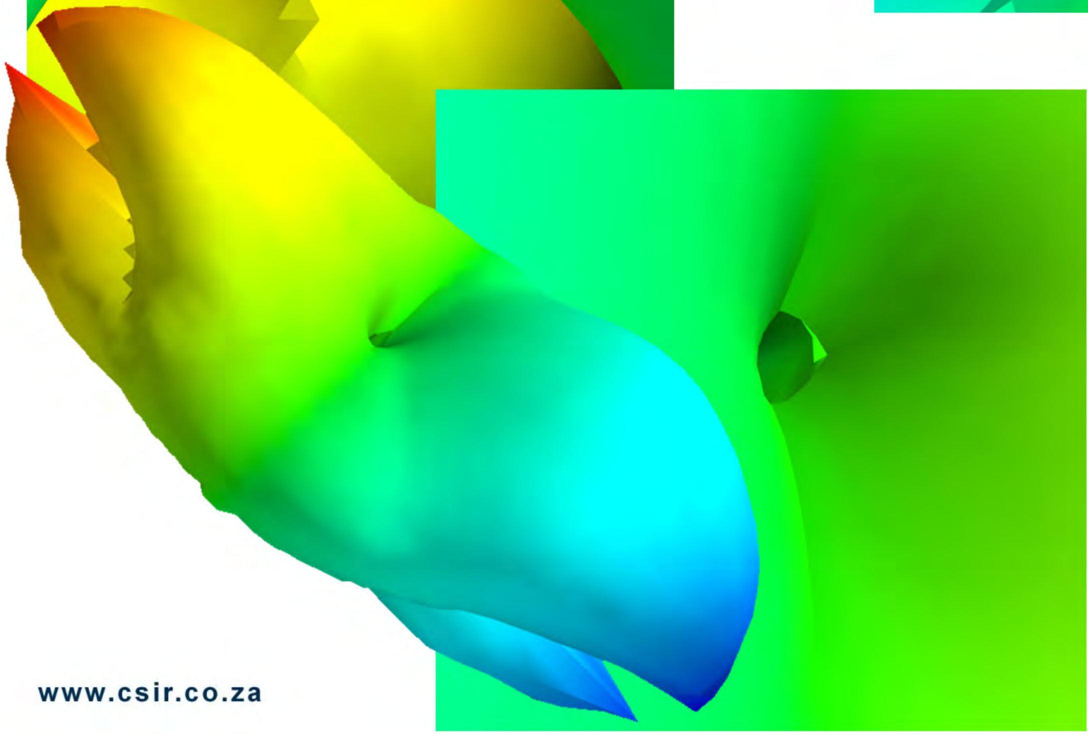


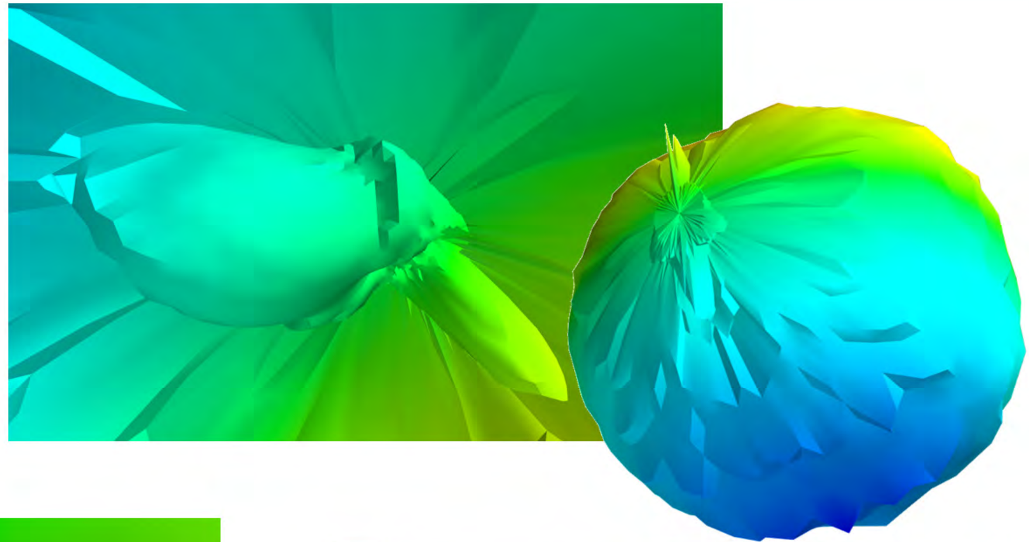
Going Inside!

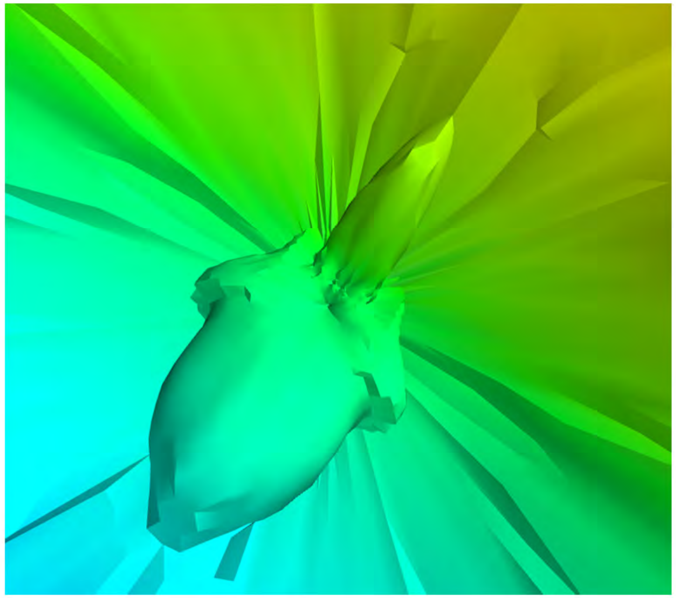
You can actually go inside these shapes!

Going Inside!









Requirements

- Moderate hardware requirements.
- Supported on Linux & Windows.
- Software requirements (all are free):
  - Python 2.7.3.
  - Numpy 1.6.1.
  - Scipy 0.10.1.
  - Matplotlib 1.1.
  - Mayavi 4.1.

our future through science

Authors, Sponsors & Users

- Collaborative effort between
  - CSIR, South Africa.
  - Denel Dynamics, South Africa.
  - Instituto Tecnologico de Aeronautica, Brazil.
- Used in CSIR and Denel for R&D, simulation model development and analysis.
- Targeting academic environment.
- Working towards the tool of choice in infrared laboratories.

Open Source Considerations

Pyradi is available as open source software.

Mozilla Public License 1.1:

- Authors retain ownership of their respective contributions.
- Modifications by users must be released under compatible terms.

Potential users are encouraged to join in, and commit changes, updates and new contributions.

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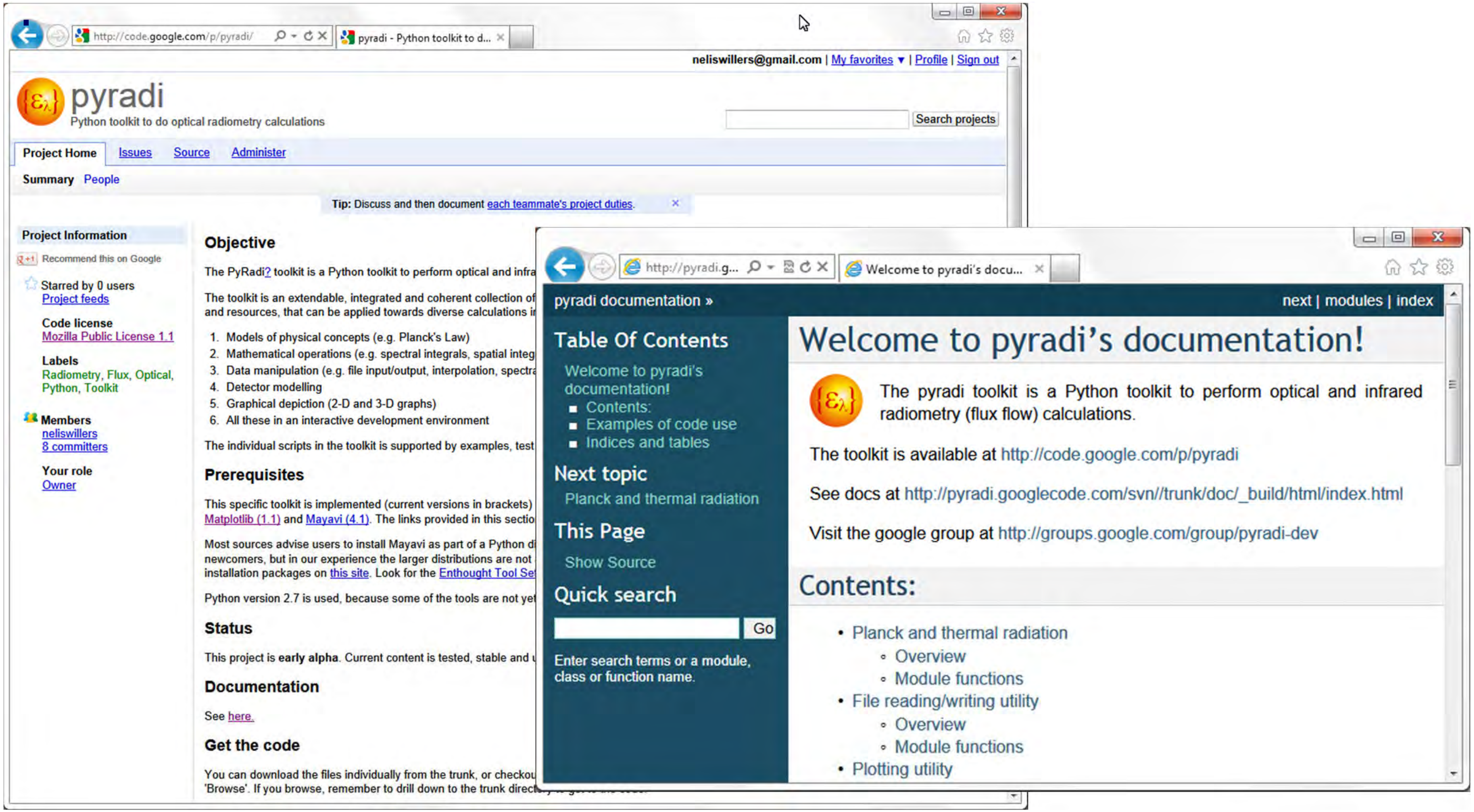
Hosted at Google Code: pyradi

http://code.google.com/p/pyradi
http://pyradi.googlecode.com/svn//trunk/doc/_build/html/index.html



Closing

- Pyradi only recently started – already paying dividends.
- Visualisation proved to be most valuable.
- All are welcome to use and contribute.