Nice!

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

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ABSTRACT

Electro-optical system design, data analysis and modelling involves a significant amount of calculation and processing. Many of these calculations are of a repetitive and general nature, suitable for adding to a generic toolkit. The availability of a toolkit facilitates and increase productivity during subsequent tool development. The concept of an extendible toolkit lends itself naturally to the open-source philosophy, where the toolkit user-base develops the capability cooperatively, for mutual benefit. This paper covers the underlying philosophy to the toolkit development, brief descriptions and examples of the various tools used and an overview of the electro-optical toolkit.

The toolkit is an extendable, integrated and coherent collection of basic functions, code modules, documentation, example templates, tests and resources, that can be applied towards diverse calculations in the electro-optics domain. The toolkit covers (1) models of physical concepts (e.g. Planck's Law), (2) mathematical operations (e.g. spectral integrals, spatial integrals, convolution), (3) data manipulation (e.g. input/output, interpolation, normalisation), and (4) graphical visualisation (2-D and 3-D graphs).

Toolkits are commonly written in scriptable languages, such as Python and Matlab. This specific toolkit is implemented in Python and its associated modules Numpy, SciPy, Matplotlib, Mayavi, and PyQt/PySide. In recent years these tools have stabilised and matured sufficiently to support mainstream tool development. Collectively, these tools provide a very powerful capability, even beyond the confines of this toolkit alone. Furthermore, these tools are freely available.

Rudimentary radiometric theory is given in the paper to support the examples given. Examples of the use of the toolkit described in the paper include (1) spectral radiometric calculations of arbitrary source-medium-sensor configurations, (2) spectral convolution processing, (3) 3-D noise analysis, (4) loading of text, binary and FLIR Inc `*.ptw` files, (5) data visualisation in 2-D and 3-D graphs and plots, (6) reading Modtran `tape7` files, (7) detector modelling from details/design parameters, (8) colour coordinate calculations, and (9) various utility functions.

The toolkit was developed as a co-operative effort between the CSIR (South Africa), Denel SOC (South Africa) and DCTA (Brazil). The project, available on Google Code at `http://code.google.com/p/pyradi`, is managed in accordance with general practice in the open source community.

Keywords: Pyradi, radiometry, infrared calculation

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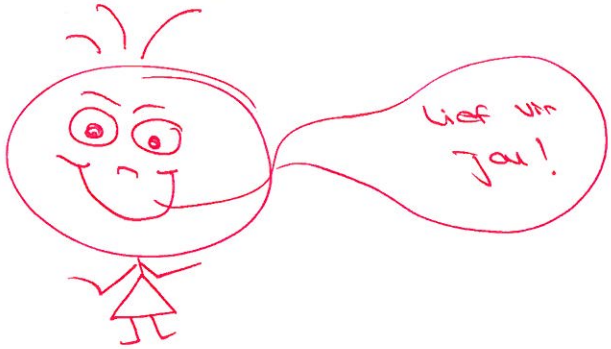

Where v is the output signal voltage, r_{01} is the distance between elemental area $d(\cos\theta_0 A_0)$ and $d(\cos\theta_1 A_1)$, ϵ_λ is the source spectral emissivity, $L_\lambda(T, d(\cos\theta_0 A_0))$ is the Planck Law radiation at temperature T at location $d(\cos\theta_0 A_0)$, $\tau_{a\lambda}$ is the atmospheric spectral transmittance, $\tau_{s\lambda}$ is the sensor optics spectral transmittance, $\mathcal{R}_\lambda$ is the spectral detector responsivity in [A/W], Z_t is the amplifier transimpedance gain in [V/A]. The spectral integral $\int_0^\infty d\lambda$ accounts for the total flux for all wavelengths, the spatial integral $\int_{A_0} d(\cos\theta_0 A_0)$ accounts for flux over the total area of the source, and the spatial integral $\int_{A_1} d(\cos\theta_1 A_1)$ accounts for the total area of the receiving area.

A spectral variable can be considered a function of wavelength. Consider two sets A and B. The set A, called the *domain*, is a set of numbers which represents the wavelengths, wavenumbers or frequencies at which the spectral variable is defined. The set B, called the *codomain* or spectral quantity, is the set of values of the spectral variable at the specific points defined in the domain A. We define the spectral variable (a function) f from A to B such that for each $a \in A$, there is a unique $f(a) = b \in B$. Examples of B are spectral emissivity, spectral transmittance or spectral detector responsivity. The top graphic in Figure 1 illustrates the reasoning behind the spectral integral as a product, followed by an integral (summation),

$$\int_0^\infty \epsilon_\lambda L_\lambda(T)\tau_{a\lambda}\tau_{s\lambda}\mathcal{R}_\lambda \, d\lambda, \qquad (2)$$

where the spectral variability of the source, medium and sensor parameters are multiplied as spectral variables and afterwards integrated over all wavelengths to yield the total in-band signal. The domain of spectral quantities can be stated in terms of a wavelength, wavenumber, or less often, temporal frequency. The toolkit must be able to support all three domain types, as well as the conversion of spectral densities (such as [W/(m^2.μm)] to [W/(m^2.cm^{-1})]).

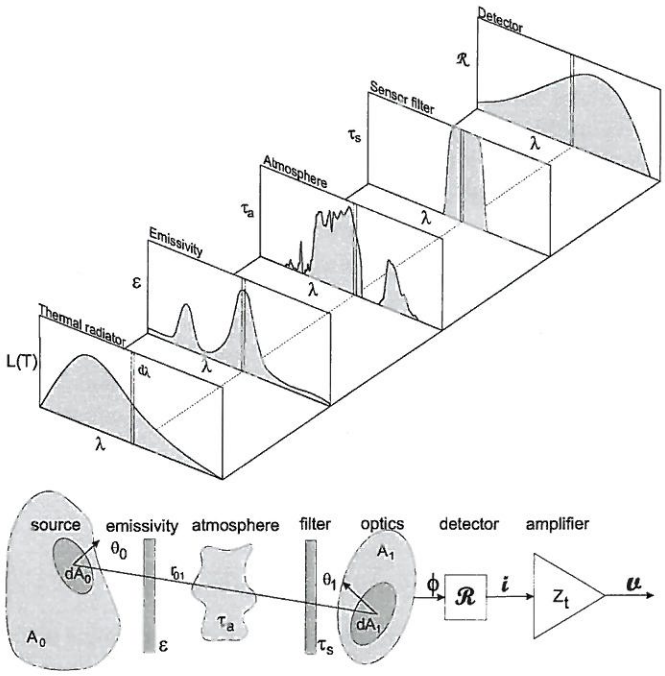

Figure 1. Simple model of a sensor

Likewise, the source radiance is integrated over the two respective areas of the target A_0 and the sensor aperture A_1. Note that if the sensor field of view footprint at the source is smaller than the physical source area, only the flux emanating from the footprint area is integrated.

Fundamental to almost all electro-optics calculations are the use of Planck's Law for thermal radiation. According to Planck's Law the maximum spectral radiant emittance, for a given temperature T, and the emittance temperature derivative, are given by

$$M_{e\lambda}(T) = \frac{2\pi hc^2}{\lambda^5\left(e^{\frac{hc}{\lambda kT}} - 1\right)}, \qquad \frac{dM_{e\lambda}(T)}{dT} = \frac{2\pi hc^2 x e^x}{T\lambda^5\left(e^{\frac{hc}{\lambda kT}} - 1\right)^2}, \qquad (3)$$

where $x = \frac{hc}{\lambda kT}$, c is the speed of light, λ is wavelength, h is Planck's constant, k is the Boltzman constant, yielding emittance in units of [W/m^3] and the derivative in units of [W/(m^3·K)]. The tookit must support the calculation of Planck's Law in any of the three spectral domain variables: wavelength [μm], wavenumber [cm^{-1}] and frequency [Hz].

Under condition that a narrow-band optics filter is used in the system in Figure 1, the spectral integral, Equation 2, can be written, by change of variable $\lambda = \lambda_c - x$, as follows

A common need is for the reading of instrument data files, such as from imaging radiometers. Unfortunately each instrument has its own, often proprietary, data format, but it would be convenient to be able to read such files in the toolkit. The toolkit provides the capability to read FLIR Inc.[5] `*.ptw` files.

Modern software users seem to require Graphical User Interfaces (GUI) before accepting new software. Sadly so, since sometimes the GUI comes in the way, or limits the software useability. In particular, the GUI can limit the automation of repetitive tasks. However, some tasks do lend themselves better to GUI interaction, such as a structured walk through a tree of decisions, where future decisions depend on the current decision. One such example is compiling a Modtran tape5 data file; indeed an arduous task in a text editor! The construction of selected GUI applications may be addressed in future, but not in the short term.

3. DESIGN CONSIDERATIONS

3.1 Language Considerations

The requirements for an electro-optical calculation environment can be met by most modern computer languages, such as FORTRAN, JAVA, C/C++ or similar. However these languages often do not provide a native graphics toolkit and fails on the ease of implementing operations such as spectral multiplication and integration.

There are a number of languages that provides built-in operations on scalars, vectors and arrays/matrices by single operators. Examples of such languages are Matlab[6] (or its open source equivalents SciLab[7] and Octave[8]) and PYTHON[9] together with NUMPY[10] and Matplotlib.[11] These languages offer the following benefits: (1) A spectral variable is easily modelled as a vector or column in an array or matrix. All spectral vectors are easily converted and interpolated to the same spectral values or converted between wavelength, wavenumber and frequency. (2) Spatial (area) integrals are readily computed by expressing the shape as a two-dimensional array. (3) Vector or array variables can be loaded from ASCII files with simple commands. (4) The graphics capabilities are powerful, easy to use. (5) An interactive environment supports very fast development time, as well as the capability to write script files for more complex problems. (6) The capability to write your own often-used functions or subroutines into re-usable toolboxes or modules.

For spectral calculations and plotting, such as shown here, the two products are practically equal in ease of use and capability. Both languages require equal effort in becoming a fluent and effective user. Python is a better (and constantly re-) engineered language, while Matlab grew out of a linear algebra background with some flawed design decisions for general programming purposes. Python has a large number of modules providing a considerable capability as a general purpose language, while Matlab has a large number of specialised and esoteric scientific and engineering toolboxes. The associated Python data visualisation tools, Matplotlib[11] and Mayavi,[12] provide considerably stronger capability than their Matlab equivalent. Matlab is proprietary source and carries a hefty price tag (especially for the toolboxes), while Python is free and open source.

After extensive use in industrial and academic environments, of both Matlab and Python, specifically for modelling radiometry systems, we decided to continue only with Python. This decision was not taken on emotional or ideological grounds, but is based purely on our perception of Python as a better all-round scripting language with better data visualisation tools. The Python[9] language has a number of associated modules NUMPY,[10] SciPy,[10] Matlplotlib,[11] Mayavi,[12] and PyQt[13]/PySide.[14] In recent years these tools have been well tested, stabilised and matured sufficiently to support mainstream tool development. Collectively, these tools provide a very powerful capability, even beyond the confines of this toolkit alone. Furthermore, these tools are freely available. PyQt carries some licence restrictions, but all the other packages are not encumbered by restricting licence constraints.

3.2 Toolkit structure

The toolkit is a loose collection of files, with minimal interdependency between them. These module files contain classes and functions of similar nature, providing a coherent functionality. The current set of files are:

ryplanck.py This module provides functions for Planck Law emittance calculations, as well as temperature derivative calculations. The functions provide spectral emittance in $[W/(m^2 \cdot *)]$ or $[q/(s \cdot m^2 \cdot *)]$, given the temperature and a vector of one of wavelength, wavenumbers or frequency (six combinations each for

4.1 Sensor irradiance calculation

The first example is a relatively complete worked example. The objective is to calculate the signal of a simple sensor, detecting the presence or absence of a flame in the sensor field of view. The sensor is pointed to an area just outside a furnace vent, against a clear sky background. The sensor must detect a change in signal indicating the presence of a flame at the vent.

The sensor has an aperture area of 7.8×10^{-3} m^2 and a field of view of 1×10^{-4} sr. The sensor filter spectral transmittance is shown in Figure 3. The InSb or PbSe detector has a peak responsivity of 2.5 A/W and normalised spectral response shown in Figure 3. The preamplifier transimpedance is 10000 V/A.

The flame area is 1 m^2, the flame temperature is 1000 °C, and the emissivity is shown in Figure 3. The emissivity is 0.1 over most of the spectral band, due to carbon particles in the flame. At 4.3 μm there is a strong emissivity rise due to the hot CO_2 in the flame.

The distance between the flame and the sensor is 1000 m. We use the MODTRAN Tropical climatic model. The path is oriented such that the sensor stares out to space, at a zenith angle of 88°. The spectral transmittance and path radiance along this path is shown in Figure 3.

The peak in the flame emissivity and the dip in atmospheric transmittance are both centered around the 4.3 μm CO_2 band. In order to determine the flux transferred one must perform a spectral calculation taking these strong spectral variations into account.

The signal caused by the atmospheric path radiance is given by Equation 1, where the integrals over the surfaces of the flame and sensor are just their respective areas. The signal caused by the flame is given by:

$$v = Z_t \omega_{\text{optics}} A_{\text{optics}} \int_0^\infty L_{\text{path}\lambda} \tau_{s\lambda} \mathcal{R}_\lambda \, d\lambda. \tag{9}$$

where ω_{optics} is the sensor field of view, A_{optics} is the optical aperture area, $L_{\text{path}\lambda}$ is the spectral path radiance and the rest of the symbols are as defined for Equation 1.

An extract of the code to perform this calculation, and the resultant output, are as follows (file available on the web site):

```
# 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
(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 )

#plot the data
plot1= ryplot.Plotter(1, 2, 2,'Flame sensor',figsize=(12,8))
#it seems that all attempts to plot in same subplot space must use same ptitle.
plot1.plot(1, "Spectral","Wavelength [$\mu$m]", "Relative magnitude", wavel, detR,\
     plotCol=['b'], label=['Detector'])

# 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
```

4.3 Spectral convolution

Spectral resolution matching is required when different sources provide spectral data with different spectral resolution. One such example is shown where the signal from a Bunsen burner is performed at 4 cm^{-1} and atmospheric transmittance data is calculated at 1 cm^{-1}. The left-hand side of Figure 4 shows the inappropriate combination of spectra at different spectral resolutions. On the right-hand side the same operation is performed but with resolution matched data.

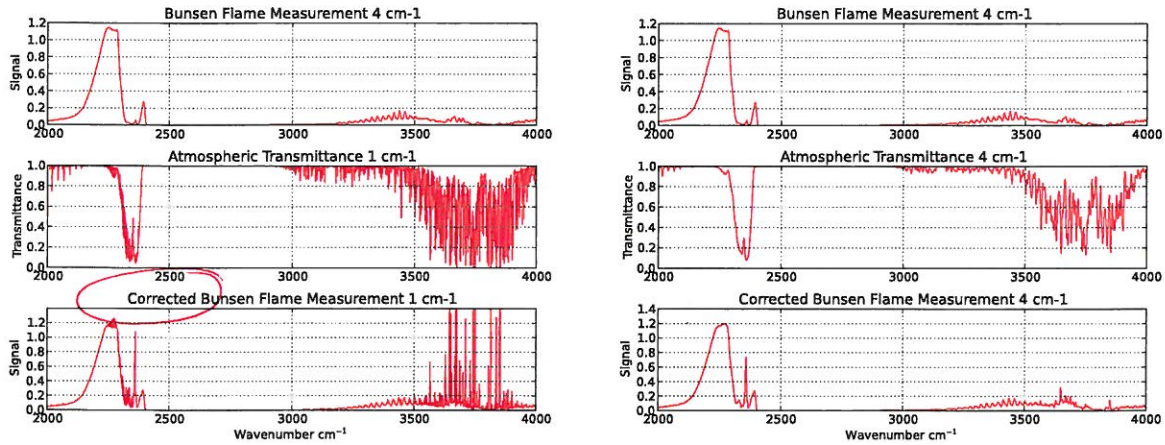

Figure 4. Example of spectral convolution calculations

4.4 3-D noise analysis

3-D noise analysis & and reading of binary files and plot of images

4.5 Reading FLIR Inc PTW files

Certain infrared imagers of FLIR Inc.[5] store their data in a propriety format tagged with a `*.ptw` extension. This format is graphically summarised in Figure 5. The main header section describes the database itself, as well as all parameters of acquisition. The size of the header is expressed in the first line, making future changes to the main header a possibility. A stream of frames follows the main header. These frames are each started with a frame header, containing the parameters specific to the frame, e.g. frame time, subwindowing and integration time.

The aim of the python code ryptw.py is to read all the header parameters and the image data, to provide an easy means to facilitate data analysis of single frames. The code has no graphical user interface, as it is not a stand-alone analysis tool, but merely a way to read the acquisition parameters and the data frame(s) to be used in further analysis. The current version of the code reads the file as digital levels, but it is planned to include camera calibration later, such as to yield radiance or temperature values.

The call to the code is a two step process, where the header information is read first, and using that header information, a specific frame can be extracted. A complete example of reading the `*.ptw` file is given on the web site. A sample call can be a shown following.

```
ptwHeader = ryptw.readPTWHeader(filename)
ptwFrame = ryptw.getPTWFrame (ptwHeader, framenumber)
```

Figure 5. FLIR Inc. `*.ptw` file format outline

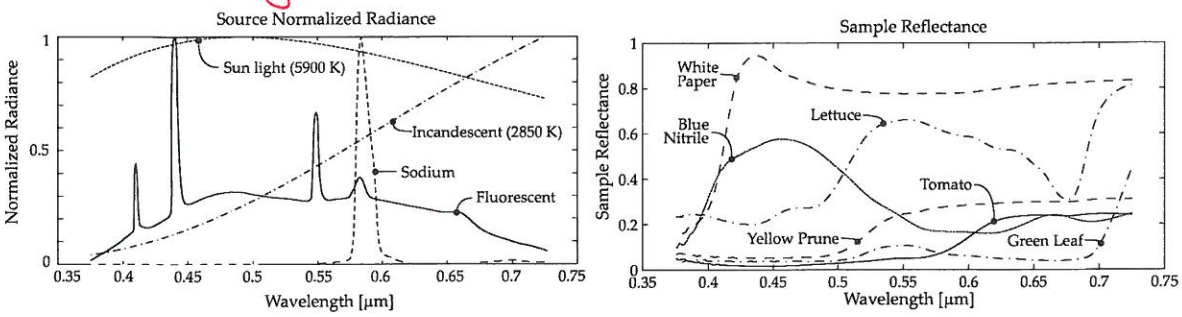

Figure 7. Normalised source radiance and sample reflection

The model provides a spectral response, and several figures of merit, highlighting the fetectivity and I×V characteristics.

4.9 Colour coordinate calculations

This section explores these subtleties as an application of normalising and radiometric concepts, rather than the human perception of colour. Four sources are considered, with normalised spectra shown in Figure 7. The first light source is a 'daylight' fluorescent light source, the second source is the sun modeled as a thermal radiator at 5900 K, the third source is an incandescent light globe at a temperature of 2850 K and the fourth source is a low pressure sodium lamp. The samples illuminated by the sources are a red tomato, lettuce, a yellow prune, a dark green leaf, a blue Nitrile (latex-like) surgical glove and standard white printing paper. Figure 7 shows the spectral reflectance of the samples. These diffuse reflection spectra were measured with an ASD spectroradiometer, illuminating the sample with a bright light at short distance. The fruit samples all demonstrated considerable light propagation deeper into the fruit. The blue glove was located on top of a Spectralon white reference (note the considerable 'white' reflectance beyond 0.55 μm). The colour coordinates of the samples, in the different light sources are shown in Figure 8. Note how, under the near-monochromatic sodium illumination, the sample colour coordinates converge to the same colour, that of the source.

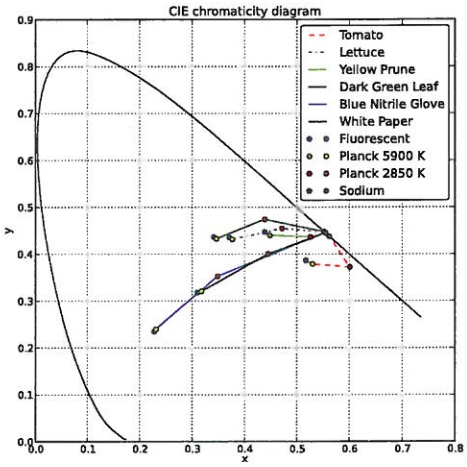

Figure 8. Example of spectral convolution calculations

4.10 Utility Functions

A number of utility functions are provided. Figure 9 shows the results of two simple parametric functions providing a photon spectral response shape and maximally flat filters. A function is also provided to calculate the effective value according to Equation 7. Functions are provided for conversion between spectral density vales (i.e. between [W/(m^2·μm)], [W/(m^2·cm^{-1})], and [W/(m^2·Hz)]. Similar functions are also provided for the conversion between spectral vales (i.e. between [μm], [cm^{-1}], and [Hz)].

6. FUTURE WORK

The current focus in the toolkit is on providing a strong set of functions suitable for use in user's scripts. Graphical user interfaces, using PyQt, are used extensively in our work, but these are mostly project specific. One application that may interest some readers is a schema-based GUI editor to traverse and edit a tree of XML documents. This and other GUI tools may by added to pyradi later. Such tools may include a GUI for editing Modtran tape5 files, or viewing/processing `*.ptw` files.

The analysis of measured radiometric data constitutes a significant portion of the pyradi team's work. The intent is to rewrite current Matlab code into pyradi modules that will be added to the repository.

At current pyradi is not yet available as an installable Python package, users are recommended to checkout from the subversion repository at Google Code. This approach ensures that users can easily update to the latest version. If there is sufficient interest, pyradi may be released in the form of an installation package.

Pyradi is an ongoing project, supporting activities in the original development teams' respective laboratories. Pyradi is also used to support the worked examples in an upcoming book.[2]

7. CONCLUSION

The pyradi toolkit is intended to provide researchers with a set of tools to simplify complex radiometry calculations and data visualisation. It is foreseen that the toolkit will grow with time from its current modest beginning with the addition of new functionality.

The value of the toolkit is already evident in our respective laboratories, inviting and accelerating new tool development. Pyradi is offered as an open source product with the hope that others will also benefit from our work.

ACKNOWLEDGMENTS

The authors wish to thank FLIR Advanced Thermal Solutions for the permission to publicly release our Python version of the `*.ptw` file reader. Please note that the copyright to the proprietary `*.ptw` file format remains the property of FLIR Inc.

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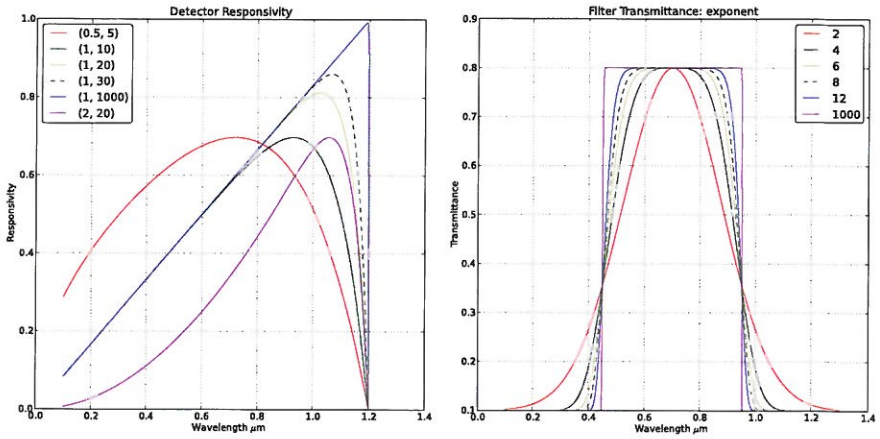

Figure 9. Example of spectral convolution calculations

5. AVAILABILITY, DOCUMENTATION, AND CONTRIBUTING

Pyradi is managed in accordance with general practice in the open source community. Pyradi is stored in a subversion repository on Google Code, at `http://code.google.com/p/pyradi`. The toolkit files can be downloaded one-by-one using a web browser, or by using a download tool.[17] It is recommended however, that a subversion client be used to 'check out' and 'commit' the code (instructions are given on the web site).

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

Pyradi documentation is available at `http://pyradi.googlecode.com/svn//trunk/doc/_build/html/index.html`. Documentation is extracted from the comments in the Python code files, using the Sphinx documentation generator. At the moment there is no User Guide, but complete commented example code is included at the end of each module file.

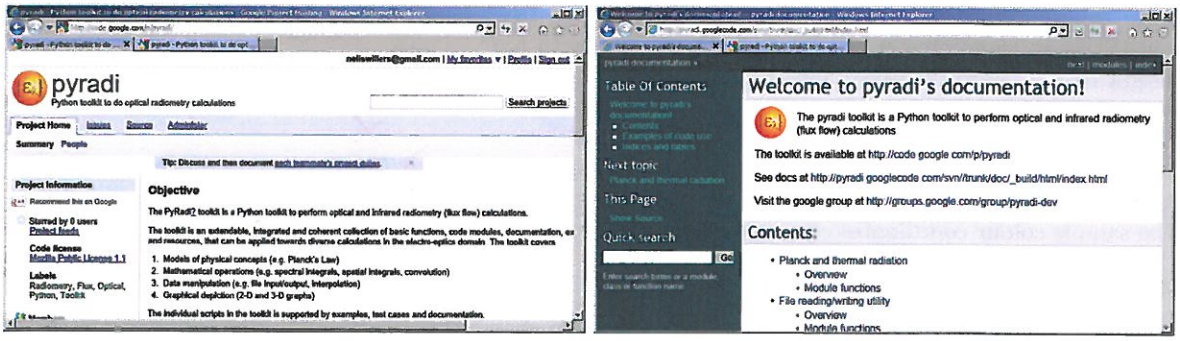

Figure 10. Pyradi repository and documentation websites

Pyradi has only moderate hardware requirements and was tested under Windows and Linux operating systems. It should run on other operating systems as well. At the time of writing the following software versions were used: Python 2.7.3, Numpy 1.6.1, Scipy 0.10.1, Matplotlib 1.1, Mayavi 4.1.

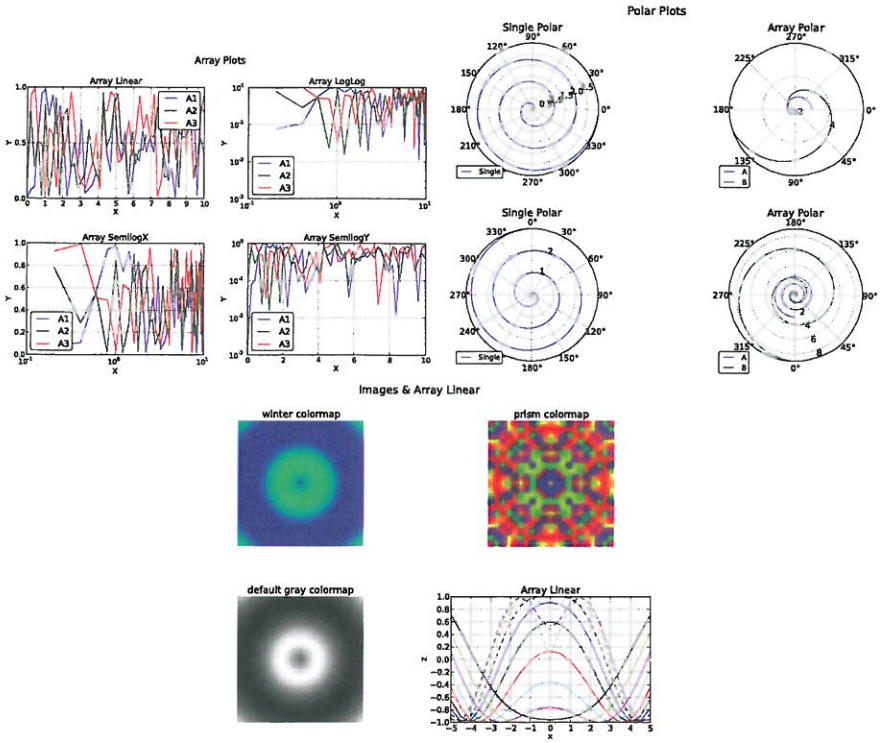

Figure 6. Cartesian, polar and image plots

4.6 Data plotting

Figure 6 shows a variety of cartesian, polar and image plots. Note the polar plot direction and zero rotational offset variations. All 2-D plotting routines support the plotting of an arbitrary number of multiple lines, for array data. Image data can be calculated in code or read in from data files.

Mayavi-based 3-D plotting of trajectories (Pieter)

Mayavi-based 3-D plotting of iso-surfaces (e.g. 3D polar intensities) (Luty)

4.7 Reading Modtran data

Modtran: running MODTRAN, reading tape7 file, extract prescribed columns & resample to required spectral interval (Tami)

4.8 Detector Modelling

The detector modelling module provides a comprehensive detector model, based on physical design parameters, giving the user accurate control over key model behaviour elements.

IR detectors can be designed to be photodetectors or thermo-detectors. In this case, the work focuses in photovoltaic IR photodetectors. This kind of detector is often called photodiode because it is a semiconductor diode (p-n junction) which is light sensitive [??]. This kind of detector was chosen due to its facility to be found, being used worldwide in different kind of applications. In this work, a monopixel IR detector is simulated using classical parameters as inputs for the calculation, such as detector area, bandgap energy, doping, detector temperature among others. In the source code, all the equations and resutling functions are described and referenced in order to allow the user to understand the procedure step by step. It is important to note that all the equations and parameters used are from classical models found in the literature, giving generality and reliability to the procedure.

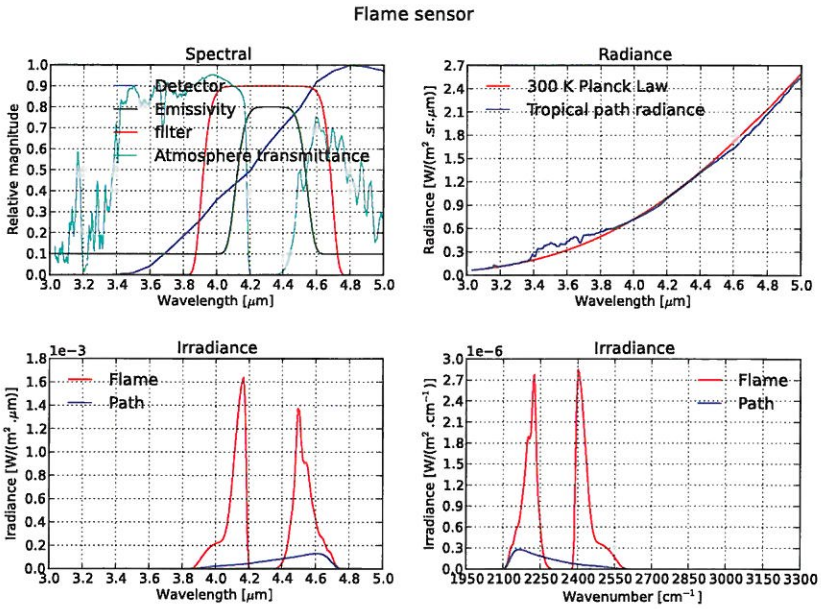

Figure 3. Flame sensor example spectral data

```
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

# first do for 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 * filter * fill * opticsFOV
totalirradianceFlame=numpy.trapz(inbandirradianceFlame.reshape(-1,1),waven,axis=0)[0]
signalFlame = totalirradianceFlame *transZ*responsivity *opticsArea

plot1.saveFig('flamesensor01.eps')

Optics   : area=0.0078 m^2 FOV=0.0001 [sr]
Aplifier: gain=10000.0 [V/A]
Detector: peak responsivity=2.5 [A/W]
Flame    : temperature=1273.16 [K] area=1 [m^2] distance=1000 [m] fill=0.01 [-]
Flame    : irradiance= 3.29e-04 [W/m^2] signal= 0.0641 [V]
Path     : irradiance= 5.45e-05 [W/m^2] signal= 0.0106 [V]
```

It is clear that the flame signal is six times larger than the path radiance signal, even though the flame only fills 1% of the sensor field of view.

4.2 Solid angle calculation

Array processing in Python and Matlab condenses and simplies most two-dimensional calculations significantly. The code to solve the integral in Equation 5, for W=104, D=90, H=60 is as follows:

Matlab code:

```
delta = 0.5;
x = [-45:delta:45];
y = [-52:delta:52];
a = ones(size(y))' * x ;
b = (ones(size(x))' * y)' ;
gv=(1 ./ ((a/60).^2  + (b/60).^2  +1  )).^(3/2);
solidAngle = delta.^2*trapz(trapz(gv))/(60*60)
```

Python code:

```
import numpy as np
x,y = np.mgrid[-45:45:181j, -52:52:209j]
gv = (1 / ( (x/60)**2 + (y/60)**2 +1 ) ) **(3./2)
a = np.trapz(gv, dx=0.5)
solidAngle = np.trapz(a, dx=0.5)/(60*60)
print(solidAngle)
```

emittance and temperature derivative). The total emittance can also be calculated by using the Stefan-Boltzman equation, in [W/m^2] or [q/(s·m^2)].

ryfiles.py This module provides functions for file input/output. These are all wrapper functions, based on existing functions in other Python classes. Functions are provided to save a two-dimensional array to a text file, load selected columns of data from a text file, load a column header line, read raw binary files, read Modtran Tape7 files (Tami), compact strings to include only legal filename characters, and a function from the Python Cookbook[15] to recursively match filename patterns.

ryplot.py This module provides functions for plotting cartesian and polar plots. This class provides a basic plotting capability, with a minimum number of lines. These are all wrapper functions, based on existing functions in other Python classes. Provision is made for combinations of linear and log scales, as well as polar plots for two-dimensional graphs, and image plotting. The module can also plot line (trajectory) data and iso-surface data in three-dimensional graphics. Luty and Pieter The Plotter class can save files to disk in a number of formats.

ryutils.py This module provides various utility functions for radiometry calculations. Functions are provided for a maximally flat spectral filter, a simple photon detector spectral response, effective value calculation, conversion of spectral domain variables between [μm], [cm^{-1}] and [Hz], conversion of spectral density quantities between [μm], [cm^{-1}] and [Hz] and spectral convolution.

rychroma.py This module provides rudimentary colour coordinate processing. Calculate the CIE 1931 rgb chromaticity coordinates for an arbitrary spectrum.

ryptw.py This module provides the capability to read FLIR Inc `*.ptw` files. All information in the file header is read and made available with the image frames.

ry3dnoise.py This module provides utilities to calculate three-dimensional noise parameters[16] of an image sequence. Riana to complete

rydetector.py This module provides a detector spectral model, based on academic and well known parameters and models found in the classical literature. The model is built to be able to calculate and predict the main figures of merit for infrared detectors such as its detectivity, responsivity and noise equivalent power (NEP). Also, the I×V characteristics are calculated to allow the user to compare the model with real operational measurements done in a laboratory.

The toolkit does not employ software exceptions for error handling, but rather signal errors by return value.

3.3 Numerical Approximations

The spectral integral in Equation 2 and spatial integrals can be calculated very simply by virtue of the theory of the Riemann integral as sums over ever decreasing intervals. Likewise can spatial integrals be done as the sum of small elements over the surface of the object.

$$\int_0^\infty \epsilon_\lambda L_\lambda(T)\tau_{a\lambda}\tau_{s\lambda}\mathcal{R}_\lambda \, d\lambda \approx \sum_{i=0}^{\infty} \epsilon_{\lambda i} L_{\lambda i}(T)\tau_{a\lambda i}\tau_{s\lambda i}\mathcal{R}_{\lambda i} \, \Delta\lambda \tag{8}$$

Integrals are at best only approximations of reality. In the pyradi toolkit integrals are calculated by us

4. EXAMPLE APPLICATIONS

The examples of the toolkit application shown here are for illustration purposes only, the code itself is available in the module files on the website (see Section 5).

$$\int_{\lambda_c-\frac{\Delta\lambda}{2}}^{\lambda_c+\frac{\Delta\lambda}{2}} \epsilon_\lambda L_\lambda(T)\tau_{a\lambda}\tau_{s\lambda}\mathcal{R}_\lambda \, d\lambda = \int_{-\frac{\Delta\lambda}{2}}^{+\frac{\Delta\lambda}{2}} \epsilon_x L_\lambda(T)\tau_{ax}\tau_{s(\lambda_c-x)}\mathcal{R}_x \, dx \tag{4}$$

These equations illustrate very clearly that the irradiance measured with the filter centered around wavelength λ_c includes source energy from $\lambda_c - \frac{\Delta\lambda}{2}$ to $\lambda_c + \frac{\Delta\lambda}{2}$. Apart from the spectral selection, the filter has an additional effect by smoothing the spectrum being observed, since the filter has a non-zero spectral width. Equation 4 is called a convolution integral since it describes the convolution between the product $\epsilon_{\lambda_c} L_{\lambda_c} \tau_{a\lambda_c} \mathcal{R}_{\lambda_c}$ and τ_s. The convolution integral is an important step in the processing of spectral data with different spectral resolutions.

There are a plethora of colour space definitions, each optimised for different applications. Essentially, the calculation of colour coordinates is a radiometric calculation involving normalization with given spectral weights. One common colour space is the CIE 1931 tristimulus values XYZ, or the xyY chromaticity colour space.[3,4] The toolboox must have provide at least rudimentary capabilities for colour space calculation.

Non-trivial real-world problems require integration over spatial surfaces, i.e. over the surface of extended objects and large solid angles. One example is the solid angle of a large rectangular plate, such as shown in Figure 2. The geometric solid angle, ω_s, and projected solid angle, Ω_s, of the rectangular flat surface, as seen from a reference point centred above the plate, are given by the following two equations:

$$\omega_s = \int_W \int_D \frac{dw\ dd}{H^2} \left(\frac{H}{\sqrt{w^2+d^2+H^2}} \right)^3 \tag{5}$$

$$\Omega_s = \int_W \int_D \frac{dw\ dd}{H^2} \left(\frac{H}{\sqrt{w^2+d^2+H^2}} \right)^4 \tag{6}$$

where W and D are the dimensions of the rectangle and H is the reference point height above the plate. The integral is performed along the W and D dimensions with increments of dw and dd. The slant range between the reference point and the elemental area $dd \times dw$ is $r = H/\cos\theta$. Even though each problem formulation is different, the toolkit must be able to support the calculation of such spatial integrals.

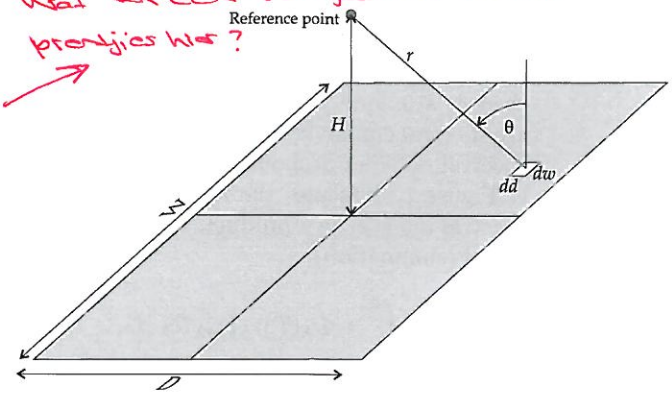

Figure 2. Solid angle of a centred flat plate

2.2 General Software Requirements

In addition to the domain-specific requirements, there are also requirements to read data files, interpolate data and visualise results. Data visualisation is a very important element in the understanding and validation of the calculated results—errors are more readily recognised in graphical visualisation than in tabular data. There is also a need for housekeeping tools for interpolation, normalisation and so forth.

Data visualisation is required in the form of two-dimensional (x, y) and three-dimensional (x, y, z) data graph plots. Two-dimensional data graphs must include combinations of linear and log scale plots, as well as polar plots. Three dimensional data graphs must include mesh grid plots and three-dimensional iso-plots.

One popular normalisation method, attempting to calculate the effective value of a spectral variable is given by

$$\mathcal{F}_{\text{eff}} = \frac{\int_0^\infty \mathcal{F}_\lambda \mathcal{G}_\lambda d\lambda}{\int_0^\infty \mathcal{G}_\lambda d\lambda} \tag{7}$$

where $\mathcal{F}_\lambda$ is the spectral variable in question and $\mathcal{G}_\lambda$ is some common spectral variable. Note that the effective value of $\mathcal{F}$ depends on the spectral shapes of both $\mathcal{F}$ and $\mathcal{G}$; the effective value of $\mathcal{F}$ thus calculated therefore applies only to the specific $\mathcal{G}$ used in the calculation.

1. INTRODUCTION

Electro-optical system design involves the system integration of a diverse set of technologies and concepts, covering areas such as real world object signatures, atmospheric effects, optics, optical detectors, electronics and signal processing. The design process involves the optimisation of several (often interrelated) parameters in this electro-optical system. Such optimisation requires modelling of the relevant components in the system and performing trade-off calculations and data analysis with these models.

Many of these calculations are of a repetitive and general nature, suitable for adding to a generic toolkit. The availability of a well designed toolkit facilitates and increase productivity during subsequent tool development, where new tools are added to an ever-increasing set of tools. The concept of an extendible toolkit lends itself naturally to the open-source philosophy, where the toolkit user-base develops the capability cooperatively, for mutual benefit.

The development of this toolkit is following the Unix philosophy for software development, summarised in the words of Doug McIlroy: "Write programs that do one thing and do it well. Write programs to work together." In broader terms the philosophy was stated by Eric Raymond[1] (only selected items shown here): (1) Rule of Modularity: Write simple parts connected by clean interfaces. (2) Rule of Clarity: Clarity is better than cleverness. (3) Rule of Composition: Design programs to be connected to other programs. (4) Rule of Simplicity: Design for simplicity; add complexity only where you must. (5) Rule of Parsimony: Write a big program only when it is clear by demonstration that nothing else will do. (6) Rule of Transparency: Design for visibility to make inspection and debugging easier. (7) Rule of Robustness: Robustness is the child of transparency and simplicity. (8) Rule of Representation: Fold knowledge into data so program logic can be stupid and robust. (9) Rule of Economy: Programmer time is expensive; conserve it in preference to machine time. (10) Rule of Generation: Avoid hand-hacking; write programs to write programs when you can. (11) Rule of Optimisation: Prototype before polishing. Get it working before you optimise it. (12) Rule of Extensibility: Design for the future, because it will be here sooner than you think.

The Pyradi* toolkit is an extendable, integrated and coherent collection of basic functions, code modules, documentation, example templates, tests and resources, that can be applied towards diverse calculations in the electro-optics domain. The fundamental principle in constructing this toolkit is therefore to write a number of cooperating specialised modules, where each module focusses on one task and perform this task with minimal workload on the user.

While several toolkits for Matlab and Python exist in other scientific domains, there are no radiometry toolkit readily available.

This paper covers the domain requirements for the toolkit, the language selection considerations, the toolkit design considerations and the structure of the toolkit. Several worked examples of the toolkit are presented. Finally, the instructions for downloading the toolkit is given.

2. REQUIREMENTS FOR TOOLKIT

2.1 Electro-Optical Domain Requirements

A typical toolkit (very much simplified) requirement is the calculation of the detector current of an electro-optical sensor viewing an extended target object. In this example case the effect of atmospheric path radiance is not included. The system can be conceptually modelled as shown in Figure 1, comprising a radiating source with spectral radiance, an intervening medium (e.g. the atmosphere), a spectral filter, some optics, a detector and an amplifier. The amplifier output signal can be calculated[2] by integrating Equation 1 over all wavelengths, over the full source area A_0 and over the optical aperture area A_1,

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

*The name pyradi is derived from the combination of the two words 'Python' and 'Radiometry'. In accordance with Python practice it is spelt with all lowercase letters. For grammatical purposes the name pyradi is capitalised according to English grammar rules, where necessary.