Simulation of Radar Profiles for Satellites

Daniel Topa
daniel.topa@hii.com

Huntington Ingalls Industries
Mission Technologies

November 18, 2024

Abstract

A brief survey of characterizing the three dimensional radar cross section of satellites. The process of finding the optimal Fourier expression for each band is explored and different success measures are presented.

Contents

1 Writ Large

Radar is an invaluable tool for space domain awareness which can characterize not only location, but also orientation of satellites in space. It can answer where antennas are pointed and how a space craft is maneuvering. The open question is one of interpreting the radar return section. The key value is the amount of energy returned by reflection, and this is the essence of the radar cross section (res).

Figure 1 shows a sample radar cross section measurement for a vintage A-26 Invader. The strength of the return signal varies over several orders of magnitude depending upon the viewing

angle.

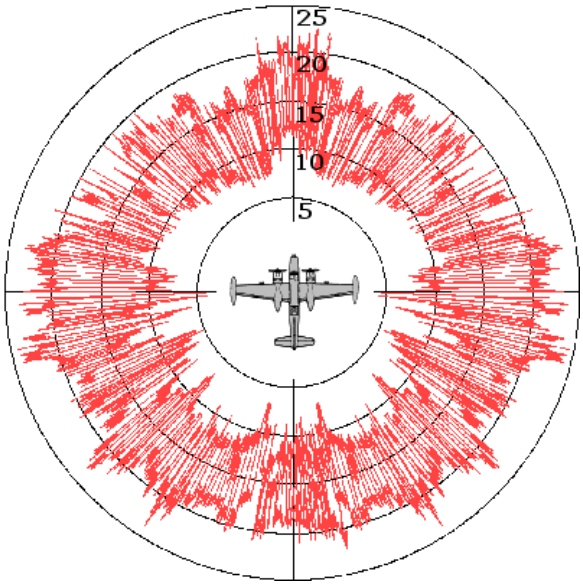


Figure 1: A radar cross section measurement for the A-26 Invader taken from the Wikipedia article on Radar Cross Section show energy change where 0 db represents 1 milliwatt return energy.

A simplified aircraft model in figure 2 presents requisite variation without over-complications and makes the point that even a stealthy aircraft can present large cross sections at proper view angles as seen in table 2.

Look angle

The purpose of this analysis is to start with a CAD model of a structure and simulate the radar cross section, a sample show in figure 3.

render the radar cross section into a form like

$$\sigma_3(\theta) = 35.237 \pm 0.012 + (1.675 \pm 0.018)\cos\theta + (-3.434 \pm 0.018)\cos 2\theta + (-0.866 \pm 0.018)\cos 3\theta + (5.386 \pm 0.018)\cos 4\theta + (-1.280 \pm 0.018)\cos 5\theta + (1.379 \pm 0.018)\cos 6\theta + (-0.675 \pm 0.018)\cos 7\theta$$

where θ is an azimuthal angle with $\theta = 0$ representing a nose-one view and $\pm\pi representing a tail-on view$

1.1 Toy Satellite Model

A toy satellite model is much easier to start with for developing a data analysis can reduction chain. The model below (figure /reftab:toy-sat) features a spherical body and readily distinguishable solar panels.

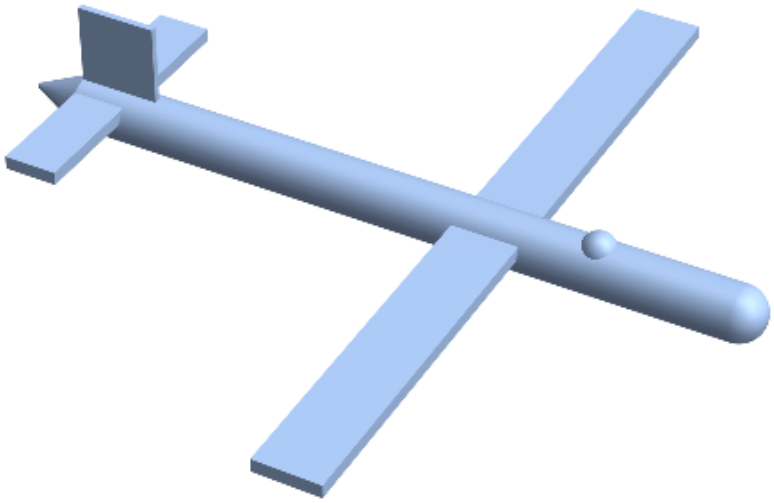


Figure 2: Toy model for aircraft. Although simplistically rendered, this representation is adequate for over the horizon radars.

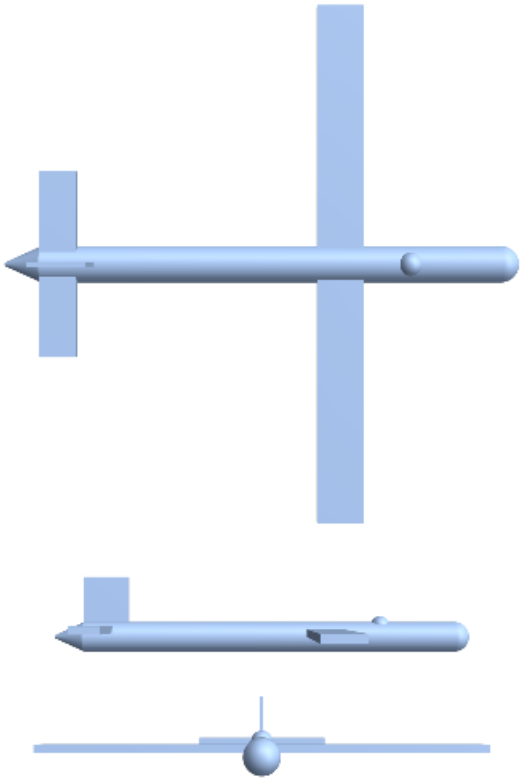


Table 1: Different aircraft views present very different cross-sectional areas.

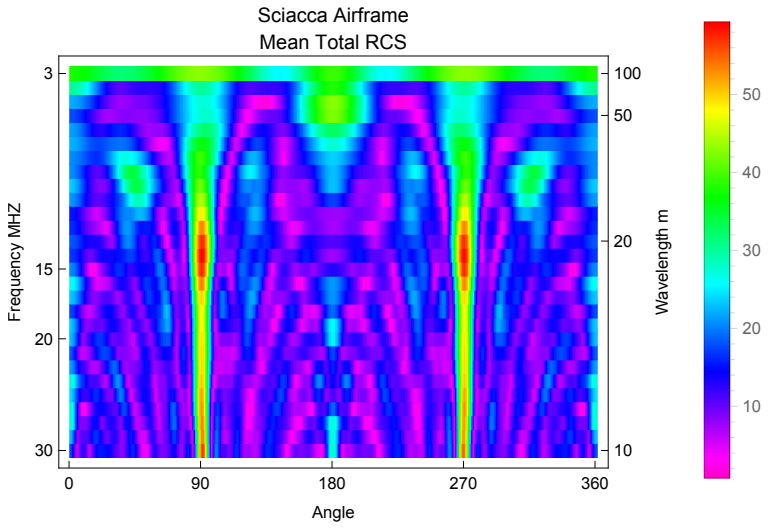


Figure 3: Output for a radar backscatter simulation for radar frequencies from $3 - 30$ MHz, corresponding to wavelengths of $10 - 100$ m.

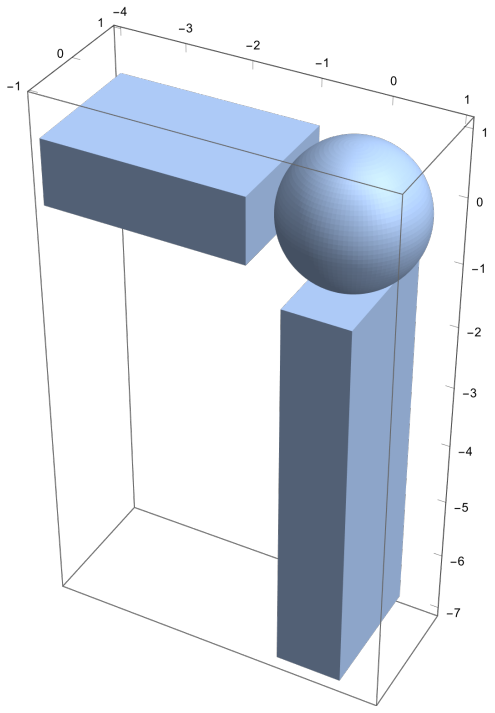
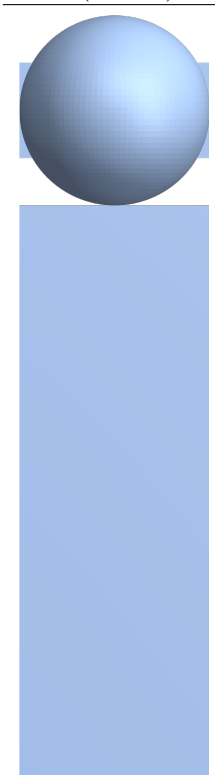
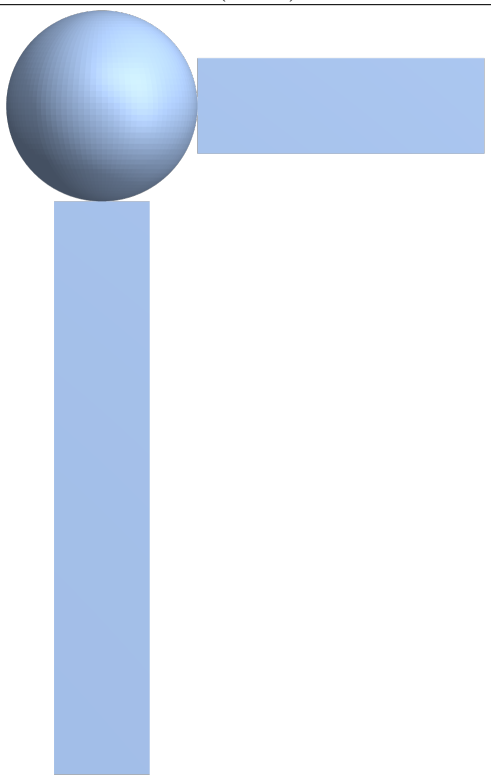
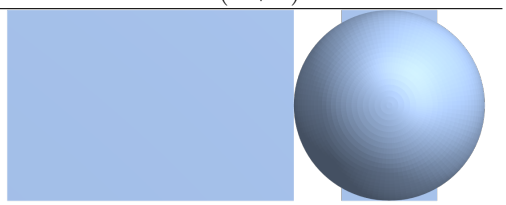
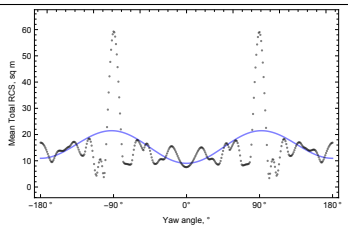
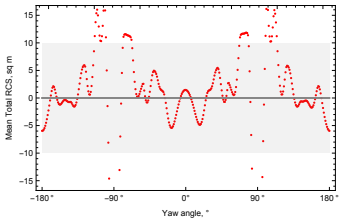
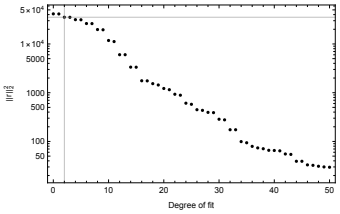
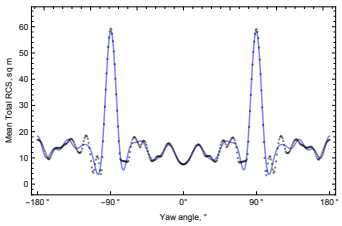
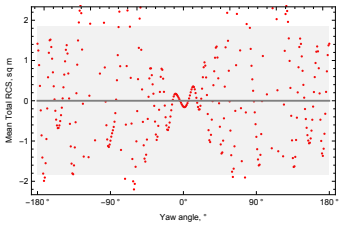
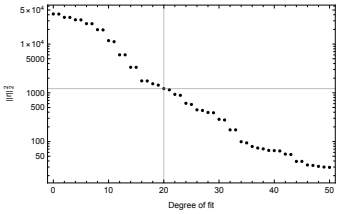
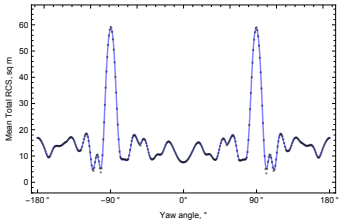
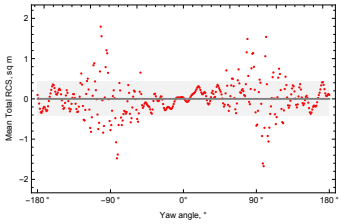
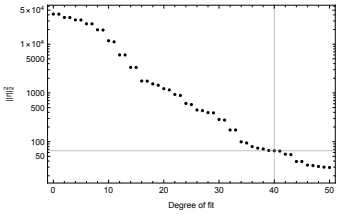


Figure 4: A toy satellite model designed to present a spherical backscatter and resonances at 6, 3, 2, and 1 meter wavelengths.

Table 2: Contrasting views of a toy satellite present very different cross sectional areas, A.

$A \approx (\pi + 12)\, r^2$	$A = (\pi + 9)\, r^2$	$A \approx (\pi + 6)\, r^2$
		

d	Data and Fourier Representation	Residual Fit Error	Total Error for Fit Sequence
$d = 2$			
$d = 20$			
$d = 40$			

2 Mathematical Precís

2.1 Models of Radar Cross Section

$$\sigma_\nu(\alpha) \approx \frac{a_0}{2} + \sum_{k=1}^{d} a_k \cos k\alpha + b_k \sin k\alpha \tag{1}$$

Amplitudes and Errors for $\nu = 3$ MHz and $d = 7$:

$$\begin{aligned}\sigma_3(\theta) = a_0 &+ a_1\cos\theta + a_2\cos 2\theta + a_3\cos 3\theta \\ &+ a_4\cos 4\theta + a_5\cos 5\theta + a_6\cos 6\theta + a_7\cos 7\theta\end{aligned}$$

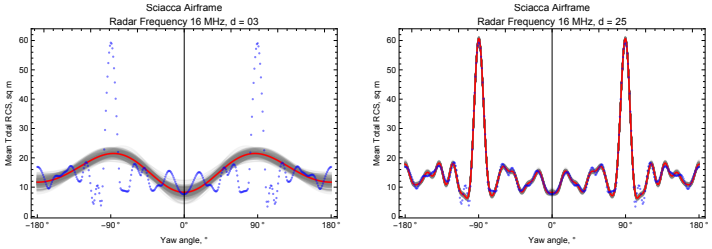
$$\begin{aligned}\sigma_3(\theta) = 35.237 \pm 0.012 &+ (1.675 \pm 0.018)\cos\theta + (-3.434 \pm 0.018)\cos 2\theta + (-0.866 \pm 0.018)\cos 3\theta \\ &+ (5.386 \pm 0.018)\cos 4\theta + (-1.280 \pm 0.018)\cos 5\theta + (1.379 \pm 0.018)\cos 6\theta + (-0.675 \pm 0.018)\cos 7\theta\end{aligned}$$

2.2 Models of Increasing Fidelity

2.3 Running the Code

```
./MMoM_4.1.12 sample.geo
```

Table 3: Seeing the uncertainties in the fit parameters.



2.4 Radar

[Topa 2020c] [Topa 2020c] Working with CAF files, producing output, compressing data. Topa 2020d Topa (2020d)

2.5 Process

1	Create CAD model	CAD software
2	Convert CAD to `*.obj`	CAD software
3	Convert `*.obj` to `*.facet`	Mathematica, Fortran
4	Input properties to `materials.lib`	`VIM`
5	Set radar frequencies	`VIM`
6	**Simulate radar irradiation**	`Mercury MoM`
7	Harvest reflection values from output	Mathematica, Fortran, Python
8	Describe RCS as a series of amplitudes	Not written

Table 4: Start with a CAD model and construct a Radar Cross Section model

3 Overview: Modeling Radar Cross Section

3.1 Radar

Wave speed equation

$$\lambda\nu = c \tag{2}$$

(A) Build a CAD model of the satellite (*.cad)
(B) Seal the CAD mesh
(C) Create geometry file (*.geo)
(D) Irradiate object with Mercury MoM
(E) Harvest backscatter
(F) Construct RCS
(G) Resolve RCS measurements into spherical harmonics

3.2 Process

(A) Build a CAD model of the satellite (*.cad)

band	ν	λ
HF	$3 - 30$ MHz	$10 - 1$ m
UHF	$30 - 300$ MHz	$0.1 - 0.01$ m
VHF	$300 - 1000$ MHz	$0.01 - 0.03$ m
L	$1 - 2$ GHz	$30 - 15$ mm
S	$2 - 4$ GHz	$15 - 7.5$ mm
C	$4 - 8$ GHz	$7.5 - 3.7$ mm
X	$8 - 12$ GHz	$3.7 - 2.5$ mm
Ku	$12 - 18$ GHz	$2.5 - 1.7$ mm
K	$18 - 27$ GHz	$1.7 - 1.1$ mm
Ka	$27 - 40$ GHz	$1.1 - 0.75$ mm
V	$40 - 75$ GHz	$0.75 - 0.4$ mm
W	$75 - 110$ GHz	$0.4 - 0.27$ mm
mm	$110 - 300$ GHz	$0.27 - 0.1$ mm

Table 5: IEEE Standard Designations for Radar Bands (Bruder et al. 2003).

(B) Seal the CAD mesh
(C) Create geometry file (*.geo)
(D) Irradiate object with Mercury MoM
(E) Harvest backscatter
(F) Construct RCS
(G) Resolve RCS measurements into spherical harmonics

4 Computing the Radar Cross Section

The computation of the radar cross section is based on a simple scenario guided by Maxwell's equations. A radar illuminates the target with radar energy. The target, acting like an antenna, reradiates the energy and illuminates the radar receiver. The radar cross section is measurement of the difference between energy absorbed and energy radiated.

One form of the radar cross section equation is

$$\sigma = 4\pi r^2 \frac{S_r}{S_t} \tag{3}$$

where r is the distance to the target, S_t is the energy *intercepted* by the target and S_r is the energy *radiated* by the target. The result has units of area and can be compared to an ideally reflecting sphere.

The areal measure σ is computed through numerical simulation by the program Mercury MoM.

4.1 Maxwell's Equations

The mathematical foundation for the radar cross section computation is the set of Maxwell's equations. Start with two conservative fields on a simply connected domain, the electric field $\mathbf{E}\colon \mathbb{R}^3 \mapsto \mathbb{R}^3$, and the magnetic field $\mathbf{B}\colon \mathbb{R}^3 \mapsto \mathbb{R}^3$. We can relax the requirements for the electric current $\mathbf{J}\colon \mathbb{R}^3 \mapsto \mathbb{R}^3$. The differential form of Maxwell's equations in SI units is

$$\begin{array}{rclcrcl} \nabla \cdot \mathbf{E} & = & \frac{\rho}{\epsilon_0} & & \nabla \times \mathbf{E} & = & -\partial_t \mathbf{B} \\ \nabla \cdot \mathbf{B} & = & 0 & & \nabla \times \mathbf{B} & = & \mu_0 \left(\mathbf{J} + \epsilon_0 \partial_t \mathbf{E} \right) \end{array} \tag{4}$$

ϵ_0	vacuum electric permittivity	8.854×10^{-12} F m^{-1}
μ_0	vacuum magnetic permeability	1.257×10^{-7} N A^{-2}

Table 6: Constants used in Maxwell's equations

The fundamental physical constant in SI units are given in table 6.

4.2 Method of Moments

There is a rich mathematical toolkit for the solution of Maxwell's equations. Mercury MoM uses the method of moments (MoM), also known as the boundary element method (BEM). Maxwell's equations in integral form

$$\begin{array}{rclcrcl} \nabla \cdot \mathbf{E} & = & \dfrac{\rho}{\epsilon_0} & \Rightarrow & \displaystyle\oint_{d\Omega} \mathbf{E} \cdot d\mathbf{S} & = & \displaystyle\int_{\Omega} \rho dV \\ \nabla \times \mathbf{E} & = & -\partial_t \mathbf{B} & \Rightarrow & \displaystyle\oint_{d\Omega} \mathbf{B} \cdot d\mathbf{S} & = & 0 \\ \nabla \cdot \mathbf{B} & = & 0 & \Rightarrow & \displaystyle\oint_{d\Sigma} \mathbf{E} \cdot d\mathbf{l} & = & -\dfrac{d}{dt}\mathbf{B} \cdot d\mathbf{S} \\ \nabla \times \mathbf{B} & = & \mu_0 \left(\mathbf{J} + \epsilon_0 \partial_t \mathbf{E}\right) & \Rightarrow & \displaystyle\oint_{d\Sigma} \mathbf{B} \cdot d\mathbf{l} & = & \mu_0 \displaystyle\int_{\Sigma} \left(\mathbf{J} + \epsilon_0 \dfrac{d}{dt}\mathbf{E}\right) \cdot d\mathbf{S} \end{array} \tag{5}$$

The method of moments creates dense matrices which implies quadratic growth in storage and computation time as the problem scales up.

4.3 Mercury MoM Example

The power of Mercury MoM is the ability to simultaneously solve equations with millions of unknowns using a patented low rank approximation method for the linear system.

Internally, the Mercury MoM package resolves the signal emitted from the target into two complex electric fields: θ for the vertical component and ϕ for the horizontal component. As these fields are complex, they each have orthogonal real and imaginary components.

The prescription for the mean total radar cross section is taken from the Sciacca report as the average of the total field energy

$$\langle \sigma_T \rangle = \tfrac{1}{2} \left(\theta^* \theta + \theta^* \phi + \phi^* \theta + \phi^* \theta\right), \tag{6}$$

and is assigned areal units of squared meters m^2.

5 Fourier Expansion

5.1 Why Fourier?

What is the best way to approximate information in the cross sections curves shown in figure **??**? Given that the data is periodic over the unit circle,

$$\sigma_\nu (\alpha, \beta) = \sigma_\nu (\alpha + 2\pi, \beta) \tag{7}$$

an obvious choice is the Fourier series. For example, a dth order approximation can be written as

$$\sigma_\nu\left(\alpha, \beta_0 = \tfrac{\pi}{12}\right) \approx \frac{a_0}{2} + \sum_{k=1}^{d} a_k \cos k\alpha + b_1 \sin k\alpha. \tag{8}$$

What does this series represent? It represents a sequence of oscillations about the mean value.

There are three powerful theoretical reasons which support this choice. The first is the convergence of the series. The Weierstrass Approximation Theorem states that the polynomial approximation of smooth curves converges *uniformly*. That is, we can define a maximum error $\epsilon > 0$ and we are guaranteed the existence of $N \in \mathbb{Z}^+$ such that

$$\left\| \sigma_\nu\left(\alpha, \beta_0\right) - \frac{a_0}{2} - \sum_{k=1}^{N} a_k \cos k\alpha + b_k \sin k\alpha \right\|_\infty \leq \epsilon. \tag{9}$$

The ability to choice a maximum error is both remarkable and useful. However, the application to trigonometric polynomials, while valid, is not immediate and left for another document.

The second reason is the Riesz–Fischer theorem. While often cited as evidence that the Lebesgue space L^2 is complete, it also establishes that an infinite series whose terms converge quadratically represents an L^2 function. And so the amplitudes, the a and bv values, will eventually converge at least quadratically.

The final reason is the often-overlooked fact that of all the orthogonal polynomials, only the trigonometric polynomials are orthogonal in both the continuous topology of L^2 and and the discrete orthogonality of l^2. Having an orthogonal basis decouples the problem and can be solved mode-by–mode, obviating the need to solve a large linear system.

5.2 Orthogonality

Given non-zero integers m and n, the expression of orthogonality in L^2 can be written as

$$\begin{aligned}
\int_{-\pi}^{\pi} \sin\left(mx\right) \sin\left(nx\right) dx &= \pi \delta_n^m \\
\int_{-\pi}^{\pi} \cos\left(mx\right) \cos\left(nx\right) dx &= \pi \delta_n^m \\
\int_{-\pi}^{\pi} \cos\left(mx\right) \sin\left(nx\right) dx &= 0 \\
\int_{-\pi}^{\pi} \sin\left(mx\right) dx &= 0 \\
\int_{-\pi}^{\pi} \cos\left(mx\right) dx &= 0
\end{aligned} \tag{10}$$

where δ_n^m is the Kronecker delta tensor. To complete the toolkit to solve the linear system, recall that

$$\int_{-\pi}^{\pi} 1 dx = 2\pi. \tag{11}$$

The linear system decouples and amplitudes for each mode can be computed independently:

$$\begin{aligned}
a_0 &= \tfrac{1}{\pi} \int_{-\pi}^{\pi} f(x) dx \\
a_k &= \tfrac{1}{\pi} \int_{-\pi}^{\pi} f(x) \cos kx dx \\
b_k &= \tfrac{1}{\pi} \int_{-\pi}^{\pi} f(x) \sin kx dx
\end{aligned} \tag{12}$$

where $k = 1, 2, 3, \ldots$.

5.3 Projection

Consider the low–order approximation

$$f(\varphi) \approx \frac{a_0}{2} + a_1 \cos\varphi + a_2 \cos 2\varphi. \tag{13}$$

To compute the amplitudes $a = \{a_0, a_1, a_2\}$, use Hilbert's projection theorem, which is tantamount to using the method of least squares. Multiply both side of the equation by $\cos j\varphi$ and integrate over the domain to isolate the contribution of a_j. For example, to isolate the component a_2,

$$\begin{aligned} \int_{-\pi}^{\pi} f(\varphi) \cos 2\varphi d\varphi &\approx \int_{-\pi}^{\pi} \left(\frac{a_0}{2} + a_1 \cos\varphi + a_2 \cos 2\varphi \right) \cos 2\varphi d\varphi. \\ &= a_2 \int_{-\pi}^{\pi} \cos^2 2\varphi d\varphi. \end{aligned} \tag{14}$$

The result is the rather general formula

$$a_2 = \frac{1}{\pi} \int_{-\pi}^{\pi} f(\varphi) \cos 2\varphi d\varphi. \tag{15}$$

Because the basis functions are orthogonal, the modes are decoupled and the amplitudes can be computed independently.

5.4 Discrete Topology

The continuum formulation in L^2 is useful for understanding the critical components of the theory and makes a natural starting point for discussing the discrete topology of l^2. The moment we discretize the problem in a computer code, we switch from the continuum to a discrete space. Out of all the known orthogonal polynomials, only two are orthogonal in both L^2 and l^2, and these are the sine and cosine functions.

However, because of sampling mesh that was used in Mercury MoM, the data vectors are *not* orthogonal. But resolution is deferred until the end.

5.5 Special Case: The Mean

The Fourier series resolves a function into successively higher oscillations about a constant value. This constant value is the mean, and it is a least squares solution and in this effort, is a valuable bellwether.

5.5.1 The Method of Least Squares

$$r^2 = \sum_{k=1}^{m} \left(\sigma(\alpha_k, \beta_0) - \mu \right)^2 \tag{16}$$

$$D_\mu r^2 = -2 \left(\sigma(\alpha_k, \beta_0) - \mu \right) = 0 \tag{17}$$

The least squares solution for the parameter μ is simply the average of the data:

$$\mu = m^{-1} \sigma(\alpha_k, \beta_0). \tag{18}$$

Compare to a_0

5.5.2 Continuum to discrete

The continuum formulation translates to discrete spaces using the idea of the integral as a Riemann sum:

$$\int_{-\pi}^{\pi} \cos j\alpha d\alpha \quad \Rightarrow \quad \sum_{k=1}^{m} \cos\left(j\alpha_k\right) \Delta_k. \tag{19}$$

Here Δ_k, the interval length, corresponds to the Riemann integration measure $d\alpha$. A basic result from the calculus is that the average $\langle f\left(x\right)\rangle$ of an integrable function over a finite, ordered interval (a, b) is

$$\langle f\left(x\right)\rangle = \frac{\int_b^a f(x)dx}{b-a}, \tag{20}$$

where the interval length $L = b - a$. The connection to the discrete case is clear with the realization that the Mercury MoM results are spaced at regular intervals, that is,

$$\Delta_k = \Delta.$$

Then the interval length is

$$L = \sum_{k=1}^{m} \Delta_k = \sum_{k=1}^{m} \Delta = m\Delta. \tag{21}$$

$$\frac{\int_b^a f(x)dx}{L} \quad \Rightarrow \quad \frac{\sum_{k=1}^{m} f(x)\Delta}{m\Delta} = \frac{\sum_{k=1}^{m} f(x)}{m} \tag{22}$$

5.6 Linear Independence

5.7 Quality of Fit

6 File Types

Standard file types

1. `*.obj`
2. `*.txt`

Intrinsic file types

1. `*.geo`
2. `*.facet`

6.1 Geometry Files `*.obj`

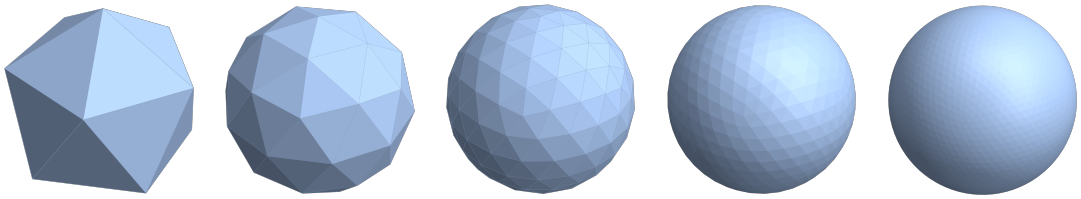
The geometry files are the primary input to Hg MoM.

1. Mathematica: Import/Export format OBJ
2. Wikipedia: Wavefront .obj file
3. All3DP: The OBJ File Format – Simply Explained

Listing 1: The `*.obj` file for the sphere with 20 facets.

```
# Created with the Wolfram Language : www.wolfram.com
mtllib sphere-d050-01.mtl

# 12 vertex positions
v  13.81966018676758 42.53253936767578 22.36067962646484
v  -13.81966018676758 42.53253936767578 -22.36067962646484
v  -36.18033981323242 26.28655624389648 22.36067962646484
v  -36.18033981323242 -26.28655624389648 22.36067962646484
v  -13.81966018676758 -42.53253936767578 -22.36067962646484
v  13.81966018676758 -42.53253936767578 22.36067962646484
```



20 80 320 1280 5120

Table 7: A sphere resolved into facets in an `*.obj` file. The application irradiates each facet and aggregates the output.

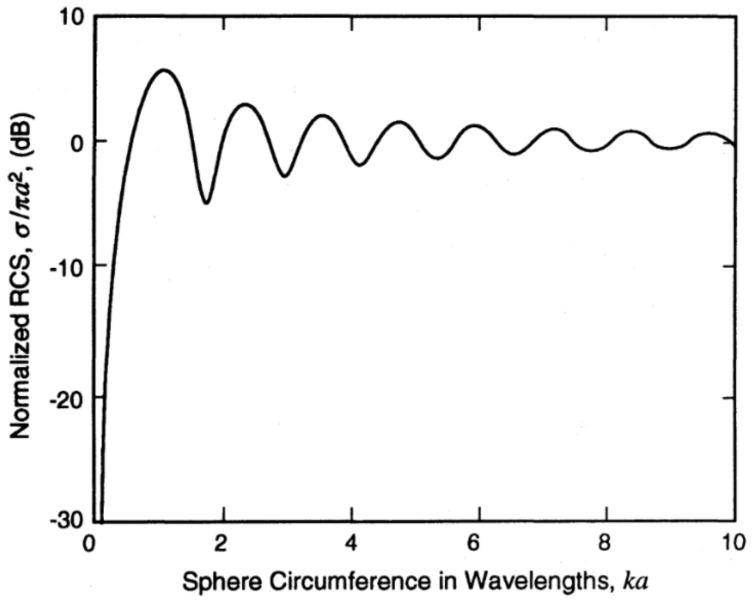


Figure 4.2. Sphere RCS backscatter as a function of *ka* as computed by the algorithm shown in Listing 4.1.

Table 8: Closed form solution for spherical scattering taken from Knott, Schaeffer, and Tulley 2004, p. 123.

```
v  36.18033981323242 26.28655624389648 -22.36067962646484
v  -44.72135925292969 0 -22.36067962646484
v  44.72135925292969 0 22.36067962646484
v  36.18033981323242 -26.28655624389648 -22.36067962646484
v  0 0 50
v  0 0 -50

# 0 UV coordinates

# 0 vertex normals

# Mesh '' with 20 faces
usemtl DefaultMaterial
f  1// 2// 3//
f  4// 5// 6//
f  2// 1// 7//
f  4// 3// 8//
f  9// 6// 10//
f  3// 4// 11//
f  2// 7// 12//
f  3// 2// 8//
f  2// 12// 8//
f  12// 5// 8//
f  7// 1// 9//
f  5// 4// 8//
f  6// 5// 10//
f  5// 12// 10//
f  12// 7// 10//
f  7// 9// 10//
f  4// 6// 11//
f  6// 9// 11//
f  9// 1// 11//
f  1// 3// 11//
```

Listing 2: The `*.facet` file for the sphere with 20 facets.

```
facimusFacet.f08  2020-06-25 11:34:36
    1
<partName>
0
     12
     13.819660      42.532539      22.360680
    -13.819660      42.532539     -22.360680
    -36.180340      26.286556      22.360680
    -36.180340     -26.286556      22.360680
    -13.819660     -42.532539     -22.360680
     13.819660     -42.532539      22.360680
     36.180340      26.286556     -22.360680
    -44.721359       0.000000     -22.360680
     44.721359       0.000000      22.360680
     36.180340     -26.286556     -22.360680
      0.000000       0.000000      50.000000
      0.000000       0.000000     -50.000000
    1
<partName>
      3     20      0      0      0      0      0
      1      2      3      0
      4      5      6      0
      2      1      7      0
      4      3      8      0
      9      6     10      0
      3      4     11      0
      2      7     12      0
      3      2      8      0
      2     12      8      0
     12      5      8      0
      7      1      9      0
      5      4      8      0
      6      5     10      0
```

```
      5     12     10      0
     12      7     10      0
      7      9     10      0
      4      6     11      0
      6      9     11      0
      9      1     11      0
      1      3     11      0
```

6.2 New Efforts

7 Running Mercury Method of Moments

7.1 Inputs

Consider an example with the sphere.

Listing 3: "tabula-rasa.geo"

```
ego

!Mercury MoM input file, VIE/SIE Version 4.x compatible (VIE/Dual Sided SIE)

&MM_MOM
  bUseACA = .TRUE.,
  bSolve_ACA = .TRUE.,
  bOutOfCore = .TRUE.,
  bNormalizeToWaveLength = .FALSE.,
  bNormalize             = .FALSE.,
  dCloseLambda  = 0.100000,
  ACA_Factor_Tol = 0.000010,
  ACA_RHS_Tol = 0.000100,
  Point_Tolerance = 0.001000,
  nLargestBlockSize = 400,
  MemorySize_GB = -1.000000,
  stackSize_GB = -1.000000,
  nFillThreads = -1,
  nFillMKLThreads = 1,
  nLUThreads = -1,
  nLUMKLThreads = 1,
  nRHSThreads = 1,
  nRHSMKLThreads = 1,
  bOutputACAGrouping     = .FALSE.,
  bOutputRankFraction    = .FALSE.,
  bLimitLUColumns        = .FALSE.,
  Lop_Admissibility = WEAK,
  Kop_Admissibility = CLOSE
/

&Scratch_Memory
  Scratch_RankFraction_Z     = 0.300000,
  Scratch_RankFraction_LU    = 0.600000,
  Scratch_RankFraction_RHS   = 0.500000,
  Scratch_RankFraction_Solve = 1.000000,
  MemoryFraction_Z           = 0.950000,
  MemoryFraction_Scratch_LU  = 0.500000,
  MemoryFraction_LU          = 1.000000,
  MemoryFraction_RHS         = 0.500000,
  MemoryFraction_Solve       = 0.900000,
/

&QUADRATURE
  NTRISELF    = 7,
  NTRINEAR    = 3,
  NTRIFAR     = 3,
  NTETSELF    = 11,
```

```
  NTETNEAR    = 4,
  NTETFAR     = 4,
  NQGAUSS  = 4,
/

FREQUENCY
  mhz
  nu-mhz  nu-mhz  1   !Freq Start, Freq Stop, Number of Frequencies

Excitation
  MONOSTATIC

Angle Cut
  1
  0.000000  359.000000  360
  AZIMUTH
  90.000000

Boundary Conditions
PEC-Materials.lib
4
V_FREE_SPACE => Free_Space
V_PEC => PEC
V_PMC => PMC
V_NULL => NULL
1
0 BC_PEC V_FREE_SPACE

SIE
myFacet.facet
m

Geometry_End

! Fiducial run
```

Listing 4: A simple `*.facet` file

```
facimusFacet.f08  2020-06-25 11:34:36
    1
<partName>
0
     12
     13.819660      42.532539      22.360680
    -13.819660      42.532539     -22.360680
    -36.180340      26.286556      22.360680
    -36.180340     -26.286556      22.360680
    -13.819660     -42.532539     -22.360680
     13.819660     -42.532539      22.360680
     36.180340      26.286556     -22.360680
    -44.721359       0.000000     -22.360680
     44.721359       0.000000      22.360680
     36.180340     -26.286556     -22.360680
      0.000000       0.000000      50.000000
      0.000000       0.000000     -50.000000
    1
<partName>
      3     20      0      0      0      0      0
      1      2      3      0
      4      5      6      0
      2      1      7      0
      4      3      8      0
      9      6     10      0
      3      4     11      0
      2      7     12      0
      3      2      8      0
      2     12      8      0
     12      5      8      0
      7      1      9      0
```

```
 5   4   8   0
 6   5  10   0
 5  12  10   0
12   7  10   0
 7   9  10   0
 4   6  11   0
 6   9  11   0
 9   1  11   0
 1   3  11   0
```

7.2 Outputs

```
 Freq   =    10.00E+00 MHz
 Lambda =    29.98E+00 m
 k      =   209.58E-03 m-1

BACKSCATTER RCS RESULTS .....

 Theta, Phi, Theta-Theta (complex efield), Phi-Theta (complex efield), Theta-Phi (complex efield), Phi-Phi (complex efield)

     90.0000,      0.0000,(  0.2333228E-01,  0.1410688E-03),(  0.8868390E-04,  0.5353989E-05),(  0.8868393E-04,  0.5354086E-05),(  0.2275015E-01,  0.1270486E-03)
     90.0000,      1.0000,(  0.2333244E-01,  0.1402642E-03),(  0.8605096E-04,  0.5259093E-05),(  0.8604993E-04,  0.5248534E-05),(  0.2274918E-01,  0.1264947E-03)
     90.0000,      2.0000,(  0.2333259E-01,  0.1393928E-03),(  0.8339065E-04,  0.5144119E-05),(  0.8338990E-04,  0.5151524E-05),(  0.2274821E-01,  0.1259348E-03)
     90.0000,      3.0000,(  0.2333274E-01,  0.1384604E-03),(  0.8070502E-04,  0.5039024E-05),(  0.8070488E-04,  0.5032761E-05),(  0.2274726E-01,  0.1253780E-03)
     90.0000,      4.0000,(  0.2333289E-01,  0.1374878E-03),(  0.7799496E-04,  0.4922949E-05),(  0.7799467E-04,  0.4916130E-05),(  0.2274633E-01,  0.1248239E-03)
     90.0000,      5.0000,(  0.2333302E-01,  0.1364364E-03),(  0.7526141E-04,  0.4795374E-05),(  0.7526139E-04,  0.4787100E-05),(  0.2274541E-01,  0.1242470E-03)
     90.0000,      6.0000,(  0.2333315E-01,  0.1353522E-03),(  0.7250279E-04,  0.4655677E-05),(  0.7250353E-04,  0.4652742E-05),(  0.2274450E-01,  0.1236636E-03)
     90.0000,      7.0000,(  0.2333328E-01,  0.1342022E-03),(  0.6972432E-04,  0.4524583E-05),(  0.6972397E-04,  0.4519492E-05),(  0.2274361E-01,  0.1230949E-03)
     90.0000,      8.0000,(  0.2333339E-01,  0.1330091E-03),(  0.6692425E-04,  0.4379594E-05),(  0.6692352E-04,  0.4374137E-05),(  0.2274274E-01,  0.1225020E-03)
     90.0000,      9.0000,(  0.2333351E-01,  0.1317574E-03),(  0.6410291E-04,  0.4236832E-05),(  0.6410385E-04,  0.4231747E-05),(  0.2274190E-01,  0.1219020E-03)
     90.0000,     10.0000,(  0.2333361E-01,  0.1304482E-03),(  0.6126419E-04,  0.4088875E-05),(  0.6126271E-04,  0.4079980E-05),(  0.2274107E-01,  0.1213053E-03)
     90.0000,     11.0000,(  0.2333371E-01,  0.1290931E-03),(  0.5840381E-04,  0.3920618E-05),(  0.5840345E-04,  0.3921868E-05),(  0.2274026E-01,  0.1207031E-03)
     90.0000,     12.0000,(  0.2333380E-01,  0.1276849E-03),(  0.5552738E-04,  0.3757901E-05),(  0.5552594E-04,  0.3756007E-05),(  0.2273948E-01,  0.1200838E-03)
     90.0000,     13.0000,(  0.2333388E-01,  0.1262230E-03),(  0.5263346E-04,  0.3593899E-05),(  0.5263261E-04,  0.3591580E-05),(  0.2273871E-01,  0.1194466E-03)
     90.0000,     14.0000,(  0.2333395E-01,  0.1247289E-03),(  0.4972452E-04,  0.3426847E-05),(  0.4972324E-04,  0.3422775E-05),(  0.2273798E-01,  0.1188115E-03)
     90.0000,     15.0000,(  0.2333402E-01,  0.1231622E-03),(  0.4679928E-04,  0.3249850E-05),(  0.4679913E-04,  0.3247067E-05),(  0.2273727E-01,  0.1181715E-03)
     90.0000,     16.0000,(  0.2333408E-01,  0.1215549E-03),(  0.4386077E-04,  0.3066160E-05),(  0.4386053E-04,  0.3071021E-05),(  0.2273658E-01,  0.1175054E-03)
     90.0000,     17.0000,(  0.2333414E-01,  0.1199063E-03),(  0.4090846E-04,  0.2884632E-05),(  0.4090883E-04,  0.2891672E-05),(  0.2273593E-01,  0.1168209E-03)
     90.0000,     18.0000,(  0.2333418E-01,  0.1182040E-03),(  0.3794509E-04,  0.2701195E-05),(  0.3794405E-04,  0.2696849E-05),(  0.2273530E-01,  0.1161288E-03)
     90.0000,     19.0000,(  0.2333422E-01,  0.1164673E-03),(  0.3497020E-04,  0.2512710E-05),(  0.3497056E-04,  0.2501005E-05),(  0.2273469E-01,  0.1154252E-03)
     90.0000,     20.0000,(  0.2333425E-01,  0.1146772E-03),(  0.3198408E-04,  0.2319652E-05),(  0.3198424E-04,  0.2317885E-05),(  0.2273412E-01,  0.1146969E-03)
     90.0000,     21.0000,(  0.2333428E-01,  0.1128494E-03),(  0.2898948E-04,  0.2112308E-05),(  0.2898854E-04,  0.2120017E-05),(  0.2273357E-01,  0.1139418E-03)
     90.0000,     22.0000,(  0.2333429E-01,  0.1109812E-03),(  0.2598479E-04,  0.1921074E-05),(  0.2598468E-04,  0.1917728E-05),(  0.2273306E-01,  0.1131798E-03)
     90.0000,     23.0000,(  0.2333430E-01,  0.1090673E-03),(  0.2297422E-04,  0.1725964E-05),(  0.2297450E-04,  0.1716165E-05),(  0.2273258E-01,  0.1123858E-03)
     90.0000,     24.0000,(  0.2333430E-01,  0.1071143E-03),(  0.1995689E-04,  0.1524590E-05),(  0.1995638E-04,  0.1524156E-05),(  0.2273213E-01,  0.1115781E-03)
     90.0000,     25.0000,(  0.2333429E-01,  0.1051199E-03),(  0.1693341E-04,  0.1322952E-05),(  0.1693271E-04,  0.1316243E-05),(  0.2273170E-01,  0.1107367E-03)
     90.0000,     26.0000,(  0.2333428E-01,  0.1030911E-03),(  0.1390601E-04,  0.1110616E-05),(  0.1390536E-04,  0.1106821E-05),(  0.2273132E-01,  0.1098675E-03)
     90.0000,     27.0000,(  0.2333426E-01,  0.1010452E-03),(  0.1087428E-04,  0.9074643E-06),(  0.1087365E-04,  0.9026098E-06),(  0.2273096E-01,  0.1089735E-03)
     90.0000,     28.0000,(  0.2333423E-01,  0.9894501E-04),(  0.7839484E-05,  0.7072128E-06),(  0.7838623E-05,  0.7006824E-06),(  0.2273064E-01,  0.1080477E-03)
     90.0000,     29.0000,(  0.2333420E-01,  0.9680697E-04),(  0.4801968E-05,  0.4874063E-06),(  0.4802196E-05,  0.4862423E-06),(  0.2273035E-01,  0.1070995E-03)
     90.0000,     30.0000,(  0.2333416E-01,  0.9465464E-04),(  0.1765148E-05,  0.2732763E-06),(  0.1764301E-05,  0.2821041E-06),(  0.2273009E-01,  0.1061108E-03)
     90.0000,     31.0000,(  0.2333411E-01,  0.9246088E-04),( -0.1273034E-05,  0.7069519E-07),( -0.1272663E-05,  0.7093635E-07),(  0.2272987E-01,  0.1050739E-03)
     90.0000,     32.0000,(  0.2333405E-01,  0.9023387E-04),( -0.4309802E-05, -0.1458179E-06),( -0.4310374E-05, -0.1394553E-06),(  0.2272967E-01,  0.1040102E-03)
     90.0000,     33.0000,(  0.2333399E-01,  0.8799594E-04),( -0.7344976E-05, -0.3539628E-06),( -0.7344815E-05, -0.3522355E-06),(  0.2272952E-01,  0.1029183E-03)
     90.0000,     34.0000,(  0.2333392E-01,  0.8569709E-04),( -0.1037675E-04, -0.5588603E-06),( -0.1037787E-04, -0.5538839E-06),(  0.2272940E-01,  0.1017700E-03)
     90.0000,     35.0000,(  0.2333385E-01,  0.8340531E-04),( -0.1340611E-04, -0.7677730E-06),( -0.1340637E-04, -0.7624512E-06),(  0.2272931E-01,  0.1005938E-03)
     90.0000,     36.0000,(  0.2333376E-01,  0.8107661E-04),( -0.1643024E-04, -0.9759825E-06),( -0.1643008E-04, -0.9753808E-06),(  0.2272925E-01,  0.9937227E-04)
     90.0000,     37.0000,(  0.2333368E-01,  0.7871235E-04),( -0.1944779E-04, -0.1176726E-05),( -0.1944765E-04, -0.1178540E-05),(  0.2272923E-01,  0.9810377E-04)
     90.0000,     38.0000,(  0.2333359E-01,  0.7633654E-04),( -0.2246019E-04, -0.1377676E-05),( -0.2246095E-04, -0.1376291E-05),(  0.2272925E-01,  0.9677992E-04)
     90.0000,     39.0000,(  0.2333349E-01,  0.7394435E-04),( -0.2546455E-04, -0.1582781E-05),( -0.2546509E-04, -0.1583517E-05),(  0.2272929E-01,  0.9543045E-04)
     90.0000,     40.0000,(  0.2333338E-01,  0.7153424E-04),( -0.2846110E-04, -0.1786374E-05),( -0.2846093E-04, -0.1782039E-05),(  0.2272937E-01,  0.9402471E-04)
     90.0000,     41.0000,(  0.2333328E-01,  0.6909868E-04),( -0.3144751E-04, -0.1982437E-05),( -0.3144809E-04, -0.1981662E-05),(  0.2272949E-01,  0.9257005E-04)
     90.0000,     42.0000,(  0.2333316E-01,  0.6664295E-04),( -0.3442489E-04, -0.2177858E-05),( -0.3442387E-04, -0.2174608E-05),(  0.2272963E-01,  0.9106311E-04)
     90.0000,     43.0000,(  0.2333303E-01,  0.6418363E-04),( -0.3739010E-04, -0.2378527E-05),( -0.3739017E-04, -0.2372635E-05),(  0.2272981E-01,  0.8950324E-04)
     90.0000,     44.0000,(  0.2333291E-01,  0.6171301E-04),( -0.4034362E-04, -0.2561433E-05),( -0.4034395E-04, -0.2563795E-05),(  0.2273003E-01,  0.8788771E-04)
     90.0000,     45.0000,(  0.2333278E-01,  0.5922416E-04),( -0.4328624E-04, -0.2751016E-05),( -0.4328505E-04, -0.2742658E-05),(  0.2273027E-01,  0.8622059E-04)
     90.0000,     46.0000,(  0.2333264E-01,  0.5670952E-04),( -0.4621203E-04, -0.2930050E-05),( -0.4621215E-04, -0.2936943E-05),(  0.2273055E-01,  0.8449983E-04)
     90.0000,     47.0000,(  0.2333250E-01,  0.5419380E-04),( -0.4912426E-04, -0.3104662E-05),( -0.4912537E-04, -0.3112095E-05),(  0.2273086E-01,  0.8272303E-04)
     90.0000,     48.0000,(  0.2333236E-01,  0.5167195E-04),( -0.5202224E-04, -0.3285702E-05),( -0.5202286E-04, -0.3284841E-05),(  0.2273119E-01,  0.8090130E-04)
     90.0000,     49.0000,(  0.2333221E-01,  0.4914165E-04),( -0.5490336E-04, -0.3457679E-05),( -0.5490287E-04, -0.3454552E-05),(  0.2273156E-01,  0.7901491E-04)
     90.0000,     50.0000,(  0.2333206E-01,  0.4659708E-04),( -0.5776730E-04, -0.3628157E-05),( -0.5776656E-04, -0.3622614E-05),(  0.2273197E-01,  0.7707268E-04)
     90.0000,     51.0000,(  0.2333190E-01,  0.4405807E-04),( -0.6061237E-04, -0.3786502E-05),( -0.6061319E-04, -0.3788289E-05),(  0.2273240E-01,  0.7505807E-04)
     90.0000,     52.0000,(  0.2333174E-01,  0.4150420E-04),( -0.6343987E-04, -0.3945118E-05),( -0.6344026E-04, -0.3940577E-05),(  0.2273285E-01,  0.7301238E-04)
```

8 Additional Information

8.1 YouTube Videos

YouTube offers useful didactic presentations and simulations.

1. The Radar cross-section of backscattering objects
2. Basic Concepts of Radar Cross Section (RCS)
3. Mie scattering
4. Mie theory (BME51 Lecture 5)
5. Mie Scattering

8.2 Further Reading

Radar rudiments

1. D. K. Barton and H.R. Ward (1969). *Handbook of Radar Measurement*. New York, NY: Penguin Random House
2. Andrei A. Kolosov (1987). *Over the Horizon Radar*. Artech House. ISBN: 9780890062333. URL: `https://us.artechhouse.com/Over-the-Horizon-Radar-P254.aspx`
3. Peyton Z Peebles (2007). *Radar principles*. John Wiley & Sons

Radar cross section

1. JW Jr Crispin (2013). *Methods of radar cross-section analysis*. Elsevier
2. Allen E Fuhs (1982). *Radar cross section lectures*. Monterey, California, Naval Postgraduate School. URL: `https://calhoun.nps.edu/server/api/core/bitstreams/9e69ec48-4628-4243-9f9b-7e879521f7f8/content`
3. Eugene F Knott, John F Schaeffer, and Michael T Tulley (2004). *Radar cross section*. SciTech Publishing
4. M Madheswaran and P Suresh Kumar (2012). "Estimation of wide band radar cross section (RCS) of regular shaped objects using method of moments (MOM)". in: *Ictact Journal on Communication Tech-nology* 3.2, pp. 536–541

Method of Moments

1. Walton C Gibson (2021). *The method of moments in electromagnetics*. Chapman and Hall/CRC
2. Roger F Harrington (1987). "The method of moments in electromagnetics". In: *Journal of Electromagnetic waves and Applications* 1.3, pp. 181–200
3. Cai-Cheng Lu and Chong Luo (2003). "Comparison of iteration convergences of SIE and VSIE for solving electromagnetic scattering problems for coated objects". In: *Radio Science* 38.2, pp. 11–1
4. Jiade Yuan, Changqing Gu, and Guodong Han (2009). "Efficient generation of method of moments matrices using equivalent dipole-moment method". In: *IEEE Antennas and Wireless Propagation Letters* 8, pp. 716–719

Using Mercury MoM and post-processing

1. Daniel Topa (Mar. 2020c). *Radar Cross Section Models for AFCAP Dashboard: Rapid Report 2020-02: Corrected*. Briefing
2. Daniel Topa (Apr. 2020a). *Mercury Method of Moments Adjunct Visualization Tool: Trials and Tribulations*. Tech. rep. ARFL/RVB
3. Daniel Topa (Apr. 2020d). *Radar Cross Section: Phase 1 Summary Report*. Tech. rep. ARFL/RVB
4. Daniel Topa (2020b). *Mercury Method of Moments: AFRL Quick Start Guide*. Tech. rep. AFRL

A Mercury Method of Moments: Data Formats

A.1 Numeric Results

The MoM RCS data is delivered in a matrix with m rows and n columns (standard matrix addressing).

$1 \leq m \leq 28$ MHz (integer steps)
$1 \leq n \leq 90$ degrees (integer steps)

The matrix is WIDE (more columns than rows)

Frequency partition: row 1: 3 MHz row 2: 4 MHz . . . . row 28: 30 Mhz
Let r index the rows. Then frequency ν is in row $= \nu - 2$
Angular partition col 1: 0 col 2: 1 . . . col 181: 180
col 1 col 2 col 3 col 181 0 1 2 . . . 180
Let c be the column index. The measurement for angle alpha is in column $c = alpha + 1$

The test asset is symmetric: $\sigma(\alpha) = \sigma(-\alpha)$

But the matrix can easily be delivered in other forms, such as the transpose (interchange rows and columns), or packed into a linear array.

Sample:

4.16411, 4.14247, 4.07319, 3.95637, 3.79263, 3.58287, 3.32827, 3.0303, . . .
18.2776, 18.2369, 18.1199, 17.9248, 17.6523, 17.3041, 16.8817, 16.3876, . . .
25.6306, 25.5886, 25.463, 25.2538, 24.9618, 24.5882, 24.1346, 23.6028, . . .
. . .

Includ rcs-backscatter-sphere.pdf

B Mercury Method of Moments: Software Toolkit

Mercury MoM produces thousands of lines of output to a `*.4112.txt` file, a mix of numbers and strings. Once the data portions are located, they can be harvested straightaway. However, the text messages include debug information and the text patterns are varied.

Data analysis on data sets with a large number of facets can take several hours.

B.1 `rcsharvester.f08`

```
!  harvest the electric field values from the ASCII file *.4112.txt mixed text and numeric
lines
!  compute the mean total RCS and write these values
```

B.1.1 Class Electric Fields: `m-class-electric-fields.f08`

B.1.2 `m-class-electric-fields.f08`

The primary output of the simulation are the electric fields. Lines 17-24 define the class; the remainder of the codes is for methods. The input electric field is resolved into two polarization axes: horizontal

and vertical. Each of these fields are resolved into horizontal and vertical components creating four complex vectors (line 21) whose length matches the angular sample size.

The class `m-class-electric-fields.f08` reads the text file and harvests the electric fields eventually passing back a composite value (lines 65-66) for all four components of the scattering return.

```
1  ! Parses alphanumeric line from MoM *.4112.txt and extracts electric field values
2  module mClassElectricFields
3
4      use mFormatDescriptors,             only : fmt_stat, fmt_iomsg
5      use mLibraryOfConstants,            only : cZero, MoMlineLength, messageLength
6      use mPrecisionDefinitions,          only : ip, rp
7
8      implicit none
9
10     integer ( ip ) :: left = 0, right = 0
11     integer :: io_stat = 0
12     character ( len = messageLength ) :: io_msg = ""
13     character ( len = 15 )            :: number = ""
14
15     ! theta = azimuth
16     ! phi = elevation (North Pole = 0, equator = 90)
17     type :: electricFields
18         real     ( rp ) :: meanTotalRCS = 0.0_rp
19         real     ( rp ) :: dBsm  = 0.0_rp
20         real     ( rp ) :: theta = 0.0_rp, phi = 0.0_rp
21         complex  ( rp ) :: thetaTheta = cZero, thetaPhi = cZero, phiTheta = cZero, phiPhi = cZero
22     contains
23         procedure, public :: gather_mean_total_rcs => gather_mean_total_rcs_sub
24     end type electricFields
25
26     private :: gather_mean_total_rcs_sub
27     private :: compute_mean_total_rcs_sub, compute_dbsm_sub, extract_electric_fields_sub
28     private :: gather_complex_field_sub, gather_real_field_sub
29
30     ! parameters
31     integer ( ip ), parameter :: mll = MomlineLength
32     ! finger print of data line: start and stop positions for each numerical field
33     ! load matrix as columns
34     ! sample data line:
35     !      90.0000,      0.0000,( -0.4572920E+05,  0.8350829E+05),(  0.2034567E+06, -0.9493007E+05),(  0.2034813E+06, -0.9492184E+05),( -0.1727375E+06,  0.3787291E+05)
36     integer, parameter :: endpoints ( 1 : 10, 1 : 2 ) = &
37         reshape ( [ [  1, 14, 28, 44, 62, 78,  96, 112, 130, 146 ], &
38     [ 12, 25, 42, 58, 76, 92, 110, 126, 144, 160 ] ], [ 10, 2 ] )
39     ! constructor
40     type ( electricFields ), parameter :: electricFields0 = &
41         electricFields ( meanTotalRCS = 0.0, theta = 0.0, phi = 0.0, &
42         thetaTheta = cZero, thetaPhi = cZero, phiTheta = cZero, phiPhi = cZero )
43 contains
44
45     ! master routine: only exposed procedure
46     subroutine gather_mean_total_rcs_sub ( me, textLine )
47         class ( electricFields ),       target :: me
48         character ( len = mll ), intent ( in ) :: textLine
49             call extract_electric_fields_sub ( me, textLine )
50             call compute_mean_total_rcs_sub  ( me )
51             call compute_dbsm_sub            ( me )
52         return
53     end subroutine gather_mean_total_rcs_sub
54
55     ! Sciacca prescription
56     subroutine compute_dbsm_sub ( me )
57         class ( electricFields ), target :: me
58             me % dBsm = 10.0_rp * log10 ( me % meanTotalRCS )
59         return
60     end subroutine compute_dbsm_sub
61
62     ! Sciacca prescription
63     subroutine compute_mean_total_rcs_sub ( me )
64         class ( electricFields ), target :: me
65             me % meanTotalRCS = abs ( me % thetaTheta ) + abs ( me % thetaPhi ) &
66                               + abs ( me % phiTheta ) + abs ( me % phiPhi )
67             me % meanTotalRCS = me % meanTotalRCS / real ( 2, kind = rp )
68         return
69     end subroutine compute_mean_total_rcs_sub
70
71     subroutine extract_electric_fields_sub ( me, textLine )
72         class ( electricFields ),       target :: me
73         character ( len = mll ), intent ( in ) :: textLine
74         integer ( ip ) :: position = 0
75             ! move across text line gathering numeric values
76             position = 1
77             call gather_real_field_sub  &
78                 ( position = position, real_value = me % theta, textLine = textLine, fmt = "( f12.4 )" )
79             call gather_real_field_sub  &
80                 ( position = position, real_value = me % phi,   textLine = textLine, fmt = "( f12.4 )" )
81             call gather_complex_field_sub  &
82                 ( position = position, complex_value = me % thetaTheta, textLine = textLine )
83             call gather_complex_field_sub  &
84                 ( position = position, complex_value = me % thetaPhi,   textLine = textLine )
85             call gather_complex_field_sub  &
```

```
                ( position = position, complex_value = me % phiTheta,   textLine = textLine )
            call gather_complex_field_sub  &
                ( position = position, complex_value = me % phiPhi,     textLine = textLine )
        return
    end subroutine extract_electric_fields_sub

    subroutine gather_real_field_sub ( position, real_value, textLine, fmt )
        real ( rp ),             intent ( out )   :: real_value
        integer ( ip ),          intent ( inout ) :: position
        character ( len = mll ), intent ( in )    :: textLine
        character ( len =   9 ), intent ( in )    :: fmt
            left  = endpoints ( position, 1 )
            right = endpoints ( position, 2 )
            write ( number, fmt = 100 ) textLine ( left : right )
                if ( io_stat /= 0 ) then
                    write ( * , fmt = '( 3g0 )' ) "Failure to WRITE string value '", trim ( textLine ( left : right ) ) , "'."
                    write ( * , fmt = fmt_stat  ) io_stat
                    write ( * , fmt = fmt_iomsg ) trim ( io_msg )
                    stop "Error occured in module 'mClassElectricFields', subroutine 'gather_real_field_sub'."
                end if
            read  ( number, fmt = fmt ) real_value
                if ( io_stat /= 0 ) then
                    write ( * , fmt = '( 5g0 )' ) "Failure to READ string value '", trim ( textLine ( left : right ) ) , &
                        "' as a REAL number using format descriptor ", fmt, "."
                    write ( * , fmt = fmt_stat  ) io_stat
                    write ( * , fmt = fmt_iomsg ) trim ( io_msg )
                    stop "Error occured in module 'mClassElectricFields', subroutine 'gather_real_field_sub'."
                end if
            position = position + 1
        return
        100 format ( g0 )
    end subroutine gather_real_field_sub

    subroutine gather_complex_field_sub ( position, complex_value, textLine )
        complex ( rp ),          intent ( out )   :: complex_value
        integer ( ip ),          intent ( inout ) :: position
        character ( len = mll ), intent ( in )    :: textLine
        real ( rp ) :: x = 0.0_rp, y = 0.0_rp
            call gather_real_field_sub ( position = position, real_value = x, textLine = textLine, fmt = "( e15.7 )" )
            call gather_real_field_sub ( position = position, real_value = y, textLine = textLine, fmt = "( e15.7 )" )
            complex_value = cmplx ( x, y )
        return
    end subroutine gather_complex_field_sub

end module mClassElectricFields
```

B.1.3 Class Data File: `m-class-data-file.f08`

```
module mClassDataFile

    use, intrinsic :: iso_fortran_env,  only : iostat_end
    ! classes
    use mClassAverages,                 only : average, average0
    use mClassElectricFields,           only : electricFields, electricFields0
    use mClassMesh,                     only : meshReal
    use mAllocations,                   only : allocationToolKit, allocationToolKit0
    use mAllocationsSpecial,            only : allocate_rank_one_averages_sub
    ! utilities
    use mLibraryOfConstants,            only : fileNameLength, messageLength, MoMlineLength
    ! use mBulkRCS,                       only : BulkRCS, BulkRCS0
    use mFileHandling,                  only : safeopen_readonly, safeopen_writereplace
    use mFormatDescriptors,             only : fmt_one, fmt_stat, fmt_iomsg, fmt_shape2
    use mPrecisionDefinitions,          only : ip, rp
    use mTextFileUtilities,             only : count_lines_sub, mark_frequencies_sub,read_text_lines_sub, file_closer_sub, &
                                               iostat_check_sub
    ! use mTextFileUtilities,             only : count_lines_sub, file_closer_sub, iostat_check_sub, mark_frequencies_sub, &
    !                                            parse_name_sub, read_text_lines_sub
    implicit none

    ! parameters
    integer ( ip ), parameter :: fnl = fileNameLength, msgl = messageLength, mll = MoMlineLength
    character ( len = 9 ), parameter :: strAzimuth   = "azimuth  "
    character ( len = 9 ), parameter :: strElevation = "elevation"
    character ( len = * ), parameter :: moduleCrash  = "Program crashed in module 'mClassDataFile', "

    integer :: io_stat = 0
    character ( len = msgl ) :: io_msg = ""

    type :: dataFile4112
        ! rank 2
        real ( rp ),             allocatable :: rcs_table  ( : , : ) ! angle mesh length x nu mesh length
        real ( rp ),             allocatable :: dbsm_table ( : , : ) ! angle mesh length x nu mesh length
        ! ! rank 1
        integer ( ip ),          allocatable :: lineNumbersFrequency ( : )!, &
!                                               lineNumbersFinished  ( : )
        type ( average ),        allocatable :: perFrequencyAverage  ( : )  ! nu mesh length
        type ( average )                     :: globalAverage
        character ( len = mll ), allocatable :: lines4112Text ( : )        ! length numlines4112Text
```

```
        ! rank 0
        type ( electricFields ) :: eFields = electricFields0
        type ( meshReal ) :: meshFrequency, &
                             meshFreeAngle
        integer ( ip ) :: numFrequencies   = 0, &
                          numFixedAngles   = 0, &
                          numFreeAngles    = 0, &
                          numMeasurements  = 0, &
                          numLines4112Text = 0
        integer ( ip ) :: io_unit = 0
        character ( len =   9 ) :: angleFixedType  = "", angleFreeType = ""
        character ( len = fnl ) :: file4112Name = "", fileRCStxtName = "", fileRCSbinaryName  = "", &
                                                      filedBsmTxtName = "", filedBsmBinaryName = ""
        ! allocation tools
        type ( allocationToolKit ) :: myKit = allocationToolKit0
    contains
        procedure, public :: allocate_rcs_tables               => allocate_rcs_tables_sub, &
                             allocate_rcsAverages              => allocate_rcsAverages_sub, &
                             characterize_rcs_by_frequency     => characterize_rcs_by_frequency_sub, &
                             check_rcs_table_structure         => check_rcs_table_structure_sub, &
                             establish_free_angle_mesh         => establish_free_angle_mesh_sub, &
                             establish_frequency_mesh          => establish_frequency_mesh_sub, &
                             extract_rcs_from_4112_file        => extract_rcs_from_4112_file_sub, &
                             harvest_frequencies               => harvest_frequencies_sub, &
                             set_file_names                    => set_file_names_sub, &
                             set_free_angle_azimuth            => set_free_angle_azimuth_sub, &
                             set_free_angle_elevation          => set_free_angle_elevation_sub, &
                             write_rcs_file_set                => write_rcs_file_set_sub, &
                             write_rcs_binary                  => write_rcs_binary_sub, &
                             write_rcs_csv                     => write_rcs_csv_sub, &
                             write_dBsm_binary                 => write_dBsm_binary_sub, &
                             write_dBsm_csv                    => write_dBsm_csv_sub, &
                             write_summary_by_frequency        => write_summary_by_frequency_sub, &
                             write_summary_for_all_frequencies => write_summary_for_all_frequencies_sub
    end type dataFile4112

    private :: allocate_rcs_tables_sub, allocate_rcsAverages_sub, &
               establish_free_angle_mesh_sub, establish_frequency_mesh_sub, extract_rcs_from_4112_file_sub, &
               harvest_frequencies_sub, &
               set_file_names_sub, set_free_angle_azimuth_sub, set_free_angle_elevation_sub, &
               write_summary_by_frequency_sub, write_summary_for_all_frequencies_sub

contains

    subroutine characterize_rcs_by_frequency_sub ( me )
        class ( dataFile4112 ), target :: me
        type ( average ), pointer :: p => null ( )
        integer ( ip ) :: kFrequency = 0

            sweep_frequencies: do kFrequency = 1, me % numFrequencies
                p => me % perFrequencyAverage ( kFrequency )
                    call p % find_max_and_min          ( vector = me % rcs_table ( 1 : me % numFreeAngles, kFrequency ) )
                    call p % compute_mean_and_variance ( vector = me % rcs_table ( 1 : me % numFreeAngles, kFrequency ), &
                                                           one = me % meshFreeAngle % one )
                p => null ( )
            end do sweep_frequencies

        return
    end subroutine characterize_rcs_by_frequency_sub

    module subroutine write_summary_for_all_frequencies_sub ( me )
        class ( dataFile4112 ), target :: me
        integer ( ip ) :: kFrequency = 0, first = 0, last = 0, numConvolution = 0
        real ( rp ), allocatable :: global_rcs ( : ), one ( : )
            ! allocate memory for all RCS measurements
            numConvolution = me % numFrequencies * me % numFreeAngles
            call me % myKit % allocate_rank_one_reals ( real_array = global_rcs, index_min = 1, index_max = numConvolution )
            call me % myKit % allocate_rank_one_reals ( real_array = one,        index_min = 1, index_max = numConvolution )
            ! load data vector
            sweep_frequencies: do kFrequency = 1, me % meshFrequency % numMeshElements
                first = ( kFrequency - 1 ) * me % numFreeAngles + 1
                last  = first + me % numFreeAngles - 1
                global_rcs ( first : last ) = me % rcs_table ( 1 : me % numFreeAngles, kFrequency )
            end do sweep_frequencies
            ! compute extrema
            one ( : ) = global_rcs ( : ) - global_rcs ( : ) + 1.0_rp
            call me % globalAverage % find_max_and_min          ( vector = global_rcs ( 1 : numConvolution ) )
            call me % globalAverage % compute_mean_and_variance ( vector = global_rcs ( 1 : numConvolution ), one = one )
            write ( * , * )
            write ( * , fmt = 100 ) me % globalAverage % mean, &
                                    me % globalAverage % standardDeviation, &
                                    me % globalAverage % extrema % minValue, &
                                    me % globalAverage % extrema % maxValue
        return
        100 format ( "Aggregate for all RCS measurements: mean = ", g0, " +/- ", g0, ", min = ", g0, ", max = ", g0 )
    end subroutine write_summary_for_all_frequencies_sub

    module subroutine write_summary_by_frequency_sub ( me )
        class ( dataFile4112 ), target :: me
        integer ( ip ) :: kFrequency = 0
            write ( * , * )
            sweep_frequencies: do kFrequency = 1,   me % meshFrequency % numMeshElements
```

```
                write ( * , fmt = 100 ) kFrequency, me % meshFrequency % meshValues ( kFrequency ), &
                                                    me % perFrequencyAverage ( kFrequency ) % mean, &
                                                    me % perFrequencyAverage ( kFrequency ) % standardDeviation, &
                                                    me % perFrequencyAverage ( kFrequency ) % extrema % minValue, &
                                                    me % perFrequencyAverage ( kFrequency ) % extrema % maxValue
            end do sweep_frequencies
        return
        100 format ( I3.3, ". nu = ", g0, ", mean RCS = ", g0, " +/- ", g0, ", min = ", g0, ", max = ", g0 )
    end subroutine write_summary_by_frequency_sub

    module subroutine write_rcs_file_set_sub ( me )
        class ( dataFile4112 ), target :: me
            call me % write_rcs_csv     ( )
            call me % write_rcs_binary  ( )
            call me % write_dBsm_csv    ( )
            call me % write_dBsm_binary ( )
        return
    end subroutine write_rcs_file_set_sub

    module subroutine write_rcs_binary_sub ( me )
        class ( dataFile4112 ), target :: me
        integer ( ip )           :: io_rcs = 0
        character ( len = msgl ) :: crashChain = ""

            crashChain = moduleCrash // "subroutine 'write_rcs_binary_sub'."

            open ( newunit = io_rcs, file = me % fileRCSbinaryName, action = 'WRITE', status = 'REPLACE', form = 'UNFORMATTED', &
                                    iostat = io_stat, iomsg = io_msg )
            call iostat_check_sub ( action = "UNFORMATTED OPENING", fileName = me % fileRCSbinaryName, crashChain = crashChain, &
                                    iostat = io_stat, iomsg = io_msg )

            write ( io_rcs, iostat = io_stat,  iomsg = io_msg ) me % rcs_table ( 1 : me % meshFreeAngle  % numMeshElements, &
                                                                                1 : me % meshFrequency  % numMeshElements )
            call iostat_check_sub ( action = "UNFORMATTED WRITE to", fileName = me % fileRCSbinaryName, crashChain = crashChain, &
                                    iostat = io_stat, iomsg = io_msg )
            call file_closer_sub ( io_unit = io_rcs, fileName = me % fileRCSbinaryName, crashChain = crashChain )

        return
    end subroutine write_rcs_binary_sub

    module subroutine write_rcs_csv_sub ( me )
        class ( dataFile4112 ),         target :: me
        integer ( ip ) :: kFrequency = 0, kFreeAngle = 0, &
                          io_out = 0
        character ( len = msgl ) :: crashChain = ""

            crashChain = moduleCrash // "subroutine 'write_rcs_csv_sub'."
            io_out = safeopen_writereplace ( me % fileRCStxtName )
            ! write RCS values one row (frequency) at a time
            sweep_frequencies: do kFrequency = 1, me % meshFrequency % numMeshElements
                write ( io_out, fmt = me % meshFreeAngle % valuesFormatDescriptor ) ( me % rcs_table ( kFreeAngle, kFrequency ), &
                        kFreeAngle = 1, me % meshFreeAngle % numMeshElements )
                call iostat_check_sub ( action = "WRITE to", fileName = me % fileRCStxtName, crashChain = crashChain, &
                                        iostat = io_stat, iomsg = io_msg )
            end do sweep_frequencies
            ! close io handle
            call file_closer_sub ( io_unit = io_out, fileName =  me % fileRCStxtName, crashChain = crashChain )

        return
    end subroutine write_rcs_csv_sub

    module subroutine write_dBsm_binary_sub ( me )
        class ( dataFile4112 ), target :: me
        integer ( ip )           :: io_rcs = 0
        character ( len = msgl ) :: crashChain = ""

            crashChain = moduleCrash // "subroutine write_dBsm_binary_sub'."

            open ( newunit = io_rcs, file = me % filedBsmBinaryName, action = 'WRITE', status = 'REPLACE', form = 'UNFORMATTED', &
                                    iostat = io_stat, iomsg = io_msg )
            call iostat_check_sub ( action = "UNFORMATTED OPENING", fileName = me % fileRCSbinaryName, crashChain = crashChain, &
                                    iostat = io_stat, iomsg = io_msg )

            write ( io_rcs, iostat = io_stat,  iomsg = io_msg ) me % dBsm_table ( 1 : me % meshFreeAngle  % numMeshElements, &
                                                                                  1 : me % meshFrequency  % numMeshElements )
            call iostat_check_sub ( action = "UNFORMATTED WRITE to", fileName = me % fileRCSbinaryName, crashChain = crashChain, &
                                    iostat = io_stat, iomsg = io_msg )
            call file_closer_sub ( io_unit = io_rcs, fileName = me % filedBsmBinaryName, crashChain = crashChain )

        return
    end subroutine write_dBsm_binary_sub

    module subroutine write_dBsm_csv_sub ( me )
        class ( dataFile4112 ),         target :: me
        integer ( ip ) :: kFrequency = 0, kFreeAngle = 0, &
                          io_out = 0
        character ( len = msgl ) :: crashChain = ""

            crashChain = moduleCrash // "subroutine 'write_dBsm_csv_sub'."
            io_out = safeopen_writereplace ( me % filedBsmTxtName )
            ! write RCS values one row (frequency) at a time
            sweep_frequencies: do kFrequency = 1, me % meshFrequency % numMeshElements
```

```
225                 write ( io_out, fmt = me % meshFreeAngle % valuesFormatDescriptor ) ( me % dBsm_table ( kFreeAngle, kFrequency ), &
226                         kFreeAngle = 1, me % meshFreeAngle % numMeshElements )
227                 call iostat_check_sub ( action = "WRITE to", fileName = me % filedBsmTxtName, crashChain = crashChain, &
228                                         iostat = io_stat, iomsg = io_msg )
229             end do sweep_frequencies
230             ! close io handle
231             call file_closer_sub ( io_unit = io_out, fileName =  me % fileRCStxtName, crashChain = crashChain )
232
233         return
234     end subroutine write_dBsm_csv_sub
235
236     subroutine set_file_names_sub ( me, file4112Name )
237         class ( dataFile4112 ),         target :: me
238         character ( len = fnl ), intent ( in ) :: file4112Name
239         integer ( ip ) :: nameLength = 0
240
241             nameLength =        len ( trim ( file4112Name ) )
242             me % file4112Name       = trim ( file4112Name )
243             me % fileRCStxtName     = trim ( file4112Name ( 1 : nameLength - 4 ) ) // ".rcs.txt"
244             me % fileRCSbinaryName  = trim ( file4112Name ( 1 : nameLength - 4 ) ) // ".rcs.r32"
245             me % filedBsmTxtName    = trim ( file4112Name ( 1 : nameLength - 4 ) ) // ".dBsm.txt"
246             me % filedBsmBinaryName = trim ( file4112Name ( 1 : nameLength - 4 ) ) // ".dBsm.r32"
247
248         return
249     end subroutine set_file_names_sub
250
251     subroutine allocate_rcsAverages_sub ( me )
252         class ( dataFile4112 ), target :: me
253             call allocate_rank_one_averages_sub ( rank_1_average = me % perFrequencyAverage, &
254                                                   index_min = 1, index_max = me % numFrequencies )
255         return
256     end subroutine allocate_rcsAverages_sub
257
258     subroutine allocate_rcs_tables_sub ( me )
259         class ( dataFile4112 ), target :: me
260             call me % myKit % allocate_rank_two_reals (  rank_2_real_array = me % rcs_table,           &
261                                                          dim1_index_min = 1, dim1_index_max = me % numFreeAngles, &
262                                                          dim2_index_min = 1, dim2_index_max = me % numFrequencies )
263             call me % myKit % allocate_rank_two_reals (  rank_2_real_array = me % dBsm_table,           &
264                                                          dim1_index_min = 1, dim1_index_max = me % numFreeAngles, &
265                                                          dim2_index_min = 1, dim2_index_max = me % numFrequencies )
266         return
267     end subroutine allocate_rcs_tables_sub
268
269     subroutine establish_frequency_mesh_sub ( me )
270         class ( dataFile4112 ), target :: me
271             ! count lines in MoM file (e.q. 14844)
272             call count_lines_sub ( fullFileName = me % file4112Name, numLines = me % numLines4112Text )
273             ! allocate object to hold text of MoM file as a collection of text lines
274             call me % myKit % allocate_rank_one_characters ( character_array = me % lines4112Text, &
275                                                              index_min = 1, index_max = me % numLines4112Text )
276             ! load MoM text into memory to count frequencies and angles
277             call read_text_lines_sub ( fileName = me % file4112Name, linesText = me % Lines4112Text )
278             ! sift through text lines for " Freq ="
279             call me % harvest_frequencies ( )
280         return
281     end subroutine establish_frequency_mesh_sub
282
283     ! sweep through character array looking for "  Freq"
284     ! store these values in a temporary array until nuMesh is allocated
285     subroutine harvest_frequencies_sub ( me )
286         class ( dataFile4112 ), target :: me
287         ! pointers
288         !character ( len =  mll ),   pointer :: p => null ( )
289         type ( meshReal ),          pointer :: q => null ( )
290         type ( allocationToolKit ), pointer :: s => null ( )
291         ! temp arrays
292         real    ( ip ) :: tempFrequencyValues   ( 1 : 500 )
293         integer ( ip ) :: tempLineNumsFrequency ( 1 : 500 )
294         ! scalars
295         integer ( ip ) :: numfrequencies = 0, kFrequency = 0
296
297             ! find lines containing " Freq ="
298             call mark_frequencies_sub ( lines4112Text = me % lines4112Text,    &
299                                         numLines4112Text = me % numLines4112Text, &
300                                       tempFrequencyValues = tempFrequencyValues,   &
301                                     tempLineNumsFrequency = tempLineNumsFrequency, &
302                                           numfrequencies = numfrequencies )
303
304             ! record what we have learned about the mesh
305             q => me % meshFrequency
306                 q % numMeshElements = numfrequencies
307                 ! allocate data objects
308                 call q % allocate_mesh_real (  )
309                 s => me % myKit
310                     call s % allocate_rank_one_integers ( integer_array = me % lineNumbersFrequency, index_min = 1, &
311                                                           index_max = q  % numMeshElements )
312                 s => null ( )
313                 ! move temporary array data into data object
314                 do kFrequency = 1, q % numMeshElements
315                      q % meshValues           ( kFrequency ) = tempFrequencyValues   ( kFrequency )
316                     me % lineNumbersFrequency ( kFrequency ) = tempLineNumsFrequency ( kFrequency )
```

```
317                 end do
318                 me % numFrequencies = q % numMeshElements
319                 call q % analyze_mesh_values ( )
320             q => null ( )
321         return
322     end subroutine harvest_frequencies_sub
323
324     subroutine extract_rcs_from_4112_file_sub ( me )
325         class ( dataFile4112 ),         target :: me
326         ! locals
327         !real    ( rp )            :: sigma = 0.0_rp
328         integer ( ip )            :: kFrequency = 0, kFreeAngle = 0, linePosition = 0
329         character ( len = mll )   :: textLine
330
331             ! open *.4112.txt file, read text lines into memory
332             call read_text_lines_sub ( fileName = me % file4112Name, linesText = me % lines4112Text )
333             ! sweep and harvest RCS value
334             sweep_frequencies: do kFrequency = 1, me % numFrequencies
335                 linePosition = me % lineNumbersFrequency ( kFrequency ) + 8
336                 sweep_free_angles: do kFreeAngle = 1, me % numFreeAngles
337                     textLine = me % lines4112Text ( linePosition )
338                     call me % eFields % gather_mean_total_rcs ( textLine = textLine )
339                         me % rcs_table  ( kFreeAngle, kFrequency ) = me % eFields % meanTotalRCS
340                         me % dBsm_table ( kFreeAngle, kFrequency ) = me % eFields % dBsm
341                     linePosition = linePosition + 1
342                 end do sweep_free_angles
343             end do sweep_frequencies
344
345         return
346     end subroutine extract_rcs_from_4112_file_sub
347
348     subroutine set_free_angle_elevation_sub ( me )
349         class ( dataFile4112 ), target :: me
350             me % angleFreeType  = strElevation
351             me % angleFixedType = strAzimuth
352         return
353     end subroutine set_free_angle_elevation_sub
354
355     subroutine set_free_angle_azimuth_sub ( me )
356         class ( dataFile4112 ), target :: me
357             me % angleFreeType  = strAzimuth
358             me % angleFixedType = strElevation
359         return
360     end subroutine set_free_angle_azimuth_sub
361
362     subroutine establish_free_angle_mesh_sub ( me, angle_min, angle_max, angle_count )
363         class ( dataFile4112 ), target :: me
364         real    ( rp ), intent ( in ) :: angle_min, angle_max
365         integer ( ip ), intent ( in ) :: angle_count
366
367             me % meshFreeAngle % meshAverage % extrema % minValue = angle_min
368             me % meshFreeAngle % meshAverage % extrema % maxValue = angle_max
369             me % meshFreeAngle % numMeshElements = angle_count
370             me % numFreeAngles                   = angle_count
371
372             call me % meshFreeAngle % allocate_mesh_real (  )
373             call me % meshFreeAngle % compute_real_mesh_length ( )
374             call me % meshFreeAngle % compute_real_mesh_interval ( )
375             call me % meshFreeAngle % populate_real_mesh ( )
376             call me % meshFreeAngle % populate_integer_mesh ( )
377
378         return
379     end subroutine establish_free_angle_mesh_sub
380
381     subroutine check_rcs_table_structure_sub ( me )
382         class ( dataFile4112 ), target :: me
383             write ( * , * )
384             write ( * , fmt = '(  g0 )' ) "#  #  Dimensions for RCS data container  #  #"
385             write ( * , * )
386             write ( * , fmt = '(  g0 )' ) "# Expected dimensions:"
387             write ( * , fmt = '( 2g0 )' ) "# Number of radar frequencies scanned by MoM:   ",               me % numFrequencies
388             write ( * , fmt = '( 4g0 )' ) "# Number of ", me % angleFreeType, " angles scanned by MoM:  ",   me % numFreeAngles
389             write ( * , * )
390             write ( * , fmt = '( 2g0 )' ) "# Container MoM 4112.txt file: rcs_table"
391             write ( * , fmt = '( 6g0 )' ) "# Free angle dimension = ",  size   ( me % rcs_table, 1 ), &
392                                                " indices run from ", lbound ( me % rcs_table, 1 ), &
393                                                " to ",               ubound ( me % rcs_table, 1 )
394             write ( * , fmt = '( 6g0 )' ) "# Frequency dimension  = ",  size   ( me % rcs_table, 2 ), &
395                                                " indices run from ", lbound ( me % rcs_table, 2 ), &
396                                                " to ",               ubound ( me % rcs_table, 2 )
397             write ( * , * )
398         return
399     end subroutine check_rcs_table_structure_sub
400
401 end module mClassDataFile
```

C Mercury Method of Moments: Distribution and Rights

C.1 Distribution Letter for Software

The subsequent distribution letter was signed by Randy J. Petyak of the NASA Software Release Authority and describes terms for distribution, Government rights, and the ITAR status of the software.

December 11, 2019

Air Force Research Laboratory
RVB
3550 Aberdeen Ave SE
Kirtland Air Force Base, NM 87117-5776
Attn: Mr. Nelson Bonito

Subject: Transmittal of Mercury MoM version 4.1.12, MM_Viz Code.

This distribution letter details the terms for distribution, the Government rights in the software, and the ITAR status of the software. The software usage agreement you signed covers Mercury MoM and MMViz executable codes on both Linux 64 bit and Windows 64 bit. The Mercury MoM software is copyrighted by Matrix Compression, LLC. of which the Government retains certain rights to the software, and must be controlled as outlined in the signed Software Usage Agreement.

NASA furnishes this software under the condition that no further dissemination of the software shall be made without prior written permission of the NASA Langley Research Center. Additionally, this software has been designated as ITAR and needs appropriate protection while on the DVD or on an installed machine.

Note: The software falls under the purview of the U.S. Munitions List (USML), as defined in the International Traffic in Arms Regulations (ITAR), 22 CFR 120-130, and is export controlled. It shall not be taken out of the U.S. nor transferred to foreign nationals in the U.S. or abroad, without specific approval of a knowledgeable export control official, and/or unless an export license/license exemption is obtained/available from the United States Department of State. Violation of these regulations is punishable by fine, imprisonment, or both.

We are interested in your use of this software and the results you obtain. Please include us on your mailing list for any publications that may result from your use of this code.

If you have any additional questions related to your request, please contact me.

Randy J. Petyak
NASA Software Release Authority
(202) 358-4387

C.2 Copyright Statement by the Author

C.3 Legal Statement

MERCURY MOM™
Copyrighted
US Patents: 7,742,886; 7,844,407; 8,209,138; 8,725,464

This software was developed under NASA Contracts NAS1-02057, NAS1-02117, NNL08AA00B, and NNL13AA08B, and the U.S. Government retains certain rights.

MATRIX COMPRESSION TECHNOLOGIES, LLC
John Shaeffer
3278 Hunterdon Way
Marietta, Georgia 30067
john@shaeffer.com
770.952.3678

==========

C.4 Obtaining Software and Documentation

For more information regarding this document contact the following:

Kam W. Hom
NASA
Langley Research Center
Mail Stop 207
Hampton, Virginia 23681-2199
757-864-9608
kam.w.hom@nasa.gov

or

Jeffrey A. Miller, PhD
NASA
Langley Research Center
Mail Stop 207
Hampton, Virginia 23681-2199
757-864-9611
jeffrey.allen.miller@nasa.gov

Figure 5: Contact information to request Mercury MoM Software and Documentations

C.5 Distribution Contents

C.5.1 Executables

1. Linux 64-bit
2. Windows 64-bit

C.5.2 Documentation

The distribution includes four documents in PDF which are marked as CUI:

1. User's Guide
2. Pill Tutorial
3. Code Validation Report
4. Benchmark Tests

D Using Python to Create Spreadsheets

Some users preferred to digest the radar data in spreadsheet form. The Python toolkit xlswriter simplifies moving the data into `*.xlsx` form.

The spreadsheets eschew row-column notation (e.g. `A4`) and makes use of variables and named ranges to simplify the interpretation of the results.

D.1 Inputs

D.1.1 Main

Main module:

```
#! /usr/bin/python3

# # Daniel Topa

# # Excel tools
# xl_new_workbook( workbook_title )
# xl_sheet_requirements( this_workbook )
# xl_sheet_generate( this_workbook, title_sheet )
# xl_s( this_workbook )
# xl_sheet_header_footer( this_worksheet )

# # imports
import os               # probe, change directories
import sys              # python version
import datetime         # https://stackoverflow.com/questions/415511/how-to-get-the-current-time-in-python
import numpy as np
import pandas as pd
import xlsxwriter       # API for Excel
from xlsxwriter.utility import xl_rowcol_to_cell
import numpy as np
import pandas as pd

import cls_TestObject

# # modules
def xl_new_workbook( testObject ):

    MoMresults = xlsxwriter.Workbook( testObject.outputFile )
    print( "output file %s" % testObject.outputFile )
    print( "source file %s" % testObject.sourceFile )

    xl_sheet_master( MoMresults, testObject ) # MoM summary
    xl_add_data_sheets( MoMresults, testObject ) # MoM summary
    xl_sheet_provenance( MoMresults ) # provenance sheet

    return MoMresults;

#  ==   ==   == ==   ==   == ==   ==   == ==   ==   ==  #

def xl_add_data_sheets( this_workbook, testObject ):

    format_MoM_title = this_workbook.add_format( )
    format_MoM_title.set_bold( )
    format_MoM_title.set_font_color( "red" )

    format_MoM_head = this_workbook.add_format( )
    format_MoM_head.set_bold( )

    format_MoM_polarization = this_workbook.add_format( )
    format_MoM_polarization.set_bold( )

    number_format = this_workbook.add_format({'num_format': '#,##0.000'})

    # https://xlsxwriter.readthedocs.io/format.html#set_center_across
    cell_format = this_workbook.add_format()
    cell_format.set_center_across()

    for index in range( 1, 29 ):
        # add sheet and tag header and footer
        title = str( index + 2 ) + ' MHz'
        print ( 'adding sheet %s' % title )
        s = xl_sheet_generate( this_workbook, title )
        xl_sheet_header_footer( s )
        s.write( "A1", "MoM 4.1.12 output (*.dat)", format_MoM_title )
        #
        s.write( "A3", "azimuth, °", format_MoM_head )
        s.write( "B3", "HH, dBsm",   format_MoM_head )
        s.write( "C3", "VV, dBsm",   format_MoM_head )
        s.write( "D3", "HV, dBsm",   format_MoM_head )
        s.write( "E3", "VH, dBsm",   format_MoM_head )
        #
        s.write( "H3", "mean", format_MoM_head )
        s.write( "J3", "standard deviation", format_MoM_head )
        #
        s.write( "G4", "HH", format_MoM_polarization )
        s.write( "G5", "VV", format_MoM_polarization )
        #
    #    AttributeError: 'str' object has no attribute '_get_xf_index'
    #    s.write( "I4", "HH", u"\u00B1" )
        s.write( "I4", "±", cell_format )
        s.write( "I5", "±", cell_format )
        s.set_column( "I:I", 3 )

        # = AVERAGE( B5:B364)
        # = STDEV( B5:B364 )
```

```
        s.write( "H4", '= AVERAGE( B5:B364)', number_format )
        s.write( "H5", '= AVERAGE( C5:C364)', number_format )
        s.write( "J4", '= STDEV( B5:B364 )',  number_format )
        s.write( "J5", '= STDEV( B5:B364 )',  number_format )

        # read in data file
        filename = './data/sphere-005-' + testObject.resolution + '-' + str( index + 2 ).zfill(2) + '.4112.dat.txt'
        s.write_string( "D1", filename )
        data = pd.read_csv( filename, delimiter=r"\s+", header = None )
        data_np = data.values
        row = 3
        col = 0
        for line in range( 0, len ( data_np ) ):
            cell = xl_rowcol_to_cell ( row, col )
            s.write( row, col, data_np[ line ][ 0 ], number_format )
            s.write( row, col + 1, data_np[ line ][ 1 ], number_format )
            s.write( row, col + 2, data_np[ line ][ 2 ], number_format )
            s.write( row, col + 3, data_np[ line ][ 3 ], number_format )
            s.write( row, col + 4, data_np[ line ][ 4 ], number_format )
            row += 1

    return

#  ==   ==   == ==   ==   == ==   ==   == ==   ==   ==  #

def xl_sheet_generate( this_workbook, title_sheet ):

    # insure every worksheet has a header and footer
    mySheet = this_workbook.add_worksheet( title_sheet )
    xl_sheet_header_footer( mySheet )

    return mySheet;

#  ==   ==   == ==   ==   == ==   ==   == ==   ==   ==  #

def xl_sheet_provenance( this_workbook ):

    # Define some global names.
    this_workbook.define_name( 'c_', '=299792458' )
    # forensic info
    s = xl_sheet_generate( this_workbook, "provenance" )
    #  # special formats
    # https://xlsxwriter.readthedocs.io/format.html?highlight=bold

    # method 1
    # setting the property as a dictionary of key/value pairs in the constructor
    format_title = this_workbook.add_format( )
    format_title.set_bold( )
    format_title.set_font_color( "blue" )

    # method 2
    # passing a dictionary of properties to the add_format() constructor
    format_time = this_workbook.add_format( {'num_format': 'yy/mm/dd hh:mm'} ) # https://xlsxwriter.readthedocs.io/working_with_dates_and_time.html

    # widen first columns
    s.set_column( "A:A", 15 )
    s.set_column( "B:B", 13 )

    # https://xlsxwriter.readthedocs.io/worksheet.html
    s.write_url( "A1", "https://en.wikipedia.org/wiki/Computational_electromagnetics", string = "Radar Cross Section Measurements" )

    #  #  provencance
    s.write( "A3", "Workbook created by", format_title )
    #s.write( "A1", tip, "boo" )

    # python notebook which creates workbook
    s.write( "A4", "python source" )
    s.write( "B4", os.path.basename( __file__ ) ) # charlie.py

    # current working directory
    s.write( "A5", "directory" )
    s.write( "B5", os.getcwd( ) ) # /Volumes/Tlaltecuhtli/repos/GitHub/topa-development/python/xlsx

    # python version
    s.write( "A6", "python version" )
    s.write( "B6", sys.version ) # "3.7.0 (default, Jun 28 2018, 07:39:16) [Clang 4.0.1 (tags/RELEASE_401/final)]"

    #  #  environment variables
    # practise row, col notation
    col = 0 # starting column
    row = 7 # starting row
    s.write( row, col, "Environment variables", format_title ); row += 1

    s.write( row, col, "$USER" ) # l127914
    s.write( row, col + 1, os.environ[ "USER" ] ); row += 1

    s.write( row, col, "$HOSTNAME" ) # Cauchy.Schwarz
    s.write( row, col + 1, os.environ[ "HOSTNAME" ] ); row += 1

    s.write( row, col, "$HOME" ) # /Users/l127914
    s.write( row, col + 1, os.environ[ "HOME" ] ); row += 1

```

```
178     s.write( row, col, "timestamp" ) # 11/21/18 16:18
179     s.write( row, col + 1, datetime.datetime.now( ), format_time ); row += 1
180 
181     #  #  Excel info routines
182     # https://xlsxwriter.readthedocs.io/working_with_formulas.html
183 
184     row += 1 # jump
185     s.write( row, col, "XL info function", format_title ); row += 1
186 
187     s.write( row, col, "platform" ) # mac
188     s.write_formula( row, col + 1, '= INFO( "system" )' ); row += 1
189 
190     s.write( row, col, "recalculation mode" ) # Automatic
191     s.write_formula( row, col + 1, '= INFO( "recalc" )' ); row += 1
192 
193     s.write( row, col, "active sheets" ) # 1
194     s.write_formula( row, col + 1, '= INFO( "numfile" )' ); row += 1
195 
196     s.write( row, col, "cursor" ) # $A:$A$1
197     s.write_formula( row, col + 1, '= INFO( "origin" )' ); row += 1
198 
199     s.write( row, col, "XL release" ) # 16.16
200     s.write_formula( row, col + 1, '= INFO( "release" )' ); row += 1
201 
202     s.write( row, col, "application directory" ) # /Users/dantopa/Library/Containers/com.microsoft.Excel/Data/Documents/
203     s.write_formula( row, col + 1, '= INFO( "directory" )' ); row += 1
204 
205     s.write( row, col, "operating systems" ) # Macintosh (Intel) Version 10.13.3 (Build 17D47)
206     s.write_formula( row, col + 1, '= INFO( "osversion" )' ); row += 1
207 
208     return
209 
210 #  ==   ==   == ==   ==   == ==   ==   == ==   ==   ==  #
211 
212 def xl_sheet_header_footer( this_worksheet ):
213 
214     # header: sheet name (center)
215     # footer: date/time, page number, path/file
216 
217     myheader = "&C&12&A" # fontsize 12
218     myfooter = "&L&8&T\n&8&D" + "&C &P / &N" + "&R&8&Z\n&8&F" # fontsize 8
219 
220     this_worksheet.set_header( myheader )
221     this_worksheet.set_footer( myfooter )
222 
223     return
224 
225 #  ==   ==   == ==   ==   == ==   ==   == ==   ==   ==  #
226 
227 def xl_sheet_master( this_workbook, testObject ):
228 
229     number_format = this_workbook.add_format({'num_format': '#,##0.000'})
230 
231     masterRow = 0
232     masterCol = 0
233     xl_set_label_column ( this_workbook, testObject, masterRow, masterCol )
234 
235     dataRow = 8
236     dataCol = 0
237     s = this_workbook.get_worksheet_by_name( testObject.masterSheet )
238     for index in range(1, 29):
239         dataCol += 1
240         nu = index + 2
241         xl_computation ( s, dataRow, dataCol, nu, number_format )
242 
243     return
244 
245 #  ==   ==   == ==   ==   == ==   ==   == ==   ==   ==  #
246 
247 # https://xlsxwriter.readthedocs.io/working_with_cell_notation.html
248 def xl_computation ( wsheet, row, col, nu, number_format ):
249 
250     # frequency
251     wsheet.write_number ( row, col, nu )
252 
253     # wavelength =  c_ / ( B11 * 1000000 )
254     cell = xl_rowcol_to_cell ( row, col )
255     wsheet.write ( row + 1, col, '= c_ / ( ' + cell + ' * 1000000 )', number_format ); row += 1
256 
257     # = radius / wavelength
258     cell = xl_rowcol_to_cell ( row, col )
259     wsheet.write ( row + 1, col, '= radius / ' + cell, number_format ); row += 3
260 
261     # MoM average dBsm  = '30 MHz'!$H4
262     wsheet.write_formula(row, col, "= '" + str( nu ) + " MHz'!$H$4", number_format ); row += 1
263     # relative error dBsm
264     cell = xl_rowcol_to_cell ( row - 1, col )
265     wsheet.write_formula ( row, col, '= 1 - size_optical_dbsm / ' + cell, number_format ); row += 2
266 
267     # rcs, sq m  = 10^( B15 / 10 )
268     cell = xl_rowcol_to_cell ( row - 3, col )
269     wsheet.write_formula ( row, col, '= 10^( ' + cell + ' / 10 )', number_format ); row += 1
```

```
    # rel error (sq m)  =  1 - size_optical_sq_m / B18
    cell = xl_rowcol_to_cell ( row - 1, col )
    wsheet.write_formula ( row, col, '= 1 - size_optical_sq_m / ' + cell, number_format )

    return

#  ==   ==   == ==   ==   == ==   ==   == ==   ==   ==  #

def xl_set_label_column( wbook, testObject, row, col ):

    # method 1
    # setting the property as a dictionary of key/value pairs in the constructor
    format_title = wbook.add_format( )
    format_title.set_bold( )
    format_title.set_font_color( "blue" )

    format_label = wbook.add_format( )
    format_label.set_bold( )

    # https://xlsxwriter.readthedocs.io/example_defined_name.html
    # https://docs.python.org/2.0/ref/strings.html
    wbook.define_name( 'c_', '=299792458' )
    #string = '\'=' + str( testObject.sizeValue / 2 ) + '\''
    #print( 'string = %s' % string )
    wbook.define_name( 'radius', '=5' )
    wbook.define_name( 'size_optical_sq_m', '=\'' + testObject.masterSheet + '\'!$B$6' )
    wbook.define_name( 'size_optical_dbsm', '=\'' + testObject.masterSheet + '\'!$B$7' )

    # sheet operations
    s = xl_sheet_generate( wbook, testObject.masterSheet )
    s.set_first_sheet( )

    # widen first columns
    s.set_column( "A:A", 17 )
    s.set_column( "B:B", 10  )

    # column of labels
    s.write_string( row, col, 'INPUT', format_title ); row += 2

    s.write( row, col, 'MoM output:', format_label )
    s.write( row, col + 1, testObject.sourceFile ); row += 2

    s.write( row, col, testObject.sizeName, format_label );
    s.write( row, col + 1, testObject.sizeValue )
    s.write( row, col + 2, 'm' );  row += 1

    s.write( row, col, 'optical size', format_label )
    s.write( row, col + 1, '= pi() * radius^2' )
    s.write_string( row, col + 2, testObject.areaUnits ); row += 1
    s.write_formula( row, col + 1, '= 10 * LOG10( size_optical_sq_m )' );
    s.write( row, col + 2, 'dB area' ); row += 2

    s.write( row, col, 'frequency (MHz)', format_label ); row += 1
    s.write( row, col, 'wavelength (m)', format_label ); row += 1
    s.write( row, col, 'radius / lambda', format_label ); row += 2

    s.write( row, col, 'MoM average (dbSm)', format_label ); row += 1
    s.write( row, col, 'rel error (dbSm)', format_label ); row += 2

    s.write( row, col, 'rcs, sq m', format_label ); row += 1
    s.write( row, col, 'rel error (sq m)', format_label )

    xl_sheet_header_footer( s )


    return

# root@f21d93a5a2e9:sphere $ python tools_xl.py
#
# root@f21d93a5a2e9:sphere $ date
# Wed Jun 24 01:19:38 MDT 2020
#
# root@f21d93a5a2e9:sphere $ pwd
# /Tlaloc/python/sphere
```

D.1.2 Class Test Object

Radar return data.

```
#!/usr/bin/python3

# # Daniel Topa

# imports
import math                # pi
import uuid                # Universal Unique IDentifier
#from pathlib import Path   # rename file

```

```
class TestObject( object ):
    def __init__( self ):

        self._descriptor      = None    # sphere
        self._sizeName        = None    # diameter
        self._sizeValue       = None    # 10
        self._sizeUnits       = None    # m
        self._areaValue       = None    # pi r^2
        self._areaUnits       = None    # m^2
        self._resolution      = None    # 04
        self._mastersheet     = None    # sphere, d = 10 m
        self._sourceFile      = None    # *.dat
        self._sourcePath      = None    # absolute path to *.dat
        self._sourcePathFile  = None    # path + source file name
        self._outputFile      = None    # *.xlsx
        self._outputPath      = None    # absolute path to *.xlsx
        self._outputPathFile  = None    # path + *.xlsx
        self._uuid            = uuid.uuid4( ) # de facto time stamp

#   P R O P E R T I E S   #

    @property
    def descriptor( self ):
        """Descriptor (sphere, cube, etc.)"""
        return self._descriptor

    @property
    def sizeName( self ):
        """Name of size parameter (edge, radius, etc.)"""
        return self._sizeName

    @property
    def sizeValue( self ):
        """Length parameter"""
        return self._sizeValue

    @property
    def sizeUnits( self ):
        """Units (m, mm, etc.)"""
        return self._sizeUnits

    @property
    def areaValue( self ):
        """Area"""
        return self._areaValue

    @property
    def areaUnits( self ):
        """Area units (m^2, mm, etc.)"""
        return self._areaUnits

    @property
    def masterSheet( self ):
        """Name of master sheet"""
        return self._masterSheet

    @property
    def sourcePath( self ):
        """Path (absolute) to source file"""
        return self._sourcePath

    @property
    def sourceFile( self ):
        """Path + Name for input file"""
        return self._sourceFile

    @property
    def outputFile( self ):
        """Name of output file"""
        return self._outputFile

    @property
    def outputPath( self ):
        """Path (absolute) to output file"""
        return self._outputPath

    @property
    def outputPathFile( self ):
        """Path + Name for output file"""
        return self._outputPathFile

    @property
    def uuid( self ):
        """Universal unique identifier: connects requirements to source document"""
        return self._uuid

#   S E T T E R S   #

    @descriptor.setter
    def descriptor( self, value ):
        self._descriptor = value

```

```
102     @sizeName.setter
103     def sizeName( self, value ):
104         self._sizeName = value
105 
106     @sizeValue.setter
107     def sizeValue( self, value ):
108         self._sizeValue = value
109 
110     @sizeUnits.setter
111     def sizeUnits( self, value ):
112         self._sizeUnits = value
113 
114     @areaValue.setter
115     def areaValue( self, value ):
116         self._areaValue = value
117 
118     @areaUnits.setter
119     def areaUnits( self, value ):
120         self._areaUnits = value
121 
122     @masterSheet.setter
123     def masterSheet( self, value ):
124         self._masterSheet = value
125 
126     @sourcePath.setter
127     def sourcePath( self, value ):
128         self._sourcePath = value
129 
130     @sourceFile.setter
131     def sourceFile( self, value ):
132         self._sourceFile = value
133 
134     @outputFile.setter
135     def outputFile( self, value ):
136         self._outputFile = value
137 
138     @outputPath.setter
139     def outputPath( self, value ):
140         self._outputPath = value
141 
142     @outputPathFile.setter
143     def outputPathFile( self, value ):
144         self._outputPathFile = value
145 
146 #   D E L E T E R S   #
147 
148     @descriptor.deleter
149     def descriptor( self ):
150         del self._descriptor
151 
152     @sizeName.deleter
153     def sizeName( self ):
154         del self._sizeName
155 
156     @sizeValue.deleter
157     def sizeValue( self ):
158         del self._sizeValue
159 
160     @sizeUnits.deleter
161     def sizeUnits( self ):
162         del self._sizeUnits
163 
164     @areaValue.deleter
165     def areaValue( self ):
166         del self._areaValue
167 
168     @areaUnits.deleter
169     def areaUnits( self ):
170         del self._areaUnits
171 
172     @masterSheet.deleter
173     def masterSheet( self ):
174         del self._masterSheet
175 
176     @sourcePath.deleter
177     def sourcePath( self ):
178         del self._sourcePath
179 
180     @sourceFile.deleter
181     def sourceFile( self ):
182         del self._sourceFile
183 
184     @outputFile.deleter
185     def outputFile( self ):
186         del self._outputFile
187 
188     @outputPath.deleter
189     def outputPath( self ):
190         del self._outputPath
191 
192     @outputPathFile.deleter
193     def outputPathFile( self ):
```

```
194         del self._outputPathFile
195 
196     @uuid.deleter
197     def uuid( self ):
198         del self._uuid
199 
200 #   M E T H O D S   #
201 
202     def print_attributes( self ):
203         print('\nSource attributes:')
204         print( 'descriptor     = %s' % self.descriptor )
205         print( 'sizeName       = %s' % self.sizeName )
206         print( 'sizeValue      = %s' % self.sizeValue )
207         print( 'sizeUnits      = %s' % self.sizeUnits )
208         print( 'sourcePath     = %s' % self.sourcePath )
209         print( 'sourceFile     = %s' % self.sourceFile )
210         print( 'sourcePathFile = %s' % self.sourcePathFile )
211         print( 'outputFile     = %s' % self.outputFile )
212         print( 'outputPath     = %s' % self.outputPath )
213         print( 'outputPathFile = %s' % self.outputPathFile )
214         print( 'uuid           = %s' % self.uuid )
215         return
216 
217 #  ==   ==   == ==   ==   == ==   ==   == ==   ==   ==  #
218 
219     def scenario( self ):
220         self.setup_io( ) # establish outut file
221         #self.read_MoM_file( )
222         self.area_circular( ) # compute area for given geometry
223         return
224 
225 #  ==   ==   == ==   ==   == ==   ==   == ==   ==   ==  #
226 
227     def read_MoM_file( self ):
228         ## ## read source file
229         print ( "reading source file %s" % self.sourceFile )
230         # https://stackoverflow.com/questions/3277503/in-python-how-do-i-read-a-file-line-by-line-into-a-list
231         with open( self.sourceFile ) as f:
232             self.col_lines = f.read( ).splitlines( )
233             self.numLines = len( self.col_lines )
234         return
235 
236 #  ==   ==   == ==   ==   == ==   ==   == ==   ==   ==  #
237 
238     def setup_io( self ):
239         # combine path and file name
240         self.sourcePathFile  = self.sourcePath + self.sourceFile
241         self.outputPathFile  = self.outputPath + self.outputFile
242         self.masterSheet     = self.descriptor + ', ' + self.sizeName[0] + ' = ' + str( self.sizeValue ) + ' ' + self.sizeUnits
243         return
244 
245 #  ==   ==   == ==   ==   == ==   ==   == ==   ==   ==  #
246 
247     def area_circular( self ):
248         # combine path and file name
249         self.areaValue = math.pi * ( self.sizeValue / 2 )**2
250         return
251 
252 #  ==   ==   == ==   ==   == ==   ==   == ==   ==   ==  #
253 
```

D.1.3 Excel Details

Toolkit for writing to spreadsheets.

```
1  #! /usr/bin/python3
2  
3  # # Daniel Topa
4  
5  # # Excel tools
6  # xl_new_workbook( workbook_title )
7  # xl_sheet_requirements( this_workbook )
8  # xl_sheet_generate( this_workbook, title_sheet )
9  # xl_s( this_workbook )
10 # xl_sheet_header_footer( this_worksheet )
11 
12 # # imports
13 import os              # probe, change directories
14 import sys             # python version
15 import datetime        # https://stackoverflow.com/questions/415511/how-to-get-the-current-time-in-python
16 import numpy as np
17 import pandas as pd
18 import xlsxwriter      # API for Excel
19 from xlsxwriter.utility import xl_rowcol_to_cell
20 import numpy as np
21 import pandas as pd
22 
23 import cls_TestObject
24 
```

```
# # modules
def xl_new_workbook( testObject ):

    MoMresults = xlsxwriter.Workbook( testObject.outputFile )
    print( "output file %s" % testObject.outputFile )
    print( "source file %s" % testObject.sourceFile )

    xl_sheet_master( MoMresults, testObject ) # MoM summary
    xl_add_data_sheets( MoMresults, testObject ) # MoM summary
    xl_sheet_provenance( MoMresults ) # provenance sheet

    return MoMresults;

#  ==   ==   == ==   ==   == ==   ==   == ==   ==   ==  #

def xl_add_data_sheets( this_workbook, testObject ):

    format_MoM_title = this_workbook.add_format( )
    format_MoM_title.set_bold( )
    format_MoM_title.set_font_color( "red" )

    format_MoM_head = this_workbook.add_format( )
    format_MoM_head.set_bold( )

    format_MoM_polarization = this_workbook.add_format( )
    format_MoM_polarization.set_bold( )

    number_format = this_workbook.add_format({'num_format': '#,##0.000'})

    # https://xlsxwriter.readthedocs.io/format.html#set_center_across
    cell_format = this_workbook.add_format()
    cell_format.set_center_across()

    for index in range( 1, 29 ):
        # add sheet and tag header and footer
        title = str( index + 2 ) + ' MHz'
        print ( 'adding sheet %s' % title )
        s = xl_sheet_generate( this_workbook, title )
        xl_sheet_header_footer( s )
        s.write( "A1", "MoM 4.1.12 output (*.dat)", format_MoM_title )
        #
        s.write( "A3", "azimuth, °", format_MoM_head )
        s.write( "B3", "HH, dBsm",   format_MoM_head )
        s.write( "C3", "VV, dBsm",   format_MoM_head )
        s.write( "D3", "HV, dBsm",   format_MoM_head )
        s.write( "E3", "VH, dBsm",   format_MoM_head )
        #
        s.write( "H3", "mean", format_MoM_head )
        s.write( "J3", "standard deviation", format_MoM_head )
        #
        s.write( "G4", "HH", format_MoM_polarization )
        s.write( "G5", "VV", format_MoM_polarization )
        #
    #    AttributeError: 'str' object has no attribute '_get_xf_index'
    #    s.write( "I4", "HH", u"\u00B1" )
        s.write( "I4", '±', cell_format )
        s.write( "I5", '±', cell_format )
        s.set_column( "I:I", 3 )

        # = AVERAGE( B5:B364)
        # = STDEV( B5:B364 )
        s.write( "H4", '= AVERAGE( B5:B364)', number_format )
        s.write( "H5", '= AVERAGE( C5:C364)', number_format )
        s.write( "J4", '= STDEV( B5:B364 )',  number_format )
        s.write( "J5", '= STDEV( B5:B364 )',  number_format )

        # read in data file
        filename = './data/sphere-005-' + testObject.resolution + '-' + str( index + 2 ).zfill(2) + '.4112.dat.txt'
        s.write_string( "D1", filename )
        data = pd.read_csv( filename, delimiter=r"\s+", header = None )
        data_np = data.values
        row = 3
        col = 0
        for line in range( 0, len ( data_np ) ):
            cell = xl_rowcol_to_cell ( row, col )
            s.write( row, col, data_np[ line ][ 0 ], number_format )
            s.write( row, col + 1, data_np[ line ][ 1 ], number_format )
            s.write( row, col + 2, data_np[ line ][ 2 ], number_format )
            s.write( row, col + 3, data_np[ line ][ 3 ], number_format )
            s.write( row, col + 4, data_np[ line ][ 4 ], number_format )
            row += 1

    return

#  ==   ==   == ==   ==   == ==   ==   == ==   ==   ==  #

def xl_sheet_generate( this_workbook, title_sheet ):

    # insure every worksheet has a header and footer
    mySheet = this_workbook.add_worksheet( title_sheet )
    xl_sheet_header_footer( mySheet )

```

```
117     return mySheet;
118
119 #  ==   ==   == ==   ==   == ==   ==   == ==   ==   ==  #
120
121 def xl_sheet_provenance( this_workbook ):
122
123     # Define some global names.
124     this_workbook.define_name( 'c_', '=299792458' )
125     # forensic info
126     s = xl_sheet_generate( this_workbook, "provenance" )
127     #  # special formats
128     # https://xlsxwriter.readthedocs.io/format.html?highlight=bold
129
130     # method 1
131     # setting the property as a dictionary of key/value pairs in the constructor
132     format_title = this_workbook.add_format( )
133     format_title.set_bold( )
134     format_title.set_font_color( "blue" )
135
136     # method 2
137     # passing a dictionary of properties to the add_format() constructor
138     format_time = this_workbook.add_format( {'num_format': 'yy/mm/dd hh:mm'} ) # https://xlsxwriter.readthedocs.io/working_with_dates_and_time.html
139
140     # widen first columns
141     s.set_column( "A:A", 15 )
142     s.set_column( "B:B", 13 )
143
144     # https://xlsxwriter.readthedocs.io/worksheet.html
145     s.write_url( "A1", "https://en.wikipedia.org/wiki/Computational_electromagnetics", string = "Radar Cross Section Measurements" )
146
147     #  #  provencance
148     s.write( "A3", "Workbook created by", format_title )
149     #s.write( "A1", tip, "boo" )
150
151     # python notebook which creates workbook
152     s.write( "A4", "python source" )
153     s.write( "B4", os.path.basename( __file__ ) ) # charlie.py
154
155     # current working directory
156     s.write( "A5", "directory" )
157     s.write( "B5", os.getcwd( ) ) # /Volumes/Tlaltecuhtli/repos/GitHub/topa-development/python/xlsx
158
159     # python version
160     s.write( "A6", "python version" )
161     s.write( "B6", sys.version ) # "3.7.0 (default, Jun 28 2018, 07:39:16) [Clang 4.0.1 (tags/RELEASE_401/final)]"
162
163     #  #  environment variables
164     # practise row, col notation
165     col = 0 # starting column
166     row = 7 # starting row
167     s.write( row, col, "Environment variables", format_title ); row += 1
168
169     s.write( row, col, "$USER" ) # l127914
170     s.write( row, col + 1, os.environ[ "USER" ] ); row += 1
171
172     s.write( row, col, "$HOSTNAME" ) # Cauchy.Schwarz
173     s.write( row, col + 1, os.environ[ "HOSTNAME" ] ); row += 1
174
175     s.write( row, col, "$HOME" ) # /Users/l127914
176     s.write( row, col + 1, os.environ[ "HOME" ] ); row += 1
177
178     s.write( row, col, "timestamp" ) # 11/21/18 16:18
179     s.write( row, col + 1, datetime.datetime.now( ), format_time ); row += 1
180
181     #  #  Excel info routines
182     # https://xlsxwriter.readthedocs.io/working_with_formulas.html
183
184     row += 1 # jump
185     s.write( row, col, "XL info function", format_title ); row += 1
186
187     s.write( row, col, "platform" ) # mac
188     s.write_formula( row, col + 1, '= INFO( "system" )' ); row += 1
189
190     s.write( row, col, "recalculation mode" ) # Automatic
191     s.write_formula( row, col + 1, '= INFO( "recalc" )' ); row += 1
192
193     s.write( row, col, "active sheets" ) # 1
194     s.write_formula( row, col + 1, '= INFO( "numfile" )' ); row += 1
195
196     s.write( row, col, "cursor" ) # $A:$A$1
197     s.write_formula( row, col + 1, '= INFO( "origin" )' ); row += 1
198
199     s.write( row, col, "XL release" ) # 16.16
200     s.write_formula( row, col + 1, '= INFO( "release" )' ); row += 1
201
202     s.write( row, col, "application directory" ) # /Users/dantopa/Library/Containers/com.microsoft.Excel/Data/Documents/
203     s.write_formula( row, col + 1, '= INFO( "directory" )' ); row += 1
204
205     s.write( row, col, "operating systems" ) # Macintosh (Intel) Version 10.13.3 (Build 17D47)
206     s.write_formula( row, col + 1, '= INFO( "osversion" )' ); row += 1
207
208     return
```

```
209
210 #  ==   ==   == ==   ==   == ==   ==   == ==   ==   ==  #
211
212 def xl_sheet_header_footer( this_worksheet ):
213
214     # header: sheet name (center)
215     # footer: date/time, page number, path/file
216
217     myheader = "&C&12&A" # fontsize 12
218     myfooter = "&L&8&T\n&8&D" + "&C &P / &N" + "&R&8&Z\n&8&F" # fontsize 8
219
220     this_worksheet.set_header( myheader )
221     this_worksheet.set_footer( myfooter )
222
223     return
224
225 #  ==   ==   == ==   ==   == ==   ==   == ==   ==   ==  #
226
227 def xl_sheet_master( this_workbook, testObject ):
228
229     number_format = this_workbook.add_format({'num_format': '#,##0.000'})
230
231     masterRow = 0
232     masterCol = 0
233     xl_set_label_column ( this_workbook, testObject, masterRow, masterCol )
234
235     dataRow = 8
236     dataCol = 0
237     s = this_workbook.get_worksheet_by_name( testObject.masterSheet )
238     for index in range(1, 29):
239         dataCol += 1
240         nu = index + 2
241         xl_computation ( s, dataRow, dataCol, nu, number_format )
242
243     return
244
245 #  ==   ==   == ==   ==   == ==   ==   == ==   ==   ==  #
246
247 # https://xlsxwriter.readthedocs.io/working_with_cell_notation.html
248 def xl_computation ( wsheet, row, col, nu, number_format ):
249
250     # frequency
251     wsheet.write_number ( row, col, nu )
252
253     # wavelength =  c_ / ( B11 * 1000000 )
254     cell = xl_rowcol_to_cell ( row, col )
255     wsheet.write ( row + 1, col, '= c_ / ( ' + cell + ' * 1000000 )', number_format ); row += 1
256
257     # = radius / wavelength
258     cell = xl_rowcol_to_cell ( row, col )
259     wsheet.write ( row + 1, col, '= radius / ' + cell, number_format ); row += 3
260
261     # MoM average dBsm  = '30 MHz'!$H4
262     wsheet.write_formula(row, col, "= '" + str( nu ) + " MHz'!$H$4", number_format ); row += 1
263     # relative error dBsm
264     cell = xl_rowcol_to_cell ( row - 1, col )
265     wsheet.write_formula ( row, col, '= 1 - size_optical_dbsm / ' + cell, number_format ); row += 2
266
267     # rcs, sq m  = 10^( B15 / 10 )
268     cell = xl_rowcol_to_cell ( row - 3, col )
269     wsheet.write_formula ( row, col, '= 10^( ' + cell + ' / 10 )', number_format ); row += 1
270     # rel error (sq m)  =  1 - size_optical_sq_m / B18
271     cell = xl_rowcol_to_cell ( row - 1, col )
272     wsheet.write_formula ( row, col, '= 1 - size_optical_sq_m / ' + cell, number_format )
273
274     return
275
276 #  ==   ==   == ==   ==   == ==   ==   == ==   ==   ==  #
277
278 def xl_set_label_column( wbook, testObject, row, col ):
279
280     # method 1
281     # setting the property as a dictionary of key/value pairs in the constructor
282     format_title = wbook.add_format( )
283     format_title.set_bold( )
284     format_title.set_font_color( "blue" )
285
286     format_label = wbook.add_format( )
287     format_label.set_bold( )
288
289     # https://xlsxwriter.readthedocs.io/example_defined_name.html
290     # https://docs.python.org/2.0/ref/strings.html
291     wbook.define_name( 'c_', '=299792458' )
292     #string = '\'=' + str( testObject.sizeValue / 2 ) + '\''
293     #print( 'string = %s' % string )
294     wbook.define_name( 'radius', '=5' )
295     wbook.define_name( 'size_optical_sq_m', '=\'' + testObject.masterSheet + '\'!$B$6' )
296     wbook.define_name( 'size_optical_dbsm', '=\'' + testObject.masterSheet + '\'!$B$7' )
297
298     # sheet operations
299     s = xl_sheet_generate( wbook, testObject.masterSheet )
300     s.set_first_sheet( )
```

```
301
302     # widen first columns
303     s.set_column( "A:A", 17 )
304     s.set_column( "B:B", 10  )
305
306     # column of labels
307     s.write_string( row, col, 'INPUT', format_title ); row += 2
308
309     s.write( row, col, 'MoM output:', format_label )
310     s.write( row, col + 1, testObject.sourceFile ); row += 2
311
312     s.write( row, col, testObject.sizeName, format_label );
313     s.write( row, col + 1, testObject.sizeValue )
314     s.write( row, col + 2, 'm' );  row += 1
315
316     s.write( row, col, 'optical size', format_label )
317     s.write( row, col + 1, '= pi() * radius^2' )
318     s.write_string( row, col + 2, testObject.areaUnits ); row += 1
319     s.write_formula( row, col + 1, '= 10 * LOG10( size_optical_sq_m )' );
320     s.write( row, col + 2, 'dB area' ); row += 2
321
322     s.write( row, col, 'frequency (MHz)', format_label ); row += 1
323     s.write( row, col, 'wavelength (m)', format_label ); row += 1
324     s.write( row, col, 'radius / lambda', format_label ); row += 2
325
326     s.write( row, col, 'MoM average (dbSm)', format_label ); row += 1
327     s.write( row, col, 'rel error (dbSm)', format_label ); row += 2
328
329     s.write( row, col, 'rcs, sq m', format_label ); row += 1
330     s.write( row, col, 'rel error (sq m)', format_label )
331
332     xl_sheet_header_footer( s )
333
334
335     return
336
337 # root@f21d93a5a2e9:sphere $ python tools_xl.py
338 #
339 # root@f21d93a5a2e9:sphere $ date
340 # Wed Jun 24 01:19:38 MDT 2020
341 #
342 # root@f21d93a5a2e9:sphere $ pwd
343 # /Tlaloc/python/sphere
344
345
```

D.2 Outputs

The main module arranges the output data by creating a tab for each separate radar frequency in the range $3 - 30$ MHz. Other tabs contain aggregate information and diagnostics.

```
 1 #! /usr/bin/python3
 2
 3 # # Daniel Topa
 4
 5 # # imports
 6 import datetime             # timestamps
 7 import os                   # opeating system
 8 import sys                  # python version
 9 from pathlib import Path    # rename file
10 import xlsxwriter           # API for Excel
11 import tools_xl             # spreadsheet authoring tools
12 # home brew
13 # classes
14 import cls_TestObject
15
16 #  ==   ==   == ==   ==   == ==   ==   == ==   ==   ==  #
17
18 if __name__ == "__main__":
19
20     series = '050'
21     object = cls_TestObject.TestObject( )     # instantiate TestObject
22     # populate object properties
23     object.descriptor = "sphere"
24     object.sizeName   = "diameter"
25     object.sizeValue  = 10
26     object.sizeUnits  = "m"
27     object.areaUnits  = "m^2"
28     object.resolution = "03"
29     object.sourceFile = "sphere-" + series + "-" + object.resolution
30     object.sourcePath = "/Tlaloc/python/sphere/"
31     object.outputFile = 'sphere-d' + series + '-res' + object.resolution + '.xlsx'
32     object.outputPath = "/Tlaloc/python/sphere/"
33     object.setup_io( )
34     object.area_circular( )
35
36     # container for MoM data and results
37     MoMresults = tools_xl.xl_new_workbook( object )
```

```
38
39      # close MoMresults
40      MoMresults.close( )
41      print( "\n", datetime.datetime.now( ) )
42      print( "source: %s/%s" % ( os.getcwd( ), os.path.basename( __file__ ) ) )
43      print( "python version %s" % sys.version )
44
45  # root@f21d93a5a2e9:sphere $ date
46  # Wed Jun 24 01:20:41 MDT 2020
47  #
48  # root@f21d93a5a2e9:sphere $ pwd
49  # /Tlaloc/python/sphere
50  #
51  # root@f21d93a5a2e9:sphere $ python MoM.py
52  # output file RCS-sphere-10.xlsx
53  # source file sphere-050-01
54  # adding sheet 3 MHz
55  # adding sheet 4 MHz
56  # adding sheet 5 MHz
57  # adding sheet 6 MHz
58  # adding sheet 7 MHz
59  # adding sheet 8 MHz
60  # adding sheet 9 MHz
61  # adding sheet 10 MHz
62  # adding sheet 11 MHz
63  # adding sheet 12 MHz
64  # adding sheet 13 MHz
65  # adding sheet 14 MHz
66  # adding sheet 15 MHz
67  # adding sheet 16 MHz
68  # adding sheet 17 MHz
69  # adding sheet 18 MHz
70  # adding sheet 19 MHz
71  # adding sheet 20 MHz
72  # adding sheet 21 MHz
73  # adding sheet 22 MHz
74  # adding sheet 23 MHz
75  # adding sheet 24 MHz
76  # adding sheet 25 MHz
77  # adding sheet 26 MHz
78  # adding sheet 27 MHz
79  # adding sheet 28 MHz
80  # adding sheet 29 MHz
81  # adding sheet 30 MHz
82  #
83  #  2020-06-24 01:20:46.349142
84  # source: /Tlaloc/python/sphere/MoM.py
85  # python version 3.7.7 (default, Jun 22 2020, 22:42:46)
86  # [GCC 10.1.0]
87
88  # $ lsb_release -a
89  # LSB Version:  :core-4.1-amd64:core-4.1-noarch
90  # Distributor ID:   CentOS
91  # Description:  CentOS Linux release 7.8.2003 (Core)
92  # Release:  7.8.2003
93  # Codename: Core
```

References

1. Barton, D. K. and H.R. Ward (1969). *Handbook of Radar Measurement*. New York, NY: Penguin Random House.
2. Bruder, J et al. (2003). "IEEE standard for letter designations for radar-frequency bands". In: *IEEE Aerospace & Electronic Systems Society*, pp. 1–3.
3. Crispin, JW Jr (2013). *Methods of radar cross-section analysis*. Elsevier.
4. Fuhs, Allen E (1982). *Radar cross section lectures*. Monterey, California, Naval Postgraduate School. URL: `https://calhoun.nps.edu/server/api/core/bitstreams/9e69ec48-4628-4243-9f9b-7e879521f7f8/content`.
5. Gibson, Walton C (2021). *The method of moments in electromagnetics*. Chapman and Hall/CRC.
6. Harrington, Roger F (1987). "The method of moments in electromagnetics". In: *Journal of Electromagnetic waves and Applications* 1.3, pp. 181–200.
7. Knott, Eugene F, John F Schaeffer, and Michael T Tulley (2004). *Radar cross section*. SciTech Publishing.

8. Kolosov, Andrei A. (1987). *Over the Horizon Radar*. Artech House. ISBN: 9780890062333. URL: https://us.artechhouse.com/Over-the-Horizon-Radar-P254.aspx.
9. Lu, Cai-Cheng and Chong Luo (2003). "Comparison of iteration convergences of SIE and VSIE for solving electromagnetic scattering problems for coated objects". In: *Radio Science* 38.2, pp. 11–1.
10. Madheswaran, M and P Suresh Kumar (2012). "Estimation of wide band radar cross section (RCS) of regular shaped objects using method of moments (MOM)". In: *Ictact Journal on Communication Tech-nology* 3.2, pp. 536–541.
11. Peebles, Peyton Z (2007). *Radar principles*. John Wiley & Sons.
12. Topa, Daniel (Apr. 2020a). *Mercury Method of Moments Adjunct Visualization Tool: Trials and Tribulations*. Tech. rep. ARFL/RVB.
13. — (2020b). *Mercury Method of Moments: AFRL Quick Start Guide*. Tech. rep. AFRL.
14. — (Mar. 2020c). *Radar Cross Section Models for AFCAP Dashboard: Rapid Report 2020-02: Corrected*. Briefing.
15. — (Apr. 2020d). *Radar Cross Section: Phase 1 Summary Report*. Tech. rep. ARFL/RVB.
16. Yuan, Jiade, Changqing Gu, and Guodong Han (2009). "Efficient generation of method of moments matrices using equivalent dipole-moment method". In: *IEEE Antennas and Wireless Propagation Letters* 8, pp. 716–719.