The Practicality of a Seemingly Simple Project to Learn the Secrets of the Universe. Or How Physics is Like Making a Cake.

David Alan Smith, Utah State University
The Practicality of a Seemingly Simple Project to Learn the Secrets of the Universe. Or How Physics is Like Making a Cake

April 14, 2014

A senior seminar presented by

David A. Smith
Outline

• Introduction/Motivation
• Radio Telescope Design
• Data Collection
• Data Analysis
• Final Thoughts
Introduction/Motivation

Purpose of Senior Seminar?
Introduction/Motivation

Demonstrate Learning
Introduction/Motivation

Present Research
...But Why The Title?
...But Why The Title?

• I’ve built lots of antennas
...But Why The Title?

• I’ve built lots of antennas
  • Didn’t seem too difficult
...But Why The Title?

• I’ve built lots of antennas...
  
  • Didn’t seem too difficult...
  
  • Parabolic dish antenna...
...But Why The Title?

• I’ve built lots of antennas...

  • Didn’t seem too difficult...

  • Parabolic dish antenna...

  • Radio telescope just an antenna
...But Why The Title?

• I’ve built lots of antennas...

  • Didn’t seem too difficult...

  • Parabolic dish antenna...

  • Radio telescope just an antenna

  • ARRL Antenna Book...
...But Why The Title?

\[ F_c = \frac{6917.26}{d(\text{inches})} \]

“The circular feed can be made of copper, brass, aluminum, or even tin in the form of a coffee or juice can... The circular feed must be within a proper size (diameter) range for the frequency being used. This feed operates in the dominant circular waveguide mode known as the \( TE_{11} \) mode. The guide must be large enough to pass the \( TE_{11} \) mode with no attenuation, but smaller than the diameter that permits the next higher \( TM_{01} \) mode to propagate.”
...But Why The Title?

\[ F_c = \frac{6917.26}{d \text{(inches)}} \]

“The circular feed can be made of copper, brass, aluminum, or even tin in the form of a coffee or juice can... The circular feed must be within a proper size (diameter) range for the frequency being used. This feed operates in the dominant circular waveguide mode known as the \( TE_{11} \) mode. The guide must be large enough to pass the \( TE_{11} \) mode with no attenuation, but smaller than the diameter that permits the next higher \( TM_{01} \) mode to propagate.”

20 years ago these words meant nothing to me
...But Why The Title?

\[
F_c = \frac{6917.26}{d(\text{inches})}
\]

“The circular feed can be made of copper, brass, aluminum, or even tin in the form of a coffee or juice can... The circular feed must be within a proper size (diameter) range for the frequency being used. This feed operates in the dominant circular waveguide mode known as the \( TE_{11} \) mode. The guide must be large enough to pass the \( TE_{11} \) mode with no attenuation, but smaller than the diameter that permits the next higher \( TM_{01} \) mode to propagate.”

20 years ago these words meant nothing to me

Now I understand what they mean!
...But Why The Title?

\[ F_c = \frac{6917.26}{d(\text{inches})} \]

- Where did this equation come from?
...But Why The Title?

\[ F_c = \frac{6917.26}{d(\text{inches})} \]

- Where did this equation come from?
- Would it be possible to derive it?
...But Why The Title?

\[ F_c = \frac{6917.26}{d(\text{inches})} \]

- Where did this equation come from?
- Would it be possible to derive it?
- Became important part of project
So how is physics like making a cake?
So how is physics like making a cake?

Two ways to make a cake...
So how is physics like making a cake?

Two ways to make a cake...

• Buy a box...
So how is physics like making a cake?

Two ways to make a cake...

- Buy a box...
- Add some stuff...
So how is physics like making a cake?

Two ways to make a cake...

- Buy a box...
- Add some stuff...
- Eat cake!
So how is physics like making a cake?

Two ways to make a cake...

• Buy a box...
• Add some stuff...
• Eat cake!

Or...
So how is physics like making a cake?

Two ways to make a cake...

• Buy a box...  • Add some stuff...  • Eat cake!

Or...

• Learn about the ingredients...
So how is physics like making a cake?

Two ways to make a cake...

• Buy a box...  • Add some stuff...  • Eat cake!

Or...

• Learn about the ingredients...
  • Understand how they work together...
So how is physics like making a cake?

Two ways to make a cake...

- Buy a box...
- Add some stuff...
- Eat cake!

Or...

- Learn about the ingredients...
  - Understand how they work together...
  - Master the art of baking a cake...
So how is physics like making a cake?

Two ways to make a cake...

- Buy a box...
- Add some stuff...
- Eat cake!

Or...

- Learn about the ingredients...
  - Understand how they work together...
  - Master the art of baking a cake...

...From scratch!
Use the box...

\[
KE = \frac{1}{2}mv^2
\]

\[
F_c = \frac{6917.26}{d(\text{inches})}
\]
Use the tools...

\[ E \equiv \gamma mc^2 \Rightarrow E_{\text{kin}} = mc^2 \left( \frac{1}{\sqrt{1 - \left(\frac{u^2}{c^2}\right)}} - 1 \right) \]
Radio Telescope Design

“A telescope is an instrument that aids in the observation of remote objects by collecting electromagnetic radiation.”

http://en.wikipedia.org/wiki/Telescope

10” Reflector/Dobsonian Mount

Electromagnetic radiation between 400-700 nanometers
Radio Telescope Design

Parabolic Reflector

- 6-foot diameter
- Focal length 17.25 inches
- Dish gain at 4GHz ≈ 35dB
- LNB Gain ≈ 66 dB
- System Gain ≈ 101 dB

3 dB double signal; 10dB increases by 10
1 watt → $1.25 \times 10^{10}$ watts!

Electromagnetic radiation between 7-8 centimeters
Radio Telescope Design

Detail of feed system

- “Diamond” LNB
  - Low Noise Block Down Converter
  - Input 3.7-4.3 GHz
  - Output 950-1450 MHz
- Wave Guide
  - $TE_{11}$ mode
  - Inner diameter 2.10” (5.334 cm)

According to the ARRL formula:

$$TE_{11} \rightarrow F_c = \frac{6917.26}{2.10} = 3.3 \text{ GHz}$$

$$TM_{01} \rightarrow F_c = \frac{9034.85}{2.10} = 4.3 \text{ GHz}$$
Radio Telescope Design

Let’s try to derive the cutoff frequency

Start with the following assumptions:
• Wave guide is perfect conductor
• Inside the material \( \mathbf{E} = 0 \) and \( \mathbf{B} = 0 \)
• At boundary \( \Rightarrow \mathbf{E}^\parallel = 0 \) and \( \mathbf{B}^\perp = 0 \)
• \( k \) is real
• The area inside the wave guide approximate free space

Then generally,
\[
\mathbf{E}(x, y, z, t) = \mathbf{E}_0(x, y)e^{i(kz-\omega t)}
\]
\[
\mathbf{B}(x, y, z, t) = \mathbf{B}_0(x, y)e^{i(kz-\omega t)}
\]

The electric/magnetic fields must satisfy Maxwell’s equations in the interior of the wave guide:
\[
\nabla \cdot \mathbf{E} = 0 \quad \nabla \cdot \mathbf{B} = 0 \quad \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad \nabla \times \mathbf{B} = \frac{1}{c^2} \frac{\partial \mathbf{E}}{\partial t}
\]

The goal is to find functions for \( \mathbf{E}_0 \) and \( \mathbf{B}_0 \) so the fields obey Maxwell’s Equations subject to the boundary conditions. Confined waves are not generally transvers. To fit the BC longitudinal components \( E_z \) and \( B_z \) are included such that
\[
\mathbf{E}_0 = E_{0x}\hat{x} + E_{0y}\hat{y} + E_{0z}\hat{z} \quad \mathbf{B}_0 = B_{0x}\hat{x} + B_{0y}\hat{y} + B_{0z}\hat{z}
\]

Radio Telescope Design

Each of those components are functions of \( x \) and \( y \). Next the curl of \( \mathbf{E} \) and \( \mathbf{B} \) are evaluated. According to Griffiths, these equations can all be solved for \( E_x, E_y, B_x, B_y \). Griffiths states, “It suffices, then, to determine the longitudinal components. If we knew those, we could quickly calculate all the others, just by differentiating. Inserting equations for \( E_x, E_y, B_x, B_y \) into the divergence equations yields uncoupled equations for \( E_z \) and \( B_z \)” leaving us with,

\[
\begin{align*}
\left[ \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \left( \frac{\omega}{c} \right)^2 - k^2 \right] E_z &= 0 \\
\left[ \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \left( \frac{\omega}{c} \right)^2 - k^2 \right] B_z &= 0
\end{align*}
\]

TE Waves when \( E_z = 0 \) \hspace{2cm} TM Waves when \( B_z = 0 \)

We want the TE mode, so \( E_z = 0 \)

The proof of the above statement is given in Griffiths, page 427
Radio Telescope Design

Looking back for a moment to Maxwell's Equations then taking the curl of both sides,

\[ \nabla \times (\nabla \times \mathbf{B}) = \nabla \times \left( \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} \right) \rightarrow \quad \nabla^2 \mathbf{B} = \mu_0 \varepsilon_0 \frac{\partial^2 \mathbf{B}}{\partial t^2} \rightarrow \quad \nabla^2 \mathbf{B}_z = \mu_0 \varepsilon_0 \frac{\partial^2 \mathbf{B}_z}{\partial t^2} \]

**⇒** \[ \mathbf{B}_z = \mathbf{B}_0 e^{i(kz - \omega t)} \]

In cylindrical coords \( B_z \) is a function of \( r \) and \( \varphi \) so the Laplacian is recast. Making the full substitution for \( \mathbf{B}_z \) we have

\[ \nabla^2 \mathbf{B}_z = \frac{1}{r} \frac{\partial}{\partial r} \left[ r \frac{\partial \mathbf{B}_0 e^{i(kz - \omega t)}}{\partial r} \right] + \frac{1}{r} \frac{\partial^2 \mathbf{B}_0 e^{i(kz - \omega t)}}{\partial \varphi^2} + \frac{\partial^2 \mathbf{B}_0 e^{i(kz - \omega t)}}{\partial z^2} = \mu_0 \varepsilon_0 \frac{\partial^2 \mathbf{B}_0 e^{i(kz - \omega t)}}{\partial t^2} \]

Then doing derivatives, cancelling exponentials, and rearranging we see that

\[ \frac{1}{r} \frac{\partial}{\partial r} \left[ r \frac{\partial \mathbf{B}_0}{\partial r} \right] + \frac{1}{r} \frac{\partial^2 \mathbf{B}_0}{\partial \varphi^2} = \mathbf{B}_0 (k^2 - \mu_0 \varepsilon_0 \omega^2) \]

We can now use separation of variables...
Radio Telescope Design

\[ \mathbf{B}_{0z} = R(r)\Phi(\varphi) \]

\[ \Rightarrow \frac{\partial \mathbf{B}_{0z}}{\partial r} = \frac{\partial R}{\partial r}\Phi \]

\[ \Rightarrow \frac{\partial^2 \mathbf{B}_{0z}}{\partial \varphi^2} = \frac{\partial^2 \Phi}{\partial \varphi^2} R \]

Subbing in for \( \mathbf{B}_{0z} \), multipling by \( r^2 \), dividing by \( R(r)\Phi(\varphi) \), then moving things around we get

\[ \frac{r}{R} \frac{\partial}{\partial r} \left[ r \frac{\partial \mathbf{R}}{\partial r} \right] - r^2 (k^2 - \mu_0 \varepsilon_0 \omega^2) = -\frac{1}{\Phi} \frac{\partial^2 \Phi}{\partial \varphi^2} \]

Depends on \( \mathbf{R} \)...

Depends on \( \Phi \).

Since equal, constant. Call the constant \( m^2 \)

\[ \Rightarrow \Phi = A \cos(m_\varphi \varphi) + B \sin(m_\varphi \varphi) \]
Radio Telescope Design

\[
\frac{r \, \partial}{R \, \partial r} \left[ r \, \frac{\partial R}{\partial r} \right] - r^2 (k^2 - \mu_0 \varepsilon_0 \omega^2) = m_r^2
\]

Two new variables:

\[
h = \sqrt{(k^2 - \mu_0 \varepsilon_0 \omega^2)} \quad x = r \sqrt{(k^2 - \mu_0 \varepsilon_0 \omega^2)} \quad \Rightarrow x \equiv hr \Rightarrow r = \frac{x}{h} \Rightarrow dr = \frac{dx}{h} \Rightarrow \frac{1}{r} = \frac{h}{x}
\]

Multiply through by \( \frac{R}{r^2} \), inserting the new variables, and using the product rule give us

\[
\frac{\partial^2 R}{\partial x^2} + \frac{1}{x} \frac{\partial R}{\partial x} - R \left(1 - \frac{m_r^2}{x^2}\right) = 0
\]

This is a Bessel Equation of Order “n” with a general solution given as

\[
R(x) = A_m J_m(x) + B_m Y_m(x)
\]

\(J_m(x)\) is a Bessel Function of the first kind, \(Y_m(x)\) is a Bessel Function of the second kind. Apparently, \(Y_m(0) \rightarrow \infty\) which would cause the solution to be “unnatural,” leaving us with

\[
R = A_m J_m(hr)
\]
Radio Telescope Design

\[ R(x) = A_m J_m(x) + B_m Y_m(x) \]

Plot of Bessel Function of the First Kind \((J_m(x))\)
Radio Telescope Design

\[ R(x) = A_m J_m(x) + B_m Y_m(x) \]

Plot of Bessel Function of the Second Kind \((Y_m(x))\)

...blows up at \(x=0\)
Radio Telescope Design

Plot of Derivative of Bessel Function of the First Kind ($J'_{m}(x)$)

MatLab syntax: numeric::fsolve(diff(besselJ(1, x), x) = 0, x= 1..2)

$x \approx 1.841183781$
Radio Telescope Design

We finally have our solution for $B_{0z}$. Putting everything together we have,

$$B_z = A_m J_m (hr) [A \cos (m \phi \varphi) + B \sin (m \phi \varphi)] e^{i(kz - \omega t)}$$

The decoupled second-order equations for $E$ and $B$ are identical in form. Hence,

$$E_z = A_m J_m (hr) [A \cos (m \phi \varphi) + B \sin (m \phi \varphi)] e^{i(kz - \omega t)}$$

$E_z$ is a function of $r$ and $\varphi$. Plugging $E_z$ into Maxwell’s Equations in cylindrical form allows us to solve for $E_\varphi$. Hence,

$$\nabla \times E = \left[ \frac{1}{r} \frac{\partial E_z}{\partial \varphi} - \frac{\partial E_z}{\partial z} \right] \hat{r} + \left[ \frac{\partial E_z}{\partial z} - \frac{\partial E_z}{\partial r} \right] \hat{\varphi} + \frac{1}{r} \left[ \frac{\partial (rE_z)}{\partial r} - \frac{\partial E_z}{\partial \varphi} \right] \hat{z} = - \frac{\partial B_z}{\partial t}$$

$$\Rightarrow E_\varphi = h_r A_{mn} J_m (hr) [A \cos (m \phi \varphi) + B \sin (m \phi \varphi)] e^{-ih_z z} = 0$$

Since $J'_m (hr)$ is the only term that depends on $r$, and since at the boundary $r=R$ it follows that $E_\varphi$ must equal zero when $r=R$, then it follows that $J'_m (hr) R = 0$. Then we can say that

$$h_r R \equiv \chi_{mn} \Rightarrow h_r = \frac{\chi_{mn}}{R}$$

$\chi_{mn}$ is the $n$th root of the derivative of the Bessel function of the first kind, of the $m$th order.

So the $TE_{11}$ mode means the 1st root of the Bessel function of the first kind of the 1st order.

Radio Telescope Design

\[ h^2 = h_r^2 + h_z^2 \]

\[ \Rightarrow h_z = \sqrt{(h^2 - h_r^2)} \]

\[ \Rightarrow h_z = \sqrt{\left(h^2 - \left(\frac{\chi_{mn}}{R}\right)^2\right)} \]

The cutoff frequency is when \( h_z = 0 \) \( \Rightarrow h = \frac{\chi_{mn}}{R} \) \( \Rightarrow h_c = \omega_c \sqrt{\mu_0 \mu \varepsilon_0} = \frac{\chi_{mn}}{R} \)

\[ \Rightarrow \frac{\chi_{mn}}{R} = \omega_c \sqrt{\mu_0 \mu \varepsilon_0} \]

\[ \Rightarrow \frac{\chi_{mn}}{R} = 2\pi f_c \sqrt{\mu_0 \mu \varepsilon_0} \]

\[ \Rightarrow f_c = \frac{\chi_{mn} \sqrt{\mu_0 \mu \varepsilon_0}}{2\pi R} \Rightarrow f_c = \frac{\chi_{mn}}{2\pi R} c \]
Radio Telescope Design

\[ c \cong 186,282.397 \frac{\text{miles}}{\text{second}} = 11,802,852,688 \frac{\text{inches}}{\text{second}} \]

\[ \chi_{11} \cong 1.841183781 \]

\[ f_c = \frac{(1.841183781)(1.18 \times 10^{10})}{2\pi \frac{D}{2}} = \frac{6917262457}{D} \text{ Hz} \]

\[ = \frac{6917.26}{D} \text{ MHz} \]
Radio Telescope Design

\[ c \approx 186,282.397 \frac{\text{miles}}{\text{second}} = 11,802,852,688 \frac{\text{inches}}{\text{second}} \]

\[ \chi_{11} \approx 1.841183781 \]

\[ f_c = \frac{(1.841183781)(1.18 \times 10^{10})}{2\pi \frac{D}{2}} = \frac{6917262457}{D} \text{ Hz} \]

\[ = \frac{6917.26}{D} \text{ MHz} \]
Radio Telescope Design
Radio Telescope Design

Front view
- Freq: 950-2150
- Modified for voltage output
- Mic cable to laptop
- “Radio SkyPipe”

Back view
- Detail of modification
- Thanks Tyler Hooker!
Data Collection
Drift Scan Technique

- Allow Sun to pass through beam of radio telescope
- Difficult to point accurately

Path of Sun due to rotation of Earth

Radio Telescope Beam Width

Sun
Data Collection

Screen shot of typical Radio SkyPipe chart.

x-axis=time, y-axis=relative signal power

AOS

LOS

Background signal (quiet sky)
Data Collection

Interesting bumps. Telescope lobes?
Data Collection

Large dip right in center. Due to feed system?
Data Analysis

Analysis Procedure
• Smooth the chart (averaging)
• Get max, min, half-power
• Get calibration signal
  • 300 K building (house)
• Plug numbers into Excel
• Solar Brightness Temp

Data Points
• Sun Max
• Quiet Sky
• Calibration
• Half-power

Calculations
• True Sun
• True Calibration
• HP elapsed time
• HP beam width
• Antenna Sun Temp
• Solar Temp
• Antenna Temp
Data Analysis

Calculations

True Calibration = \( Calibration - Quiet\ Sky \)

True Sun = \( Sun\ Max - Quiet\ Sky \)

Solar Antenna Temp = \( \left( \frac{True\ Sun}{True\ Calib} \right) \times Temp \)

Half-power = \( (Sun\ Max + Quiet\ Sky)^{\frac{1}{2}} \)

Half-power elapsed time = \( HPT_1 - HPT_2 \)

Half-power Beam Width = \( \frac{Half-power\ elapsed\ time}{0.25^\circ} \)

Solar Temp = \( Solar\ Ant\ Temp \times \left( \frac{HPBW}{0.5^\circ} \right)^2 \)

Data Analysis

The Solar Atmosphere

Solar Temp at 4.0 GHz

54,111 Wilson and Thursby, 1999

40,000 Kundu, 1965

27,000 Koglin, 1994
### Data Analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Maximum</td>
<td>6442</td>
</tr>
<tr>
<td>Quiet Sky</td>
<td>2985</td>
</tr>
<tr>
<td>Calibration Signal</td>
<td>5106</td>
</tr>
<tr>
<td>Half-Power Figure</td>
<td>4713.5</td>
</tr>
<tr>
<td>Half-Power Time 1</td>
<td>13</td>
</tr>
<tr>
<td>Half-Power Time 2</td>
<td>31.2</td>
</tr>
<tr>
<td>Elapsed Time (mins)</td>
<td>18.2</td>
</tr>
<tr>
<td>HPBW (Degrees)</td>
<td>4.6</td>
</tr>
<tr>
<td>True Calibration</td>
<td>2121</td>
</tr>
<tr>
<td>True Solar Signal</td>
<td>3457</td>
</tr>
<tr>
<td>Signal to Calibration</td>
<td>1.6</td>
</tr>
<tr>
<td>Calibration Temp (F)</td>
<td>70</td>
</tr>
<tr>
<td>Calibration Temp (K)</td>
<td>325.4</td>
</tr>
<tr>
<td>Antenna Temp (K)</td>
<td>530.3214</td>
</tr>
<tr>
<td>Solar Temp (K)</td>
<td>43916</td>
</tr>
<tr>
<td>Antenna Temp (K)</td>
<td>457.9142</td>
</tr>
</tbody>
</table>

### Screen shot from Excel
## Data Analysis

<table>
<thead>
<tr>
<th></th>
<th>6835</th>
<th>6833</th>
<th>5706</th>
<th>6614</th>
<th>5199</th>
<th>5631</th>
<th>6952</th>
<th>7079</th>
<th>6829</th>
<th>6904</th>
<th>5755</th>
<th>5265</th>
<th>6442</th>
<th>6715</th>
<th>6864</th>
<th>5894</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Max</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quiet Sky</td>
<td>3444</td>
<td>3247</td>
<td>3227</td>
<td>4134</td>
<td>3201</td>
<td>3409</td>
<td>3168</td>
<td>3179</td>
<td>3007</td>
<td>3039</td>
<td>3402</td>
<td>2967</td>
<td>2985</td>
<td>2918</td>
<td>3286</td>
<td>3274</td>
</tr>
<tr>
<td>Calibration</td>
<td>4952</td>
<td>4952</td>
<td>4952</td>
<td>4952</td>
<td>4952</td>
<td>4952</td>
<td>5730</td>
<td>5730</td>
<td>5730</td>
<td>5730</td>
<td>5106</td>
<td>5106</td>
<td>5106</td>
<td>5106</td>
<td>4552</td>
<td>4552</td>
</tr>
<tr>
<td>True Calibration</td>
<td>1508</td>
<td>1705</td>
<td>1725</td>
<td>818</td>
<td>1751</td>
<td>1543</td>
<td>2562</td>
<td>2551</td>
<td>2723</td>
<td>2691</td>
<td>1704</td>
<td>2139</td>
<td>2121</td>
<td>2188</td>
<td>1266</td>
<td>1278</td>
</tr>
<tr>
<td>True Solar Signal</td>
<td>3391</td>
<td>3586</td>
<td>2479</td>
<td>2480</td>
<td>1998</td>
<td>2222</td>
<td>3784</td>
<td>3900</td>
<td>3822</td>
<td>3865</td>
<td>2353</td>
<td>2298</td>
<td>3457</td>
<td>3797</td>
<td>3578</td>
<td>2620</td>
</tr>
<tr>
<td>HPBW</td>
<td>4.4</td>
<td>4.4</td>
<td>3.1</td>
<td>3.3</td>
<td>2.4</td>
<td>2.5</td>
<td>4.2</td>
<td>3.9</td>
<td>4.3</td>
<td>4.3</td>
<td>2.5</td>
<td>2.6</td>
<td>4.6</td>
<td>5.4</td>
<td>3.44</td>
<td>2.27</td>
</tr>
<tr>
<td>Solar Max/Quiet Sky Ratio</td>
<td>2.0</td>
<td>2.1</td>
<td>1.8</td>
<td>1.6</td>
<td>1.6</td>
<td>1.7</td>
<td>2.2</td>
<td>2.2</td>
<td>2.3</td>
<td>2.3</td>
<td>1.7</td>
<td>1.8</td>
<td>2.2</td>
<td>2.3</td>
<td>2.1</td>
<td>1.8</td>
</tr>
<tr>
<td>Calibration/Quiet Sky Ratio</td>
<td>1.4</td>
<td>1.5</td>
<td>1.5</td>
<td>1.2</td>
<td>1.5</td>
<td>1.5</td>
<td>1.8</td>
<td>1.8</td>
<td>1.9</td>
<td>1.9</td>
<td>1.5</td>
<td>1.7</td>
<td>1.7</td>
<td>1.7</td>
<td>1.4</td>
<td>1.4</td>
</tr>
<tr>
<td>Solar Max/Calibration Ratio</td>
<td>1.4</td>
<td>1.4</td>
<td>1.2</td>
<td>1.3</td>
<td>1.0</td>
<td>1.1</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
<td>1.1</td>
<td>1.0</td>
<td>1.3</td>
<td>1.3</td>
<td>1.5</td>
<td>1.3</td>
</tr>
<tr>
<td>True Solar/True Calibration Ratio</td>
<td>2.2</td>
<td>2.1</td>
<td>1.4</td>
<td>3.0</td>
<td>1.1</td>
<td>1.4</td>
<td>1.5</td>
<td>1.5</td>
<td>1.4</td>
<td>1.4</td>
<td>1.4</td>
<td>1.1</td>
<td>1.6</td>
<td>1.7</td>
<td>2.8</td>
<td>2.1</td>
</tr>
<tr>
<td>Estimated Solar Temp</td>
<td>54401</td>
<td>52145</td>
<td>17282</td>
<td>40708</td>
<td>8321</td>
<td>10942</td>
<td>32543</td>
<td>29901</td>
<td>32929</td>
<td>33306</td>
<td>11271</td>
<td>9122</td>
<td>43916</td>
<td>20327</td>
<td>31579</td>
<td>22906</td>
</tr>
</tbody>
</table>

Screen shot from Excel
Final Thoughts
Secrets of the Universe...

• Bessel Functions...
• Limb Darkening...
• Limb Brightening...
• Solar Atmosphere...
• Brightness Temperature...
• HPBW...
• Radio SkyPipe...
Final Thoughts

Thank You...

Dr. C. D. Hoyle – Advisor/Professor/Mentor

Dr. Ken Owens – Professor/Mentor

Dr. Ryan Campbell – Professor/Mentor

Physics Department and Staff
Final Thoughts

Thank You...

Shannon!
Final Thoughts

List of references


Several other excellent papers...


“A Brief Theoretical View On Cylindrical Waveguides And Optical Fibers,” Vardiambasis


“Microwave Observations of the Quiet Sun,” Shibasaki

“Black Body Temperature of the Sun at 4 GHz,” Koglin, 1994

“Radio Astronomy Experiments at 4 GHz,” Tapping