Analyses of Coherent Lidar Wind Measurement Missions

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Introduction

This report details work carried out under NASA contract NAS8-38609 delivery order no. 128.

Much of the work undertaken involved additions to the coherent lidar model, including the addition of performance as a function of altitude (Chapter 1. and Appendix I), a receiver design section (Chapter 2. and Appendix III), the development of a simple orbit model Appendix II) suitable for use in plotting orbits, swath and shot patterns and estimating power availability (Appendix IV) and the inclusion of Fascode derived atmospheric extinction (Chapter 3.).

Considerable time was occupied with assisting NASA MSFC in the design and analysis of lidar instruments, both for the AEOLUS conceptual designs within MSFC (one such analysis is included in Appendix IV) and of proposed NASA MSFC instruments for the New Millennium Program.
Chapter 1. Coherent lidar performance as a function of altitude

The minimum detectable backscatter level for a coherent Doppler lidar instrument is a function of
the range to the target and of the optical properties of the atmosphere between the lidar and target.
The space-based coherent lidar model developed previously was modified to permit the calculation
of the minimum detectable backscatter as a function of altitude. Figure (1-1) shows a representa-
tive output plot. It should be noted that typically backscatter vs. altitude plots have the
altitude on the y-axis as this is more intuitive however, limitations of the plotting facilities within
the programming package prevent placing the independent variable (altitude) on the y-axis and
the dependent variable (backscatter) on the x-axis. This disadvantage is offset by the ability to
easily cut and paste the calculated results from the model into a presentation quality graphics
package when necessary.

Figure (1-1) A representative backscatter sensitivity as a function of altitude plot.

It can be seen from the figure that the altitude interval between data points increases at higher alti-
tudes - this was implemented to speed up calculation of results. Close to the earth’s surface, the
atmospheric extinction varies considerably as a function of altitude and this will affect the back-
scatter sensitivity so the data points are calculated frequently (100 m vertical separation). Table
(1.1) lists the altitude ranges at which the various step sizes are used. It should be noted that these
steps represent the points at which the backscatter sensitivity is calculated and not the step size for
calculation of the atmospheric extinction. For each backscatter sensitivity calculation point the
atmospheric extinction to that altitude is calculated using the full resolution of the model (100 m in the vertical over the complete altitude range).

<table>
<thead>
<tr>
<th>Altitude Range (m)</th>
<th>Altitude step (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z \leq 500$</td>
<td>100</td>
</tr>
<tr>
<td>$500 &lt; z \leq 2000$</td>
<td>250</td>
</tr>
<tr>
<td>$2000 &lt; z \leq 8000$</td>
<td>1000</td>
</tr>
<tr>
<td>$8000 &lt; z \leq 19999$</td>
<td>2000</td>
</tr>
</tbody>
</table>

Table 1.1: Step sizes used for calculation of the backscatter sensitivity as a function of altitude (see text).

The code for this task is listed in Appendix I.
Chapter 2. Receiver Design

2.1 The Doppler shift problem

A concern in the design of a suitable receiver for a space based coherent lidar, such as the AEO-LUS[1],[4] instrument design studied at NASA MSFC, is that the instrument will probably employ some form of scan geometry[2] and will consequently see an azimuth angle dependent Doppler shift due to components of the spacecraft velocity and earth rotational velocity. The spacecraft induced Doppler shift is the major component and is simply given by:

\[
\delta f (\lambda, h, z, \varphi_n, \varphi_{az}) = \frac{2}{\lambda} \nu_{sat}(h) \sin (\text{nadalt}(h, \varphi_n, z)) \cos (\varphi_{az})
\]

(2-1)

where \(\lambda\) is the operating wavelength, \(h\) is the instrument orbit height, \(z\) is the target altitude, \(\varphi_n\) is the instrument nadir angle and \(\varphi_{az}\) is the instrument azimuth angle relative to the satellite velocity vector (Figure (2-1)). As a consequence of the earth’s curvature, the nadir angle at the target is slightly larger than the nadir angle at the instrument and the function \(\text{nadalt}(h, \varphi_n, z)\) in equation (2-1) determines the target nadir angle (assuming a spherical earth) by:

\[
\text{nadalt}(h, \varphi_n, z) = \sin \left( \frac{\sin (\varphi_n)}{(r_e + z)} \right)
\]

(2-2)

Figure (2-1) The geometry of the satellite velocity vector, ground track vector, instrument line-of-sight, nadir and azimuth angles.
where \( r_e \) is the radius of the earth. Table (2.1) shows both the actual value of \( \text{nadt}(h,\phi_n,z) \) and the percentage error in \( \delta f(\lambda,h,z,\phi_n,\phi_{az}) \) that would occur if the change in nadir angle due to the earth's curvature was not accounted for. The table shows these values for a target altitude of 0 m and several values of spacecraft altitude and nadir angle.

<table>
<thead>
<tr>
<th>Nadir, (deg.)</th>
<th>Altitude, (km)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>350</td>
<td>525</td>
<td>825</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>31.9</td>
<td>32.9</td>
<td>34.9</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>42.8</td>
<td>44.3</td>
<td>46.9</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>54.1</td>
<td>56.4</td>
<td>60.5</td>
<td></td>
</tr>
</tbody>
</table>

\[ a) \]

\[ b) \]

Table (2.1) a) Actual nadir angle at the ground when the change in nadir angle due to the earth’s curvature is accounted for and b) the percentage error introduced into the spacecraft induced frequency shift when this effect is not considered.

The Doppler shift due to the earth’s rotational velocity is a function of both the latitude of the spacecraft and the azimuth angle. The earth’s rotational velocity at any latitude is simply given by:

\[
V_e (\text{lat}) = V_{eq} \cos (\text{lat})
\]

(2-3)

where \( V_{eq} \) is the earth’s rotational velocity at the equator and \( \text{lat} \) is the latitude of interest. Appendix II shows an orbit calculation and plot in which the change in the angle between the spacecraft velocity vector and the lines of longitude and latitude as a function of latitude can clearly be seen. For every latitude there is some azimuth angle at which the full Doppler shift due to the earth’s rotation will be seen. As the maximum value of this shift occurs at the equator, all the plots shown here assume the spacecraft orbit is crossing the equator as this introduces the maximum perturbation due to the earth’s rotational velocity. Any design that accommodate this maximum value will be able to accommodate smaller frequency shifts at other latitudes. The two micron wavelength region currently being studied for an operational space based lidar instrument means that this varying Doppler shift will be large. Figure (2-2) shows this Doppler shift as a function of azimuth angle for a two micron instrument with a 30 deg. nadir angle and a 350 km high orbit. The dotted straight lines represent the bandwidth (~1.3 GHz) of commercially available InGaAs detectors. It is obvious that the bandwidth of the detector is insufficient to cover the bandwidth of the signal.

2.2 Conceptual design of the optical portion of the receiver

To overcome this, the gross Doppler shift due to the component of the spacecraft velocity can be removed by using a frequency tunable local oscillator. An idealised frequency tuning curve for such a local oscillator is also shown in Figure (2-2) together with the residual frequency shift seen by the detector - the frequency shift for both positive and negative maximum horizontal wind velocities (± 100 m/s for the case considered here). Present in the residual frequency shift is the
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Figure (2-2) Doppler frequency shifts due to the component of the spacecraft velocity seen by the satellite, typical detector bandwidths, an idealized local oscillator tuning range and the resultant signal bandwidth as a function of telescope azimuth angle.

component of the earth's rotation which causes the center frequency to vary as a function of azimuth angle as discussed previously.

If a tunable local oscillator is used there must be some scheme to ensure that the frequency difference between the local oscillator and the pulsed laser is known. Figure (2-3) shows one possible scheme in which a master oscillator is frequency locked against a reference, such as a Fabry-Perot cavity. The figure also shows the various optical frequencies, \( f_x \) at different portions of the receiver where the subscript x is either mo, lo or t which represent the master oscillator, local oscillator and pulsed transmitter laser respectively. The frequency is also potentially a function of time and \( f_x(t1) \) represents the time of the outgoing (transmitted) pulse and \( f_x(t2) \) represents the returning signal pulse a few milliseconds later. The object to be measured, the Doppler shift induced on the signal due to the spacecraft velocity, earth's rotational velocity and the atmospheric wind velocity is \( \delta f_p \). The output from the master oscillator is then used for three purposes:

1.) to control the output frequency of the pulsed laser by injection seeding.

2.) as a local oscillator for heterodyning against the output from the pulsed laser. This verifies the frequency of the pulsed transmitter laser is correct and also measures the spectrum of the pulsed laser.

Chapter 2
3.) as a local oscillator for heterodyning against the output of the tunable local oscillator so that the tunable oscillator offset from the transmitter laser can be correctly determined. The heterodyne beat frequencies \( f_A(t_1) \), \( f_B(t_2) \) and \( f_C(t_2) \) on each of the detectors A, B and C respectively are given by:

\[
\begin{align*}
\quad f_A(t_1) &= f(t_1) - f_{mo}(t_1) \quad (2-4) \\
\quad f_B(t_2) &= f_{mo}(t_2) - f_{lo}(t_2) \quad (2-5) \\
\quad \text{and} \\
\quad f_C(t_2) &= f(t_1) + 8f_w - f_{lo}(t_2) \quad (2-6)
\end{align*}
\]

Combining these we obtain:

\[
\delta f_T = f_C(t_2) + f_{mo}(t_2) - f_B(t_2) - f_A(t_1) - f_{mo}(t_1) \quad (2-7)
\]

which expresses the Doppler shift frequency in terms of the measured heterodyne frequencies and the master oscillator frequency. Provided that over the round trip time of the signal (~3 ms @ 350 km altitude, 30 deg nadir angle) the master oscillator frequency is stable then the master oscillator frequencies in equation (2-7) cancel and we are left with an expression that contains only measurable parameters.

### 2.3 Conceptual design of the electronic portion of the receiver

The electronics design concept discussed here was originally sketched out by Mr. Steve Johnson of the NASA Marshall Space Flight Center.

The function of the electronics portion of the receiver, shown in block form in Figure (2-4) is to reduce the bandwidth of the signal as much as possible so that it can be readily digitised and stored efficiently. Figure (2-5)A shows the frequencies out of the optical detector after the optical heterodyne mixing has removed the gross Doppler shift due to the spacecraft velocity. It can be seen that the magnitude of the frequency shift due to the Doppler shift from the component of the earth's rotational velocity is large compared to the wind signal. In order to reduce the A/D bandwidth requirements to a minimum, the signal is further mixed with a frequency synthesised local oscillator in the electronics of the receiver. Figure (2-5)B shows the frequency tuning required from this local oscillator as a function of azimuth angle and Figure (2-5)C shows the signal after mixing with this electronic local oscillator. It can be seen that the frequency of the signal is now independent of the azimuth angle, i.e. all the frequency perturbation effects have been removed. The only remaining task is to split the signal into I and Q components and digitise it. Figure (2-5)D shows the frequency bandwidths required at various points through the electronics design.
Figure (2-3) Schematic showing frequency relationships between components of the optical portion of the receiver.
2.3.1 Optical detector shot noise performance

In order for the optical heterodyne detection system to work, the noise on the detector must be dominated by the local oscillator shot noise. The two major noise contributors are the shot noise and the Johnson noise in the detector. The noise on the detector is given by:

\[
N = \frac{2e^2\eta P_{LO}B_S}{h\nu} + \frac{4kT_eB_S}{R_e}
\]

where

\[
\frac{1}{R_e} = 2 - B_D C \\
N = \frac{2e^2\eta P_{LO}B_S}{h\nu} + 8\pi kT_e B_D C B_S
\]

Figure (2-4) Block diagram of the electronic portion of the receiver.

where \( e, \eta, P_{LO}, B_S, h, \nu, k, T_e, R_e, B_D \) and \( C \) are the charge on an electron, detector quantum efficiency, local oscillator power, search bandwidth, Planck's constant, LO frequency, Boltzmann constant, equivalent detector temperature and resistance, detector bandwidth and detector capacitance respectively. shows the noise characteristics for a detector with 3 pF of capacitance\(^3\), an operat-
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A) Frequencies at the detector output.

B) Tuning curve of the electronic local oscillator.

C) Output from the mixer.

D) Bandwidths required in the receiver.

Figure (2-5) A series of plots showing frequencies at various points within the receiver.

The shot noise dominates the detector noise characteristics out to ~1.5 GHz.

2.3.2 Data Rates

Figure (2-7) shows a summary of the data requirements from the design, it includes the effect of:

1.) nadir pointing errors - if there is an error in the nadir angle then it will have two effects on the data requirement. If the nadir angle becomes larger (smaller) then the line of sight component of the horizontal wind velocity becomes larger (smaller) and a larger (smaller) A/D rate than that required for the ideal case is needed. In conjunction with this the path length through the atmosphere will become longer (shorter) for an increase (decrease) in the nadir angle.
2.) transmitter/local-oscillator offset errors - the frequency offset between the transmitted pulse can not be absolutely controlled. The data sampling must be designed to accommodate the size of any likely frequency offset error that may arise.

3.) sampling above the Nyquist criteria - most lidar data collection schemes generally sample the data at a rate slightly faster than that determined by the Nyquist criteria.

4.) the number of bits per sample.

5.) the maximum and minimum altitudes from which data is to be collected and the 'guard' region around this sample - the maximum and minimum altitudes are determined by the science requirements and sensitivity of the instrument. The guard region is additional data collected on either side of the data sample to ensure that no data is missed.

6.) the number of ancillary words per pulse - in order to correctly assign the collected data to a three dimensional location in the earth's atmosphere additional satellite position and pointing information must be stored with each sample. Other data such as instrument calibration information may also be required to reconstruct and calibrate the data correctly.
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<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>2.065479 μm</td>
</tr>
<tr>
<td>Max. horizontal velocity</td>
<td>100 m/s</td>
</tr>
<tr>
<td>Max. line of sight velocity (occurs at ground)</td>
<td>52.7466857 m/s</td>
</tr>
<tr>
<td>Max. nadir error (any direction)</td>
<td>±/0.1 deg.</td>
</tr>
<tr>
<td>Worst case line of sight velocity shift due to nadir error</td>
<td>12.4379616 m/s</td>
</tr>
<tr>
<td>Max line of sight velocity allowing for nadir error</td>
<td>65.1846473 m/s</td>
</tr>
<tr>
<td>Velocity bandwidth required to this point</td>
<td>130.369295 m/s</td>
</tr>
<tr>
<td>Signal bandwidth required to this point</td>
<td>128.236379 MHz</td>
</tr>
<tr>
<td>XMTR/LO frequency offset error</td>
<td>+/-5 MHz</td>
</tr>
<tr>
<td>Additional bandwidth to account for XMTR/LO offset error</td>
<td>10 MHz</td>
</tr>
<tr>
<td>Total bandwidth required</td>
<td>136.236379 MHz</td>
</tr>
<tr>
<td>Real/Complex receiver geometry</td>
<td>Complex</td>
</tr>
<tr>
<td>No. bits</td>
<td>12 bits/sample</td>
</tr>
<tr>
<td>pk. bits/s (one channel)</td>
<td>1.7983E+09 bits/s</td>
</tr>
<tr>
<td>pk. bits/s (all channels)</td>
<td>3.5966E+09 bits/s</td>
</tr>
<tr>
<td>Max altitude</td>
<td>15 km</td>
</tr>
<tr>
<td>Min altitude</td>
<td>0 km</td>
</tr>
<tr>
<td>slant range margin</td>
<td>1 km</td>
</tr>
<tr>
<td>slant range</td>
<td>18.6478888 km</td>
</tr>
<tr>
<td>digitation time</td>
<td>124.405323 μs</td>
</tr>
<tr>
<td>bits/pulse</td>
<td>447442 bits/pulse</td>
</tr>
<tr>
<td>ancillary words/pulse</td>
<td>20 words/pulse</td>
</tr>
<tr>
<td>total bits/pulse</td>
<td>447682 bits/pulse</td>
</tr>
<tr>
<td>PRF</td>
<td>20 Hz</td>
</tr>
<tr>
<td>Bits/s averaged over one second</td>
<td>895364 bits/s</td>
</tr>
<tr>
<td>Orbit duration</td>
<td>5481.50413 s</td>
</tr>
<tr>
<td>Data storage</td>
<td>4.9079E+10 bits/orbit</td>
</tr>
</tbody>
</table>

### Figure (2-7) Data requirement summary

7.) instrument pulse repetition rate - determines the number of shots and hence total number of samples collected in a given time.

### 2.4 Description of the numerical model developed

A Quattro Pro spreadsheet (Appendix III) was developed to assist analysis of the receiver design. The spreadsheet dynamically takes parameters from the previously developed space based coherent lidar model and together with some additional inputs from the user calculates and displays a conceptual receiver design. Constraints built into the model permit it to automatically adjust to correct for changes in the input variables. The goal of the model is to generate a design in which the A/D sample rate is minimised. The model is summarised over five spreadsheet notebook pages, each of which is shown in Appendix III.

The first page displays the main parameters of the model together with a plot of the optical frequencies and detector bandwidths. The second page displays a block diagram of the electronic portion of the receiver together with key frequencies at various locations throughout the receiver. Also on this page are 'buttons' to perform a recalculation of the page and to display full-screen plots of frequency vs. azimuth angle at various key locations in the design. The third page displays a plot of the detector noise characteristics. The fourth consists of smaller summary plots of all the plots available on the second page and finally the fifth page consists of a data analysis page for determining the data rate and storage requirements of a given instrument. This data analysis
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includes the effects of various errors in that receiver and instrument sub systems that may lead to an increase in the data requirement.

2.5 Discussion

In the example here it has been assumed that the mean frequency of the local oscillator is offset from the frequency of the transmitted pulse by 300 MHz. The use of this offset avoids any ambiguity in the signal and. Figure (2-8) shows the resultant frequencies when no offset between the local oscillator and transmitter laser exists. The highlighted region between ~170 and ~200 degrees together with a similar region between ~350 and ~380 degrees are areas where a frequency can represent two different wind velocities depending on the sign of the frequency. The sign of the frequency cannot be determined from the detected signal and so an ambiguity in determining the wind velocity arises.

From Figure (2-2) it can be seen that after the local oscillator has removed the gross Doppler shift due to the spacecraft’s velocity the signal frequency varies from ~14 MHz to ~600 MHz which is comfortably within the bandwidth of the detector. The only problem with this scheme is that the local oscillator is now required to tune ±3.95 GHz about a frequency offset 300 MHz from line center of the transmitter frequency. In addition to the tuning requirement, the frequency error in the local oscillator should be less than ~1 MHz in order to achieve a velocity measurement accuracy of ~1 m/s or less for the whole instrument. This combination of requirements puts severe...
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demands on the local oscillator design and performance. One possible method of relieving these demands is to adjust the local oscillator tuning so that full advantage is taken of the detector bandwidth. Figure (2-9) shows a scheme which minimises the tuning requirements of the local oscillator by maximising the use of the detector bandwidth. Note that in order to make full use of the detector bandwidth, the local oscillator offset from the transmitter frequency has been increased to 600 MHz. Table (2.2) summarises the tuning requirements of the local oscillator for the two schemes. It can be seen that for the detector bandwidth (1.3 GHz) considered, the active tuning

<table>
<thead>
<tr>
<th>Goal</th>
<th>Center Frequency Offset from Transmitter</th>
<th>Local Oscillator Tuning Range</th>
<th>Maximum Offset of Local Oscillator from Transmitter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimise detector bandwidth requirement.</td>
<td>300 MHz</td>
<td>7950 MHz</td>
<td>4275 MHz</td>
</tr>
<tr>
<td>Maximise use of detector bandwidth and minimise local oscillator tuning requirement.</td>
<td>600 MHz</td>
<td>6950 MHz</td>
<td>4075 MHz</td>
</tr>
</tbody>
</table>

Table (2.2) Tuning options summary for a detector bandwidth of 1.3 GHz.
range of the local oscillator has been reduced by ~ 1 GHz compared to the scheme that simply tunes the local oscillator over the Doppler frequency shift range due to the satellite velocity offset. Unfortunately the maximum offset of the local oscillator from the transmitter center frequency is only reduced by 200 MHz from 4275 MHz to 4075 MHz. At the time of writing this report, a local oscillator capable of demonstrating these characteristics had not been demonstrated.
Chapter 3. Other Activities

3.1 Atmospheric Extinction

The Fascode atmospheric extinction code was made operational for use with the lidar modeling program. Representative plots of extinction per km at ground level for a mid-latitude summer atmospheric model with no aerosol extinction are shown in Figure (3-1).

![Figure (3-1) Representative plots of the output from the Fascode atmospheric extinction code.]

3.2 NASA’s New Millennium Program

A series of performance analyses for both 200 mJ, 50 cm and 25 mJ, 25 cm 2. µm coherent Doppler lidar instruments was performed for NASA MSFC in support of NASA’s New Millennium Program. The instruments were similar to those developed under the AEOLUS[^4] program at MSFC.
3.3 Meetings and Conferences

A paper on the receiver design was presented at the OSA Topical Meeting on Coherent Laser Radar\textsuperscript{[5]} and a presentation was made on the New Millennium Program to the NOAA Working Group on space-based lidar winds.\textsuperscript{[6]}
Chapter 4. References


[3] Detector capacitance and local oscillator power data was provided by Dr. Farzin Amzajerdian of the Center for Applied Optics, University of Alabama in Huntsville.


Appendix I Performance vs. Altitude Code

The code listed here follows the same conventions as listed in previous reports and builds upon that code. The following table is a coded Quattro Pro macro to backsolve for the backscatter at which the probability of a good estimate is equal to 50%. It calls sections of code used in previous reports.

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 step_no</td>
<td>26</td>
</tr>
<tr>
<td>5 altitude</td>
<td>19999</td>
</tr>
<tr>
<td>6</td>
<td></td>
</tr>
<tr>
<td>7 betavalt</td>
<td>(FOR step_no,1,25,1,loop)</td>
</tr>
<tr>
<td>8</td>
<td></td>
</tr>
<tr>
<td>9 loop</td>
<td>(CALC)</td>
</tr>
<tr>
<td>10</td>
<td>(LET +&quot;A&quot;&amp;@STRING(step_no+15,0), altitude/1000)</td>
</tr>
<tr>
<td>11</td>
<td>(LET [lidar]alt,altitude)</td>
</tr>
<tr>
<td>12</td>
<td>([lidar]50%BETA_CALC)</td>
</tr>
<tr>
<td>13</td>
<td>(CALC)</td>
</tr>
<tr>
<td>14</td>
<td>(LET +&quot;B&quot;&amp;@STRING(step_no+15,0), [lidar]BETA)</td>
</tr>
</tbody>
</table>

Cell B5 calculates the altitude from the value of step_no using the following Quattro Pro formula:

@IF(step_no<7,(step_no-1)*100,@IF(step_no<13,(500+(step_no-6)*250),@IF(step_no<21,2000+(step_no-12)*1000,@IF(step_no<25,(step_no-20)*2000+10000,19999)))))

This expression simply implements the step sizes outlined in Table (1.1).
Appendix II Orbit Calculation

The Mathcad document on the following pages calculates and displays orbit plots for the purpose of determining lidar instrument swath widths, repeat cycles, shot patterns and power budgets. It is not intended to represent a detailed orbit analysis.

This mathcad document calculates a simple circular orbit by calculating the angular position in the orbit as a function of time and then translates the co-ordinates of the satellite by rotation about the axes to get latitude, longitude position relative to the earth rotating beneath the spacecraft. It is only intended to provide a conceptual view of orbits.

Set up assorted constants

\[ G = 6.67259 \times 10^{-11} \text{ m}^3 \text{kg}^{-1} \text{sec}^{-2} \quad \text{Gravitational constant} \]

\[ r_e = 6371.3 \text{ km} \quad \text{Radius of earth} \]

\[ \tau_e = 8.69988 \times 10^6 \text{ sec} \quad \text{Average solar day (24 hrs)} \]

\[ M_e = 5.979 \times 10^{24} \text{ kg} \quad \text{Mass of earth} \]

Variables

- Orbit height \( h = 350 \text{ km} \)
- Orbit Inclination \( \text{orbinc} = 98 \text{ deg} \)
- No. of orbits to plot \( n = 5 \)

Calculate basic orbit parameters

\[
V = \sqrt{\frac{GM_e}{h + r_e}} \quad \text{Velocity}
\]

\[
\tau_{\text{orbit}} = \frac{2\pi (h + r_e)}{V} \quad \text{Time for one orbit}
\]

For the orbit selected above we have:

\[
V = 7.704 \times 10^3 \text{ m/sec}^{-1} \quad \text{and} \quad \tau_{\text{orbit}} = 91.359 \text{ min}
\]

Now calculate the basic circular orbit, allowing 5 sec between points.

\[
npts = \text{ceil} \left( \frac{\tau_{\text{orbit}} \times n}{5} \right)
\]

\[
i = 0.. npts \quad t_i = i \times 5 \text{-sec} \quad \text{alpha}_i = \frac{t_i \times 2 \times \pi}{\tau_{\text{orbit}}}
\]

Change to \( x, y, z \) co-ordinates

\[
x_i = r_e \sin(90 \text{ deg}) \cos(\text{alpha}_i) \quad y_i = r_e \sin(90 \text{ deg}) \sin(\text{alpha}_i) \quad z_i = r_e \cos(90 \text{ deg})
\]

Rotate about \( x \)-axis by \( \text{orbinc} \) degrees

\[
\text{rotangle} = \text{orbinc} \quad x_1 = x_i \quad y_1 = y_i \cos(\text{rotangle}) + z_i \sin(\text{rotangle}) \quad z_1 = y_i (-\sin(\text{rotangle})) + z_i \cos(\text{rotangle})
\]

Rotate about \( z \) to account for earths rotation

\[
\text{longrot} = \text{mod} \left( \frac{360 \text{ deg} \times t_i}{60 60 24 \text{ sec}}, 360 \text{ deg} \right)
\]

\[
x_2 = x_1 \cos(\text{longrot}) + y_1 \sin(\text{longrot}) \quad y_2 = (x_1 \sin(\text{longrot})) + y_1 \cos(\text{longrot}) \quad z_2 = z_1
\]

Change from \( x, y, z \) to long, lat, alt

\[
\text{long}_i = \angle(x_2, y_2) - \pi \quad \text{lat}_i = \text{acos} \left( \frac{x_2}{\sqrt{(x_2)^2 + (y_2)^2}} \right) - \frac{\pi}{2} \quad r_1 = \sqrt{(x_2)^2 + (y_2)^2 + (z_2)^2}
\]
This portion calculates the angle that the orbit makes wrt to the lines of longitude. It does this by calculating the change in the latitude and longitude points between the current location and the previous location and uses simple geometry to calculate resultant angle using right spherical triangle geometry.

\[
dlat_i := \text{if}(i > 0, \text{lat}_i - \text{lat}_{i-1}, 0) \\
dlong_i := \text{if}(i > 0, \text{long}_i - \text{long}_{i-1}, 0)
\]

\[
dangle_i := \frac{\tan(\text{dlat}_i)}{\sin(\text{dlong}_i)} \text{ deg}
\]

Angle between orbit track and lines of longitude as a function of time.

Angle between orbit track and lines of longitude as a function of latitude.

Angle between orbit track and lines of longitude as a function of longitude.
Appendix III Receiver Design Code

The following sections list the code of the receiver design model.

(IIIa) The optical page

![Image of optical page](image)

**Assumptions**
- Constant M.O. frequency and transmitter frequency.
- Plot is for 0 deg. latitude (affects detector signal bandwidth - 0 deg. lat. is worst case).
- No earth rotation in gross signals, s/c velocity only.

**Figure (III-1) Visual appearance of the optical page.**

The page shows (Figure (III-1)), as a function of azimuth angle, a plot of the Doppler shift due to the satellite velocity, the local oscillator tuning, the detector bandwidth and the residual frequency shifts due to the wind velocity and earth’s rotational velocity. It also shows the major parameters of the model and a brief summary of the assumptions used for the plot. The graphical interface around the information is available on all the pages but for clarity will not be shown in future figures. The following listing provides the spreadsheet code embedded in the cells of the page.

```
Optical: J2: 'Lidar Receiver
Optical: J3: 'Optical
Optical: K4: 'Offset (MHz)
Optical: J5: 'M.O.
Optical: K5: 0
```
Analyses of Coherent Lidar Wind Measurement Missions

Optical:J6: 'L.O.
Optical:K6: 50
Optical:J7: 'Trans.
Optical:K7: 0
Optical:J9: 'BW (MHz)
Optical:K9: 'L.O.
Optical:K10: 0
Optical:J11: 'Detector
Optical:K11: 1250
Optical:J13: 'Other parameters
Optical:J14: 'Wavelength
Optical:K14: +[LIDAR]LAMBDA
Optical:K14: 'um
Optical:J15: 'Orb. height
Optical:K15: +[LIDAR]ORBH
Optical:J15: 'km
Optical:J16: 'Orb. incl.
Optical:K16: +[LIDAR]ORBINC
Optical:J16: 'deg.
Optical:J17: 'Nadir angle
Optical:K17: +[LIDAR]NADIR
Optical:J17: 'deg.
Optical:J18: 'Trgt. altitude
Optical:K18: +[LIDAR]ALT
Optical:J18: 'm
Optical:J19: 'Nadir at trgt.
Optical:K19: +[LIDAR]NADALT
Optical:J19: 'deg.
Optical:J20: 'Max. h. vel.
Optical:K20: 100
Optical:K20: 'm/s
Optical:J21: 'Max. los. vel.
Optical:K21: +K20*@SIN(@RADIANS(K19))
Optical:J21: 'm/s
Optical:J22: 'Min. det. f.
Optical:K22: @MIN(F:L6..F:L81)
Optical:J22: 'MHz
Optical:J23: 'Max. det. f.
Optical:K23: @MAX(F:K6..F:K81)
Optical:K23: 'MHz
Optical:J24: 'Detector
Optical:A25: 'Assumptions
Optical:J25: 'LO power
Optical:J25: 0.0016
Optical:L25: 'W
Optical:A26: 'Constant M.O. frequency and transmitter frequency.
Optical:A26: 'Bsearch
Optical:J26: +$K20*2/[LIDAR]LAMBDA*10^-6/1000000
Optical:J26: 'MHz
Optical:A27: 'Plot is for 0 deg. latitude (affects detector signal
Optical:A27: bandwidth - 0 deg. lat. is worst case).
Optical:J27: 'Temp
Optical:J27: @IF(@INT(K14)=2,300,70)
Optical:L27: 'K

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Analyses of Coherent Lidar Wind Measurement Missions

Optical:A28: 'No earth rotation in gross signals, s/c velocity only.
Optical:J28: 'Cap.
Optical:K28: 3E-12
Optical:L28: 'F

(IIIb) The electrical page

Figure (III-2) Visual appearance of the electrical page for a complex receiver design.

This page displays a block diagram (Figure (III-2) and Figure (III-3)) of the receiver electrical subsystem with critical frequencies at various points in the design. The top of the page contains a row of buttons, the first is used to run a macro (listed in Table (AIII.1)) to redraw the receiver design to match either a complex (Figure (III-2)) or real (Figure (III-3)) design depending on which the user has chosen. The remaining buttons are used to display a series of fullscreen plots which are summarised on a later page.

The top half of the block schematic is the same for both the complex and real receiver designs. The page simply contains a drawing for the bottom half of each of the receiver designs and hides/unhides them according to the value of the complex receiver variable. The code on the page is listed below:

Electrical:M5: ' R.F. LO
Electrical:B6: 'Lidar Receiver - Electrical
Electrical:M6: @MIN(F:Q6..F:Q81)
Electrical:N6: 'MHz

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Analyses of Coherent Lidar Wind Measurement Missions

Figure (III-3) Visual appearance of the electrical page for a real receiver design.

Electrical:M7: \( @\text{MAX}(F:Q6..F:Q81) \)
Electrical:N7: \( "\text{MHz} \)
Electrical:B10: \( @\text{IF}(@\text{INT}(\text{Optical}:K14)=2,"\text{InGaAs"},"\text{HgCdTe")} \)
Electrical:F10: \( \text{Preamp} \)
Electrical:I10: \( \text{Amp} \)
Electrical:K10: \( \text{RF bandpass} \)
Electrical:M10: \( \text{Mixer} \)
Electrical:T10: \( \text{Lo} \)
Electrical:U10: \( \text{Hi} \)
Electrical:B11: \( \text{Detector} \)
Electrical:K11: \( @\text{IF}(@\text{MIN}(F:L6..F:L81)<0,0,@\text{MIN}(F:L6..F:L81)) \)
Electrical:S11: \( \text{Signal} \)
Electrical:T11: +K11
Electrical:U11: +K12
Electrical:K12: \( @\text{IF}(\text{MAX}(F:K6..F:K81)<@\text{ABS}(\text{MIN}(F:L6..F:L81)),\text{ABS}(\text{MIN}(F:L6..F:L81)),\text{MAX}(F:K6..F:K81)) \)
Electrical:S12: \( \text{RF L.O.} \)
Electrical:T12: +K6
Electrical:U12: +K7
Electrical:S13: \( \text{I.F. Bandpass} \)
Electrical:T13: +K16
Electrical:U13: +K17
Electrical:S14: \( \text{A/D Lowpass} \)
Electrical:T14: +K21
Electrical:U14: \( @\text{IF}([\text{LIDAR}]\text{rcvr_type}="\text{Complex"},+K22,+I36) \)
Electrical:B15: \( \text{Amp} \)
Electrical:F15: \( \text{Limiter} \)
Electrical:I15: \( \text{Amp} \)
Electrical:K15: \( \text{IF Bandpass} \)
Analyses of Coherent Lidar Wind Measurement Missions

Electrical:M15: ' Amp
Electrical:K16: @MIN(F:R6..F:R81,F:S6..F:S81)
Electrical:K17: @MAX(F:R6..F:R81,F:S6..F:S81)
Electrical:F20: ' Mixer
Electrical:I20: ' Amp
Electrical:K20: ' Lowpass
Electrical:M20: ' A/D
Electrical:K21: 0
Electrical:K22: +M22/2
Electrical:M22: +Optical:K21*2/[LIDAR]$LAMBDA*2
Electrical:N22: 'MS/s
Electrical:B24: ' Splitter
Electrical:F24: ' Coho
Electrical:F25: +M22
Electrical:G25: 'MHz
Electrical:F27: ' Mixer
Electrical:I27: ' Amp
Electrical:K27: ' Lowpass
Electrical:M27: ' A/D
Electrical:K28: 0
Electrical:K29: +M29/2
Electrical:M29: +Optical:K21*2/[LIDAR]$LAMBDA*2
Electrical:N29: 'MS/s
Electrical:B34: ' Mixer
Electrical:F34: ' Amp
Electrical:I34: ' Lowpass
Electrical:K34: ' A/D
Electrical:K35: 0
Electrical:I36: +K36/2
Electrical:K36: +Optical:K21*2/[LIDAR]Instrument:C9*4

<table>
<thead>
<tr>
<th>A</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>42</td>
<td>rcvr_pic_displa</td>
</tr>
<tr>
<td>43</td>
<td>{IF [lidar]$rcvr_type=&quot;Complex&quot;}{BRANCH complex_rcvr}</td>
</tr>
<tr>
<td>44</td>
<td>complex_rcvr</td>
</tr>
<tr>
<td>45</td>
<td>{SETOBJECTPROPERTY &quot;[RCVRFREQ]complex_pic.Reveal/Hide&quot;,&quot;Rows,Reveal&quot;}</td>
</tr>
<tr>
<td>46</td>
<td>{BRANCH done_rcvr}</td>
</tr>
<tr>
<td>47</td>
<td>real_rcvr</td>
</tr>
<tr>
<td>48</td>
<td>{SETOBJECTPROPERTY &quot;[RCVRFREQ]real_pic.Reveal/Hide&quot;,&quot;Rows,Hide&quot;}</td>
</tr>
<tr>
<td>49</td>
<td>done_rcvr</td>
</tr>
<tr>
<td></td>
<td>{HOME}(RIGHT)(DOWN)</td>
</tr>
</tbody>
</table>

Table (III.1) The macro used to display the correct electrical block diagram.
(IIIc) The noise page

![Graph showing shot noise, Johnson noise, and total noise as a function of detector bandwidth.]

Figure (III-4) Visual appearance of the noise page.

This page simply displays the shot noise, Johnson noise and total noise as a function of the detector bandwidth required. The calculation is carried out using the following code:

```excel
Noise:D1: =Noise
Noise:A2: =Bdet
Noise:B2: =Blo
Noise:C2: =Shot
Noise:D2: =Johnson
Noise:E2: =Total
Noise:A3: =1
Noise:B3: =-(A3-$F:$G$6-Optical:$K$26*iE-06/2)
([LIDAR]$H*[LIDAR]$FREQ*I0^6)
Noise:E3: =C3+D3
Noise:A4: =100
Noise:B4: =-(A4-$F:$G$6-Optical:$K$26*1E-06/2)
```

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Analyses of Coherent Lidar Wind Measurement Missions

Noise: $D_4: +4*[\text{LIDAR}]^k*\text{Optical:}\text{K}_{27}\text{Optical:}\text{K}_{26}^2*2*\pi*\text{ABS}(A_4*10^6)*\text{Optical:}\text{K}_{28}$
Noise: $E_4: +C_4+D_4$

Each successive row repeats, incrementing the detector bandwidth until the final row is reached.

Noise: $A_{42}: 3900$
Noise: $B_{42}: -(A_{42}-F:G^6-\text{Optical:}\text{K}_{26}^*$-0.6$)^/2$
Noise: $C_{42}: +2*[\text{LIDAR}]^2*\text{Optical:}\text{K}_{25}\text{Optical:}\text{K}_{26}/(\text{LIDAR}^H\text{FREQ}^I*10^6)$
Noise: $D_{42}: +4*[\text{LIDAR}]^k*\text{Optical:}\text{K}_{27}\text{Optical:}\text{K}_{26}^2*2*\pi*\text{ABS}(A_{42}^I*10^6)*\text{Optical:}\text{K}_{28}$
Noise: $E_{42}: +C_{42}+D_{42}$

(IIId) The frequencies page

![Detector Frequencies](image1)
![Synthesized LO Frequency](image2)
![Mixer Output](image3)
![Frequency Ranges](image4)

Figure (III-5) Visual appearance of the frequency page.

This page simply displays multiple small graphs showing the frequency at various points in the receiver design.

(IIIe) The data rate calculation page

This page displays the A/D speed and data storage requirements. The code is listed below:
Analyses of Coherent Lidar Wind Measurement Missions

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>2.065479 μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. horizontal velocity</td>
<td>100 m/s</td>
</tr>
<tr>
<td>Max. line of sight velocity (occurs at ground)</td>
<td>82.7466857 m/s</td>
</tr>
<tr>
<td>Max. nadir error (any direction)</td>
<td>+/- 0.1 deg.</td>
</tr>
<tr>
<td>Worst case line of sight velocity shift due to nadir error</td>
<td>12.4379616 m/s</td>
</tr>
<tr>
<td>Max line of sight velocity allowing for nadir error</td>
<td>65.1848473 m/s</td>
</tr>
<tr>
<td>Velocity bandwidth required to this point</td>
<td>130.369295 m/s</td>
</tr>
<tr>
<td>Signal bandwidth required to this point</td>
<td>126.236379 MHz</td>
</tr>
<tr>
<td>XMTR/LO frequency offset error</td>
<td>+/- 5 MHz</td>
</tr>
<tr>
<td>Additional bandwidth to account for XMTR/LO offset error</td>
<td>10 MHz</td>
</tr>
<tr>
<td>Total bandwidth required</td>
<td>136.236379 MHz</td>
</tr>
<tr>
<td>Real/Complex receiver geometry</td>
<td>Complex</td>
</tr>
<tr>
<td>Sampling rate required/channel</td>
<td>149.860017 Msamples/s</td>
</tr>
<tr>
<td>No. bits</td>
<td>12 bits/sample</td>
</tr>
<tr>
<td>pk. bits/s (one channel)</td>
<td>1.7983E+09 bits/s</td>
</tr>
<tr>
<td>pk. bits/s (all channels)</td>
<td>3.5966E+09 bits/s</td>
</tr>
<tr>
<td>No Error</td>
<td>With Error</td>
</tr>
<tr>
<td>Max altitude</td>
<td>15 km nadir</td>
</tr>
<tr>
<td>Min altitude</td>
<td>0 km nadir</td>
</tr>
<tr>
<td>slant range margin</td>
<td>1 km</td>
</tr>
<tr>
<td>slant range</td>
<td>18.6478888 km</td>
</tr>
<tr>
<td>digitisation time</td>
<td>124.405323 μs</td>
</tr>
<tr>
<td>bits/pulse</td>
<td>447442 bits/pulse</td>
</tr>
<tr>
<td>ancillary words/pulse</td>
<td>20 words/pulse</td>
</tr>
<tr>
<td>total bits/pulse</td>
<td>447682 bits/pulse</td>
</tr>
<tr>
<td>PRF</td>
<td>20 Hz</td>
</tr>
<tr>
<td>Bits/s averaged over one second</td>
<td>8953640 bits/s</td>
</tr>
<tr>
<td>Orbit duration</td>
<td>5481.50413 s</td>
</tr>
<tr>
<td>Data storage</td>
<td>4.9079E+10 bits/orbit</td>
</tr>
</tbody>
</table>

Figure (III-6) Visual appearance of the data requirements page.

Data:A1: Wavelength
Data:B1: +Optical:K14
Data:C1: 'um
Data:A2: Max. horizontal velocity
Data:B2: 100
Data:C2: m/s
Data:A3: Max. line of sight velocity (occurs at ground)
Data:B3: +B2*@SIN(@RADIANS(E19))
Data:C3: m/s
Data:A4: Max. nadir error (any direction)
Data:B4: 0.1
Data:C4: deg.
Data:A5: Worst case line of sight velocity shift due to nadir error
Data:B5: @ABS((B2+[LIDAR]$VSAT)*(@SIN(@RADIANS(G19))-@SIN(@RADIANS(E19)))
Data:C5: m/s
Data:A6: Max line of sight velocity allowing for nadir error
Data:B6: +B3+B5
Data:C6: m/s
Data:A7: Velocity bandwidth required to this point
Data:B7: +B6*2
Data:C7: m/s
Data:A8: Signal bandwidth required to this point
Data:B8: +B7*2/(B1)
Data:C8: MHz
Data:A9: XMTR/LO frequency offset error
Data:B9: 5
### Analyses of Coherent Lidar Wind Measurement Missions

| Data: C9: | MHz |
| Data: A10: | Additional bandwidth to account for XMTR/LO offset error |
| Data: B10: | +B9*2 |
| Data: C10: | MHz |
| Data: A11: | Total bandwidth required |
| Data: B11: | +B8+B10 |
| Data: C11: | MHz |
| Data: A12: | Real/Complex receiver geometry |
| Data: B12: | +[LIDAR]rcvr_type |
| Data: A13: | Sampling rate over Nyquist |
| Data: B13: | 1.1 |
| Data: C13: | ' (1 = Nyquist, 2 = Twice as many samples as Nyquist etc.) |
| Data: A14: | Sampling rate required/ channel |
| Data: B14: | @IF(B12="Complex",+B11*B13,+B11*B13*2) |
| Data: C14: | Msamples/s |
| Data: A15: | No. bits |
| Data: B15: | 12 |
| Data: C15: | bits/sample |
| Data: A16: | pk. bits/s (one channel) |
| Data: B16: | +B15*B14*10^6 |
| Data: C16: | bits/s |
| Data: A17: | pk. bits/s (all channels) |
| Data: B17: | (@IF(B12="Complex",2,1))*B16 |
| Data: C17: | bits/s |
| Data: E17: | No Error |
| Data: G17: | With Error |
| Data: A18: | Max altitude |
| Data: B18: | 15 |
| Data: C18: | km |
| Data: D18: | nadir |
| Data: E18: | @DEGREES(@ASIN(([LIDAR]$ORBH*10^3+([LIDAR]$RE)*@SIN(@RADIANS([LIDAR]$NADIR))/( [LIDAR]$RE+B18*1000)))) |
| Data: F18: | deg. |
| Data: G18: | @DEGREES(@ASIN(([LIDAR]$ORBH*10^3+([LIDAR]$RE)*@SIN(@RADIANS([LIDAR]$NADIR+B4))/( [LIDAR]$RE+B18*1000)))) |
| Data: H18: | deg. |
| Data: A19: | Min altitude |
| Data: B19: | 0 |
| Data: C19: | km |
| Data: D19: | nadir |
| Data: F19: | deg. |
| Data: G19: | @DEGREES(@ASIN(([LIDAR]$ORBH*10^3+([LIDAR]$RE)*@SIN(@RADIANS([LIDAR]$NADIR+B4))/( [LIDAR]$RE+B19*1000)))) |
| Data: H19: | deg. |
| Data: A20: | slant range margin |
| Data: B20: | 1 |
| Data: C20: | km |
| Data: A21: | slant range |
| Data: C21: | km |
| Data: A22: | digitisation time |

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Analyses of Coherent Lidar Wind Measurement Missions

Data: B22: \((2*B21*1000)/[\text{LIDAR}]^C/10^\circ\) 
Data: A23: bits/pulse 
Data: B23: \(\text{CEILING}(B17*B22/10^6,1)\) 
Data: C23: bits/pulse 
Data: A24: ancillary words/pulse 
Data: B24: 20 
Data: C24: words/pulse 
Data: A25: total bits/pulse 
Data: B25: \(+B23+(B24*B15)\) 
Data: C25: bits/pulse 
Data: A26: PRF 
Data: B26: \(+[\text{LIDAR}]^PRF\) 
Data: C26: Hz 
Data: A27: Bits/s averaged over one second 
Data: B27: \(+B25*B26\) 
Data: C27: bits/s 
Data: A29: Orbit duration 
Data: B29: \(+[\text{LIDAR}]^STORB\) 
Data: C29: s 
Data: A30: Data storage 
Data: B30: \(+B29*B27\) 
Data: C30: bits/orbit 
Data: B31: \(+B30/B15\) 
Data: C31: words/orbit

(IIIf) The calculation page

### OPTICAL PORTION OF RECEIVER

<table>
<thead>
<tr>
<th>Telescope</th>
<th>Laser frequency offsets</th>
<th>Laser frequency diffs</th>
<th>Sat. Velocity</th>
<th>Earth orb.</th>
<th>Sat. earth wind</th>
<th>Residual after LO (deg on electronics)</th>
<th>detector BW</th>
<th>Detector f</th>
</tr>
</thead>
<tbody>
<tr>
<td>Azimuth</td>
<td>M.O.</td>
<td>Tx</td>
<td>L.O.</td>
<td>M.O. - Tx</td>
<td>M.O. - L.O.</td>
<td>dVs</td>
<td>dVe</td>
<td>dVp</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>50</td>
<td>0</td>
<td>-50</td>
<td>3934.791457</td>
<td>32.938543</td>
<td>4018.798</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>0</td>
<td>50</td>
<td>0</td>
<td>-50</td>
<td>3912.813368</td>
<td>12.548938</td>
<td>3863.276</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>0</td>
<td>50</td>
<td>0</td>
<td>-50</td>
<td>3888.408337</td>
<td>0</td>
<td>3947.571</td>
</tr>
</tbody>
</table>

| 345       | 0    | 0  | 50   | 0          | -50         | 3900.716958 | 92.461549  | 3844.251 | 3844.251 | 3792.108 | 1250  | -1250 | 3914.251 |
| 350       | 0    | 0  | 50   | 0          | -50         | 3875.013133 | 73.124905  | 3898.271 | 3898.271 | 3844.251 | 3844.251 | 3792.108 | 1250  | -1250 | 3914.251 |
| 355       | 0    | 0  | 50   | 0          | -50         | 3819.813838 | 53.231804  | 3821.125 | 3821.125 | 3794.125 | 3794.125 | 1250  | -1250 | 3871.125 |
| 360       | 0    | 0  | 50   | 0          | -50         | 3804.791457 | 32.938543  | 4018.798 | 3618.652 | 3608.798 | 3868.798 | 3668.852 | 3844.251 | 3844.251 | 1250  | -1250 | 3898.798 |

Figure (III-7) Visual appearance of the calculation page.

This page contains the code to calculate the local oscillator frequency offsets. It is not intended to be part of the user interface, although it is accessible to the user. Figure (III-7) shows the top and bottom of the page and the code is listed below:

F:B1: '----------
F:D1: '----------
F:E1: '----------
F:F1: '----------
F:G1: '----------
F:H1: '----------OPTICAL PORTION OF RECEIVER

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Analyses of Coherent Lidar Wind Measurement Missions

F:L1: '--------------
F:M1: '----------------------------------
F:N1: '----------------->
F:H2: 'Frequency shift (MHz) due to:
F:A3: 'Telescope
F:B3: 'Laser frequency offsets
F:E3: 'Laser frequency diffs.
F:G3: 'Sat. Velocity
F:I3: 'Sat. +earth. + wind
F:K3: 'Residual after LO
F:M3: 'detector BW
F:O3: 'Detector frequencies
F:Q3: 'Mixer
F:R3: 'Output from
F:A4: 'Azimuth
F:C4: 'MHz
F:F4: 'MHz
F:I4: 'dVs+dVe
F:J4: 'dVs+dVe
F:K4: '(sig. on electronics)
F:M4: ''MHz
F:O4: ''MHz
F:Q4: 'Frequency
F:R4: 'Mixer
F:A5: '(deg)
F:B5: 'M.O.
F:C5: 'Tx
F:D5: 'L.O.
F:E5: 'M.O.-Tx
F:F5: 'M.O.-L.O.
F:G5: 'dVs
F:H5: 'dVe
F:I5: '+Vmax
F:J5: '-Vmax
F:K5: 'max
F:L5: 'min
F:M5: 'det+
F:N5: 'det-
F:O5: 'max
F:P5: 'min
F:Q5: 'MHz
F:R5: ''MHz
F:R6: '
F:B6: +Optical:$K5
F:C6: +B6+$Optical:$K7
F:D6: +Optical:$K6+$Optical:$K10*@COS(@RADIANS(A6))
F:E6: +B6-C6
F:F6: +B6-D6
F:G6: +[LIDAR]$VSAT*2/[LIDAR]$/LAMBDAC@SIN(@RADIANS([LIDAR]$NAD-ALT))@COS(@RADIANS(A6))

Appendix III
Analyses of Coherent Lidar Wind Measurement Missions

The code repeats on successive rows, incrementing the azimuth each time. Finally the end of the table is reached:

<table>
<thead>
<tr>
<th>Column</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>A81</td>
<td>360</td>
</tr>
<tr>
<td>B81</td>
<td>+Optical:$K6$</td>
</tr>
<tr>
<td>C81</td>
<td>+$B1+$Optical:$K7$</td>
</tr>
<tr>
<td>D81</td>
<td>-$Optical:$K6+$Optical:$K10$@COS(@RADIANS(A81))</td>
</tr>
<tr>
<td>E81</td>
<td>+$B1-$C81</td>
</tr>
<tr>
<td>F81</td>
<td>+$B1-$D81</td>
</tr>
<tr>
<td>G81</td>
<td>+[LIDAR]$VSAT<em>2/[LIDAR]$LAMBDA</em>@SIN(@RADIANS([LIDAR]$NADALT))*@COS(@RADIANS(A81))</td>
</tr>
<tr>
<td>H81</td>
<td>+2*[LIDAR]$VEARTH*@SIN(@RADIANS(8-A81)) *@SIN(@RADIANS([LIDAR]$NADALT))/[LIDAR]$LAMBDA</td>
</tr>
<tr>
<td>I81</td>
<td>+$G81+$H81+2<em>Optical:$K20</em>@SIN(@RADIANS([LIDAR]$NADALT))/[LIDAR]$LAMBDA</td>
</tr>
</tbody>
</table>

Appendix III
Analyses of Coherent Lidar Wind Measurement Missions

F:K81: +I81+F81
F:L81: +J81+F81
F:M81: +SOptical:$K$11
F:N81: -SOptical:$K$11
F:O81: @ABS(K81)
F:P81: @ABS(L81)
F:Q81: (O81+P81)/2+Electrical:$F$25
F:R81: @ABS(Q81-O81)
F:S81: @ABS(Q81-P81)
Appendix IV AEOLUS Power Budget on Free Flyer Spacecraft

The enclosed plots show the average power requirements for a 0.4 J CO$_2$ AEOLUS instrument with a dual-look fixed telescope arrangement mounted on a generic spacecraft. A 350 km, 98 degree orbit was assumed and the worst case orbit (maximum time in the shade) was considered. Three different power management schemes have been considered:

A) The laser is operated at a constant 20 Hz PRF for 5% of the orbit during the shade portion of the orbit.
B) The laser is operated at a constant 20 Hz PRF for 5% of the orbit during the sun portion of the orbit.
C) The laser is not turned on during the orbit.

For each shot management scheme the following parameters were plotted as a function of time:

- **Power:** This shows the average power requirements over one scan. The power requirement calculated is for the total spacecraft system, not just the AEOLUS instrument.
- **Battery capacity:** This shows the charge remaining in the batteries as a function of time / latitude.

During the non-operational period of the orbit, it is assumed that all systems are operational and only the laser pulsing is turned off. The instrument is composed of several sub-systems which are powered continuously. The power for each of these sub-systems was provided by Steve Johnson, MSFC EB-54, and are listed in Table IV.1).

<table>
<thead>
<tr>
<th>Sub-system</th>
<th>Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal control system</td>
<td>142</td>
</tr>
<tr>
<td>Laser</td>
<td>80</td>
</tr>
<tr>
<td>Receiver</td>
<td>60</td>
</tr>
<tr>
<td>Power conversion and distribution</td>
<td>50</td>
</tr>
<tr>
<td>Data acquisition and control</td>
<td>22</td>
</tr>
<tr>
<td>Lidar control</td>
<td>15</td>
</tr>
<tr>
<td>Wiring Harness (1% of power distributed)</td>
<td>4</td>
</tr>
</tbody>
</table>

Table (IV.1) Instrument Standby Power Requirements
Analyses of Coherent Lidar Wind Measurement Missions

<table>
<thead>
<tr>
<th>Sub-system</th>
<th>Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>373</td>
</tr>
</tbody>
</table>

**Table (IV.1) Instrument Standby Power Requirements**

During operation the laser sub-system requires an additional 236 W and the wiring harness power loss is increased to 6 W. The remaining parameters used in the model are listed in Table IV.2).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power required by satellite</td>
<td>150 W</td>
</tr>
<tr>
<td>Solar array power generation</td>
<td>800 W</td>
</tr>
<tr>
<td>Solar cell losses (account for deterioration over mission life)</td>
<td>5% of total solar pwr.</td>
</tr>
<tr>
<td>Number of batteries on spacecraft</td>
<td>1</td>
</tr>
<tr>
<td>Storage capacity (single battery)</td>
<td>40 A-hr</td>
</tr>
<tr>
<td>Discharge depth allowed on batteries (fraction of maximum capacity)</td>
<td>0.7</td>
</tr>
<tr>
<td>Maximum charging rate of batteries (fraction of max. cap./hr.)</td>
<td>0.5</td>
</tr>
<tr>
<td>Efficiency of charging battery</td>
<td>0.866</td>
</tr>
<tr>
<td>Efficiency of battery discharge</td>
<td>0.866</td>
</tr>
<tr>
<td>LAWS laser PRF</td>
<td>20 Hz</td>
</tr>
<tr>
<td>LAWS laser duty cycle over one orbit</td>
<td>5%</td>
</tr>
<tr>
<td>Satellite speed</td>
<td>7.6059 km.s⁻¹</td>
</tr>
<tr>
<td>Orbit height</td>
<td>350 km</td>
</tr>
<tr>
<td>Orbit occultation occurs above</td>
<td>49 degrees</td>
</tr>
<tr>
<td>Average earth radius</td>
<td>6371.315 km</td>
</tr>
</tbody>
</table>

**Table (IV.2) Parameters for a 9 μm AEOLUS on a Freeflyer Spacecraft.**
Figure (AIV-1) shows the variation in latitude as a function of time for the orbit considered.

Figure (IV-1) Variation of latitude with time over one orbit.
Figure (IV-2) The total power consumption and battery charging histories for one orbit when the laser is pulsed during the shade portion of the orbit.

From Figure (IV-2) it can be seen that the batteries on the spacecraft are fully recharged before the orbit is over. The period from completion of recharging the batteries to the end of the orbit period represents a period when the power available from the solar arrays is not fully utilised. The energy ‘lost’ during this period can be divided by the total orbit time to give an average spare power capacity of the solar arrays. This spare capacity is ~28 W for this scenario. It can be seen that the transition from shade to sun results in a reduction of the power required. This is due to the elimination of the inefficiency of operating from the batteries.
Figure (IV-3) The total power consumption and battery charging histories for one orbit when the laser is pulsed during the sun portion of the orbit.

From Figure (AIV-3) it can be seen that the batteries on the spacecraft are fully recharged before the orbit is over. The spare capacity is ~ 31 W for this scenario.
Figure (IV-4) The total power consumption and battery charging histories for one orbit when the laser is not pulsed over the whole orbit.

From Figure (IV-4) it can be seen that the batteries on the spacecraft are fully recharged before the orbit is over. The spare capacity is ~42 W for this scenario.

(IVa) Conclusions

The difference between no laser operation and worst case operation (pulse during the shade) is ~14 W averaged over one orbit and thus it can be concluded from this analysis that the standby power requirement is the driver for an instrument of this design. Careful consideration of which sub-systems could be turned-off or placed in a reduced power consumption mode during the peri-
Analyses of Coherent Lidar Wind Measurement Missions

ods when the laser is not operational could result in a considerable power saving. Conversely increasing the duty cycle of the laser would result in a minimal increase in the solar power required for the current design.
<table>
<thead>
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