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1 INTRODUCTION

This document analyses the effect of wind on the VISTA telescope Altitude axis, and concludes that a tip-tilt system should not be required for the VISTA telescope, subject to the various assumptions described below.
It supersedes reference RD02, presented at the VISTA Close-out Review on 23/24 July 2001.

The estimates of the wind effects on the VISTA Altitude axis in document RD02 are based on previous work by Ravensbergen (RD01) on the ESO VLT telescope.

The general process of wind torque estimation used still seems to be acceptable, but some of the assumptions used in RD01 are re-examined in this note, as they are crucial to the final result.

The performance of the Tip-tilt compensation loop is not re-evaluated, as the following analysis indicates that it is not required to meet the System Image Quality.

The technique used to produce the results in this note is the mathematical frequency equivalent method outlined in RD01, RD02 and implemented in Mathcad.
A Microsoft Word copy of the Mathcad file is attached as an Appendix.

In addition, a separate analysis by Fisher Astronomical Systems Engineering (FASE) is also appended to this document as a separate section. This uses more detailed structure calculations and two different analysis techniques to evaluate the wind effects, and produces similar results to the Ravensbergen-type calculations used in the main body of this report. It should be noted that they are based on initial approximations of the VISTA telescope structure from the VISTA Close-out review, rather than the more detailed drawing set now available.

2 Acronyms and Abbreviations

EED Encircled Energy Diameter
ESO European Southern Observatory
WHT William Herschel Telescope
VLT Very Large Telescope

3 Applicable and Referenced Documents

The following technical papers are referred to in the text.

[RD01] Main Axes Servo Systems of the VLT, Martin Ravensbergen
SPIE Vol 2199, pp 997-1005.

[RD02] Estimate of Windshake on Altitude Axis, Effect of Tip-Tilt Compensation
VIS-TRE-ATC-00002-0008 Issue 1.0

[RD03] System Image Quality Error Budget of the VISTA Telescope
VIS-TRE-ATC-00002-0001 Issue 2

[RD04] Overview of the VISTA Telescope Design for the Phase 'A' Close-out Review
VIS-TRE-ATC-00120-0007 Issue 1.0

4 DISCUSSION

4.1 Von Karman Wind Parameters

There was not sufficient data available in RD01 to evaluate the derivation of some the Von Karman wind parameters used. However Appendix 2 considers the method used produces a slight overestimate in results.

The allowable limit for altitude windshake is allocated to be 0.04 arcsec rms, derived from the SIQ Budget (RD03) for the whole telescope. The rationale here is that the wind will either have maximum effect in Altitude with Altitude vertical (which is what the calculations assume) and the Altitude rotation axis at 90 degrees to the wind direction, or maximum effect in Azimuth with Altitude horizontal and Altitude rotation axis parallel to the wind direction. However, in the latter case the Altitude axis is partly screened by the dome, and considering the higher stiffness of the Azimuth axis, the effect of wind force on it should be smaller than on the Altitude axis.

4.2 Altitude Inertia

The resultant position error due to wind torque is proportional to the assumed Inertia of the Altitude axis. Reference document RD02 used an early estimate based on a lighter structure than that now envisaged. Two current inertia estimates (one internal note from R.Bennet and reference RD04, AMOS section) now suggest around 242000 Kgm^2, about 2.5 times the original figure – this gives an immediate improvement in the estimated windshake.

4.3 Control Bandwidths

The control bandwidths expected are highly dependant on the actual mechanical resonant behaviour of the telescope structure – which can be different from the predicted behaviour obtained by methods such as finite-element techniques.
A simple resonance has been included in the Mathcad file to give an indication of the effects, (see appended Mathcad file) but the actual behaviour will be much more complex, probably with overlapping and adjacent multiple resonances.

It should also be noted that many telescopes use notch filters to alleviate the effects of mechanical resonances – these can be very effective if the resonances do not vary substantially due to gravity, temperature or life. As the benefits are uncertain, no notch filters have been assumed in the analysis, though it should be noted that they are used with the VLT telescope.

4.3.1 Position Bandwidth

The analysis in RD02 assumed a (position) bandwidth of 2.5 Hz, extrapolated from verbal information on the bandwidths obtained with the VLT telescope. Recent discussions with M.Fisher have indicated that the measured bandwidth of the WHT telescope is around 2.7 Hz, with an Altitude free rotor resonant frequency of 8.0 Hz.

The expected design value of the first resonant frequency of the VISTA telescope is expected to be around 14 Hz, and this resonance should have effect over a narrower frequency range than the more highly damped drive-chain WHT resonances.
We should therefore have good confidence in a position bandwidth of at around 5.0 Hz, with a possibility of increasing it towards 10 Hz.

4.3.2 Velocity Bandwidth

In addition, the assumption used throughout these analyses that the Altitude velocity bandwidth is twice the position bandwidth, is also pessimistic, given that WHT velocity bandwidths (for example) are 10 times the position loop bandwidths.

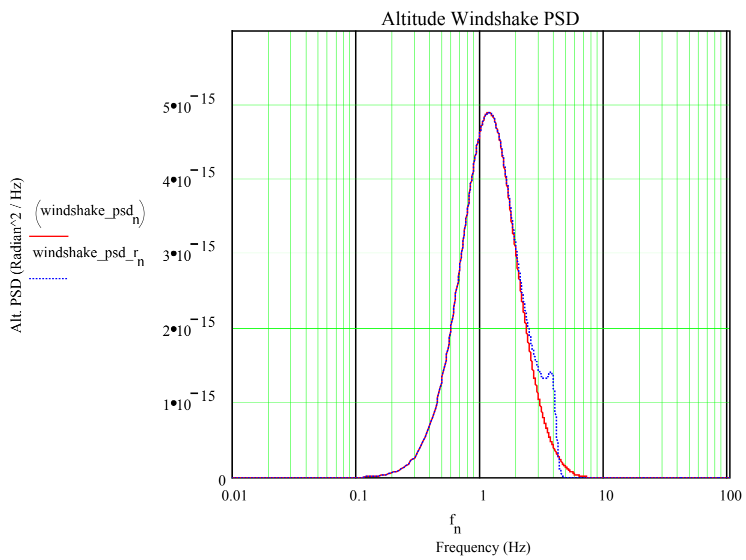
With a 5 Hz position bandwidth, if the velocity bandwidth could be increased from 10Hz to 40 Hz, then the results presented below would be similar to the 10 Hz bandwidth numbers, assuming any degradation in Altitude compliance was negligible.

5 RESULTS

Calculation results are as follows. Note that as wind velocity 'v' was varied, the effective RMS wind torque 'σ' was increased also, in proportion to the square of the velocity.
The nominal RMS wind torque used in RD02 was changed to 152 Nm for a wind speed of 6.0 m/s using new torque estimates from M.Fisher (200 Nm at 6.9 m/s).

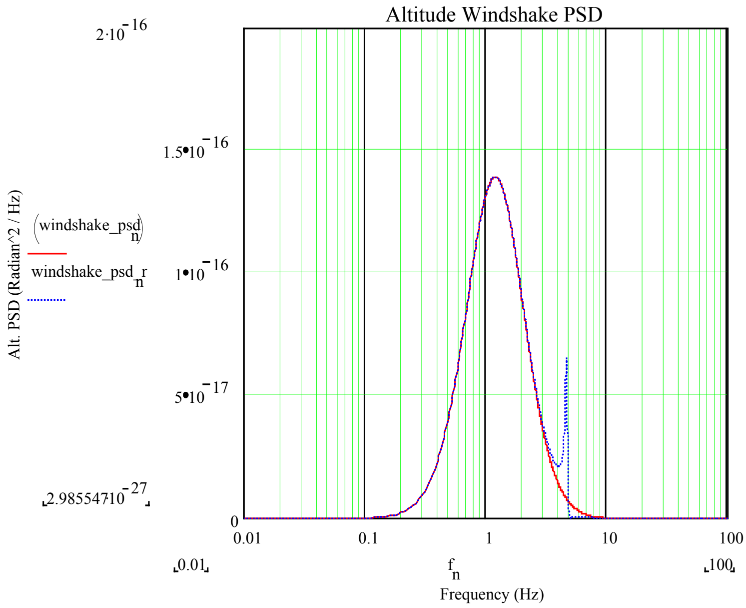
NOMINAL DATA :
RMS wind toque σ = 152 Nm
Outer scale of turbulence L = 0.6
internal mean wind speed v = 6.0 m/s
Area for aerodynamic correction factor A = 8.75 m^2
Altitude Inertia = 242000 Kgm^2
Position (-3dB) Bandwidth = 5 Hz
Velocity (-3dB) Bandwidth = 10 Hz

5.1 *Results for 5 Hz position bandwidth with 10 Hz velocity loop*



Nominal Altitude windshake (area under graph) = 0.02 arcsec rms
The internal wind velocity has to increase to 7.7 m/s, making σ = 250 Nm rms, before the estimate exceeds the requirements of 0.04 arsec rms.

5.2 *Results for 10 Hz position bandwidth with 20 Hz velocity loop*



(Note different y-axis scale to graph in 4.1)

Nominal windshake = 0.0035 arcsec rms

The internal wind velocity has to increase to 14.6 m/s, making σ = 905 Nm rms, before the estimate exceeds the requirements of 0.04 arcsec rms.

6 CONCLUSIONS

There is good confidence in obtaining a position bandwidth of 5 Hz, and a velocity bandwidth of 10 Hz.
The nominal windshake, assuming the validity of the wind calculations, meets the budget requirements up to dome *internal* wind speeds of nearly 8 m/s.

If Altitude bandwidth could be increased to 10 Hz, and velocity bandwidth was increased to 20 Hz, the calculations indicate that the estimated windshake requirements are within budget up to a dome *internal* wind speed of over 14 m/s.

Therefore, the assumptions and calculations above indicate that a fast Tip-tilt stage is unlikely to be required for the VISTA telescope.

7 APPENDIX A - MATHCAD File

Altitude Windshake B.Stobie UKATC 11/09/01

- From 'Main Axes Se rvo System of the VLT - Martin Ravensbergen
Advanced technology Optical Telescopes V, SPIE Vol 2199.

$nv := 1$

Mean wind speed (m/s) $v := 6.0 \cdot nv$

Outer scale of turbulence (m) $L := 0.6$ $nmax := 10^4$

RMS Wind torque (Nm) $\sigma := 152 \cdot nv^2$ $n := 1 .. nmax$

Frequency (Hz) $f_n := \frac{n}{10^2}$

Von Karman Spectrum

$fmin := f_1$ $fmin = 0.01$

$$S\_VK_n := \frac{4 \cdot L \cdot \sigma^2}{v \cdot \left[1 + 70.8 \cdot \left(\frac{f_n \cdot L}{v}\right)^2\right]^{\frac{5}{6}}}$$

$fmax := f_{10^4}$ $fmax = 100$

$freq\_band := (fmax - fmin)$

This has to multiplied by the square of the aerodynamic correction factor :

$na := 1$

Area of structure (m^2) $A := \frac{70}{8} \cdot na$

$$\chi_n := \frac{1}{\left[(2) \cdot f_n \cdot \frac{\sqrt{A}}{v}\right]^{\frac{4}{3}} + 1}$$

$A = 8.75$

The wind torque spectrum is therefore

$$S\_wind_n := S\_VK_n \cdot (\chi_n)^2$$

$S\_wind_1 = 9.202 \cdot 10^3$

$$average := \frac{\sum S\_wind}{nmax}$$

$approx\_int := average \cdot freq\_band$

$rms := \sqrt{approx\_int}$ $rms = 74.168$

The windshake position PSD is obtained by multiplying the wind torque spectrum by the square of the Altitude compliance : (compliance = position/torque)

Altitude inertia $J := 242000$ Kgm^2

(To give 10 Hz pos loop, 20 Hz rate)

Pos Integrator time constant $ti := 0.2$

Vel Integrator time constant $tv := 0.0625$

Velocity gain $Kr := \frac{3\cdot 10^7}{tv}$

Position gain $Kp := \frac{35}{ti}$

Define the Laplace variable 's' $s_n := j \cdot 2\cdot\pi\cdot f_n$

Define a resonance characteristic with a resonance peak at 14 Hz, and 2% damping :

$fr := 14 \qquad fa := 5$

$res\_f0 := fa \qquad rf := \left(\frac{fa}{fr}\right)^2$

$res\_w0 := 2\cdot\pi\cdot res\_f0$

$res\_d := 0.02$

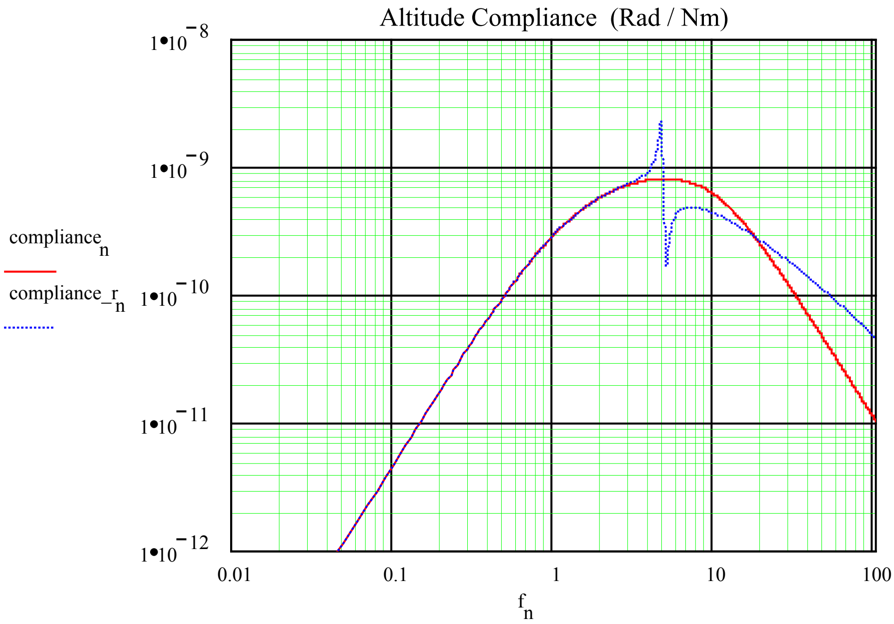
$$res_n := \frac{(s_n)^2 + 2\cdot res\_d\cdot res\_w0\cdot s_n + res\_w0^2}{rf\cdot(s_n)^2 + 2\cdot res\_d\cdot res\_w0\cdot s_n + res\_w0^2}$$

$$compliance_n := \left| \frac{(s_n)^2}{(s_n)^4\cdot J + Kr\cdot(1 + s_n\cdot tv)\cdot\left[(s_n)^2 + (Kp\cdot ti\cdot s_n) + Kp\right]} \right|$$

(This equation from block diagram analysis)

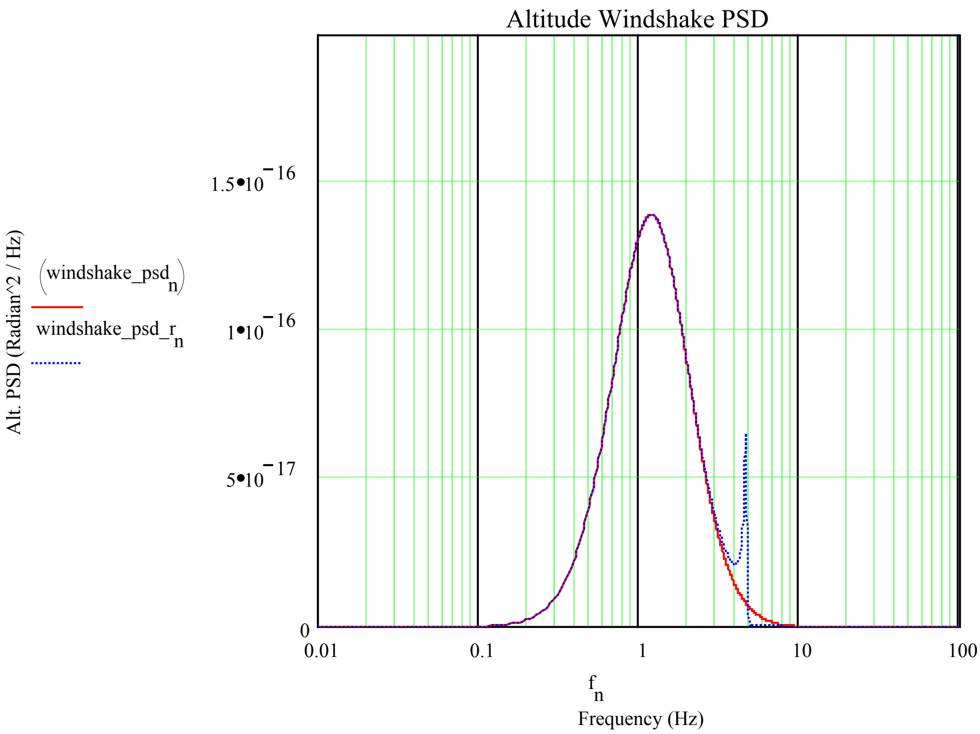
Compliance with resonance :

$$compliance\_r_n := \left| \frac{(s_n)^2\cdot res_n}{(s_n)^4\cdot J + Kr\cdot res_n\cdot(1 + s_n\cdot tv)\cdot\left[(s_n)^2 + (Kp\cdot ti\cdot s_n) + Kp\right]} \right|$$



$$windshake\_psd_n := S\_wind_n \cdot \left(compliance_n\right)^2$$

$$windshake\_psd\_r_n := S\_wind_n \cdot \left(compliance\_r_n\right)^2$$



The RMS windshake is the square root of the integral of the Power Spectral Density, over the bandwidth of interest.
- Calculate the approximate Integral, and take the square root to obtain the RMS

$$average := \frac{\sum windshake\_psd}{nmax}$$

$$approx\_int := average \cdot freq\_band$$

$$rms := \sqrt{approx\_int}$$

$$rms\_arcsec := rms \cdot 3600 \cdot \frac{180}{\pi}$$

$$rms\_arcsec = 3.41 \cdot 10^{-3}$$

$$average\_r := \frac{\sum windshake\_psd\_r}{nmax}$$

$$approx\_int\_r := average\_r \cdot freq\_band$$

$$rms\_r := \sqrt{approx\_int\_r}$$

$$rms\_arcsec\_r := rms\_r \cdot 3600 \cdot \frac{180}{\pi}$$

$$rms\_arcsec\_r = 3.51 \cdot 10^{-3}$$

1 APPENDIX 2 - F.A.S.E. CALCULATIONS

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The effect of wind turbulence on VISTA

Martin Fisher 22 September 2001

2 Introduction

The aim of this document is to help in the discussions that are required in order to decide if VISTA should be fitted with a fast tip-tilt secondary to remove the effects of windshake on the altitude axis. The effect of wind on structures is a complex issue and, in the absence of wind tunnel testing or computer flow simulations, only estimates can be made which are based on general empirical findings in the texts or specific findings related to existing telescopes and enclosures. While it is impossible to compute the exact flow around even relatively simple shapes, the effects of the flow on the structure are reasonably well understood and confirmed by empirical results. However, one of the most important factors in studies of this kind is determining the characteristics of the approaching flow and in this respect we can only rely on data provided for the ESO site. A further complication is the influence of the enclosure on the wind striking the telescope. Again, the availability of data is limited and only that determined and presented by ESO is considered, although it is supported to some extent by other texts[3,4].

Two methods are examined to assess the effect of wind turbulence on the VISTA structure. Both are derived from work undertaken by ESO but are supported by references to other texts on wind loading. The ESO methodologies are presented in papers by Quattri, Zago and Plotz[1] and by Ravensbergen[2], both referring to the design and control of the VLT. The former methodology involves a more detailed calculation of the effect of aerodynamic attenuation on the telescope structure, i.e. the effect due to de-correlation of the forces due to wind turbulence on significant areas or dispersed structures. The latter methodology is a simplification, not justified, for which parameters are stated and not developed.

The aim of this document is to calculate estimates of the disturbance torque about the altitude axis of VISTA and compare results from these two methodologies. From this it should be possible to decide if the simplified approach is valid for VISTA, which is an unusually short, squat structure.

Firstly, the two methodologies are described. Then the technique for calculating the wind torque is presented with results for a general, simple model of VISTA. Thirdly, the wind torque due to the turbulence component is determined for each approach and the effect on the telescope tracking is reviewed. Finally, the placing of reasoned bounds on the problem is discussed.

3 Methodologies

Here the two approaches to calculating the effect of wind turbulence on telescope structures are described:

3.1 The Ravensbergen Calculation

Ravensbergen's approach is to use the von Karman expression for the wind spectrum (see below) to describe the approaching flow but with parameters that are considered existent in the enclosure with optimum setting of the wind shields and louvers while the external wind speed is 18ms^{-1}, i.e. at the observing limit. In this equation, the first approximation is to use the RMS wind torque instead of the RMS wind velocity. This implies that the RMS wind torque has been calculated under the same conditions or has been determined from wind tunnel tests. The von Karman spectrum is then multiplied by the square of the aerodynamic attenuation factor to give a spectrum of the disturbance torque. This spectrum is then used in combination with the square of the disturbance rejection transfer function of the altitude servo to produce a spectrum of the angular displacement of the altitude axis and hence, by integration and taking the square root, the RMS tracking error due to wind disturbance. The expression for the aerodynamic attenuation factor is an empirical one, determined for flat plates normal to the principal axis of the turbulent flow. The area that is specified in this expression is the area of the plate and hence the de-correlation is effective over the whole area. The area actually applied in the expression is the area contained in the 'outline' of the telescope structure above the altitude axis. This is an approximation of the more detailed approach whereby the area of each significant component of the structure is treated individually with the application of the aerodynamic attenuation factor and then the spatial extent of the whole structure is accounted for by computing the cross-correlation terms of all the components. So how valid is this approximation? The expressions used are:

For the von Karman wind spectrum:

$$S(f) = \frac{\sigma^2 4L}{v\left[1 + 70.8\left(\frac{fL}{v}\right)^2\right]^{5/6}} \qquad \text{<0.1>}$$

Where:
f = frequency (Hz)
σ = RMS wind torque (Nm)

ν = mean wind velocity (m/s)
L = outer scale of turbulence (m)

For the aerodynamic attenuation factor:

$$\chi(f) = \frac{1}{1 + \left(2f\frac{\sqrt{A}}{v}\right)^{4/3}} \qquad \text{<0.2>}$$

Where:
f = frequency (Hz)
ν = mean wind velocity (m/s)

A = area to be used for the de-correlation of the wind turbulence

For the VLT, the parameters used were:

ν = 5.76 m/s; L = 0.6m; A = 70 m^2 and σ = 2.26 kNm

For VISTA we shall use:

ν = 6.9 m/s; L = 0.6m; A = 16.5 m^2 and σ is to be determined.

This means that the same scale of turbulence is assumed but not justified but a slightly higher mean velocity is assumed (25kph). The area is the approximate outline above the altitude axis of the current VISTA design. The RMS wind torque is to be calculated from the detailed component forces on the telescope and the turbulence intensity corresponding to the wind velocity assumed in the enclosure.

3.2 The Quattri, Zago and Plotz method

This method is based on the relationship between the Fourier transform of the angular displacements, the linear transfer function of the servo, the torque/velocity transfer function and the Fourier transform of the wind velocity function:

$$D(f) = H_{DT} H_{TU} U(f) \qquad \text{<0.3>}$$

Where H_{DT} is the servo transfer function, H_{TU} is the torque/velocity transfer function and $U(t)$ is the wind velocity function over a given time interval.

The torque/velocity transfer function is calculated from the total effect of all the structural components to be considered. For each component the term is given by:

$$H_{ii} = z_i C_{Di} S_i \rho U \chi_i \qquad \text{<0.4>}$$

Where:
z_i = the distance of the centre of pressure of the component to the altitude axis
C_{Di} = the drag coefficient of the element
S_i = the reference area (normally the cross-section) of the element
ρ = the air density
U = the mean wind velocity
χ_i = the aerodynamic attenuation factor for that component

Having obtained the wind torque for each component the cross terms between all components can be computed and this is given by:

$$H_{ij}^2 = 2 H_i H_j \sqrt{e^{-7\frac{f}{U}|d_i - d_j|}} \qquad \text{<0.5>}$$

Where $(d_i - d_j)$ is the vector distance between the centres of pressure of the two components and the factor 2 indicates that only one of the correlation terms for that pair need be calculated. The overall torque/velocity transfer function is then given by:

$$H_{TU}(f) = \sqrt{\sum_i \sum_j H_{ij}^2} \qquad \text{<0.6>}$$

Part of the above method (i.e. excluding the aerodynamic attenuation correction) can be used to calculate an estimate of the RMS wind torque to be used in the Ravensbergen approach. This will allow for comparison of the un-attenuated wind torque spectrum with both the approximately corrected wind torque spectrum and the more detailed correction.

4 Detailed Calculation of Wind Torque

4.1 Calculation of the torque/velocity transfer function

The VISTA telescope structure is split into 16 components: two top-end rings; the secondary unit; four secondary unit support vanes; the eight serurrier trusses and 50% of the centre section. These are chosen with the following assumptions in mind:

- There is no effective shading of one component by another, hence all eight vanes are considered as well as both the upwind and downwind parts of the top end ring.
- The same turbulent flow acts on all surfaces although may be less correlated over the area of the structure.
- Only the forces on the components above the altitude axis are considered and hence these represent a worst-case condition in the enclosure.
- The components are simple shapes such as cylinders, plates or boxes so that the Reynolds number for these may be simply calculated.

The calculation of the wind torque is undertaken in the Excel spreadsheet shown below:

Enter wind speed in km/hr:	25	V =	6.9	m/sec
Mass density of air (kg/m^3):	0.96	(at 2500m)		
Reynolds No. Re = V*D/v				
Kinematic viscosity, v	1.36E-05			
D = characteristic length				

Elevation (Above axis)	Shape	Re	Drag coeff	length m	width/dia m	No.	centroid z(m)	centroid y(m)	unit area m^2
Top-end ring (part 1)	cylinder	153186	0.6	5	0.3	1	2.75	0	1.5
Top-end ring (part 2)	cylinder	153186	0.6	5	0.3	1	2.75	0	1.5
Secondary unit	cylinder	561683	0.3	2	1.1	1	2.75	0	2.2
Secondary vane ULHS	plate	51062	2	2	0.1	1	3	-1.5	0.2
Secondary vane URHS	plate	51062	2	2	0.1	1	3	1.5	0.2
Secondary vane LLHS	plate	51062	2	2	0.1	1	2.75	-1.5	0.2
Secondary vane LRHS	plate	51062	2	2	0.1	1	2.75	1.5	0.2
Truss 1	cylinder	76593	1.2	2.8	0.15	1	1.6	-1.25	0.42
Truss 2	cylinder	76593	1.2	2.8	0.15	1	1.6	1.25	0.42
Truss 3	cylinder	76593	1.2	2.8	0.15	1	1.6	2.5	0.42
Truss 4	cylinder	76593	1.2	2.8	0.15	1	1.6	2.5	0.42
Truss 5	cylinder	76593	1.2	2.8	0.15	1	1.6	1.25	0.42
Truss 6	cylinder	76593	1.2	2.8	0.15	1	1.6	-1.25	0.42
Truss 7	cylinder	76593	1.2	2.8	0.15	1	1.6	-2.5	0.42
Truss 8	cylinder	76593	1.2	2.8	0.15	1	1.6	-2.5	0.42
50% Centre section	box	612745	2	5.4	1.2	0.5	0.3	0	3.24

The Reynolds number is calculated from the shape and area of the object and the wind velocity. The drag coefficient is obtained, using the Reynolds number, from standard tables for the shapes. The centroids are the distances of the centres of pressure (area) from the projection of the altitude axis (y) on to the y-z plane and from the tube axis (z) on to the y-z plane. The data required for the torque/velocity transfer function are the drag coefficient, the unit area and the centroids. For each component the torque/velocity transfer function is given by equation <0.4>. The aerodynamic attenuation factor is a function of frequency and so the results are an array *n* x *f*, where *n* are the sixteen components of the structure and *f* are the frequency increments desired. The column sum of this array is called Hii and is the total wind torque/velocity function for the components of the structure at the frequencies specified (aerodynamic attenuation is only applied to the components themselves and no account is taken of their distribution). In addition, the DC or zero frequency torque/velocity value, H0, is calculated by summing the component contributions without multiplying by χ_i, the aerodynamic attenuation factor. The next stage is to obtain all cross terms of the torque/velocity transfer function. This is achieved by creating a three-dimensional array *n* x *n* x *f* using the Kroniker tensor product function and multiplying each term by the correlation factor. The cross terms are the off-diagonal products and are summed for each frequency plane by forming the array sum and subtracting the sum of the diagonal elements. In doing this, it is then not necessary to include the factor of 2 in equation <0.5>.

The square root of this sum, called H_{TU}, is the torque/velocity transfer function, including the effect of turbulence de-correlation over the whole structure. The approximation of applying aerodynamic attenuation directly to the whole outline of the structure rather than to individual components and then cross-correlating, is tested by multiplying the DC value, H0, by the aerodynamic attenuation factor with A equal to the area of the outline. This produces a 1 x *f* vector called H0mod. The DC values of H0 are tabulated below and totals 130 Nm/m/sec.

Elevation (Above axis)	Shape	Drag coeff	unit area m^2	H0 Nm/m/s
Top-end ring (part 1)	cylinder	0.6	1.5	16.3944
Top-end ring (part 2)	cylinder	0.6	1.5	16.3944
Secondary unit	cylinder	0.3	2.2	12.0226
Secondary vane ULHS	plate	2	0.2	7.9488
Secondary vane URHS	plate	2	0.2	7.9488
Secondary vane LLHS	plate	2	0.2	7.2864
Secondary vane LRHS	plate	2	0.2	7.2864
Truss 1	cylinder	1.2	0.42	5.3416
Truss 2	cylinder	1.2	0.42	5.3416
Truss 3	cylinder	1.2	0.42	5.3416
Truss 4	cylinder	1.2	0.42	5.3416
Truss 5	cylinder	1.2	0.42	5.3416
Truss 6	cylinder	1.2	0.42	5.3416
Truss 7	cylinder	1.2	0.42	5.3416
Truss 8	cylinder	1.2	0.42	5.3416
50% Centre section	box	2	3.24	12.8771

The resulting transfer functions for Hii, H_{TU} and H0mod are shown in Figure 1. It is evident that applying aerodynamic attenuation only to the structural components, (Hii), produces attenuation of the torque at frequencies above about 1Hz. However, with cross-correlation of the structural component contributions included, (HTU), the attenuation starts at about 0.1Hz and after 1Hz is only 25% of the Hii value. The approximate solution, (H0mod), obtained by applying the aerodynamic attenuation factor simply to the outline area is somewhat lower still, underestimating the calculated torque function, but can be regarded as a useful approximation.

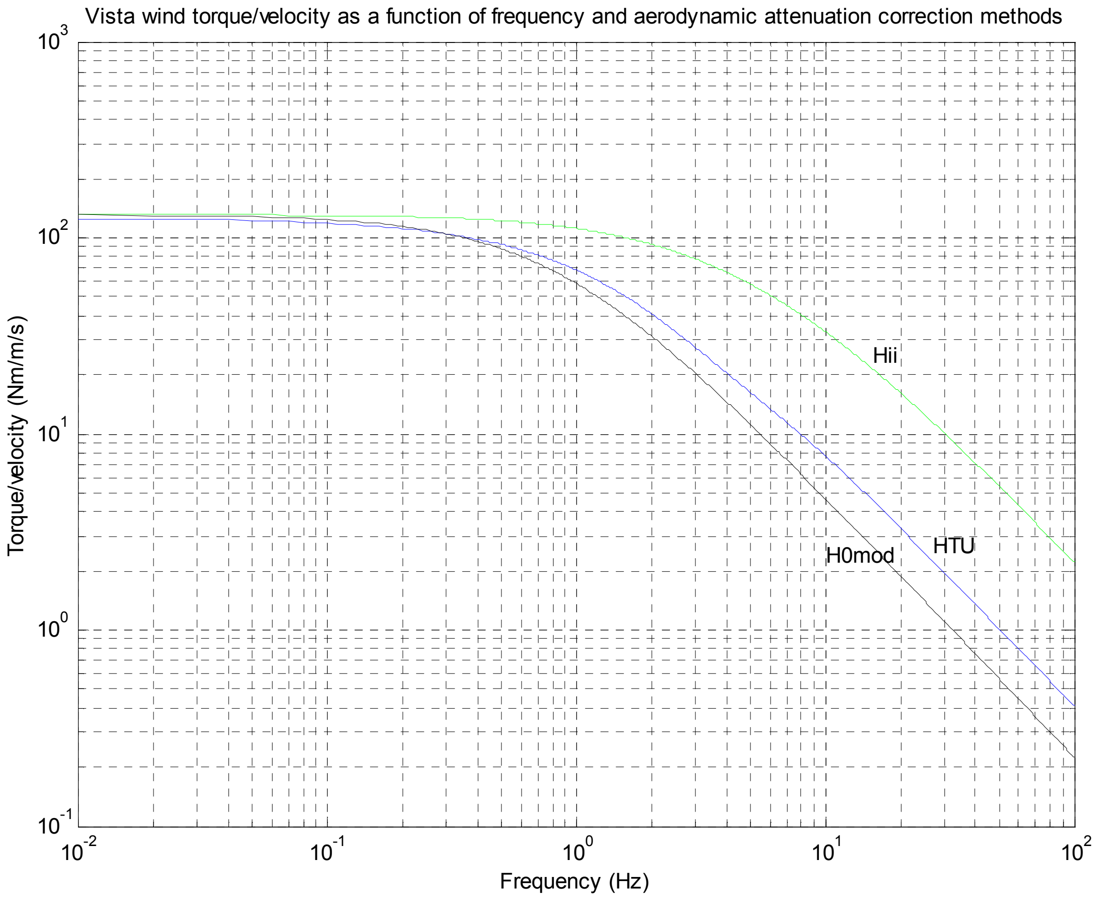

Figure 1: VISTA torque/velocity transfer function

4.2 The von Karman wind spectrum

The von Karman spectrum is given by:

$$\frac{nS(n)}{u_*^2} = \frac{4\beta \frac{nL_u^x}{U}}{\left[1 + 70.8\left(\frac{nL_u^x}{U}\right)^2\right]^{5/6}} \qquad \text{<1.1>}$$

Where:
u_*^2 is the shear or friction velocity
n is the frequency in Hz
β relates the turbulence to the roughness length
L_u^x is the longitudinal integral scale

Since: $\overline{u}^2 = \beta u_*^2$ and the turbulence intensity $I(z) = \frac{\sqrt{\overline{u}^2}}{U} = \frac{\sigma}{U}$ where σ is the RMS wind velocity, then by substituting these in equation <1.1> and letting $f = n$ the von Karman spectrum becomes:

$$S(f) = \frac{4\sigma^2 \frac{L}{U}}{\left[1 + 70.8\left(\frac{fL}{U}\right)^2\right]^{5/6}} \qquad <1.2>$$

To characterise this spectrum for Cerro Paranal, the value of L is chosen from ESO documents while the calculation of U and σ is given in Appendix B. These values are:

L = 0.6m; U = 6.9m/s and σ = 1.4m/s. The von Karman spectrum is shown in Figure 2. The integrated power and RMS wind velocity are shown in Figure 3- to verify that the frequency range chosen produces the correct RMS level.

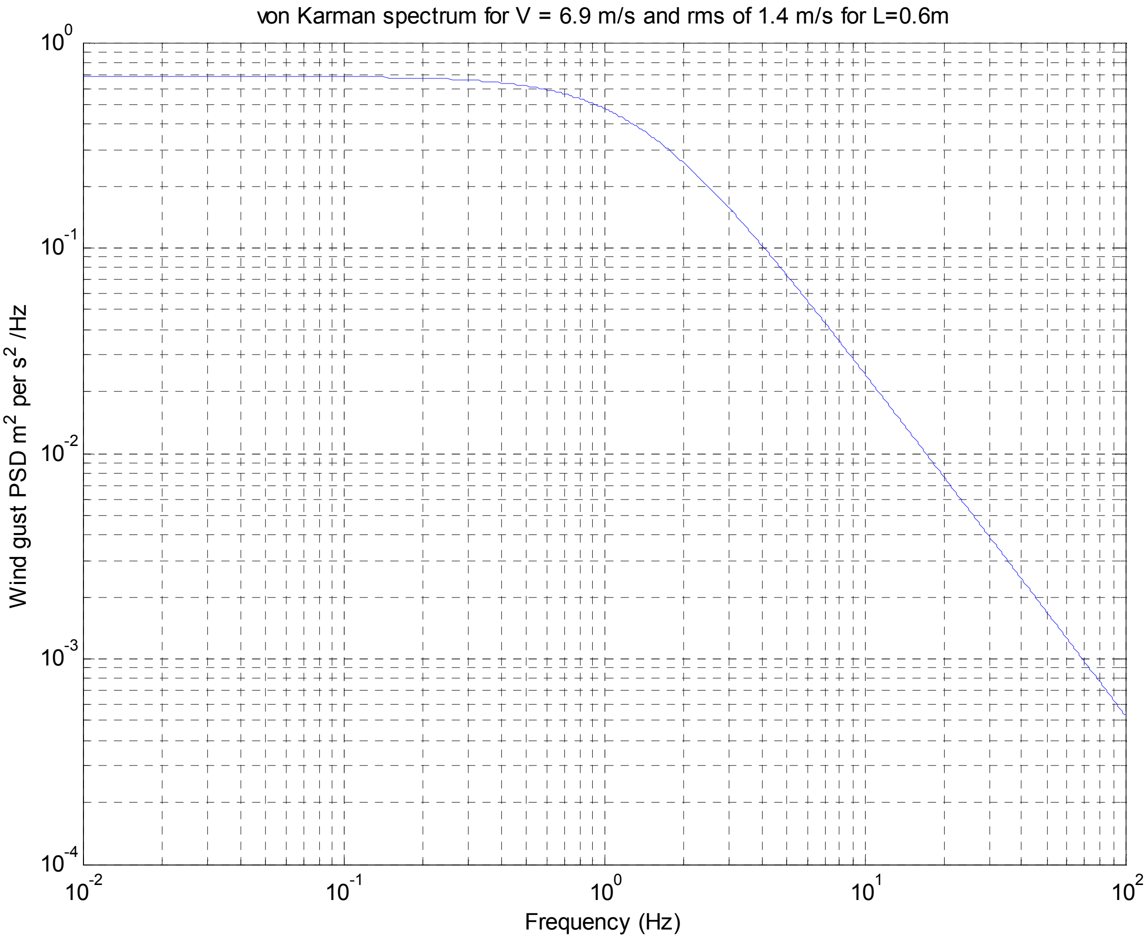

Figure 2: The von Karman wind turbulence power spectrum

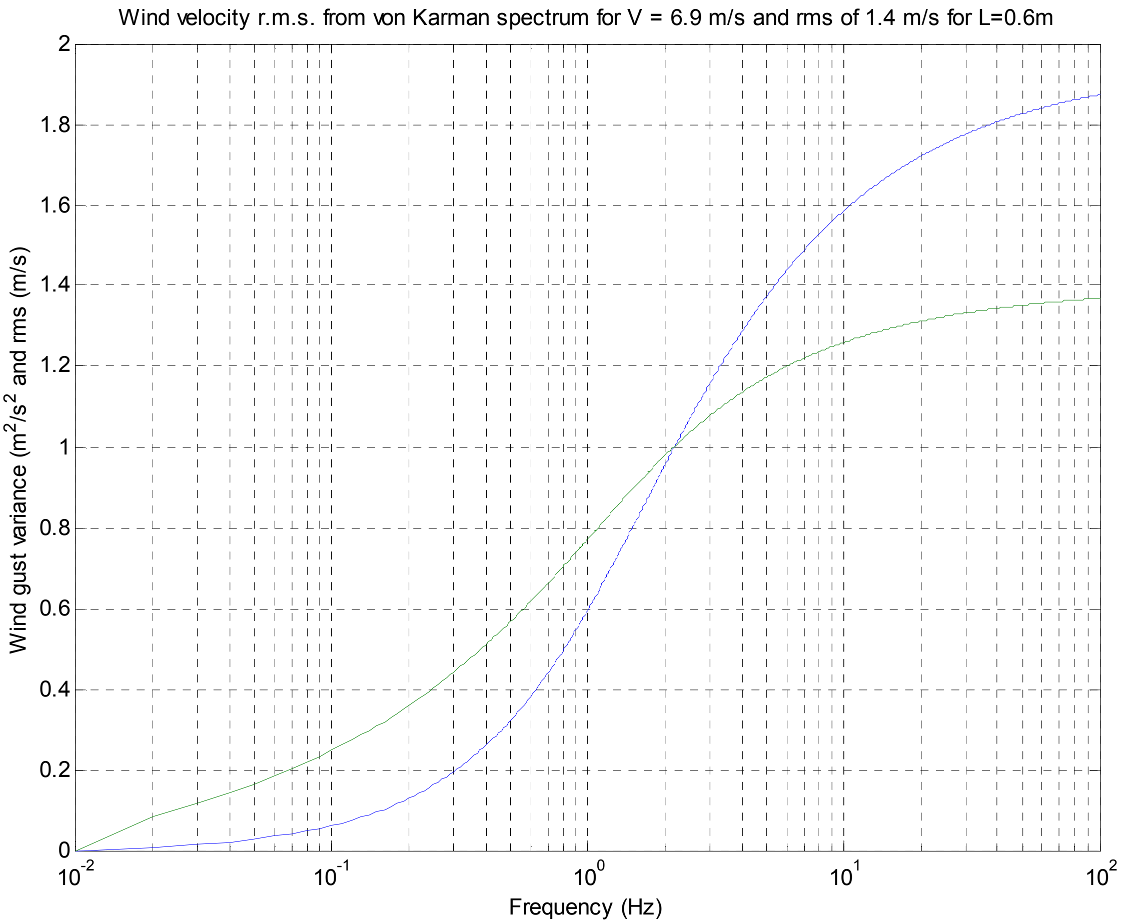

Figure 3: Integrated power and RMS level of von Karman spectrum

4.3 Calculation of wind torque spectra

There is now sufficient information to calculate the wind torque spectra and resulting RMS wind torque for each of the methods used. To obtain these, the $H_{TU,}$ H0mod and the DC level of the wind torque/velocity component, H0sum, are each squared and multiplied by the von Karman spectrum. These are shown in **Figure 4**. Also shown are the results of using the RMS wind torque, obtained from H0sum in conjunction with the von Karman spectrum, in the Ravensbergen method. These are designated xH0 and xH0mod and closely match H0 and H0mod results, as is to be expected if the calculations are consistent.

The square roots of the cumulatively integrated spectra are shown in **Figure 5**. The RMS value of each function is that level reached at the right hand side of the plot. So the value of H0 to be substituted in the Ravensbergen method is σ = 180Nm which is reasonably close to the value of 200Nm produced by simple scaling of the absolute wind torque described in an earlier communication and referred to in Appendix A. It is still clear that the approximate method produces lower results than the does the detailed calculation of H_{TU} but, bearing this in mind the approximate method is still reasonably valid.

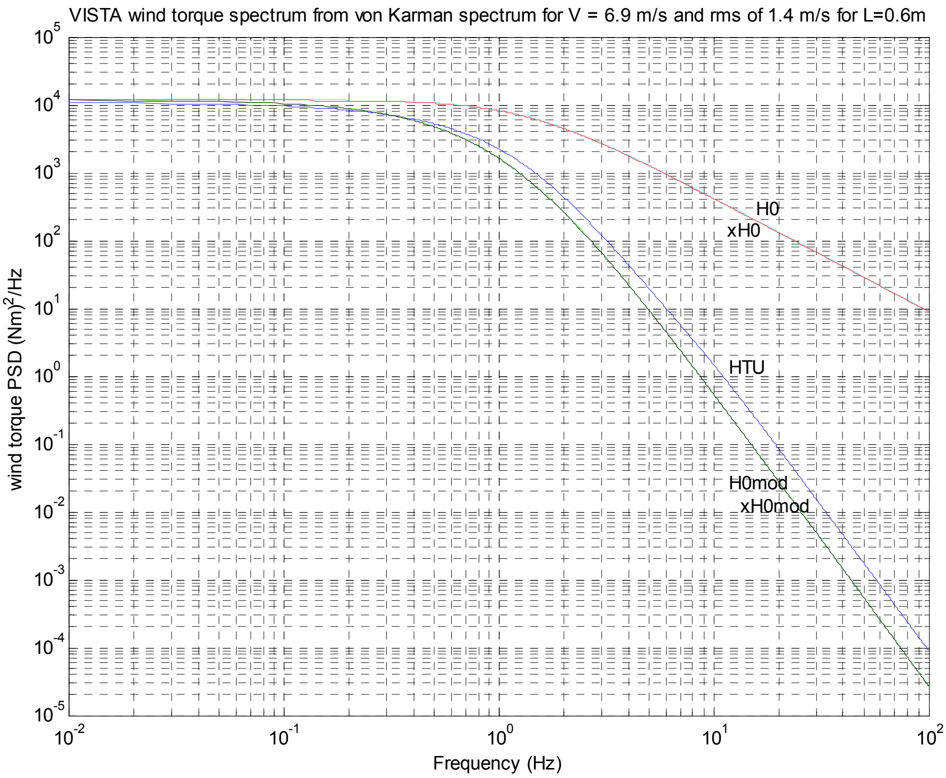

Figure 4: VISTA wind torque spectrum

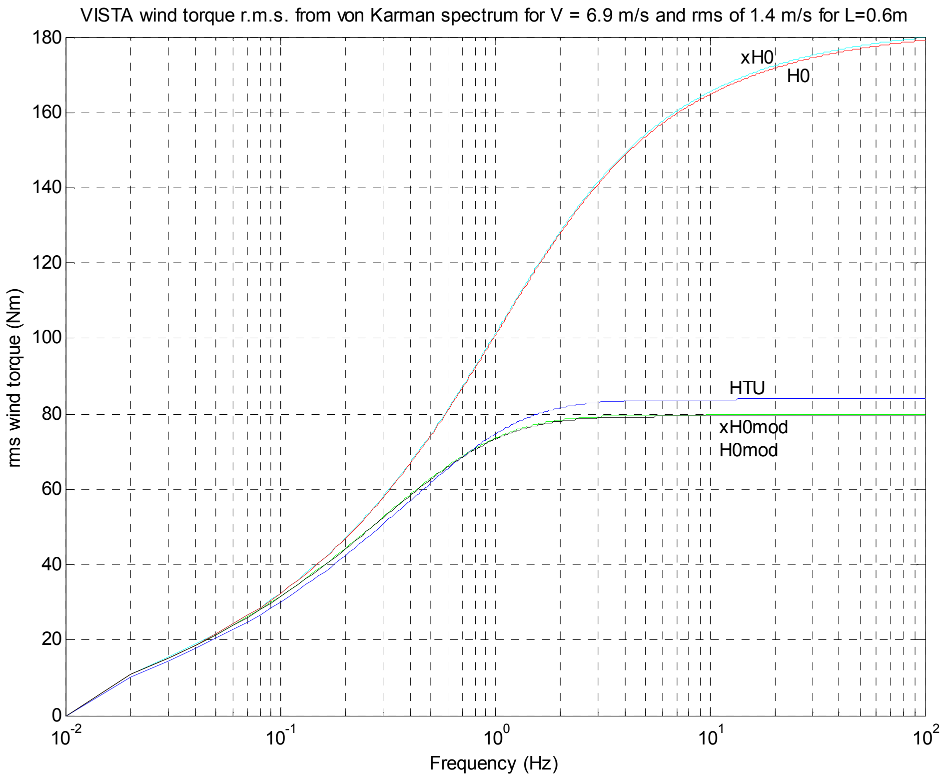

Figure 5: VISTA RMS wind torque

4.4 Effect on Tracking Performance

It is evident from the cumulative RMS function of H_{TU} that there is very little additional energy above 2 Hz and so a servo position bandwidth of 5Hz should be able to reject much of the disturbance, which occurs between 0.01Hz and 1Hz. To evaluate the tracking performance, the von Karman wind torque spectrum with aerodynamic correction is multiplied by the square of the disturbance rejection transfer function, as described in Ravensbergen's paper. To obtain this transfer function a representative dynamic model of VISTA is required together with an appropriate servo controller design. Initially this model can be linear and use lumped parameters to represent the inertia, stiffness and damping of the major components. An FEA of the altitude dependent components of the telescope, including the pier and ground if necessary, should provide the structural frequencies required to model the tracking loop. The most important features that the FEA must address are the locked rotor mode of the altitude drive and the first few eigenfrequencies of the tube. The locked rotor mode will also depend on where the velocity feedback signal is observed. If mechanical bearings are being considered then the model should also be developed to include non-linear friction to verify that performance requirements can still be met. Other effects, such as motor cogging and ripple torque, would also need to be included.

4.5 Bounding the Problem

The uncertainties in the overall evaluation of the tracking error have differing degrees and need to be assessed. Each of the following includes a measure of allowance for error in assessment:

- The FEA results will produce a reasonable structural description of the telescope and indicate appropriate velocity and position loop bandwidths. A margin of error can be assigned to this by reducing all frequencies by a suitable percentage, e.g. 20%.
- The calculation of drag on the structure already has a margin of error applied in that all components see the same wind profile and there is no shading taken into account. In addition, the mean wind speed used is 6.9m/s as opposed to 5.76m/s for the VLT analysis, an increase of 20%.
- The von Karman wind spectrum is the most likely area of greatest uncertainty. The range of L, the outer scale of turbulence, is not known. However, the value of turbulence intensity used ($I_z = 0.2$) is a severe one.

The drag calculations already have a margin of error incorporated in them. The servo bandwidth can also be determined and a margin of error assigned. The von Karman spectrum will have a margin of error incorporated in it due to the calculation of the RMS torque using both the increased mean wind velocity and a turbulence scale that results in a severe turbulence intensity value. Since the value of L in the von Karman spectrum influences the amplitude and frequency of the spectrum then the effect of its variation, i.e. its sensitivity, can be assessed. For example, if L is doubled to 1.2m then the magnitude of the spectrum increases (from 0.69 to 1.36 at low frequencies below 0.1 Hz) while the break frequency of the high frequency asymptote reduces (from 1.2 Hz to 0.7 Hz). This increases the RMS wind velocity at frequencies below 10Hz (typically from 1.25 m/s to 1.32 m/s at 10Hz) but produces very little difference above 10 Hz. The value of RMS wind torque increases from 85 Nm to 104 Nm with very little increase above 1 Hz, as shown in Figure 6, which suggests a sensitivity of 1/5 or thereabouts. If L is reduced to 0.3m then the von Karman spectrum amplitude reduces to 0.34 and the break frequency shifts to 2.3 Hz. This illustrates how turbulence energy is transferred to higher frequencies when the scale length is reduced. The RMS wind torque under these circumstances reduces to 65 Nm with very little increase above 3 Hz as shown in Figure 7. This indicates a similar sensitivity to the previous case.

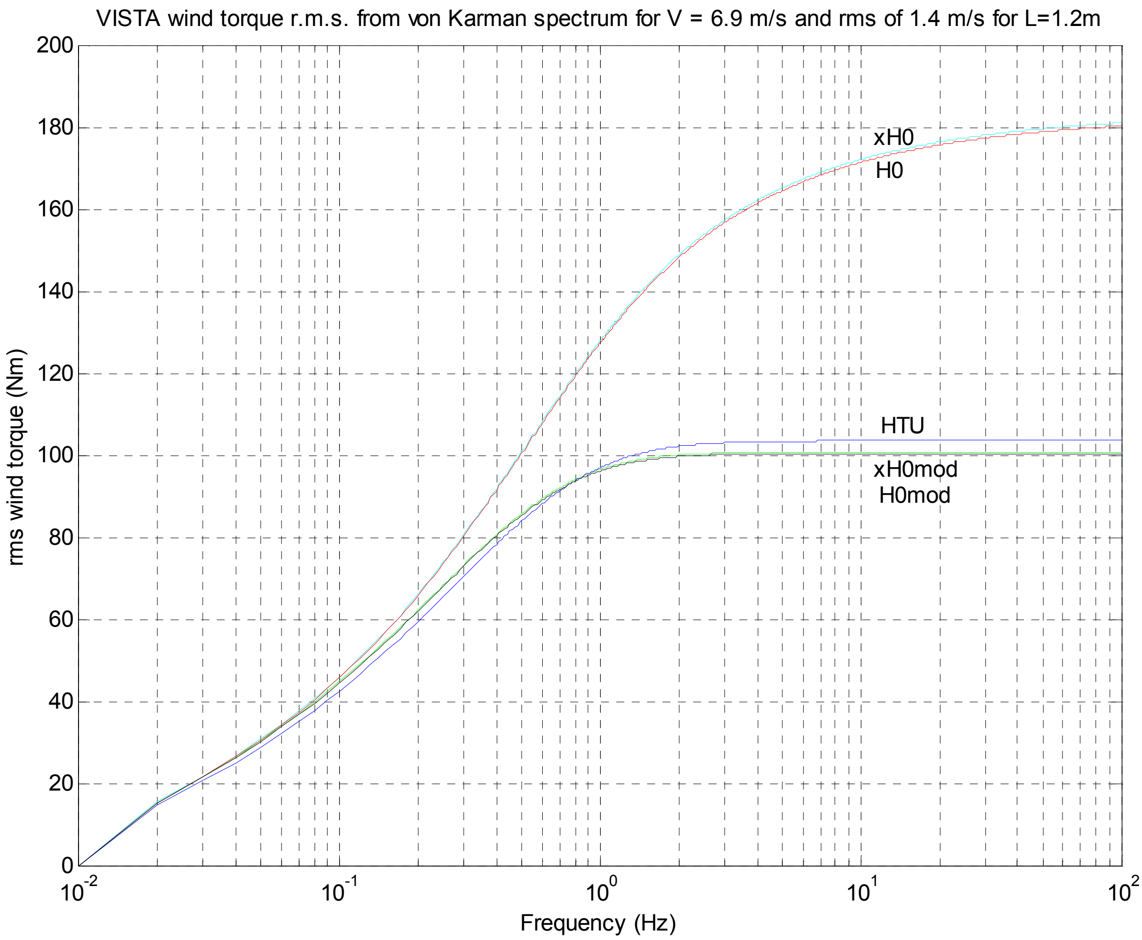

Figure 6: VISTA wind torque RMS for L increased to 1.2m

The actual turbulence is likely to be a combination of the modified external enclosure wind turbulence, for which the terrain determines the scale length and is likely to be of the order of metres or tens of meters, and the enclosure induced turbulence of shorter scale length. The longer scale length turbulence will have a higher amplitude but will be rejected more by the servo's low frequency disturbance rejection profile while the short scale length turbulence will only be effective in the 0.1 Hz to 2Hz region. This is because at short scale lengths of 0.3m, i.e. the diameter of the top end ring, there is little significant contribution to the RMS wind torque. Consequently, the error margin to be considered is that caused by underestimation of the scale length. Since doubling the scale length increases the RMS wind torque by only 20% then it would seem sensible to allow a reasonable margin of wind torque directly, say 50%, knowing that this represents a considerable increase in scale length which in itself works in favour of the servo's disturbance rejection.

There are two other factors to consider. Firstly, the mean wind speed to be used for all these calculations is based on VLT experience and measurements at La Silla. It seems to be generally accepted that the external mean wind speed is reduce by a factor of between two and three within the enclosure, the energy being transferred to shorter scale turbulence and, to some extent, dissipated by aerodynamic damping. The figure used in these calculations is a factor of 1/2.6 of the maximum operating wind speed at Cerro Paranal. Secondly, the aerodynamic attenuation factor is determined empirically, but for flat plates rather than cylinders. That this expression is also used for aeroplanes as well as open frame structures and for large buildings gives one confidence that it is equally applicable to telescopes.

The parameters of direct interest then are the servo bandwidth, the internal mean wind velocity and, possibly, the scale length of the turbulence. These can be used, in conjunction with a suitable model of the altitude axis, to calculate the RMS tracking error for particular margins of error. In addition, the maximum margin of error for each individual parameter (while the others are at nominal values) can be determined to give a measure of the sensitivity of that parameter relative to the others.

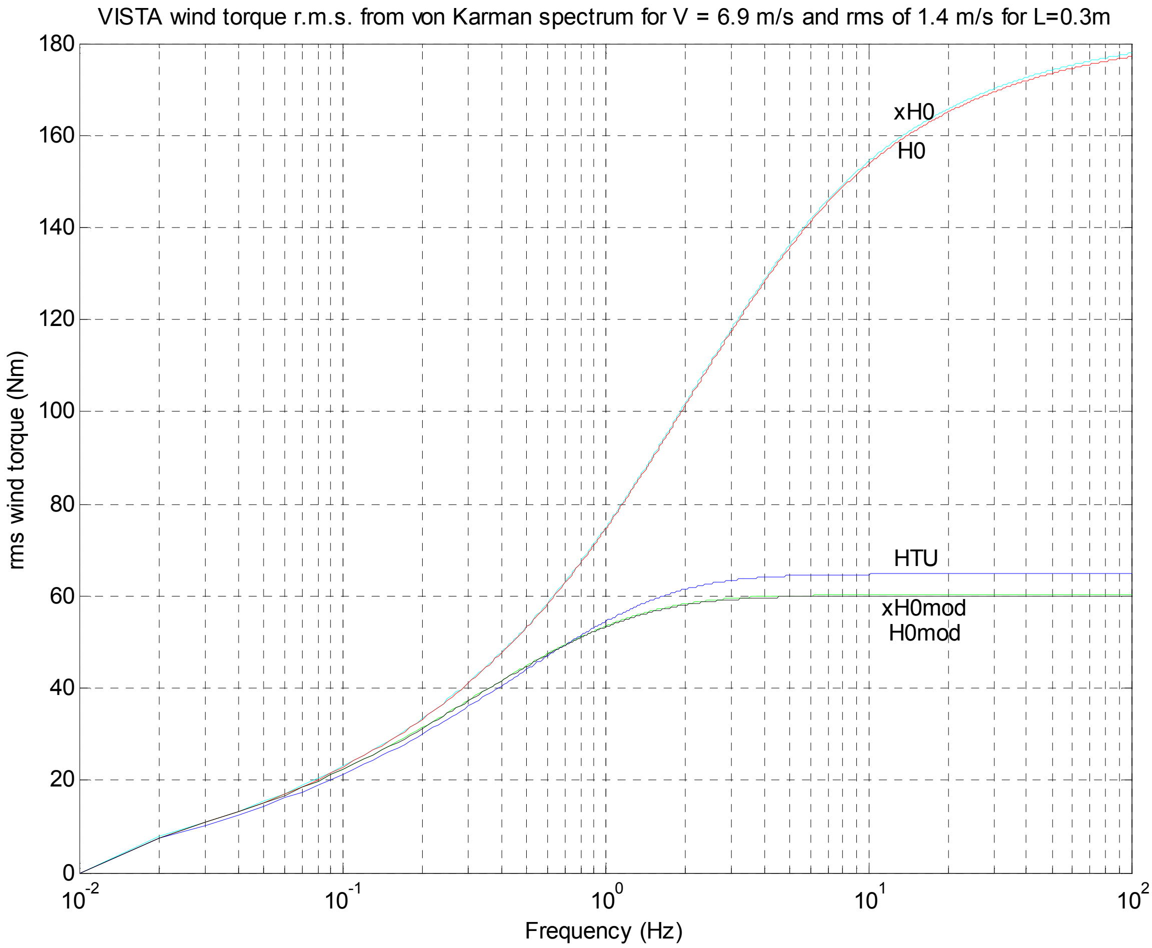

Figure 7: VISTA RMS wind torque for L decreased to 0.3m

4.6 Conclusions

The approximate method, described by Ravensbergen, overestimates the attenuation from aerodynamic effects but only by about 10%. Bearing this in mind it is a reasonable approximation to use to avoid detailed calculation of the wind torque spectrum.

The application of the aerodynamic attenuation factor over the outline area of telescope takes no account of the crosswind turbulence form and neither does the detailed calculation. This could be taken into account in the detailed calculation by only considering vertical separation of the components. However, the presence of the enclosure slit and windscreen is likely to produce a reasonably random turbulence scale in all directions.

The validity of the von Karman spectrum, in the context of telescopes within enclosures, is not addressed here. There is concern (page 60 of reference 3) that it does not represent the higher frequency components of longitudinal turbulence very well when using large-scale features to determine L. Consequently the use of a low value of L (0.6m) may be sufficient for the scales we are interested in but we do not know how valid this is. Turbulent wake theory[4] predicts size of vortices based on the longest dimension of a 'bluff object' that are consistent with empirical results but how this may be related with enclosure slits and wind screens is not clear. However, the RMS wind torque is not particularly sensitive to changes in scale length and increases in RMS wind torque due to increases in scale length are partially offset by the servo's ability to reject the associated lower frequencies. The effects of higher frequencies, associated with a decrease in scale length, are offset by decreased amplitude and by aerodynamic attenuation.

There is a reasonable margin of error inherent in most calculations but further allowance can be made for specific parameters such as servo bandwidth and mean wind velocity in the enclosure. A suitable dynamic model of the VISTA elevation axis can be used to determine the sensitivity and limits of each of these parameters as well as to determine the tracking error in the presence of other effects such as friction and motor torque disturbances.

The limited amount of information available from ESO does suggest that calculation of windshake was valid for the VLT and that the RMS position error due to wind disturbance is of the order of 0.2 to 0.3 arcsec while the secondary tip-tilt compensation is turned off.

4.7 References

1. Design evolution and performance evaluation of the VLT telescope structure.
   M. Quattri, L. Zago and F. Plotz; ESO conference publication.
2. Main axis servo systems of the VLT
   M. Ravensbergen; SPIE Vol 2199
3. Wind Effects on Structures.
   E. Simiu and R.H. Scanlan; Wiley 1996
4. Applications of Random Vibrations
   N.C. Nigram and S. Narayanan; Springer-Verlag 1994

5 Appendix A : Static Wind Torques

5.1 Communication

Part of email from Martin Fisher to Brian Stobie on 31 August 2001

I have been looking at how ESO derives the rms wind velocity from the mean velocity. This seems to be how ESO arrives at the rms wind torque figure of 2.26kNm for the VLT. According to Zago (1985) the standard deviation ,s, of the wind velocity, V, is determined from the turbulence intensity, Iz.

s = Iz.V

There are plots of Iz versus wind speed for Paranal and, although they scatter much more at low wind velocities, the maximum value of Iz for a particular velocity seems to be adopted. Hence for free air flow (outside enclosure) Iz is 0.17 at 9m/sec and 0.13 at 18m/sec. Behind 50% wind-screens (which is what this paper is about) an 18m/sec wind reduces to 9m/sec but Iz increases to 0.2 (and the peak in the spectrum shifts to higher freqs).

If we assume that Iz is 0.2 inside the enclosure then for the 6.9m/sec mean wind speed the rms will be

0.2 x 6.9 = 1.38 m/sec

(Also in some ESO papers I have seen references to typical rms wind fluctuations of 0.5m/sec and ones of 1m/sec for more the more untypical conditions.)

Then the rms wind torque (using the spread sheet value of 453 Nm) scales by (I think) sqrt(1.38/6.9) = 0.447, to give 202Nm. If you use the spread sheet to note the increase in wind torque by entering 6.9 +1.4 (or 25 km/hr to 30 km/hr) then you get 199Nm so I think this result is OK, if not rigourous. So if you stick 200Nm in your model as opposed to VLT/8 you're a bit better off, although it shows the scaling was a good point to start.

5.2 Static wind torque calculation

The spreadsheet showing the calculation of the static wind torque at a wind speed of 6.9m/s is shown on the next page. Note that, in this case, the top end ring is split into eight sections (as it might be manufactured), which are dealt with according to their orientation with the wind. The rather more simplistic approach of using two cylinders, each the width of the telescope produces very similar results and was used for the model in this paper.

Enter wind speed in km/hr:	25	V =	6.9	m/sec
Mass density of air (kg/m^3):	0.96	(at 2500m)		
Reynolds No. Re = V*D/v				
Kinematic viscosity, v	1.36E-05			
D = characteristic length				

Elevation (Above axis)	Shape	Re	Drag coeff	length m	width/dia m	No.	centroid m	unit area m^2	eff. area m^2	wind speed m/sec	pressure kg/m^2	force N	torque Nm	Static Mo m^3
Top-end ring (part 1)	cylinder	153186	0.4	2.25	0.3	2	2.75	1.35	0.54	6.9	23.1	12.5	34.4	1.485
Top-end ring (part 2)	cylinder	153186	0.6	1.6	0.3	4	2.75	1.92	1.152	6.9	23.1	26.7	73.3	3.168
Top-end ring (part 3)	cilinder	153186	0.8	0.7854	0.3	2	2.75	0.14137	0.1131	6.9	23.1	2.6	7.2	0.311018
Secondary unit	cylinder	561683	0.3	2	1.1	1	2.75	2.2	0.66	6.9	23.1	15.3	42.0	1.815
Secondary vanes	plate	51062	2	2	0.1	4	2.75	0.8	1.6	6.9	23.1	37.0	101.9	4.4
Trusses (8 off)	cylinder	76593	1.2	2.8	0.15	8	1.6	3.36	4.032	6.9	23.1	93.3	149.3	6.4512
50% Centre section	box	306373	2	5.4	0.6	1	0.3	3.24	6.48	6.9	23.1	150.0	45.0	1.944
								13.0114	14.5771			337.4	453.1	19.57422

Elevation (Below axis)	Shape	Re	Drag coeff	length m	width/dia m	No.	centroid m	unit area m^2	total area m^2	wind speed m/sec	pressure kg/m^2	force N	torque Nm	Static Mo m^3
50% Centre section	box	306373	2	5.4	0.6	1	0.3	3.24	6.48	6.9	23.1	150.0	45.0	1.944
Mirror cell	cylinder	2399918	0.8	1	4.7	1	1.3	4.7	3.76	6.9	23.1	87.0	113.1	4.888
Instrument	cylinder	653595	0.3	0.83	1.28	1	2.17	1.0624	0.31872	6.9	23.1	7.4	16.0	0.691622
Instrument (boxes)	box	306373	2	0.6	0.3	2	2.17	0.36	0.72	6.9	23.1	16.7	36.2	1.5624
								9.3624	11.2787			261.1	210.3	9.086022

centroid above elevation axis:	1.8
centroid below elevation axis:	1.3
Static tube moment U (m^3):	26.2
Static tube moment L (m^3):	14.6623
Sum of moments (m^3):	40.9
Total tube area:	22.3738
Elevation bearing force (N):	598.5

Torque = 0.5 * effective moment * velocity^2 * mass density = 453.107 assuming wind affects only the part of the telescope above the altitude axis.

6 Appendix B : Calculation of U and σ

The calculation of U and σ for use in wind spectrum estimation.

The mean wind speed U(z):

$$U(z) = \frac{1}{k} u_* \ln \frac{z}{z_0} \qquad \text{<1.3>}$$

where k = the von Karman coeffcient = 0.4

The turbulence intensity:

$$I(z) = \frac{\sqrt{\overline{u}^2}}{U} = \frac{\sigma}{U} \qquad \text{<1.4>}$$

The longitudinal turbulence fluctuations:

$$\overline{u}^2 = \beta u_*^2 \qquad \text{<1.5>}$$

The relationship between β and z_0 is tabulated:

Z_0	0.005	0.07	0.30	1.00	2.50
β	6.5	6.0	5.25	4.85	4

Hence for an altitude of 20m above a terrain of uneven sand/rock (z_0=0.2m) and for U = 18m/s the external turbulence intensity is calculated as follows:

$$18 = \frac{1}{0.4} u_* \ln \frac{20}{0.2}$$

$$u_* = \frac{0.4 \times 18}{4.6} = 1.56$$

Then since $\beta \sim 5.5$:

$$\overline{u}^2 = 5.5 \times 1.56^2 = 13.44$$

The turbulence intensity and rms turbulence velocity are:

$$I(z) = \frac{\sqrt{13.44}}{18} = 0.2$$

$$\sigma = \sqrt{13.44} = 3.67 m/s$$

The effect of enclosure and windscreen is to reduce the stream velocity by a factor of between two and three. ESO use a value of 5.76m/s for internal mean wind speed for an external wind speed of 18m/s. For the VISTA calculation, we use a value of 6.9m/s for the internal flow. When the flow is reduced by windscreens, the turbulence intensity is also reduced but the PSD shifts to higher frequencies. This is reflected in the use of the short scale length in the von Karman spectrum. However, assuming the turbulence intensity is not reduced a value for σ inside the enclosure is:

$$\sigma = 0.2 \times 6.9 = 1.38 m/s$$

This agrees well with ESO observations of wind turbulence velocities of up to 1m/s RMS at La Silla in terrain wind speeds of 15m/s and so the value of 1.4m/s seems acceptable for VISTA calculations.