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Change Record

Issue	Date	Section(s) Affected	Description of Change/Change Request Reference/Remarks
1.0	7/14/03	All	First Issue
1.1	3/16/04	4.3.1.11	Per RID 110. Clarified intent.
	3/16/04	4.3.2.12	Corrected typo per RID 113.
	3/16/04	4.5.2	Fixed RSS Totals per RID 114
	3/16/04	4.3.2.1	Corrections per "vertex_qsmodel.pdf" of SCC
1.1	3/16/04	4.3.3, 4.5.3, 4.5.1	Corrected preliminary RMS scale factor; updated text and calculations – 4.5.3; Reconciled 4.5.3 and 4.5.1 Cass Errors
2.0	5/27/04	Numerous	Updated for FDR. Includes nonlinear simulation inputs.
2.1	6/4/04	Table 4.5.1-2	Corrected math errors, AD05 Reference

Table of Contents

1 Introduction

This report generates the positioning error budgets for the telescope. There are modest changes for this release. A more extensive update is expected in the near future.

2 Acronyms and Abbreviations

VRSI	VertexRSI
VIS	VISTA
TRE	Technical Report

3 Applicable and Referenced Documents

In this section all the documents referred to in the Analysis Report are listed. Issues are listed for reference, but the latest issue should be applicable.

	Title	Number & Issue
AD01	Technical specification for the Telescope Structure Work Package	VIS-SPE-ATC-01000-006 (3.0)
AD02	Electrical And Mechanical Characteristics Of Earth Station Antennas For Satellite Communications	ANSI/EIA-411-A-1986
AD03	Quasi Static Pointing Error Clarification	TBD 0.1 Draft
AD04	Vista Telescope Control System Simulation	VIS-ANA-VER-01001-09009 (2.0)
AD05	Telescope Structure FEA	VIS-ANA-VER-03001-0252-B
AD06	Email of P. Jeffers	5/7/04
AD07	Telescope Structure FEA	VIS-ANA-VER-01001-0252-B

4 Analysis Report

The convention of AD01 using arc seconds only for on-sky terms *is not used* in this document. Instead, we have attempted to clearly label the applicable results. For example, Cassegrain errors apply to the Cass rotational axis, and the on-sky result is listed separately. We chose this approach as we give formulas for some error terms and did not want to mix units and have conversions between essentially the same formulas in different sections of this document.

4.1 Scope

As there is significant overlap in terms, definitions, calculations, and formulas, several error budgets from AD01 will be examined, specifically:

Open Loop Tracking (8.5.2 a and b)
Quasi-Static Pointing, repeatable and nonrepeatable (8.4.2, Table 5)
Cassegrain Tracking (10.5.2, Table 16)

4.2 Assumptions

Each error term will be discussed in detail, but some of the repetitive concepts are discussed here. Errors are bias terms (constants), random equal probability events, or presumed Gaussian. The difference in the latter two cases is just the distribution of the errors and the appropriate conversion to and from RMS and peak. This is important only because some errors are best determined as peak, but we are realistically and contractually more interested in RMS values.

Mechanical error terms may be random upon installation (unknown value and direction of error), but deterministic once installed. The variation of some of these errors is known and is frequently a coordinate rotation (sine/cosine) type change. In general, we will presume the steepest slope (rate of error change) for such terms. Thus we will use sine coupling rather than cosine coupling for small angle changes away from a reference location. In some case, the calibration location (zero point) may change the value over a given travel distance by reducing the effective travel by a factor of up to two.

We will mostly ignore elevation angle effects on azimuth terms, taking the worst-case spec parameters as applicable for el=0. While azimuth dynamics increase as elevation angles increases, sky sensitivity (cross-elevation) to azimuth errors decrease by the same factor.

Correlated errors will be algebraically summed. Uncorrelated errors are generally combined by Root-Sum-Square (RSS) mathematics. This is actually somewhat conservative for Gaussian terms, as the correct combination of Gaussian errors is a Rayleigh distribution. For two equal errors, the RSS method gives an increase of 1.41, while Rayleigh gives 1.15. This will overstate the combined error by 22%. This summation error decreases for non-equal error terms. The complexity of the Rayleigh method is generally too high, and not all terms are either random or Gaussian. The simplicity and universality of RSS is much more attractive. Knowing there is some conservatism in the combination mathematics is also helpful.

The system gracefully handles saturation effects, but we are presuming nominal operation for the analysis. That is, motors are not in saturation and other similar transient effects. These issues are addressed separately, but are not a practical problem for the components and architecture selected.

4.2.1 Definitions

The first definitions are from EIA-411A, and are very general. Specific definitions for this program are listed at the end of this section.

4.2.1.1 EIA-411A

Bias Error: Bias error is an error component which is nonvarying over short periods of time and is not corrected.[i]

Correlated Error: Correlated errors are those errors that are or can be mathematically related in such a manner that they are not independent.[ii]

Nonrepeatable Error: See random error.

Peak Error: The peak value of an error source shall be interpreted as follows:

a. for deterministic errors, it shall be the extreme value;

b. for normally distributed errors about a zero mean, it shall be three times sigma. Unknown distributions are assumed to be normally distributed.

c. for all other distributions, it shall be the value where the cumulative probability of occurrence equals to 99.87 percent.[iii]

Pointing Error: Pointing accuracy is the precision achieved under specified operating conditions.

The pointing error is a measure of pointing accuracy (about a nominal position) and is defined as the space angle difference between the command vector and the actual position of the optical axis.[iv]

Random Error: Random error is an error component whose instantaneous time variation is not practically predictable as a function of any system or environmental parameter.[v] This type of error is also referred to as a nonrepeatable error.

Repeatable Error: See systematic error.

Systematic Error: A systematic error is an error component whose value repeats for the same set of operational conditions and can be removed by calibration.[vi] This type of error is also referred to as a repeatable error.

4.2.1.2 Vista Definitions

Quasi-static pointing Error: the differential pointing error on-axis after rotation of the telescope axes through various specified angles. It excludes tracking errors and wind effects. This is a two-axis budget.

Open loop tracking accuracy: the RMS angular error between the commanded target position and the actual target position, excluding the mean offset over the given timescale. Low frequency spatial errors are assumed to be corrected. This is a three-axis budget.

Cassegrain Tracking: This is the same as open loop tracking, but applies to just the instrument axis.

Elevation is used interchangeably with Altitude as one of the primary rotational axes.

4.3 Model/Error Terms

4.3.1 Quasi-Static Pointing Accuracy

The final mount pointing accuracy is a combination of the fundamental mechanical accuracy and repeatability combined with the calibration software/model/data acquired by VISTA. The bias correction model supplied by VISTA will address the repeatable quasi-static error, but estimates for the entire error are included for planning purposes.

The definition and split of pointing and tracking VISTA has chosen is slightly different than our standard practice. We normally look at tracking errors (in this case, either guided or open loop tracking) and absolute pointing errors, either corrected or uncorrected. The quasi-static definition falls closer to the latter, but omits some of the random error components. For analysis purposes, this is fine. In practice, measuring these errors will not be possible without including additional error components, making verification more difficult.

Defining the pointing error as a function of axis travel range also couples time into the error budget. As some errors are more time dependent than angle dependent, this is an important issue. If we presume sidereal rate tracking for the entire angle, an approximate time can be derived and from this time differential, a thermal distortion value can be derived. This does not necessarily correspond to the actual use, as a slew motion could be used to traverse the angle and acquire a new target. In general, this would result in lower errors, as the thermal characteristics would be unchanged. This issue has been resolved with VISTA direction on the thermal budgets (AD06).

For the non-repeatable errors, these will be dominated by the encoder errors and thermal errors, and thus our previous discussion of the coupling of time to angle, thermal sensitivity, and the general thermal design philosophy. The calibration literature reports optical instruments in the 0.5 to 3 arc second RMS absolute pointing error range, with most systems in the mid to high end of this range. We would certainly expect VISTA to be a ~1-2 arc second pointing instrument, as reflected by the budget. We will attempt to estimate the less than full sky non-repeatable numbers, but these are considerable harder to determine. By definition, short-period errors tend to be uncalibratable and therefore random. This means that we are attempting to predict the nearly unpredictable. Fortunately, results are measurable and thus predictable via experience. For SOAR, even in a thermally uncontrolled environment, we achieved large angle repeatability of ~0.6 arc second, and small angle repeatability of ~0.1 arc second RMS. Thus this difficult analysis task is backed by data showing close agreement with the VISTA requirements.

The quasi-static budget is a useful operational concept, but actual measurement of the error will likely include the random components from the tracking error, especially when measuring the smaller non-repeatable error terms. Repeatable error terms are covered first, with nonrepeatable error terms addressed in later sections.

The fundamental errors due to run-out and first and second harmonic machining errors are removed by the four read head per axis approach. This is fortunate, as most machining errors are represented by the fundamental and second harmonic. Residuals are typically very small, and any other systematic errors can be corrected. For budgeting purposes, we use the specified accuracy of the tape/read head system, modified by the number of read heads and averaging effects. In practice, this should more than cover the encoder component errors.

4.3.1.1 Level

Level, or tilt, is the accuracy to which the azimuth rotational axis may be aligned to the local vertical. The value for this error term is estimated and listed in the summary table. Since the error is essentially sinusoidal, the RMS error is 71% of the peak. This error term is separately specified as less than 31 arc seconds to allow for reasonable installation tolerances. The table uses a smaller value as we expect to do better than 31 arc seconds. As this is fully repeatable, this error is not of great concern.

4.3.1.2 Az/El Axis Orthogonality

The error in orthogonality alignment of the azimuth axis to the elevation axis is listed in the summary table. The RMS computation assumes that this error results in a linear error as a function of elevation angle. This is the worst case possible for computing the RMS value and is therefore a somewhat conservative value. This error term is separately specified as less than 31 arc seconds to allow for reasonable installation tolerances. The table uses a smaller value as we expect to do better than 31 arc seconds. As this is fully repeatable, this error is not of great concern.

4.3.1.3 Optical/El Axis Orthogonality

The alignment error in orthogonality alignment of the optical axis to the elevation axis is listed in the summary table. The RMS computation assumes that this error results in a linear error as a function of elevation angle. This is the worst case possible for computing the RMS value and is therefore a somewhat conservative value. See also 4.3.1.5.2.

4.3.1.4 Foundation Displacement

Foundation displacement causes a very slow shift after installation in the level error term defined above. With the quality of foundation expected for this structure, changes in the foundation are not expected. Tilt in the foundation is effectively the same as verticality errors and thus can be considered included in this term. Finally, this is an easily calibrated error source so small changes are of little concern. This term is therefore not listed in the summary tables.

4.3.1.5 Structural Distortion, Gravity Dead Load

As the antenna rotates in elevation, the optical axis shifts due to changes in gravity loading on the structure. The azimuth axis has a smaller error component due to asymmetries in the M2 trusses.

The error budgets contain an estimate for repeatable and non-repeatable structural deformation. In practice, only the non-repeatable term is really of consequence in actual operation.
The gravity deformation equations for pointing error derived from the FEA AD07 are as follows:

Delta-alt = -36.1 sine (theta-23.125^{o}) + 33.2 (arc sec) - Theta is the elevation angle, in degrees.

Delta-az = 9.48 sine (theta+3.85^{o}) – 9.48 (arc sec)

For the full sky case, we use theta1 =90 and theta2 =20 and take the difference. Since error at zenith is zero, this gives RSS(35.2, 5.6) = 35.6 a-s. For 60 degrees of travel, we use el=30 and 90, giving RSS(28.9,4.2)=29.2. For 2 degrees of travel, we use [sine(2) – sine(0)] as the scaling factor. We ignore the slight offset in the zero crossing point between the axes for simplicity, giving a very slightly larger number. Thus for 2 degrees we have RSS(1.26,0.33)=1.30 a-s, and 0.17 degrees gives RSS(0.11,0.03)=0.12 degrees. To map these to RMS, we use the typical sine scaling of 0.707.

Nonrepeatable estimates are much harder. We have not been able to identify any likely sources of such error that are not covered in other sections (wind, thermal). The curve fit to the deflections is very good, with a peak error of 0.07 a-s. We choose to use this as the peak estimate for nonrepeatable errors, scaled by the sine of the angle traversed for small angles, and the large angles as in the previous paragraph. To map these to RMS, we use the typical sine scaling of 0.707. For example, the 2^{o} entry is 0.707*0.07* sine(2) = 0.0017 a-s.

4.3.1.6 Encoder Structural

The structure can have two errors. The first error is any windup/deflection between the true optical axis and the encoder pickoff point. This portion of the error is covered under gravity deflection. The second error is any angular or parallel misalignment of the axis pickoff to the encoder axis of rotation. The encoder is machined into the elevation (and Cassegrain) axis and thus is a co-linear as feasible. The azimuth axis may have slightly greater misalignment, on the order of the fundamental tilt. A simple tilt of the measurement axis against the rotational axis is calibratable. The four read head approach will also compensate for some periodic error. Any high spatial frequency, random components are included under the encoder error budget.

4.3.1.7 Encoder Offset

The encoder readings must be offset adjusted once installed. Typically this is done by testing on known targets, such as reference stars. Field experience and customer feedback indicate that a per axis error of 1% of the beamwidth peak can be achieved for RF systems. With the much greater sensitivity of this optical instrument, and with quality modelling software, this error is effectively zero. Any residuals are presumed to be included in other terms.

4.3.1.8 Thermal

Thermal error is theoretically repeatable, but practically a large component is non-repeatable due to the complexity of this topic. In many cases, the non-repeatable component is not applicable as the system is reference to the sky and thus errors are eliminated for the short-term. The thermal gradients table (4.3.1.8-1) shows the thermal differentials to be applied for each case. Sensitivity to thermal errors was assessed by applying a 1 degree C delta across the elevation axis, resulting in a 1.4 arc second pointing error. This is rather conservative, as most locations are not as sensitive as the example chosen, and causing such large masses to achieve such a delta requires time and a sustained differential. Per AD06, the coupling of thermal errors to time and distance is resolved by VPO direction as shown below.

	Thermal Gradients, Deg C			
Terms	**Full Sky**	**60 Deg**	**2 Deg**	**0.17 Deg**
Repeatable	0.9	0.9	0.05	0.05
Nonrepeatable	0.1	0.1	0.05	0.05
Time	0.4/hr	0.4/hr	0.4/hr	0.4/hr
	Errors, Arc-Seconds RMS			
Repeatable	1.26	1.26	0.07	0.07
Nonrepeatable	0.14	0.14	0.07	0.07

Thermal Gradients and Resultant Errors, Table 4.3.1.8-1

4.3.1.9 Axis Wobble

The primary error component in axis wobble is due to the azimuth support mechanism imperfections. This term is used for elevation error due to azimuth motion. The wobble is the deviation about the smooth error curve resulting from axis tilt or level. The basic level error is discussed previously.

The figure shown below illustrates residual bearing wobble errors derived from actual test data collected on the SOAR telescope. A precision Taleyvel electronic level was used for this test, cable of sub arc second accuracy. For the data taken, the statistically significant harmonic components, up through the fifth harmonic, have been removed. This is therefore an approximation of the non-repeatable error terms, with the repeatable errors removed. Greater effort might reduce these values, as they represent just one measurement cycle. The RMS error of this data over a full sky pointing is computed to be 0.21 arc seconds. Because of the coarse nature of the data taken, it is difficult to make absolute inferences to the nature of the bearing wobble on the 2 degree scale. Utilizing the data, an estimate for the 2-degree scale error can be computed to be 0.03 arc seconds RMS.

The data, taken in a thermally uncontrolled environment, is more limited by the measurement process than the bearing and bearing interface flanges and thus operational experience should be somewhat better.

With just the fundamental tilt removed, the error is slightly larger at about 0.36 arc seconds RMS, and this value will be used for the uncorrected budget.

Cross-elevation or azimuth error due to elevation motion is far less than elevation error (due to azimuth motion) because of the small, precise bearings, good bearing spatial separation, and error cancellation due to the dual bearings not having identical manufacturing imperfections. We have used ½ the azimuth value for this value.

4.3.1.10 Residual Errors

The random errors will of course limit the ability to measure the systematic error terms. Thus there is some component of the bias terms remaining from the correction process. By definition, this is effectively unmeasureable and thus is not allocated to the individual terms. A small budget is left as a matter of conservatism, but practically the residual errors are not distinguishable from other random components.

4.3.1.11 Cassegrain Errors

The nominal mapping between Cass rotational errors and on-sky error is discussed in the Cassegrain sections. For simplicity, the budget assumes that all Cass rotational errors cause pointing/tracking errors.

4.3.2 Open Loop Tracking Accuracy

4.3.2.1 Angle Encoding System

These optical tape (ERA 780) devices mounted on the 1.68 meter diameter machined ring provide 29 bits (0.002 arc seconds) resolution. This is generated by 40 micron periods plus the built-in 4096X interpolation of the IK320 card. A single read head's specification provides a (3-micron) 0.75 arc second accuracy, although this is frequently bettered in practice. To remove eccentricity errors and to statistically average errors, four read heads per axis provide a net expected encoder accuracy of 0.37 arc seconds peak per axis for Az and alt. If we model the error as a sinusoid rather than white noise, we get 0.26 arc seconds RMS per axis. While the error will of course be random, a sinusoid is both more conservative and more intuitively appealing as an error model for this term.

Small angle errors are dominated by 40 micron scale cyclical errors. These are typically 1% peak of the scale or 0.4 microns or 0.1 arc second per head or 0.05 per axis, and this agrees reasonably well with SOAR measurements. RMS would be 0.7 of the peak. The actual system works by averaging about 400 of the fundamental periods due to the physical size (~17mm) of the optical read head. This angle corresponds to about 1 degree of travel, or about 4.5 minutes of sidereal travel. Thus for motion within a read head's field, errors will tend to correlate as many of tape cycles in the field of view will be common, and the 1% error will tend to dominate. As axis motion exceeds the field of view, accuracy will of course likely still be better than the full-travel, specified value, but performance is not well characterized. The 1% error (0.4 micron) will occur, along with some component of the 3 micron large-scale error. By manufacturer spec, a 3 micron error would be acceptable. However, as a practical estimate, we will assume that the 3 micron error behaves as a 12 cycle sinusoid. For a 2 degree spatial motion, this would result in 1.2 micron large scale error and a 0.4 micron short scale error. The RMS of this is hard to determine, as we are already extrapolating. The axis peak is 1.6 microns or 0.4 arc seconds. The RMS of the short period error is 0.71 of the peak value. The long wave error is approximated as a straight line, so the error is ~0.58/2 (per VPO discussion, the average is removed) of the peak. The two are uncorrelated, and thus should be RSS combined. For the overall system, the other axis error should be RSS added in as well. We have presumed 2 degrees of travel, so the alternate axis error is just the short period error. This yields RSS(1.2*0.29, 0.4*0.71, 0.4*0.71) = 0.53 microns or 0.133 arc seconds.

The mid-distance values of encoder performance are a method of finding a rational estimate for something that is not well defined. In practice, it is generally recognized that these tapes are the standard of the optical community via their use and selection for numerous telescopes. Examples include all 4 VLT instruments, 2Mass, Sloan, SOAR, and both Gemini locations. As this approach has proven satisfactory for large and small telescopes, it should perform well for this project.

The IK320 card used in the LCU has 'short wave compensation'. This should remove some of the 1% error terms, but it is not possible to quantify this improvement via Heidenhain literature.

4.3.2.2 Encoder Electronics

The encoder electronics specified accuracy is used in the budget. The RMS conversion accuracy is 1/3 the peak error.

4.3.2.3 Timing Delays

Any constant delays in the pointing loop cause bias errors. These delays result from the finite time required to read the position encoders and calculate position error. The specified budget of 1 ms delay is used. The specified el axis velocity is approximately 17 arc seconds/second, and the az axis velocity is compatible with this value when secant corrected for 88 degree operation. Thus 17 arc sec/second, slightly above sidereal, is used yielding an on-sky peak error of 0.017 arc sec. We anticipate that the actual results will be somewhat better, as the 1 ms value will probably be a generous budget.

For the Cassegrain axis, the full ~480 arc sec/s value must be used, yielding 0.48 arc seconds error. This is an acceptable value, but is one of the larger terms. As the VISTA-specified equipment will determine the as-installed performance, this is not under VRSI control. For bias errors a time correction may be used to address this term. We expect that jitter errors will be less than the 1 ms specified, and jitter errors may or may not manifest themselves as on-sky errors.

4.3.2.4 Trajectory Dynamics

Trajectory dynamics are quite benign. We anticipated a Ka of 6 or more and used this in the computations. Actual Ka values improve performance beyond shown here, and were about 12 or more, depending upon the axis. The steady state lag error is given by the target acceleration divided by the Ka. Quality velocity feedforward further improves the effective Ka by a factor of 10 or more. This gives an effective Ka of 60. As with the axis velocity terms, only one axis will have significant accelerations at a time for tracking. Thus the larger error of the two values specified is used at ~0.5 arc sec/s^2. This gives an error of 0.0083 arc seconds. For the Cassegrain axis, the full ~10 arc sec/s^2 value must be used, yielding 0.17 arc seconds error. This is a significant overstatement of the RMS error as little operation will occur at the worst-case zenith angle. Even for tracks that go through the maximum angle, the time of relatively high acceleration is short. For now, we chose to use the maximum steady state error for the RMS total and do not take advantage of the time RMS correction.

4.3.2.5 Wind

The altitude nonlinear simulation (AD04) of VonKarman spectrum simulation results in an RMS error at the control system of 0.04 arc seconds. The Titus spectrum gives 0.014 arc seconds RMS. Both values are remarkably close to the original proposal estimates. The azimuth values were 0.0013 arc seconds peak for VonKarman and were not studied further because they are so small. With the large difference in error response and low correlation between axis errors at most wind angles, the azimuth term is neglected.

For motion beyond the servo axis, the wind PSD is applied to the FEA and the equivalent beam motion of M2 is computed. This cannot be corrected by the high bandwidth mount control system, and thus is termed uncontrolled. This wind error is shown in AD05. This is primarily M2 deflection and is not corrected by the servo system. Analysis of these errors is difficult due to the nature of statistics and the FEA tool. The quantity of interest is the motion of the beam. However, we only have the motion of two locations, M1 and M2. We do not know if these move together or separately. The 'correct' statistical combination of the values will always 'add' the variances while subtracting the covariance. This is statistically correct, but it is certainly possible that the motions cancel or partially cancel. Thus we compute the mathematically correct value, along with an optimistic value presuming cancellation. The true value is likely between the two numbers computed. It turns out that the cross-elevation/alt (azimuth) motion of M2 has low covariance and thus only one value is needed.

The resulting M2 errors then need to be combined with the servo errors from the simulation. Only the Alt error is significant. Because the source of the error is common (wind), we must presume that these errors add. Note that this may not be the case, as the servo and structure have complex phase behaviour. Finally, there are two spectrums generating servo errors from the simulation report. While it is not exactly correct to combine Titus servo errors with VonKarman structural errors, this helps create a reasonable approximation and it does not seem worthwhile to run Titus on the structure. (We already know that the result will create smaller errors.) But this combination is not as strange as it first seems. A mixture of optimistic and pessimistic assumptions is often quite reasonable.

The wind specification is very challenging. A small reduction in either the mean or gust values would quickly pull the system very clearly under specification in all cases. This means that most operational cases will be satisfactory with a high degree of certainty. The mapping from the dome design to the pedestal requirements is not clear to VRSI. It should be clear, however, that the dome operation could be refined to assist in reducing wind when necessary without lowering flushing in low-flow conditions. This appears to be a very cost effective method of performance control and risk reduction.

	RMS, Arc Seconds		
	AZ	**ALT**	**Total RMS, Equal Weight Az/Alt**
Wind Errors, Uncontrolled	0.067	0.028	
Wind Errors, Controlled, VK	0.0013	0.040	
Wind Total, Optimistic	0.0683	0.068	0.068
Wind Errors, Uncontrolled	0.067	0.0915	
Wind Errors, Controlled, VK	0.0013	0.04	
Wind Total	0.0683	0.1315	0.093

Table 4.3.2.5-1, VonKarman RMS Total Wind Errors

	RMS, Arc Seconds		
	AZ	**ALT**	**Total RMS, Equal Weight Az/Alt**
Wind Errors, Uncontrolled	0.067	0.028	
Wind Errors, Controlled, Titus	0.0013	0.014	
Wind Total, Optimistic	0.0683	0.042	0.057
Wind Errors, Uncontrolled	0.067	0.0915	
Wind Errors, Controlled, Titus	0.0013	0.014	
Wind Total	0.0683	0.1055	0.074

Table 4.3.2.5-2, Titus RMS Total Wind Errors

Wind Error Summary RMS, Arc Seconds		
	Optimistic	**Standard**
Titus	0.057	0.074
VonKarman	0.068	0.093

Table 4.3.2.5-3, Summary, RMS Total Wind Error Range

4.3.2.6 Limit Cycle

Limit cycle error behaviour occurs due to quantization and the friction behaviour of the system. Limit cycle occurs due to the control systems inability to exactly fulfil a command, and is always at least +/- 0.5 LSB.

Limit cycle normally occurs only at zero speed, as the inertia of the system and the lack of friction direction reversals inhibits this behaviour during motion. For sidereal tracking, if one axis is at zero speed, the other axis is moving at approximately sidereal rate. Our design philosophy takes the very conservative approach of requiring a zero-speed axis for budgeting purposes, forcing the worst possible case. However, we take advantage of the geometry by requiring tracking performance at zero speed in only one axis at a time. Thus, we choose the worst case axis as our budget using our conservative design philosophy. As SOAR exhibited no measurable limit cycle, we anticipate the same. However, the simulation showed a significant value and this is placed in the table

The simulation (AD04) also showed some residual error while in motion. This appears to be a combination of friction effects and velocity quantization. This error term is also small, but larger than expected. The larger of the limit cycle or the velocity quantization is appropriate in the budget.

4.3.2.7 Quantization - Position Command

Errors in the source data are not budgeted. As the command and feedback resolution are the same, only one error term is applicable and the feedback resolution error is listed in the budget.

4.3.2.8 Quantization - Position Feedback

Position feedback is quantized to 0.0024 arc second resolution. The peak error due to this quantization is ½ the resolution. The probability density function for this error is equal or constant probability over a range of +/-peak error. Thus for two axes this comes to 0.001 arc seconds. This term is actually somewhat a duplicate, as it is captured in the simulation under either limit cycle or velocity quantization.

4.3.2.9 Amplifier Bias and Drift

The control system uses a digital position loop. The position command, feedback and error are digital signals. The only possibility for bias or drift in these signals is position feedback from the encoder. However, the encoder accuracy term derived elsewhere incorporates the effects of any bias. The position loop compensation (and the integrator in particular) is also implemented digitally, so no bias can occur at this point. Therefore, no budget is assigned to amplifier bias.

4.3.2.10 Gear Ripple

Gear ripple was shown negligible in the simulation, analysis, and field data. A budget of 0.01 arc seconds is left as margin for the geared AZ axis. As the elevation/alt is direct drive, no gear ripple is applicable.

4.3.2.11 Torque Ripple

Numerous techniques are used to suppress torque ripple. High quality brushless DC motors with sine drive amplifiers are crucial to low torque ripple. For elevation, the direct drive manufacturing techniques include a non-integral pole to slot ratio to create a ‘skewed armature’ effect that minimizes ripple from manufacturing errors. In azimuth, the gear train desensitises the axis to torque variations.

Measured running torque (via an axis motor current command test point) found that variations of running torque in 360° of azimuth travel were undetectable, and further that the running torque required was the same in both CW and CCW directions. The measured elevation torque variations of only 34 Nm peak to peak, or ±0.2% of available motor torque during a 0.2°/s slew velocity run. We used 120 Nm torque ripple in the model. It could not be discerned if this was due to bearing drag variations or to other loads such as the cable wrap. Starting torque variation for the altitude axis was less than 5% of the running torque. Again the control loops have such quality characteristics that this very low torque variation did not create position error values of concern. The simulation (AD04) shows no effect from torque ripple.

A value of 0.01 arc seconds is left as a budget.

4.3.2.12 Tachometer Errors

The axis encoder is used as the primary rate feedback for the elevation axis. Thus any tachometer errors are included in the encoder error terms. For the azimuth axis, no velocity – dependent errors were measurable on the SOAR mount (Cass should therefore be similarly small). Previous computations for tachometer ripple suggest that 0.003 RMS is a reasonable value. This low value is consistent with our inability to measure any tachometer errors and thus has empirical confirmation.

4.3.3 Cassegrain Errors

A Cassegrain rotator budget is made of terms previously described, so much of the explanation is omitted.

The wind error is eliminated in this budget. The Cass instrument is reasonably symmetrical with low wind loading, and is significantly shielded by the Cass cable wrap and the structure. The Cass wind loads are already applied to the alt/az axes and we did not wish to overstate loads. The low sensitivity between rotation and on-sky errors means that errors are not as important as the primary axes. A very rough estimate of wind torque for Cass was ~3 Nm compared to ~200 N-m friction, so the wind was ignored.

The simulation (AD04) determined gear ripple to be effectively zero, but a value of 0.01 is left in the budget. Limit cycle was 0.4 arc seconds RMS. Most of the other terms were taken from equivalent primary axis terms.

The mapping from the rotary error to the on-sky absolute pointing is shown in the last row. The peak mapping from arc seconds of rotary error to arc seconds of sky error is given by:

SkyError (as) = $3600*1.67/2*\text{sine}(1/3600^{o}) = 0.0146$. The RMS is $1/6^{0.5}$ of the peak, for a square focal plane. Thus the RMS mapping is 0.00596 or ~1/168.

The cable wrap drive is not a source of jitter to this axis. We have carefully selected components and an architecture that does not couple, limit cycle, or generate high frequency torque disturbances. Any residual force on the instrument axis will be part of the motor torque budget, but will change very slowly. The stiff, high bandwidth instrument servo loop will easily reject such forces.

VISTA guidance is that Cass errors are primarily of interest for 30 minute periods. This may be used for computing time averages, but this has not been done as the analysis to date meets specification.

4.3.4 Error Combinations

In some cases, error terms should be examined as part of the total budget, and not in isolation. We have previously mentioned that full limit cycle of az and alt should not occur simultaneously, as these occur as zero speed and it is not possible to follow a sky target and have zero speed in both axes. Another example is limit cycle and acceleration lag. 'High' acceleration for tracking does not occur at zero speed. Thus the budgets take the maximum of the appropriate terms, not the RSS combination of errors. The larger of acceleration lag or velocity error is compared to the limit cycle and the largest value is used. In effect, if these dynamics are dominant, they will be RSS combined later in the table. If not, one term will remain to be combined with the other residual errors.

Acceleration lag and velocity lag are normally somewhat independent in time and the RSS captures the combination reasonably well.

4.4 *Loading Cases*

The loading cases are described under the specific heading topics.

4.5 *Results*

4.5.1 *Open Loop Tracking*

Table 4.5.1-1 shows tracking errors without wind. As we have discussed, this budget is likely high. To recap, several of the smaller error terms appear to be zero, but values were left in the budget. The key errors are the encoder small signal error and the azimuth limit cycle. The encoder small signal errors will be reduced by the IK320 board operation. The azimuth limit cycle is an upper bound, and is quite likely zero. This could be re-written to show non-wind errors of ~0.02 arc seconds as a lower bound. We chose to show values that have direct backing from computations, even though we believe these values are high for reasons extensively discussed.

Table 4.5.1-2 combines the non-wind errors with various wind terms. The variability in wind terms is discussed in that section. The results are scattered about the desired value.

Table 4.5.1-3 combines table –1 errors for the 5 minute case with wind errors, resulting in all values below specification.

Open Loop Tracking Budget, Excluding Wind, Table 4.5.1-1

	RMS, Arc Seconds		
	AZ	**ALT**	**BEAM RADIAL TOTAL**
Friction/Limit Cycle – or -	0.042	0.005	
Velocity Quantization – or -	0.0087	0.0071	
Acceleration Lag – or -	0.0083	0.0000	
Selection of Maximum	0.042	0.0071	0.042
Torque Ripple	0.01	0.01	0.014
Gear Ripple	0.01		0.01

Quantization	0.0007	0.0007	0.0010
Timing Delay/Velocity Lag	-	-	0.017
Tachometer Errors			0.003
Thermal			0.0023
Encoder	-	-	0.05
Cassegrain Error	-	-	0.004
Total, 15 Seconds	-	-	0.070
Specification, 15 Seconds	-	-	0.1
Encoder, 5 Minutes	-	-	0.2
Thermal, 5 Minutes	-	-	0.0467
Total, 5 Minutes	-	-	0.217
Specification, 5 Minutes	-	-	0.25

Table 4.5.1-2, Summary Tracking Budget, 15 Seconds

Error Summary, 15 Seconds RMS, Arc Seconds		
	Optimistic	**Standard**
Titus	0.09	0.102
VonKarman	0.098	0.116

Table 4.5.1-3, Summary Tracking Budget, 5 Minutes

Error Summary, 5 Minutes RMS, Arc Seconds		
	Optimistic	**Standard**
Titus	0.224	0.229
VonKarman	0.227	0.236

4.5.2 Quasi-Static Pointing

For errors that reduce by the travel range, we take the steepest slope to determine the result for a smaller angle. Thus a sine wave has the steepest slope at zero, and the reduction for 60 degrees of travel is sine(60).

Pointing Error Budget, Non-Repeatable Residuals, Table 4.5.2-1

	Arc Seconds, RMS			
Terms	**Full Sky**	**0.17 Deg**	**2 Deg**	**60 Deg**
Axis Wobble, Az	0.21	0.004	0.03	0.21
Axis Wobble, El	0.1	0.002	0.015	0.1
Encoder	0.37	0.05	0.133	0.37
Jitter Terms	N/A	N/A	N/A	N/A
Gravity	0.033	0.0002	0.0017	0.025
Thermal	0.14	0.07	0.07	0.14
Residual Errors	0.01	0.01	0.01	0.01
Total, Structural	0.460	0.087	0.154	0.460
Specification	1.0	0.1	0.25	0.5

Pointing Error Budget, Repeatable Terms, Table 4.5.2-2

	Arc Seconds, RMS			
Terms	**Full Sky**	**0.17 Deg**	**2 Deg**	**60 Deg**
Azimuth Verticality	10	0.030	0.349	8.66
Az/El Ortho	5	0.015	0.174	4.33
Optical/El Ortho	5	0.015	0.174	4.33
Axis Wobble, Az	0.35	0.01	0.05	0.35
Axis Wobble, El	0.17	0.005	0.025	0.17
Jitter Terms	N/A	N/A	N/A	N/A
Gravity	25.2	0.085	0.92	20.6
Thermal	1.26	0.07	0.07	1.26
Total, Structural	28.0	0.117	1.02	23.2
Specification	15.0	0.1	0.5	8.0

4.5.3 Cassegrain Tracking

Cassegrain Error Budget, All Terms, Table 4.5.3-1

	RMS, Arc seconds on Cassegrain Axis	
	360 Travel	**60 Deg Travel**
Friction/Limit Cycle – or -	0.40	0.40
Timing/Velocity Lag – or -	0.48	0.48
Velocity Quantization – or -	0.0075	0.0075
Selection of Maximum	0.48	0.48
Torque Ripple	0.01	0.01
Gear Ripple	0.01	0.01
Quantization	0.006	0.006
Acceleration Lag	0.17	0.17
Encoder	0.26	0.26
Axis Alignment	10	7.07
Bearing Wobble	0.2	0.2
Tachometer Errors	0.03	0.03
Thermal	0.3	0.3
Cassegrain Error, RSS Total	10.02	7.10
Specification	31	-
Total Error On-Sky Pointing	0.060	0.042

Cassegrain Error Budget, Random-Only Terms, Table 4.5.3-2

	RMS, Arc seconds on Cassegrain Axis	
	360 Travel	**60 Deg Travel**
Select Max from table-1	0.48	0.48
Torque Ripple	0.01	0.01
Gear Ripple	0.01	0.01
Acceleration Lag	0.17	0.17
Quantization	0.006	0.006
Encoder	0.26	0.26
Bearing Wobble	0.2	0.2
Tachometer Errors	0.03	0.03
Thermal	0.3	0.3
Cassegrain Error, RSS Total	0.68	0.68
Specification	9.3	1.2
Total Error On-Sky Pointing	0.0040	0.0040

4.5.4 Total Pointing Estimates

By request, this section addresses total pointing. There is no specification for these values, but this is provided for reference. Thermal gradients are increased to 4 deg C for this section to allow for multiple hour and/or night-to-night thermal variations. Whether thermal is repeatable or nonrepeatable is debateable. With sufficient effort, at least some of the thermal variations should be calibratable, and thus repeatable. We arbitrarily chose 3C as repeatable and 1C as nonrepeatable. The repeatable error table does not include the effects of calibration, except for presuming that encoder bias is removed.

Non-Repeatable Absolute Pointing Residual Estimates, Table 4.5.4-1

	Arc Seconds, RMS
Terms	**Full Sky**
Axis Wobble, Az	0.21
Axis Wobble, El	0.1
Encoder	0.37
Jitter Terms	0.10
Gravity	0.033
Thermal (1 Deg C)	1.4
Cassegrain	0.004
Residual Errors	0.01
Total	1.47

Repeatable Absolute Pointing Estimates *Without* Calibration, Table 4.5.4-2

	Arc Seconds, RMS
Terms	**Full Sky**
Azimuth Verticality	10
Az/El Ortho	5
Optical/El Ortho	5
Axis Wobble, Az	0.35
Axis Wobble, El	0.17
Encoder Error	0.37
Jitter Terms	N/A
Gravity	28
Cassegrain	0.06
Thermal (3 Deg C)	4.2
Total, Structural	30.9

4.6 Conclusions

The specifications are discussed in rough order of importance. With the clarification in the thermal components of the budget, the open loop tracking is meeting specification for the 5 minute requirement. The second largest error term is the encoder. As previously described, the behaviour of the tape over these distances is difficult to determine.

The 15 second requirement results, conservatively budgeted, are scattered -10/+16% around the specification. We consider this to be in specification.

The quasi-static non-repeatable errors meet the budgets.

The Cassegrain errors all seem well in hand, and there is additional margin available.

The quasi-static repeatable errors do not meet the budget due primarily to gravity-induced deflections. These are simple terms for a pointing model to correct. A waiver is in process.

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ii. ELECTRONIC INDUSTRIES ASSOCIATION, p. 3-7.

iii. ELECTRONIC INDUSTRIES ASSOCIATION, p. 3-7.

iv. ELECTRONIC INDUSTRIES ASSOCIATION, p. 3-3.

v. ELECTRONIC INDUSTRIES ASSOCIATION, p. 3-7.

vi. ELECTRONIC INDUSTRIES ASSOCIATION, p. 3-8.