Confidential

ALMA Antenna Technical Working Group Report

2004 - September 29

Signatures of the Evaluation Team Members

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1. SUMMARY

Pursuant to the charge given this committee, our conclusions can be summarized as follows:

1.1 VERTEXRSI PROPOSAL

1. The photogrammetry measurements on the prototype telescope indicate that the focal length change as a function of elevation is about 1.5 times larger than predicted by the FEM. The opto-mechanical data shows a larger and more complex deviation from the FEM, but these results may be due to unexpectedly large deformations in the mount supporting the laser transmitter. The gravitational deformations represent 8% of the RSS in a total surface error budget of 22 μm. If the error components due to gravity and wind (included because a weaker BUS would also deflect more in the wind - the wind deflections represent 15% of the RSS) are scaled up by a factor 1.5 and the telescope surface is effectively set at the rigging angle, either by measurements at that angle or using a corrected FEM to extrapolate from measurements at low elevations, then the projected peak RMS surface error would be 24 μm. Under these assumptions the antenna would still meet the specification. If, however, the BUS does have deformations that differ from those predicted by the FEM, these are likely to have a non-homologous form, in which case the residual errors would scale by a larger factor than that seen in the change in the focal length. The evidence for excess deformations is not yet compelling, but we regard it as sufficiently strong for this area to be regarded as a high risk at present. Additional measurements are required to settle this issue. We also have a concern that, with no temperature regulation in the walls of the receiver cabin, the gradients may be larger than assumed and that this would cause excess deformations in the dish.

2. The proposed metrology system has not been extensively tested. We believe that it is based on sound principles that should work satisfactorily, although its performance has not yet been proven. The measured offset pointing performance of the prototype telescope was good. The measured servo tracking error is however significantly larger than predicted. With the metrology system in operation, the predicted nighttime offset pointing error has an RSS of 0.595 arcsec, leaving no margin for the increased servo tracking error. The risk of not meeting the offset pointing requirements occurs in the tightest configurations when wind turbulence may dramatically increase the variability of the wind forces on short timescales. Overall this presents a small risk to the project.

1.2 ALENIA PROPOSAL

1. There is no evidence that the FEM for the AEC prototype is incorrect. For the Alenia telescope of very similar design and with a projected net surface error budget of 19 μm, the gravitational and wind deformation components in the surface error budget that would be affected by FEM errors represent 7% of the RSS (root square sum) errors. The risk of the telescope not meeting the RMS surface specification of 25 μm because of gravitational deformations is therefore low, but the Alenia FEM still needs to be verified by measuring the elevation dependent deformations of the first production antenna.

2. The proposed metrology system is untested and has potential flaws associated with using tiltmeters at the ends of the yoke arms, even to correct for thermal deformations. If the proposed metrology system fails to work satisfactorily, then an alternate method will be required to correct for the wind effects and a robust thermal correction algorithm, probably based upon the temperature sensors, will need to be developed. This represents a significant risk until a suitable system is devised. The main case in which uncorrected offset pointing errors are likely to be a problem is when there are high winds and the antennas are closely packed.

2. INTRODUCTION AND SCOPE

2.1 CHARGE TO THE COMMITTEE

This committee was tasked by the ALMA Executives with addressing a few specific technical issues concerning the proposals from VertexRSI and Alenia to manufacture the production antennas for ALMA. The complete charge to the committee is given in appendix A. The four questions that were to be addressed are:

1. Will the proposed antenna designs maintain surface accuracy specifications over all elevation ranges?
2. To what extent can the proposed metrology systems reliably improve the pointing performance of the proposed antenna designs in order to meet the required ALMA pointing specifications?
3. Comment on the maintainability of the two proposed designs and establish a first estimate of lifecycle costs for the operational lifetime of the telescope.

The committee was to assess the technical risk and determine if modifications are required to mitigate the risk in these areas.

The most critical and demanding performance specifications for the ALMA antennas are the surface precision and pointing referred to in questions #1 and #2 above and the report concentrates on these questions. Although question #3 is important to the project, there is insufficient information available to this committee to make a meaningful evaluation of this issue.

2.2 METHODOLOGY

Ascertaining the surface and pointing performance of telescopes intended to meet the demanding ALMA specifications is a very complex and difficult task. It is beyond the capabilities of this committee to cover all aspects of these performance criteria given the limited time and resources available to this committee. The error budgets for the surface error and pointing precision have many terms, some of which only the manufacturer can properly estimate. The approach taken in this report is to look at new or recently measured error terms and update the error budgets using this information. The risk assessment is then a matter of trying to assign probabilities that the error terms are realistic and likely to be achieved.

Fortunately the two proposals closely follow the design of the two ALMA prototype antennas that were assembled and tested at the ALMA Test Facility (ATF) on the VLA site.

<u>VertexRSI:</u>

The VertexRSI proposal is only slightly modified from the VertexRSI ALMA prototype, although it does differ from the prototype in two areas:

1. The proposed antenna does not have the active temperature control of the receiver cabin walls that was used in the prototype antenna.
2. Two additional tiltmeters will be located in the yoke arms near the elevation bearings.

Alenia:

The Alenia proposal is closely modeled on the AEC prototype with several modifications:

1. The antenna will have a three point interface to the antenna pad.
2. The azimuth bearing will be a three row roller bearing.
3. The apex support structure will be modified.
4. The proposed metrology system consists of four tiltmeters and many temperature sensors and is very different from what AEC built into their prototype antenna.

The extensive measurements and evaluation of these two prototype antennas by the AEG is the primary source of information for updating the error budgets. While much of this information is still being evaluated and written up, the executive summary provided to us by the ALMA Executives has been the primary source of measurement data.

The exception to this is the evaluation of the metrology systems. The metrology instrumentation never reached a fully functional condition and therefore little useful information about such systems was obtained. The AEG obtained much useful information about the pointing performance without any metrology corrections, but those measurements did not fully exercise some of the critical weather conditions for which the metrology systems were intended to compensate. The committee has had to rely on their past experience and understanding of telescope structures to evaluate the proposed metrology systems and suggest improvements.

2.3 GENERAL STATEMENT

The prototype antennas utilize state-of-the-art technology and are among the most precise radio telescopes ever fabricated. Evaluating the performance of such high performance telescopes is a very challenging task and the AEG has done an excellent job in carrying out this task. This being said, it is still necessary to compare the performance of the production antenna designs against the extremely demanding ALMA specifications. This report attempts to carry out a careful review of the available information and evaluate the risk associated with the proposed designs.

This report is the consensus opinion of the four committee members whose names appear on the signature page of this report.

3. WILL THE PROPOSED ANTENNA DESIGNS MAINTAIN SURFACE ACCURACY SPECIFICATIONS OVER ALL ELEVATION RANGES?

This question arose as a result of a statement in the AEG Executive Summary that, for the VertexRSI prototype antenna, "the difference between the FEM and the measurements suggests that the BUS is slightly less stiff than predicted by the FEM".

The optical/mechanical measurements on the antenna were performed under the leadership of Albert Greve. Together with him, we have re-analyzed his measurements. Greve also discussed the measurements in detail with the VertexRSI engineers. The results of these activities are ambiguous. It is not clear whether the stability of the laser mounting plate might have influenced the results of the measurements and hence the conclusions. If the laser mounting was indeed as stiff as planned, the Quadrant Detector measurements indicate a substantial deviation of the stiffness of the BUS from the FEA in a sense that the BUS is less stiff than predicted. In order to put this inference on a sure footing, further analysis and measurements of the mounting plate would be necessary as a minimum and it would be highly desirable to repeat the measurement with a new mount.

This is a time consuming business, which we nevertheless suggest be undertaken by the ALMA Antenna IPT with the assistance of the Antenna Evaluation Group.

An analysis of the elevation-dependent change in focal length derived from photogrammetry measurements differs significantly from FEA prediction. As the photogrammetry measurements and FEA were both "contractor deliverables", this represents a disagreement between a measurement done by the contractor and their FEA model. We have carefully studied the photogrammetry results and performed our own analysis of the fits and derived focal lengths. This suggests that the FEA might underestimate the deformations of the real BUS structure by almost a factor 1.5.

The photogrammetry at 5 degrees elevation carries the most leverage in determining the magnitude of the disagreement with the FEA. VertexRSI has suggested that the photogrammetry measurement made at 5 degrees elevation is discrepant on the basis of a recent re-analysis of their photogrammetry measurements. Exclusion of this one data point would indicate an agreement between the best-fit focal length as a function of elevation derived from photogrammetry and that predicted by the FEA over the limited elevation range of 30 - 90 degrees. VertexRSI based their rejection of the 5 degree point on bad weather, the fact that excluding it produces a better fit, and that including it implies an unphysical non-linear behavior. ALMA staff members talked to VertexRSI about these issues and found VertexRSI's arguments not persuasive. They found no compelling reason to treat the result at 5 degrees elevation differently from the other surface maps. We agree. The Committee understands that further photogrammetry is being undertaken by VertexRSI to resolve this issue.

Pending additional measurements done by VertexRSI and a successful outcome from the analysis of the optical/mechanical measurements, we remain concerned about BUS errors due to gravity as a function of the elevation angle of the antenna. Because the accurate reflector measurement with holography could only be performed at one elevation (9 degrees), we have no independent data for the prototype antennas on the important parameter of the reflector rms error variation with elevation.

3.1 ERROR BUDGETS AS PRESENTED BY THE COMPANIES

Table 1. **Summary of reflector error budgets.**

Prototype and tendering values from Vertex and AEC/Alenia

	Ver-pro	**Ver-bid**	**AEC-pro**	**Alen-bid**
Panels				
Manufacturing	8.0	8.0	8.50	4.50
Aging	2.0	2.0	2.00	2.00
Gravity	2.4	2.4	4.15	6.90
Wind	1.1	1.1	1.3	2.50
Absolute Temperature	0.6	0.6	3.65	0.80
Temperature Gradients	2.7	2.7	3.16	2.15
Total Panel	**9.1**	**9.1**	**10.9**	**9.1**
Backing Structure				
Gravity (Ideal) **	6.2	6.2	6.66	7.6/5.0
Gravity (Departure from ideal)	3.0	3.0	2.00	2.00
Wind	8.4	8.4	3.15	0.25
Absolute Temperature	5.0	5.4	3.20	2.95
Temperature Gradients	1.1	9.3	1.00	4.71
Aging	2.0	---	3.00	3.00
Total Back-up Structure	**12.2**	**15.3**	**8.8**	**10.1/8.3**
Panel Mounting				
Absolute Temperature	0.6	0.6	2.00	4.00
Temperature Gradients	0.0	0.0	0.00	0.00
Panel Location in Plane	2.0	2.0	3.00	3.00
Panel Adjustment Perpend.	3.0	3.0	3.00	2.00
Gravity	0.0	0.0	0.00	0.00
Wind	0.0	0.0	0.00	0.00
Total Panel Mounting	**3.7**	**3.7**	**4.7**	**5.4**
Secondary Mirror				
Manufacturing	2.0	2.0	5.91	5.83
Gravity	2.0	2.0	0.10	0.10
Wind	1.0	1.0	0.13	0.13
Absolute Temperature	1.0	1.0	4.50	4.50
Temperature Gradients	2.0	2.0	3.00	3.00
Aging	3.0	3.0	2.00	2.00
Alignment	3.0	3.0	2.04	1.92
Total Secondary Mirror	**5.7**	**5.7**	**8.5**	**8.4**
Holography Measurement	10.0	10.0	10.0	10.0
Other Errors	2.0	2.0	2.0	2.0
TOTAL	**19.54**	**21.61**	**19.86**	**19.66 /19.1**

** Vertex gives values after "rigging" at 41.3° el. AEC/Alenia give the value at 45° el. without rigging. With rigging at 45°, the lower value pertains.

In the context of our charge we have studied the applicable sections of the bidding documents for the reflector surface accuracy, as well as those in the documentation of the prototype antennas. The summary table of the tolerance contributions to the surface accuracy is presented here in tabular form and discussed below. In addition we comment on the results of the measurements of the two prototype antennas. We discuss the Alenia and VertexRSI antennas separately below, although the data are assembled in Table 1.

The overall reflector rms error is composed of several components (panel, panel mounting, BUS and setting), most of which are subject to the varying environmental parameters, like wind and temperature changes, as well as elevation dependent gravitational deformation. Table 1 shows the breakdown of the total error over these components.

The reflector surface accuracy tables provided by VertexRSI and Alenia show confusing numbers for the gravity deformation. While VertexRSI presents the value 6.2 μm, assuming a "rigging" elevation angle of 41.3 degrees, Alenia gives the squared average of the zenith and horizon deformations. Applying a rigging angle near 45°, one obtains an "effective" maximum rms of 5.0 μm for the Alenia BUS.

3.2 THE VERTEXRSI ANTENNA

3.2.1 PANELS

The VertexRSI panels are machined aluminum panels of relatively small size. They have a relatively large manufacturing error, but a small gravitational deformation. The overall accuracy is about 9 μm rms.

3.2.2 BUS

1. The temperature effects are strong (particularly the gradient) because the receiver cabin in not regulated. As in earlier work, VertexRSI uses assumed gradients of 6 K (0.5 K per metre) along the cross-elevation direction and 4 K along the axial (z) direction. But the additional cabin wall variation is assumed to be limited to a sinusoid around the wall with 1 K amplitude. This seems small to us for real situations that could occur at the site. At 19% of the RSS, temperature gradients are the largest component in the surface error budget and so this presents a significant risk. Measurements on the prototype antenna of the actual gradients in the receiver cabin walls with the temperature regulation system turned off should be carried out as soon as possible.
2. The wind deformation is 8.4 μm, a large value comparable to the (non-rigged) gravity value. We have difficulty understanding this behavior, because in most antenna designs the wind deformation is significantly smaller than the pure (not rigging-angle corrected) gravitational deformation.

3.2.3 PANEL MOUNTING AND SUBREFLECTOR

Vertex proposes a subreflector with an astonishingly small fabrication error of only 2 μm and remarkably small temperature errors. Lacking detailed information on the proposed design, we cannot make further comments.

3.2.4 OVERALL SURFACE ACCURACY

The Vertex design adds up to an overall surface error of 21.6 μm, including the 10 μm holography accuracy and 2 μm others errors required by the ALMA specifications. The AEG holography measurements covered a variety of wind and thermal conditions. Combining the wind and thermal components for the panels and BUS for the prototype antenna comes to a net RSS error of 9.9 μm. This is close to the 10 μm repeatability achieved with the AEG holography system. The AEG holography measurements probably would not have distinguished this amount of error in the 20 μm rms maps, but they can rule out these errors being as large as twice their predicted value.

3.2.5 DEPENDENCE ON ELEVATION ANGLE

The "rigging corrected" gravitational BUS component to the reflector error is 6.2 μm for the VertexRSI design. This will vary with elevation angle, in principle between zero and the value given. Let us now assume (*as an illustration, based on the suggestion from the* *photogrammetry data*) that the gravitational deformations in the real BUS structure would be 1.5 times those calculated from the FEA. Adjusting this error component would increase the overall reflector error of the VertexRSI antenna from 21.6 to 22.7 μm. This assumes that the factor of 1.5 applies to all stiffness components and that the telescope retains the same degree of homology. If the change in stiffness is not uniform, then the degree of homology will probably decrease and the gravity component of the surface rms after removing the best fit parabaloid would most likely increase by more than the factor of 1.5.

If the structure were less stiff than assumed in the FEA, the wind deformations would also increase. On the face value of the presented numbers, the effect on the Vertex antenna would be comparable to that of the gravity and the reflector would be 24.5 μm, just inside the specification of 25 μm under conditions of strong wind.

There is one other aspect that must be mentioned here. The reflectors of the ALMA antennas will be adjusted with the aid of holography at an elevation angle of at most 10 degrees at the OSF. To obtain the best performance over the intermediate elevation range, the panel setting should be "biased" to obtain a minimum error at an angle of about 45 degrees. To do this, we need accurate and reliable FEM data of the deformations between the setting angle of 10° and the "rigging" angle of 45°. This is an additional concern arising from an uncertain FEM.

3.3 THE ALENIA DESIGN

3.3.1 PANELS

Both AEC and Alenia propose to use Media Lario (ML) electroformed Nickel panels. There are significant changes between the AEC CDR documentation and the Alenia proposal, as is obvious from the Table. However, the Alenia numbers agree with those of Media Lario on the prototype panels, as given in the ML report ("structural and thermal analysis"). Thus we conclude that the Alenia panels are essentially identical to the actual panels delivered by AEC for the prototype antenna. The AEC CDR document probably reflects an earlier stage of the ML panel development.

3.3.2 BUS

As noted above, Alenia gives the squared average of the zenith and horizon deformations. Applying a rigging angle near 45°, one obtains an "effective" maximum rms of 5.0 µm for the Alenia BUS. This number has been added to the appropriate line in Table 1.

We make the following comments

1. The gravity deformation is small and the wind effect is predicted to be under 1 µm.
2. Thermal deformations, in particular the gradient component, are also small. The receiver cabin of CFRP is not expected to give a significant contribution to this error, as seems to be borne out by the numbers.

3.3.3 PANEL MOUNTING AND SUBREFLECTOR

Despite the fact that the Alenia panel adjuster incorporates a temperature compensating system, Alenia has increased the expected absolute temperature effect from 2 to 4 µm.

The Alenia subreflector tolerances are identical to those of the AEC prototype.

3.3.4 OVERALL SURFACE ACCURACY

The Alenia design adds up to an overall surface error of 19.1 µm, including the 10 µm holography accuracy and 2 µm others errors required by the ALMA specifications. The AEG holography measurements covered a variety of wind and thermal conditions. Combining the wind and thermal components for the panels and BUS for the prototype antenna comes to a net RSS error of 7.2 µm. This is less than the 10 µm repeatability achieved with the AEG holography system. The AEG holography measurements probably would not have distinguished this amount of error in the 15 µm rms maps, but they can rule out these errors being larger than about twice their predicted value.

3.3.5 DEPENDENCE ON ELEVATION ANGLE

The "rigging corrected" gravitational BUS component to the reflector error is 5.0 µm for the Alenia design. This will vary with elevation angle, in principle between zero and the value given.

Let us now assume (*as an illustration, taking the same uncertainty as suggested in the VertexRSI design*) that the gravitational deformations in the real BUS structure would be 1.5 times those calculated from the FEA. Adjusting this error component would increase the overall reflector error of the Alenia design from 19.1 to 19.9 μm, thus remaining within the 25 μm specification.

If the structure were less stiff than assumed in the FEA, the wind deformations would also increase. Taking the presented numbers at face value, the Alenia antenna would not suffer noticeably.

3.4 WHAT CAN WE SAY FROM THE MEASUREMENTS ON THE PROTOTYPE ANTENNAS?

The estimated error on the holographic surface error determination is about 5 μm. Repeated measurements over several days under varying environmental conditions (see the plots in the "Executive Summary Report") indicate variations in the surface rms of a few microns peak-to-peak for both the VertexRSI and AEC antenna. This indicates a rather weak dependence on temperature change and solar illumination. The influence of the wind is not easy to judge, because most measurements were done under quite calm conditions. During the VertexRSI measurements the wind was calm; only during the AEC measurements were 10 m/s wind velocities encountered. These had no discernable influence on the reflector accuracy.

With the aid of the API laser-interferometer, quadrant detectors and accelerometers direct measurements of structural deformation were made. Bear in mind that these measurements are difficult, in that it is sometimes difficult to separate a movement of the measurement system from that of the structure. As mentioned in the introduction to this report, a careful re-examination of measurements and FEA model predictions of the deflection of the rim of the VertexRSI BUS have yielded disparate results. Further analysis by the AEG is currently underway.

Opto-mechanical measurements on the AEC antenna showed very small deformations of the reflector rim, too noisy to draw quantitative conclusions, but of a magnitude similar to the FEA prediction.

4. TO WHAT EXTENT CAN THE PROPOSED METROLOGY SYSTEMS RELIABLY IMPROVE THE POINTING PERFORMANCE OF THE PROPOSED ANTENNA DESIGNS IN ORDER TO MEET THE REQUIRED ALMA POINTING SPECIFICATIONS?

4.1 GENERAL COMMENTS

It is important to recognize that the main factors determining the pointing accuracy of an antenna are, 1) the stiffness and stability of the structure and mount, 2) the quality of the bearings, encoders and drives, and 3) the properties of the control system. It is essential that these basic aspects of the design are satisfactory. If they are, then there may indeed be scope for reducing some of the residual errors by using additional measurement devices which we here give the general name "metrology systems".

The fact that both the prototype antennas come fairly close to meeting the demanding ALMA pointing requirements without employing metrology systems is very encouraging. The range of conditions encountered at the ATF does not necessarily cover the full span that is specified for operation on the ALMA site. Without metrology, the prototype designs were not able to meet the aspect of the ALMA specification that requires that the pointing model remain unchanged for long periods. This is not, in our view, a very critical requirement. Similarly, the specification that the offset pointing error budget should include the full effect of a steady wind appears to us to be conservative. In practice this error component is only likely to be important in the most compact configurations when wind turbulence may dramatically increase the variability of the wind forces on short timescales. Overall this presents a small risk to the project. These are aspects of performance that a good metrology system should improve, as well as helping to maintain good pointing over a wide range of environmental conditions.

It should also be noted that the issue of path-length or "delay" stability is intimately related to that of pointing. Both involve mechanical and thermal deformations of the dish and the mount, and the magnitudes of the motions involved are comparable (10 microns displacement over a distance of 5 metres corresponds to an angle of 0.4 arc seconds).

Simple estimates (now confirmed by the measurements on the prototypes) of the deformations that could arise from, e.g. temperature changes in the structure, show that at least a basic metrology system is necessary to ensure that the delay specifications are met.

4.2 THE VERTEXRSI ANTENNA

4.2.1 INTRODUCTION

The metrology apparatus described in the proposal includes:

(i) 20 temperature sensors in the yoke.

(ii) 4 linear displacement sensors attached to the CFRP frame inside the yoke

(iii) 4 inclinometers, two in the base (both below the azimuth bearing) and one at the top of each yoke arm near the elevation encoders.

The proposal gives figures for the delay and pointing errors, where the corrections from the metrology system have been included, which would meet the ALMA requirements[1]. There is little margin in the offset pointing under nighttime conditions (0.595 arc sec compared to the specification of 0.6 arc seconds) but the position is rather better for the other cases.

The proposal does not give budgets showing the various contributions to these error estimates or figures for the performance to be expected without applying the metrology corrections. At the time of writing new information has just been received giving the overall pointing errors in the case that there are no metrology corrections applied. In the worst case (absolute pointing in the daytime) these are large (greater than 10 arc seconds) indicating that the metrology system will have to work well to bring the performance within the 2 arc second specification. In the absence of a detailed error budget in the proposal the detailed error budget from the VertexRSI prototype CDR will be used. The description of the algorithms to be used in applying the data from the metrology sensors to make corrections also appears to be incomplete – for example no expressions are given showing how the data from the inclinometers at the top the yoke arms are used. Given this, the Working Group is only able to make rather qualitative statements about the proposed system.

Our comments are as follows:

1. The data from the temperature sensors on the yoke can be used to estimate delay changes due to thermal expansion in the yoke. This is necessary and has been demonstrated to work in the evaluation of the prototypes. They could also be used to estimate tilts at the top of the yoke, but the proposal makes it clear that this is not intended, because this information is available from the linear displacement sensors.
2. The displacement sensors could in principle measure the thermal expansion of the yoke, which is required for monitoring the delay, but the proposal indicates that this is not the intention. The differences between the pairs of sensors at the top of each arm will measure the tilts due to temperature gradients. Importantly they should also be sensitive to some of the effects of wind forces. We think that this is a good approach

[1] The repeatable delay appears to be outside the specification as the value given has been reduced by a factor of ten from that calculated on the grounds that all the antennas will be the same. This relaxation is not allowed by the specification.

in principle. The linearity of the displacement sensors and their stability as a function of time and temperature is important but is not discussed.

3. Regarding the inclinometers, we agree that inclinometers in the base may provide some useful information on tilts of the foundation, but we note that such devices are subject to slow long-term drifts that cannot be zeroed-out in this location. An inclinometer situated on-axis above the azimuth bearing could provide more directly useful information on tilts and the zero points can then be obtained by rotating the antenna. The inclinometers on the tops of the yoke arms will be subjected to significant accelerations when the antenna moves in azimuth. This means that it will not be possible to use their readings in many important operational conditions. We are also skeptical about the accuracy that will be achieved by inclinometers that have recently been subjected to such accelerations even after the acceleration is removed. The proposal does not say what these inclinometers are to be used for but in later clarifications it was stated that they might not be used on the production antennas. We feel that the information they produce might be useful for correcting longer term drifts. They could also be helpful in validating the use of the displacement sensors and thermometry for correcting wind and thermal distortion while the antenna is not moving or tracking slowly. Thus it makes sense to outfit the first antenna with these extra tiltmeters but not necessarily all of the antennas.

4.2.2 MODIFICATIONS THAT WOULD IMPROVE THE PROPOSED METROLOGY SYSTEM

More temperature sensors should be provided, including some on the walls of the receiver cabin, in the base and on the apex structure.

A tiltmeter should be installed in an on-axis position above the azimuth bearing.

The performance and stability of the linear displacement sensors and the stability of the frame from which they get their measurements need to be demonstrated by an appropriate combination of analysis and testing.

4.2.3 REMAINING RISKS

There is no direct evidence that the proposed VertexRSI design will fail any of the pointing performance specifications. There is however evidence from the evaluation of the VertexRSI prototype that some of the quantities measured – for example the tracking errors seen within the servo system and the short-term pointing fluctuations as seen by the accelerometers on the back-up structure – already take up a significant fraction of the allowable budget, so that very little margin remains for other contributions. This means that the metrology system, which is as yet unproven, must work at least as well as expected to keep the pointing within specification.

The BUS stiffness and cabin temperature gradients that were discussed in section 3.2.2 could also have a detrimental effect on pointing but we do not have a quantitative assessment of the magnitude of these errors.

4.3 ALENIA DESIGN

4.3.1 INTRODUCTION

The metrology apparatus described in the proposal includes:

(i) 100 temperature sensors distributed over the structure

(ii) 4 inclinometers, one in the base (below the azimuth bearing), one on-axis above the azimuth bearing, mounted on a special CFRP support structure, and one at the top of each yoke arm.

The proposal gives detailed breakdowns for the delay and pointing errors, covering both the cases where metrology corrections are included and where they are not. Detailed descriptions of the algorithms to be used in applying the data from the metrology sensors are given. When the metrology is included there is no margin in the offset pointing under nighttime conditions (0.6 arcsec, which is the specification) but the position is rather better for the other cases.

When the metrology correction is not included, there are large residual errors that would be well outside the specification if they were left uncorrected. The largest contributions to these errors come from the deformations due to thermal gradients. The thermal gradients have been estimated by thermal models that were used to determine the equilibrium temperature distributions under worst-case conditions. The thermal gradients derived from the models are still large in these cases: much larger than the gradients seen on the prototype antennas. Part of this difference must reflect the more extreme conditions assumed for the ALMA site, but it may also be due to the fact that the relatively long time constants for an insulated system have not been taken into account in the thermal model used. In any case it is clear that the metrology system has to correct for substantial thermal deformations and that the main method of doing this in the proposed system is to use data from the inclinometers.

Our comments on the proposed system are as follows:

1. The data from the temperature sensors is being used to monitor and correct for delay changes due to thermal expansion in the yoke. This is necessary and has been demonstrated to work in the evaluation. Local distortions in the region around the encoders are also being monitored and used to correct the pointing. These contributions are small and would probably not be significant if the yoke is covered with thermal insulation so that large local thermal gradients are avoided.

2. Regarding the inclinometers, we agree that an inclinometer in the base may provide some useful information on tilts of the foundation, but we note that such devices are subject to slow long-term drifts that cannot be zeroed-out in this location. The inclinometer situated on-axis above the azimuth bearing can provide more directly useful information on tilts and the zero points can be obtained by rotating the antenna. This seems to us to be a good feature. The inclinometers on the tops of the yoke arms will be subjected to significant accelerations when the antenna moves in azimuth. This means that it will not be possible to use their readings unless the antenna is moving at nearly constant velocity in azimuth. In their response to questions the contractors argued that the time-constants of the inclinometers are quite short and that readings will be on scale within a few seconds of a switching movement being completed, but will take several more seconds for the inclinometers to yield

measurements accurate enough to apply to any pointing correction algorithm. We remain skeptical about the accuracy that will be achieved by inclinometers under these conditions.

4.3.2 Modifications that would improve the proposed metrology system

The vendor has agreed to insulate the yoke. This should decrease the thermal deformation problems. It may be possible to correct some of the pointing errors due to thermal effects by using measurements of temperature in the structure.

Possible approaches to correcting for wind induced pointing and delay errors include monitoring wind speed with anemometers on or near the telescope and/or monitoring the forces on the antenna via the currents in the servo motors.

4.3.3 Remaining risks

The performance of the inclinometers on the tops of the yoke arms is critical to this metrology system. In particular they are required to ensure that the specifications on the offset pointing and delay errors are met in high winds. We feel that the risk of them not performing correctly as a result of the accelerations to which they are subjected is high.

It should be relatively straightforward to address this issue by tests on either the prototype antennas or a laboratory test rig. If the results show that good performance cannot be achieved then an alternative approach will need to be developed.

The metrology system proposed by Alenia and even some aspects of the modifications proposed in this report are not proven and as with any project there is significant risk associated with implementing new techniques. It will take the diligent effort of both the vendor and ALMA personnel to successfully implement, develop algorithms and verify any metrology system on the first few production antennas at Atacama.

5. COMMENT ON THE MAINTAINABILITY OF THE TWO PROPOSED DESIGNS AND ESTABLISH A FIRST ESTIMATE OF LIFECYCLE COSTS FOR THE OPERATIONAL LIFETIME OF THE TELESCOPE.

We understand that ALMA project staff are in the process of writing a report on this aspect of the two proposed antennas. Given the paucity of information in the proposals on this topic, the disparate cost basis for their maintenance cost estimates and the lack of experience of the committee members in this field; we do not have any significant information to contribute to this discussion. We feel that the parallel efforts being conducted by the ALMA project to assess maintainability and life cycle costs can lead to a better analysis of this issue.

6. APPENDIX A: ANTENNA TECHNICAL WORKING GROUP CHARGE

Foreword:

AUI and ESO are currently seeking clarification from two bidders as a prelude to contracting the procurement of the ALMA production antennas. Following a joint technical evaluation of the Reponses received from bidders to both North America and Europe, each Executive is carrying out its own procurement process under the Contracts Selection Committee (AUI) and the Contract Award Committee (ESO). These committees will ultimately make recommendations to the selection officials for the respective Executive, the NRAO Director and AUI President for North America and the ESO Director General for Europe.

Charge:

As a part of the due diligence required of the CSC and CAC, the Technical Working Group (TWG) shall investigate specific technical questions relevant to whether the two designs are expected to fulfill the Technical requirements of the ALMA project. For each of the specific technical issues raised by the two Executives the group shall provide the following advice to the committees:

- Based on an analysis of all available data, determine the level of remaining technical risk
- Determine if any specific modification to the proposed design are required to mitigate any remaining technical risk.

Specific Technical Issues:

- Will the proposed antenna designs maintain surface accuracy specifications over all elevation ranges?
- To what extent can the proposed metrology systems reliably improve the pointing performance of the proposed antenna designs in order to meet the required ALMA pointing specifications?
- Comment on the maintainability of the two proposed designs and establish a first estimate of lifecycle costs for the operational lifetime of the telescope.
- Other issues resulting from interaction with the antenna vendors.

The TWG will base its assessment on all available information including:

- The proposals submitted by the vendors
- The supplementary materials supplied by the vendors in response to written questions and face-to-face meetings (as documented in written minutes)
- The Executive Summary of the AEG report
- The experience gained on the two prototype antennas in so far as it can be extrapolated to the proposed designs.
- Other relevant available data (e.g. Apex data)
- Consultation with relevant experts provided by the Executives on request.

Schedule:

A report on the above technical issues should be submitted to the two Executives on or before 10th September. Answers to specific questions should be supplied to the two Executives as soon as available. The report will not interfere with the procurement activities of the two Executives but is fully expected to be delivered prior to the approval of the final contracts.

Proposed members:
D.Woody, Chairman
R. Hills,
J.Magnum,
J.Baars,
and
T.Beasley, JAO, Observer

Members of the Antenna IPT and their expert support staff will be made available on the request of the Chairman. In all areas where a specific investigation has to be instigated there should be representatives from both Executives assigned to the task.