**Submillimeter Array Technical Memorandum

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Classification of Pointing Errors

Introduction

The philosophy for how to specify pointing and tracking accuracy to potential antenna vendors is presented in Technical Memorandum #26. In summary, the overall blind pointing error for an individual antenna has three components: a "fixed" pointing error with a time scale comparable to a mosaic observation or greater, a drift pointing error with time scales on the order of a few minutes to a few hours , and a random/tracking error. Hereafter, these errors will be referred to as the initial, drift, and random components of the pointing error respectively. The random component is a relative error in that it is an offset relative to any arbitrary pointing angle. It will be specified directly to the vendor and is further divided into two components: the residual servo error (the difference between the commanded encoder reading and the actual reading) and errors due to deflections of the structure not sensed by the encoders. The vender is free to allocate the total random component between these two components.

The initial and drift components are absolute errors i.e they are related directly to the celestial coordinate system. The accuracy of these components required for the SMA antennas cannot be achieved directly and we will use a pointing model which corrects for the initial and drift components. These components will not be specified directly to the vendor. Instead, we will derive specifications for the individual errors or groups of individual errors which make up the initial and drift components. The derivation of these specifications must insure that the antenna can ultimately point to the required accuracy once the pointing model is implemented. The purpose of this memo is to establish a framework for deriving specifications for the individual error components and allocation of the total pointing error budget between the initial, drift, and random components. During this process we must be very careful to balance the allocation of errors in accordance with the difficulty in controlling each error and the effects of the different types of errors on array performance. Our goal is to allow prospective vendors as much freedom as possible in the allocation of errors. However, we must make some basic allocations so that the vendor has specifications which can be clearly verified by analysis and/or test.

Error Description

The classification of errors into initial, drift, and random components is defined in terms of individual antennas. For interferometry there is a fourth error component which is a fixed global offset of the entire array. This error is not effected by the individual performance of the antennas and will not be specifically addressed here. Errors for the individual antennas must be further defined in terms of the array. Initial errors are assumed to be uncorrelated among antennas across the array; drift errors are assumed to be correlated, and random errors are assumed to be uncorrelated. Wood's simulations (1) for the SMA appear to suggest that large variations in the random component did not cause large variations in array performance. Wood's work did not consider variations of the initial or drift components. Further simulations must be done before we can establish specifications for the initial, drift, and random components. We must also consider single dish operations and it is possible that this operating mode may set the specification for the initial and random components while the array operations set the specification for the global offset and drift errors. In any event, once the specifications for these errors are set, derived specifications for the individual errors or groups of individual errors which make up the initial and drift components must be established while the random component can be passed directly to the vendor.

The first step in deriving specifications for individuals errors or groups of individual errors is to identify and classify the errors. There are two general classes of errors: one due to errors in the geometry of the antenna and one due to the accuracy of the pointing command. For an alt/az mount the errors due to antenna geometry naturally separate into elevation and cross-elevation components. The alt/az mount geometry has four geometrical constraints which must be maintained to have zero pointing error: the azimuth axis must be aligned to the astronomical zenith, the elevation and azimuth axes must be orthogonal, the zero point of the elevation encoder must be aligned to the RF beam, and the RF and elevation axes must be orthogonal. Table 1 characterizes deviations from these geometrical constraints in terms of elevation and cross elevation error components. When these geometrical constraints are maintained there is no pointing error associated with telescope geometry. However, there are additional pointing errors due to inaccuracies in the pointing command caused by atmospheric conditions, timing errors, longitude/latitude errors, etc. These errors do not naturally divide into cross elevation and elevation components and they will be expressed as RMS beam radial errors.

Physical description of error	Contributors	Error Function	Error Comp.	Error Class
Non-orthogonal alignment of RF and elevation axes (con't) (cross elevation error)	Beam wave guide mirror alignment errors due to initial set-up	$e_{34xel}=c_9$	Initial	3
	Thermal deformation of reflector/subreflector/beam guide structure	$e_{35xel}=f_{26}(T)$	Drifts)	4
	Deformation of the reflector / subreflector/beam guide structure due to wind	$e_{36xel}=f_{27}(W)$	Random	5

Table 3: Description and classification of errors (con?).

Geometry constraint	Type of error caused by deviation
Azimuth axis alignment to astronomical zenith	Elevation error which varies with the sine of the azimuth angle and a cross-elevation error which varies as the sine of the azimuth angle and the cosine of the zenith angle
Orthogonality of elevation and azimuth axes	Cross-elevation error which varies as the cosine of the zenith angle
Alignment of elevation encoder, zero-point to the RF beam	Elevation
Orthogonality of RF beam and elevation axis	Cross-elevation

Table 1: Classification of geometry errors into elevation and cross-elevation error components

The errors must also be classified by the technique used to correct them. Ideally we would like to measure each error contributor independently and generate a correction term for each which can be used in the pointing model. Unfortunately, this is not practical because of the interdependence of the sources of error, difficulties in devising test methods for measuring some of the errors, and the basic fact that some of the errors are random in nature. The method used to correct a particular error depends on our ability to accurately measure the error directly and/or whether the error is an initial, drift, or random type error.

All errors which can be measured directly to the required accuracy will be corrected by taking direct measurements. We will designate these as Class 1 errors. The other errors which are not random and are of a linear form, which is known, will be corrected using either an optical or radio pointing model. Errors which are a function of the mount only will be corrected using the optical pointing model. Errors which are due to the orientation of the RF beam relative to the mount will be corrected using the radio pointing model. The pointing models use a least squares method to best fit a pointing data set so that the residual sum of the errors is minimized. Errors corrected by the optical pointing model will be designated as Class 2 errors while ones corrected by the radio pointing model will be classified as Class 3 errors.

Random errors and other nonlinear errors or errors whose forms are unknown and cannot be determined are essentially uncorrectable with the pointing models. It is possible to correct some of these errors via real time measurements and generation of real time corrections. This type of error will be designated as Class 4. The remaining errors are essentially uncorrectable and are designated as Class 5. The definition of error classes is summarized in Table 2.

Error Class	Correction Technique
1	Measured directly
2	Corrected by optical pointing model
3	Corrected by radio pointing model
4	Corrected by real time measurements
5	Uncorrected

Table 2: Error classes by correction technique.

To identify individual error sources, causes for deviations from each of the four geometrical constraints were determined as well as causes for uncertainty in the pointing command. Table 3 lists each of the error sources and classifies them as to type of error component and type of correction technique. The following nomenclature is used in the Table 3: t - time, T - temperature , AZ - azimuth angle, Z - zenith angle, W - wind speed / direction, LRR - locked rotor resonance, c_i - a constant, f_i - an unknown function. Classification of the errors is not always completely correct according to the definitions for initial, drift, and random components. Where this is the case the table is annotated with the reasoning for the classification. These annotations are: (1) Thermal deflections of the antenna structures are not necessarily uniform among all antennas in the array. Terrain, wind conditions, and the effect of clouds could all cause variation in thermal deflections between antennas. However, thermal conditions will in general be very similar for all antennas and drift errors tend to have a greater effect on array performance as mentioned above. So I have conservatively assumed that errors due to thermal deflections are drift type errors. (2) The error due to gravity unbalance about the azimuth axis will not vary over time. However, it is best classified as a drift type error because it is uniform among all antennas in the array. (3) Likewise, the error due to gravity sag will not vary over time. However it is uniform among all antennas in the array and is best classified as a drift type error.

Physical description of error	Contributor Error Function	Error Comp.	Error Class	
Tilt between azimuth axis and astronomical zenith (cross-elevation errors)	Azimuth bearing wobble	$e_{7xel}=f_1(AZ) \cdot SIN(f_2(AZ) - AZ) \cdot COS(Z)$	✋■♓♦♓♋●	1
	Sum of alignment errors (error between grav. vector and astro. zenith and error between grav. vector and nominal azimuth axis)	$e_{8xel}=c_1 \cdot SIN(c_2 - AZ) \cdot COS(Z)$	✋■♓♦♓♋●	2
	Earth movement	$e_{9xel}=f_3(t) \cdot SIN(f_4(t) - AZ) \cdot COS(Z)$	❒♓♐♦	4
	Pedestal deflections due to thermal effects	$e_{10xel}=f_5(T) \cdot SIN(f_6(T) - AZ) \cdot COS(Z)$	Drift(1)	4
	Pedestal deflections due to wind effects	$e_{11xel}=f_7(W) \cdot SIN(f_8(W) - AZ) \cdot COS(Z)$	Random	4
	Pedestal defl. due to gravity unbalance about az axis for designs which have unbalance.	$e_{12xel}=f_9(AZ) \cdot SIN(Z) \cdot SIN(c_3 - AZ)$	Drift(2)	2

Table 3: Description and classification of errors (con't).

Physical description of error	Contributor Error Function	Error Comp.	Error Class	
Tilt between azimuth axis and astronomical zenith (elevation errors)	Azimuth bearing wobble	$e_{1el} = f_1(AZ) \cdot COS(f_2(AZ) - AZ)$	Initial	1
	Sum of alignment errors (error between grav. vector and astro. zenith and error between grav. vector and nominal azimuth axis)	$e_{2el} = c_1 \cdot COS(c_2 - AZ)$	[illegible]	2
	Earth movement	$e_{3el} = f_3(t) \cdot COS(f_4(t) - AZ)$	Drift	4
	Pedestal deflections due to thermal effects	$e_{4el} = f_5(T) \cdot COS(f_6(T) - AZ)$	Drift(1)	4
	Pedestal deflections due to wind effects	$e_{5el} = f_7(W) \cdot COS(f_8(W) - AZ)$	Random	4
	Pedestal defl. due to gravity unbalance about az axis for designs which have unbalance.	$e_{6el} = f_9(AZ) \cdot SIN(Z) \cdot COS(c_3 -$ [illegible]	Drift(2)	2

Table 3: Description and classification of errors.

Physical description of error	Contributors	Error Function	Error Comp.	Error Class
Non-orthogonal alignment of azimuth and elevation axes (cross elevation error which varies with the cosine of the zenith angle)	Elevation bearing run out	$e_{13xel}=f_{10}(Z)\cdot COS(Z)$	Initial	1
	Alignment errors due to errors in physical measurements	$e_{14xel}=c_4\cdot COS(Z)$	Initial	2
	Pedestal deflections due to thermal effects	$e_{15xel}=f_{11}(T)\cdot COS(Z)$	Drift(1)	4
	Pedestal deflections due to wind effects	$e_{16xel}=f_{12}(W)\cdot COS(Z)$	Rando m	4

Table 3: Description and classification of errors (con?).

Physical description of error	Contributors	Error Function	Error Comp.	Error Class
Error between elevation encoder and RF beam (elevation error)	Grav. sag of refl. and subrefl. (includes repeatable errors in subrefl. positioning sys.)	$e_{17el}=c_5 \cdot SIN(Z)$	Drift (3)	3
	Elevation encoder zero point setting error	$e_{18el}=c_6$	Initial	2
	El. encoder error including effects of mounting and couplings	$e_{19el}=f_{13}(Z)$	Initial	1
	El. servo error i.e. diff. between commanded encoder reading and actual reading due to limit cycle, velocity lag, and wind	$e_{20el}=f_{14}(W, LRR, STICTION)$	Random	5
	El. subreflector positioning error (random error associated with the subreflector positioning system)	$e_{21el}=f_{15}(SUB POSISYS)$	Random	5
	Beam wave guide mirror alignment errors due to wind deformations	$e_{22el}=f_{16}(W)$	Random	5
	Beam wave guide mirror alignment errors due to bearing run out and wobble	$e_{23el}=f_{17}(Z)$	Initial	1

Table 3: Description and classification of errors (conk).

Physical description of error	Contributors	Error Function	Error Comp.	Error Class
Error between elevation encoder and RF beam (con't) (elevation error)	Beam wave guide mirror alignment errors due to thermal deformations	$e_{24el}=f_{18}(T)$	Drift (1)	4
	Beam wave guide mirror alignment errors due to initial set-up	$e_{25el}=c_7$	Initial	3
	Thermal deformation of reflector/subreflector structure	$e_{26el}=f_{19}(T)$	Drift (1)	4
	Deformation of the reflector / subreflector structure due to wind	$e_{27el}=f_{20}(W)$	Rando m	5

Table 3: Description and classification of errors (conk).

Physical description of error	Contributors	Error Function	Error Comp.	Error Class
Non-orthogonal alignment of RF and elevation axes (cross elevation error)	Azimuth encoder zero point setting error	$e_{28xel}=c_8 \cdot COS(Z)$	✋■♓♦♓♋●	2
	Azimuth encoder error including effects of mounting and couplings	$e_{29xel}=f_{21}(AZ) \cdot COS(Z)$	Initial	1
	Azimuth servo error i.e. difference between commanded encoder reading and actual reading due to limit cycle, velocity lag, and wind rejection	$e_{30xel}=f_{22}(SERVO) \cdot COS(Z)$	Random	5
	Beam wave guide mirror alignment errors due to wind deformations	$e_{31xel}=f_{23}(W)$	Random	5
	Beam wave guide mirror alignment errors due to bearing run out and wobble	$e_{32xel}=f_{24}(Z)$	Initial	1
	Beam wave guide mirror alignment errors due to thermal deformations	$e_{33xel}=f_{25}(T)$	Drift(1)	4

Table 3: Description and classification of errors (con't).