The Establishment of Pointing Model for the Shanghai VGOS Radio Telescope

Zhengxiong Sun\textsuperscript{1,2}, Jinqing Wang\textsuperscript{1} and Guangli Wang\textsuperscript{1}

\textsuperscript{1}Shanghai Astronomical Observatory, Chinese Academy of Sciences, china 2000030
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Abstract. Using a pointing model is a common practice among radio telescopes devoted to astronomy to correct for mechanical misalignments. Pointing accuracy is one of the most important indicators for the performance of radio telescopes, especially radio telescopes with a large diameter or which operate at high frequencies. The general requirement for deviation in pointing is less than 10% of the antenna’s half-power beamwidth. The method to establish the pointing model for the Shanghai VGOS radio telescope is described. Obtaining a large amount of test data by scanning the strong power source in the whole sky zone. Fitting these data by Gaussian to find the pointing deviation. We believe that a physical model is more desirable since it allows to identify the source of the pointing errors and may help in removing or minimizing the causes. Finally, an eight-parameter pointing model is built after fitting all the collected single-point errors. It is verified that the model works well in the broadband feed systems.

1. Introduction
The demand for higher precision measurements in Very Long Baseline Interferometry (VLBI) continues to grow, which drives the technical development of next generation international VLBI stations called the VLBI Global Observing System (VGOS). Antennas specifically designed for geodetic VLBI are changing, transitioning from using large, slow moving antennas observing at S/X (“legacy” systems) to using small, fast antennas with broad-band receivers, the so-called VGOS systems\cite{1}. The Shanghai VGOS station is located in the courtyard of existing TM65m radio telescope, which is 13.2 m diameter, dual-reflector systems with a ring-focus sub-reflector. It is instrumented with a broadband feed systems, which works in the 3-18Ghz range with dual-linear polarization to provide VGOS capability. The antenna rotates -275° to 275° on azimuth direction, which calculated from the south and 0° to 90° on elevation direction. The maximum speed of the antenna on azimuth direction is 12°/s with the maximum acceleration of 2.5°/s\textsuperscript{2}. The maximum speed of antenna on elevation direction is 6°/s with the maximum acceleration of 2.5°/s\textsuperscript{2}. Shanghai VGOS is the newest addition to the VGOS project, and can be seen in Fig.1.
2. Observing Strategy
The aim of scanning bright sources in the whole day zone is to obtain a good pointing model of the antenna, characterized in our case by a set of 8 parameters with a physical meaning[2]. If these parameters are unknown or poorly determined they cause azimuth and elevation errors which depend on elevation and azimuth and are proportional to the errors in the parameters. Parameters are obtained by least square analysis and the fit improves when the coverage of azimuth and elevation is best. In order to maximize the sky coverage it is important to choose 5 or 6 bright sources whose declinations produce different elevations when they transit the local meridian.

There are two strategies to observe several sources from their rise to their set: the simplest one is to track each source for a long time and then proceed with the next one. A better strategy is to perform one double pointing scan on each source and repeat the cycle, which is to scan the source in the positive and negative direction then calculate the average value of the deviations in both directions. Some sources will be over the horizon, and others will be below at a given time. Therefore the cycle at any time is done with those sources which are visible. This solution minimizes the observing time, provides a good sky coverage and prevents systematic effects[3].

In the process of observation, we are to scan each source and repeat the cycle. Converting the RF signal into baseband signal through the down converter to record the total power of 20MHz bandwidth signal (Shanghai VGOS station only has a broadband reception system, which works in the 3-18GHz range. We established the pointing model at 8GHz). Simultaneously recording the values of the antenna encoder and command position at the azimuth and elevation positions. Because of the existence of background noise, the power distribution will not satisfy a pure Gaussian term. So some polynomial are added to the fitting model. Hence an expression of Gaussian function in addition to a fourth polynomial is adopted, as shown by Eq.(1). Fig.2, a fitting with the Gaussian and fourth terms shows its power amplitude[4]. The horizontal coordinate indicates the difference between the antenna pointing control command and the actual position of the antenna. The vertical coordinates indicates the power amplitude. As is known, if the antenna has no pointing error, then the deviation between the antenna position and the source position will be zero while the antenna scans a radio source, and the total power reading will be maximum. Therefore, find out the deviation of the antenna relative to the radio source at the peak time of total power reversely, the pointing error of the antenna at this position can be obtained.

\[
    f(k) = a(1) \times e^{-0.5 \times (k-a(2))/a(3)^2} + a(4) \times k^4 + a(5) \times k^3 + a(6) \times k^2 + a(7) \times k + a(8)
\]

(1)
Figure 2. Fitting with the Gaussian and fourth terms

3. Pointing Model
The deviation in pointing of the antenna can be decomposed into azimuth-axis tilt error, the vertical error between the azimuth axis and the elevation axis, the collimation error (the axis of the antenna beam is not exactly perpendicular to the elevation axis), the azimuth and elevation-axis coding zero-error, gravitational deflection error, etc. Since the errors are relatively small, the final pointing deviation is the algebraic sum of all these partial deviations in the linear calibration model[5]. The widely used pointing calibration models are constructed as shown by Eq.(2) and Eq.(3).

\[ \Delta AZ = p1 + p3 \times \tan(EL) \cos(AZ) + p4 \times \tan(EL) \sin(AZ) + p5 \times \tan(EL) - p6 / \cos(EL) \]  

\[ \Delta EL = p2 - p3 \times \sin(EL) + p4 \times \cos(AZ) + p7 \times \cos(EL) + p8 / \tan(EL) \]  

Where, \( \Delta AZ \) and \( \Delta EL \) are the pointing errors for azimuth and elevation. \( p1 \) is the azimuth-axis encoder offset, \( p2 \) is the elevation-axis encoder offset, \( p3 \) is the tilt of azimuth axis along North - South direction, \( p4 \) is the tilt of azimuth axis along a East -West direction, \( p5 \) is the lack of orthogonality between the azimuth and elevation exis, \( p6 \) is collimation error, also known as non orthogonality between the radio beam and the elevation axis ,\( p7 \) is the gravitational deflection error and \( p8 \) is the residual error due to atmospheric correction. Fig.3 shows examples of the sky coverage. The antenna makes a double pointing drift on one source and then moves to another and this is repeated for 5 or 6 sources in total. This cycle is repeated for 24 hours and a good sky coverage is obtained after 1 day.
Figure 3. Sky coverage, X axis is azimuth and Y axis elevation. Sources were tracked alternatively using a cycle. It takes less time and avoids systematic errors.

In total 218 valid data points have been collected in all. Their error distributions in azimuth and in elevation are shown in Fig.4 and Fig.5. The mark “o” in the figures represents the pointing deviation of the antenna, the mark “□” represents the pointing model value, and the mark “+” represents the residuals. As illustrated by the figures, these points are rather homogeneously distributed in a wide sky area for both azimuth and elevation, and have a very good distribution of residuals. The azimuth residual of the azimuth error distribution is 23.2 arcsec, its corrected value can reach 8.58 arcsec, and the elevation residual of the elevation error distribution is 18.94 arcsec, its corrected value is reduced to 8.02 arcsec. The deviation in pointing can be decomposed into two dimensions, the antenna’s azimuth and elevation. Pointing accuracy ± (RMS) of the antenna can be expressed as shown by Eq.(4).

\[ \delta = \sqrt{\sum (\delta^2(AZ)_i \times \cos^2(EL_i)) + \delta^2(EL)_i} / (n-1) \]  

(4)

Where \( \delta(AZ)_i \) is the azimuth residual of the i-th observation point, Where \( \delta(EL)_i \) is the elevation residual of the i-th observation point, \( EL_i \) is the antenna elevation angle of the i-th observation point and n is the number of observations. The distributions of the overall residuals in both azimuth and elevation are shown in Fig.6: the residual before correction is 25.03 arcsec, and after correction it is reduced to 11.75 arcsec.
Figure 4. Distribution of single-point fitting errors and their residuals in the azimuth direction

Figure 5. Distribution of single-point fitting errors and their residuals in the elevation direction

Figure 6. Distribution of the overall residuals

We have put the pointing model parameters into the antenna control program. When the antenna tracks the radio source, it can be seen that the signal to noise ratio (SNR) on the antenna power record
is significantly improved. We will continue to conduct pointing modeling on this basis to improve antenna pointing accuracy.

4. References

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