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GAIN DEGRADATION OF KVN 21-M SHAPED CASSEGRAIN ANTENNA DUE TO MISALIGNMENT OF ANTENNA OPTICS

Moon-Hee Chung[1]†, Do-Young Byun[1], and Vladimir B. Khaikin[2]
[1]Radio Astronomy Division, KASI, 61-1, Hwaam-dong, Yusong-gu, Taejon 305-348, Korea
[2]The Special Astrophysical Observatory of RAS, 194021 St. Petersburg, Russia
email: mhchung@kasi.re.kr

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ABSTRACT

In this paper, gain loss of KVN (Korean VLBI Network) 21-m shaped Cassegrain antenna due to misalignment of antenna optics is calculated using ray-tracing method. It enables us to estimate alignment tolerances of feed and sub-reflector positioning. According to numerical results, KVN 21-m shaped Cassegrain antenna's gain loss is more sensitive to positions of feed and sub-reflector than in case of the equivalent classical Cassegrain antenna. The result of calculation is believed to be utilized as a possible guideline when checking the performance of the antenna system.

Key words: ray tracing, antenna optics, shaped Cassegrain antenna, alignment tolerance

1. INTRODUCTION

The KVN (Korean VLBI Network) is a millimeter-wave VLBI system of which observation frequency bands cover 22 GHz up to 129 GHz. It is also expected that the operation frequencies will be expanded to S and X bands for Geodesy observation. The antenna system of KVN consists of three shaped Cassegrain reflector antennas. Its construction is under way now and a first KVN antenna will be installed by next year. In this context, it may be necessary to be capable of characterizing the antenna performance before the antenna installation is finished. One way of the characterizations is to estimate effects of antenna optics misalignment on the antenna peak gain.

Many millimeter-wave antennas employ Cassegrain type reflectors which consist of parabolic and hyperbolic surfaces for main and sub-reflectors, respectively. If the aperture efficiency or antenna gain is a critical design goal, a shaped reflector can be used to have uniform aperture illumination for higher aperture efficiency or antenna peak gain. That is the reason why the antenna company Antedo, Inc., contracted to build the KVN antenna system adopted a shaped Cassegrain antenna to meet the requirement of the KVN antenna efficiency. Shaping antenna surfaces must result in violation of the Abbe sine condition which leads to a narrow field of view (Hudson 1989, Padman 1995). It is a penalty for higher peak gain of shaped antennas. Although a narrow field of view is unacceptable for multi-feed array system, the KVN was initially planned to use a single feed for each observation band at the focal plane and the narrow field of view does not seem to pose a problem. But the narrow field of view for a shaped reflector antenna may produce loss in gain due to misalignment of antenna optics more likely than in case of classical Cassegrain antennas.

†corresponding author

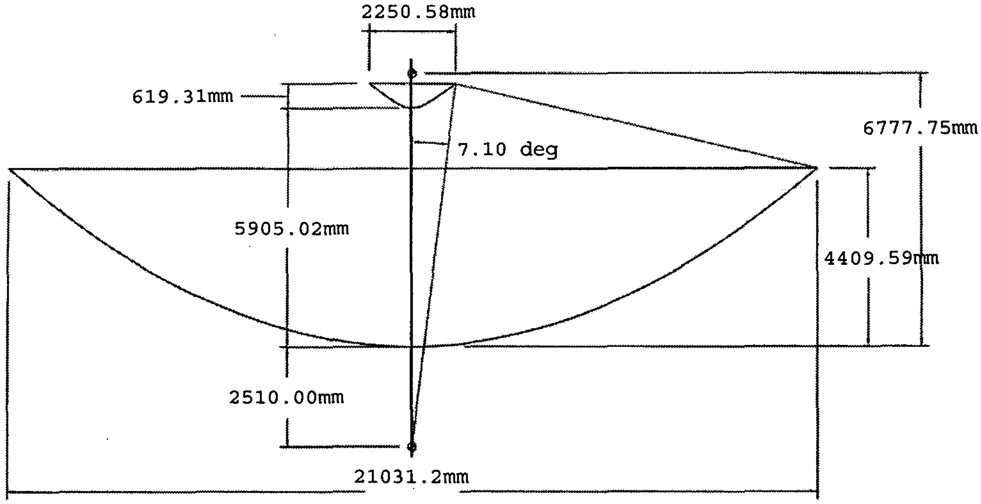

Figure 1. Geometry and dimensions of KVN 21-m shaped Cassegrain antenna (Antedo, Inc. 2005, Technical Memo, KVN-21M-TM-130).

Table 1. Parameters of the equivalent classical Cassegrain antenna.

Antenna Parameters	Specification
Diameter of main-reflector	21031.2 mm
Diameter of sub-reflector	2250.6 mm
Focal length of main-reflector	6586.3 mm
Angle subtended by sub-reflector	7.1 deg
Effective focal length	84750.0 mm
Magnification	12.9
Inter-focal distance	9290.0 mm
Feed edge taper	-17.0 dB

As millimeter-wave reflector antennas are generally large compared to the wavelengths of interest, it is possible to use geometric optics for the analysis of a reflector antenna's performance. Traditionally ray-tracing method based on geometric optics was developed for the optical design but it can be also employed to design and analyze millimeter-wave shaped reflector antennas of which surfaces are deviated from conic sections.

The aim of this paper is to evaluate alignment tolerances of feed and sub-reflector positioning for KVN 21-m shaped Cassegrain antenna by applying ray-tracing method to the calculation of gain loss. In addition, numerical results are compared with an equivalent classical Cassegrain antenna whose antenna parameters are derived from KVN 21-m shaped Cassegrain antenna.

2. KVN 21-M SHAPED CASSEGRAIN ANTENNA

Figure 1 illustrates the geometry and dimensions of KVN 21-m shaped Cassegrain antenna. As shown in the figure, the shaped antenna is similar to Cassegrain type antenna. The only difference is that the surfaces of main and sub-reflectors are somewhat deviated from parabolic and hyperbolic

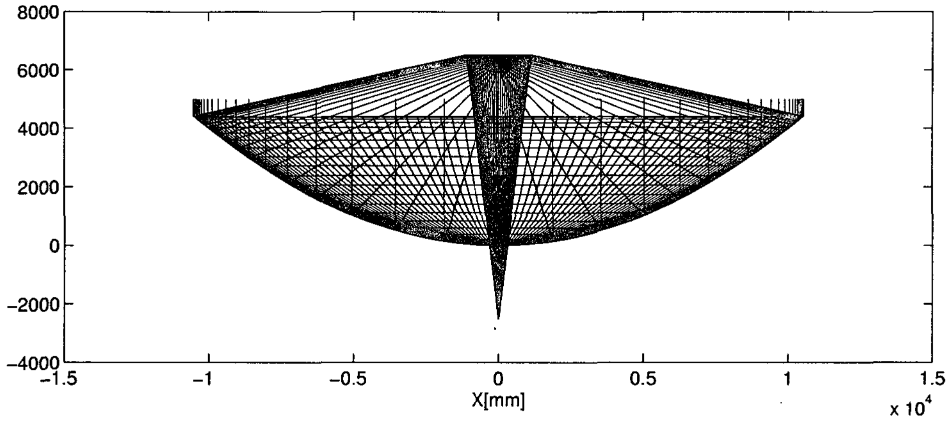

Figure 2. Ray-tracing layout of KVN 21-m shaped Cassegrain antenna.

ones of classical Cassegrain antenna.

One can determine antenna parameters of an equivalent classical Cassegrain antenna which has the same diameters of main and sub-reflectors as the original shaped antenna. Table 1 shows those parameters which will be used to make comparisons with numerical results of KVN 21-m shaped Cassegrain antenna

3. RAY-TRACING METHOD AND ANTENNA GAIN

Ray-tracing method is based on geometric optics in which diffraction effects due to finite wavelength are not considered. According to the reciprocity theorem in antenna, the properties of antenna in the receiving mode can be obtained by analyzing the antenna in the transmitting mode. Then, rays are assumed to start from the focal point or system focus of KVN 21-m shaped Cassegrain antenna and the rays reflected on the sub and main-reflectors are sequentially calculated with Snell's law. The algorithm of ray-tracing used in this paper is well explained in Sletten (1981) but the approximation technique of shaped antenna's curves is different from Sletten's one in which a shaped reflector's surface was defined by a grid of fixed points. After having implemented Sletten's approach in a programming code, it was found that the grid approximation did not give accurate results. Then, approximation using polynomials for curved surfaces of the shaped antenna was utilized in this paper. When the resultant rays on the aperture plane of main-reflector have been obtained, the optical path lengths of each ray between the predefined focal point and the antenna aperture plane can be calculated. The optical path lengths are constant unless the feed and sub-reflector misalignments or antenna surface deformation occur. Deviation of optical path lengths from a constant value leads to phase errors on the antenna aperture plane. These phase errors or deviations cause gain reduction and antenna beam squint. Figure 2 depicts a ray-tracing layout of KVN 21-m shaped Cassegrain antenna.

When the phase error distribution (δ) on the aperture plane of antenna is small (less than a radian), Ruze (1966) derived an approximation for gain loss or ratio of the reduced gain (G) to the peak gain (G_0) defined in eq. (1) as follows:

$$\frac{G}{G_0} \cong 1 - \bar{\delta^2} + \bar{\delta}^2, \tag{1}$$

where

$$\bar{\delta^2} = \frac{\int_0^{2\pi} \int_0^1 f(r,\phi)\delta^2(r,\phi) r dr d\phi}{\int_0^{2\pi} \int_0^1 f(r,\phi) r dr d\phi}, \tag{2}$$

and

$$\bar{\delta} = \frac{\int_0^{2\pi} \int_0^1 f(r,\phi)\delta(r,\phi) r dr d\phi}{\int_0^{2\pi} \int_0^1 f(r,\phi) r dr d\phi}. \tag{3}$$

In the above eqs. (2, 3), $f(r,\phi)$ is an illumination function across the aperture plane of main-reflector and r, ϕ are normalized radius and azimuth angle, respectively. The aperture illumination is determined by the design of antenna surface shape and the feed radiation pattern, of which taper is recommended to be –17 dB at the sub-reflector's edge for KVN 21-m shaped Cassegrain antenna. The aperture illumination for shaped antennas has generally more uniform distribution than classical Cassegrain antennas. For the calculation of gain degradation due to misalignment of feed and sub-reflector, it is assumed that the aperture illumination is nearly even across the aperture plane and its taper at the edge is around –17 dB.

4. NUMERICAL RESULTS OF GAIN LOSS DUE TO MISALIGNMENTS OF FEED AND SUB-REFLECTOR

Loss in gain of antenna may be caused by several factors like sub-reflector blockage and illumination spillover. But only phase deviation due to feed and sub-reflector misalignments is considered for the gain loss calculation in this paper.

Figures 3 and 4 show distributions of optical path errors across the aperture plane of KVN 21-m shaped Cassegrain antenna, which result from the axial displacements of the feed toward sub-reflector (24 mm) and the sub-reflector toward feed (0.21 mm), respectively. The optical path error distributions have symmetrical patterns on the axis because the shaped antenna consists of axially symmetric reflectors. Calculated gain losses due to on-axis displacements of feed and sub-reflector are presented in Figures 5 and 6. It is found that there is no great difference of gain losses between KVN 21-m shaped Cassegrain antenna and its equivalent classical Cassegrain antenna for on-axis feed displacement.

The lateral or off-axis displacements of feed and sub-reflector cause optical path deviations across the aperture plane of KVN 21-m shaped Cassegrain antenna as shown in Figure 7 and 8. When calculating such optical path deviations due to lateral displacement, a linear least-squares fit plane of the optical path error should be subtracted from the calculated optical path error in order to have residual path deviation across the aperture plane of antenna. Off-axis displacement of feed and sub-reflector results in a tilt of the plane wave across the antenna aperture, which can be corrected by offset pointing of the antenna. Then, only residual path deviations, which are illustrated in Figure 7 and 8, affect gain reduction due to lateral displacement. The calculated path deviation distributions for off-axis displacements of feed and sub-reflector are asymmetric across the aperture plane. Consequently the far-field radiation pattern must be also asymmetric.

With calculated path deviation distributions, gain loss can be calculated using eq. (1), of which results are presented in Figure 9 and 10. In the equivalent classical Cassegrain antenna, no reduction

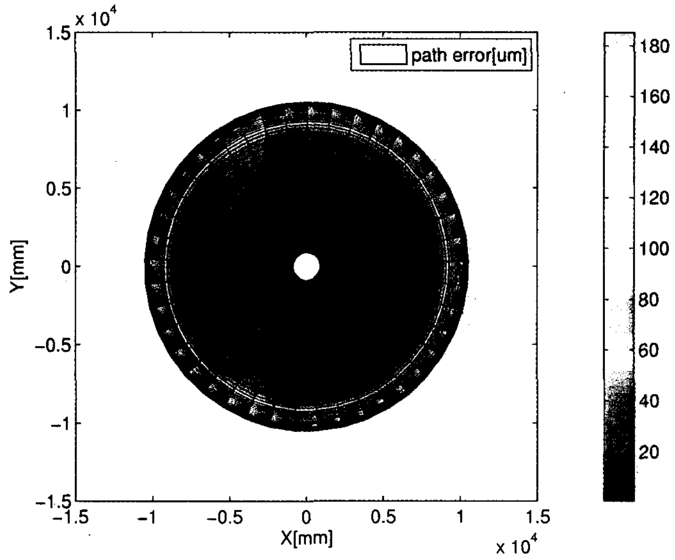

Figure 3. Optical path error distribution across the aperture plane of KVN 21-m shaped Cassegrain antenna due to on-axis feed displacement of 24 mm toward sub-reflector ($\lambda = 3$ mm).

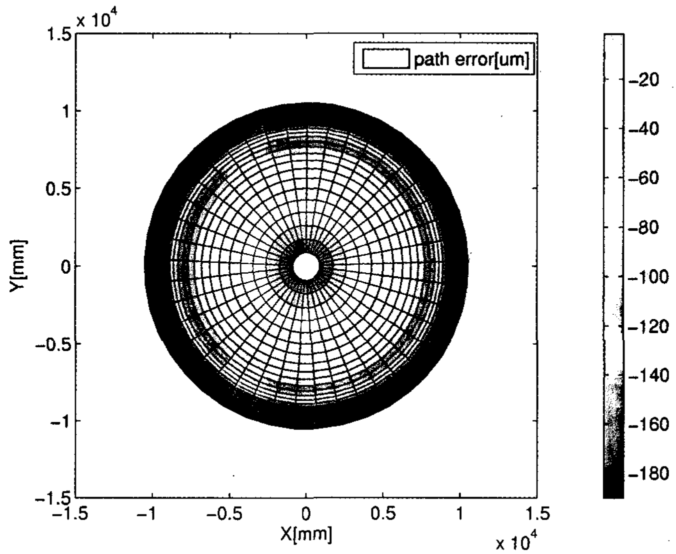

Figure 4. Optical path error distribution across the aperture plane of KVN 21-m shaped Cassegrain antenna due to on-axis sub-reflector displacement of 0.21 mm toward feed ($\lambda = 3$ mm).

of gain is found for off-axis displacement of the feed less than 4 wavelengths. It can be explained by the fact that its effective focal length is very long in comparison with the diameter of main-

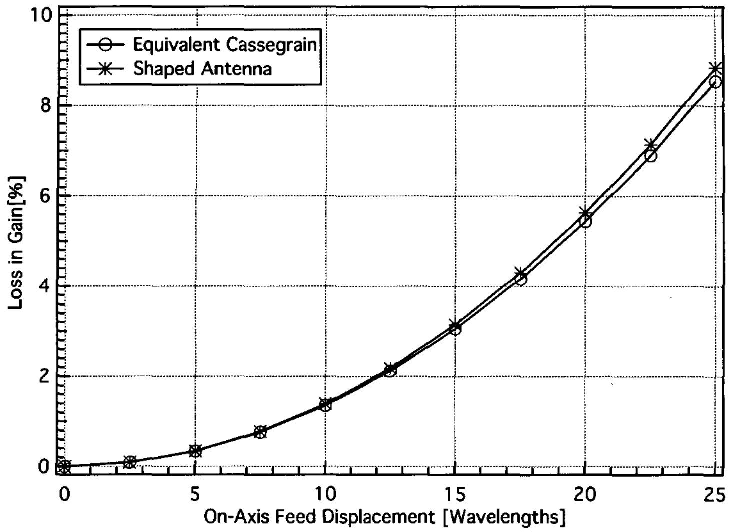

Figure 5. Gain loss (in percent) as a function of on-axis feed displacement (in wavelengths).

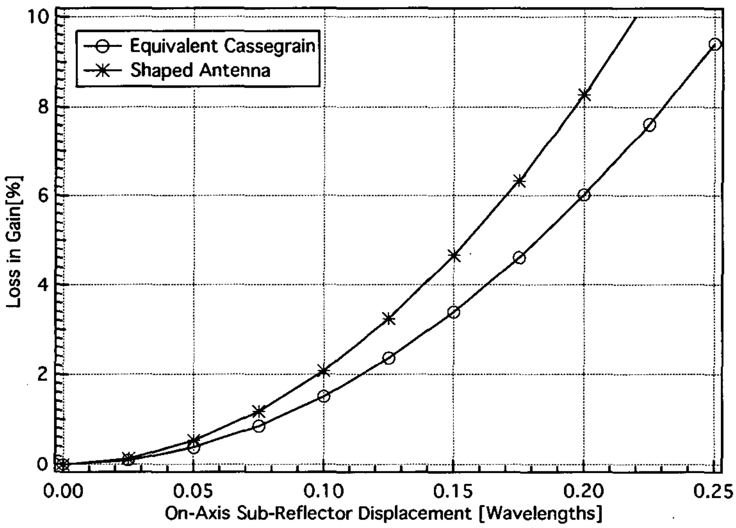

Figure 6. Gain loss (in percent) as a function of on-axis sub-reflector displacement (in wavelengths).

reflector and small lateral displacement of the feed does not greatly affect the path length error across the aperture of main-reflector. Contrary to the equivalent Cassegrain antenna, KVN 21-m shaped Cassegrain antenna's gain loss is very sensitive to off-axis feed displacement as shown in Figure 9. Tendency of gain reduction due to lateral displacement of the feed for KVN 21-m shaped Cassegrain antenna is extremely different from its equivalent Cassegrain antenna. It is believed that

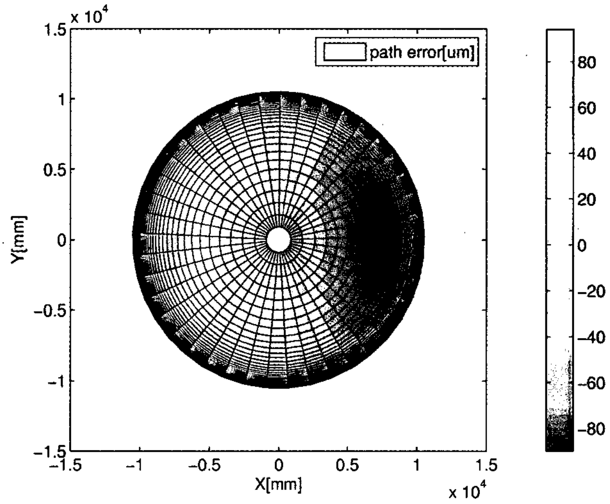

Figure 7. Optical path error distribution across the aperture plane of KVN 21-m shaped Cassegrain antenna due to off-axis feed displacement of 3.6 mm along the positive x direction ($\lambda = 3$ mm).

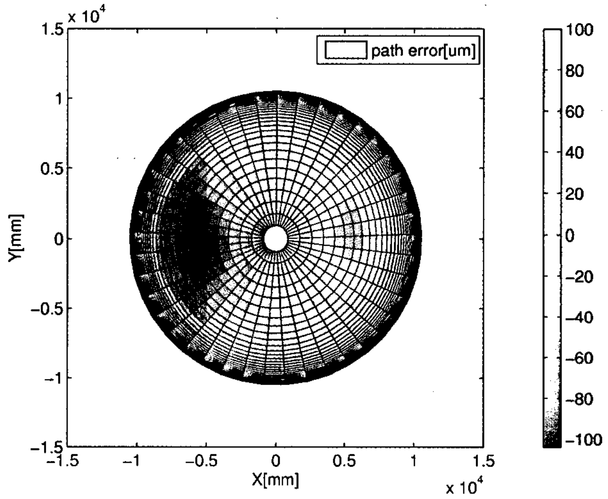

Figure 8. Optical path error distribution across the aperture plane of KVN 21-m shaped Cassegrain antenna due to off-axis sub-reflector displacement of 0.48 mm along the positive x direction ($\lambda = 3$ mm).

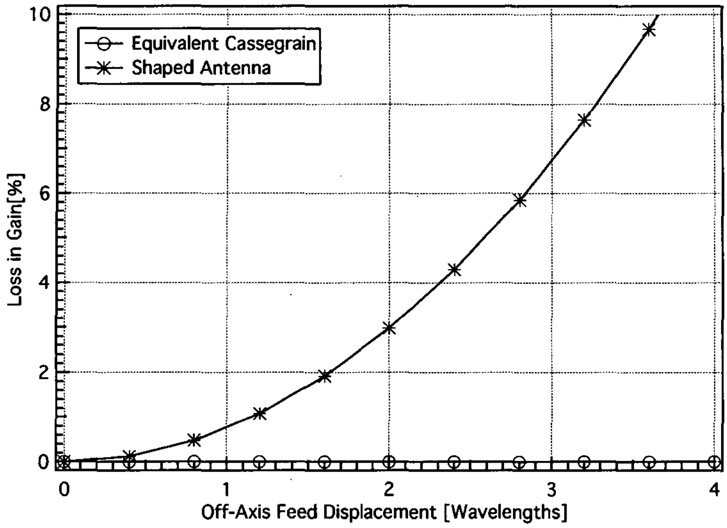

Figure 9. Gain loss (in percent) as a function of off-axis feed displacement (in wavelengths).

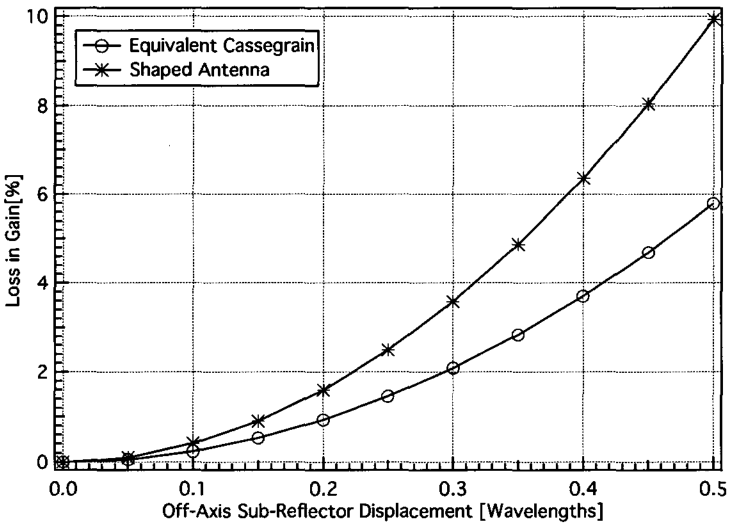

Figure 10. Gain loss (in percent) as a function of off-axis sub-reflector displacement (in wavelengths).

a narrow field of view due to shaping surfaces of antenna deteriorates image quality at the focal plane and this leads to gain reduction at the feed position departed from the focal point of shaped antenna. It can be said that the increased aperture efficiency by shaping antenna surfaces is achieved at the expense of more rigorous alignment tolerance of the off-axis displacement compared to its equivalent Cassegrain antenna.

Table 2. Alignment tolerances within 1 % loss in gain for KVN 21-m shaped Cassegrain antenna.

Optics Parameters	Tolerance (in wavelengths)
on-axis feed displacement	$< 8\lambda$
on-axis sub-reflector displacement	$< 0.07\lambda$
off-axis feed displacement	$< 1.2\lambda$
off-axis sub-reflector displacement	$< 0.16\lambda$

5. CONCLUSIONS

To quantify the gain loss of KVN 21-m shaped Cassegrain antenna due to axial and lateral displacements of feed and sub-reflector, a 3D ray-tracing code has been developed and applied to both KVN 21-m shaped Cassegrain antenna and its equivalent classical Cassegrain antenna. The numerical result of ray-tracing analysis allows us to place limits on alignment tolerances of feed and sub-reflector positioning. The estimated alignment tolerances for loss in gain less than 1 % are presented in Table 2.

Our calculation indicates that there is the difference of gain degradation due to misalignment of the antenna optics between KVN 21-m shaped Cassegrain antenna and the equivalent classical Cassegrain antenna. The gain loss of KVN 21-m shaped Cassegrain antenna is dramatically more vulnerable to lateral displacement of feed and sub-reflector compared with its counterpart, equivalent classical Cassegrain antenna. Then, alignment tolerances must be applied more strictly to KVN 21-m shaped Cassegrain antenna than its equivalent classical Cassegrain antenna so that a minimum loss in gain can be kept.

The ray-tracing analysis provides the information concerning the phase error distribution across the aperture plane of KVN 21-m shaped Cassegrain antenna. The phase error due to off-axis displacement of feed or sub-reflector may be compensated by small lateral shift of another component because optical path errors due to lateral movement of feed and sub-reflector have similar asymmetric distributions. In addition, the calculated phase error distribution may be used to predict the far-field radiation pattern of KVN 21-m shaped Cassegrain antenna which can be directly compared with observations of radio sources.

The antenna gain reduction is caused by various factors like antenna panel surface accuracy, illumination spillover, sub-reflector blockage, coupling efficiency between the antenna main beam and the feed horn. The ray-tracing method based on geometric optics gives only gain loss due to optical path length error caused by misalignment of the antenna optical components. At the higher frequencies like 129 GHz, the antenna panel surface accuracy will be one of dominant factors affecting the gain degradation of KVN 21-m shaped Cassegrain antenna. But the ray-tracing analysis may shed light on understanding about the gain degradation due to the lateral displacement of feed and sub-reflector in which the classical aberration theory does not give accurate result. In addition, it is believed to provide a possible guideline for the antenna calibration and alignment during and after KVN 21-m shaped Cassegrain antenna installation.

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