ngVLA Electronics Memo # 18

A Turnstile Orthomode Transducer (OMT) Design for the ngVLA Band 3 Receiver

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Abstract

A turnstile OMT design for use in the ngVLA Band 3 receiver front-end is explored. The design is based on an existing X-band turnstile OMT that was initially designed for the expanded Very Large Array (EVLA) X-band receiver. Electromagnetic simulation is used to design and optimize the performance for use in ngVLA Band 3.

1 Introduction

The ngVLA receiver front-ends with axially corrugated feed horns in Bands 3-6 require a waveguide OMT to separate the incoming signal into two linear polarizations. This is a critical component in order to achieve a good receiver noise temperature, polarization purity, and low bandpass ripple receiver performance.

In this memo, an OMT for ngVLA Band 3 is designed based on an existing NRAO design by S. Srikanth for X-band [1], originally intended (but not used) for the EVLA X-band (8-12 GHz) receiver. The OMT was, however, recently used in the Green Bank Telescope (GBT) X-band receiver [2]. This OMT appears to be relatively compact in size and designed for a frequency range somewhat lower than that of ngVLA Band 3. Given the total available volume for cooled components in the receiver signal chain is more tightly constrained for Band 3 relative to the higher frequency bands, it was selected for study: however, the design could readily be scaled and modified as necessary for use in the other bands.

2 ngVLA Receiver Front-End Application

The block diagram for ngVLA receiver front-end Bands 3-6 from [3] is shown in Figure 1, with Band 3 operating over 12.3–20.5 GHz. The diagram shows the OMT with a single input from the feed horn and two outputs for each of the linear polarizations.

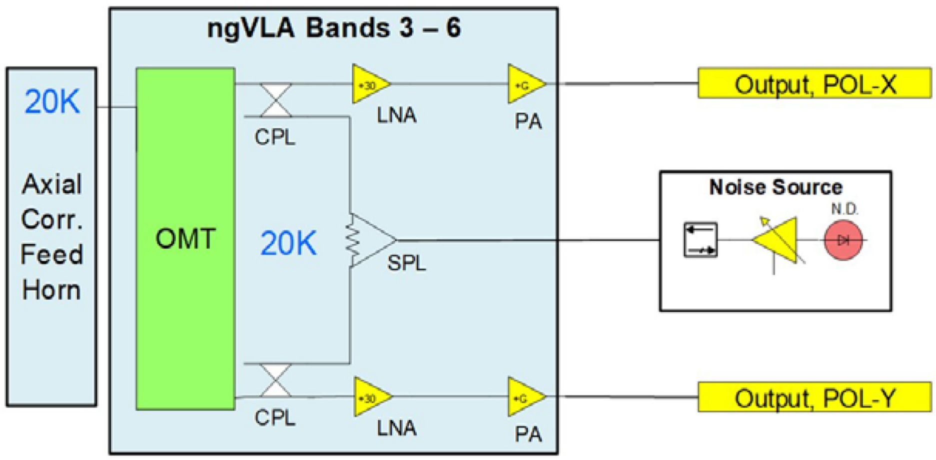


Figure 1. ngVLA Receiver Band 3-6 Front-End Block Diagram [3]

The OMT design needs to separate out the orthogonal linear polarizations with low cross-polarization, while minimizing addition of noise and ripple in the receiver. OMTs are 3-port devices, with a circular or square waveguide port (Port 1) from the feed horn as its input, and two rectangular waveguide output ports (Ports 2 and 3), each containing one of the two separated linear polarizations injected at the Port 1 input. Additionally, there is leakage, or cross-polarization, of the undesired polarization on each port output. With two modes at Port 1, the nomenclature used to describe the transmission thru paths with low insertion loss are S(2,1:1) and S(3,1:2), while the cross-polarized terms are S(2,1:2) and S(3,1:1). Return losses are S(1:1,1:1) and S(1:2,1:2) for the two modes on Port 1, and S(2,2) and S(3,3) for Port 2 and Port 3, respectively. In this memo, insertion loss and return loss are used interchangeably with their corresponding s-parameters. The sign (positive/negative) of these parameters and mismatch loss effects on insertion loss are ignored. The design goals in Table 1 were set as initial targets.

Table 1. ngVLA Band 3 OMT Design Goals

Specification	Requirement or Target Value
Bandwidth	12.3 – 20.5 GHz (1.67:1)
Insertion Loss	0.1 dB, max (both polarizations)
Return Loss	25 dB, min (all ports)
System Cross Polarization*	30 dB, min
OMT Cross Polarization	40 dB, min
In-band Trapped Mode Resonances	None
Input Waveguide Port	Circular, 17.08 mm diameter
Output Waveguide Ports	WR56.3 14.30 mm x 7.15 mm (0.563” x 0.2815”)
Operating Temperature	20 K

* System Cross Polarization includes the antenna optics, feed horn, and receiver

Mechanically, the OMT needs to fit in the cartridge, interface to the feed horn port centered axially in the cartridge diameter, and enable the remainder of the components to be successfully integrated inside the cartridge. Clearance between the receiver components and the 1st stage radiation shield is essential to account for tolerances and other adjustments that can be performed on the cartridge. The clearance required to the radiation shield is estimated to be 2-3 mm nominally.

Images showing the current cartridge (v2.2) isometric and top / cross-section views are shown in Figure 2 and Figure 3, respectively.

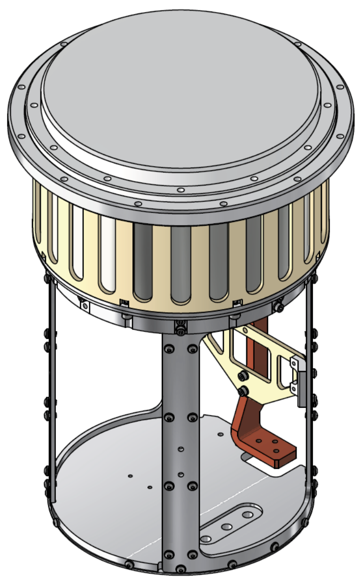


Figure 2. Band 3 Receiver Cartridge Isometric View [4]

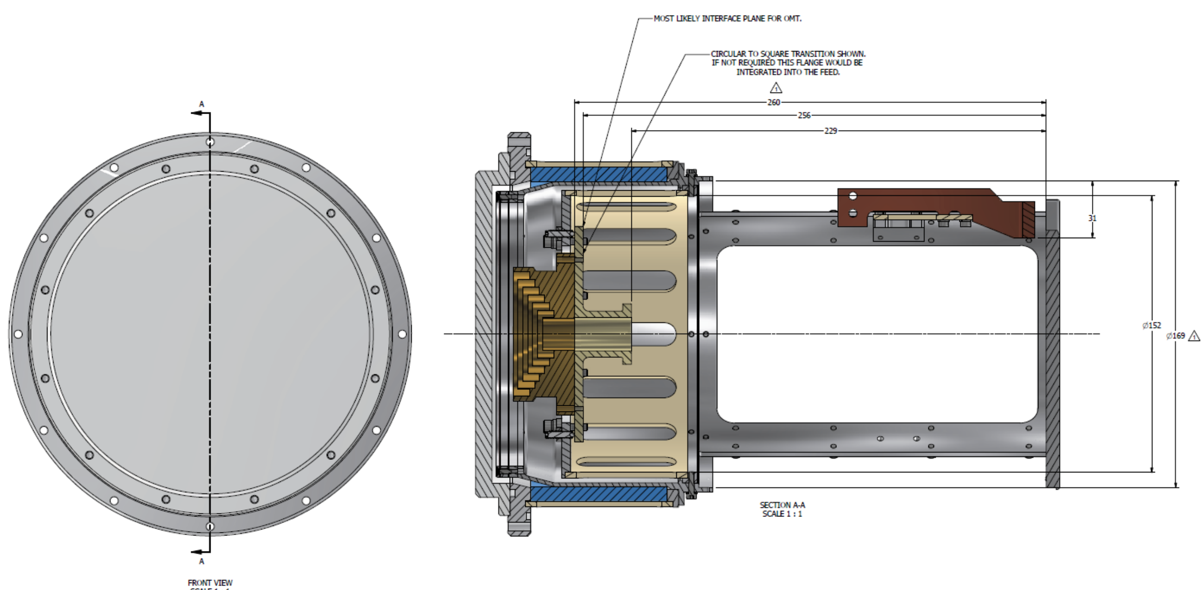


Figure 3. Band 3 Receiver Cartridge Top and Cross-section Views [4]

3 OMT Design and Simulation

3.1 Existing X-band design

The existing 8-12 GHz X-band electromagnetic design is shown in Figure 4. The main features of this design are:

- Square waveguide input, to accommodate a polarization converter assembly between the feed horn and OMT (for native circular polarization required on the EVLA).
- Equal length H-plane bends off of all 4 turnstile ports, with stepped waveguide to keep the overlapping bends separated, and allow for a highly compact, stacked structure along the z-axis.
- Separately-machined and installed E-plane Y-combiners on the output ports, to allow flexibility in output port orientation (0 or 180 degrees).

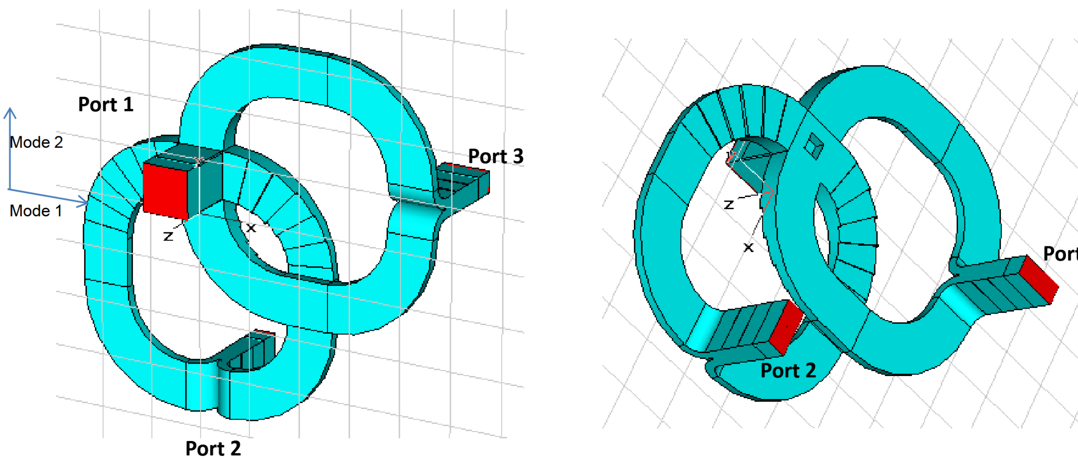


Figure 4. Existing X-band OMT Electromagnetic Design [1]

This design was originally simulated in CST Microwave Studio with return loss, insertion loss, and cross-polarization results in Figure 5, Figure 6, and Figure 7 respectively.

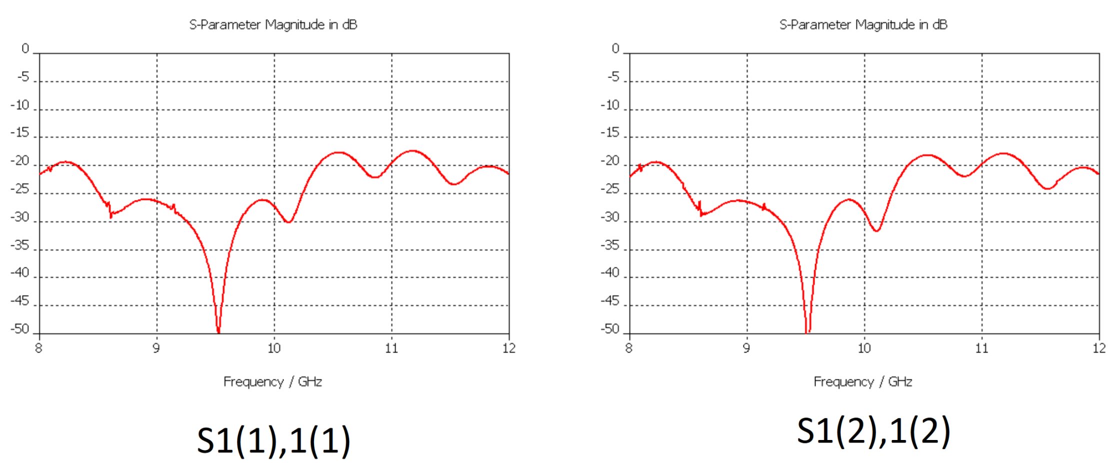
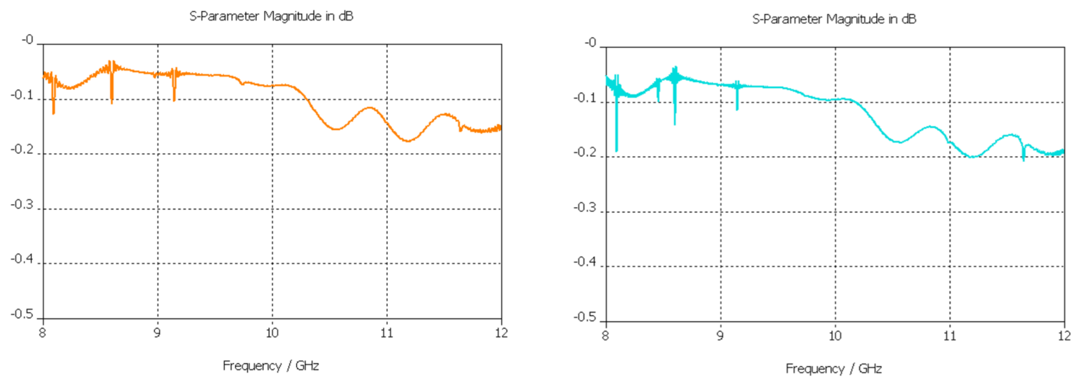
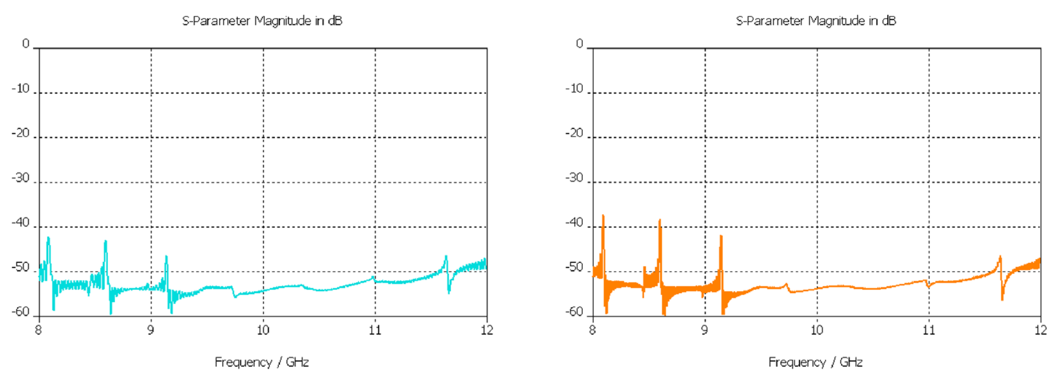


Figure 5. Simulated Return Loss for X-band OMT [1]



S2(1),1(1) S3(1),1(2)

Figure 6. Simulated Insertion Loss for X-band OMT [1]



S3(1),1(1) S2(1),1(2)

Figure 7. Simulated Cross-polarization for X-band OMT [1]

The simulations indicate the following worst-case results over 8-12 GHz:

- Return Loss > 17.5 dB
- Insertion Loss < 0.2 dB
- Cross-polarization > 37 dB

A mechanical design was built, consisting of a somewhat large number of components as shown in Figure 8. The assembly was deemed to be fairly straightforward if the parts are machined correctly. At the time of EVLA construction more than 20 years ago, the flatness and fit of the parts was considered to be somewhat challenging, but today more complicated assemblies like this are built often [5], [6].

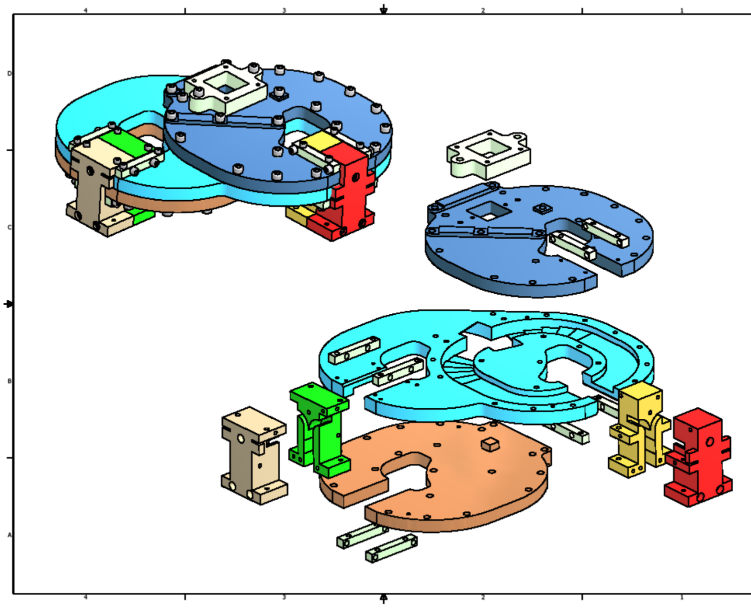
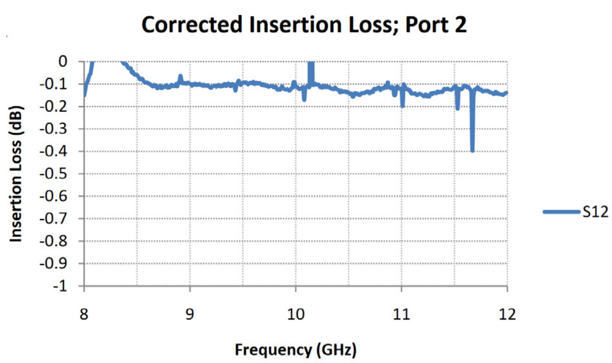


Figure 8. Existing X-band OMT Mechanical Design [1]

Overall, there appeared to be good correlation in the simulated and measured return loss reported in [1]. With "pinning", insertion loss matched fairly closely, but had some larger in-band resonances compared to simulation. These are fairly narrow in frequency, but have max amplitude ~0.4 dB. Cross-polarization also had resonances that peaked up to ~20 dB. Measured results are shown in Figure 9.



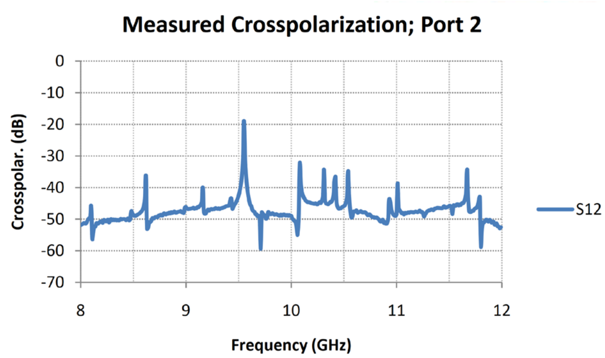


Figure 9. (Left) Measured Insertion Loss and (Right) Cross-polarization for X-band OMT [1]

3.2 ngVLA Band 3 Design

3.2.1 Design Overview

For ngVLA Band 3, there are some issues to address when scaling the design directly from the existing X-band OMT design.

- *Input port type*. A circular waveguide input port is required, rather than a square waveguide port. Thus, a change in the input turnstile and matching geometry is necessary.
- *Performance*. More difficult goals for this design are set: 25 dB return loss, 0.1 dB insertion loss, and 40 dB cross-polarization. Optimization will be used to try to meet these targets.

- *Bandwidth*. The ngVLA Band 3 design requires a higher ratio bandwidth than the X-band OMT. X-band with standard WR90 waveguide has a lower cutoff frequency (f_c) of 6.6 GHz, with operation between 8 GHz (1.21 f_c) and 12 GHz (1.82 f_c), or a ratio bandwidth of 1.5:1. The ngVLA Band 3 design uses a custom waveguide size (WR56.3) having a lower cutoff of 10.5 GHz, and operation between 12.3 GHz (1.17 f_c) and 20.5 GHz (1.95 f_c), for a ratio bandwidth of ~1.67:1. Re-design and optimization will be used to try to meet the performance targets over this wider bandwidth.
- *Size and port locations/orientations*. The OMT and the rest of the front-end components need to fit into the allotted cartridge volume. An effort will be made to reduce size when possible in order to achieve a physical fit in the cartridge.
- *In-band resonances*. An attempt will be made to reduce the in-band resonances observed in the X-band design simulation and measurement.
- *Dimensions and tolerances.* As we scale to higher frequencies, the dimensions will get smaller and possibly more difficult to manufacture.

For each section of the OMT (turnstile junction, bends, and Y-combiner), a model is built, simulated, and optimized. Finally, the sections are integrated together to analyze the full OMT.

3.2.2 Section Design and Optimization

Each section in the OMT is optimized for return loss performance over the frequency band using Ansys HFSS, a 3D full-wave Finite Element Method (FEM) field solver. A perfect electrical conductor (PEC) is set on all waveguide surfaces for optimization and the insertion loss of each section is ignored until the OMT is assembled in a full simulation. The multi-objective genetic algorithm (MOGA) was the optimization algorithm. After MOGA, other gradient approaches, including manual tweaking, were attempted in order to see if improved performance was possible. The goal for return loss is initially set to 31 dB for each section, since a sum root of squares of these equivalent return loss sections would achieve the cascaded 25 dB goal for the full OMT. A max delta S for mesh convergence is set to 0.005 followed by a frequency sweep from 12.3 to 20.5 GHz, in 15 steps for optimization, and in 0.05 GHz steps for final results plotting.

3.2.2.1 Turnstile Junction

The turnstile junction is assembled with a 17.08 mm diameter circular waveguide and a matching structure. One, two, and three-cylinder matching structure geometries were simulated and optimized. It was found that a two-cylinder matching structure achieves much better return loss than a single cylinder, but three cylinders do not provide any apparent improvement. In order to reduce simulation time for optimization, the design is split into half with a perfect H symmetry boundary and port impedance multiplier of two. The size of each rectangular waveguide port at the turnstile junction is the same as on the OMT output ports.

The dimensions of the matching cylinders after optimization are shown in Table 2.

Table 2. Turnstile Junction Matching Dimensions

Parameter	Dimension
Lower Cylinder Diameter	10.35 mm
Upper Cylinder Diameter	5.30 mm
Lower Cylinder Height	1.47 mm
Upper Cylinder Height	2.74 mm

Next, the full 5-port model in Figure 10 was simulated, with two modes on the circular waveguide Port 1 and one mode on the rectangular waveguide Ports 2-5.

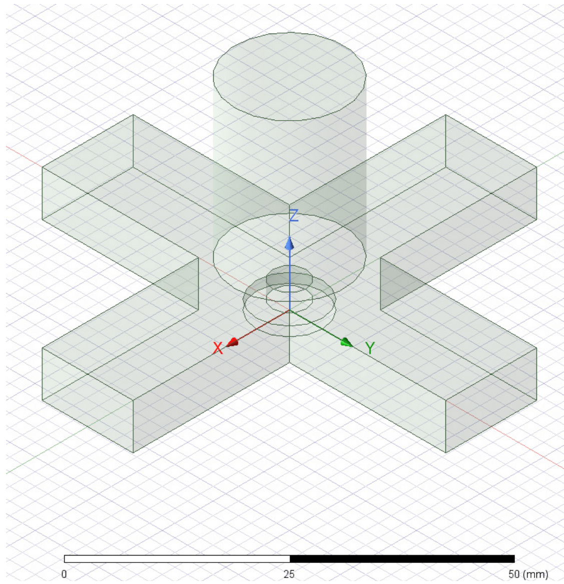


Figure 10. Turnstile Junction Model (Two-Cylinder Matching Located at the Coordinate Origin)

The simulated return loss at the circular waveguide port is shown in Figure 11. There are peaks at the low, mid, and high frequencies in the band at ~29 dB. For this section, the 31 dB return loss goal could not be achieved through optimization.

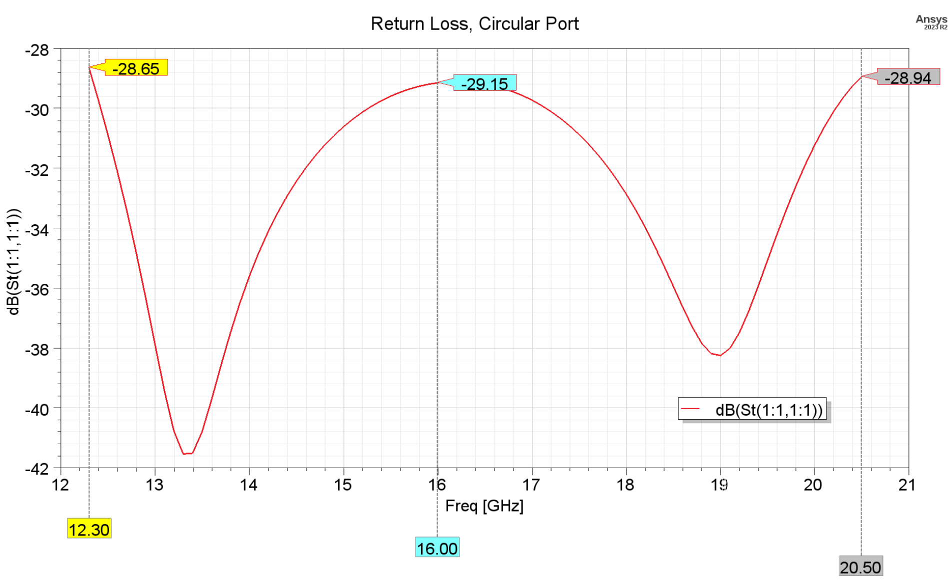


Figure 11. Simulated Return Loss S(1:1,1:1) at Circular Waveguide Port, Turnstile Junction

3.2.2.2 Reduced height H-plane Bend

Reduced height waveguide bends are used in the OMT. Nominally, the height of this waveguide is selected to be 0.4*14.30 mm = 5.72 mm. The bend radius is swept from 10.16 mm to 25.4 mm in 2.54 mm steps (0.4 to 1 inch in 0.1-inch steps). The model is shown in Figure 12.

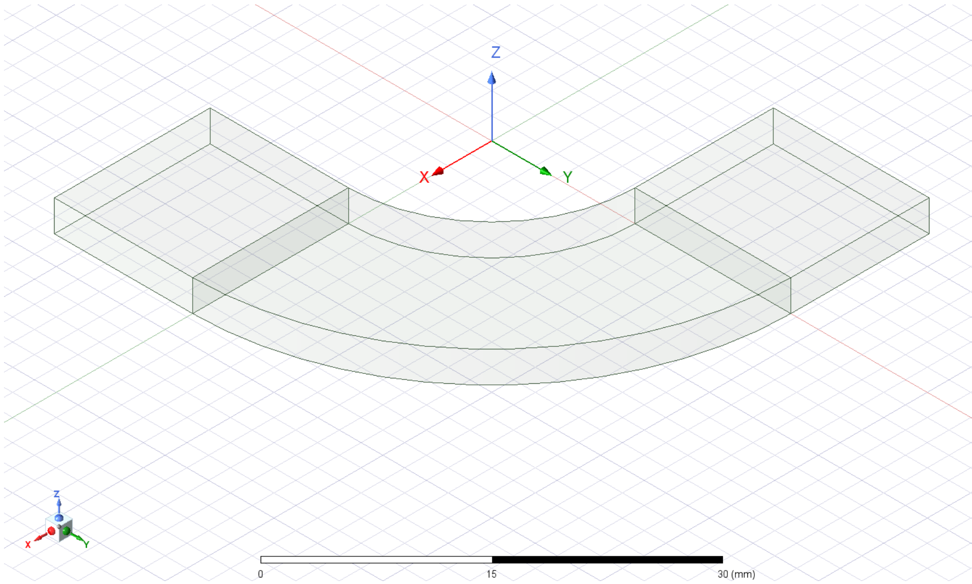


Figure 12. Reduced Height H-plane Bend Model

The simulated return loss for selected bend radii is shown in Figure 13. With a radius greater than or equal to 15.24 mm (0.6 inches), the worst-case simulated return loss is better than 35 dB, which more than meets the 31 dB goal.

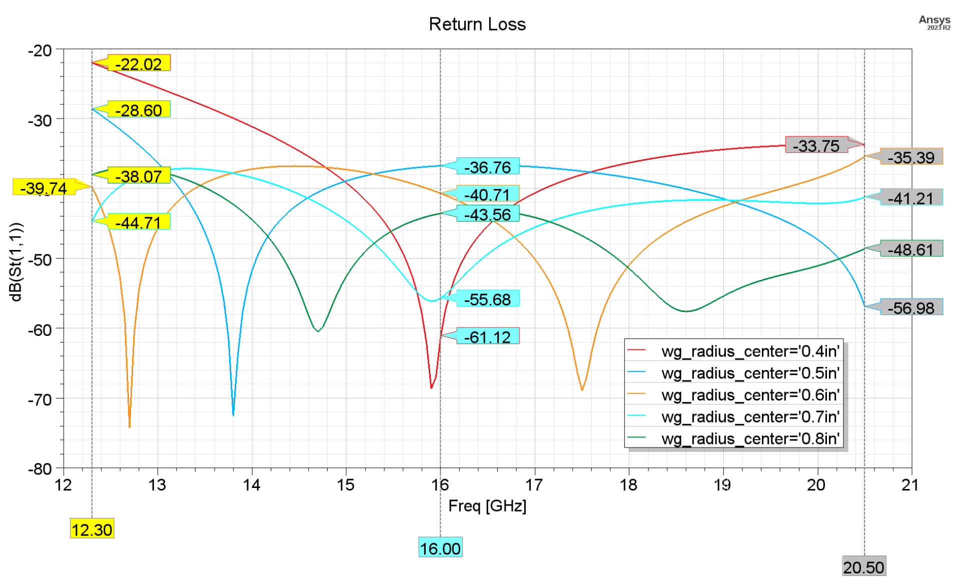


Figure 13. Simulated Return Loss S(1,1), Reduced Height H-plane Bend

3.2.2.3 H-plane Bend with stepped transition

The H-plane bend with stepped transition is optimized with radii of 15.24 mm to 25.4 mm (0.6 to 1 inches). An additional goal here is to use as small of a radius as possible in order to minimize the size of the OMT.

Note that the bend radius used in the X-band design was 41.87 mm, equivalent to a bend radius of 26.16 mm when scaled to Band 3. While the existing X-band design used five steps, it was found that one of the steps will be very slight in magnitude, difficult to manufacture, and did not appear to add much value to the performance. Four equal length steps were chosen and the geometry of these were optimized for each bend radius.

The model for the bend with 4-step transition is shown in Figure 14. A fillet radius of 0.61 mm (0.024 inches) is added where an end mill is expected to leave a radius in a machined part. This had a minimal impact on the simulation result.

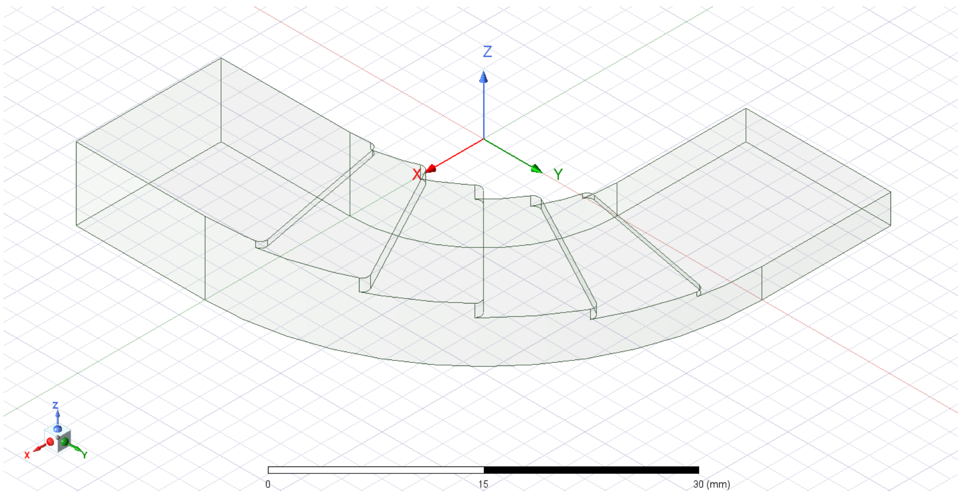


Figure 14. H-plane Bend With Stepped Transition Model

The optimized dimensions for this section are shown in Table 3.

Table 3. H-plane Bend with Stepped Transition Dimensions

Parameter	Dimension
Angle, Each Step	19°
Step 1 Height	6.50 mm
Step 2 Height	5.16 mm
Step 3 Height	3.94 mm
Step 4 Height	3.18 mm
Waveguide Bend Radius	17.78 mm

The results of the simulation are shown in Figure 15. The optimization indicated that there were no substantial gains in return loss performance with a bend radius larger than 17.78 mm (0.7 inches), which achieves 29 dB return loss. This section fell short of meeting the 31 dB return loss goal.

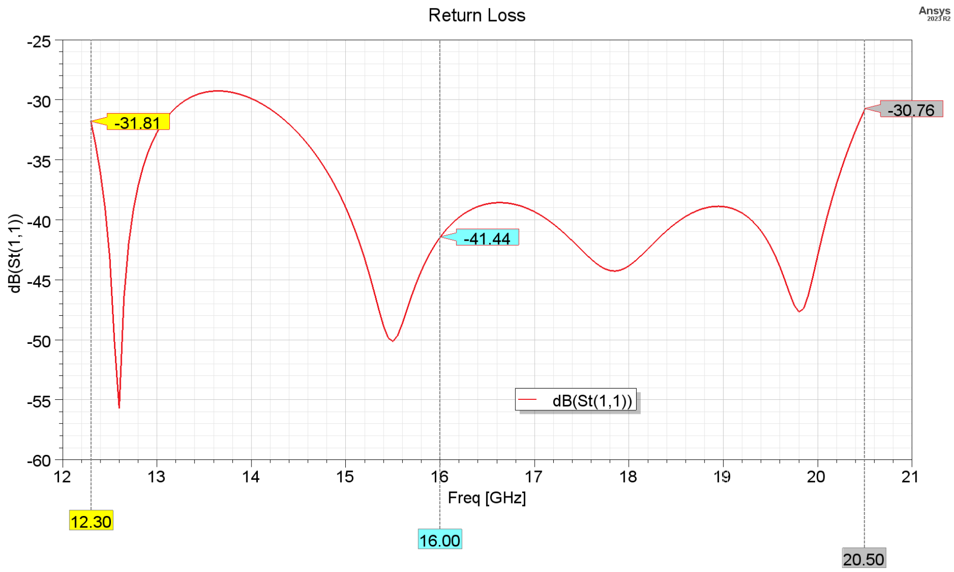


Figure 15. Simulated Return Loss S(1,1), H-plane Bend with Stepped Transition

3.2.2.4 Y-combiner

The Y-combiner from the X-band design was scaled to WR56.3. This model is shown in Figure 16.

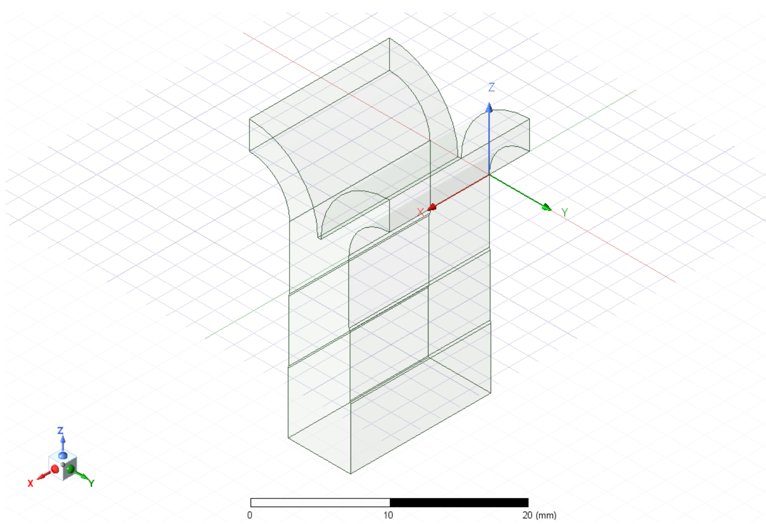


Figure 16. Y-combiner Model From Original X-band Design (Scaled)

This section met the performance goals without alteration; however, this Y-combiner does have some potential issues. For one, the output waveguide was scaled from WR90, which has an aspect ratio of 0.4, rather than 0.5 as is typical. Additionally, the very small steps used in the Y-combiner make fabrication problematic when scaled to higher frequencies. Thus, two alternative Y-combiners shown in Figure 17 were considered:

- *Version 1:* A small bend radius in the combiner arms, followed by a combined output with a linear taper to full height WR56.3 waveguide.
- *Version 2:* A large bend radius with a linear taper in each combiner arm, followed by a combined output directly to full height WR56.3 waveguide.

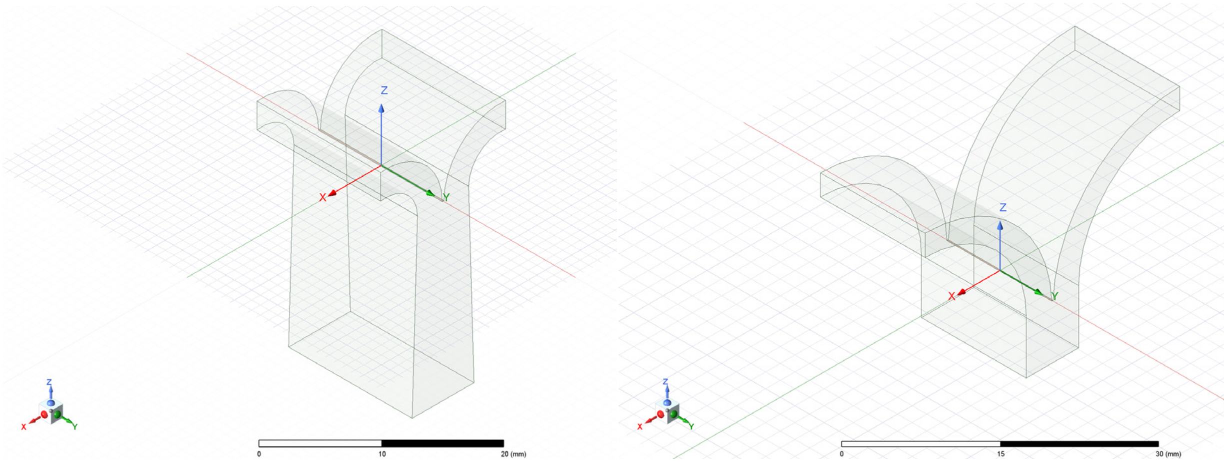


Figure 17. Alternative Y-combiners: (Left) Version 1 and (Right) Version 2

The simulation results comparing the three designs is shown in Figure 18. Each geometry achieved better than the 31 dB return loss goal on the output port, but the new Version 2 design appeared to be the best. For the full OMT, initial simulations were carried out with the scaled X-band combiner and final OMT simulations used the new Version 2 design.

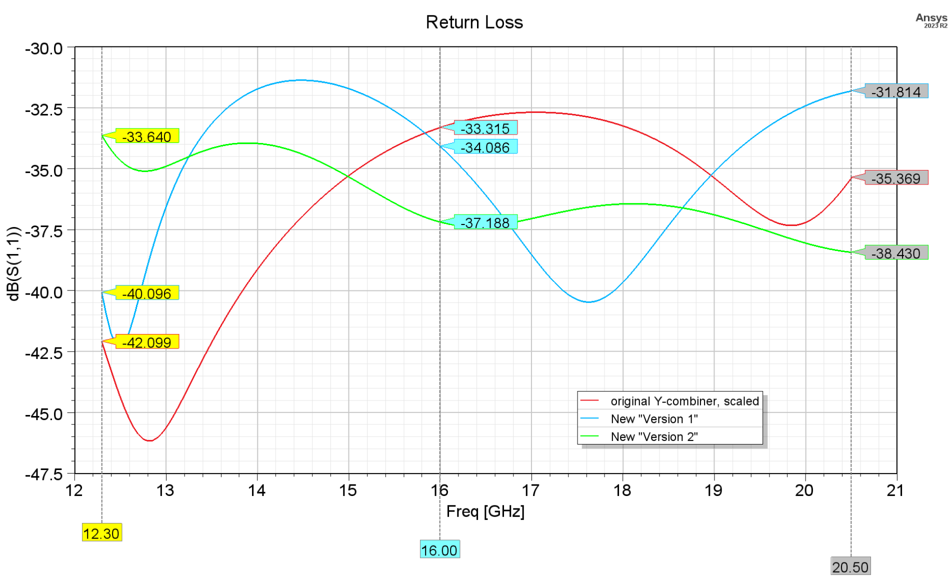


Figure 18. Simulated Output Return Loss S(1,1), Y-combiner Comparison

3.2.2.5 90-degree twist

A 90-degree twist is not technically required as part of the OMT, but may be necessary due to space constraints in the Band 3 cartridge. Thus, a 5 cm length 90-degree twist in WR56.3 was modeled initially in TICRA Champ, then exported to HFSS for simulation. Waveguide twists are available commercially for many standard waveguide sizes, but there may be some challenges in fabricating this part, either as a separate component, or integrated with the OMT assembly. The model is shown in Figure 19.

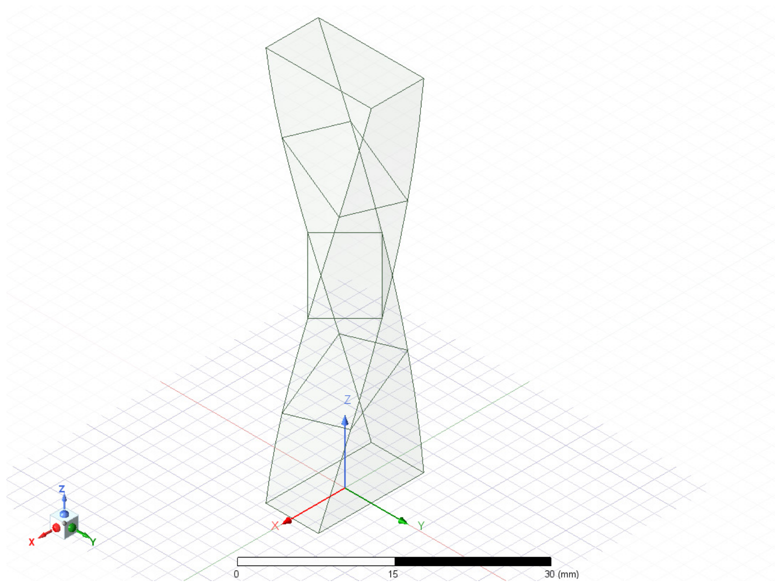


Figure 19. 90-degree Twist Model

The simulated return loss of the 5 cm long 90-degree twist is shown in Figure 20. Note that better than the original 31 dB return loss goal is achieved, but it is an additional section that was not originally accounted for. There is expected to be some small degradation to the overall OMT return loss when this section is added.

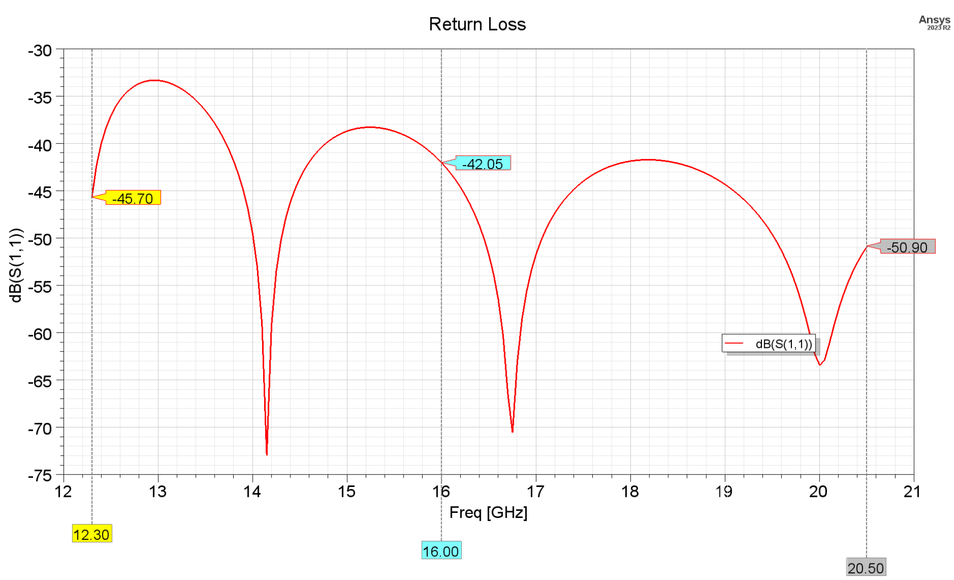


Figure 20. Simulated Return Loss S(1,1), 90-degree Twist

3.2.3 Full OMT Simulations

The four sections (turnstile junction, reduced height bend, bend with stepped transition, and scaled Y-combiner) were integrated into the full OMT. At the interconnection points between the turnstile and bend, and between the bends, variable lengths of rectangular waveguide were added. A model with zero length between the turnstile and bend is shown in Figure 21. Room temperature (RT) Aluminum 6061-T6 electrical conductivity 2.502 x 10^7 S/m is now set on the surfaces, with no roughness.

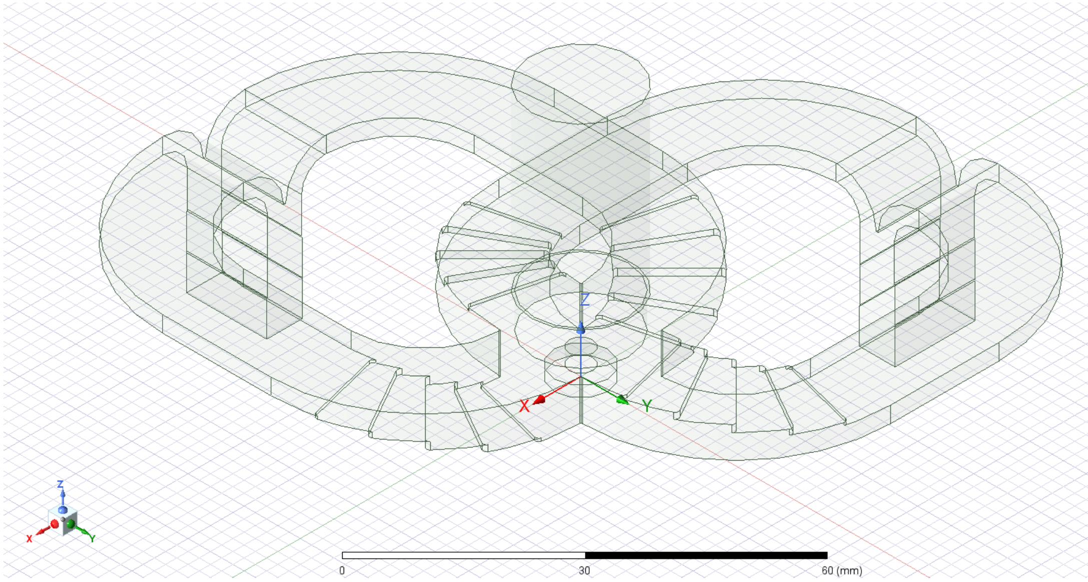


Figure 21. OMT Model (Zero-length Waveguide Between Turnstile and Bend)

In the initial simulations, with no added length between the turnstile and bend, it was found that there was degraded return loss, cross-polarization, and in-band resonances. Higher-order modes can be excited at the turnstile, and without a length of waveguide following the junction to absorb them, trapped mode resonances can manifest, evident by the appearance of sharp suckouts or spikes in the passband responses.

Accordingly, the OMT model was revised to include a section of straight rectangular waveguide between the turnstile junction and first bend. As a consequence, the same length rectangular waveguide is added between the reduced height smooth bend and Y-combiner. Additionally, for mechanical reasons, rectangular waveguide length also needs to be added between the stepped bend and reduced height smooth bends. A revised model is shown in Figure 22, with a 12.70 mm (0.5 inches) section between the turnstile and stepped bend and 20.32 mm (0.8 inches) between the stepped bend and smooth bend. Note that particular lengths of waveguide are shown, but the model is parameterized and these lengths are varied in simulation.

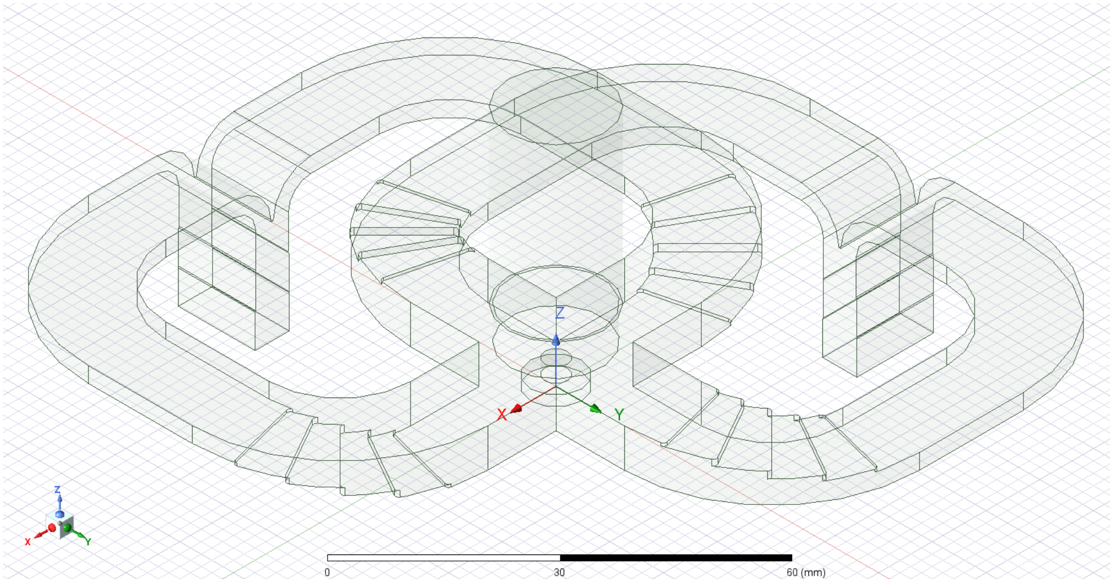


Figure 22. OMT model (12.70 mm Length Waveguide Between Turnstile and Bend)

As the length of the waveguide between the turnstile junction and first bend was swept, the analysis showed that performance improved with length. Simulation results for 2.54, 7.62, and 12.70 mm (0.1, 0.3, and 0.5 inches) are shown in Figure 23, Figure 24, and Figure 25 for return loss, transmission, and cross-polarization respectively. At 12.70 mm (0.5 inches), the worst-case input return loss was 23.7 dB, insertion loss was 0.11 dB, and cross-pol was 53.7 dB. Note that with this length, the trapped-mode resonances are now only evident in the cross-pol response, and at a very low level.

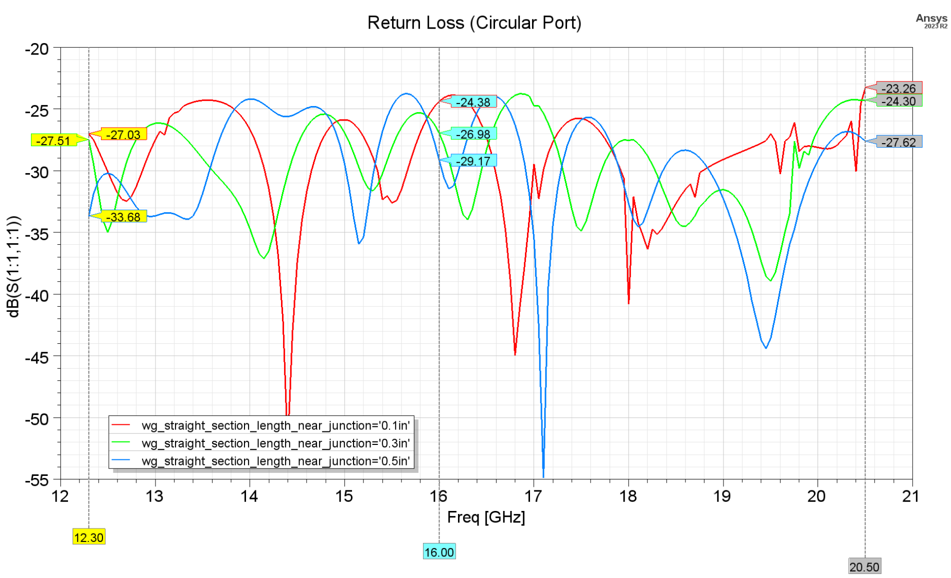


Figure 23. Simulated Return Loss S(1:1,1:1), Initial OMT with Swept Length of Rectangular Waveguide Section

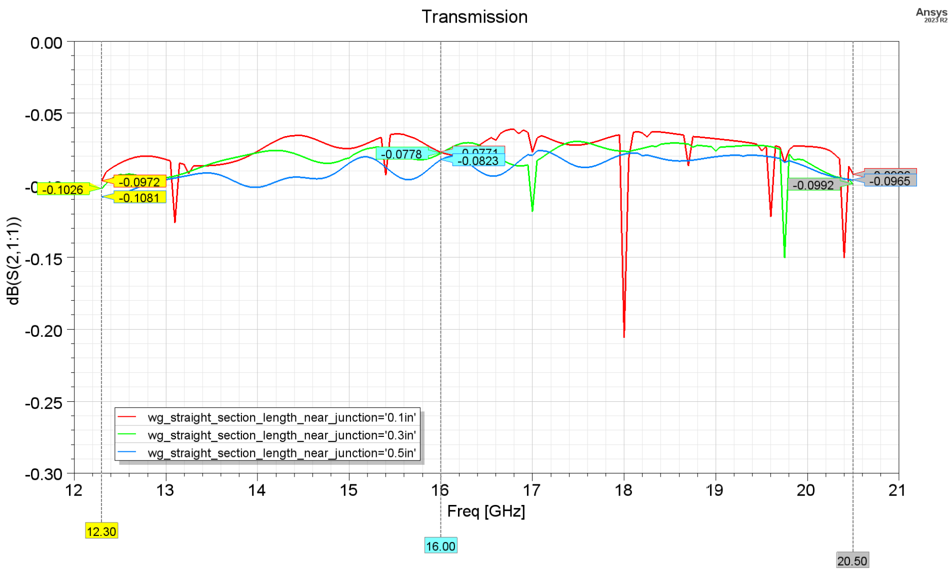


Figure 24. Simulated Transmission S(2,1:1), Initial OMT with Swept Length of Rectangular Waveguide Section

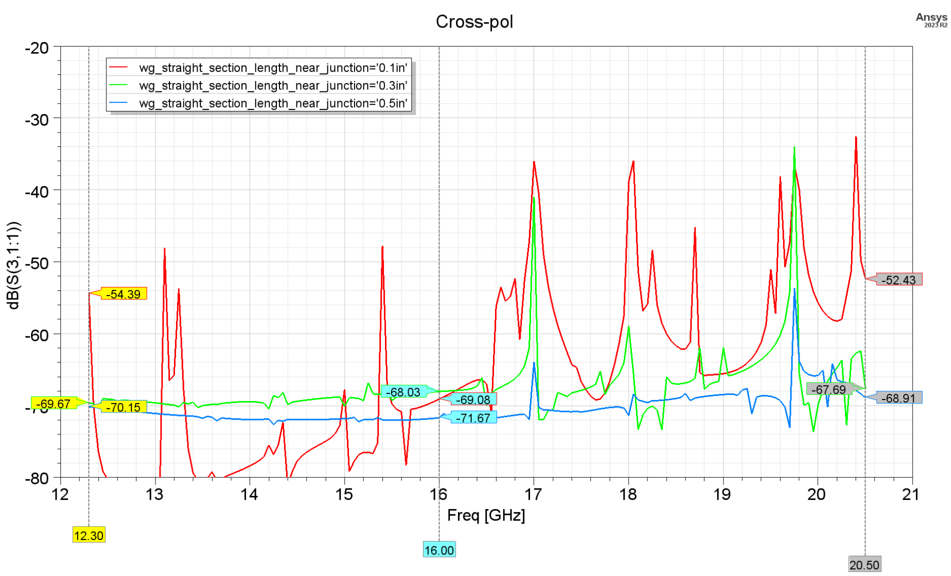


Figure 25. Simulated Cross-polarization S(3,1:1), Initial OMT with Swept Length of Rectangular Waveguide Section

When 12.70 mm extra length of waveguide is added near the turnstile, the extents of the component grow significantly, to about 67.31 mm (2.65 inches) radially from the center of the circular waveguide input. At this size there is less available volume for a physical housing around the waveguide structures, while maintaining the desired 3 mm clearance to the radiation shield. While it appears feasible, a separate mechanical design study is needed to determine whether there will be interference issues, assuming the current volume constraints in the Band 3 receiver cartridge

At the integrated OMT level, now using the new "Version 2" Y-combiner, another optimization is run with the turnstile and stepped bend as parameters. This is a longer simulation, but led to a small improvement in worst-case return loss from 23.3 to 24.0 dB as shown in Figure 26.

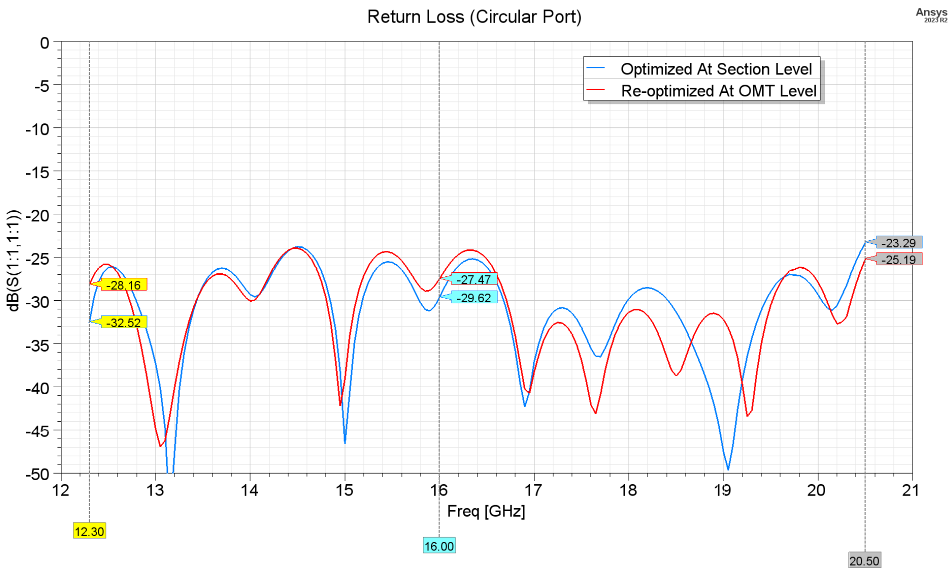


Figure 26. Simulated Return Loss S(1:1,1:1), Before and After Optimization on Integrated OMT model

A final consideration is the output port orientations on the OMT. This design, utilizing H-plane bends out of the turnstile, results in particular output port orientations. The current Band 3 cartridge has tight space constraints, and it was found that these output port orientations are less than optimal for fitting the remaining components in the receiver cascade. A 90-degree twist will put the output ports in a better orientation for this. The model with twists is shown in Figure 27.

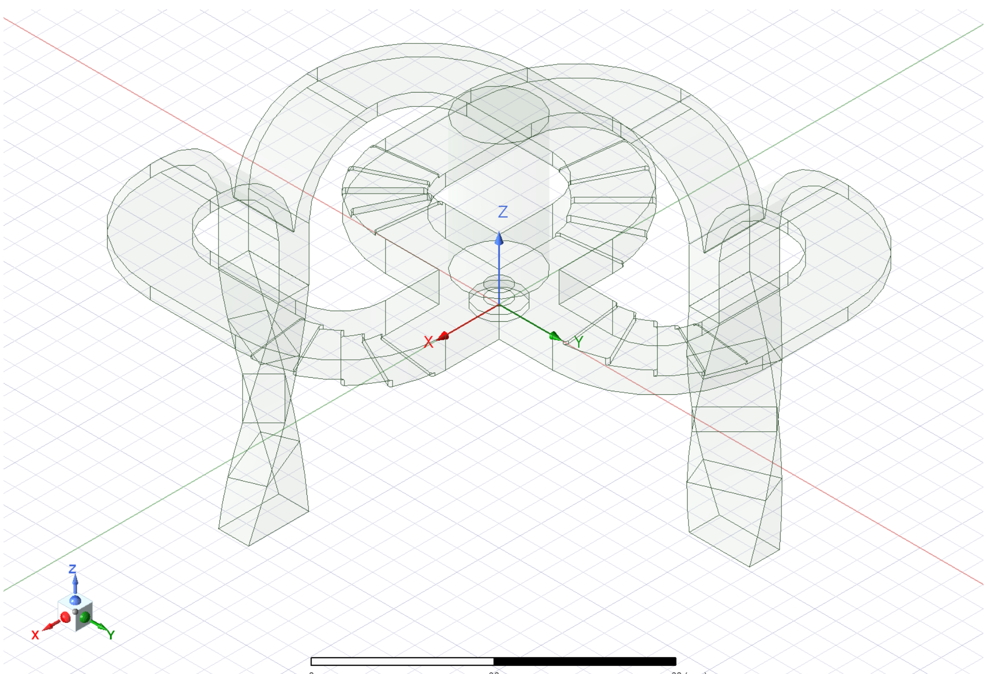


Figure 27. Turnstile OMT model with 90-degree twist on each output

Simulation results with and without the 90-degree twists for the full OMT return loss, transmission, and cross-polarization are shown in Figure 28, Figure 29, and Figure 30 respectively.

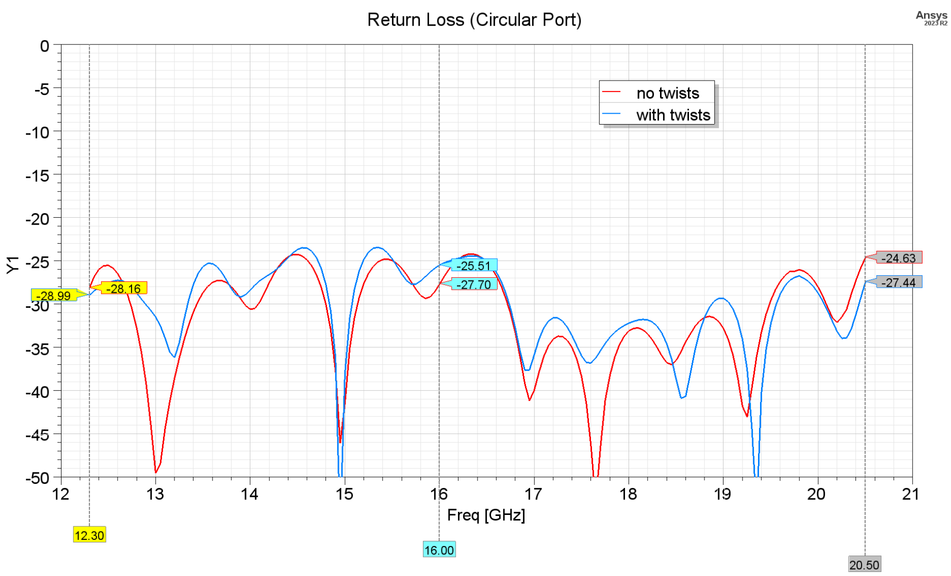


Figure 28. Simulated Return Loss S(1:1,1:1), Final OMT

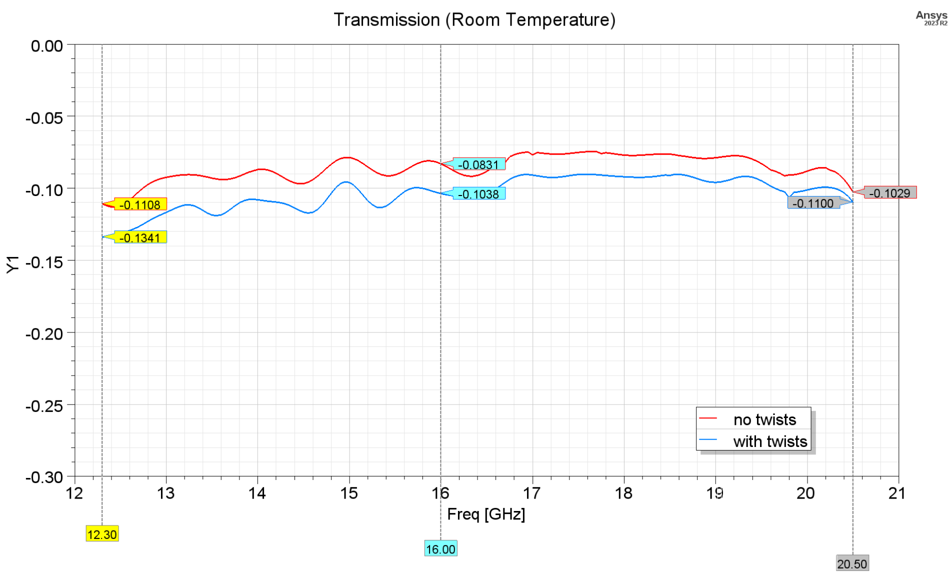


Figure 29. Simulated Transmission S(2,1:1), Final OMT

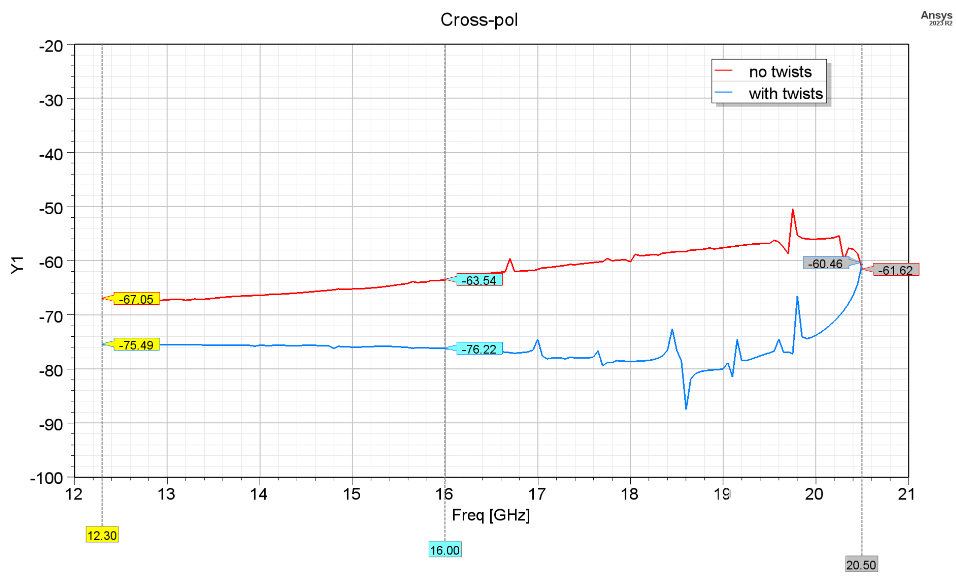


Figure 30. Simulated Cross-polarization S(3,1:1), Final OMT

At the actual operation temperature of 20 K, the electrical conductivity (σ) of Aluminum 6061 T6 will improve. The simulation value is expected to be roughly 1.67 times higher than room temperature, estimated from data in [7]. With this higher conductivity of 4.2 x 10^7 S/m, the max simulated insertion loss S(2:1,1) is a bit lower than at room temperature. With the 90-degree twists the max is 0.105 dB, which is very close to meeting the goal. Without twists, the design goal is met. The simulation result for transmission at 20 K is shown in Figure 31.

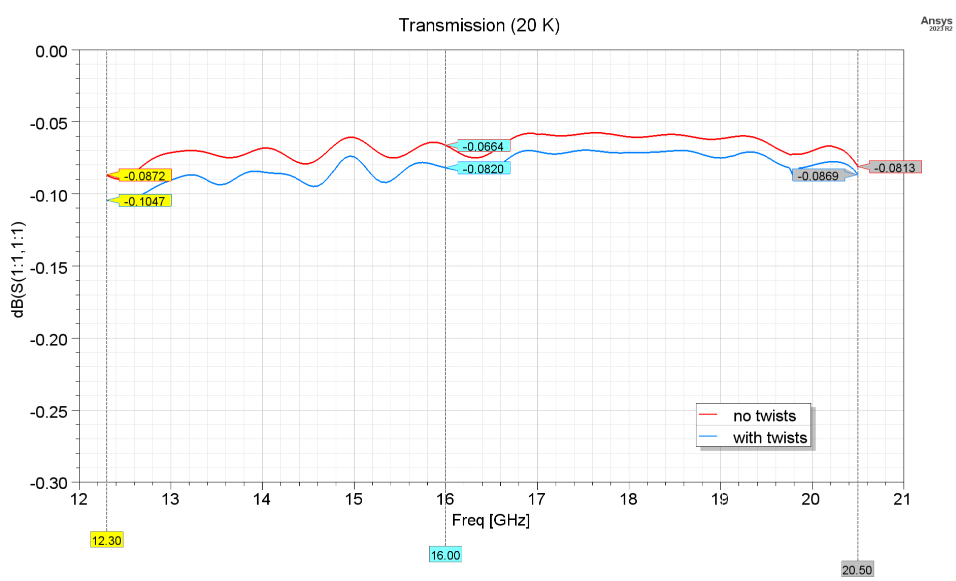


Figure 31. Simulated Transmission S(2,1:1), Final OMT, 20 K

3.2.4 Design Summary

The dimensions of the OMT before and after re-optimization at the top level are summarized in Table 4. Note that only the dimensions of the turnstile junction matching and stepped bend were allowed to vary.

Table 4. Dimensions of Turnstile and stepped bend after re-optimization

Parameter	Original Dimensions	Re-Optimized at OMT (no twists)
Lower Cylinder Diameter	10.35 mm	10.43 mm
Upper Cylinder Diameter	5.30 mm	5.42 mm
Lower Cylinder Height	1.47 mm	1.44 mm
Upper Cylinder Height	2.74 mm	2.67 mm
Angle, Each Step	19°	18.8°
Step 1 Height	6.50 mm	6.53 mm
Step 2 Height	5.16 mm	5.28 mm
Step 3 Height	3.94 mm	4.01 mm
Step 4 Height	3.18 mm	3.20 mm
Waveguide Bend Radius	17.78 mm	17.78 mm

A comparison of design target vs. simulation is shown in Table 5. Note that system cross polarization was not evaluated.

Table 5. OMT Simulation vs. Design Targets

Specification	Requirement or Target Value	This Design (with twists)
Bandwidth	12.3 – 20.5 GHz (1.67:1)	12.3 – 20.5 GHz (1.67:1)
Insertion Loss	0.1 dB, max (both polarizations)	0.136 dB (RT, $\sigma = 2.5\times10^{7}$ S/m) 0.105 dB (20 K, $\sigma = 4.2\times10^{7}$ S/m)
Return Loss	25 dB, min (all ports)	23.6 dB
System Cross Polarization*	30 dB, min	(TBD)
OMT Cross Polarization	40 dB, min	57 dB
In-band Trapped Mode Resonances	None	Negligible
Input Waveguide Port	Circular, 17.08 mm diameter	Circular, 17.08 mm diameter
Output Waveguide Ports	WR56.3 14.30 mm x 7.15 mm	WR56.3 14.30 mm x 7.15 mm

* System Cross Polarization includes the antenna optics, feed horn, and receiver

4 Conclusions

A turnstile OMT was designed for ngVLA Band 3 based on an existing NRAO X-band design. Simulated results nearly meet the design goals at nominal dimensions. The design is compact, fabrication could be relatively straightforward, and the paths for each polarization are identical, allowing for an easier conversion to circular polarization downstream in the correlator. Additional design or optimization on the turnstile junction and stepped bend may lead to further improvements in return loss and insertion loss.

With the added rectangular waveguide lengths to avoid trapped modes, the lateral extent of the OMT assembly is larger than originally expected, but it still appears that it will fit in the Band 3 cartridge volume.

90-degree twists on the outputs are not required, but may be advantageous for Band 3, where fitting all the receiver components in the allotted cartridge volume may be challenging. A detailed mechanical design of the OMT, fabrication, and testing would follow-on from this study, if merited.

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- S. Sturgis – Band 3 cartridge mechanical studies.
- W. Klahold – Information on the X-band OMT used in the GBT.
- G. Morris – Information about X-band OMT design assembly and machining.

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