Development of Feed Systems for Spacecraft Reflector Antennas

Ramesh Chandra Gupta, Khagindra K. Sood, Rajeev Jyoti

Abstract – **This paper presents the design and development of new feed horn for spacecraft reflector antenna. Predicted RF performances of the feed systems agree with respective measured result with small deviation. Some issues related to C-band feed system such as impact of TM_{01} mode on cross-polarization and its suppression employing a TM_{01} mode-suppressor section between horn and ortho-mode transducer (OMT), impact of horn outer structure such as feed-strut interface on RF performance are investigated in this contribution. The outer feed structure (such as feed-struts interface) degrades cross-polar level of the feed. A compact and light-weight Ku-band plane-walled multi-mode horn with good RF performance has been devised and developed by judicious combination of stepped section preceded by 4-node spline-profiled section.**

Keywords – **Horn antenna, satellite antenna, low-scattering, prime-focus reflector.**

I. Introduction

The core requirements of feed system for space-borne reflector antenna are: rotationally symmetric radiation pattern, a high degree of polarization-purity, minimized volumetric size and reduced aperture cross-sectional area of the feed to reduce blockage and scattering due to the ray bundle reflected from the reflector, light weight. The Feed system also needs specific requirements, such as low side lobe level, low ohmic loss, and high aperture efficiency depending upon nature of space-mission. By judicious design of the internal profile of the horn, the core and specific radiation properties can be achieved. Choked circular horn [1]-[2], SCRIMP horn [3], dual-mode horn [4], plane-walled profiled horns [5]-[6] are widely used as primary feeds for prime-focus/offset single shell reflector antenna for spacecraft and ground station applications due to their fabrication simplicity, easy mounting with antenna and excellent radiation characteristics. For prime focus reflector antenna design challenges for feed system are high RF performance and low feed scattering since feed is kept at focal point; which is relatively high field intensity zone. For offset reflector antenna, feed scattering is not much prominent because feed is place with sufficient offset clearance with reflector optics; however compact, light-weight and high RF performance feed are essential requirement.

This paper reports the design, analysis and development of two feed systems that can be employed to illuminate spacecraft reflector antenna. The first feed system is designed for dual linear-polarized 0.7m prime-focus reflector antenna (focal length=0.3m) operating at 6.7-7 GHz (upper-extended C-Rx band). The dual linear-polarized C-Rx/Rx feed system consists of choked horn, mode suppressor and slot-coupled stepped rectangular OMT. First of all, the horn antenna and OMT are designed and analysed in modular approach. Then C-band feed system is optimized in integrated configuration to achieve specified RF performance with mechanical requirements and constraints. In integrated feed optimization approach, TM_{01}-mode in circular waveguide is sufficiently suppressed to get good RF performance. It is found that the outer-body constitution of the horn (strut-feed interface or bracket) degrades cross-polarization of the feed. Second feed is designed for single linear-polarized extended Ku-band 2.0m offset reflector antenna (focal length 2.4m and offset clearance 245mm). The Ku-band horn, named as ‘stepped-spline-profiled horn (SSPH); is plane-walled multi-mode horn having smaller volume and light-weight. The Ku-band SSPH horn has been designed, optimized and developed by judicious combination of stepped section preceded by spline-profiled section to get specified RF performance. Though the feed systems are designed for C- and Ku-band respectively, the underlying concepts are generic in nature and may be readily tailored to other frequencies.

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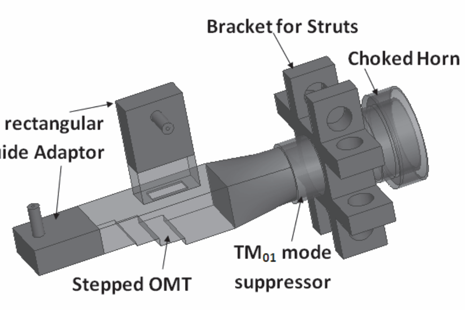
II. Design and Development of Feed System

Figs. 1 and 2 present geometry and photograph of feed horn developed at C- and Ku-band as a feeds for prime-focus and offset reflector antennas, respectively. The horns are analyzed and optimized using mode matching technique based software Ticra CHAMP and built-in ‘Genetic Algorithm’ optimization technique. The feed components such as ortho-mode transducer (OMT) and TM_{01}-mode-suppressor are analyzed using mode-matching technique based Mician μWave wizard and finite element method based software HFSS. “Evolution’ optimization technique of Mician is used to optimize electrical performance of the feed components. The feed system is manufactured by using aluminum alloy 6061T6 with aid of computerized numerically controlled (CNC) turning machine and other mechanical fabrication machines. The subsequent subsections articulate design and critical issues of different type of feed systems and its components.

A. Design of C-band Feed System for Prime Focus Reflector Antenna

There is the requirement of a dual linear-polarized feed as a constituent of an unshaped 0.7m prime focus reflector antenna (focal length=300mm) at Upper-Extended-C Receive Band (6.7-7.0 GHz) for satellite communication, which must be very compact apart from providing a high RF performance (such as better return loss, low cross-polar level) to ensure higher XPD (cross-polarization discrimination) and better

EOC gain at antenna system level over wide land mass coverage (in present case India). The design challenges and complexity imposed on the feed system are good primary RF performance and low feed-scattering with mechanical realization constraints. The higher order interaction between feed-reflector, feed-struts and struts-reflector is taken place in case of prime-focus reflector antenna which degrades edge of coverage (EoC) gain and XPD of the reflector antenna. As, we know, prime focus reflector antenna converges parallel ray impinging on its parabolic surface at its focal point where feed is situated. The feed repulses these converged rays hitting on its outer body which degrades cross-polarization of prime-focus reflector antenna. By reducing aperture cross-section of primary feed, the degradation in secondary cross-polarization pattern can be minimized. Also, side arm of OMT perturbs secondary rays and degrades XPD of the prime-focus reflector antenna. Keeping these aspects in mind, a C-Rx feed system has been devised to have the smallest possible aperture cross-section and a reduced side arm length of OMT. The bracket for struts (i.e. strut-feed interface) is designed similar to hash-shape having cylindrical holes in its wall. The hash-shed feed-strut interface supports feed system at focal point of reflector antenna with the help of quadrupod struts lying in direction of polarization. These holes reduce weight and echo area of the feed systems. The interface is kept much behind from horn aperture so that primary pattern of feed degraded least. Thus feed scattering for secondary rays is reduced. As shown in Figure 1, the C-Rx feed system comprises single choked horn, slot-coupled stepped rectangular waveguide ortho-mode transducer (OMT), circular-to-rectangular smooth transition, mode suppressor and coax-to-rectangular waveguide adapters. Radiall® TNC Female coaxial connector and gold-plated aluminium alloy 6061-T6 cylindrical probe have been used in the top-launching adapters. The probes are gold-plated so that it can be soldered with TNC connectors. The choked horn is designed for edge taper -10.8 dB to -12.3 dB at ±60.5°. The OMT is designed by using guideline given in [7].The input radius of the horn is so selected that only TE_{11} symmetric mode can propagate at the throat at the operating frequency band. The aperture radius of the horn is chosen to give required beamwidth at the band. Thus, the axial distance (0.04λ at centre frequency) and width of slot controls edge taper of the radiation pattern. The choke is chosen so that the slot is about 0.11λ breadth and 0.29λ deep at the centre frequency. The thickness of teeth is kept 1.5mm. The length of the feed is kept equal to the maximum allowable length by design constraint. Depth of slot controls cross-polarization of the pattern. Dimensions of direct and coupled ports of OMT are chosen so that TE_{10} mode can propagate with good impedance matches. In present case, full height WR-137 (34.8mm×15.8mm) waveguide is found appropriate for the OMT. The common port of the OMT is configured rectangular (34.8mm×26.5mm) instead of usual square cross-section configuration [7].The broad dimension of the rectangular common port is kept equal to the broad dimension of rectangular waveguide of direct port (Full Height WR-137).The developed C-band feed system has diameter 57.6mm (~1.3λ at lower frequency) and total length 232.6 mm (~5.2λ at lower frequency). The height and width of three



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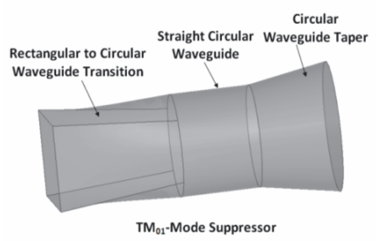

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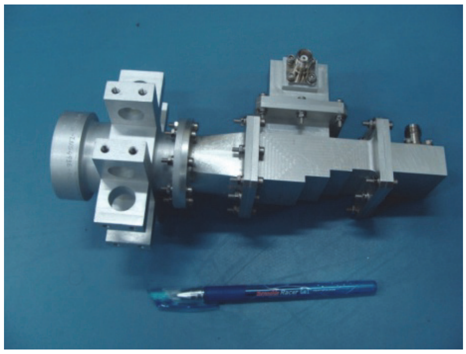

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Fig. 1. C-Rx Feed System (a) Schematic Diagram, (b) Enlarged View of TM_{01} Mode Suppressor and (c) Photograph of fabricated feed

asymmetric rectangular step sections between direct port and common port are optimized that act as virtual short for the wave input from coupled port and reflected to common port thus good direct port to coupled port isolation is achieved. The dimensions of longitudinal slot are optimized so that maximum power is coupled between common port and coupled port. When the OMT is attached with horn antenna with the help of the transition, TM_{01} mode is generated due to the asymmetric placement of the slot in OMT and rectangular cross-section of OMT common port. This TM_{01} mode deteriorates cross-polar level of horn antenna (Figure-5). This TM_{01} mode is suppressed below -39 dB by utilizing a “TM_{01}-mode suppression technique” (Fig. 1(b)) which consists of a rectangular to circular waveguide transition and a straight circular waveguide followed by circular waveguide taper. The radius of straight circular waveguide is chosen such that it does not support to propagate TM_{01} mode for operating frequency band. The length of rectangular to circular waveguide transition, radius and length of straight circular waveguide and length of circular taper are judiciously optimized so that TM_{01} mode becomes evanescent in feed system and TM_{01} mode is suppressed below to ~ -39 dB and better cross-polar level along with better return loss are achieved at feed level. Simultaneously, very low Port to port isolation is achieved. In present case TM_{01}-mode suppressor is designed for 4.4% bandwidth, but it can be applied and optimized for higher bandwidth feed system. At outer surface of feed system, a bracket is provided for interfacing four struts behind the aperture; as shown in Fig. 1. Analysed ohmic losses of the C-band feed for aluminium alloy are -0.09 to -0.095 dB for coupled port channel and -0.10 to -0.170 dB for direct port channel. Analysed phase centre for ±60.5° is at horn aperture (0 mm). The weight of the feed unit is 540 gm. The measured XPD of prime-focus reflector antenna is better than -30 dB over India coverage; establish the successful design of the feed system.

B. Design of Ku-band Horn for Offset Reflector Antenna

An innovative 'Stepped spline-profiled Horn (SSPH)'for specified RF performance at Ext-Ku-Transmit band (10.95-11.7 GHz) has been devised by integration of multiple stepped section and a spline-profiled section (Figure 2). The SSPH horn is designed for edge taper -11 dB to -17 dB at ±26°. The stepped section of the horn acts as a mode converter. Input waveguide radius of the horn is selected such that only fundamental mode; TE_{11} can propagate at input waveguide of the horn. The input radius of the horn is 10mm. Three steps provide wider bandwidth for good return loss and lower cross-polar level for present case. More number of steps can provide much wider bandwidth for specified RF performance. The horn is excited with TE_{11} mode, the slope discontinuity of horn flare generates higher order modes. By properly profiling the longitudinal horn flare, we can control amplitude and phase of higher order mode at the aperture of the horn to achieve expected RF performance. For this reason, 4-node spline profile section is chosen for Ku-Tx horn antenna apart from stepped mode generator. Spline-profiled section controls beamwidth and gain of the horn. The radius and length of the stepped section and parameters of 4-node spline-profiled section are optimized to get low cross-polar level, good return loss and desired illumination taper at reflector edge over Extended-Ku band. Spline-profile helps to reduce length of the horn. The horn radius of spline-profiled section, *r*, is approximated by the following best fit polynomial function in term of the distance along the length of the horn, z, as:

$$(z) = -2.084\,z^3 - 0.903\,z^2 + 10.987\,z + 29.627\,, \qquad (1)$$

where *z* is in mm originated from beginning of spline-profiled section after stepped section. Input radius of spline section is 18.6mm and length is 60mm. Aperture radius of the horn is 35.4mm. The developed Ku-band feed system has diameter 80mm and total length 92.3 mm. This horn is a very light weight in comparison to corrugated horn. The feed is intended for mono linear-polarized for 2.0m offset reflector antenna (focal length 2.4m and offset clearance 245mm). Smooth-walled circular to rectangular waveguide transition (WR-75) is designed to connect horn antenna with coax to waveguide adapter. The coax (SMA) to rectangular waveguide adapter excite TE_{11} mode in SSPH horn antenna. The transition is optimized with objective good return loss. The optimized length of the transition is 40mm. Analysed ohmic losses of the Ku-band feed for aluminium alloy are -0.02 to -0.04 dB for direct port channel. Analysed phase centre for ±26° is ~ 28.4 mm inside the horn aperture. Total weight of the feed unit including transition and adapter is 480 gm.

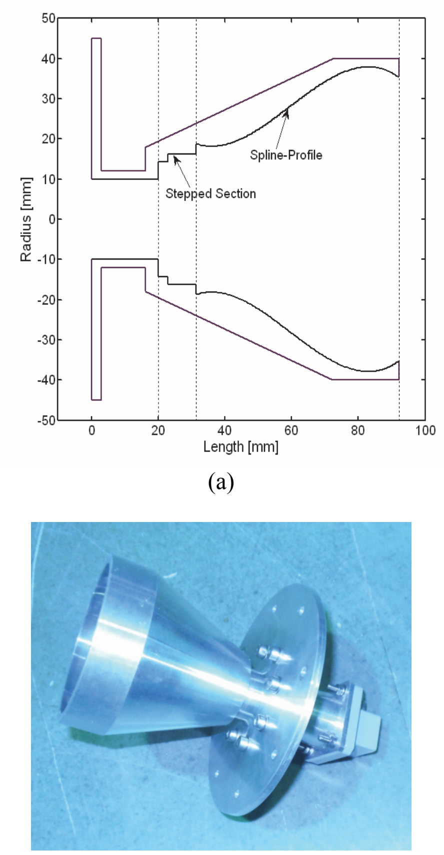


Fig. 2. Ku-Band Stepped Spline-profiled Horn: (a) Schematic Geometry and (b) Photograph of fabricated horn

III. RESULTS AND DISCUSSION

The return loss of the feed systems is measured using R&S ZVK-40 vector network analyzer (VNA). The radiation pattern is measured in SAC-ISRO anechoic chamber. Following subsections describe measured/predicted results and significant aspects of the feed systems.

A. Results of C-Rx/Rx Feed System for Prime Focus Reflector

Fig. 3 compares predicted and measured return losses at direct and coupled port and port to port isolation for upper-extended C-Band Feed Unit. Measured and predicted results are in agreement with small difference. The deviations between measured and predicted return loss/port to port isolation may be due to calibration reference of VNA is at coaxial port instead of waveguide port, imperfect assembly, measurement uncertainty, scattering etc.

Fig. 4 shows measured and predicted co-polar and cross-polar radiation patterns in D-plane of dual-polarized upper-extended C-Band feed system with TM_{01}-Mode Suppressor for direct and coupled ports excitations at 6.7 GHz and 7 GHz. The results have agreement with small deviation. The small deviation between measured and predicted pattern results may be due to measurement uncertainty, imperfect assembly and integration. For medium gain antenna; scattering from nearby structure such as mounting plate of the feed system, supporting tower [8], etc are also responsible for these deviation.

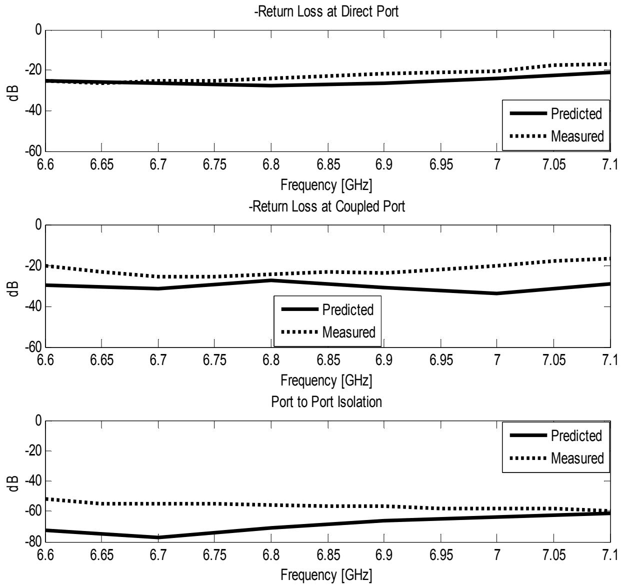


Fig. 3. Return losses at direct and coupled port and port to port isolation of C-Rx Feed System

Magnitudes of TM_{01} mode for C-Rx Feed System with and without TM_{01} mode suppressor are illustrated in Fig. 5(a). Impacts of TM_{01} mode excitation in OMT and effect of bracket for struts on cross-polar level are depicted in Figs 5(b) and 5(c) for direct and coupled port excitations, respectively. The feed system without TM_{01} mode compensation (that is the feed comprising only horn, OMT and rectangular to circular waveguide transition) has serious impact on cross-polar level in 45°-plane at higher frequency for direct port chain. It generates cross-polar in 90°-plane also. TM_{01} mode has negligible impact on cross-polar level over the frequency band for coupled port chain. Feed system with TM_{01} mode compensating technique; maintain good cross-polar level over the band and for both polarizations. The bracket for struts degrades cross-polar level for both polarizations over the band. The field at feed-strut interface are added or subtracted with feed radiation pattern and alters the resultant radiation pattern.

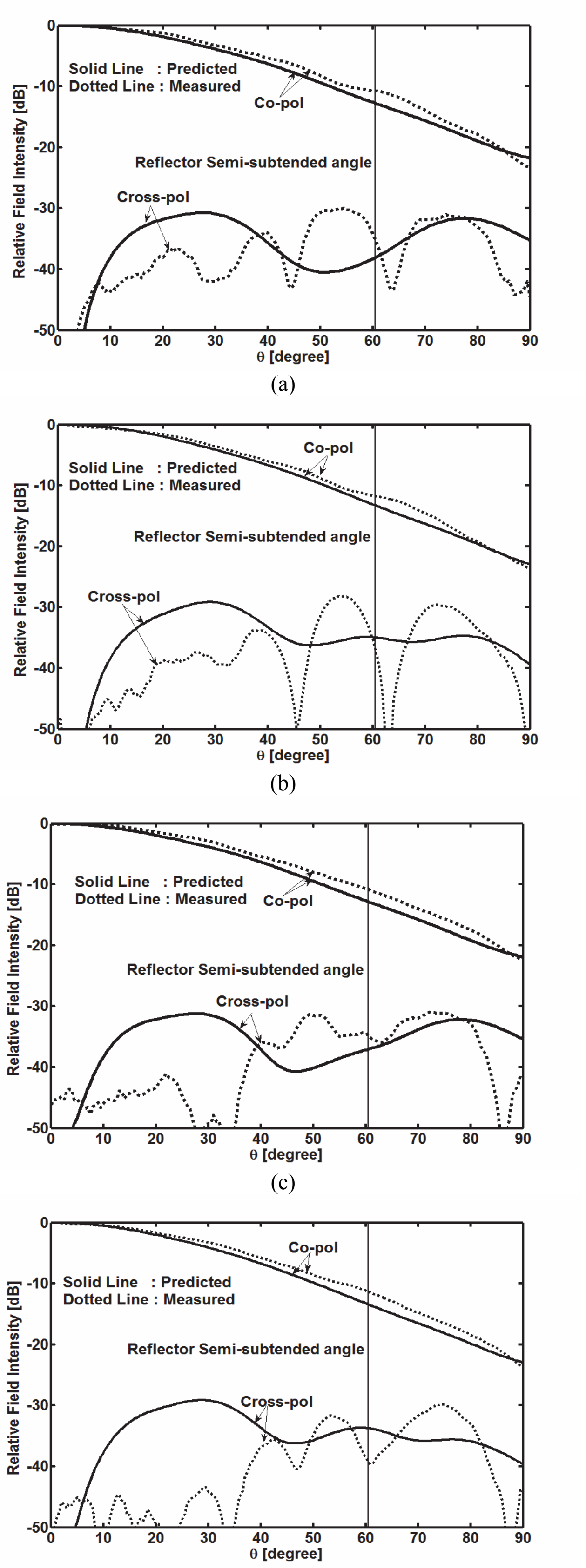
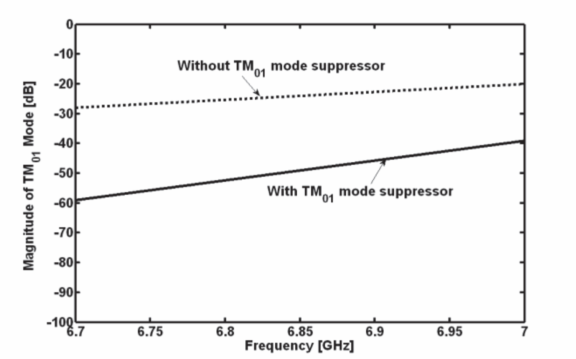


Fig. 4. Radiation Pattern in 45°-plane of C-Rx Feed System for excitation of (a) coupled port (6.7 GHz), (b) coupled port (7 GHz), (c) direct port (6.7 GHz) and (d) direct port (7 GHz)



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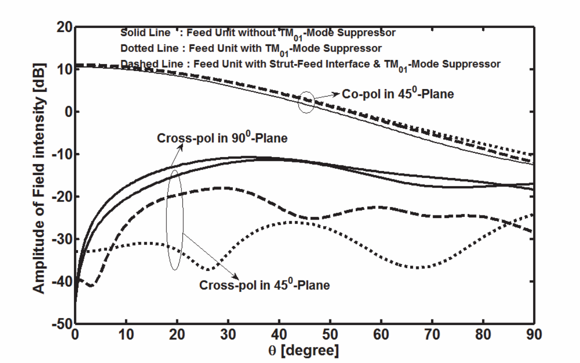

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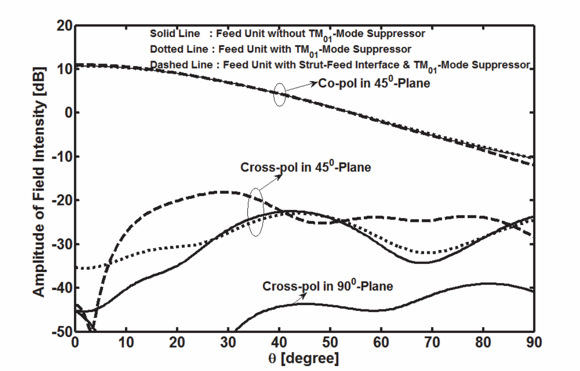

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Fig. 5. C-RxFeed System with/without TM_{01} mode suppressor & struts bracket: (a) Magnitude of TM_{01} mode, (b) radiation pattern at 7 GHz for direct port and (c) radiation pattern at 7 GHz for coupled port excitation

The sub-efficiencies using equations given in [8] of the C-Rx feed horn are estimated and given in Table I for 0.7m prime focus reflector antenna (focal length=300 mm, semi-subtended angle=60.5°).

TABLE 1
SUB-EFFICIENCIES OF THE C-RX FEED SYSTEM

Sub-efficiencies	Frequency	
	6.7 GHz	7.0 GHz
Illumination Efficiency	80.18 %	78.65 %
Spill-over Efficiency	91.55 %	92.66 %
Phase Efficiency	99.99 %	99.99 %
Polarization Efficiency	99.96 %	99.93 %
Center blockage Efficiency	97.49 %	97.41 %
Total Efficiency	71.52 %	70.94 %

B. Results of Ku-band Horn for Offset Reflector Antenna

Predicted and measured return losses at input port are compared in Fig. 6 and have good agreement for Ku-Band Stepped-Spline-profiled Horn (SSPH). The difference between the two results may be due to calibration reference of VNA is at coaxial port instead of waveguide port and imperfect assembly. Measured return loss is better than 17 dB over the operating frequency band.

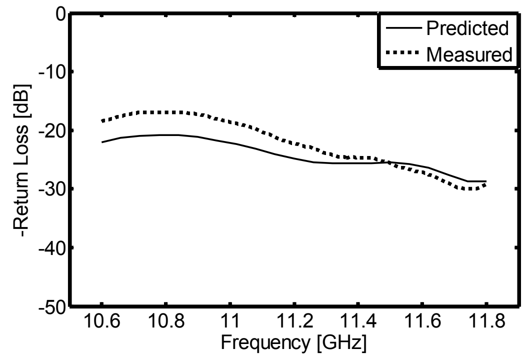
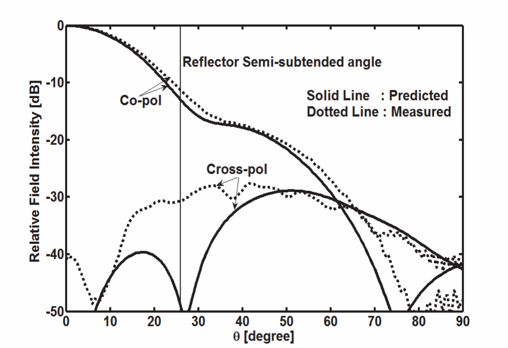
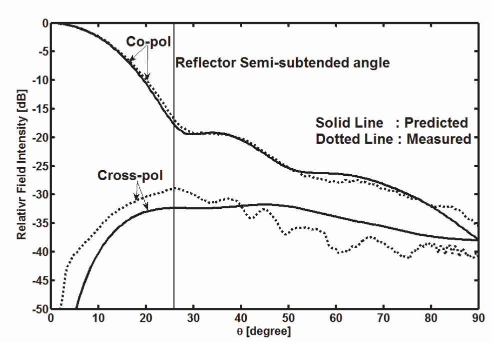


Fig. 6. Return loss of Ku-TxStepped spline-profiled horn (SSPH)

Fig. 7 shows measured and predicted co-polar and cross-polar (in 45°-plane) radiation patterns for Ku-Tx Stepped-Spline-profiled Horn (SSPH) at 10.95 GHz and 11.7 GHz. The predicted and measured patterns have agreement with each other. The small deviation between measured and predicted patterns may be due to measurement uncertainty, imperfect assembly and integration. Spurious noise and scattering from nearby structure such as mounting plate of the feed system, supporting arm and tower [9] are also responsible for these deviations.



(a)



(b)

Fig. 7. Radiation pattern of Ku-Tx stepped spline-profiled horn (SSPH) at (a) 10.95 GHz and (b) 11.7 GHz in D-plane

IV. CONCLUSION

A C-Rx/Rx feed system with good RF performance and low scattering for prime focus reflector antenna at 6.7-7 GHz is realised and characterised. The TM_{01}-mode is carefully controlled to get good RF performance along with mechanical constraints. Struts bracket at outer body of the feed unit degrades cross-polarization of the feed for both polarizations. Further, a plane-walled horn at Ku-Txband, namely 'stepped-spline-profiled horn (SSPH)' is also developed for offset reflector antenna and good measured RF performance is achieved. Internal cavity of the SSPH horn; consists of stepped section preceded by spline-profiled section. Both the feed can be designed for other frequency band and higher RF performance as a feed for spacecraft reflector antenna. The presented feed systems provide low-scattering and light-weight feed solution for reflector antenna.

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