ATA Memo #48

Proposed Modifications of the ATA Feed Tip

G. Engargiola

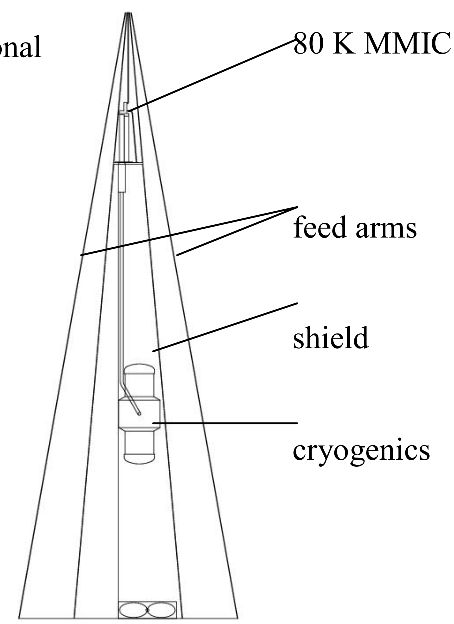
June 4, 2002

The log-periodic design of the ATA front-end is currently optimized for minimum noise temperature. Unfortunately, it is difficult to fabricate, especially at the high frequency end. Also, the cryostat incorporates taperline baluns which may produce sharp RF resonances. In this memo I discuss options for modifying the ATA feed by translating the dewar signal feedthrough 2″. back from the feed tip, thereby increasing the width of the vacuum bulkhead from 0.150″ to nearly 0.495″. This greatly facilitates the manufacture of the front-end dewar. In this memo, we consider the effects of linking the feed tip to the dewar signal feedthrough with either 210 Ω twin leads or suitably miniaturized taperline baluns at ambient temperature. Relocating the baluns outside the cryostat mitigates the problem of RF resonances, simplifies the electrical feedthrough into the dewar, and reduces the thermal load on the cryogenic work surface. These proposed modifications make it feasible to extend the high frequency limit of the feed from 11 to 22 GHz.

I. Introduction

The present ATA feed design incorporates a conducting pyramidal shield with a 10° opening angle inside orthogonal non-planar log-periodic antennas with 20° opening angles. (Figure 1)

Figure 1 – Cross sectional view of the ATA feed.

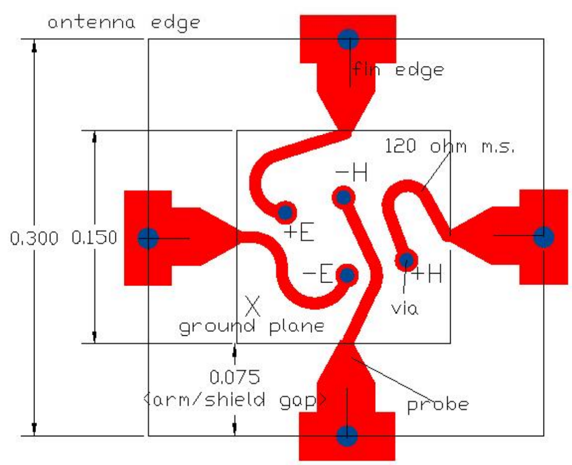


The antenna arm structure has been optimized for low SWR (1.2), high gain (12 dB), and low cross polarization coupling (-26 dB). The input impedance at the antenna arm terminals is 210 Ω. The inner feed shield is the outer shell of a cryostat containing a pulse tube refrigerator which cools transmission lines, MMIC amplifiers, and baluns to 80 K.

The LP antenna and shield are truncated 0.831″ from a common vanishing point on a shared axis to insure small variations of the impedance and beam pattern up to 11.2 GHz. A 2 × 2 array of 0.010″ wires spaced ~0.030″ × 0.060″ are threaded into the truncated tip of the shield through hermetic seals in the vacuum bulkhead, 0.150″ wide. The 4-wire array conducts balanced signals with cross-coupling < -30 dB. Near the feed tip, the average clearance of wires from the dewar wall is less than 0.040″, making fabrication tolerances here inconveniently small, leaving highly limited space for thermal insulation layers.

This cryostat geometry, while difficult to construct, yields an optimal noise temperature for the front-end by minimizing the length of the signal path in ambient temperature medium. Until recently, we quoted 12 K as the noise temperature contribution from ambient temperature conductors, approximately the same as the noise temperature contribution from the cryogenic MMIC amplifiers. The first method-of-moment calculations for an early feed prototype were performed with Zeland Software's IE3D at the highest gridding resolution practical for us at the time (12 cells/wavelength). These implied an ohmic loss in the antenna arms as high as 4%. More recent simulations of the ATA feed arms with higher resolution (20 cells/wavelength) predict 2.1% ohmic loss.

Figure 2 – connection PC board links the antenna terminals for two polarization channels to twin leads in the dewar.

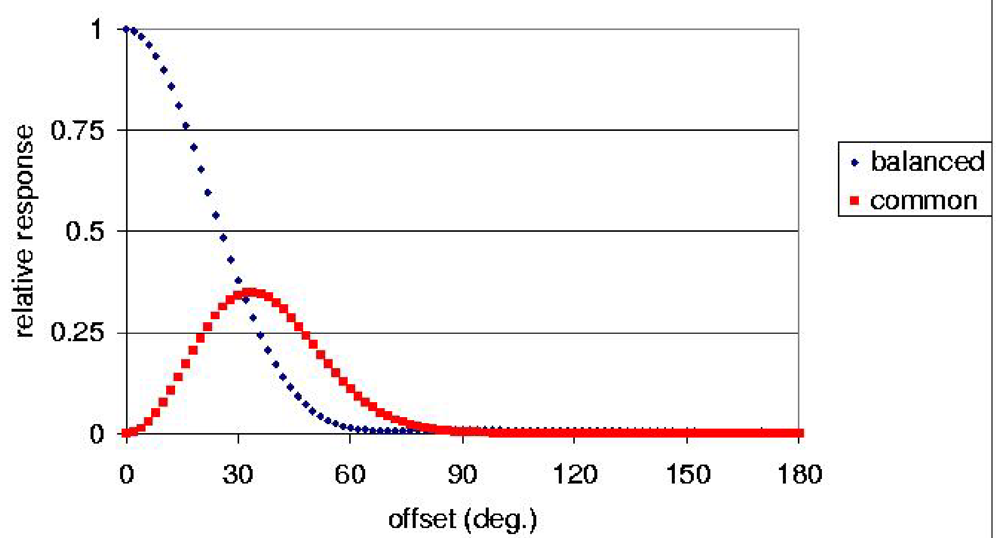


Signals from antenna terminals are connected to twin leads in the dewar with a 0.300″ × 0.300″ plastic PC board (Figure 2). Its 0.150″ × 0.150″ ground plane is flush, and electrically continuous, with the tip of the shield. Each antenna terminal is jumpered by a printed inductive probe to 105 Ω microstrip line on the truncated shield tip. The tightly meandering microstrip lines are terminated by vias which thread through holes in the PC board ground plane and pierce a glass pressure seal, connecting to the 4-wire array in the dewar. This allows signals from orthogonal polarizations to enter the shield on well isolated two-wire transmission lines. In the first iteration of the PC board, the traces – all the same length to assure phase balance – were 0.300″. Loss due to the board was estimated to be 1%. However, a revision of the design reduced their lengths by 0.200″. Hence, we now estimate loss in the connection PC board to be 0.3%.

A revised quote for the combined noise temperature of the antenna and connection PC board is 7 K. The reduction is roughly equivalent to the noise temperature of a 2″ section of 210 Ω twin lead at 295 K.

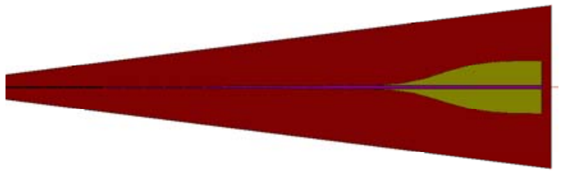
Besides the fabrication challenges, another much discussed aspect of the frontend design is the installation inside the cryostat of a taperline balun cooled to 80 K. The walls of the cryostat surrounding the suspended substrate striplines of the balun could permit the propagation of coaxial transmission line modes. These couple to antenna sidelobes arising from common mode excitation of the antenna terminals, which raise the noise temperature of the front-end. (The azimuthally averaged profiles shown below in Figure 3 are normalized to total power.)

Figure 3 Beam profiles for balanced and common mode excitation of antenna terminals



Another point of concern, first raised by S Weinreb, is that by its nature the taperline balun can have spurious resonances when its length is some multiple of a half-wavelength of the applied signal. To the extent that the balun can be modeled as uniform coupled 10″ lines with one lead terminated to ground through a small resistance, linear simulations predict identical high-Q resonances at 500 MHz intervals.

Both points were investigated in full wave simulation for a 10″ taperline balun on plastic substrate placed inside a square pyramidal shield (Figure 4). IE3D ver 9.0 can quickly locate narrow resonances in a broadband RF circuit using an adaptive fitting routine (AIF) for computing S parameters.



10” balun in conductive shield

Figure 4 – a taperline balun fabricated on Cuflon ($\varepsilon_r = 2.0$) inside a section of the pyramidal shield.

Simulations predict that when the shielded balun is excited at the twin lead end with an odd mode, a series of high-Q resonances occur at frequency intervals of 600 MHz. In particular, near complete reflection occurs at 0.985 GHz, 1.570 GHz, 2.115 GHz, 2.610 GHz, etc. The simulation must be gridded at 15 cells/wavelength and frequencies must be sampled at 5 MHz intervals to detect these resonances which have a 10 dB width of < 20 MHz (Figure 5).

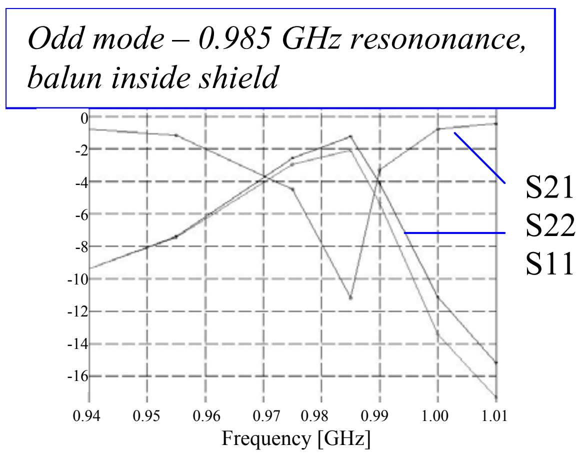


Figure 5 – first resonance in the ATA feed passband due to placement of taperline balun in shield. The 10 dB width of the RF resonance is 20 MHz. Very high Q suggests the odd mode is somehow coupling to a cavity mode.

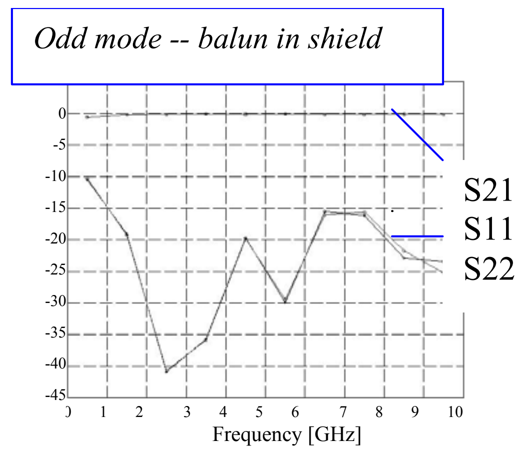


Figure 6 – Overall return loss of shielded balun looks good when sampled coarsely: sharp resonances are missed completely.

If the frequency sampling is made coarse the resonances are smoothed out or missed altogether (Figure 6). Over the rest of the passband, however, the circuit works properly as a balun. If the balun is removed from its shield and grounded only along its unbalanced edge, many of the resonances are dramatically weakened. For example, the RF resonance at 0.985 GHz is both shifted upward in frequency and significantly broadened – the transmission is reduced by only ~ 1 dB (Figure 7).

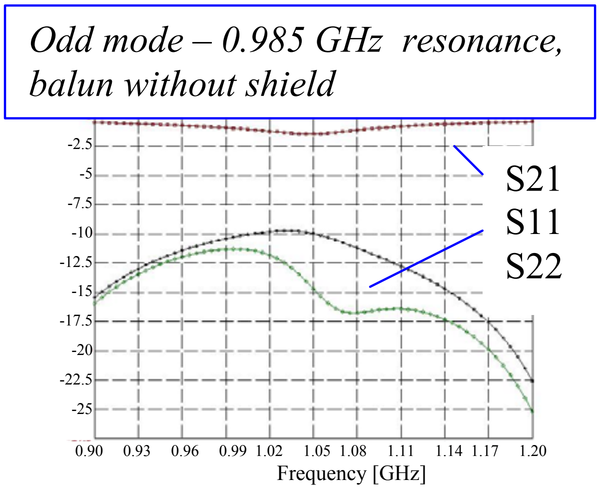


Figure 7 – Q of resonances greatly decreases when balun is mounted outside shield.

RF resonances possibly arise from weak coupling of balanced input signals to high-Q cavity modes in the shield. This may happen at either termination of the balun, but especially at the unbalanced end where the configuration of leads and dewar walls is the most asymmetric, resulting in the excitation of coaxial (or waveguide) modes.

When the twin leads of the shielded balun are excited with an even mode, the transmission to the microstrip end is less than –10 dB, except near 1 GHz (Figure 8). This simulation was run at a gridding resolution of 10 cells/wavelength for speed.

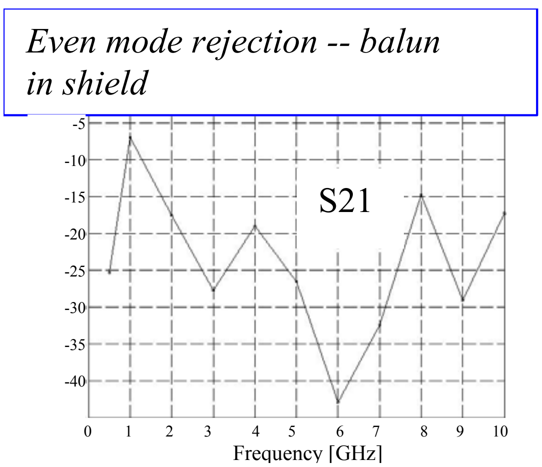


Figure 8 – a simulation with coarse frequency sampling and low resolution gridding shows even mode rejection by balun in shield of > 13 dB.

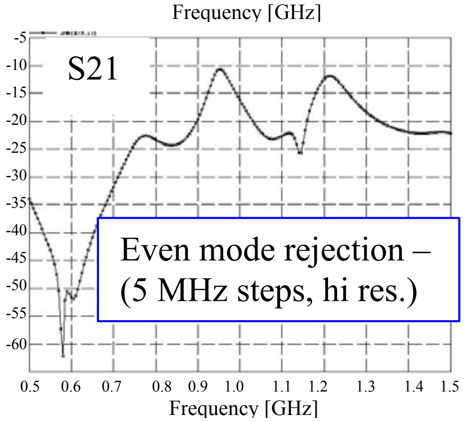


Figure 9 – a simulation wth 5 MHz frequency sampling between 0.5 – 1.5 GHz and fine resolution gridding shows that near 1 GHz the even mode rejection of the shielded balun is still good.

The simulation for the even-mode excitation in the wavelength range 0.5 – 1.5 GHz was repeated at a higher gridding resolution of 15 cells/wavelength (Figure 9). This shows that rejection of the even mode in this frequency range is still < –10 dB. Indeed, a prototype feed incorporating a balun of Figure 4 design produced beam patterns indistinguishable to within range error from those computed for balanced excitation of the antenna terminals (ATA Memo #45). Even mode rejection depends on symmetric placement of the balun with respect to shield walls, especially at the feed tip. Figure 10 illustrates the point that even and odd modes remain isolated only if the twin leads are centered at the shield opening. When the twin leads are offset, the lines are no longer balanced and even and odd modes can couple. A cooled resistive vane in the cryostat can be used to suppress any coaxial modes (ATA Memo #35) that may arise from either the geometry of the unbalanced end or fabrication error at the balanced end. Alternatively, a resistive film such a nickel chromium can be plated onto the balun traces. The odd mode will be conducted between the low loss faces of the balun leads but the coaxial mode will propagate between the shield and the lossy side of the trace.

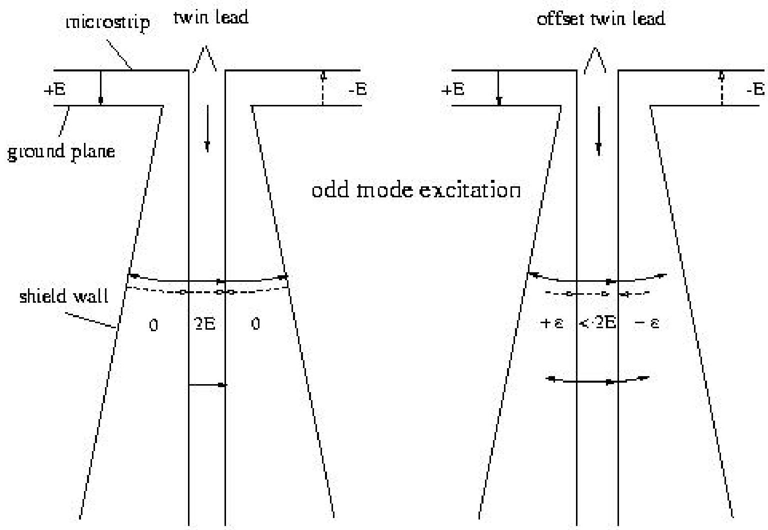


Figure 10 – schematic illustrates how the even mode can couple into twin leads if they are misaligned in shield.

Asymmetry at feed tip couples even and odd modes.

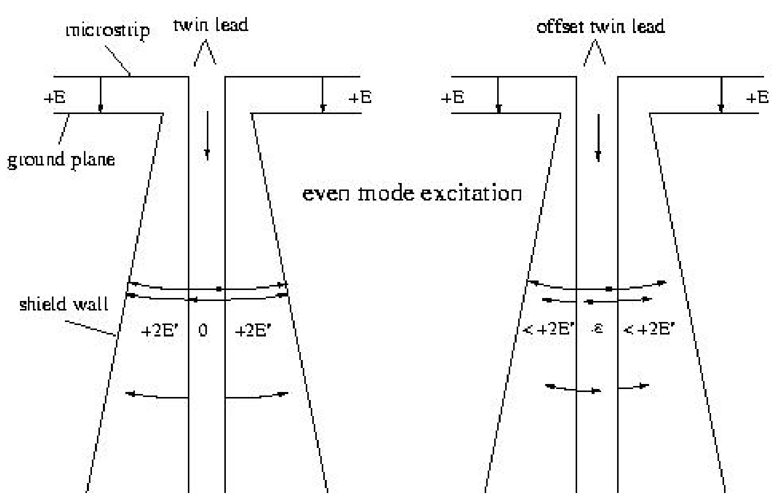


Figure 11 shows transmission through a test circuit made from back-to-back baluns enclosed in a long rectangular metal box. The balun design is shown in Figure 4. Measurements were made with an. Agilent 8722ES with 6 MHz. resolution. Resonances appear at 300 MHz intervals (blue line); this is consistent with our simulations since the total length of the circuit is double that of the simulation circuit. Placing absorber around the microstrip/coax transitions on both ends of the test circuit heavily attenuates resonances (red line). However, care must be taken not to introduce signal loss by putting absorber too close to unbalanced terminals. For the measurement shown, the loss caused by absorber at 5 GHz was 0.15 dB, unacceptable even if the absorber were 80 K. Other methods described – a vane or resistive plating of the traces – may be more selective in attenuating only the even mode. Experimentation with a prototype dewar will be necessary.

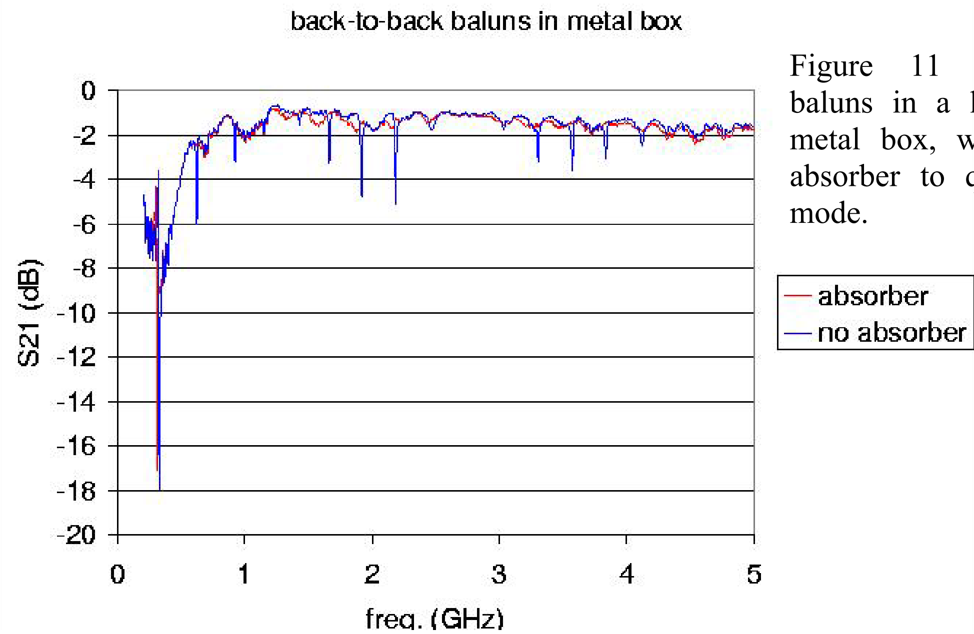


Figure 11 – back-to-back baluns in a long, rectangular metal box, with and without absorber to quench the even mode.

II. Options for Modifying the Feed Tip

As discussed, there are two concerns about the ATA frontend cryostat. (1) Its narrow geometry ends in a small grounded aperture into which 4 leads must be symmetrically threaded so as to minimize the excitation of radiation modes between the leads and the metal shield. (2) Incorporated in the cryostat is a taperline balun which will generate a combline of RF resonances when enclosed by conducting walls. There are two options for mitigating one or both of these concerns (i) a shield tip with 210 Ω twin lead extensions at ambient temperature and pressure inside and (ii) a shield tip with external baluns attached. Both options are based on the idea of translating the vacuum bulkhead from a position flush with the ground plane of the connection PC board back 2″ where the width of the cryostat is ~0.495″, about 3.3 times wider than at the feed tip (Figure 12).

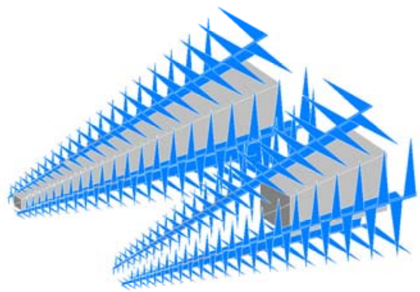


Figure 12 – truncating the dewar volume. Shifting back vacuum bulkhead 2″ creates a 0.495″ opening for input leads but increases length of signal path in ambient medium.

This leaves adequate clearance for dewar insulation, the dewar wall thickness, and two twin lead pairs, which must be far enough from each other so as not to cross couple yet far enough away from the dewar walls for their impedance not to be significantly modified.

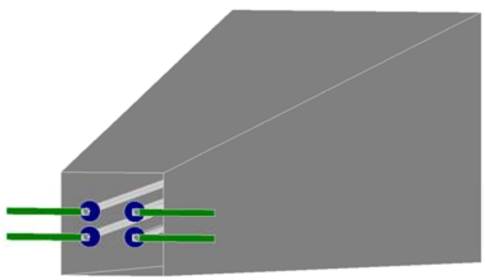


Figure 13 – an extension of the shield, to be attached to the dewar electrical feed-through. Twin lead-to-microstrip transitions are shown at the tip of the module, representing the connection PC board.

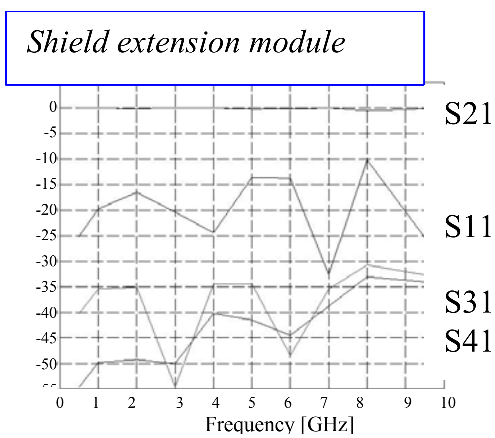


Figure 14 – Simulation results of shield extension module.: cross coupling of lead pairs < -30 dB and return loss < -13 dB

(i) Shield Tip with 210 Ω Twin Lead Extension – In the simplest approach, the vacuum bulkhead is recessed into the shield by approximately two inches. This should have no effect on the radiation patterns of the feed since the geometery of shield and arms remains unaltered. Signals from the feed arms are linked from the bottom of the connection PC board to a signal feedthrough in the vacuum bulkhead by twin-leads. The 210 Ω two lead pairs can be fabricated from gold-plated precision manufactured 0.010″ stainless steel tubing (hypodermic needles) held at 0.029″ by dielectric beads Alternatively, 0.010″ lead pairs separated by 0.027″ can be printed on 0.010″ thick crystal quartz. X-tal quartz is favorable for two reasons: its smooth surface keeps conductive losses to a minimum; its loss tangent at room temperature is 0.0001, 10 times less than Duroid 5880 and 15 times less than alumina or x-tal sapphire. Tapering of the wires or microstrip traces from 0.010″ at the PC board to 0.020″ at the vacuum feed-through

complicates fabrication but reduces the noise contribution from these lines by approximately 33%, reducing the noise temperature contribution of the extension module to ~4 K. The assembly is most conveniently manufactured as a detachable module (Figure 13).

The loss in 210 Ω twin leads consisting of 0.010″ wide flat trace on substrate or 0.010″ diameter round wire, free standing, is ~ 0.045 dB per inch. Care must be taken to connect these twin leads so they generate a minimum SWR since they will be completely enclosed in a metal chamber at the tip of the pyramid. Simulations show a return loss over the feed passband of < -13 dB and cross coupling of < -30 dB (Figure 14). We assumed the lines were bounded by a shield (the shield extension module) and threaded through 0.030″ holes at either end. Twin lead-to-microstrip transitions similar to the connection PC board were included in the simulation. Since there are back-to-back twin lead/microstrip transitions in our model the return loss shown in the figure should be reduced by 3 dB. If each via is offset 0.004″ toward the microstrip, from the center of the corresponding hole in the PC board ground plane, the return loss of the transition can be reduced 3 - 5 dB. The lowered return loss arises from a reduction in lumped inductance due to shortening of the leads which jumper microstrip to via. It also arises from an increase in capacitance on one side of the ground plane hole, which concentrates field lines under the edge of the microstrip, giving a better match to the quasi-TEM microstrip mode. Offsetting the center conductor in a coaxial connector to get a better impedance and field match to a microstrip has been previously realized in both in-line and right-angle transitions (J.S. Izadian & S. M. Izadian, "Microwave Transition Design", Artech House, 1988; "Electromagnetic Field Matching to Thin Microstrip Transmission Lines," *Microwave Product Division Catalog/Accessories Applications*, Southwest Microwave, Inc., ACC113; M. Morgan & S. Weinreb, "A Millimeter Wave Perpendicular Coax-to-Microwave Transition", 2002 IEEE MTT Symposium.)

Another advantage to the shield extension module is that, if desired – and for a small increase in noise temperature – the log-periodic feed can be extended closer to its vanishing point. The vacuum bulkhead remains fixed in location at a place where it will have a convenient width. Extending the feed tip to 0.415″ – that is, extending both the shield module and antenna arms toward the vanishing point by 0.415″ – raises the noise temperature at frequencies < 12 GHz by less than 1.4 K but increases the highest frequency of operation from 11 to 22 GHz. The diameter of the twin lead traces must also be tapered down to 0.005″ so that their interlead- and pair-separation can be tapered to 0.015″ and 0.030″, respectively, for attachment to the half-scale (0.075″) connection board.

(ii) Shield Tip with External Baluns – As an alternative approach to making the feed cryogenics more easily manufacturable, the taperline baluns may be modified to be placed at the tip of the shield, outside the cryostat.

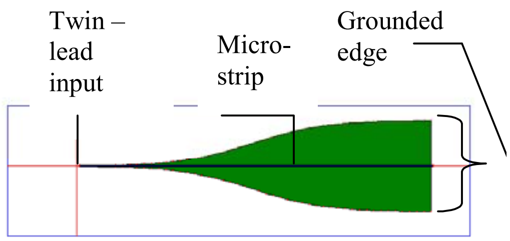


Figure 15 – a balun realized on either sapphire (ε_r ~ 9.5) or quartz (ε_r ~ 3.7) substrate.The impedance match is 210/105 Ω, with broadside coupled lines at balanced input. Absent in design is the asymmetric tapered twin leads in the plastic balun discussed previously.

This requires miniaturizing the balun by fabricating it on a rigid higher dielectric constant substrate like quartz (ε_r ~ 3.7) or sapphire (ε_r ~ 9.5) without the asymmetric taperline section for the 210/50 Ω impedance transformation (Figure 15). For example, a 1″ long balun has been designed for fabrication on sapphire and a 2″ balun designed for fabrication on quartz (Figures 16 – 17). It is possible to achieve a 210/105 Ω impedance transformation from the balanced to the unbalanced port with the abbreviated balun design. One lead flares out to form a ground plane approximately the width of the vacuum bulkhead (the shield aperture). Weak, narrow RF resonances still appear in the balun passband due to proximity of the antenna arms (Figure 18).

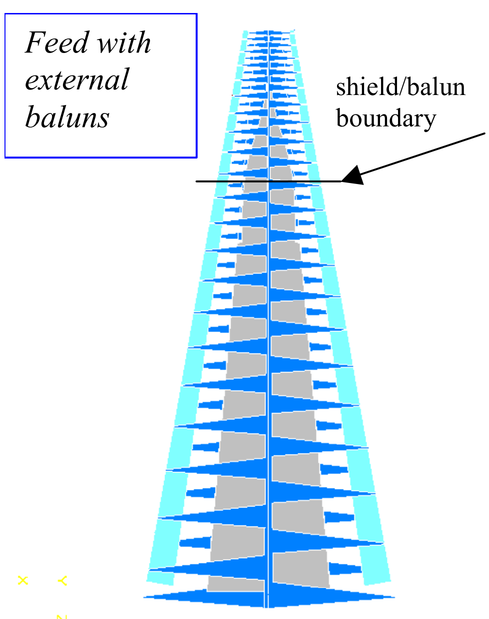


Figure 16 – baluns attached at the high frequency end of the feed external to the dewar.

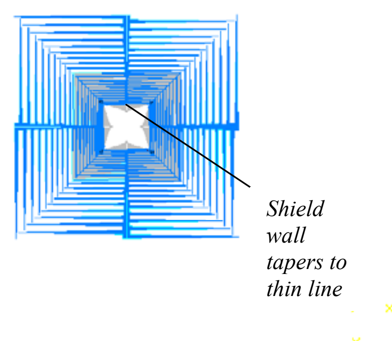


Figure 17 – face-on view of feed with external baluns. Their presence has small effect on beam patterns at frequencies > 7 GHz.

If the balun ground edge is attached where the shield wall ends, extending the conductor of the shield wall in coplanar fashion, signals from a 210 Ω balanced port can be brought down from a pair of antenna terminals and fed into the dewar with a single coaxial line. An unbalanced 105 Ω line, on the balun inner surface, enters the vacuum bulkhead close to the shield wall

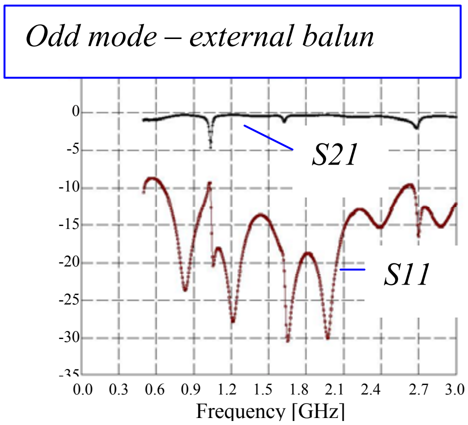


Figure 18 – resonances persist in feed passband for placement of balun at shield tip, external to dewar. RF resonances appear significantly weakened.

This approach has several benefits. It is much simpler to design and construct a signal feedthrough for a coaxial line than a balanced line. Twin leads in the dewar – which as previously mentioned can conduct an unwanted even mode – are eliminated. There are now two rather than four conductors linking the cryogenic work surface to ambient temperature, thereby reducing heat conduction and the length of lead necessary to make the temperature transition. The even-mode rejection of the feed is greatly enhanced. Finally, the majority of resonances in the balun are weakened.

In the face-on view of the modified feed it appears that there are four baluns (Figure 17). Actually, there are only two on orthogonal, adjacent shield faces –extensions on the opposite shield faces replicate the grounded balun trace to preserve the four-fold symmetry of the feed. This prevents excitation of unwanted antenna modes.

There is also an important difference between option (i) to modifying the feed and option (ii).Whereas extending the antenna arms to 22 GHz is optional when the baluns are in the shield, it is a necessity when they are outside. Option (i) requires no redesign of the connection PC board. However, in option (ii) there is no ground reference at the tip so signals from individual antenna arms need not be connected to uncoupled 105 Ω microstrip lines.

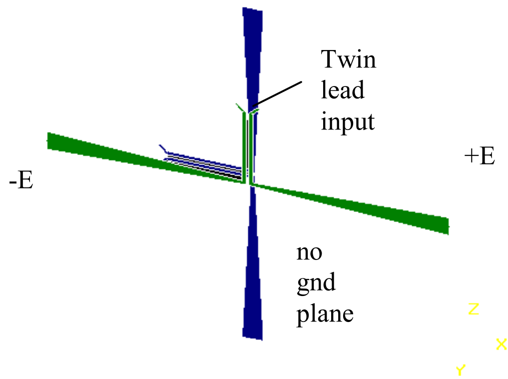


Figure 19 – Traces of connection PC board without ground plane. There is no ground reference at the tip of the feed in the external balun arrangement.

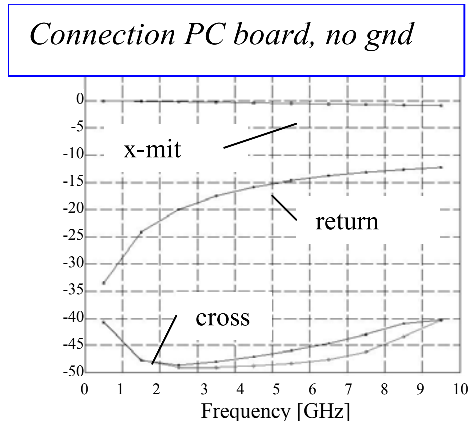
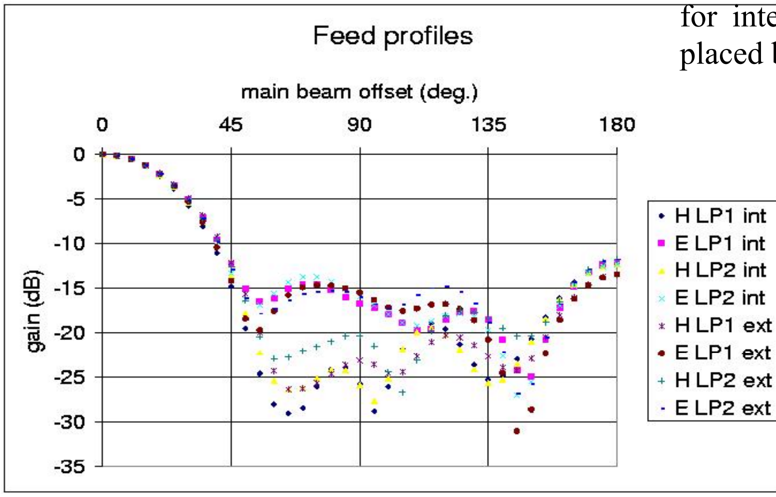


Figure 20 --S parameters of the reduced size connection board without groundplane. Inductance is held to a tested acceptable minimum which requires separation of antenna terminals to be kept no wider than 0.150″

Instead, each balun may be connected via a straight 0.0375″ segment of 210 Ω twin-lead to the center of a connection board without a ground plane, where the conductors split out at right angles before attaching to opposite antenna arms (Figure 19). Leads for opposite polarizations must be patterned on opposite sides of the connection board. S-parameters for this connection PC board without ground plane are shown in Figure 20. There is surprisingly low cross-polarization coupling (< -30 dB) and the return loss remains -15 dB – -25 dB for the antenna connection if the separation between the antenna terminals is kept less than 0.150″, hence the need to extend the antenna arms closer to the vanishing point. Of necessity, the upper frequency limit of the feed is raised to 22 GHz.

At frequencies > 7GHz, the tapering of the ground plane underneath the finline slightly enhances sidelobe emission , reducing the illumination efficiency from 85 % to 83 %, and increasing cross-polarization coupling from –26 dB to –21 dB. External baluns with LP1 feed arms (wider boom, no fin) give an illumination efficiency of 79 % and cross-pol. coupling of -15 dB. Beam profiles for LP1 and LP2 feeds with external and internal baluns are shown in Figure 21. The face-on current distribution for LP2 with external baluns is shown in Figure 22.

Figure 20 – LP1 and LP2 feed profiles for internally (int) and externally (ext) placed baluns.



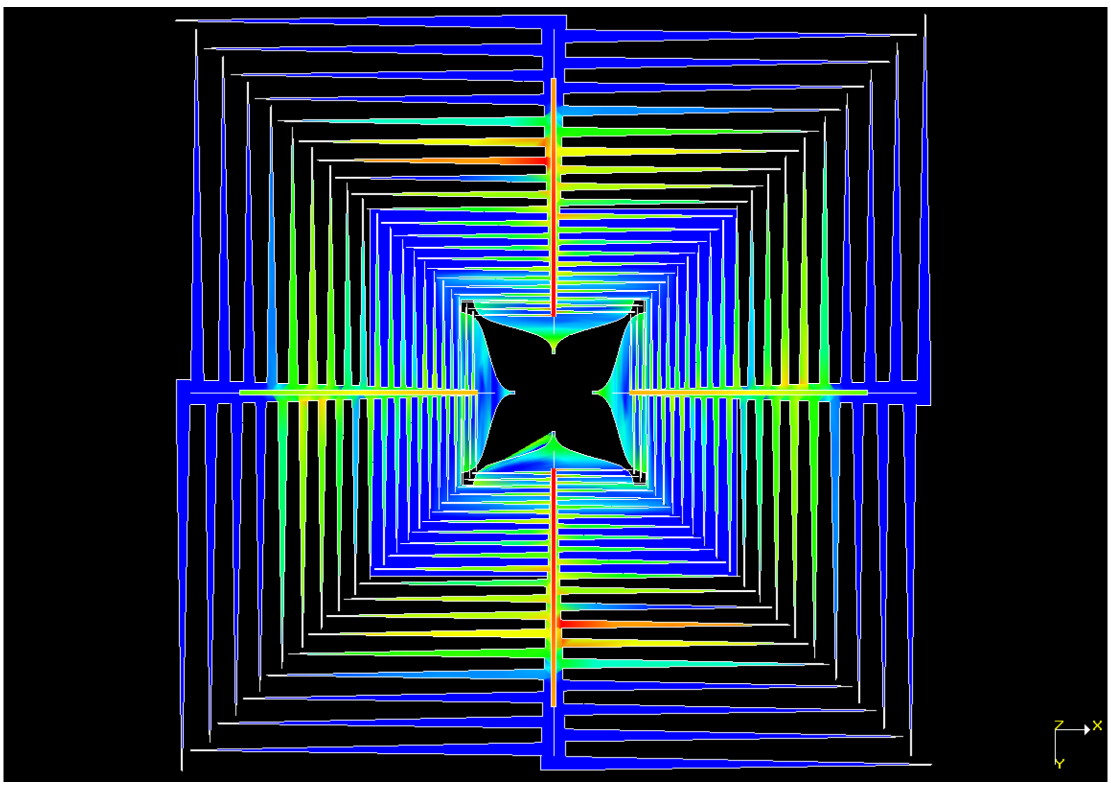


Figure 22 – current distribution on LP2 with external baluns at feed tip.

III. Conclusion

Fabrication of the feed can be facilitated by translating the vacuum bulkhead of the dewar 2″ back from the tip. Signals from the antenna tip can be transmitted to the dewar over 210 Ω twin lead or a by a 210/105 Ω miniaturized taperline balun. Both approaches have similar impact on the front-end noise temperature, raising it approximately 5 K.

However, we previously overestimated the noise temperature of the ATA feed by 5 K so we can choose to modify the feed to simplify dewar construction and predict the same system temperatures as in ATA Memo #45: 40 – 50 K for 0.5 – 11.2 GHz. In the external balun arrangement, direct coupling of energy from feeder modes between the LP antenna arms and the external baluns has not been formally treated in this memo but is believed to be small. Therefore, in choosing the external balun approach over the shield extension module, one must weigh the relative benefits of weaker RF resonances in the balun, a simpler electrical feed-through design, a lower heat load on the cryogenic work surface, and higher even mode suppression against 6 dB better cross pol. isolation and 2% higher illumination efficiency at frequencies higher than 7 GHz.. Placing the baluns externally will require some additional engineering effort. Nevertheless, this is a promising design modification which may alleviate space constraints at the narrow end of the dewar as well as eliminate the need for introducing RF absorbers into the vacuum.