Low-cost, Low-loss, Ultra-wideband Miniaturized Feed for Modern Interferometric Radio Telescopes

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We have developed, built, and tested a new feed design for interferometric radio telescopes with “large-N, small-D” designs. Those arrays require low-cost and low-complexity feeds for mass production on reasonable timescales and budgets, and also require those feeds to be miniaturized to minimize obstruction of the dishes, along with having ultra wide bands of operation for most current and future science goals. The feed presented in this paper modifies the exponentially tapered slot antenna (Vivaldi) and quad-ridged flared horn antenna designs by having an oversized backshort, a novel method of miniaturization that is well-suited for deeper dishes. It is made of laser cut aluminum and printed circuit boards, such that it is inexpensive ($\lesssim 75$ USD when purchased in bulk) and quick to build; it has a 5:1 frequency ratio, and its size is approximately a third of its longest operating wavelength. We present the science and engineering constraints that went into design decisions, the development and optimization process, and the simulated performance. We optimized and built a version of this feed design for the Canadian Hydrogen Observatory and Radio-transient Detector (CHORD) prototypes. When simulated on CHORD’s very deep dishes ($f/D = 0.21$), with CHORD’s custom first stage LNAs, the on-sky system temperature $T_{\text{sys}}$ of the complete receiving system from dish to digitizer remains below 30 K over the 0.3–1.5 GHz band, and maintains an aperture efficiency $\eta_A$ between 0.4 and 0.6. The feed is designed to slightly under-illuminate the CHORD dishes, in order to minimize coupling between array elements and spillover.

Keywords: CHORD; radio astronomy; feed; receiver; cosmology; fast radio bursts.

1. Introduction

Modern advances in telecommunication technology and improvements in computing capabilities have enabled radio astronomers to build “large-N, small-D” observatories—where $N$ is the number of dishes, and $D$, their diameter—such as the DSA-2000, HIRAX, the SKA and its precursors, or PUMA, which is set to have $N = 32,000$ (Carilli & Rawlings 2004, Lonsdale et al. 2009, Booth & Jonas 2012, DeBoer et al. 2017, Hallinan et al. 2019, Bandura et al. 2019, Saliwanchik et al. 2021). This requires the design of low-cost and low-complexity signal chains, from dish to digitizer, so that arrays with $N \gtrsim O(1000)$ can be built on realistic budgets and timelines. The feeds also need to be miniaturized, since the small diameter of the dishes means that they are easily obstructed. An important science goal for those observatories is 21 cm intensity mapping, which additionally requires very low-noise, dual-polarized, ultra-wideband receivers—see Furlanetto et al. 2006, Pritchard & Loeb 2012, and Liu & Shaw 2020 for in-depth reviews of the science and constraints.

We present a feed design that meets those challenges. It follows the design of an exponentially tapered slot antenna (Vivaldi), and is also inspired by recent literature on the quad-ridge flared horn (QRFH) feed
designs (Flygare, 2022). One of its novel feature is having the cut behind the exponential taper—the back-short, see Figure 1—be oversized, which extends its band towards the lower frequencies while maintaining the overall size of the feed near or below $0.3 \times 0.4\lambda_0$ (length $\times$ width) in size for each polarization, where $\lambda_0$ is the longest wavelength at which it operates, at a 5:1 frequency ratio. Many degrees of freedom in the feed and balun geometries allow for a fine-tuning of the impedance and beam shape for the specific requirements of a given array, and we summarize an optimization routine that can be used to adapt the feed to such requirements. The feed is laser cut out of 3.175 mm-thick aluminum, and the baluns are printed on 0.8 mm-thick low-loss ($D_{k} \sim 3.5$) substrates. The manufacture process allows the feed to be quickly mass-produced below the 75 USD price point, and the choice of substrates results in negligible losses in dielectrics ($\sim -35$ dB, or 0.1 K).

We show an implementation of this feed design for the Canadian Hydrogen Observatory and Radio-transient Detector (CHORD), an array of 512 closely packed 6 m prime-focus dishes set to be by the mid-2020’s in British Columbia, Canada, along with two “outrigger” stations for VLBI, on the US East and West coasts. CHORD will aim at mapping neutral hydrogen at redshifts $z < 3.7$, detecting and precisely locating fast radio bursts (FRBs) and other radio transients, probing cosmic magnetism, and more (Vanderlinde et al., 2019). Over most of its 0.3–1.5 GHz frequency coverage, the CHORD feed exhibits on-sky system temperature $T_{sys} \lesssim 30$ K, and maintains an aperture efficiency $\eta_A$ between 0.4 and 0.6 when mounted on CHORD’s very deep $f/D = 0.21$ dishes. The feed’s dimensions remain near or below $0.3 \times 0.4\lambda_0$ in size, such that dish blockage is minimized. The manufacture of all its parts—laser cut aluminum, and PCBs—is automated, and the materials are inexpensive, so that it can be mass produced at low cost.

In section 2 we present the considerations and constraints that have led to the design decisions. Then, in section 3, we summarize the modeling, optimization, and manufacture process. We present simulated and measured performances in section 4. Lastly, in section 5, we describe CHORD and its specific constraints, and we present the performance of the feed when used with the CHORD dishes and custom LNAs.

2. Design choice, considerations, and constraints

2.1. Miniaturization

The design chosen for the feed is that of an exponentially tapered slot antenna, commonly known as a “Vivaldi” feed, inspired by the one used for HERA (Gibson, 1979; Fagnoni et al., 2021). The Vivaldi design is ultra-wideband, easy to build, can be made to be dual-polarized, and has many degrees of freedom to optimize for a desired feed size, impedance and beam shape.

The degree of freedom that we chose to precisely tune in order to miniaturize the feed is the shape of its outline, as this can be done without increasing cost, complexity, or losses. For example, it has been shown that narrowing each polarization plane by cutting a second exponential taper along their outer edges, and, in the space thus created, adding carefully shaped stubs where longer wavelength currents can circulate, allows for the feed to radiate lower frequencies without increasing its dimensions (Wu et al., 2015; Liu et al., 2016; Yang et al., 2017). This approach was explored for our uses, but we found that some out-of-phase radiation happened through the added stubs at higher frequencies, suppressing the forward gain especially when the feed was used inside deeper dishes (see subsection 5.2 for discussion about dish depth). We instead achieved a degree of miniaturization by engineering the feed outline through a novel method: by significantly increasing the size of the backshort to approximately $0.15\lambda_0$. The overall size of the feed presented in section 5 is kept at $0.3 \times 0.4\lambda_0$, significantly below the $\sim 0.5\lambda_0$ length of a non-miniaturized Vivaldi feed.

2.2. Comparison with quad-ridged horns

The self-supporting Vivaldi design is equivalent to an open boundary QRFH design. An exhaustive review of the QRFH family of feeds in the context of radio astronomy is presented in Flygare 2022, where it is noted that deeper dishes, with $f/D \lesssim 0.3$, are harder to illuminate over wide bands, especially using low-cost, low-complexity feeds that cannot make use of intricate flared horns, choke rings, or dielectric loads, to shape their beam. In section 4, we show that our design does achieve good illumination ($\eta_A \sim 0.5–0.6$) on
deep dishes, while indeed being inexpensive and simple to manufacture. In subsection 5.2 we discuss the benefits of an under-illuminated dish is desirable for CHORD’s science goals.

Note that additional degrees of freedom in the feed outline have been explored in the QRFH literature. For instance, any active segment of the outline can be replaced by a spline, as shown in Dong et al. 2018 and Flygare et al. 2019, and alternate backshort geometries are presented in Jacobs 2012. Both of these methods open a broader parameter space to potentially reach more a desirable impedance and beam shape. These options have not been explored yet for the feed design proposed in this paper.

3. Development

3.1. Modeling the feed

The feed was modeled and simulated using CST Microwave Studio. It is composed of two perpendicular polarization planes, that we call the petals, each equipped with a small microstrip balun, and one circular plane at the back—the backplane—that mostly serves mounting purposes. Apart from the locations of the baluns, which must be offset along the untapered slot (see Figure 3a), the petals are identical. The offset in the positions of the baluns results in a negligible difference in the impedance matching between the two polarizations (see Figure 5). That difference could be corrected for by optimizing the dimensions of the baluns separately, but we found that it was not necessary to reach standard performance requirements. The petals are extruded profiles of a closed planar curve, which is presented in Figure 1 and defined by the following features:

(1) a large circular cut at the back, called the backshort, providing a control over impedance, and ensuring radiation does not occur in that direction,
(2) a short untapered slot, where the baluns are attached,
(3) an exponential taper, defined by \( x(t) = \alpha_p \left( e^{\beta_p t} - 1 \right) \),
(4) a straight extension of the taper,
(5) the rest of the contour, which is defined entirely for structural reasons, and to leave space for first-stage amplification.

Additional cuts are made inside that profile to accommodate screws, connectors, cables, and first-stage amplification, as can be seen in Figure 2. Those cuts do not affect the performance of the feed, as the only electrically active parts are the inside edges of the petals. The relevant free parameters of that design are the diameter of the backshort, the length and width of the untapered slot, the length and maximum opening of the exponential taper, the taper rate parameter \( \beta_p \), and the total width of the petals, which include the taper’s straight extension and the blended corners. The taper rate parameter \( \alpha_p \) is not free, as it is uniquely determined by the taper’s length and width.

The petals and backplane’s thickness is fixed at 3.175 mm (1/8 in.), which is a standard metal thickness in North America, and is thick enough that the feed is self-supporting without needing to be printed on a substrate. The material chosen is aluminum as it has a high conductivity, it is light, inexpensive, and its oxidization has negligible effects on performances at low frequencies.

A microstrip balun is added over the untapered slot of each petal, as shown in Figure 3a. It is a simple double-sided PCB, consisting in a microstrip on one side, and a grounded shield on the other. The balun is raised 0.8 mm above the petal, leaving an air gap between them—we call it a floating balun—with the microstrip’s side facing the petals. This minimizes losses in materials that would otherwise occur between the balun and the petal if it was filled with a dielectric, as the electric field density is high in that region. The baluns shown in Figure 2 and Figure 3 are terminated with a short—an off-the-shelf connection pin—to the petal on one side, and with an SMA connector on the other.

The balun’s microstrip is also exponentially tapered, and its degrees of freedom are: its length, width at either end, and taper rate parameter \( \beta_b \)—as was the case for the petal’s taper, the balun taper rate parameter \( \alpha_b \) is not free, since it is determined by the taper width and length. The balun thickness is also fixed, at 0.8 mm, because anything thinner would lack the structural integrity needed for the floating balun design, and anything thicker would necessitate the untapered slot to be wider, pushing the feed’s impedance away from the 50 Ω goal. The choice of substrate for the balun affects both the impedance, and
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Fig. 1: Diagram of a feed petal. The backshort (1) prevents propagation towards the back of the feed, and adds a degree of freedom to the impedance control. The untapered slot (2) is where the baluns are attached. Most of the power radiates out of the exponential taper (3) and its straight extension (4). The rest of the feed is mostly not electrically active, so the shape of the outline (5) is determined for practical reasons: structural integrity, and leaving enough room for first stage amplifiers. The proportions on this diagram are just for indicative purposes, since they should be optimized for a specific reflector geometry, first-stage LNA impedance, and overall science goals—this diagram is loosely proportional to the CHORD feed, presented in section 5.

the losses in dielectrics. We found that it is hard to reach a $50 \, \Omega$ impedance across the band with teflon ($D_k \sim 2.1$), and FR-4 ($D_k \sim 4.5$) is too lossy. The baluns tested were thus printed on Rogers RO4003C, with $D_k = 3.55$.

3.2. Optimization

The success of the optimization process relies on the fact that array elements in “large-$N$, small-$D$” observatories are electrically small, such that with modern high performance computing facilities, simulations that include the dish converge relatively quickly. This allows us to use algorithms that require a large number of iterations, and exhaustively explore a vast parameter space, optimizing the dish beam properties directly without having to estimate them based on simulations of the feed alone. Nonetheless, for efficiency, some steps in the strategy we propose do exclude specific parts of the system—either the baluns or the dish, and their respective free parameters—depending on what is being optimized.

Before the optimization starts, the feed dimensions are estimated based on the desired frequency band: the total width and length should be about a third of the longest wavelength, and just a bit less than half of that for the backshort diameter and taper length.

The optimization process consists in three steps, that are repeated with different optimization algorithms. These algorithms are built into the simulation software, and are chosen as a function of the number of parameters, and distance from the desired goal function minimum. The parameters are allowed to vary freely, with the lower bounds set by technical and practical considerations (e.g. the untapered slot must be wide enough to accommodate the baluns), and the upper bounds are chosen following the requirement that the feed should be relatively small.
Fig. 2: Completed feed, including the microstrip baluns. There are cuts in the petals that are added to accommodate screws, cables, connectors, and first stage amplification. There is also a stabilizer piece, inserted in the exponential taper, made of polycarbonate. It is mostly transparent to electromagnetic radiation at low frequencies. This version of the feed design is the one optimized for CHORD, as presented in section 5.

In the first step, the feed is optimized over all the petal and balun parameters for impedance matching close to 50 Ω, with a covariance matrix adaptation evolution strategy (CMA-ES) algorithm, because CMA-ES performs well with a large number of varying parameters, far from the goal function minimum [Hansen, 2006].

In the second step, the full dish is added to the model, but the baluns are removed to limit the mesh resolution and simulation time, and another CMA-ES optimization run is performed, this time optimizing the beam shape. Depending on the specific science goals, this can mean a high forward gain, a low spillover, or another metric. In those simulations, the balun parameters are not considered, but one new parameter is added, that is, the best position of the feed with respect to focus—analogous to a weighed average of the phase center over frequency. Also, the parameters that were found in the first optimization run are kept within a narrower range.

In the third step, the dish is removed, the baluns are added back, and only the balun parameters are optimized over, to try and correct for the impedance changes caused by the previous step without affecting the beam shape. This time, however, the algorithm chosen is Nelder-Mead, which performs well over a small number of parameters [Singer & Nelder, 2009].

Those three steps are then repeated once. For the first two steps, the range of variation for the parameters is narrowed, and a trust-region framework algorithm is used for optimization, which performs well when near the desired goal function minimum [Yuan, 1999]. The third step is also repeated, and can
be performed with either the Nelder-Mead (because there are only a few parameters involved) or trust-region framework (due to proximity to goal function minimum) algorithm—both taking similar numbers of iterations to converge, at that point in the process. At the end, a full simulation that includes both the dish and the baluns is performed, to check that the performance is as desired. This process is summarized in Figure 4.

3.3. Manufacture

Once the feed model meets the performance goals in simulations, some details are added for practical reasons. For instance, holes are added on the petals and in the backplane, to make room for screws, connectors, cables, and first-stage amplification. A piece of polycarbonate is also inserted in the exponential taper, for stabilization purposes. The piece is 3 mm in thickness, and is practically invisible to the feed, causing less than $-30$ dB (0.3 K) in losses across the band. Like the aluminum, it is laser cut, adding no complexity to the design. Once the parts are laser cut, and the baluns are printed, everything is assembled with rivets or screws. The resulting assembled feed is shown in Figure 2.

4. Performance

The feed that we built and tested was optimized for the CHORD observatory, as described in section 5. It is made to match the custom CHORD first-stage LNA’s optimum impedance for minimum noise, and have a beam that meets the constraints set by CHORD’s science goals. However, since we argue that this feed design could be used for other “large-$N$, small-$D$” arrays, we present more generic benchmarks for that feed—the reflection coefficient referenced to 50 $\Omega$, beam shape, aperture efficiency, contribution to $T_{sys}$ from spillover at various focal ratios, and cross-polarization. Those should be interpreted as the typical, but not optimal, performance measures for a feed built following our proposed design. They already meet standard benchmarks, and can be improved once optimized for a given observatory.

The reflection coefficient of the feed is measured at the SMA-end of the balun with a vector network analyzer. The simulated and measured reflection coefficients for both polarizations, referenced to 50 $\Omega$, are presented in Figure 5. Measurements match simulation, and both are below -10 dB over a 5:1 band—0.3 to 1.5 GHz in this case—averaging around -16 dB for polarization 0, and -13 dB for polarization 1.

The simulated beams of the feed are presented in Figure 6 at 0.3, 0.9, and 1.5 GHz, along three different azimithal cuts. Along the $\phi = 0^\circ$ cut, the low frequency beam is nearly isotropic, peaking near $\theta = 60^\circ$. 

Fig. 3: (a) Two microstrip baluns, as installed on each polarization petals of the feed. The offset between their positions only results in a negligible difference in impedance (see Figure 5). Not shown: the short to the petal, on the other end, which is done through an off-the-shelf connection pin. (b) The microstrip baluns, before being equipped with an SMA connector and installed on the feed.
Fig. 4: Overview of the optimization process. First, the optimization aims for the desired impedance; the feed petals and baluns are included in the simulation and allowed to vary. Then, the optimization aims to improve the beam shape depending on the science goals (minimizing spillover, maximizing forward gain, etc.); the baluns are removed from the simulation, and a fixed dish is added. Finally, the optimization aims for impedance again; the dish is removed, the baluns are added back, and the petal parameters are fixed. This is meant to try and fix any impedance changes that may have occurred in the previous step. This whole process is repeated twice, with different algorithms. At each step, the range of the parameters are narrowed.

This is caused by the oversized backshort, necessary to maintain an adequate impedance match at those low frequencies while keeping the feed relatively small to minimize blockage of the aperture (see section 2). Those very wide beams are well suited for deep dishes: most of the power near $\theta \sim 90^\circ$ is captured by the dish when $f/D \leq 0.25$, and the portion that spills over is radiated towards the sky rather than the ground, when pointed near zenith.

Figure 7 shows the expected trade-off between aperture efficiency and ground illumination: as the dish gets deeper, the illumination decreases on both the dish and the ground. The focal ratio where the average aperture efficiency over the band is maximized, at $\bar{\eta}_A = 0.54$, is $f/D = 0.25$. We note that since the beam is so wide at low frequencies, the dish remains well illuminated at that end of the band, even down to $f/D = 0.18$. This results in a downward slope in aperture efficiency over frequency, which could be used to maintain a more constant beam width over the band. That may be desirable, for instance, to reduce foreground leakage in 21 cm experiments [Alonso et al., 2015]. The optimal dish depth will ultimately depend on the specific science goals and constraints of a given observatory and, as explained in section 5, the CHORD dishes were chosen to be have a focal ratio of $f/D = 0.21$. The aperture efficiency is nearly as high as $f/D = 0.25$, but the ground illumination contributes $5 \sim 7$ K less to the system temperature. Note that spillover was not the only factor in favour of a lower focal ratio: mitigation of crosstalk, as described in subsection 5.2, was also considered. In simulations with multiple dishes, not presented in this paper, we found that going from $f/D = 0.25$ to $f/D = 0.21$ significantly reduced adverse coupling effects.

Figure 8a shows the co- and cross-polarization beams, along with their ratios, for a given polarization plane, simulated with a 6 m reflector with $f/D = 0.21$ fed with the feed design. Within the HPBW, the ratio between the co- and cross-polarizations remain below -20 dB almost everywhere, except at higher frequencies along the $\phi = 45^\circ$ cut.

In Figure 8b, the minimum and average intrinsic cross-polarization ratio (IXR) within the half-power beam width (HPBW) is presented for the same simulation. The IXR is a figure of merit for cross-polarization
Fig. 5: Reflection coefficient over a 5:1 band, from 0.3 to 1.5 GHz (shaded), for both polarizations, in simulation, and measured with a vector network analyzer connected to the baluns through SMA connectors. Measurements agree with simulation, and both polarizations clear the standard -10 dB threshold over band. The average reflection coefficient is -16 dB for polarization 0, and -13 dB for polarization 1.

Fig. 6: Simulated beam of the feed alone at 0.3, 0.9, and 1.5 GHz. The wide beams at low frequencies are mostly captured by the very deep dish. The feed beams are very wide at low frequencies due to the size of the feed’s backshort, which is oversized to maintain a good impedance match at that end of the band.

Introduced in [Carozzi & Woan 2011] specifically for radio astronomy purposes, that is independent of the coordinate system, contrary to the cross-polarization isolation (XPI) or discrimination (XPD). It is equal to

\[
\text{IXR} = \left| \frac{\sigma_{\text{max}} + \sigma_{\text{min}}}{\sigma_{\text{max}} - \sigma_{\text{min}}} \right|^2,
\]

where \(\sigma_{\text{max}}\) and \(\sigma_{\text{min}}\) are the maximum and minimum singular values of the dish beam’s Jones matrix. We are not aware of an industry standard for that metric, but large-\(N\) astrophysical observatories such as the SKA have quoted IXR \(\geq 15\) dB everywhere within the HPBW as a specification, which this feed design clears [Dewdney et al., 2013].
Fig. 7: (Top) Simulated aperture efficiency of the feed when placed in dishes with various focal ratios. (Bottom) Simulated contributions to $T_{\text{sys}}$ from spillover when the feed is placed in those same dishes of varying depths. It is notable that the average aperture efficiency peaks at $f/D = 0.25$, which is a consequence of the very wide beams shown in Figure 6. The system temperature due to spillover increases quickly as the dishes get shallower, a focal ratio of $f/D = 0.25$ already causing a 5-7 K increase over $f/D = 0.21$. CHORD’s science goals favour a low system temperature over a high aperture efficiency, and for that reason, along with crosstalk mitigation (see section 5), it was decided that $f/D = 0.21$ was the ideal depth.

5. Implementation on CHORD

5.1. CHORD overview

CHORD’s main core will be localized at the Dominion Radio Astrophysical Observatory (DRAO), near Penticton, in British Columbia, Canada. It will be comprised of 512 closely packed 6 m prime-focus dishes, distributed in a regular rectilinear array, with East-West and North-South shortest baselines of 6.3 m and 8.5 m, respectively. The dishes will have an inclination range of 30° from zenith, in the North-South direction only. The bandwidth of its receiver will be 0.3 to 1.5 GHz (Vanderlinde et al., 2019).

The science and engineering considerations that lead to those design decisions are not the subject of this paper, but a quick summary of those relevant to the optimization of the feed design are presented here.

5.2. Crosstalk

The very short 6.3 m baselines—corresponding to a $\lesssim 1\lambda_0$ gap from the edge of one dish to the next—are determined by the cosmology goals, as large scales of the matter power spectrum are only accessible with short baselines in cross-correlation. This proximity increases the mutual coupling (crosstalk) between array elements, which has the undesired effect of correlating noise radiated out of the receivers, or picked up from the ground. Moreover, crosstalk causes the sky signal to be reflected from one array element and detected by another, adding chromaticity to the measurement. This chromaticity complicates the process of subtracting galactic foregrounds, which makes use of their otherwise smooth spectrum. Calibrating the instrument to take crosstalk into account in analysis is an active area of research (see Kern et al., 2019, Kern et al., 2020 and Josaitis et al., 2022) but we can mitigate that issue by minimizing the coupling.
Fig. 8: (a) Co- and cross-polarization beams and ratios at various frequencies and φ-cuts within the dish beam’s HPBW, simulating the feed inside a 6 m reflector with $f/D = 0.21$. The shaded region corresponds to the HPBW. At almost every point in the HPBW, the co/cross-polarization levels stay below -20 dB, apart from the worst expected φ-cut ($\phi = 45^\circ$) at higher frequencies, where it gets near -10 dB. (b) Average and minimum intrinsic cross-polarization ratio (IXR) within the same dish beam’s HPBW. The IXR is agnostic of coordinate system, and a higher value is better.

power in the design phase. Additionally, due to the faintness of the low redshift 21 cm signal—$\sim 0.1$ mK brightness temperature—the constraints on noise are very strict, at $T_{\text{sys}} < 30 K$ across the band, with
ground illumination being a large contributor. One way to reduce both crosstalk and spillover in other observatories has been by engineering the optics of the reflectors, for instance, by using carefully shaped sub-reflectors and shields (Welch et al., 2009; Theron et al., 2012; Pellegrini et al., 2021; Lehmensiek & de Villiers, 2021). However, due to the cost and complexity constraints, those approaches are not possible with CHORD, which will use prime-focus dishes. Instead, the CHORD dishes minimize crosstalk and spillover by being very deep, with $f/D = 0.21$, the edges of the dish thus effectively acting as a shield.

5.3. Optimization for CHORD

Before running the optimization process described in subsection 3.2, we must determine targets based on the science goals and constraints for CHORD. The most important constraint is the system temperature, since it determines the signal-to-noise ratio of the observatory as it measures an extremely faint cosmological signal. The main contributions to $T_{sys}$ over which the feed can be optimized—that is, excluding the sky and the LNA minimum noise temperature—are the ground illumination, and the mismatch between the feed reflection coefficient ($\Gamma_S$) and the LNA optimum reflection coefficient for minimum noise ($\Gamma_{opt}$).

The impedance goal function, used in the first and third step of the optimization algorithm, was thus proportional to the second term on the right-hand-side of:

$$F = F_{\min} + 4R_n Z_0 \frac{|\Gamma_S - \Gamma_{opt}|}{(1 - |\Gamma_S|^2)(1 + \Gamma_{opt})^2},$$

(2)

where $F$ is the noise figure, $F_{\min}$ is the LNA’s minimum noise figure, $R_n$ is its equivalent noise resistance, and $Z_0$ is the reference impedance. Equation 2 is taken from Ludwig & Bretchko 2000.

The ground illumination target was set to minimize the integrated power pattern at $\theta > 90^\circ$ and, with a smaller weight, at $\theta > 60^\circ$ to account for CHORD’s full inclination range. Defining the function $P(\theta_c)$ as

$$P(\theta_c) = \int_0^{360^\circ} \int_0^{180^\circ} U(\theta, \phi) \sin(\theta) d\theta d\phi,$$

(3)

where $U(\theta, \phi)$ is the normalized power pattern of the dish and $\theta_c$ is the cutoff angle beyond which radiation must be minimized. The quantities to minimize are thus $P(90^\circ)$, and $P(60^\circ)$.

We also maximize the aperture efficiency, given by

$$\eta_A = \frac{A_{\text{eff}}}{A_{\text{phys}}}$$

(4)

where

$$A_{\text{eff}} = \frac{\lambda^2 G}{4\pi},$$

(5)

with $\lambda$, the wavelength, $G$, the gain at boresight, and $A_{\text{phys}}$, the size of the physical aperture $\pi R^2$, $R = 3$ m.

The optimizer produces an individual goal function proportional to the distance of each of the quantities mentioned above from their respective targets, and the sum of these individual goal functions is minimized by the algorithms mentioned in subsection 3.2. While the noise matching optimization steps only involves one quantity (the noise figure), the steps that optimize the beam properties involves three ($P(90^\circ)$, $P(60^\circ)$, and $\eta_A$), which are of two different nature (integrated power pattern, and power at boresight), with different target values, such that their respective goal functions have different scales. Thus, before the optimization run starts, we manually weigh the individual goal functions by hand, multiplying each of them by a different real number between 0 and 1, such that their scales are similar, and none drives the optimization process all by itself.

We found that between spillover and reflection coefficient ($\Gamma_{opt}$ vs $\Gamma_S$) mismatch, the latter was more sensitive to parameter changes in terms of increasing $T_{sys}$. Thus, after the first step of the optimization process, where a good impedance match was found, the parameter space was strictly narrowed, to avoid getting too far from that impedance while optimizing the beam. The dimensions that the algorithm converged to are presented in Table 1.
Table 1: List of the free parameters for the optimization algorithm described in Figure 4, along with their optimal values when optimizing for CHORD, that were used for building the feed.

| Free parameter               | Optimal value |
|------------------------------|---------------|
| Backshort diameter           | 65 mm         |
| Untapered slot width         | 7.5 mm        |
| Untapered slot length        | 37 mm         |
| Petal taper length           | 93 mm         |
| Petal taper opening width    | 238 mm        |
| Petal taper parameter $\beta_p$ | 0.037     |
| Petal total width            | 378 mm        |
| Balun microstrip length      | 48.3 mm       |
| Balun microstrip width (port side) | 0.6 mm  |
| Balun microstrip width (short-to-petal side) | 4.3 mm |
| Balun microstrip taper rate parameter $\beta_b$ | 0.428     |

5.4. CHORD receiver performance

The 5:1 CHORD bandwidth makes the LNA noise matching challenging, as the LNA’s $\Gamma_{\text{opt}}$ exhibits a negative-capacitance response, which is not possible to realize with Foster matching networks over the full bandwidths (Belostotski et al., 2012). The approach taken for the CHORD LNA was to bring $\Gamma_{\text{opt}}$ close to $50 \Omega$ by employing a combination of wideband matching at the LNA input and by using the intrinsic feedback through the parasitic gate-drain capacitance of the input stage transistor (Zailer et al., 2020; Beaulieu et al., 2016; Belostotski & Haslett, 2007). The noise matching of the LNA can be understood from Figure 9a, where a Smith chart, referenced to $50 \Omega$, plots both $\Gamma_{\text{opt}}$ and $\Gamma_S$. Both the LNA and the feed maintain their $\Gamma_{\text{opt}}$ and $\Gamma_S$, respectively, near 0 (i.e. 50 $\Omega$) over the band, except at the very low end for the LNA. More importantly, both of the reflection coefficients intersect at multiple frequencies realizing broadband noise matching.

Figure 9b shows the on-sky system temperature $T_{\text{sys}}$ with its individual contributions. Those are the ground and sky illumination, losses in dielectrics, LNA noise—both its minimum noise and that from the noise match with the feed impedance—and noise from the backend of the signal chain. It meets the CHORD specification of $T_{\text{sys}} < 30 \text{ K}$ over nearly all the band, apart from the lower end where the sky gets too bright. One significant contributor to the noise temperature is the spillover, which competes directly with aperture efficiency $\eta_A$: to reduce ground illumination, the feed’s beam needs to be more directed, which under-illuminates the dish and reduces forward gain. Varying the feed dimensions allows for a fine-tuning of that trade-off, and the final design was chosen to maintain $T_{\text{sys}}$ at specification values, while keeping $\eta_A$ near 50%. The simulated aperture efficiency on the CHORD dishes is presented in Figure 7, as the $f/D = 0.21$ line.

The simulated CHORD dish beams are presented in Figure 10. As explained in section 4, despite the very wide feed beams, the dish beams have narrow main lobes since the feed beams are captured by the deep $f/D = 0.21$ dishes. The side lobe levels remains below -20 dB across the band.

6. Conclusion

We have developed a feed design that is well-suited for “large-\(N\), small-\(D\)” observatories, especially when the dishes are very deep ($f/D \lesssim 0.25$). The feed is quick to assemble ($\sim 15$ minutes) and inexpensive to manufacture ($\lesssim 75$ USD). It is made of laser cut aluminum, with compact PCB baluns, such that it exhibits negligible losses in materials. It achieves a 5:1 frequency ratio while remaining small ($\lesssim 0.3 \times 0.4 \lambda_0$), thanks to an innovation: increasing the size of the backshort. It meets standard benchmarks in impedance and aperture efficiency when fed into very deep dishes ($f/D \lesssim 0.3$). We present a strategy to efficiently optimize both impedance and beam properties using different algorithms depending on the number of free
Fig. 9: (a) $\Gamma_{\text{opt}}$ and $\Gamma_S$, on a Smith chart referenced to 50 $\Omega$. Both remain close to 50 $\Omega$ over most of the band, except for $\Gamma_{\text{opt}}$ near 0.3 GHz. This partly explains the sharp increase in the LNA noise match contribution to $T_{\text{sys}}$ at the very low end of the band, in (b). (b) Individual contributions to $T_{\text{sys}}$.

Fig. 10: Simulated CHORD dish (6 m, $f/D = 0.21$) radiation patterns when fed with the proposed feed, at 0.3, 0.9, and 1.5 GHz, along three azimuthal cuts. The wide beams at low frequencies shown in Figure 6 are mostly captured by the very deep dish, leading to narrow main beam, high forward gain, and relatively low sidelobe levels ($\leq$-20 dB).

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