Chapter 1

Introduction and Background

Radio astronomy instrumentation has consistently been at the forefront of microwave electronics from feed antennas, through low-noise amplifiers (LNAs) and to back-end electronics. Since Karl Jansky first discovered the radio emission from the Milky Way in 1932, each of these components has undergone tremendous development resulting in orders of magnitude improvement in sensitivity and bandwidth of receivers. Today, the key components of a typical radio astronomy receiver that primarily determine sensitivity and bandwidth are:

1. Corrugated horn feed antenna with about octave bandwidth;
2. Silicon germanium (SiGe), indium phosphide (InP), or gallium arsenide (GaAs) low-noise amplifier with at least octave bandwidth;
3. Digital back-end electronics, such as correlators, spectrometers, etc., capable of processing multi-GHz bandwidths simultaneously.

This dissertation is about pushing the *simultaneous* bandwidth of the first two components in pursuit of decade-bandwidth radio astronomy receivers.

In addition to system versatility, motivations for decade-bandwidth radio astronomy are two-fold. First, simultaneous frequency coverage enables exploration of new scientific questions. In particular, transient and continuum radio astronomy would benefit the most from decade or near-decade bandwidths. Some scientific applications are the following:

1. Observations of pulsed (pulsars) and transient radiation which occur in limited time periods but over many octaves of frequency (0.6 to 3 GHz and 2 to 12 GHz are desired bands). The detection sensitivity and timing accuracy can be enhanced by receiving systems matched to this wide spectrum and the pulsar timing observations are of great interest for the detection of gravitational waves [1];
2. For very long baseline interferometry (VLBI) observations where large bandwidth (2 to 14 GHz) increases sensitivity and removes fringe ambiguity [2, 3];

Figure 1.1: Receiver room of the Green Bank Telescope

3. For measuring the spectral shape (spectral index) of continuum radio sources (such as supernova remnants and quasars) which helps to determine the emission mechanism [4, 5];
4. While spectral line observations typically require the highest sensitivity and may thus not be the first candidate for decade-bandwidth systems, such systems could still prove valuable to search for radio spectral lines with large unknown red-shifts (8 to 50 GHz would be useful).

The second, and arguably more practical, motivation for decade-bandwidth radio astronomy instrumentation is cost. Recent trends in radio astronomy are in the direction of increased number of elements, be it dishes or focal plane elements, simultaneously covering decade bandwidths. For example, the Square Kilometer Array (SKA) is currently the biggest radio telescope project and when completed, it will consist of roughly 3000 dishes and possibly many more dipole elements which, in aggregate, will amount to a square kilometer collecting area [6, 7].

Realizing telescopes such as the SKA using today's octave-bandwidth receivers could be so costly to the point of being impossible. As an example, Figure 1.1 shows the receiver room of the Green Bank Telescope (GBT) operated by the National Radio Astronomy Observatory in Green Bank, West Virginia which covers 100 MHz to 100 GHz with more than 10 front-end receivers. Each front-end involves a feed antenna, an LNA, and associated cryogenics. Suppose the cost of each receiver is \$100,000 and the target frequency range is much smaller than the GBT, e.g., 1 GHz to 10 GHz as is suggested for initial phase of the SKA. This frequency range can be covered with a single decade-bandwidth receiver instead of four octave-bandwidth ones. The total savings in receiver electronics costs is \$300,000 per antenna or \$900 million for 3000 dishes. Even with a more conservative approach which assumes two near-decade-bandwidth receivers, the cost savings is \$600 million. And this does not even include savings in power and maintenance bills!

This thesis is divided into two parts:

1. **The quadruple-ridged flared horn (Chapters 2–4):** The first part begins with an overview of radio telescope reflector antennas and the common metrics used to evaluate their performance. The requirements of radio telescope feed antennas are discussed in length. In Chapter 3, the quadruple-ridged flared horn (QRFH)—a near-constant-beamwidth reflector antenna feed capable of achieving 7:1 frequency bandwidths—is introduced and its design and analysis are detailed. This discussion is followed by five example QRFH designs demonstrating suitability of the quad-ridged horn in wide range of radio telescopes.
2. **Compound-Semiconductor LNAs (Chapters 5–7):** The topic of the second part of the thesis is design, analysis and measurements of wideband LNAs on two state-of-the-art high electron mobility transistor (HEMT) processes which are introduced in Chapter 5. The results of extensive dc, small-signal and noise characterization of discrete transistors from both processes are described in Chapter 6. In the last chapter of this part, design and measurements of LNAs fabricated on these processes achieving decade bandwidth and more are detailed.

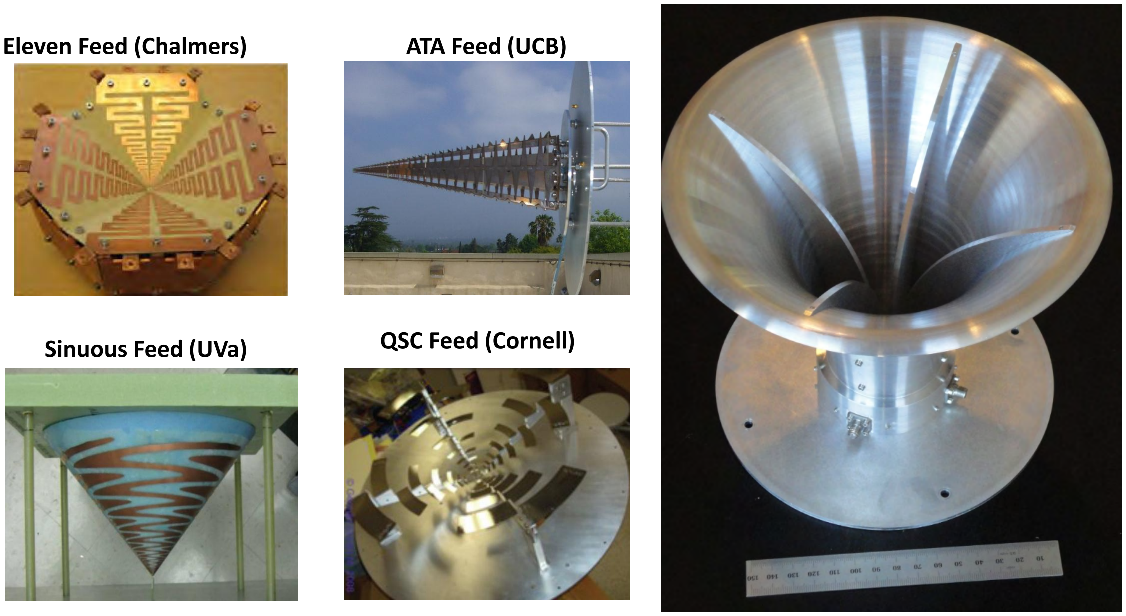
1.1 State of the art in Wideband Feeds

As alluded to earlier, corrugated horns are the standard bearer in terms of reflector antenna feeds for applications above 0.5 GHz requiring the highest sensitivity such as radio astronomy. They meet or exceed all the performance requirements of a radio telescope feed antenna, namely they achieve:

1. almost Gaussian, circularly symmetric radiation pattern with a prescribed nominal beamwidth;
2. little to no change in radiation patterns with frequency;
3. very low sidelobes;
4. excellent cross-polarization;
5. constant or near-constant phase center with frequency.

However, these desirable characteristics can only be realized over a 2:1 frequency bandwidth at most. The bandwidth limitation arises from two factors: 1) depth of corrugations in the horn are proportional to quarter wavelength; 2) ortho-mode transducers used to obtain dual linear polarization.

Due to increasing interest in decade-bandwidth radio astronomy, there has been much emphasis in feed antennas achieving such large bandwidths in the last couple years. As a result, number of ultra-wideband feed antennas with dual linear polarization have emerged. For instance, the four feed antennas under consideration for the SKA project are:



(a) (b)

Figure 1.2: Photographs of the (a) “log-periodic” type wideband feeds, (b) quad-ridged flared horn, all of which are currently under consideration for the SKA project.

1. Eleven feed from Chalmers University of Technology [8];
2. Allen Telescope Array (ATA) feed from University of California Berkeley [9];
3. Quasi self-complementary feed from Cornell University;
4. Sinuous feed from University of Virginia [10]

whose photographs are shown in Figure 1.2(a). It is seen that all are of the “log-periodic” type. As a result, they possess a lot of similar features. Table 1.1 summarizes key features of all of these feed antennas in addition to the quad-ridged flared horn.

Because log-periodic antennas are frequency independent, they maintain constant beamwidth with frequency [11]. This is the case for the three of the four wideband feeds listed above where the exception is the sinuous feed which exhibits more beamwidth variation resulting in somewhat elliptical radiation patterns. On the other hand, the first three feeds, especially the Eleven and the ATA feeds, achieve constant beamwidth over $\geq$ 7:1 frequency bandwidths with fairly good circular symmetry of radiation patterns. Another similarity between these feeds is that they all have differential inputs with 200-260 Ω nominal input impedance. All but the Eleven feed require either two differential LNAs or four single-ended LNAs which need to be gain and phase matched. The Eleven feed employs eight single-ended, matched LNAs or four differential LNAs where each pair of differential LNAs also have to be matched. The ATA feed exhibits significant phase center

	Radiation Pattern Features	Input Imp.	Bandwidth	Cost Est.
Corr. horn	Almost Gaussian beam, constant with freq; low sidelobes, excellent x-pol; const phase center can be designed for different beamwidths	50 Ω	2:1	Low
Eleven feed	Const beamwidth with circular beam; mediocre x-pol; const phase center; tough to change beamwidth	200 Ω diff	7:1	High
ATA feed	Const beamwidth with circular beam; mediocre to poor x-pol; large phase center variation; tough to change beamwidth	200 Ω diff	10:1	Med. to high
QSC feed	Const beamwidth with circular beam; mediocre-poor x-pol; tough to change beamwidth	200 Ω diff	10:1	N/A
Sinuous feed	Mediocre beamwidth stability w/ elliptical beam; mediocre x-pol; const phase center; tough to change beamwidth	200 Ω diff	4:1	Medium
QRFH	**Good beamwidth stability in E & D-planes; mediocre x-pol; small phase center variation; can be designed for different beamwidths**	**50 Ω**	**5:1 – 7:1**	**Low**

Table 1.1: Summary of key features of the five ultra-wideband feeds under consideration for the SKA project

variation with frequency while the others have constant or near-constant phase centers. Finally, nominal beamwidths of these antennas cannot easily be changed to accommodate different reflector antenna optics.

On the other hand, the quadruple-ridged flared horn described in the first part of this thesis possesses two unique capabilities when compared to the other wideband feeds. Its most distinct feature is the ability to design the horn to have a nearly constant beamwidth over a $\geq$ 5:1 frequency band for nominal 10 dB beamwidths between 30 and 140 degrees. Similar to corrugated horns, this flexibility is a result of the horn radiation patterns being primarily determined by the so-called flare angle, defined and explained in Chapter 3. Therefore, this horn could enable broadband frequency coverage on radio telescopes of different optical configurations. The second unique feature of this horn is that its input impedance could be designed to have a nominal value between 50 and 100 Ω while requiring only one single-ended LNA per polarization. This further reduces costs of the next generation telescope systems. Presently, the only disadvantage of the QRFH is the poor beamwidth stability in $\phi = 90°$ plane, while it exhibits good beamwidth stability in $\phi = 0°, 45°$ planes. Phase center variation of the horn is small enough that its impact on aperture efficiency over the desired frequency range is very small.

1.2 State of the art in Wideband LNAs

Compound semiconductor low-noise amplifiers (LNAs) have long been the leading front-end receiver component in applications requiring state-of-the-art performance such as defense, remote sensing, and radio astronomy. Among these, radio astronomy systems require the lowest noise temperature and very high gain stability under cryogenic operation. Today, III-V semiconductor amplifiers dominate radio astronomy receivers due to the pioneering work of Weinreb in 1980 [12] demonstrating the superior performance of these technologies.

Increasing number of elements simultaneously covering decade bandwidths in next generation radio telescopes necessitate very large number of ultra-widebandwidth LNAs with low power consumption. Traditionally, InP has been the semiconductor of choice in radio astronomy microwave and millimeter-wave LNAs due to its superior noise and gain performance up through 150 GHz [13, 14, 15, 16, 17, 18] beyond which super-conducting mixers have been employed. However, due to its niche market, InP has seen the slowest development pace compared to GaAs and silicon. Moreover, centimeter-wave LNAs designed at Caltech and fabricated by Northrop Grumman Corporation have exhibited no improvement in cryogenic noise in addition to roughly 50% yield after pre-selecting MMICs at room temperature based on gate leakage and pinch-off characteristics [19]. This is primarily due to the fact that NGC's InP process is research-oriented rather than a commercial process and is primarily aimed for millimeter-wave electronics as evidenced by record-breaking results produced by NGC InP amplifiers operating above 75 GHz up to 0.5 THz (see [20, 21] as well as some of the references earlier in this paragraph).

As radio astronomy receivers get more complex and require many more elements, there is renewed emphasis on cost, yield and process stability. This leads to reconsideration of GaAs which is commercially more attractive and thus, has enjoyed more investment in process development in recent years [22, 23, 24]. In the second part of this dissertation, room temperature and cryogenic performance of discrete transistors and MMIC LNAs achieving very low noise over decade bandwidths from two state-of-the-art HEMT processes: 35 nm InP pHEMT and 70 nm GaAs mHEMT are investigated. The two LNA designs presented herein cover the following frequency ranges: 1) 1–20 GHz; 2) 8–50 GHz.

In cm-wave astronomy, typical frequency bands of interest for MMIC LNAs have been: 1–12, 4–8, 4–12, 2–14, 3–18 GHz[1]. Another motivation for the 1–20 GHz LNAs designed in this research is the possibility of covering all of these frequency bands in one MMIC. While the packaged amplifier could be optimized for specific frequency bands by specialized input matching networks, a versatile MMIC covering 1-20 GHz could prove very useful and convenient. Additionally, such an LNA with good low-power performance would be very attractive as IF amplifier following SIS mixers whose IF

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[1] These are in addition to more traditional hybrid LNAs usually covering octave bandwidths.

	Technology	BW [GHz]	Gain [dB]	NF [dB]	$\lvert S_{11}\rvert$ [dB]	Power [mW]
Caltech WBA13	0.1 μm InP	1–12	38	1 @ 300 K 0.08 @ 20 K	-15	15-20
Caltech 6-18	0.1 μm InP	6–18	35	0.09 @ 20 K	-15	12
LNF (Chalmers)	0.13 μm InP	1–12	38	0.9 @ 300 K 0.08 @ 12 K	-12	15-20
LNF (Chalmers)	0.15 μm GaAs	6–20	31	1 @ 300 K 0.15 @ 10 K	-10	22

Table 1.2: Key performance specifications of four cryogenic LNAs covering 1–20 GHz

bandwidths reach 15 GHz. Table 1.2 lists key performance metrics of four state-of-the-art cryogenic MMIC LNAs covering subsets of this frequency range.

A cryogenic low-noise amplifier covering 8–50 GHz is not currently available for radio astronomy applications. Instead, typical LNAs in radio astronomy usually only cover a waveguide band, e.g., 26–40 GHz. For instance, a 30–43 GHz amplifier designed at Caltech and fabricated on NGC 0.1 μm InP process achieves 30 dB gain and noise figure of 2 dB at 300 K and 0.36 dB at 20 K with 15–20 mW DC power consumption. Wider bandwidth LNAs with similar or somewhat higher noise performance is of interest as IF amplifier following hot-electron-bolometer (HEB) super-conducting mixers. Another motivation for this LNA in this research has been integration of such a MMIC into a future 8–50 GHz quad-ridged flared horn.

1.3 Publications

Parts of this research has been published as listed below:

- **A. Akgiray** and S. Weinreb, "Noise Measurements of Discrete HEMT Transistors and Application to Wideband, Very Low Noise Amplifiers," submitted to *IEEE Trans. Microwave Theory Tech.*, Jan 2013.

- R. Keller, C. Kasemann, S. Weinreb, **A. Akgiray**, U. Bach, P. Freire, K. Grypstra, R. Karuppusamy, M. Kramer, P. Müller, F. Schäfer and B. Winkel, "An Ultra Broad Band Radiometer Receiver for the Effelsberg 100m Telescope," in press, *Advances in Radio Science*, Jan 2013.

- **A. Akgiray**, S. Weinreb and W. A. Imbriale, "Circular Quadruple-Ridged Flared Horn Achieving Near-Constant Beamwidth Over Multi-Octave Bandwidth: Design and Measurements," *IEEE Trans. Antennas Propag.*, vol. 61, no. 3, 2013.

- W. A. Imbriale, S. Weinreb, G. Jones, H. Mani, and **A. Akgiray**, "The Design and Performance of a Wideband Radio Telescope for the GAVRT Program," *IEEE Trans. Antennas Propag.*, vol. 59, no. 6, pp. 1954-1962, 2011.

- **A. Akgiray** and S. Weinreb, "The quadruple-ridged flared horn: A flexible, multi-octave reflector feed spanning $f/0.3$ to $f/2.5$," ***invited paper***, *the 7th European Conference on Antennas and Propagation,* Gothenburg, Sweden, April 2013.
- M. Varonen, R. Reeves, P. Kangaslahti, L. Samoska, **A. Akgiray**, K. Cleary, R. Gawande, A. Fung, T. Gaier, S. Weinreb, A. C. S. Readhead, C. Lawrence, S. Sarkozy, and R. Lai, "A 75-116-GHz with 23-K noise temperature at 108 GHz," to be presented at the *2013 IEEE International Microwave Symposium,* Seattle, WA, USA, June 2013.
- **A. Akgiray** and S. Weinreb, "Ultrawideband Square and Circular Quad-Ridge Horns With Near-Constant Beamwidth," presented at *2012 IEEE International Conference on Ultra-Wideband,* Syracuse, NY, USA, September 2012.
- S. Weinreb, **A. Akgiray** and D. Russell, "Wideband Feeds and Low Noise Amplifiers for Large Arrays," presented at *XXX URSI General Assembly and Scientific Symposium of International Union of Radio Science,* Istanbul, Turkey, August 2011.
- **A. Akgiray**, W. A. Imbriale and S. Weinreb, "Design and Measurements of Dual-Polarized Wideband Constant-Beamwidth Quadruple-Ridged Flared Horn," *2011 IEEE Int. Symposium on Antennas and Propag. and USNC/URSI National Radio Science Meeting,* Spokane, WA, USA, July 2011. ***Student Paper Competition Honorable Mention***
- W. A. Imbriale and **A. Akgiray**, "Performance of a Quad-Ridged Feed in a Wideband Radio Telescope," *5th European Conference on Antennas and Propag.,* Rome, Italy, April 2011.
- **A. Akgiray** and S. Weinreb, "Wideband Near-Constant Beamwidth Flared Quad-Ridge Horn Feed for Reflector Antennas in Radio Astronomy," *2011 USNC-URSI National Radio Science Meeting*, Boulder, CO, USA, January 2011.