A Low-Cost Wideband UHF Downconverter With 5:1 Tuning Range

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***Abstract*—Future telescopes being considered for radio astronomy are likely to require large numbers of low-cost downconverters with wide bandwidth, wide tuning range, and the ability to operate close to strong sources of interference. This paper presents a simple UHF downconverter with 50–60 dB gain, 3 MHz instantaneous bandwidth and typical IIP_3 of about −26 dB over a tuning range of 400 to 2000 MHz. Image rejection is 30 to 40 dB from 400 to 1000 MHz, and increases to greater than 80 dB above 1000 MHz. Selectivity is greater than 60 dB for signals 15 MHz distant. This design can currently be built in small quantities for less than $500 (U.S.) each.**

***Index Terms*—Downconverter, radio astronomy, receiver, UHF Radio.**

I. Introduction

TRADITIONAL radio telescopes use large paraboloidal reflector ("dish") antenna systems with a small number of feed elements located at the focus [1]. These feed elements are connected to low-noise amplifiers (LNAs) which dominate the system-generated noise contribution by providing high gain with low noise figure. The LNA outputs are then shifted downward in frequency ("downconverted") from the frequency of observation to a lower frequency for digitization and analysis. Relative to other applications such as radar and communications, downconverters for radio astronomy require large tuning range (as much as 5:1 at lower frequencies), large instantaneous bandwidth (1–100 MHz), and high gain. These receivers must also exhibit good linearity, albeit in the presence of signals and interference which are normally weak due to the remote sites at which radio telescopes are usually located.

Recently, there has been growing interest in using large arrays of broadbeam, low-gain antenna elements in lieu of dishes [2], [3]. In this concept, each antenna (or possibly small sub-arrays of antennas) is individually amplified by an LNA, downconverted, and digitized. The advantages of this approach include electronic beam steering, multibeaming, and adaptive nulling of interference. For such systems, the number of elements required to achieve the same effective aperture as a single large dish may be as high as 10^6. Design concepts for future telescopes envision up to 10^8 antenna elements to achieve sensitivity two orders of magnitude greater than existing telescopes [4]. Even if most of the combining associated with beamforming is done in analog fashion at the received frequency, such systems will require unprecedented numbers of LNAs, downconverters, and digitizers. Needless to say, these subsystems must be very inexpensive.

The ElectroScience Laboratory, Ohio State University, Columbus, is developing a system to demonstrate this technology, called "Argus" [3]. Currently, 64 antennas are planned. Each antenna will have a dedicated LNA, downconverter, and digitizer. This paper presents results of the design and development of a candidate downconverter for Argus [5]. This downconverter tunes continuously from 400 to 2000 MHz with 3 MHz instantaneous bandwidth. The output is centered at 60 MHz and is intended for direct IF-sampling by an analog-to-digital converter. The downconverter uses a "split-band" multiple-conversion superheterodyne design with three externally generated local oscillators (LOs). The cost per unit is well under $500 (U.S.) in small quantities. The downconverter provides 50–60 dB gain at a noise figure of 10 dB or less with input third-order intercept (IIP_3) for in-band signals between −18 dBm and −32 dBm depending on frequency.

In radio astronomy, it is typically not practical or desirable to observe at frequencies in which strong interferers appear in the passband. Thus, the in-band IIP_3 is not as important as the IIP_3 for cases in which the strongest signals are outside the 3-MHz passband. For the case in which the signals are outside the passband but within 7.5 MHz of the center frequency, the IIP_3 improves by about 7 dB. When the signals are more than 15 MHz away, the IIP_3 improves by an additional 7 dB. This combination of selectivity and relatively high IIP_3 makes this design "interference robust" in the sense that it can be used to observe in bands which are close to terrestrial interference.

An overview of the downconverter is provided in Section II of this paper. Section III includes design and construction information. Section IV presents measurements of the completed unit.

II. Downconverter Concept

A block diagram of the downconverter is shown in Fig. 1. The downconverter uses a split band multiple-conversion superheterodyne architecture. The architecture is "split band" in the sense that the "lowband" tuning range of 400–1000 MHz and "highband" tuning range of 1000–2000 MHz are isolated and processed differently. The highband is downconverted to an intermediate frequency (IF) of 600 MHz, bandlimited to 15 MHz, downconverted to 60 MHz, and then bandlimited to 3 MHz. The lowband, however, is first upconverted to 1575 MHz, bandlimited to 20 MHz, and then injected into the highband signal path. 1575 MHz was selected for this purpose due to availability of good-quality low-cost filters for the GPS market. The upconvert-downconvert approach applied to the lowband provides

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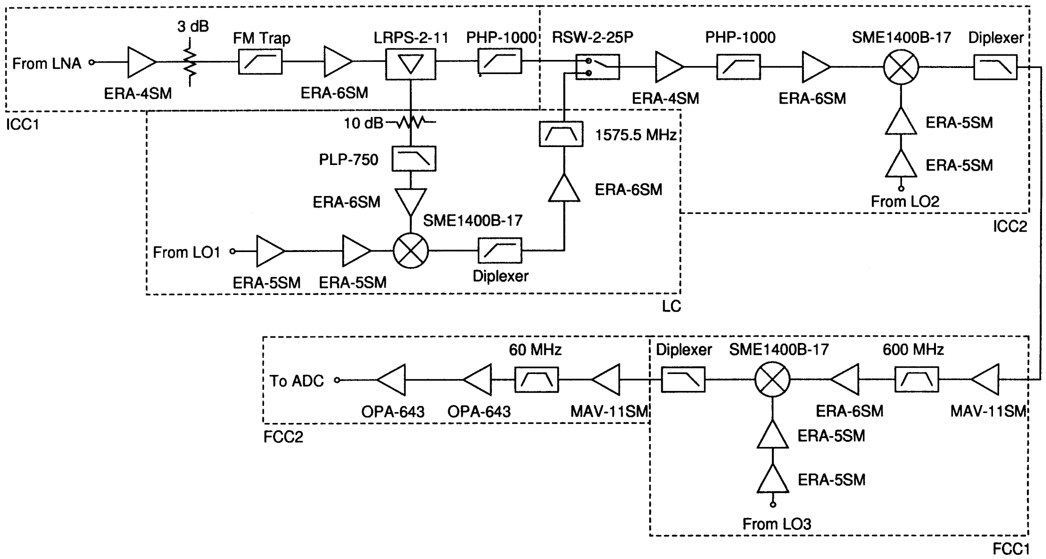

Fig. 1. Block diagram of the downconverter. Dashed lines indicate printed circuit board boundaries. See Section III for additional information.

good image rejection with relatively little impact on the overall complexity of the receiver. Switching between the two modes of operation is via an RF switch as indicated in Fig. 1.

Summary analyzes of gain, noise figure, and IIP_3[6]for this design are provided in Table I. These tables are based on data provided by the component manufacturers. Note that the performance in highband and lowband operation is quite similar. For the purposes of computing IIP_3, three classes of operation have been identified. "Class I" operation refers to the case in which the test tones are inside the 3-MHz passband. In this case, all components contribute to the linearity of the downconverter. In "Class II" operation, the test tones are outside the 3 MHz passband but inside the 15-MHz passband of the 600-MHz IF. In this case, only those components up to the 60 MHz IF filter contribute to the linearity of the downconverter. In "Class III" operation, the test tones are outside the 15-MHz passband of the 600-MHz IF. In this case, only those components up to the 600 MHz IF filter contribute to the linearity of the downconverter. As expected, the IIP_3 of the downconverter for Class II operation is considerably better than for Class I operation, about 7 dB. Similarly, the IIP_3 for Class III operation is considerably better than for Class II operation; again, about 7 dB.

TABLE I
GNI ANALYSIS. THE BOTTOM, MIDDLE, AND TOP ROWS OF EACH TABLE CORRESPOND TO CLASSES I, II, AND III, RESPECTIVELY

Stage	G dB	F dB	IIP_3 dBm
At input to 600 MHz BPF	36.5	6.6	−11.8
At input to 60 MHz BPF	43.5	6.6	−18.1
At downconverter output	63.5	6.6	−26.4

Highband operation

At input to 600 MHz BPF	36.3	10.0	−12.9
At input to 60 MHz BPF	43.3	10.0	−19.3
At downconverter output	63.3	10.0	−26.5

Lowband operation

III. DESIGN AND CONSTRUCTION

The downconverter was designed using five separate printed circuit boards (PCBs) as indicated in Fig. 1. Also indicated in Fig. 1 are the key components. Detailed schematics for the downconverter can be found in [5]. All model numbers in the figure refer to components obtained from Mini-Circuits, Inc., except for the SME1400B-17 mixers, which are by Watkins-Johnson, Inc., and the OPA-643 operational amplifiers, which are by Burr-Brown, Inc. The 1575 MHz GPS filter is a dielectric filter by Toko, Inc., and the 600-MHz filter is a helical filter also by Toko, Inc. The 60-MHz filter is a stock bandpass filter available from TTE, Inc. None of these component choices are especially critical to the design; our choices were driven mainly by ease of acquisition in small quantities. Furthermore, because many of these parts are commonly used in consumer electronics, numerous alternatives are available. The FM trap and diplexers are custom designs based on design rules described in [7], and are implemented in discrete surface mount components.

The PCBs are two-sided (two layers) using FR4 substrate material in order to minimize cost. All components were mounted on one side, with only dc power traces on the opposite side. Board interconnections were made using RG-174A coaxial cable, again, to minimize cost.

The completed downconverter unit is built into a die-cast aluminum enclosure measuring 18.8 $\times$ 11.9 $\times$ 7.8 cm, with an RF-tight heat vent in the lid. The enclosure does not include a fan or other method for heat control. It was found that the ventilation normally provided by a rack-mounted fan was sufficient to keep the unit from overheating. The unit consumes 1.15 A at 15 V dc. No attempt was made to minimize power consumption

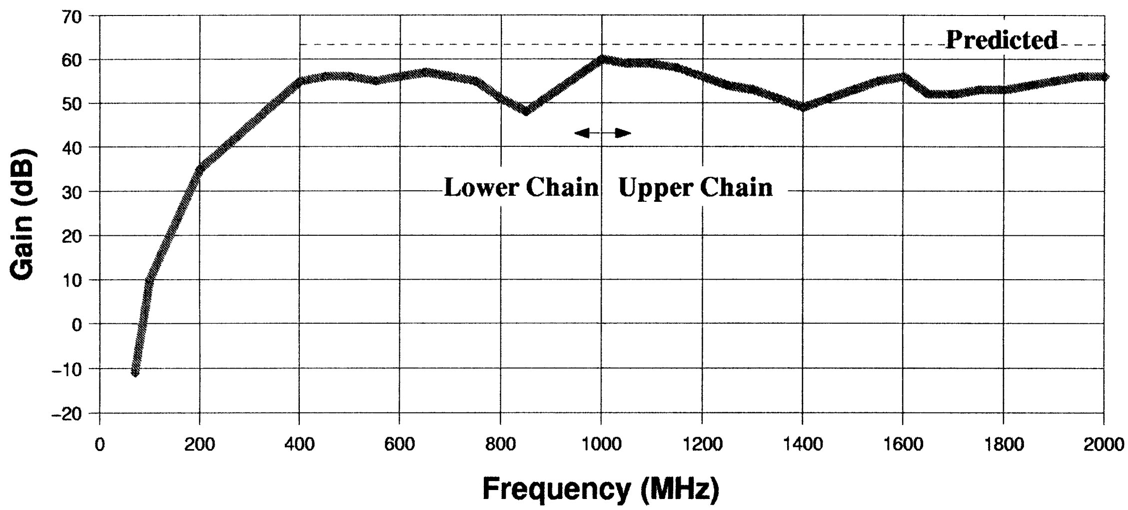

Fig. 2. Measured downconverter gain.

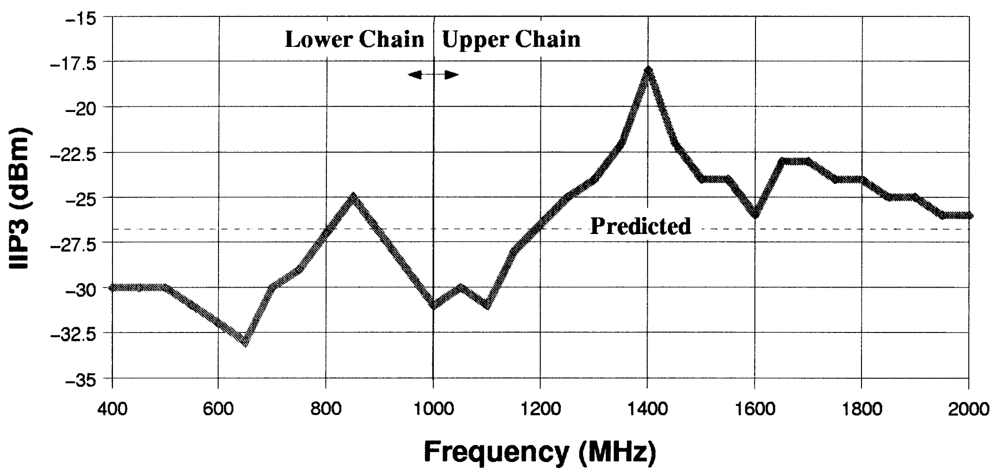

Fig. 3. Measured IIP_3 for Class I operation.

in the design; thus, considerable improvement is possible in this area.

IV. Evaluation

This section presents performance measurements for the first of the "production" downconverters to be built. Gain and IIP_3 are shown in Figs. 2 and 3, respectively. Gain varies between 50 and 60 dB over the tuning range and is somewhat lower than predicted. However, this is expected as no attempt was made to anticipate losses between components or PCBs. Also note that the gain varies significantly between 800 MHz and 1000 MHz. This is a result of the 750 MHz corner frequency of the PLP-750 lowpass filter, which was intended to provide some additional protection from strong signals present in the $800 (U.S.) MHz cellular band. Class I IIP_3 varies between extreme values of -17 dBm and -32 dBm over the tuning range, but is generally consistent with the predicted value of -26 dB.

Selectivity is illustrated in Fig. 4. Note that the selectivity exceeds 60 dB for Class III operation, allowing the downconverter to be used relatively close to bands containing strong interference.

Image rejection for the first mix is illustrated in Fig. 5. Note that the image rejection is excellent between 1000 and 1800 MHz, and is between 30 and 40 dB between 400 and 9net00 MHz. The lower image rejection for lowband operation is not of much concern since the corresponding image frequency range is between 2200 and 2750 MHz, which does not tend to exhibit strong interference and could in any event be easily improved with an additional lowpass filter preceding the downconverter. The poor image rejection above 1800 MHz, on the other hand, is a limiting factor. This is because the corresponding image band (600–800 MHz) includes mobile radio signals, which are quite strong in some locations.

Because the system noise figure in any practical radio astronomy application is set by LNAs preceding the downconverters [1], the noise figure of the downconverter itself is not of much interest. Similarly, there are no special considerations with respect to LO phase noise. In benchtop testing using LOs exhibiting phase noise density of -80 dBc/Hz or better at 1 kHz offset, our measurements indicated that the downconverter's noise figure was within 1 dB of the estimates shown in Table I.

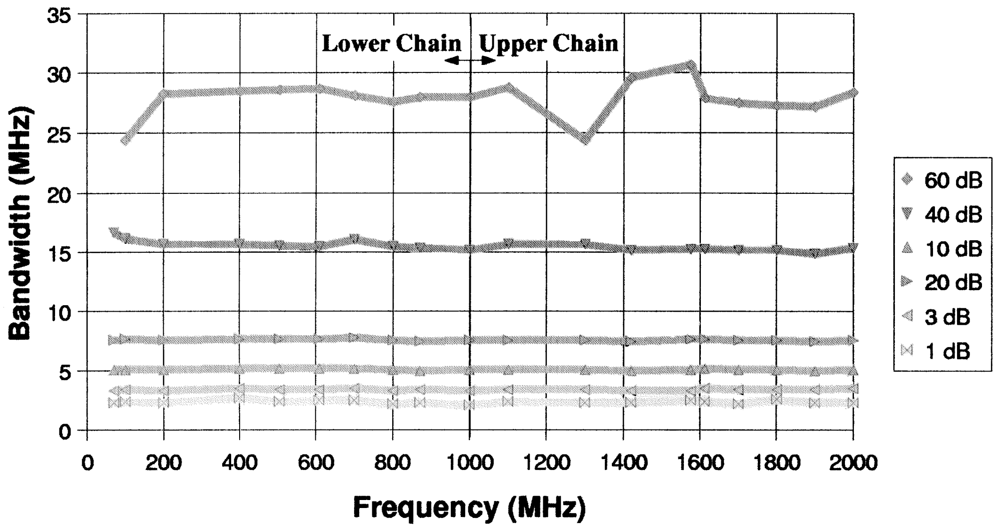

Fig. 4. Measured instantaneous bandwidth. Various curves show the bandwidth defined as indicated, e.g., the 3-dB bandwidth is about 3 MHz.

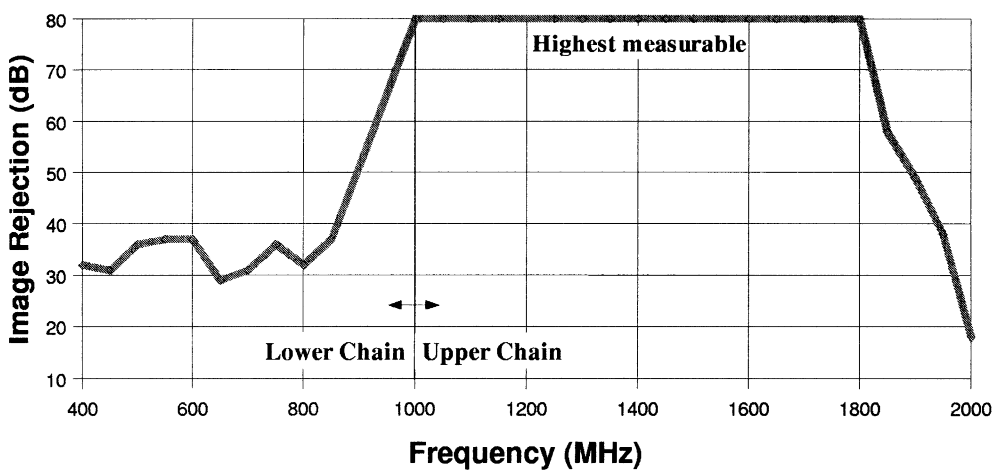

Fig. 5. Measured image rejection (accurate image rejection measurements in excess of 80 dB were not possible.).

Since the receivers are intended to be used for coherent array processing, it is also worth considering the issues of calibration and crosstalk between receivers. Due to the low gain of the receivers with respect to the overall receiver gain (from antenna terminals to A/D input is typically on the order of 100 dB), these downconverters represent no special challenges in terms of calibration. That is, we have found the achievable system calibration accuracy is not noticeably affected when using this downconverter as opposed to a more traditional downconverter consisting of connectorized components. With respect to crosstalk, we find this to be dominated primarily by the design of the LO distribution system and A/D banks. For our measurements, our LO distribution was completely passive, consisting only of power dividers. We ensured reasonably good impedance matching within the distribution system by using 6-dB attenuators at all input and output ports. Under these conditions, we found that crosstalk between receivers was less than −50 dB, and was completely dominated by coupling within our A/D banks. The new downconverters appear neither to enhance nor degrade this performance.

A total of eight downcoverters have been built to date. Measurements have been performed on several of these, with consistent results.

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