A Digital Continuum Backend
for the Green Bank Telescope 1 cm and 3 mm Receivers

A Proposal to the National Radio Astronomy Observatory

submitted by

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Contents

1 Summary

We propose to construct a digital continuum backend for use with the 1 cm and 3 mm receivers on the Green Bank Telescope. The backend will digitize and record the signals from the broad-band continuum detectors in the two receivers, generate phase-switching signals for the front-end, and demodulate the phase switch. We plan to be ready for on-telescope tests by May 2003. The estimated cost of the project is $225,220.

2 Introduction

The Robert C. Byrd Green Bank Telescope, at the National Radio Astronomy Observatory's site in Green Bank, West Virginia, is a 100-meter fully steerable telescope of novel design. Active control of the surface will allow it to operate with high efficiency at wavelengths as short as 3 mm. It will be the most sensitive fully-steerable telescope in the world. The NRAO is developing a set of receivers to cover 0.290 to 116 GHz, most of which are now in service.[1]

Receivers to cover 26–40 GHz ("1 cm") and 68–116 GHz ("3 mm") are currently being designed. They are both dual-beam, dual-polarization, pseudo-correlation receivers. They can be operated in total-power mode for spectral-line work and in beam-differencing mode for sensitive continuum observations; beam differencing suppresses atmospheric emission which is a major source of noise in observations at these frequencies.[2] Both receivers contain filter banks to split the broad continuum band into sub-bands (4 for the 1 cm receiver and 3 for the 3 mm receiver) and detectors to measure the power received in each band. There is a separate detector for each beam and each polarization, giving a total of 16 total-power measurements in the 1 cm receiver and 12 in the 3 mm receiver.

This is a proposal to design, construct, and commission a digital backend that will be the primary instrument for continuum observations with these two receivers. It will sample and digitize the total power outputs from the detectors; and control and demodulate phase switching in the pseudo-correlation front end. The time streams will be available for real-time display and recorded on disk for later analysis.

3 Scientific Requirements

The GBT is designed as a general-purpose instrument and the continuum radiometers should be suitable for a wide-range of observations from rapid scanning of strong sources to deep integrations on faint sources.

Possible scientific programs in the 1 cm and 3 mm bands include:

- Flux-density measurements of known objects, e.g., faint radio galaxies, Kuiper-belt objects.
- Deep blind surveys for faint sources, e.g., for studying cosmology and radio source evolution, and for support of other programs (e.g., CMB observations with instruments of lower resolution).
- Imaging observations of extended objects, e.g., planets.

[1] See the GBT web page, `http://www.gb.nrao.edu/GBT/GBT.html`, and the GBT User's Manual, `http://www.gb.nrao.edu/GBT/GBTMANUAL/`.

[2] The design of the 1 cm receiver is described in `http://www.gb.nrao.edu/electronics/projects/1cmRx/`, and that of the 3 mm receiver is described in `http://www.gb.nrao.edu/electronics/projects/3mmRx`.

- Studies of the anisotropy in the microwave background radiation, including the Sunyaev-Zeldovich effect in clusters of galaxies and the intrinsic anisotropy in the CMB.

Many of these programs seek the highest possible sensitivity and will require long integration times. Low-level systematic effects that only show up in long integrations can be a serious impediment. The radiometers should be designed to minimize low-level contamination and also to indicate when contamination is present. Recording two polarizations and several frequency channels provides some redundancy and allows cross-checks for contaminating signals.

Splitting the broad continuum band into several channels will provide crude spectral information (i.e., spectral index of synchrotron or thermal sources). It will also permit some data selection in cases where the signal is partly contaminated by atmospheric emission or low-level RFI.

Differencing the signals from the two beams can be used to suppress atmospheric contamination. The ability to record both the undifferenced and the differenced signals gives some flexibility and can help to characterize systematic or instrumental errors.

The receivers record both L and R polarizations. Normally the two polarizations will be added to improve sensitivity; comparison of the two polarizations provides another check for low-level errors or contamination.

4 Specifications

The digital continuum backend should digitize the output of up to 16 parallel detectors (in the 1 cm receiver; the 3 mm receiver has 12), each of which has a bandwidth of up to 8 GHz (in the 3 mm receiver; 3.5 GHz in the 1 cm receiver) with sufficient resolution to fully sample the noise, assuming a system temperature of 30 K (1 cm) or 80 K (3 mm). The signals should be integrated for a user-specified integration time with a minimum of 1 ms. The dynamic range should be sufficient to record signals of several hundred Jy without overflow.

The backend should provide programmable phase-switching signals to control the 180° phase-switches in the two arms of the pseudo-correlation receiver, and synchronously demodulate the radiometer outputs. To minimize the effects of amplifier gain variations, the phase-switch period should be as short as possible. The design goal is a period of < 1 ms.

The backend will control noise-diode calibration sources in the receivers under direction of the GBT software system.

All the radiometer output streams will be passed to the GBT control system via ethernet for archiving, display, and further manipulation (e.g., differencing, channel averaging, polarization averaging).

5 Preliminary Design

A preliminary design for the digital continuum backend, meeting the specifications listed in the previous section, is described in *A Digital Backend for the GBT 1 cm and 3 mm Continuum Radiometers* by Martin Shepherd (attached). It consists of (a) a digitization section; (b) a digital integration and phase-switch demodulation package, based on a programmable gate array (FPGA); (c) a single-board control and monitoring computer with an ethernet connection to the GBT monitor and control system. We propose to deliver two complete, identical backends, one for each receiver.

5.1 Design Issues

In this section we list a number of choices made in the course of the preliminary design. These issues should be reviewed and finalized at the Preliminary Design Review.

1. **Dynamic Range.** The most significant constraint on the design comes from the requirement to be able to observe strong sources. If a lower dynamic range were acceptable, we could both cut the data rate and increase the phase-switching frequency by using a faster, lower resolution A/D converter. Other options include: (a) not supporting observations of strong sources; (b) split the full signal range into user-switchable small and strong signal regimes, with associated complications in hardware and calibration.

2. **Phase switching.** We have chosen to supply the phase-switching signals from our back-end to the switches in the front-end, rather than synchronizing with a supplied phase switch signal. This does not preclude NRAO from using an alternate phase-switch signal when the back-end is not in use.

3. **Phase switch cycle time.** We propose a cycle period (minimum integration time) of 400 μs, requiring 100 μs integrations in the A/D converter. The actual number will be under program control, but not < 100 μs, although there is no obvious reason to run slower.

4. **Maximum integration time.** The design sets this at $2^{13} \times 100\ \mu\text{s} = 819.2$ ms, but further integration will be possible in the real-time cpu.

5. **Differencing in hardware or software.** The proposed design records all 4 demodulated outputs in each channel (L1, R1, L2, R2; with up to 4 channels) and leaves differencing to the non–real-time software. An alternate, somewhat simpler, design would form the analog differences L1$-$L2, R1$-$R2 (or L1$-$R2, R1$-$L2 depending on the front-end design) prior to A/D conversion, and would require fewer components and have a lower output data rate.

6. **Support for two receivers.** We propose to deliver two complete, identical backends. Alternate designs might time-share some of the components (digital elecetronics, computer) between the two receivers.

7. **Software interface.** We will provide a documented network-socket interface for control and data return, and work with NRAO personnel to integrate this interface into an Ygor device manager in the GBT software system. We will also provide a rudimentary user interface to the same network sockets for testing.

8. **Packaging and RFI.** We will endeavor to minimize potential RFI emission from the backend. The details of the packaging (including cooling) to accomplish this have yet to be determined.

9. **Spares.** We plan to deliver full spare parts for 10 years of operation. The spares inventory has not yet been defined.

6 Principal Interfaces

Before a detailed design can be completed, a number of interfaces with other parts of the GBT project must be fully defined. The principal interfaces include:

1. Packaging: mechanical and RFI constraints.

2. Interfaces with front-end components: radiometer outputs, phase-switch control, noise-diode control.
3. Timing: GBT 1 PPS signal.
4. Power.
5. Control interfaces (ethernet).
6. Software interfaces and Ygor functionality: control functions; data return.

7 Project Staffing and Management

Personnel assigned to this project will include:

Project Scientist Tony Readhead (no time budgeted).

Project Engineer Martin Shepherd (15 months at 60% = 9.0 months). Overall design, software, testing.

Project Manager Tim Pearson (12 months at 20% = 2.4 months). Project management, testing.

Engineer/Technician John Yamasaki (6 months). Board layout and construction, testing.

Consultant Steve Padin (no time budgeted)

Tim Pearson will act as Project Manager and primary liaison with NRAO.

8 Project Budget

We request that funds be awarded in two increments, corresponding to calendar years 2001 and 2002. Calendar year 2001 includes support for the preliminary design phase, which has now been completed.

	Year 1		Year 2		Total	
	1/1-12/31/2002		1/1-6/31/2003			
Salaries	*months*		*months*		*months*	
Total salaries	10.6	$67,206	6.8	$44,698	17.4	$111,904
Staff benefits @ 25%		$16,801		$11,175		$27,976
Total salaries and benefits		$84,007		$55,873		$139,880
Parts	*Count*					
A/D converters	32	$1,000		$0		$1,000
Real-time CPU+PSU, memory, flash disk, enclosure	2	$6,000		$0		$6,000
Altera FPGA	2	$800		$0		$800
Backend enclosure	2	$6,000		$0		$6,000
PCB fabrication	2	$8,000		$0		$8,000
Miscellaneous parts		$2,000		$0		$2,000
Spares		$3,116		$4,884		$8,000
Contingency		$3,570		$0		$3,570
Development workstation (PC)	1	$2,000		$0		$2,000
Total parts		$32,486		$4,884		$37,370
Travel						
Trips to Green Bank	5	$5,000	8	$8,000		$13,000
Total travel		$5,000		$8,000		$13,000
Indirect costs						
25% of salaries and benefits		$21,002		$13,968		$34,970
Total request		$142,495		$82,725		$225,220

9 Project Timeline

The project is divided into 4 phases:

- **Preliminary design phase.** This phase started in about January 2001, and will end with a Preliminary Design Review (Green Bank) in September 2001. The purpose of the Preliminary Design Review is to review the preliminary design (attached), verify that the specifications are correct and that the design will meet the specifications, identify and define all interfaces with other components of the GBT system, and to approve commencement of the detailed design phase. If approved, the Memorandum of Agreement will be signed at this time and funding will be authorized.

- **Detailed design phase.** This phase includes identification of all parts to be purchased, purchase of long-lead-time items, layout of PCBs, finalization of all interfaces, and design and prototyping of software and test systems. This phase will end with a Detailed Design Review (Green Bank), for which we will prepare a detailed design document, a test plan, and interface control documents. We hope that the preliminary design is sufficiently complete that the detailed design can proceed fast, and we allocate 3 months for this phase.

- **Construction and lab testing.** This includes final layout of PCBs, PCB fabrication, mechanical assembly, and complete software coding and testing. The backend will be tested in the lab at Caltech using signal generators and a software test harness. We suggest that this phase end with a Pre-Delivery Review in Pasadena, which one or two NRAO representatives will attend.

- **Integration and commissioning.** This final phase will take place in Green Bank. It will involve integration of the hardware with the GBT receivers and control/monitor system, including lab tests; followed by testing on the telescope in astronomical observations. It will end with an Acceptance Review (Green Bank) at which Caltech will present final (as-built) documentation for hardware and software and the results of the test observations.

The budget is based on the following timeline. The timeline calls for completion of the project by June 30, 2003. If the project takes longer than anticipated to complete, additional funding may be necessary. Caltech will keep NRAO fully informed of any delays in the schedule.

Sep 6, 2002	Preliminary Design Review
Sep–Dec, 2002	Detailed design phase
Dec 2002	Critical Design Review
Jan 2002–May 2003	Construction and lab testing
May 2003	Pre-Delivery Review
May–Jun 2003	Green Bank integration and on-telescope tests
Jun 2003	Acceptance Review