Receivers for the wideband Submillimeter Array

Paul K. Grimes, Raymond Blundell, Patrick Leiker, Scott N. Paine, Edward C.-Y. Tong, Robert W. Wilson, and Lingzhen Zeng.

***Abstract*—The Submillimeter Array (SMA) was conceived three decades ago as the world's first submillimeter interferometer capable of sub-arcsecond imaging in the frequency range from 200 to 700 GHz. Since it began full science operations in 2004 it has been continuously upgraded with new receiver cartridges, expanded intermediate frequency (IF) bandwidth, and augmented polarimetric and dual frequency observing modes. The next step in the development of the SMA is called the wideband Submillimeter Array (wSMA). The wSMA upgrade will replace the original SMA cryostats, receivers, and receiver selection optics with all new systems, and incorporate a number of major upgrades to the backend IF signal transport and correlator systems. This will enable the wSMA to operate with 32 GHz instantaneous bandwidth per receiver polarization, and will form the basis of future development efforts.**

***Index Terms*—Radio astronomy, submillimeter astronomy, instrumentation, submillimeter receivers.**

I. INTRODUCTION

THE SMA began full science operations in 2004 with a suite of double side band (DSB) SIS mixer receivers operating in the 230, 345, and 690 GHz bands [2]. The 345 and 690 GHz receiver sets were co-polarized and could be used in conjunction with the 230 GHz receiver sets, which were operated in the orthogonal polarization. Each of the receivers had a 2 GHz-wide IF bandwidth and a purpose-built ASIC correlator combined the signals from the different antenna pairs for a total processed on-sky bandwidth of 2 polarizations x 2 sidebands x 2 GHz = 8 GHz.

Incremental improvements to the receivers and the addition of 240 GHz and 400 GHz band receivers that overlap with the original 230 GHz and 345 GHz bands on opposite polarizations, coupled with the development and deployment of a new correlator, have resulted in significant improvements in sensitivity, chiefly through increased on-sky bandwidth, and the addition of polarimetric imaging capabilities. The total processed on-sky bandwidth is currently 48 GHz, as the DSB receivers now provide output across a 12 GHz wide IF band (4–16 GHz) and the sidebands are separated in the correlator. The additional correlator capacity to process this bandwidth is currently being commissioned.

TABLE 1
SMA VS WSMA RECEIVER SPECIFICATIONS

	SMA	wSMA
Receiver Bands (LO Tuning, factors from phase lock loop frequency)	**200** 186-242 GHz, ×2 multiplication **240**: 210-270 GHz, ×3 multiplication **300**: 271-349 GHz, ×3 multiplication **400**: 330-420 GHz, ×4 multiplication	**230**: 210-270 GHz, ×3 multiplication **345**: 280-360 GHz, ×3 multiplication
Polarization	Two single polarized receivers from two groups (**200**+**300**, **240**+**400**) 45° to elevation axis.	Dual polarized receivers 45° to elevation axis.
Receiver Selections	**200** + **240** **200** + **400** **300** + **240** **300** + **400**	**230** dual polarized **345** dual polarized **230** pol 1 + **345** pol 2 (with wire grid) **230** dual pol + **345** dual pol (with dichroic, limited tunings)
IF Band	4-16 GHz	0.1-4 GHz + 4-16 GHz (possible expansion to 20 GHz)

Comparison of the current receiver configuration of the SMA (as of May 2020) and the proposed wSMA receiver configuration.

The receivers offer good performance over a wider range of sky frequencies than the local oscillator (LO tuning ranges shown in this table. However, performance at the extreme edges of the accessible sky frequencies is not guaranteed.

Following these improvements, the next step in the ongoing development of the SMA will be to replace the original receiver cryostats and receiver selection optics with all-new hardware [3]. A major impetus for this upgrade is the need to replace the aging cryogenic systems, which are no longer supported by the

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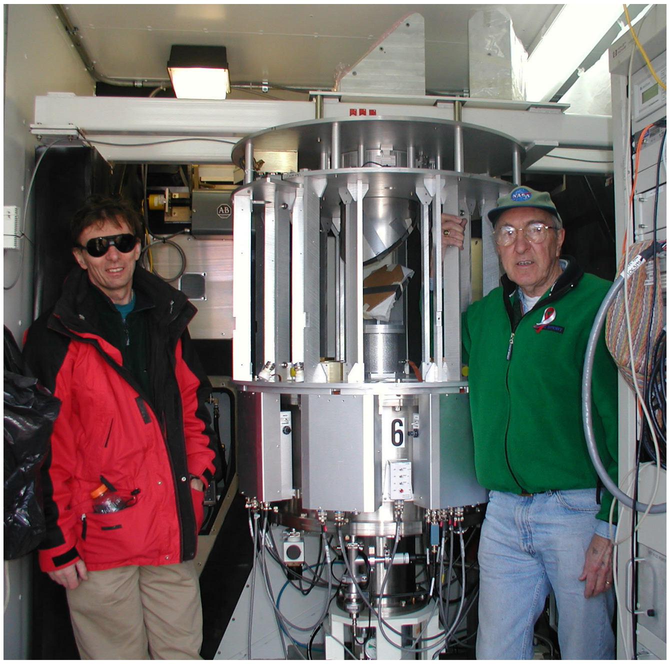

Fig. 1. SMA receiver and receiver optics cage in an SMA antenna, circa 2005. (with John Barrett and SMA Director Raymond Blundell). The SMA beam waveguide mirrors M6 and M5 are visible at the top of the image, with the optics cage containing the moving wire grid and mirror combiners below the cross-beam. The cryostat is below the optics cage, with the receiver electronics "cheeks" mounted around it.

manufacturer. This necessary replacement provides an opportunity to redesign the receiver systems to take advantage of recent developments in submillimeter receiver design, to make provision for future receiver developments, and to optimize the receiver systems for the key science goals of the SMA for the coming decade [4].

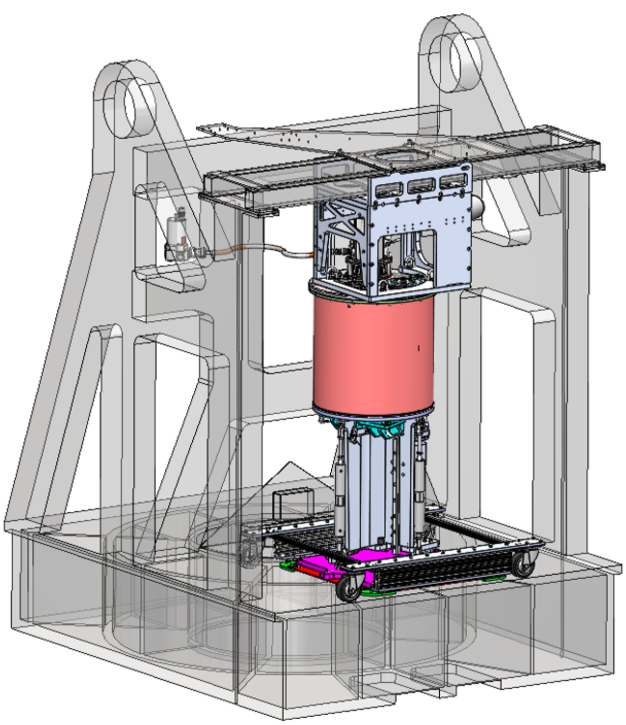

Fig. 2. wSMA Receiver cryostat (vacuum shell in pink), support structure and alignment structure in the SMA receiver cabin (existing structures are transparent). Rendering courtesy of HPD Inc.

A side-by-side comparison of the main receiver specifications for the current SMA and the wSMA is given in Table 1.

The increased receiver IF bandwidth, improved throughput due to the reduced use of room temperature and transmissive optics, incremental improvements to our SIS mixer performance, and improved coalignment of the orthogonal polarization beams on the sky introduced by this upgrade are expected to result in a significant improvement in the sensitivity of the SMA, as well as improved instrumental polarization and efficiency for polarimetric observations, and improved reliability of the receiver systems.

The upgrades to the wSMA receiver and other systems will also serve as a basis for future development of the SMA. The wSMA receiver system has been designed to allow the future development and deployment of sideband-separating receivers, and upgrades to even wider IF bandwidths, while the upgrades to the IF/LO signal transport system will provide communication capacity for digital IF transmission and other advancements.

One particular feature of the wSMA cryostat and optics design is the availability of space and an optical port to allow the installation of additional "guest" receivers alongside the wSMA receivers. It is envisioned that these guest receiver positions could be used to demonstrate new receiver technologies in an interferometer environment (e.g. multi-beam receivers or receivers using new frontend technologies), or to deploy specialized receivers for dedicated observing campaigns.

In this paper, we give an update on the status of the wSMA upgrade, describe the wSMA receiver systems, and present the key receiver technology developments that are part of the upgrade. We also present current developments for improving the calibration of the SMA/wSMA, incorporating a sky frequency dependent system noise temperature measure.

II. The wSMA Receiver Upgrade

The replacement of the SMA receivers, receiver optics, and cryogenics with a completely new receiver system is the major element of the wSMA upgrade. The existing receiver system is shown in Fig. 1, and consists of the receiver optics cage, mounted on top of the receiver cryostat, with the whole stack supported from the floor of the antenna cabin. The receiver optics cage mates to the "M456" plate that carries the SMA beam waveguide, made up of M4, M5 and M6, and the calibration load unit. This plate is supported in the receiver cabin by a beam across the cabin.

The new wSMA receiver system will replace everything between the M456 plate and the cabin floor (Fig. 2). The new cryostat will be aligned to the M456 plate by an alignment structure on top of the cryostat, and will be mechanically supported from the cabin floor by a sprung support that will ensure that the alignment structure is in compression at all times.

The new wSMA receiver cryostats will each house two dual polarization receiver cartridges, operating in two frequency bands; a low band with a local oscillator (LO) frequency from

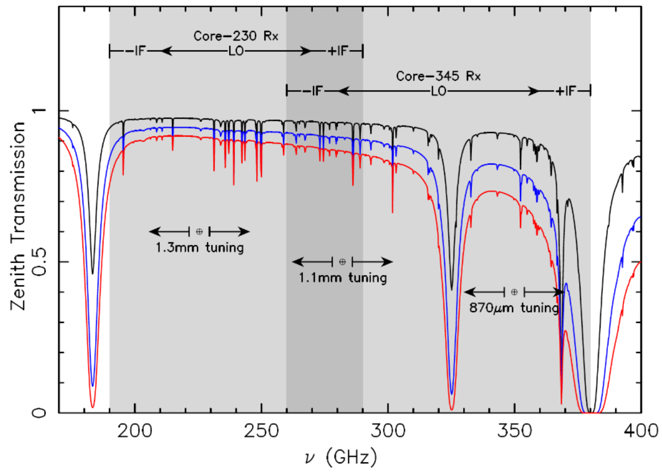

Fig. 3. wSMA receiver bands sky frequency coverage, overlaid on Maunakea sky transmission for the best 50%, 25% and 10% weather.

210 to 270 GHz, and a high band with an LO frequency from 280 to 360 GHz. The receiver system will operate with an IF of 0.1 – 16 GHz (potentially expanding to 0.1–20 GHz at a later time), giving additional frequency coverage outside of the LO tuning ranges so that continuous coverage will be obtained from ~194 to ~374 GHz. The tuning range of the wSMA receivers is shown in Fig. 3. The receivers will deliver 16 GHz bandwidth per polarization per sideband, for a total of 2x2x16 = 64 GHz of processed on-sky bandwidth.

The current room temperature receiver selection optics will be replaced with a receiver selector wheel internal to the cryostat and mounted on the 50 K radiation shield. This will allow the incoming beam to be directed to either individual receiver cartridge for dual polarization single band observing, or to split the orthogonal polarizations of the incoming beam between the receiver cartridges for dual band observing. A fourth position of the selector wheel will be available for a future cold dichroic beamsplitter to allow dual-band, dual-polarization observing.

Each wSMA receiver cartridge will use a single dual-polarized feedhorn and an orthomode transducer feeding two DSB SIS mixers to receive the two polarizations. The local oscillator signal will use waveguide LO injection in the 4 K receiver front-end module.

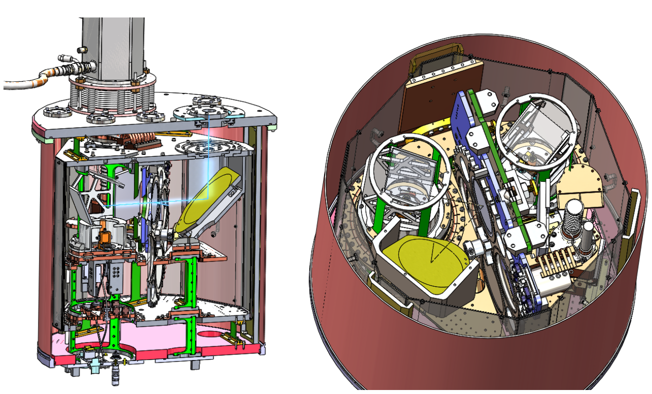

Fig. 4. Cut-away CAD renderings of the wSMA cryostat, showing the cryostat structure and the optical layout (optical path highlighted in blue on the left image). Renderings courtesy of HPD Inc.

Fig. 5. Photographs of one of the two prototype cryostats under construction at HPD Inc. (left) Complete cryostat on the support structure, with the cryostat vacuum jacket lowered and radiation shields removed to allow access to the cryostat internals. The alignment structure that positions the cryostat with respect to the SMA beam waveguide is in place on top of the cryostat, with the optical alignment telescope used for checking the alignment of the cryostat optics at the very top of the image. (center) Zoom in on the cryostat internals. The pulse tube cooler can be seen on the left of the image, with one of the two receiver cartridges front and center. (right) Receiver cartridge, with the return mirror used to test optical alignment in place. Photographs courtesy of HPD Inc.

A. Receiver cryostat

The wSMA receiver cryostat (Fig. 4) will hold the two receiver cartridges, the cold receiver selection optics and a cold calibration load. The cryostat will be cooled by a Cryomech PT-407RM or PT-410RM pulse-tube cooler driven by a variable frequency compressor unit. In contrast to the Gifford-McMahon backed Joule-Thomson coolers used in the current SMA cryostats, the remote motor pulse-tube cooler has no moving parts within the cryostat, and so should be significantly simpler to maintain.

The two receiver cartridges will be inserted from the base of the cryostat, with all receiver wiring, IF signal cables, and LO waveguides passing along the receiver cartridge to the receiver front-end. Thermal connections to the receiver cartridges will be via automatic thermal links. Installing a receiver cartridge should not require any connections to be made inside the cryostat.

The detailed cryostat design and fabrication of two prototype cryostats is being carried out by HPD Inc. (Boulder, CO). The design of the prototype cryostats has been completed, and the two prototype cryostats are now undergoing testing at HPD Inc. before delivery later this summer. Fig. 5 shows photographs of the prototype cryostat and receiver cartridge.

After acceptance tests, one prototype cryostat will be used to integrate and test wSMA receiver prototypes in the SMA Receiver Lab in Cambridge, MA, while the other will be shipped to the SMA site on Maunakea for fit and compatibility testing in an SMA antenna.

B. Receiver optical design

The quasioptical beam from the telescope is fed to both receiver cartridges via a single vacuum window and IR filter. Inside the cryostat, the beam is folded through 90° before

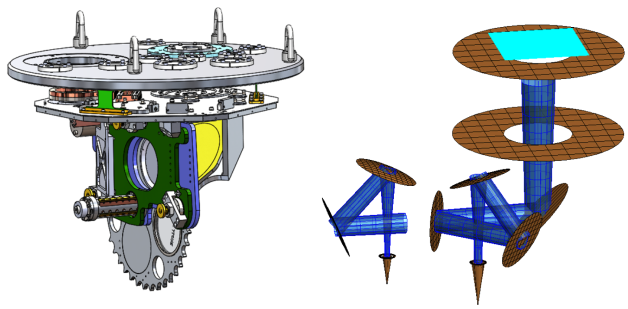

Fig. 6. (left) CAD rendering of the cryostat fold mirror and selector wheel supported from the upper vacuum plate and upper radiation shield plate of the cryostat. Rendering courtesy of HPD Inc. (right) GRASP model of the cryostat and receiver optics showing the Gaussian beam envelopes as the beams from each receiver feed pass through the receiver optics, selector wheel, fold mirror, and IR filter and vacuum window apertures.

reaching the receiver selector wheel. The selector wheel is a four-position wheel driven by a cryogenic stepper motor which can position one of four optical elements in the incoming beam. By choosing between an open port, a plane mirror and a wire grid, one or both linear polarizations of the incoming beam can be fed to either receiver cartridge. See Fig. 4, (left) and Fig. 6, (right) for illustrations of the optical layout.

The fourth position of the selector wheel will be used at a later time for a cold dichroic beamsplitter, to allow both polarizations to be fed to the two receiver channels simultaneously. Due to the close spacing in frequency of the two receiver bands, the receiver tunings available with the dichroic splitter will likely be limited to the lower end of the Low receiver and the upper end of the High receiver bands. This would allow, for example, the CO(1–2) and CO(2–3) lines at 230 GHz and 345 GHz to observed simultaneously in both polarizations, but will not allow the full frequency coverage of each receiver to be used.

From the selector wheel, the beam passes to the receiver optics on each receiver cartridge, consisting of a clamshell mirror pair that focuses the incoming beam on to the feed horns of the receiver front ends. Details of the cryostat and receiver optical design are given in [5].

The fold mirror and selector wheel optics inside the cryostat are mounted on the top plate of the cryostat radiation shield, and cooled to ~60 K. The receiver optics and receiver front end are mounted to the top of the receiver cartridges on sprung "floating 4 K plates" which are thermally strapped to the receiver cartridge cold plate that is in turn thermally linked via the automatic thermal link to the cryostat second stage cold plate. The floating part of the receiver cartridge is aligned on receiver insertion by a G10 structure that mates via a kinematic interface to the radiation shield top plate. The cryostat radiation shield top plate thus effectively serves as an optical bench that controls the alignment between all of the cooled optics and feeds.

C. Receiver cartridge and front-end design

Each wSMA receiver cartridge (Fig. 7, left) carries the receiver optics and a single front-end receiver module on the floating 4K plate, and up to four IF LNA/isolator amplifier modules on the underside of the fixed 4K plate.

The front-end receiver module (Fig. 7, right) consists of a

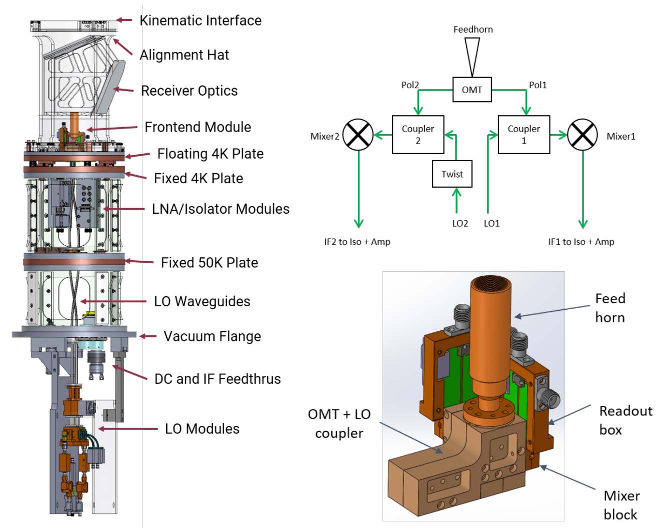

Fig. 7. (left) CAD rendering of populated wSMA receiver cartridge, with LO module installed. (upper right) Schematic of the wSMA receiver frontend, and (lower right) CAD rendering of a wSMA receiver frontend module.

single dual-polarized feedhorn and an orthomode transducer (OMT) feeding two DSB SIS mixers to receive the two polarizations. The local oscillator signals are coupled in to the signals from the OMT outputs through hybrid waveguide/planar circuit directional couplers and the combined signals are then fed to double-sideband SIS mixers.

The SIS mixers are an evolution of the wide IF band SIS mixer designs currently in use on the SMA. The design of these mixers is discussed in [6].

For the wSMA, we are proposing to incorporate a split IF output scheme to allow an IF output band from 0.1 GHz to 16 GHz or even higher. This scheme was discussed in [7], and uses a diplexer as the first element in the IF circuit, which splits the IF signal from the SIS mixer into two channels. The main 4–16 GHz IF channel will use a similar cryogenic isolator and Low Noise Factory InP HEMT LNA to that used on the SMA. The 0.1–4 GHz IF channel will be amplified by a cryogenic SiGe LNA. After amplification, the two IF channels will be brought out of the cryostat and independently transported and processed.

The front-end module (Fig. 7, lower right) will be constructed from a few integrated blocks. The profiled corrugated feed will be electroformed, and mounted on to the OMT-coupler module. The OMT and LO waveguide coupler will be built as an integrated module, with two mixer modules mounted on the outputs. The IF diplexer and bias tee for the SIS mixer will be built into the "readout box" module mounted on sides of the two mixer modules.

Further details of the front-end receiver design and the design and prototyping of the various components of the front-end are given in [8].

Local oscillator signals are injected into the signal path by waveguide directional couplers. The LO signals are fed to the front-end from the Receiver Cartridge vacuum flange using overmoded WR-10 stainless steel waveguides. The local oscillator units will be mounted to the outside of the Receiver Cartridge vacuum flange.

Both receiver bands will use LO sources based on amplifier-multiplier chains (AMC) driven by voltage-controlled oscillator (VCO) fundamental sources. After multiplication and amplification of the fundamental signal to W-band, a small portion of the generated signal is coupled out to a harmonic mixer and phase-lock loop system, which locks the LO signal to the master reference generator signals generated in the SMA control building and transmitted to all the antennas. The final multiplication to the receiver LO frequencies is then carried out by a x3 multiplier, after which the signal level is controlled by an optically controlled silicon chip attenuator [9].

Achieving IF operation down to 0.1 GHz will require significant care in the design of the AMCs in order to control excess LO sideband noise and ensure that it does not adversely affect receiver noise temperatures at low IF's. Some of the design procedures for our AMC LOs are discussed in [10].

Initially the two receiver bands will use somewhat different LO schemes. The 230 band receiver will use two independent LO AMC chains, one for each polarization, while the High band receiver will use a single LO AMC chain, with a power splitter and independent attenuators just outside the cryostat to drive the two polarization channels.

The ability to independently tune the two polarizations of the Low band receiver will be particularly useful for spectral line surveys, allowing near continuous frequency coverage over 64 GHz of bandwidth in the 194–286 GHz frequency range accessible by the Low band receiver. The High band frequency band is divided approximately in half by the deep atmospheric absorption line at 325 GHz. This line makes split tuning of the two polarization channels less useful for this band. With IF operation from 0.1–16 GHz, almost the entire useful atmospheric window between the 325 GHz and 380 GHz water vapor lines can be accessed with a single LO tuning. The High band LO units can easily be upgraded to dual AMCs with independent operation at a later date.

III. Upgrades To Other Systems

Fully utilizing the capabilities offered by the upgraded wSMA receivers also requires upgrading a number of other systems, particularly in the IF signal transport and correlator for the array.

1) IF/LO Signal Transport

The wider 16 GHz IF bandwidth being deployed now, and specified for the wSMA receivers, requires that the current analog RF-over-fiber based IF signal transport system be certified to handle that bandwidth.

A number of microwave components in the IF signal processing systems in the both the antennas and control building's correlator room have been upgraded to 18 GHz or higher components. The Ortel RF-over-fiber receiver/transmitter pairs operating at 1310 nm have been checked for performance to 16 GHz, and the few units performing below requirements were replaced with spares.

The entire IF signal transport system is now ready for 4–16 GHz analog RF-over-fiber operation. This capability is being used for the current commissioning of the 12–16 GHz IF expansion.

The proposed 0.1–4 GHz low IF expansion will also be transmitted over the same analog fiber links, either recombined into the existing channel; or transmitted on an adjacent CWDM channel, with a separate IF processor in the antenna cabin.

Currently the SMA transmits the Master Reference Generator signals for each of the two active receiver's LO references by multiplexing them onto the same analog RF-over-fiber link. This means that care must be taken when choosing tunings to avoid interference between the two MRG signals. As part of the reconfiguration of the IF for the wSMA upgrade, these two signals will be separated onto different WDM optical channels, removing the possibility of interference between them.

2) Correlator Expansion

Expanding the SMA's IF bandwidth to 4–16 GHz necessitates building more correlator capacity to handle this additional bandwidth. The expansion of the SWARM correlator [11] to handle the additional 12–16 GHz IF band is mostly complete, with two additional SWARM segments (originally called quadrants, but now six in number) currently being commissioned, each handling 2 GHz of bandwidth from both receiver channels. Additional block down-convertors have been purchased and installed, and the final steps in software deployment and science verification of the expanded correlator are now being undertaken.

Further expansion to handle the 0.1–4 GHz IF band is being planned. We expect to test the split IF system over a limited bandwidth on several SMA receivers during the latter part of this year, with an additional block downconverter, using the spare SWARM ROACH components that have recently been purchased. The full deployment of the 0.1–4 GHz IF band will occur alongside the wSMA receiver deployment.

3) Proposed next generation correlator development

With the deployment of wSMA receivers capable of wider IF bandwidths, from 0.1 to at least 20 GHz IF, and simultaneous operation of four receiver channels (dual receiver, dual polarization) at the same time using a dichroic splitter, a new correlator and IF signal transport concept is required to make use of the full capabilities of the receivers.

Concepts for a "next generation SWARM" correlator are currently being developed. Such a system will likely digitize the IF signals in the antenna cabins before transmitting data packets over high speed Ethernet links running over multiple DWDM optical fiber channels. Such a system would take advantage of the recent developments in extremely high speed Ethernet links for the general telecoms industry, and the signal transport would be based on commercial off-the-shelf technology.

IF digitization in the cabin and transmission via packetized networks on the SMA would be an enabling development for future receiver upgrades, including deployment of wide IF band sideband separating receivers, and multi-beam and other guest receivers, both of which require significantly increased flexibility in the IF signal transport and processing.

IV. Wideband Calibration

With a wide instantaneous bandwidth, as high as ~20%, the system gain and sensitivity can vary significantly as a function of observing frequency. In addition, for a double-sideband system, the sideband ratio can vary with IF frequency.

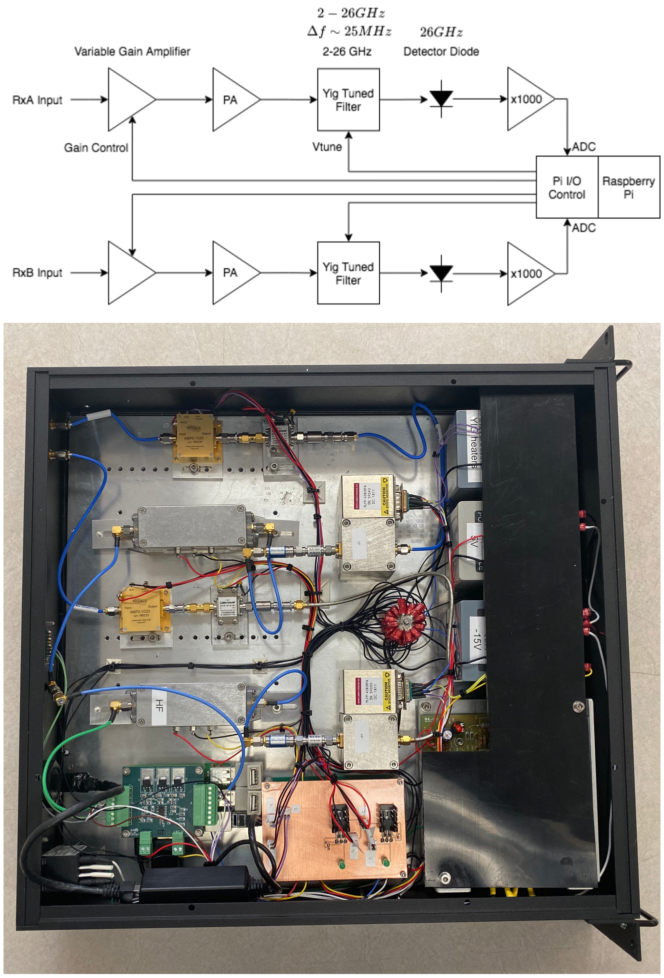

Fig. 8. Top: System diagram of a scanning spectrometer, and Bottom: photograph of the internal construction of a scanning spectrometer. RxA and RxB inputs (top left in photo) are connected to the two IF signal paths of the SMA, with one of the two operating receivers feeding each signal chain. The Raspberry Pi computer (under interface board on bottom left) controls the gain of the first amplifier and the tuning of the YIG filter, records the detector diode output, and outputs it to the SMA's control system.

Effective use of a wide-band heterodyne instrument requires knowing the system gain and sensitivity as a function of sky frequency, so that appropriate weightings can be assigned to frequency channels, and for accurate determination of spectral line ratios for different lines that appear within the bandwidth of the receivers.

For the current expansion of the SMA to 4–16 GHz IF observations, we have developed and deployed "scanning spectrometer" instruments to each of the SMA antennas. Each scanning spectrometer can determine the DSB system temperature (T_{sys}) and relative gain of the two active receiver channels as a function of IF frequency by recording spectrally resolved IF power measurements on the SMA's ambient calibration load and on the sky.

The system diagram of a scanning spectrometer is shown in Fig. 8. Each scanning spectrometer signal chain consists of a variable gain amplifier and power amplifier for gain control, a Yttrium iron garnet (YIG) tuned filter with 25 MHz bandwidth that can be swept from 2–26 GHz, a detector diode and DC amplifier, and a Raspberry Pi controlled ADC/DAC unit. By sweeping the YIG filter, a DSB IF spectrum can be recorded across the current 4–16 GHz IF bandwidth of the SMA in around one second.

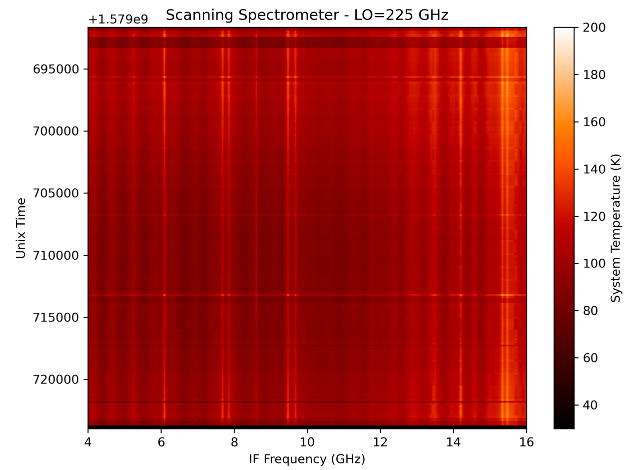

Fig. 9. Scanning spectrometer DSB Tsys data for one frequency recorded during a test observation. Vertical lines in the data correspond to stratospheric ozone lines in one of the two sidebands. Sharp horizontal lines correspond to rapid changes in the telescope pointing to switch to flux calibration and pointing targets, while slow variations track changes in atmospheric conditions and observation target elevation.

In normal observations, an IF spectrum is taken on the ambient load every time it is inserted for routine calibrations. While observing the (colder than ambient) sky, IF spectra are taken continuously at a rate at least as fast as the SMA's correlator integration rate. The T_{sys} of each receiver as a function of IF can thus be determined for each of the integrations during an observation, using the usual Y-factor method. An example of the scanning spectrometer data for one observation and receiver is shown in Fig. 9.

Since the SMA correlator separates the visibilities from the DSB receivers into two sidebands via Walsh switching, ideally we would like to determine a sideband-separated T_{sys} to correctly calibrate the sideband-separated visibilities. The broad bandwidth of the SMA typically encompasses a number of strong ozone lines, which in principle provide enough predictable spectral structure to retrieve a low-resolution sideband-separated spectral T_{sys} from the scanning spectrometer data.

The scanning spectrometer system is currently undergoing testing and integration into the SMA data acquisition system. It is expected that data from the scanning spectrometer system will be available when the SWARM correlator's 12–16 GHz extension comes online for routine observations later this year.

V. wSMA Deployment Timeline

Development and deployment of the wSMA upgrade will take several years. Over the next year, we expect to receive the two prototype cryostats, test fit one to an SMA antenna, and integrate prototype front-end receivers in the prototype cryostats, before placing an order for the full complement of production cryostats. At the same time, numerous developments will be tested and deployed on the SMA, including the Raspberry Pi based controllers for receiver optics and local oscillator units, software upgrades, and IF/LO signal transport upgrades.

Some initial elements of this upgrade program have already been completed, and are due to be released for production observing later this year. In particular, the expansion of the SMA IF bandwidth to cover an additional 4 GHz of bandwidth in the 12–16 GHz range is currently undergoing final science verification before being offered to observers in the next semester on a shared-risk basis. The scanning spectrometer systems are mostly deployed, and should be available at the same time.

Following the testing of the prototype receivers and cryostats, we expect that it will take 2–3 years to receive, integrate and deploy the wSMA receiver systems to all SMA antennas. To upgrade each antenna, the antenna must be taken into the SMA hangar to remove the existing receiver and other ancillary systems, to carry out scheduled maintenance of the antenna, and to fit the new receivers and support systems. After this, significant testing will be needed to verify the performance and calibration of the new receivers before the antenna can be incorporated into the SMA for regular array observations.

Throughout this transition period, compatibility between the upgraded and unmodified antennas will need to be maintained. To do this, we will limit normal science observations to the range of frequencies (sky and IF) that are common to both sets of antennas. The polarization basis for the new receivers has been chosen to match that of the existing receiver cartridges, and careful selection of receiver combinations and MRG frequencies will be required to successfully operate the two receiver types together.

Following the upgrade of all (or most) antennas and science verification, the extra capabilities of the wSMA will be available to all SMA observers.

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