SUMMARY OF PERSONNEL AND WORK EFFORTS

PI Walker: The proposed effort will be a major component of the PI's research over the next three years. He will have overall responsibility for the project and coordinate activities between the instrument and gondola teams. He will spend ~2 months per year working on the project. However, due to the PI's salary being maintained by his academic appointment, only 1 month of salary per year is being requested.

Co-I Chin from GSFC is Project Scientist for SWAS and will play a key role in planning our observational programs on BLAST. He will also serve as a liaison between the instrument team at Arizona and the microwave instrument group at Goddard who will assist in making the instrument flight worthy. Co-I Chin does not require salary support from this program.

Co-I Schieder from the University of Cologne has agreed to provide the SWAS backup acoustoptical spectrometer (AOS) for use with the proposed instrument. The data taken with its twin on SWAS show that it is exceedingly stable, capable of single integrations >20 hours. Although he will not be paid, Prof. Schieder and his group will support our efforts to integrate the AOS into the instrument package.

Co-I Bieging is an expert in the observation and modeling of mm/submm emission lines from evolved star envelopes. His experience will be invaluable in choosing observing targets and in the interpretation of observations. He does not request support from this project.

A Water- and Oxygen- Seeking Heterodyne Instrument for the 2-meter Balloon-Borne Telescope BLAST

1 Introduction

In our search for origins, for planetary systems like our own that might harbor life, the cyclical interplay between the interstellar medium and the stars it forms plays a pivotal role whose importance cannot be underestimated. Questions of particular importance that highlight our incomplete understanding involve the physical and chemical structure of molecular clouds, the nature of the processes that form stars within these clouds, the number and nature of planets formed from young circumstellar debris disks, and the return of potentially enriched material from evolved stars back to the interstellar medium. Crucial to each of these phases of evolution is the chemistry of two molecules deemed essential for life on Earth: oxygen and water.

Launched in December 1998, the Submillimeter Wave Astronomy Satellite (SWAS) had one preeminent goal; to conduct the first observations in the important submillimeter-wave transitions of water (H_2O and $H_2^{18}O$) and molecular oxygen (O_2), inaccessible to telescopes below the Earth's atmosphere. Over the course of three years it has surveyed nearby molecular cloud cores for H_2O and O_2 (refs), leading to new initial conditions and diagnostics for interstellar chemistry in understanding the star formation process. In particular, the extraordinary detection of water vapor toward the evolved carbon-rich star IRC+10216 (Melnick et al., 2001) may indicate the extra-solar analog of our own Kuiper Belt around IRC+10216. If this interpretation is confirmed by additional observations toward IRC+10216 and other carbon stars, it will provide a new way of probing the planet formation process and will yield important constraints to planet formation models. Another major result of the SWAS mission is the non-detection of O_2 in molecular clouds (Goldsmith et al., 2000). The nature of oxygen chemistry in molecular clouds and regions of star-birth has been rewritten as a result and is providing new insights into the most relevant interstellar processes, but more questions have been raised than answered.

These landmark results from SWAS are therefore not an end in themselves. Instead, they mark the beginning of a wave of new, more sensitive observations that will be made possible by the rapid technological advancements of detector systems at submillimeter and Terahertz (THz) frequencies. In particular, the use of cryogenically-cooled submillimeter detector systems on larger telescopes than the 0.5×0.7-meter aperture of SWAS will reap immediate and substantial gains.

We therefore propose to construct a state of the art, cryogenically-cooled, SIS receiver system (Submillimeter Astronomy Balloon Expedition Receiver, or SABER) for the Balloon Large Aperture Submillimeter Telescope (BLAST), a telescope of 2-meter aperture. Adopted broadband mixer systems are capable of observing both the 557 GHz transition of water and the 487 GHz transition of oxygen with a noise temperature an order of magnitude lower than SWAS. For observations of extended sources, integration times will be at least 100 times lower and mapping will be more than 100 times faster. However, the most impressive gains over SWAS are realized by observing unresolved sources; the BLAST/SABER combination will perform sensitive observations many *thousands* of times faster. Crucial followup programs to SWAS, such as the sensitive survey of evolved stars for water and potential cometary systems, exceptionally deep surveys for molecular oxygen in nearby molecular cloud cores, the evolutionary structure of circumstellar disks, and water in Solar System planetary atmospheres and comets can be performed with exceptional efficiency, sensitivity, and frequency agility unafforded by SWAS and *well before* the Herschel Space Observatory (HSO) launches in (estd.) 2007.

The use of SABER on BLAST will therefore provide a new, powerful probe of the interstellar medium and will serve both as a valuable & economical follow-up mission to SWAS *and* as a precursor mission for Herschel. Although the system could ultimately be used on long duration balloon flights, even a comparatively short North American flight has the potential of providing new, key information on the frequency and origin of planetary systems as well as fundamental knowledge of molecular cloud structure and chemistry.

2 Scientific Description

Molecule	**Transition**	**Frequency** (GHz)
$\mathbf{O_2}$	$3_3 \to 1_2$	**487.249**
HCN	$J = 6 \to 5$	531.716
HNC	$J = 6 \to 5$	543.897
^{13}CO	$J = 5 \to 4$	550.926
$\mathbf{H_2O}$	$1_{10} \to 1_{01}$	**556.936**
SO	$13_{14} \to 12_{13}$	560.178
H_2CO	$8_{18} \to 7_{17}$	561.899
SiO	$J = 13 \to 12$	564.243
CN	$J = 5 \to 4$	566.730
NH_3	$1_{00} \to 0_{01}$	572.498
CO	$J = 5 \to 4$	576.268
CS	$J = 12 \to 11$	587.616

Table 1: A sample of interesting lines in the 480-590 GHz regime. As with SWAS, the principal aim of SABER will be the detection of H_2O and O_2 lines. Unlike SWAS however, SABER's SIS mixers are frequency-agile, and alternate science programs can also be pursued.

2.1 *Feasibility of H_2O and O_2 Studies from a Balloon*

The wavelength regime between 700 and 200 μm contains a number of atomic and molecular emission lines that are key diagnostic probes of the interstellar medium (c.f. Table 1). Ground-based submillimeter telescopes at high, dry observing sites have some access to the rich features of this wavelength regime, but are restricted to the spectral "windows" of modest atmospheric transmission between supersaturated absorption features caused by telluric H_2O, O_2, N_2O, and O_3, among many others. However some of these atmospheric species, such as H_2O and O_2, are themselves of considerable interest in their own right, not least for their chemical significance to our origins and, on a larger scale, to the study of life in the Universe. Although placing an observatory in space eliminates this problem, it is also possible to launch a comparatively cheaper, more flexible and reusable balloon-borne telescope to a height of $\sim$40 km to overfly nearly all of the atmosphere.

In Figure 1 we have used an improved version of the AT program (Grossman 1989) to model the transmission of the atmosphere in the vicinity of the 556.937 GHz $1_{10} - 1_{01}$ transition of H_2O and the $3_3 - 1_2$ transition of O_2 at 487.25 GHz. Although telluric H_2O and O_2 features are still saturated even at an altitude of 40 km, the width of such lines is fairly narrow. Indeed, ∼90% transmission is achieved just 10 km s^{-1} from the O_2 line center, and ≥80% transmission can be found 30 km s^{-1} from the center of the H_2O line. The narrowness of these features at balloon altitudes makes the natural shift of the Local Standard of Rest with respect to the geocentric telluric lines sufficient to move most astronomical sources into regions of good atmospheric transparency much of the year.

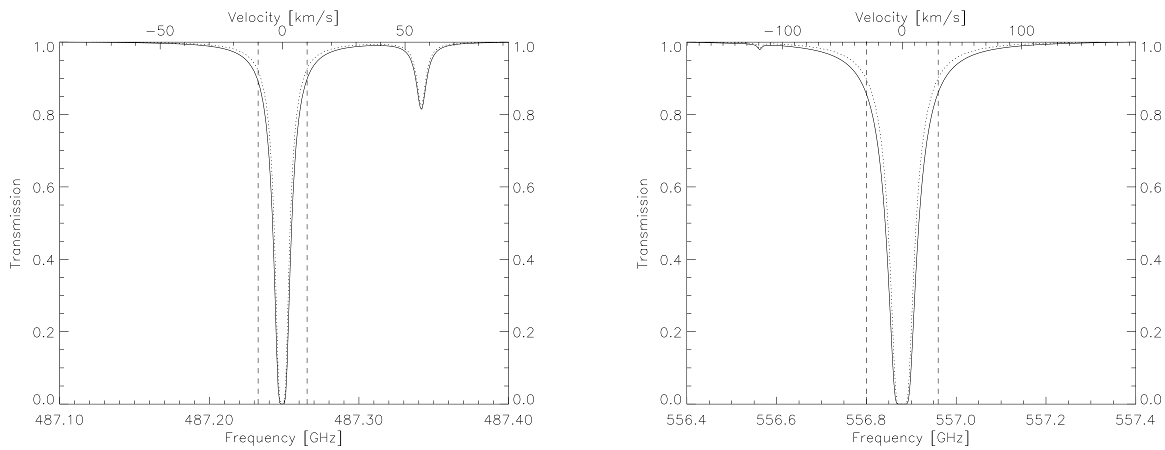

Figure 1: Atmospheric transmission in the vicinity of the 487 GHz O_2 line (left) and 557 GHz H_2O line (right), calculated using the AT program of (ref), modified to improve its internal numerical resolution at high resolving power. The solid line represents the transmission from an altitude of 39 km on a circum-continental flight over the Antarctic. The dotted line represents a short 1-2 day mission launched to an altitude of 41 km from North America (Texas). The weak atmospheric feature at 487.34 GHz is due to O_3, and although not modeled in these figures, will be insignificant over Antarctica.

This statement is depicted most clearly by Figure 2, which demonstrate the frequency shifting of astronomical spectral lines toward various sources due to the Earth's rotation and revolution about the Sun. Table 2 quantitatively demonstrates the number of days per year that an unbiased selection of interesting astronomical sources may be observed with high efficiency.

Encouraged by these results, let us explore a few of the exciting scientific possibilities afforded by the development of the SABER instrument aboard BLAST.

2.2 *Survey for Water Vapor in Carbon-Rich Evolved Stars*

The surprising detection of H_2O in the $1_{10} - 1_{01}$ 557 GHz line toward the carbon-rich post-main-sequence star IRC+10216 by Melnick et al. (2001) suggests the use of H_2O emission in such objects as a probe of vaporized cometary systems in other stellar systems, and hence a measure of the frequency and nature of planetary systems like our own in the Solar neighborhood. Such measurements would be a natural complement to the radial-velocity planet finding methods (Marcy & Butler, 2000) that are most sensitive to the detection of massive planets orbiting near their parent stars. The establishment of a technique to find analogs of "Kuiper Belts" around other stars is certainly exciting, intriguing and has far reaching consequences for the assessment of habitable planets in the Galaxy.

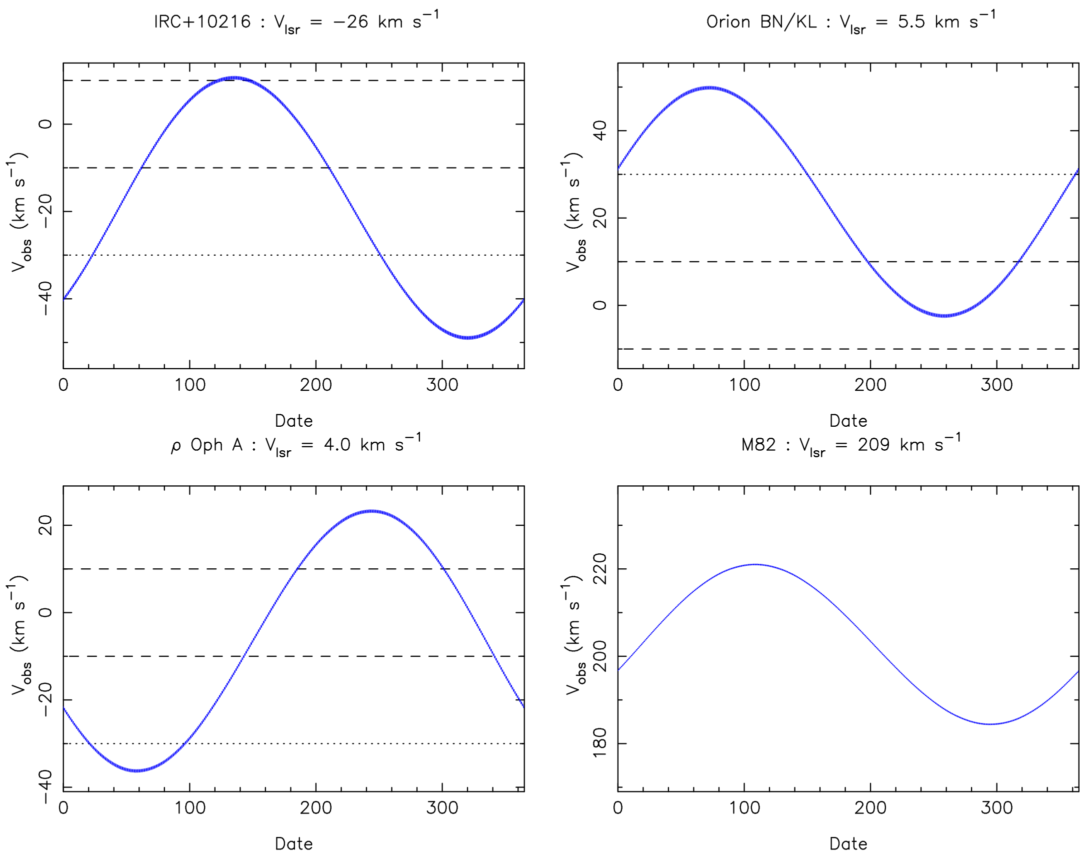

Figure 2: Spectral line frequency offsets for four representative sources compared to their telluric counterparts, expressed in km s^{-1} as a function of the day of the year. The region between the two dashed horizontal lines expresses the O_2 "zone of avoidance", within $\pm$10 km s^{-1} of the telluric O_2 line center. The dotted lines represent the H_2O "zone of avoidance", within $\pm$30 km s^{-1} of the telluric H_2O line center.

However, such powerful statements require equally compelling evidence; thus this hypothesis needs to be urgently tested. The combination of SABER and BLAST provides an outstanding facility for performing followup observations toward IRC+10216 and surveying other carbon stars to establish the frequency and nature of submillimeter H_2O emission toward carbon-rich AGB stars. We also propose to explore alternative explanations with the SABER observations, however. Specifically, we believe it is critically important to examine possible non-equilibrium chemical models for the presence of oxygen-bearing molecules in carbon star envelopes. Most AGB stars, including carbon stars like IRC+10216, are large-amplitude pulsators, and so must be driving strong shock waves of $\sim$10-30 km s^{-1} through their outer atmospheres every few hundred days. Willacy & Cherchneff (1998) computed chemical reactions for a model of the IRC+10216 envelope, in which pulsationally-driven shocks are the key non-equilibrium energy source. They found that some O-bearing molecules, e.g., SiO, are strongly enhanced to readily detectable levels. Observations of submillimeter transitions of SiO by Bieging, Shaked, & Gensheimer (2000) showed that the higher energy transitions of SiO are in fact present at large intensities in many carbon stars, and that the inferred excitation of the molecule can only be due to formation in the warm, dense inner circumstellar envelope, with SiO abundances consistent with formation behind shocks. Whether

Source	V_{lsr} (km s^{-1})	% of year observable O_2	H_2O
Carbon-Rich AGB Stars			
IRC+10216	-26	63	41
R Scl	-18	70	6.5
V384 Per	-17	67	31
R Lep	16	100	56
Y CVn	24	58	24
T Dra	-12	100	47
IRAS 17581	23	77	26
FX Ser	30	73	32
IRC+30374	-12	100	52
S Cep	-5	75	0
Star Forming Regions			
M16	24	76	26
M17	6	77	23
Orion BN/KL	5.5	67	42
NGC 2264	6.5	63	41
AFGL 2591	-7	82	39
NGC 7538	-57	100	100
ρ Oph A	4.0	77	21
Nearby Galaxies			
IC 342	35	100	51
M82	209	100	100

Table 2: A representative sample of evolved stars, star-forming regions and molecular clouds, and nearby external galaxies, their intrinsic velocities relative to the Local Standard of Rest (LSR) and their their observability in the ~500 GHz O_2 and H_2O lines. The latter is computed from the fraction of the year that the observed radial velocities exceed $\pm$10 km s^{-1} for O_2 (~90% transmission) and $\pm$30 km s^{-1} for H_2O (~80% transmission).

H_2O can also be formed in carbon stars by shock chemistry is unclear. The pure gas-phase shock models of Willacy & Cherchneff (1998) find that H_2O is enhanced for strong shocks but reduced for slower shocks. Consequently, this mechanism was rejected by Melnick et al. (2001) as requiring what they regarded as unrealistic shock parameters. However, Hollenbach (private communication) found that H_2O can be produced by shocks in such environments via grain-CO molecule collisions, which create free O that rapidly reacts with H to form H_2O. Recent numerical hydrodynamic models by Winters et al. (2001) show that in fact, sufficiently large shock velocities are predicted to occur in regions of high gas density and high grain condensation fraction, so that the shock production of H_2O should be given serious consideration. The question clearly cannot be resolved without increasing the sample of AGB carbon stars searched for H_2O emission.

To test this hypothesis, and to compare with the alternative, that H_2O in carbon star envelopes is an evaporate of primitive icy bodies like the Kuiper Belt, we will observe a large sample of carbon stars. The 1000-fold increase in speed that SABER will have over SWAS to reach a given sensitivity will make this survey feasible. With a large sample of stars, we can measure the H_2O line intensity and width, infer H_2O masses, and compare these results with the known mass-loss properties of the stellar sample. If there are correlations with current mass loss rates and velocities, then the shock hypothesis would be supported. If the H_2O is from evaporated KBOs,

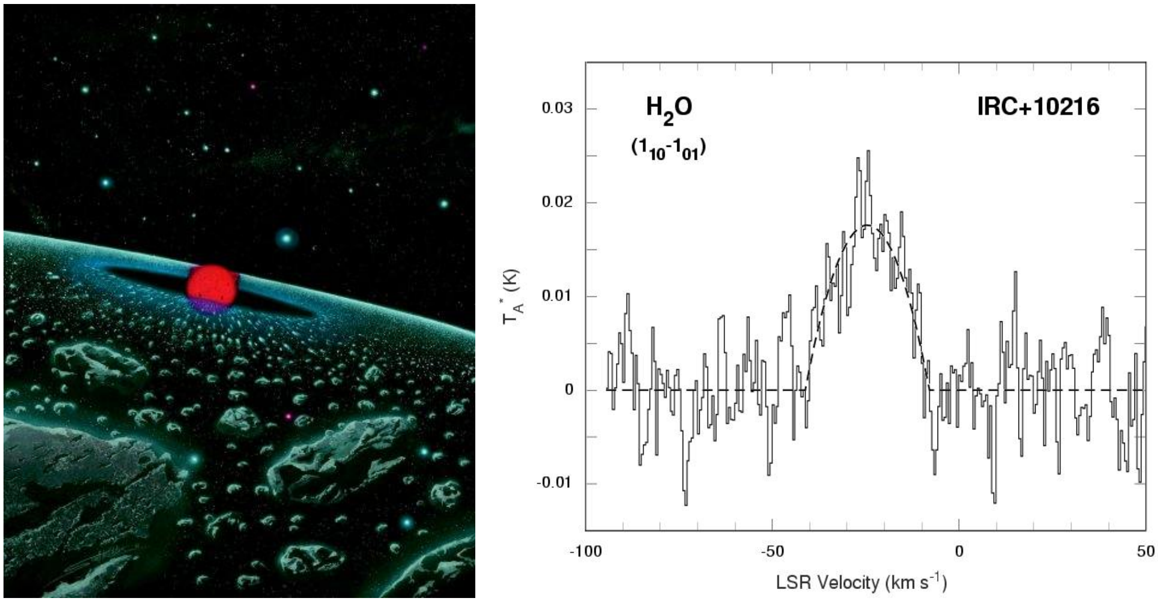

Figure 3: (left) Artist's conception of the evaporating comet hypothesis for the water vapor detection of Melnick et al. (2001) (right) toward IRC+10216. This result, obtained in almost 200 hours of on-source integration time with SWAS, is reproducible in ≈5 minutes of on-source integration time with SABER/BLAST.

one would not expect correlations with current mass loss, which is a function of the star's current evolutionary state, not its past formation history.

A further test of the origin of H_2O in carbon-rich stellar envelopes could be made with a future modification of the SABER receiver, to access the 1 THz region. By observing the H_2O $1_{11} - 0_{00}$ transition to the ground state (1.113 THz) as well as the $3_{12} - 2_{21}$ line (1.153 THz, 240 K above ground) and the $3_{21} - 3_{12}$ line at 1.163 THz (300 K above ground), we can determine unambiguously the excitation conditions of gaseous H_2O. Observations of these H_2O lines, all made with the same telescope and receiver system, will eliminate uncertainties due to different beam sizes and calibration. If produced by shocks in the inner circumstellar envelope, the higher-energy transitions should be strong and readily detectable. In contrast, if H_2O is an evaporate of ancient icy bodies, it must exist only at large distances from the star under conditions of relatively low excitation compared with the shock models. In this case, the higher excitation lines will be weak or undetectable. Hence, comparing lower and higher excitation lines of H_2O will provide a critical test of the distribution, and therefore of the formation mechanism, for H_2O in carbon star envelopes. Additionally, multi-transition data will allow precise H_2O mass determinations by constraining the molecular excitation temperature.

We point out that ISO observed and detected only a very few carbon-rich AGB and post-AGB objects in the IR lines of H_2O. Herpin and Cernicharo (2000) found H_2O in the spectrum of CRL618, which is in fact a very young planetary nebula where the inner envelope chemistry is probably dominated the UV flux of the hot central star. Yamamura et al. (2000) report a tentative detection of H_2O bands with the ISO SWS in the peculiar carbon star V778 Cygni, an object which shows silicate absorption features and which may well be a binary with a disk formed of oxygen-rich stellar ejecta. In short, these ISO detections of H_2O are hardly representative of the larger class of carbon-rich AGB stars which we aim to target with SABER. The limited spatial and spectral resolution, and the modest sensitivity of the ISO spectrometers, leave much room for improvement in searches for H_2O in carbon stars. The great advance in sensitivity over SWAS, and in both sensitivity and spectral resolution over ISO, which SABER should achieve, make our proposed survey of carbon stars well worth doing.

The first SABER observations on a 1- or 2- day balloon flight will be able to conservatively observe more than half of the 35 carbon-rich sources listed in the Groenewegen et al. 1999 catalog of AGB stars for water vapor emission to noise levels of 1-2 mK (expected emission is at the 10-20 mK level for a several M_{earth} source as in IRC+10216). We plan to allocate about 15 minutes per source, with 5 minutes for source pointing and set-up overhead, with 5 minutes total integration on target, and 5 minutes off-target (standard on-off radio observing strategy). In a full 24-hour duration flight, SABER can potentially observe 96 sources. During an additional 24-hour flight duration, SABER has the capability to retune in flight and re-observe the initial set of AGB sources for emission in other molecular species (e.g. Table 1).

As a complement to the study of carbon stars, we will also survey a sample of nearby O-rich (i.e., M spectral type) AGB stars for H_2O, O_2, and other possible diagnostic lines of inner-envelope shock chemistry. Water vapor is expected to be a dominant molecule in M-giant stellar outflows, and has in fact been detected readily in a number of such stars with ISO (e.g., in R Cas, by Truong-Bach et al. 1999; and in several K- and M-giants by Tsuji 2001). SABER observations of the 557 GHz H_2O line, with good spectral resolution, will provide crucial information on the mass loss rates and the H_2O abundance in M-giant winds. Existing CO data for these stars will also allow us to compare molecular abundances with results of theoretical chemical models (e.g., Duari et al. 1999). As a further test of the importance of pulsationally driven shocks, we will observe two sensitive molecular indicators in the M-giant sample. O_2 is predicted by Duari et al. (1999) to be quite sensitive to processing by shocks, in general being depleted, but by amounts which vary by a factor of 100 for a change in shock velocity of only 50%. Thus either a detection or an upper limit on the O_2 abundance can constrain the parameters of shock-driven chemistry in the circumstellar envelopes of M-giants. A second molecular indicator is HCN, which Bieging et al. (2000) detected readily in the short-mm and long-submm lines toward M-giants. Theoretical models predict a strong dependence of HCN abundance on shock parameters (Duari et al. 1999). Since the models predict that shock-produced HCN should form in conditions of high density and temperature, it is crucial to obtain good spectra of the higher-J lines of HCN to constrain the molecular abundance and excitation. The high quality HCN $J = 6 \rightarrow 5$ spectra (531.7 GHz) we will be able to obtain with SABER, will allow us to model the inner stellar envelopes with much better accuracy than was possible using only the lower energy $J = 4 \rightarrow 3$, $3 \rightarrow 2$, and $1 \rightarrow 0$ lines (Bieging et al. 2000). The HCN $J = 6 \rightarrow 5$ SABER data will be a critical complement to the ground-based observations made previously.

2.3 Deep Spectroscopic Searches for Interstellar O_2 in Star Forming Clouds

The distribution of oxygen in atomic and molecular form, both in the gas phase and on the surfaces of grains is a critical unknown in understanding the chemistry, the ionization structure, and the thermal balance of interstellar clouds, and hence in predicting their evolutionary course. Because of the different chemical reactivities of O, O_2, H_2O, and their ions, the overall molecular composi-

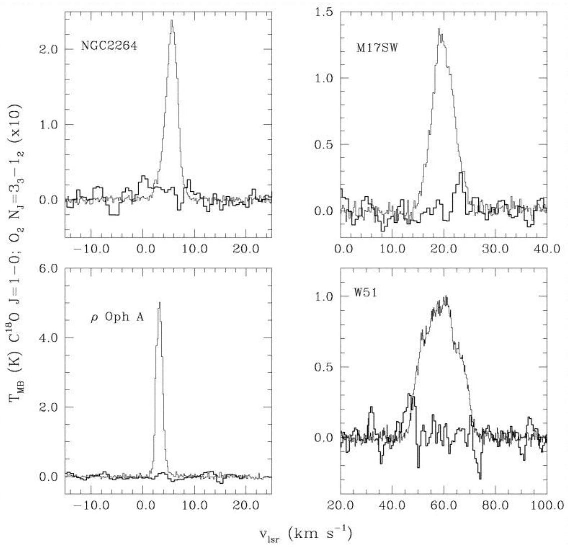

Figure 4: The deepest searches for the interstellar O_2 pivotal to models of the chemistry of molecular clouds and star-forming regions, from Goldsmith et al. (2000): the detections (thin lines) are measurements of $C^{18}O$ $J = 1 \rightarrow 0$, the non-detections (thick lines) are spectra of O_2 at the frequency of the $3_3 \rightarrow 1_2$ transition. These observations from SWAS required $\sim 10^3$ minutes of integration time each, but can be accomplished in $\leq$5 minutes with BLAST and SABER. Accounting for the distribution of oxygen in star forming clouds is a crucial step in determining the ionization and thermal balance of clouds; which partly regulates the evolution of interstellar clouds and their ability to form stars.

tion in molecular clouds is sensitive to the oxygen distribution. Understanding oxygen chemistry by establishing the abundance of oxygen-bearing species has been therefore an important goal of both theoretical and observational studies.

Although exhaustive spectral line surveys have only been undertaken for few sources (e.g. Orion BN/KL and Sgr B2), thousands of lines from over 100 different molecular species have been detected (Schilke et al., 1999). Unfortunately, only about 20% of the elemental oxygen measured in the Solar System is accounted for; the remaining repositories such as O, H_2O, O_2 and their ices lie at frequencies where atmospheric absorption prohibits their study. Airborne and space based telescopes are therefore necessary to probe these species. However even published studies are inconclusive. For example, studies of interstellar O I 1356 Å absorption (Meyer, Jura, & Cardelli, 1998) only probe diffuse interstellar gas and do not specifically address dark molecular clouds that constitute the sites of star formation. In contrast, [O I] 63 μm absorption measurements toward bright infrared continuum sources suggest that atomic oxygen may be quite abundant in molecular clouds (Poglitsch et al., 1996; Kraemer, Jackson, & Lane, 1998; Baluteau et al., 1997; Caux et al., 1999). However as their values range from 10-90% of the solar abundance, their interpretation remains controversial. The spectroscopic abilities of the Infrared Space Observatory (ISO) were capable of observing O_2 transitions shortward of 200 μm, however none of the observable transitions ($\geq$180 K above the ground state) are energetically excitable by the cold conditions prevalent in dark molecular clouds.

Balloon-borne experiments have searched for O_2 without success. The most sensitive of these (Olofsson et al., 1998) placed 3σ limits of O_2/CO=0.04 toward NGC 7538. This particular expedition is noteworthy as it also employed a cryogenic SIS receiver, however the 8 hour mission was plagued by bad beam coupling ($\eta_{\rm mb} \sim 0.1$) and garnered only 15 minutes of on-source integration time. In contrast, we expect receiver noise temperatures that are nearly 3 times lower (Section 3), a telescope with $\approx$16 times the collecting area, and many times better beam coupling efficiency.

SWAS permitted the most sensitive opportunity for O_2 detection (Goldsmith et al., 2000), but O_2 has proven elusive to even very long integrations. The most sensitive published limit on O_2 is toward the nearby ρ Oph A cloud core: $O_2/C^{18}O$=1.5, or O_2/CO=0.003 if $CO/C^{18}O\sim$500 (Wilson & Rood, 1994). Such low abundances relative to H_2, a few times 10^{-7}, are not explainable by conventional gas-phase chemical models.

Three principal hypotheses have been invoked to explain the low abundance of O_2. All of them are readily testable due to the large aperture of BLAST and high sensitivity of the cryogenic SIS mixers in SABER. It is significant to note that the best detection limit provided by SWAS toward ρ Oph A in 10^3 minutes of observing time can be reproduced by the combination of BLAST and SABER in $\leq$5 minutes of on-source integration time.

O_2 depletion: The gas-phase fractional abundance of O_2 can be reduced if the gas-phase C/O ratio is raised to $\approx$1 by preferential depletion of oxygen onto grains in the form of H_2O or other species (e.g., Hasegawa & Herbst 1993). The details and importance of grain surface depletion, reaction, and desorption processes are uncertain, but this mechanism could account for the low gas-phase abundance of O_2 in quiescent clouds. The return of water-bearing ices to the gas phase in circumstellar star-forming environments (i.e. in the disk itself, the heated envelope, or in the warm outflows driven from the central young stellar object) should liberate oxygen into the gas phase, where some molecular oxygen might then be observable. The ρ Oph cloud may well present a suitable testing ground of this idea; as the ρ Oph A cloud core has already been shown to have a low O_2 abundance, and its neighboring A2 core shows enhanced sulphur abundances (SO, SO_2 and CS) due to a low velocity outflow. The newly-formed high mass star AFGL 2591 also demonstrates abundant warm gaseous H_2O (Helmich et al., 1996) and might be expected to have returned some of its elemental oxygen to the gas phase. A modest sample of sources in varying degrees of thermal evolution should be sufficient to test this hypothesis, in addition to providing the most sensitive measurements of the O_2 abundance en route.

Chemical youth: Models of time-dependent chemistry (Bergin, Langer, & Goldsmith, 1995; Lee, Bettens, & Herbst, 1996; Millar, Farquhar, & Willacy, 1997) require over 10^5 years for the O_2 abundance to build up to 10^{-6} in typical shielded molecular environments of $n_{\rm H} = 10^{3-5}$ cm^{-3}. Thusly, the low abundance of O_2 could suggest that the molecular material has only recently been shielded from radiation. This model can also be tested, as another indication of chemical youth is a high atomic carbon abundance, which is observable via fine structure emission lines at submillimeter wavelengths. Numerous [C I] maps exist in the literature; indeed, the PI's group has mapped a 1600 square arcminutes of the ρ Oph cloud in the 492 GHz $^3P_1 -^3 P_0$ line of carbon, and find a systematically higher carbon abundance in portions of the cloud (Kulesa, Hungerford, Walker, & Black, 2001). Measurement of O_2 toward several dense cores in sources like the ρ Oph cloud can test this hypothesis.

High-ionization solutions: The bistable solutions to chemical equilibrium equations lead to an often ignored but plausible "high-ionization phase" that may explain the low abundance of O_2, by favoring atomic oxygen instead (Lee et al., 1998; Le Bourlot, Pineau des Forets, & Roueff, 1995). The symptoms of the high-ionization solutions are similar to chemical youth; namely a high atomic carbon, and low H_2O abundance. Once again, SABER can provide sensitive O_2 and H_2O measurements where SWAS has not yet ventured, and atomic carbon measurements can be obtained in advance via ground based observatories in both northern and southern hemispheres.

3 Instrument Description

3.1 Design Goals

The Schottky Diode mixers on SWAS have a typical DSB noise temperature of ∼2200K DSB (4400K SSB) (Melnick et al. 2000). SIS junction based mixers regularly achieve noise temperatures of ∼100K DSB at the same frequency. Accordingly, the next generation ESA orbital submillimeter mission, Herschel, uses SIS junctions for all the submillimeter bands. Using BLAST, there are great opportunities for sub-orbital missions before Herschel launches that can expand and improve on many areas of the groundbreaking SWAS mission. BLAST offers the ability to fly a cryogenic SIS receiver on a telescope with an aperture ∼4 times larger than that of SWAS. These two features can yield dramatically improved sensitivity to unresolved sources. We propose to build a dual polarization, state-of-the art, single sideband SIS receiver that is optimized for observing the 557 GHz line of water and the 487 GHz line of oxygen using BLAST. The receiver will be designed and constructed to provide reliable, low-noise operation within the gondola environment. It will use a fixed-tuned silicon etalon as the single sideband filter, a simple Mylar beamsplitter for the LO diplexer and a wire grid for polarization diplexing. These optics will efficiently couple the telescope beam to two SIS mixers and low noise amplifiers, all contained in a robust and simple liquid cryostat. A backup flight AOS from the SWAS project will serve as the spectrometer, and we will use proven computer-controlled bias electronics to monitor and tune the system in flight.

3.2 Optics

Figure 5 shows a schematic diagram of the receiver system. All optics are cold, with a minimum of moving parts. The cryostat is located just past the Cassegrain focus of the telescope. The beam enters the cryostat through a low-loss, AR-coated crystalline quartz window (Benford et al. 1998) and then proceeds to an offset parabola where it is collimated. The beam then passes through a quasioptical single sideband (SSB) filter. Single sideband filters offer advantages in system noise temperature, sideband calibration, and a reduction in line confusion (Jewell 1997). While our atmospheric models show that transmission should be good enough not to require a single sideband filter, the device does offer a ∼100K improvement in system temperature, in addition to the calibration advantages. Traditionally, a Martin-Puplett interferometer is used as a quasi-optical single sideband filter. While this approach has the attractive feature of frequency agility, they are also complex, and require high precision motion at 4K. We choose instead to use a silicon etalon as a single sideband filter. While these devices have narrow bandwidth, they are extremely simple. They consist of a silicon plate that is ground to the proper thickness to act as a Fabry-Perot resonant cavity. They transmit the desired sideband while reflecting the unwanted sideband to a 4K load (Mueller 2002). This etalon will be mounted on a linear actuator to allow it to be removed from the beam for observing brighter lines where single sideband operation is not critical. A simple Mylar beamsplitter functions as the LO diplexer. While there are many more efficient ways to inject the LO signal, they are unnecessary. LO power is easily available at 500 GHz, and not much is required to pump two mixers. We use a 45^{o} wire grid to split the incoming polarizations to the two SIS mixers. The mixers are coupled to the telescope beam with polyethylene coated crystalline quartz lenses and corrugated dual mode feedhorns, which offer

98% coupling to the fundamental Gaussian mode.

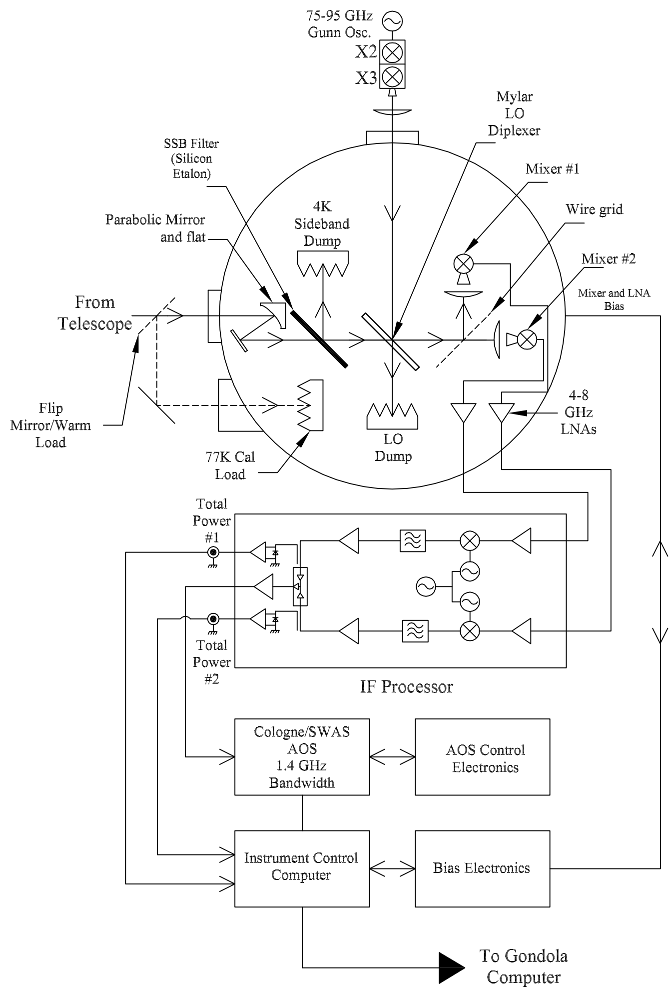

Figure 5: Schematic of overall SABER instrument design

3.3 *Mixers and Low Noise Amplifiers*

The current state of the art in SIS mixer design uses suspended stripline junctions, as pioneered by Blundell & Tong, with advanced optimized on-chip tuning structures that allow the use of tunerless mixer mounts (Blundell et al. 1995). Our mixers are an adaptation of this proven design. These mixers cover from 425-575 GHz with both high performance and reliability. Mixers optimized for 460-500 GHz ground based observations exhibit receiver noise temperatures of ∼80K DSB (Kooi et al. 1998). We expect noise temperatures of 100K or better at 557 GHz. A "standard" 492 GHz waveguide mixer offers very good performance from 425-575 GHz. We need only fabricate devices optimized for that frequency. Device runs with 557 GHz junctions are already planned at both JPL and the University of Virginia. We plan to use Chalmers developed LNAs, which offer 2K noise temperature, low power dissipation, and a 4-8 GHz IF bandwidth. The relatively high 6 GHz IF frequency simplifies the design of the IF processor necessary to feed the SWAS AOS.

3.4 Local Oscillator

A revolution in local oscillator technology has also taken place, mainly driven by ESA & NASA's Herschel mission. Past multiplier designs used whisker-contacted Varactor diodes. These devices exhibited inconsistent (sometimes time-variable) performance, high capacitance and low power handling ability. Modern LOs use monolithic diodes made with micromachining technology to offer very consistent, stable performance and very high power handling capability. Due to reduced diode capacitance and very well defined performance characteristics, exceptional performance is available from LOs with tunerless multipliers and self biased diodes (Erikson 2001). With only a backshort and tuner on a Gunn oscillator source, it is possible to obtain tens of milliwatts of LO power at 557 GHz from an extremely simple, reliable device. Since we need only adjust the two Gunn Oscillator micrometers, and a single attenuator micrometer, we can easily automate the tuning system with three computer controlled motors and a simple lookup table. No other adjustments are necessary due to the tunerless SIS mixers and LO multipliers. Since we are feeding two mixers, each sensitive to a linear polarization orthogonal to the other, we need to mount the LO such that the polarization of the LO beam is at 45^{o} to the two mixers. The frequency agility of the LO and the 700 MHz bandwidth of the backend also allows for the possibility of frequency switched observations. The BLAST telescope has no facility for chopping, so frequency switching would be an efficient observing mode for single point observations.

3.5 Backend Spectrometer

Co-I Schieder, Cologne University, will provide the spare SWAS AOS as the backend for the BLAST heterodyne project (Frerick et al. 1999). This AOS has a 2.1 GHz input frequency with 1400 MHz bandwidth and 1 MHz frequency resolution. This is a fully-functional flight-qualified AOS identical to the device now flying on SWAS. The AOS control electronics are not spaceflight qualified, but can be repackaged so they are robust enough for suborbital operations. The AOS data can be accessed every 10ms via a 16 bit parallel data bus with standard TTL logic. We are responsible for developing a data handling and storage system, which can be accomplished with fairly simple electronics and an standard PC running a real-time operating system (such as RT Linux).

3.6 IF Processor

Similar to what was done on SWAS, we plan to split the AOS passband into two 700 MHz segments. Each segment would process the spectrum from one of the two mixer/IF chains. To accomplish this, we need an IF processor to translate the frequencies of both IFs and combine them into a single 1.4-2.8 GHz signal. As shown in Figure 5, we will amplify each of the 4-8 GHz IF outputs from the mixers and then downconvert them to 1.75 GHz and 2.45 GHz respectively. Each signal is then filtered to a 700 MHz bandwidth, amplified, and combined with a Wilkinson power combiner into a single 1.4-2.8 GHz signal. The signal from mixer 1 appears from 1.4-2.1 GHz and the signal from mixer 2 is from 2.1-2.8 GHz. This IF processor contains off the shelf components from Miteq Inc. and Mini-Circuits Inc. and requires only two fixed tuned Miteq oscillators phase locked to a 10 MHz reference signal.

3.7 *Instrument Control and Integration*

We have already developed a simple, reliable computer controlled bias system for our array receivers now in operation at the AST/RO telescope at the South Pole and the Heinrich Hertz Telescope (HHT) on Mt. Graham, AZ. These systems use rack mounted cards to provide SIS, magnet and LNA bias to any number of receiver channels. The system can be controlled by any computer running Linux with a parallel port and a data acquisition card, and fits into a single 19" wide rack. A modern PC can control mixer bias, monitor the total IF power levels, and serve as the data storage system for the instrument. Via Ethernet, this type of machine can communicate with any other networkable computer, allowing great flexibility in communications with the gondola computer system.

During the design phase we will keep in close communication with the BLAST team and GSFC to ensure that the instrument design will be easy to integrate with blast, and will be able to survive the rigors of a suborbital mission. To aid in instrument integration, the BLAST team will provide us with a fully functional duplicate of the BLAST gondola electronics and data acquisition system. In addition, we will exchange personnel with both U. Pennsylvania and GSFC during the integration phase to ensure instrument compatibility and survivability.

3.8 *Calibration*

In flight calibration is a necessary task that requires more thought on a suborbital mission than with a ground based receiver. First, to measure the receiver Y-factor, we need cold and warm loads accessible during flight. We plan to use a third window in the cryostat that allows access to a cold load mounted on the 77K radiation shield. A deployable flip mirror just in front of the main cryostat window will redirect the receiver beam off a fixed flat into the calibration window. A second position of the same flip mirror assembly will bring a warm load directly into the main beam of the receiver. This warm load can also be used for chopper wheel calibration. We will be able to do both continuum and spectral line calibration on planets, as well as measure beam efficiency. This two-stage calibration, combined with single sideband operation and fixed-tuned mixers, should provide accurate, stable calibration.

3.9 *Sensitivity Estimates*

The sensitivity of a single sideband, heterodyne receiver on BLAST can be estimated by following the procedures outlined in MMA Memo 170. In this derivation both single sideband operation and atmospheric contributions are taken into account (Jewell 1997).

$$T_{SSB,DP} = \frac{2\,T_{rx}(DSB) + T_A(sky) + T_{image}}{\sqrt{2}\,\eta_l\,\eta\,\exp(-\tau)} \tag{1}$$

$$T_A(sky) = \eta_l\,T_M\,[1-\exp(-\tau)] + (1-\eta_l)\,T_{spill} + \eta_l\,T_{bg}\,\exp(-\tau) \tag{2}$$

Table 3 lists the parameter values we have chosen to estimate the BLAST system temperature. Since we also detect both polarizations, the effective system temperature is further improved by the square root of 2. The listed parameters are relatively conservative, assuming an atmospheric transmission of 80%. As the atmospheric models presented earlier show, we expect many objects to have better than 90% atmospheric transmission for a significant part of the year.

Parameter	Parameter Description	Value
T_{rx}	Receiver Noise Temperature	100K
T_{image}	Image Temperature	4.2K
T_M	Atmospheric Temperature	200K
T_{spill}	Rear Spillover Temperature	295K
T_{bg}	Background Temperature	2.7K
η_l	Rear Spillover Efficiency	0.98
η	Main Beam Efficiency	0.6

Table 3: Parameters used for the BLAST/SABER system temperature estimate following MMA Memo 170.

With these equations and parameters, we conservatively estimate the BLAST system temperature to be ∼550K SSB per mixer. Accounting for dual polarization operation, this yields a system temperature for co-added data of ∼390K. For comparison, the on orbit verified performance of SWAS is 2200K DSB, or 4400K SSB (Melnick 2000). This is an improvement of a factor of ≈11 in system temperature, or a factor of ≈125 in integration time in favor of BLAST. This estimate does not take into account the increased size of the BLAST telescope. For unresolved sources, the signal-to-noise ratio (SNR) for a given integration time increases by the square of the ratio of the beamsizes:

$$R = \left(\frac{\Omega_{SWAS}}{\Omega_{BLAST}}\right)^2 \propto \left(\frac{D_{SWAS}}{D_{BLAST}}\right)^2 = \left(\frac{2.0\text{m}}{0.625\text{m}}\right)^2 \simeq 10.2 \tag{3}$$

This gives BLAST an advantage of a factor of ≈115 in signal to noise ratio (S/N), or ≈13,000 in integration time for the same S/N toward objects unresolved with both instruments. This is why we have chosen to concentrate on observations of sources with small angular diameter, e.g. evolved stars, protostellar cores, and external galaxies.

Another new submillimeter satellite that targets water and oxygen is Odin. It was recently launched, and hopes to improve on SWAS. Odin has similar receivers to SWAS, with system temperatures of ∼2000K (Eriksson et al. 2002). Odin has a 1.1-meter telescope, almost twice as large as SWAS. BLAST is a factor of 10 more sensitive than Odin, assuming a 2000K system temperature, or a factor of ∼100 faster in integration time. For unresolved sources, the beamsize advantage is lowered to 3.3 rather than 10.2. This gives BLAST an advantage of ∼33 in achieving a given SNR, which corresponds to a reduction of ≈1100 in observing time.

Pointing is an issue that could potentially lessen the gain in observing efficiency for unresolved sources. Since the absolute pointing of the BLAST telescope is no better than 2′, we have to use a more complicated observing strategy to locate the object at the beginning of an observation. Predecessors to BLAST have demonstrated relative pointing from a planet to the target object accurate to within 20″. BLAST has a near real-time data link with the control station that allows quick-look data analysis during flight. We can remove the single sideband filter from the beam, tune the LO to CO($5 \rightarrow 4$), and quickly make a $3' \times 3'$ map of the area in the vicinity of the target object. After downloading this data to the control center, we can find the centroid of the object and offset the telescope. We will then insert the SSB filter and tune the LO to water or oxygen for the deep integration. We expect this procedure will provide relative pointing accuracy better than 20″ since we will be pointing on the target object, not another source far away. Even in the worst case of having to make an On-The-Fly map of the entire $3' \times 3'$ region, with each pixel having the same noise per beam, we only lose a factor of 20 in time. This still yields an integration time improvement over SWAS of a factor of ≈650.

4 Plan of Action

The following list summarizes a brief outline/sketch of some of the tasks to be accomplished and our expectation as to when and where each will occur.

Year 1

1. Complete detailed design of receiver front-end, both electrically and mechanically
2. Procure instrument cryostat, IF amps, LO chain and phaselock, instrument control computer
3. Assemble receiver front-end and characterize laboratory performance

Year 2

1. Obtain AOS from University of Cologne
2. Construct dual-polarization IF processor
3. Conduct lab tests of AOS/IF processor/front-end combination using existing AOS control electronics
4. Repackage control electronics for balloon operation and repeat system tests both in the lab and on the 10-meter Heinrich Hertz Telescope

Year 3

1. Complete development of hardware and software needed for integration with BLAST
2. Test instrument package with BLAST mock-up control electronics
3. Integrate instrument on BLAST Gondola and perform final system tests
4. Inaugural flight in North America

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FACILITIES, EQUIPMENT & OTHER RESOURCES

4.1 University of Arizona, Steward Observatory

Steward Observatory, in association with the Max Planck Institute for Radioastronomy, has constructed a 10-meter submillimeter-wave telescope on Mt. Graham, Arizona (the Heinrich Hertz Telescope, HHT). At the end of the second year of the proposal effort, we will test the performance of the BLAST receiver system by using it to observe the 492 GHz [C I] and 461 GHz CO $J = 4 \rightarrow 3$ lines on the HHT.

In 1992 the PI established a laboratory (the Steward Observatory Radio Astronomy Laboratory, SORAL) for the development of state-of-the-art submillimeter-wave receiver systems. The laboratory contains (or has ready access to) all the equipment (spectrum analyzers, network analyzer's, vacuum pumps, cryogenic support facilities, etc.) needed for the development of receivers. SORAL has ^{4}He and ^{3}He cryostats available for testing single pixel Nb and Nb-Au HEB mixers.

The NSF Division of Astronomical Sciences awarded the PI funds to construct a 7 element array receiver at 345 GHz. This array will begin operation on the HHT in November, 2001. In the past, SORAL has produced facility 230 and 492 GHz receivers for the HHT and, recently, was the lead group in the design and construction of a dual channel 492/810 GHz receiver and 4 pixel 810 GHz array receiver (PoleSTAR) for AST/RO at the South Pole. The 492/810 GHz receiver has been in operation for 4 years and is the primary facility receiver for the telescope. The 810 GHz array was commissioned in November 2000 and is the first array to go into operation in this important atmospheric window. This summer SORAL will be working very closely with Sigfrid Yngvesson at UMass in preparing a single pixel, 1.5 THz HEB receiver for integration onto AST/RO. The experience SORAL personnel have gained in the design and deployment of these receiver systems will be fully utilized in the construction of the proposed prototype systems.

As a result of its successful collaboration with Lincoln Laboratory in applying laser micromachining technology to the fabrication of THz components, the Physical Foundations of Enabling Technologies Program in the Engineering Division of the NSF awarded the PI a grant to construct a laser micromachining facility at Steward Observatory. This system is now fully operational and is being used to manufacture a variety of THz-frequency waveguide components.

Through a grant through the Defense University Research Instrumentation Program (DURIP), SORAL has recently purchased a new laser for the micromachining system, an e-beam evaporator for metallizing micromachined components, and a thin film deposition system for depositing nitride and other films.

SORAL also has licenses for both Hewlett Packards High Frequency Structure Simulator (HFSS) and Microwave Design System (MDS) software packages. These programs are used to accurately model and optimize mixers and other crucial receiver components.