2-2-98

Feasibility of Receivers for the LSA

LSA Receiver Working Group
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February 2, 1998

Abstract

This report discusses the feasibility of producing receivers for the Large Southern Array. The receiver construction programme will be in the form of a joint project with those US groups currently working on the development of technology for the Milli-Metre Array. The baseline design of the LSA is an array of 64, phase-locked, 12m antennas with a full complement of heterodyne receivers covering all the atmospheric windows from 30GHz to 900 GHz. The array will be located at an elevation of 5000m on a high plateau in Chile, and this will place particular demands on the ease of use and reliability of the instrumentation required. The need to produce a large number of identical receivers will also influence the development programme greatly.

The requirements for the receivers are discussed in the light of the current state-of-the-art and necessary extensions to the present technology. Critical areas that have a strong impact on performance are discussed and the main areas of development, as well as possible overlaps with other programmes (FIRST), are identified. A cost estimate based on a phased development of receivers, starting at the low-frequency end of the band and moving through to the high-frequency end of the band, is included.

Our conclusion is that the technology required to build the receivers for the LSA is largely available today, but to achieve the ultimate goals in terms of sensitivity and bandwidth (defined as being close to the physical limits), in a mass production environment, will require a significant development programme.

This report contains implicit and explicit references to earlier reports in [4] and [5].

1 Introduction

A joint LSA/MMA project calls for equipping 64 telescopes with heterodyne receivers covering the frequency range 30 GHz to 900 GHz. Due to the excellent atmospheric transparency of the 5000m site of Chajnantor in

Chile, the sensitivity of the receivers is of utmost importance. Above 100 GHz, the only receivers capable of achieving noise temperatures of 2-4 times the quantum limit, $h\nu/k$, and frequency resolutions of up to 10^8, are those based on superconducting (SIS) tunnel junctions. In these instruments the extremely-sharp nonlinearity in the current-voltage characteristic of a superconducting tunnel junction is used to mix the astronomical signal from the sky together with an artificially generated local oscillator signal. The IF signal can then be amplified using cryogenically-cooled HEMT amplifiers, and conventional room temperature amplifiers, to a level where it can be applied to a digital correlator for processing. Of course the IF signal contains all of the information that was was present in the original signal, including phase.

SIS receivers with noise temperatures of a few times the quantum limit have been demonstrated at frequencies of up to 700GHz by several groups, including a number of European groups, at observatories such as IRAM, JCMT, CSO, SEST, KOSMA etc. From 30 GHz to 100 GHz, recent and steady advances in low-noise High Electron Mobility Transistor amplifiers open up the possibility of direct amplification at the frequency of the astronomical source. The subsequent mixing can then be accomplished with a much less sensitive, and much less expensive, mixer. In effect, this means that the technology required to build receivers for the LSA is largely available. To reach the ultimate sensitivity and bandwidth, however, a significant amount of development work is necessary.

To some extent this work will parallel developments and studies currently underway for air and spaceborne instruments such as SOFIA and FIRST, and there is no doubt that the LSA will benefit from the technological enhancements and innovations being considered for these projects. The overlap is, however, not complete: the LSA will not operate at the highest frequencies being considered for FIRST, and a large number of receivers must be constructed, installed and operated in the case of the LSA. Although individual receiver systems have been demonstrated, repetitive production, on what must be considered a large scale, has not yet been attempted. It might be expected, however, that the development of space-qualified mixers, local-oscillator sources, and optics, will enable large numbers of low-noise receivers to be constructed with almost identical performance.

To ensure the success of the project, both in terms of financial viability and operational security, three, to some extent related, fundamental design philosophies must be adopted:

1. simplicity—that is to say ease of construction, installation, operation and maintenance;
2. reliability;
3. cost effectiveness—for both construction and operation.

Considerable care and project control will have to be applied at all stages of the programme to ensure that the receivers operate efficiently, reliably, and with a minimum amount of operational support. Areas of concern and potential difficulty need to be addressed at an early stage and decisive management steps will need to be taken to ensure that the correct solution is adopted. Realising success in these areas will require careful receiver definition, design and management. For some components, competitive industrial tender may be the best approach; although considerable care will be needed in order to ensure that contracts are only awarded to companies that have a strong and proven capability in the appropriate area. Much of the technology and expertise are not in the domain of commercial organisations, and, in reality, it may be difficult to find companies that can provide the required level of guarantee.

1.1 LSA Receiver requirements

The requirements for the LSA receivers are summarized in Table 1.

Parameter	Specification	state-of-art
Frequency range	30-900 GHz	30-900 GHz
Noise temperature	$4h\nu/k$ SSB	$2-10h\nu/k$ DSB
Sidebands	SSB	DSB
mixer tuning	fixed tuned	DSB fixed, SSB mech. tuned
IF Bandwidth	4 (8?) GHz	1-2 GHz
Polarization	dual, linear	dual, linear
Local oscill. tuning	electrically tuned	2-6 tuners/LO
Amplitude stability	few 10^{-3} long term, 10^{-5} short term	
Phase	stable, low noise	

Table 1: Receiver requirements for the LSA

1.2 Overview of Receiver Components

The receivers consist of the following subcomponents:

- an optical system which couples the horn of the mixer or amplifier to the telescope and, where relevant, to the local-oscillator source;
- an SIS mixer (above $\approx$ 100 GHz) or HEMT amplifier (30 to 100 GHz), which processes the signal from the sky;
- a cooled IF amplifier, for the SIS mixer, or a room-temperature mixer and amplifier, for the HEMT, which amplifies the signal to a level that is suitable for further processing;

- a phase-locked local oscillator system, which in the case of the 30-100GHz channels drives the room temperature mixers, but in the case of the 100-900GHz channels drives the SIS mixers directly;
- a cryogenic cooler and vacuum system to cool the superconducting junctions and low noise HEMT amplifiers;
- support electronics in the form of mixer bias supplies, magnet current supplies, phase-locked loops, power supplies, temperature control etc.

2 Feasibility and prospects of receiver components

2.1 Optics

The optics of the receiver have the primary task of efficiently matching the beams of the SIS mixers and HEMT amplifiers to the telescope. In the case of the mixers, the local-oscillator signal must also be injected. Clearly, this requirement means low loss in all senses: low ohmic loss and low diffraction loss at room temperature apertures. A conflicting requirement is that the signal beam must pass through the vacuum window of the cryostat.

With today's extremely low-noise SIS-mixers, the frontend optics can be responsible for a major fraction of the total receiver noise. Therefore, the number of optical components should be minimized. The MMA concept of distributing the frequency channels in the image plane of the telescope is an important step in this direction. From an optical design point of view, particular care must be taken to ensure that the off-axis aberrations are well understood and kept under control.

In the case of the SIS mixers, the LO signal must also be injected, and this can increase the number of optical components, and therefore loss in the signal path, significantly. There are various ways in which this can be avoided, and the inclusion of directional couplers in the mixer block is of interest. Like optical beam splitters, however, this approach throws away most of the available LO power: the precise fraction depending on how much injected noise can be tolerated. Another approach, which is starting to appear feasible, is to develop balanced mixers. This approach is much more economical in terms of LO power and has a number of other important advantages concerning stability and noise. The laser-photomixer option for the LO described in section 2.4 would allow us to feed in the laser power via a low-thermal conductivity optical fiber and have the photomixer in the vicinity of the SIS detector.

The design of quasioptical components and systems for millimetre-wave and submillimetre-wave receivers is well advanced. These systems have been used extensively on all of the European submillimetre-wave observatories for a number of years. Many groups in Europe have a sound working knowledge of the concepts and design techniques used at these wavelengths, and certain groups have considerable expertise in this area. There is no doubt that quasioptical design and measurement techniques will develop significantly on the timescale of the project, and already a number of major initiatives are being planned in connection with FIRST. The ability to measure the optical performance of components and systems at these wavelengths is of particular importance.

Conclusion for feasibility of optics: The tools to design quasioptical components for millimetre-wave and submillimetre-wave receivers are well understood. The task remaining is to optimize the design of low-loss windows (antireflection coatings) and high efficiency optics (horn/lens/mirror combinations), despite the off-axis positioning. These tasks are well within the capabilities and expertise of European laboratories. Some development work will be required in this area, particularly when it comes to verifying that the receivers are working in a satisfactory and identical manner.

2.2 Mixers and mm-wave HEMT amplifiers

2.2.1 Introduction and state of the art

The sensitivity of the whole telescope hinges on the frontend mixers. Superconducting mixers based on Niobium/Aluminum-Oxide/Niobium SIS tunnel junctions are presently used in nearly all millimetre-wave and submillimetre-wave spectroscopic receivers. The *double sideband* noise temperature of the *mixers* is at the $2-4h\nu/k$ level from 80 GHz (10-20K) up to the gap frequency of Niobium of about 700 GHz (70-140K). Current practical receivers, including the optics and IF contributions are at the $6h\nu/k$ (30K) level at 100GHz, $2-4h\nu/k(22-44K)$ at 230 GHz [7] and $4h\nu/k$ (140K) DSB at 700 GHz [6]. For an overview of recent receiver results see [8].

It is important to realise that the LSA requires single-sideband operation in order to suppress the atmospheric noise in the unwanted sideband. Approximately, $T_{sys}(SSB) = 2T_{sys}(DSB)$, so that only the best receivers quoted above fulfill the requirements of the LSA. Also note that line confusion between the two sidebands of a DSB mixer does not need SSB operation but can be resolved by phase switching in case of interferometric observations.

The reasons for the high sensitivity achieved to date are the intrinsic low-noise behaviour of quantum mixers and the advances that have been made in designing and fabricating almost lossless, integrated, superconducting, impedance matching circuits. These sensitivities result, however, mostly from using a 1 GHz instantaneous IF band centred somewhere in the region 1-5 GHz. As discussed below, higher IF's can increase the noise by several $h\nu/k$. Above 700 GHz, the noise temperature of practical SIS receivers presently rises to the $6-10h\nu/k$ level because of the onset of RF losses in the superconducting matching circuits, and these can only be reduced, to some degree, by using normal metal films.

The hope of using Niobium Nitride with a higher gap energy for achieving the same performance as the Niobium junctions, even above 1 THz, has not been fulfilled due to the difficulties of working with the NbN material. Initial experiments with Niobium-Titanium-Nitride, however, are strong indicators that this material will allow noise temperatures as low as $4h\nu/k$ to be achieved even at frequencies as high as 900GHz and beyond.

For many years, SIS tunnel junctions have been mounted in waveguide, and one or even two movable backshorts have been used in order to provide, in a variable manner, a large range of embedding impedances. Even when integrated tuning circuits were developed to match out the capacitance of the tunnel junction, tuners were used to compensate for a lack of understanding about the behaviour of the probe. The tuners have therefore been used to compensate for unknown electromagnetic behaviour rather than immature superconducting RF circuit technology.

Over the last few years, it became possible to build fixed-tuned mixer mounts optimized to match SIS junctions with broadband integrated tuning structures. This allows the mixers to cover a complete atmospheric window without mechanical tuning, which is an important step towards reliable, easy to operate SIS receivers that are well adapted to space, imaging arrays, or large-scale interferometer applications.

There are also examples of excellent quasi-optical mixers, mostly in the submillimeter wave range, that use planar antennas on dielectric lenses instead of waveguides. Their coupling to telescopes, however, is generally not as good as the very high coupling possible with the corrugated feedhorns and waveguide mixers.

The broadband, fixed-tuned waveguide (or quasioptical) mixers are intrinsically double sideband. If the LSA/MMA could live with DSB mixers, the mixers up to 700 GHz would use existing technology, apart from the continuous efforts to gain greater instantaneous bandwidths.

A drawback of the tunerless design is, however, that a simple method of tuning the mixer to single-sideband sensitivity is lost. As we feel that both quasioptic SSB filtering as well as the re-introduction of mechanical tuners is undesirable, or at least only acceptable as a backup solution, the SSB function has to be realized with a (rather involved) integrated circuit, which has yet to be proven. The idea here is to develop image-reject mixers by using superconducting microstrip or coplanar transmission-line couplers and a pair of tunnel junctions. A joint MRAO/KOSMA project to develop a series of finline mixers is well established, and finline technology would be a particularly effective way of fabricating these components even at the shortest of wavelengths.

MM-wave HEMT-amplifiers show encouraging results up to 100 GHz and are a viable option for these frequencies. Recent results show noise temperatures of 50K SSB at around 100 GHz corresponding to $10h\nu/k$ SSB, which has to be compared to $5h\nu/k$ for an equivalent DSB SIS mixer. Yebes is intending to investigate mm-wave HEMT amplifiers over the next few years.

2.2.2 SIS Devices, circuits, and fabrication

Niobium SIS devices for routine use in millimetre and submillimetre-receivers are currently fabricated at a few dedicated laboratories, including several European laboratories, among them IRAM, SRON, KOSMA and (in the near future) OSO. Worldwide, they are very competitive, and it is important for the well-being of the LSA that such laboratories exist.

It is hard to conceive how this very specialized fabrication can be transferred to industry in a cost-effective way. At least, the development work necessary to achieve the goals for the LSA mixers (SSB operation, wide IF bandwidth, sensitivity) can only be done in the laboratories. The current device fabrication techniques are low volume and are aimed at specialized production runs with widely varying designs. To supply the needs of the LSA, the laboratories will have to combine their efforts, and even then, they will probably need some expansion of their current facilities to cope with the quantity and variety of devices required.

The current mixer designs at millimetre wavelengths are mostly of the simple double-sideband, single-device waveguide type without any complex integrated circuitry except for the tuning circuit to compensate the device capacitance (an exception is the integrated receiver with Flux-Flow oscillator developed at SRON/IRE). A tunerless single-sideband phase quadrature mixer will require development. As said before, a finline arrangement is an interesting approach to this problem, as well as the work done by Kerr et. al [2].

The provision of SSB mixers is an important development, which would have a large impact on the performance of the LSA as a whole. Improved sensitivity, however, is obviously only gained if it is possible to achieve the same $2 - 4h\nu/k$ noise performance as todays simple DSB waveguide mixers with the more complicated integrated SSB phase-quadrature design. An additional problem is that this performance has to be maintained over an IF bandwidth of 4 or even 8GHz, which will not be easy. There is no doubt that this development will be a challenge—especially when one realises that the two mixers needed for phase-quadrature sideband separation will be noisier than a single mixer with sideband rejection—but the underlying physics strongly suggests that it can be done with the technology that is currently at hand.

At frequencies above 700 GHz, where single-sideband operation is even more desirable, because of the lower atmospheric transmission, the necessary integrated circuits cannot be made of Niobium because of the large loss above the gap frequency. The development of Niobium-Titanium-Nitride technology would increase the frequency limit to more than 900 GHz. These developments together with the integration of the first IF amplifier (see Sections 2.2.3 and 2.3) is certainly one of the major development items for LSA.

A further important point is that a very large number of mixers will have to be made. Moreover there are very strong technical arguments to the effect that for the very best performance these mixers should use rectangular waveguide and corrugated horns. Even assuming, rather modestly, 5 frequency bands across the 100-900GHz range, we conclude that at least 320 mixer blocks and corrugated horns will have to be manufactured. Clearly, it is hard to see how conventional electroforming and machining techniques could meet this demand. One possibility would be to consider the bulk manufacture of split-aluminium-block corrugated horns, with parabolic mirrors at the apertures, of the type developed at MRAO. An attempt is currently been made at MRAO to fully automate the machining of submillimetre-wave corrugated horns, and if successful this technique would be of significance to the project.

Conclusion for feasibility of devices and circuit fabrication: DSB mixers with $2-4h\nu/k$ double sideband receiver temperatures are available using existing technology from 80 to 700 GHz. Integrated tunerless single-sideband mixers having the same sensitivity are a new technology and need to be developed. This work carries the risk of not achieving the sensitivity goals, thus negating the advantage of having an intrinsically SSB mixer—although some advantages regarding calibration would still accrue. Several European laboratories have the capability to design and manufacture such circuits, or more conservatively, conventional SIS mixer chips. For mass production, the device fabrication facilities would have to be upgraded, and also elegant and automated methods for machining mixer blocks would have to be found. Finally, it is important to emphasise that a considerable amount of mixer-development expertise exists in Europe including a significant strength in the modelling of superconducting planar structures such as waveguide probes, superconducting microstrip, finline transitions, etc.

2.2.3 IF Frequency and bandwidth of mixers

Intrinsically, SIS mixers can operate up to intermediate frequencies that are a substantial fraction of the signal frequency. Also, HEMT amplifier technology is advanced enough to give broad bandwidths. As mentioned in the introduction, however, the IF center frequency of most SIS receivers is in the 1-5 GHz range, with bandwidths of 1-2 GHz. This is in contrast to the plan for the LSA/MMA, where an 8-10GHz center frequency and a 4GHz or 8GHz bandwidth is preferred. A problem with the large bandwidth is that the *impedance matching* between the mixer and the IF amplifier (typically 50 Ω) becomes increasingly difficult to maintain. This happens because the capacitance of the integrated RF tuning circuit, acting as a lumped capacitance, together with the capacitance of the junction starts to short out the intermediate frequencies. An integrated sideband-separation circuit on the mixer chip will add further capacitance. Any mismatch losses multiply the noise-temperature contribution of the following IF amplifier. A detailed discussion can be found in [3].

Conventional approaches using additional matching networks could probably achieve a 4 GHz bandwidth. Presently, designs for a 8-12 GHz IF system for SIS mixers are being developed for the ESA FIRST satellite mission. Going from 1-2 GHz HEMT amplifiers to 10 GHz HEMTs amplifiers, having current performance, would result in a noise temperature increase at the amplifier from about 4K to about 10K. The difference is multiplied by the mixer losses and all other losses between mixer and amplifier, so that the impact on receiver noise can be substantial. For a 3dB loss, this would mean an increase at 100 GHz of $2.5h\nu/k$! It is very important to realize that for continuum observations, the figure of merit is $BW \cdot T_{sys}^2$, so that the price paid for higher bandwidth can be high. If the interferometer is mainly used for spectroscopy, the figure of merit is T_{sys}^2, and so it would be wiser to sacrifice the ultra-wideband IF for better noise performance.

It may be a solution to integrate the first, and possibly the second, stage of the IF amplifier into the SIS mixer block. A recent example of this approach is described in [1] and leads to a 3-4 GHz bandwidth. Also, the integrated RF tuning circuits on the SIS chip may have to use low-capacitance coplanar line technology. Perhaps one of the biggest hazards is the lack of understanding about the instability that may arise from tightly coupling two potentially unstable, wideband devices. Clearly, this is another area for development.

Conclusion on the feasibility of having a 4-8 GHz IF bandwidth: A 4 GHz IF bandwidth is feasible with some improvement in the mixer IF matching circuit. At an intermediate frequency of 8-12GHz the capacitance of the mixer circuit and its associated RF impedance matching structures become problematic. A sideband-separation circuit adds to the capacitance and could offset the tradeoff between DSB and SSB mixers. An 8 GHz IF bandwidth with the required noise performance represents a substantial development problem. The impact on the overall figure of merit of the receivers and the consequences for the backends can be considerable and will have to be carefully analyzed before any final decision is made.

2.3 IF amplifiers

The current state-of-the-art of HEMT amplifiers is a noise temperature of about 1K per GHz, for conventional GaAs based devices, and 0.5K/GHz demonstrated and 0.25K/GHz predicted for InP([4]). Amplifier development is taking place at Yebes (Spain), DEMIRM (France), MPIfR (Germany), Chalmers (Sweden), MRAO (UK), JPL/TRW (USA), NRAO (USA). New developments at eg. Chalmers, JPL/TRW and Yebes focus on InP devices, which should result in lower power dissipation and possibly lower noise temperatures at 10GHz. Most amplifiers used in SIS mixer applications are currently 1-2 GHz wide. Low-power dissipation amplifiers for 8-12 GHz, (4GHz) IF bandwidth, are being developed for FIRST with the expectation of having 10K noise temperatures with a goal of 5K. For the very high bandwidth *and* sensitivity goals of LSA/MMA the conventional approach of building and optimizing the IF amplifier separately from the mixers might not be feasible. The first or first and second IF amplifier stage would then have to be integrated with the mixer. MRAO are developing an amplifier which uses superconducting microstrip transmission lines, and a prototype amplifier is already under construction.

Conclusion for the feasibility of producing wideband IF amplifiers: HEMT IF amplifiers for a 4 GHz bandwidth are available or are under development. The main issue is matching the amplifier to the SIS mixer, rather the performance of the amplifier or mixer itself. A substantial development effort is required if the IF amplifier is to be integrated into the mixer block. Some advantages may accrue with this approach for IF bandwidths as high as 8GHz, although, even in this case, it is still realistic to consider keeping the mixer and amplifier separate. Achieving the goal of $2 - 4h\nu/k$ over 8 GHz is not a fundamental problem but it would be a challenging technical undertaking. This development should only be considered if the impact on the whole instrument, including the backends, is fully understood.

2.4 Local Oscillators

In many ways, this part of the receiver is one of the most technically demanding and will be an instrument driver, in the same way as it is for FIRST. The use of broad-band sources without tuning mechanisms is essential. Present day millimetre and submillimetre wave sources use Gunn oscillators, in the 70-140 GHz range, together with Schottky-diode frequency multipliers. The Gunn oscillators need movable backshorts for wideband tuning. To achieve maximum bandwidth and power, existing multipliers also need movable backshorts, at least in the submillimetre-wave range. The number of backshorts increases with frequency, as the multiplication has to be achieved with only doublers and triplers. This gives rise to a multitude of tuning mechanisms, which is not acceptable for the LSA.

An alternative approach is to use a YIG-tuned microwave source, multiplied to 80-100 GHz, followed by a HEMT power amplifier, which drives fixed-tuned planar varactor frequency multipliers. The YIG oscillator is easily to tune electrically, and planar varactor circuits can be optimized to be fixed tuned over a wide bandwidth. The required millimeter-wave power amplifier is a subject of current development, and issues relating to phase noise and spurious harmonic responses of the triplers are still under consideration. FIRST is likely to use a similar system to the one described here.

As each receiver has its own set of local oscillators and multipliers, together with phase-lock electronics, the local oscillator system is is going to represent a significant fraction of the total cost. Remember that in the final stage, the receivers will have 10 frequency channels, 7 of them SIS, and the HEMT RF amplifier channels will need some kind of mixing after amplification, too.

Besides this conventional approach, there is the possibility of a laser-photonic local oscillator system, where two IR lasers are frequency locked, with the desired frequency difference in the millimetre or submillimetre-wave range, and fed to photomixers that convert the beat frequency into millimetre or submillimetre-wave power. The two powerful lasers can be in a central building and the laser power fed to each of the receivers, and photomixers, by optical fibers. This approach would probably result in a substantial reduction in cost and complexity. This possibility is currently being studied in connection with both the MMA and FIRST projects. It is, however, still in a very immature state.

All local oscillator schemes need exceptional phase stability. Except maybe for the laser-photomixer system, new technology for phase locking is not necessary, but the design has to be carefully studied at a system level.

Conclusion for the feasibility of the local oscillator system: Conventional Gunn/multiplier oscillators are available but suffer from the need of mechanical tuning. A viable alternative is a YIG-tuned microwave oscillator with HEMT power amplifiers and Schottky planar multipliers. This technology needs development, but has been demonstrated. A very attractive solution would be the laser-photomixer approach, which is completely new but is under development both in the US and Europe for FIRST and SOFIA.

2.5 Cryogenics and Dewars

The SIS mixers will have to be cooled to about 4K, and yet it is undesirable to have to supply or handle helium at the proposed site in Chile. The baseline design is therefore to use 4K closed-cycle refrigeration. Closed-cycle refrigerators for 4K are commercially available, and a number of observatories have experience in operating them. The recent development of Gifford McMahon systems that use high capacity heat exchanges will be of particular benefit to the LSA and may enable low temperatures to be reached without the need for complicated Joule-Thompson systems.

The temperature stability requirement for stable operation, especially for continuum observations in the single-dish mode, is rather stringent and amounts to a few millikelvin. This can be achieved with a closed temperature control loop using a small amount of heating, at least for the Joule-Thomson type of cryocoolers. 4K cryocoolers operating on the Gifford-McMahon principle usually have larger temperature fluctuations and drift and may need more elaborate techniques to stabilise. Careful thermal design should be able to eliminate any potential problems. Careful thermal and mechanical design will also be required to isolate the vibrating fridge head from the mixers, but techniques that use flexible straps are well established and should be straightforward to implement. In fact, one can imagine a rather elegant and compact scheme based on this relatively new type of cooler.

Dewars for cryogenic receivers are in operation at many observatories. A task for the LSA consortium will be to simplify the design of the Dewar and make it as modular as possible, so that modules for different frequencies can be removed for maintenance or added easily as higher frequency channels come into operation. Modularity is a prerequisite to make it possible to have a multinational collaboration on receiver construction, particularly if one envisages several institutions supplying receiver channels for the different frequencies.

Conclusion for the feasibility of the cryogenic system: Commercially available coolers can be used to produce reliable receivers in large quantities. The thermal stability needs to be high and vibrations must be kept to a minimum. These requirements are well within the capabilities of existing laboratories, but careful thermal and mechanical design will be required. Modularity is needed so that the construction can be phased and distributed around a number of countries.

3 Manufacturing and Industrialization

One major feature of the LSA is that a large number of receivers will have to be constructed, and this calls for a different approach to constructing instruments than is used by almost all observatories at the present time. Below, we attempt to identify those components and tasks that could probably contracted out to industry. Included in this list are only components that have to be custom made for the LSA: not components like IF cables, warm IF amplifiers, etc., which are obviously available from commercial organisations. For some of the more advanced components, such as the laser-photonic local oscillators, the question of commercial fabrication can only be answered after the development phase.

3.1 Industrial (mass) fabrication of components

All the *mechanical* parts of the receivers could be fabricated industrially; among them are the mirrors and lenses, the Dewars and Dewar modules. Manufacturing the mixer blocks requires special skills, but a number of commercial organisations may be interested in this task. Conventional local oscillator systems in the millimetre-wave range could be commercial items. The electronic systems, such as mixer bias supplies, parts of the phase-lock electronics, receiver control etc., could be manufactured commercially according to basic designs that already exist in the laboratories. As mentioned in Section 2.2.2, it is unlikely that the fabrication of the superconducting mixer devices can be commercialized at reasonable cost. There are, however, foundries like Hypres Inc. that can do at least standard processes in Niobium technology.

As far as industrialization is concerned, we feel that the best way to go would be to developed complete prototype instruments in the laboratory and then, via a small pilot series, have the majority of the instruments manufactured in industry. This approach would lessen the risk of having problems with the prototypes and would help industry to make a realistic bid.

3.2 Integration and testing/calibration

Of course, even though the majority of the components and subsystems can be produced commercially there is still the need to assemble and test the receivers and this is a major task. Integration, testing, and calibration has probably to be done at specialized laboratories. Maybe there should even be a centralised laboratory where integration, testing, calibration and maintenance of all the receivers takes place. As this center will need to hire non-expert personnel, automated test systems will have to be developed and extensive documentation will have to be kept. An arrangement like this would also make the collaboration with the MMA easier, because there should obviously be a common design for the receivers. The feasibility depends on the degree to which the receivers can be modularised.

4 Development areas for study phase

Due to time and probable financial constraints, the study phase can only do pre-development work to assess the feasibility of the advanced performance criteria discussed above. The costing for the envisaged future LSA proposal therefore has to include substantial amounts for technology development.

One major development area is the design of sideband-separating integrated SIS mixers with wide IF capability. The broadband matching of SIS mixers and IF amplifiers with the possible integration of the first, or first two, IF amplifier stages is a second field which has important implications for the overall sensitivity of the array.

Also of great importance is the development of new local oscillator concepts. HEMT millimeter wave power amplifiers would be an important step towards high power fundamental sources for planar-circuit varactor frequency multipliers. The laser-photonic mixer is a completely new technology that would need to be studied.

Although the basic development techniques for the optical systems are well understood, a study should also begin on the development of compact, low-loss, high-efficiency, easy-to-manufacture, optical systems. The need to handle the effects of aberrations caused by the off-axis geometry of some of the pixels must be considered early, as the design of the receivers may have important implications for the design of the telescopes themselves.

The question of commercial production would need some study too. A study of low-power consumption cryocoolers and modular Dewars could be initiated.

5 Proposed Receiver Concept

Receiver concepts for the early phase of the LSA can be split into advanced and conservative options:

The advanced concept would call for a complement of four receivers at 30, 100, 230 and 345 GHz with YIG-tuned, millimetre-wave power-amplified and multiplied sources as local oscillators. It is assumed that mixer development will be rapid enough that integrated sideband-separating waveguide mixers will be available. A decision would have to be made about whether to go for the 8 or 4 GHz IF bandwidth. The room temperature IF system should support the widest bandwidth that is ever likely to be required from the beginning.

A conservative approach would use mechanically-tuned Gunn oscillators followed by fixed-tuned multipliers as the local oscillator sources and double-sideband fixed-tuned waveguide mixers with an IF of 4-8 GHz. SSB operation could be made available with mechanically-tuned mixers or optics.

The Dewar and cryosystem have to be the final designs, with preference on a highly-modularised configuration.

6 Cost Projection for LSA receivers

This is a cost estimate for the development phase of a receiver which has four channels at 30 GHz, 100 GHz, 230 GHz, and 345 GHz.

Budget for LSA Receiver Development
K.Schuster & B.Lazareff, IRAM, Jan-1998

Prices in kFF
Note : add 150kFF per channel for Mxr Devt if LO's must be phase locked

Task	Area	Item	*Per Channel*	*All Channels*	*Task SubTot*
Mxr Devt					
	Labor	2 my eng	1.000		
		2my tech (incl block machining)	600		
	Materials	w/g, att, couplers	50		
		HEMT amp	15		
		warm IF	30		
		LO	130		
		test signal : sweeper + harm mxr	80		
		wet cryostat + peripherals	100		
	Test Eqpt	spec analyzer	300		
		IF power meter	40		
		RF power meter	60		
		misc	50		
	Subtotal		2.455		9.820
Junctions					
	Labor	1my phys	500		
		2 my tech	600		
	Consumables	targets, maintenance, fluids	500		
		2 masksets @ 50 each	100		
	Subtotal		1.700		6.800
HEMT devt					
	Labor	4 my @ 500		2.000	
	Supplies	InP discrete chips 2 batches		400	
		InP MMIC's 2 batches		400	
	Test Eqpt			??	
	Subtotal			2.800	2.800
LO Devt					
	Labor	4 my eng		2.000	
		4my tech		1.200	
	Supplies	mm-wave power amps		??	
		planar varactors		??	
		microwave sources		??	

	Test Eqpt		??	
	Subtotal		3.200	3.200
Cryogenics				
	Labor	1my eng	500	
		2my tech	600	
	Supplies	competing cryogenerators (3)	1.500	
		test cryostats (3)	120	
		vacum, gages, etc (3 sets)	135	
	Test equipment			
		Data loggers (3)	90	
	Subtotal		2.945	2.945
Proto Rx				
	Labor			
		2my eng	1.000	
		4my tech	1.200	
	Cryogenics			
		Cryogenerator	0	
		Cryostat	200	
	Equipment			
		Control	150	
		HEMT's	60	
		Warm IF's	120	
		LO's	0	
		Optics	120	
		RF components	200	
		Mech. comp.	70	
	Test Equipment		0	
	Subtotal		3.120	3.120
Grand total				28.685

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