Comments on the Use of MMIC's in the Q & Ka-Band EVLA Receivers
(Bob Hayward - 28 March 2002)

## Executive Summary:

This memo deals with two aspects of the design of the Q-Band and Ka-Band front-end systems which will be required for the Expanded VLA project.

The first section discusses the advantages of using RF post-amps rather than the scheme used in our current generation of Q-Band receivers where the first ?warm' amplifier is located after the mixer which converts the RF signal down to X-Band. While this IF post-amp scheme is less expensive, RF post-amps can provide a significant improvement in sensitivity. Results of a noise model estimate for the Q-Band receiver indicate that using RF post-amps can improve the receiver temperature by nearly a factor of two at the band edges.

Secondly, the advantages of using custom designed Monolithic Microwave Integrated Circuits (MMIC's) in the Q & Ka-Band receivers are explored. Following in the foot-steps of ALMA (and, to a large extent, riding on their coattails) could provide substantial cost savings for the EVLA project. A description of the required design efforts and potential costs is presented. A best case scenario could result in a savings of over $500K during Phase I of the EVLA. At worst, the MMIC option would still save about $200K. When projected into Phase II of the project the use of MMIC's could save another $700K.

## Introduction:

During Skip Thacker's recent visit to Socorro, we were interested to learn about the work that he and Eric Bryerton have been doing on MMIC amplifiers, mixers and frequency multipliers back at the Central Development Lab in Charlottesville where they are currently prototyping the LO chain for the ALMA receiver system.

As you may know, MMIC's, or Monolithic Microwave Integrated Circuits, are fast becoming the driving technology for many types of active microwave circuits and are starting to be used in the mm-wave end of the spectrum. While MMIC amplifiers are nicely geared for mass production, they still haven't achieved the sensitivity which we get from Marian Pospieszalski's cooled LNA's with their optimized discrete devices. But for post-amps, they would be ideal. Similarly, mixers & multipliers based on MMIC Schottky diode circuits are also feasible. Skip and Eric are using both types in their ALMA designs. Sandy Weinreb, now at JPL, has been an active participant in NRAO's fledgling MMIC development effort. As has been the case in the past when NRAO was pushing beyond the boundaries of commercially available technology (from the first Mark I digital correlator to the first cooled GaAs HEMT's) he has helped provided technical insight, and in this instance, access to JPL's cutting-edge resources,

One of the areas where MMIC's would come in handy for the EVLA project are the post-amps and mixer/multiplier chains required in our high-frequency receivers, especially the Q-Band (40-50 GHz) and Ka-Band (26-40 GHz) systems. Commercially available components at K-Band (18-26 GHz) & Ku-Band (12-18 GHz) are reasonably cheap so the custom MMIC solution at these frequencies isn't quite so advantageous.

The current Q-Band receivers on the VLA do not have an RF post-amp. Rather the second stage of gain comes after the Spacek mixer which down-converts the signal to a 7.7-9.1 GHz IF. When the Q-Band receivers were first built, commercially available 40-50 GHz amps were not available so post-amp gain in the IF was the only option that existed. With the advent of MMIC-based amplifiers at these frequencies, whether purchased commercially or developed in-house, Q-Band post-amps are now a practical solution.

## Noise Budget Estimates:

But do we really need an RF post-amp in the first place? All of the modern receivers on the VLA have them - the only exception at the moment is at Q-Band. Even the K-Band uses a 18-26 GHz post-amp (a Miteq JS-model) following the LNA. So the question becomes, are there improvements to be gained at Q and Ka-Band by incorporating RF post-amps? To evaluate this question, I've run up my MathCAD noise budget model for the Q-Band receiver and made comparisons of the current VLA configuration and several versions of the Block Converter scheme which was recently adopted for the baseline design. I looked at three variations of the Block Converter, one which has an IF post-amp located in a ?common' IF box, one which has an IF post-amp mounted in the receiver, and one which uses an RF post-amp in front of the block-conversion mixer. Note that there is not a lot of difference in the noise performance that will be achieved between this version of the Block Converter scheme and the original, expensive Dual-Mixer scheme that had been initially envisioned for the EVLA.

The noise model investigated several best/worst case scenarios. The Trx mainly depends on the performance of the LNA. The best case occurs when you operate at the middle of the LNA's frequency band. I used a noise temperature of 25K and a gain of 35 dB, fairly typical values for CDL 40-50 GHz amps. The worst case occurs near the band edges where the sensitivity starts to degrade (I used 35K) and the gain begins to roll off (I used 25 dB). Again, not unreasonable values. For the conversion loss of the Spacek mixer, I used its typical 8 dB spec as a best case value. Since we're using it as a block converter with an 8-18 GHz IF output, I allowed the conversion loss to degrade down to a 12 dB worst case number.

Table 1 : Trx for Several Q-Band Receiver Configurations

| Q-Band Rx Configuration | Post-Amp Location | Q-Band LNA Performance: Tn=25K/G=35dB (8 - CL - 12) | Tn=35K/G=25dB (8 - CL - 12) |
|---|---|---|---|
| Current VLA | IF | 43.5 -> 47.4 | 77.9 -> 117.4 |

| | | | |
|---|---|---|---|
| Block Convert | IF Box | 46.3 -> 54.5 | 106.1 -> 188.3 |
| | IF | 43.2 -> 46.7 | 75.1 -> 110.4 |
| | RF | 41.5 -> 41.6 | 58.5 -> 58.9 |

Assumes : LNA Tn / Gain is 25K /35 dB (best) and 35K / 25 dB (worst)
RF Post-amp has a Noise Figure of 5.0 dB and 25 dB of Gain
RF Mixer has a Conversion Loss of 8 to 12 dB (best to worst)
IF Post-amp has a Noise Figure of 2.5 dB and 25 dB of Gain
IF Cable losses between receiver and IF Converter are 3 dB
IF Band-limiting Filter has an Insertion Loss of 0.5 dB
IF Switch for receiver selection has a Loss of 0.2 dB
IF Splitter for the partitioning of the wideband IF is 4 dB

Note that the noise budget model includes all the components in front of the LNA (ie: feed, vacuum window, polarizer, cal-coupler & cooled isolator) and also accounts for the signal loss after the LNA through the stainless steel waveguide and output vacuum windows.

As a baseline, Table 1 starts off with a receiver which is more or less like the current configuration Q-Band systems but slightly modified to include the splitter needed for the processing of a block converted IF. Its signal would have the following path:

LNA + Mixer + Filter + IF Post-amp + Cable + Switch + Splitter

Table 1 shows that the current VLA Q-Band receiver gives us a Trx of about 44K when the LNA is at its best (ie: Tn=25K and G=35 dB). Should the conversion loss of the mixer increase from 8 to 12 dB, the Trx will be degraded by nearly 4K. In the worst case scenario, at the band edges where the LNA's Tn might increase by 10K and its gain drop by 10 dB, the Trx can climb up to nearly 78K. If the stages which follow the LNA didn't contribute any additional noise, you'd expect the Trx to increase by a similar amount (ie: slightly more than 10K) but we see a 34K increase. And when the mixer's CL is degraded to 12 dB, the Trx shoots up to 117K. So the current VLA receiver works OK mid-band but quickly turns ugly when the LNA or mixer performance begins to roll off.

Now for the Block Converter estimates. There were 3 flavors evaluated:

1) The first has the post-amp in the ?common' IF box. That is, the only amplification that occurs within the receiver is in the LNA. The second stage of gain comes after the IF signal makes its way from the receiver to the IF Switch Box which is shared by all of the high frequency receivers (Ku, K, Ka & Q-Band). The idea is that we could save money by eliminating the IF amps in each of these receivers. The signal path after the LNA looks like this:

LNA + Mixer + Cable + Switch + Filter + IF Post-amp + Splitter

>From Table 1 we see that the best case Trx is a little over 46K, which is worse that the current VLA receiver. This is not surprising since it has the extra insertion loss from the cable between the receiver and IF Box in front of the post-amp (I estimated 3 dB for this exercise - if it's larger, things will only get worse). If the mixer has a 12 dB insertion loss, we're now up to over 54K. For the worst case LNA we get a Trx of 106K. When the mixer has a 12 dB conversion loss, it gets even crummier at 188K, So obviously we don't want to build our receivers this

way.

2) The second style of Block Converter has the IF post-amp in the receiver (ie: directly after the mixer). This is similar to the current VLA Q-Bands. The only real difference is that the filter and switch comes after the IF post-amp, so the effective noise figure of the of the post-amp isn't degraded. The signal path after the LNA looks like this:

LNA + Mixer + IF Post-amp + Cable + Switch + Filter + Splitter

For the best case, we get a 43K receiver temperature. For the worst case, we see 110K. These are better than the current VLA systems, albeit only by a tad. But we should note that in the worst case scenario, when we have only 25 dB in the LNA and 12 dB conversion loss in the mixer, then the net gain in front of the post amp will only be 13 dB. Obviously this is a bit mediocre.

3) The final style of Block Converter has the post-amp in front of the mixer. Thus the signal path looks like:

LNA + RF Post-amp + Mixer + Cable + Switch + Filter + Splitter

Table 1 shows that the best case Trx will be about 42K - that's a couple of degrees better that the Block Conversion scheme which uses an IF post-amp. When the conversion loss of the mixer increases from 8 to 12 dB, we only see a tenth of a degree degradation (compared to over 3K for an IF post-amp). In the worst case LNA scenario, the Trx climbs up to nearly 59K. This is 16K better than the IF post-amp block converter. And when the mixer's CL degrade's to 12 dB, the Trx barely climbs by half a degree. This is nearly a factor of two better than any of the other schemes. Putting the post-amp after the LNA makes it virtually impervious to any increase in conversion loss in the mixer since we now have in close to 50 dB of gain in front of it. So a change of 4 dB in the mixer CL will have little affect on the sensitivity. So I think there is no doubt that we should adopt the RF post-amp concept for the Q and Ka-Band receivers.

## Projected Cost of the Commercial Solution:

For the EVLA, our current Q-Band receivers will have to be modified with the addition of on RF post-amp in each polarization. All of the narrowband 8.4 GHz IF filters and amplifiers will have to be discarded (this would be the case no matter what since we would have needed an 8-12 GHz IF in the original Dual-Mixer scheme and an 8-18 GHz IF for the new Block Conversion scheme).

This is as good a place as any to discuss the Ka-Band receiver and its requirements. Unlike the Q-Band, where we've already bought all the LO chains we need (at about $15K per receiver), the Ka-Band project starts with a clean slate. Not only will we need post-amps but a brand new pair of mixers and frequency triplers in each system. These are available commercially and we have estimates on what they will cost.

So how many post-amps and LO chains will we need over the EVLA project?

If we are thinking ahead, we should not only consider Phase I but Phase II as well. For Phase I we'll need a minimum of 60 post-amps for both the Q & Ka-Band receivers (ie: 28 receivers plus a minimum of 2 spares in each band). Commercial Q-Band post-amps go for about $3.5K each, Ka-Band amps are about $2.8K. Luckily we don't need any more mixers/triplers for Q-Band but we will need 60 LO chains for Ka-Band. These will be about $5.3K per polarization.

Now for Phase II. The numbers assume 8 new receivers for the New Mexico Array and the potential of 10 more to out-fit the VLBA with modern EVLA receivers (this may not necessarily be part of the Phase II plan but it doesn't hurt to contemplate how we could upgrade the VLBA suite of instruments to be comparable and/or compatible to the newer EVLA systems). If we include a couple of spares, we're talking a total of 20 receivers for Phase II. At Q-Band, we will need 40 LO chains, at $7.5K each, as well as the same number of post-amps. At Ka-Band, we'll need 40 post-amps and LO chains.

The following table summarizes the cost of these items for Phase I and Phase II. The amount of bucks required is scary. For Phase I, we'd need $210K for Q-Band and $486K for Ka-Band, for a total of $696K. And remember, this is just for the post-amp and LO chain sub-systems. Phase II could cost up to $764K, with $440K going into Q-Band and $324K into Ka-Band.

Table 2 : Estimated EVLA Costs of Commercial Q & Ka-Band Components

| Receiver | Component | EVLA Phase I | Phase II + VLBA |
|---|---|---|---|
| Q-Band | Post-amps | 60 x $3.5K = $210K | 40 x $3.5K = $140K |
| | Mixers + Mult | 0 0 | 40 x $7.5K = $300K |
| | Sub-total | $210K | $440K |
| Ka-Band | Post-amps | 60 x $2.8K = $168K | 40 x $2.8K = $112K |
| | Mixers + Mult | 60 x $5.3K = $318K | 40 x $5.3K = $212K |
| | Sub-total | $486K | $324K |
| Total per Band | | $696K | $764K |
| Grand-Total | | $1460K | |

So this is what we're up against if we go the commercial route. For Phase I alone we'll need to spend close to $700K for post-amps and LO chains. That could potentially rise to nearly one and a half million dollars over both Phases of the EVLA. So we should seriously consider other options, even if it means we need to do some in-house R&D work and/or purchasing a share of a MMIC wafer from a foundary.

## The MMIC Solution:

This is where Skip's visit, along with a number of e-mails from Eric Bryerton, may open up new possibilities for us. They have been working on building LO drivers for ALMA using MMIC's and are about to start a couple wafer runs of InP amplifiers and diode multipliers/mixers MMIC's. They advocate that using MMICs and doing the packaging ourselves could provide sizable savings for the EVLA project, especially if we can ride on ALMA's coattails. With luck, this might be done with very little investment since ALMA has already budgeted to purchase several development and production wafers.

They have been doing some R&D work with commercially available MMIC chips from Agilent, including the HMMC-5040 chip (a 18-40 GHz medium power amplifier), the UMS CHA2157 (a 45-65 GHz LNA/medium power amplifier) and the UMS CHX2091 (a 40 GHz doubler). They have developed waveguide and K-connector versions of these units using the waveguide-coax probes developed by Marian's Amplifier Group. The results of their prototypes looks encouraging

Skip & Eric intend to have some of their custom designs on two up-coming wafer runs. The first is from HRL (Hughes) for InP power amplifiers with devices up to 190 GHz. One of these designs is for the Q-band medium power amplifier for ALMA use. The circuit designs for this R&D wafer have to completed within six months, at which point it goes to the foundary to be fabricated. The MMIC chips should be available for prototype testing by the spring of 2003.

The second wafer run is a Schottky diode MMIC wafer from a company called UMS. This will include various mixers and frequency multipliers for ALMA (mostly above 75 GHz, except for one 40-50 GHz doubler). This wafer run from UMS will yield something like 1,600 circuits - many more than ALMA needs - so there would be plenty of real estate for EVLA chips. Many of the ALMA high-frequency tripler and mixer designs are being done by Matthew Morgan, a student of Sandy Weinreb's at Caltech (in exchange for some wafer space for a few of their own designs). This student has already designed a prototype tripler for ALMA which has worked well, so Eric & Skip are confident in his abilities. And CDL has just recently purchased a copy of the ADS design software so that the folks there are now in the position to do their own custom designs rather than having to farm much of it out to JPL.

As well as the circuit design for the MMIC's, any post-amp or LO chain we want to use for the EVLA will require custom microstrip input and output circuits (ie: matching networks, microstrip or co-planar transmission lines, filters, etc). Also needed is the design of the milled brass block that everything must fit into. Ideally the post-amp, mixer and LO tripler circuits required for Ka-Band could be integrated into a single block. This would not only improve the overall performance of the post-amp/LO chain combination but reduce the cost and simplify the packaging of the receiver. An integrated Q-Band post-amp/LO chain would similarly be ideal for EVLA Phase II.

Thus, if we want to go the MMIC route for the EVLA, it seems to me we have 3 options. 1) Somebody at the AOC could do the design (but it's not like we have a lot of manpower to spare on an R&D effort, or anyone with the experience at these frequencies let alone the CAD tools). 2) We could contract Sandy's student's to get the designs we need (note that this will cost us real money, perhaps about $25K per design). 3) We try to talk the folks at CDL into doing the designs.

Although Option 3 would be highly desirable, the amount of effort required by ALMA makes it unlikely that the CDL has the resources and manpower to do all of the designs for us. Thus a combination of Options 2 and 3 seems more realistic. It should be pointed out that ALMA is taking a ?redundant' design approach on many of their MMIC's with Eric and JPL doing independent designs. This spreads the risk should one MMIC circuit end up with an unintended design flaw. The EVLA mixer and multipler designs may be a little more demanding compared to those need for ALMA because of our wider bandwidths. However, they could be considered as extensions to the basic ALMA designs, so perhaps the risk is not quite that bad. If we were to contract out all of the required EVLA Phase I designs to JPL (ie: Q-Band post-amp, Ka-Band post amp, Ka-Band mixer and Ka-Band tripler), we might have to swallow upwards of $100K of design costs (I have not discussed our requirements with Sandy yet, so I'm hoping these are worst case expenses). The Phase II designs might require another $50K.

For the microstrip input and output circuits, hopefully these are small enough jobs that the CDL could tackle the design for us. For the brass block, we should be able to take the current CDL designs for the ALMA blocks and adapt them for our use (ie: the layout of our receiver will determine whether we need an in-line, U or Z configuration block).

Once we procure all the MMIC & microstrip designs we need, then we have the fabrication of the wafers to worry about. ALMA's first HRL amplifier wafer, which is mainly a ?development' wafer, could conceivably be free of charge since ALMA has already budgeted for it and the amount of real estate we need is quite small. The UMS diode wafer is also budgeted for by ALMA. Again we might be able ride along for free. Note that ALMA is making a sizable investment here, about $250K for the HRL wafer and about $90K for the UMS wafer. Designs for the post-amps as well as the mixers and triplers would have to be ready by fall of 2002.

ALMA is also planning a second HRL amplifier wafer, which will be required about a year after the first (ie: sometime in 2004). It is mainly for their production devices. About 50-75% of it will be for their ?qualified' amps so there would likely be a fair bit of room for our EVLA amps. While the number of amps we need is large by our past standards, we could get a lot of what we require in ?prototype' quantities if the initial design pans out on the first HRL wafer. But we should expect on paying at least 25% of the 2nd HRL wafer run, which at $250K means somewhere around $63K. At worst case, a 50% share would cost us about $125K.

ALMA is hoping that the single UMS wafer will give them all the mixers and multipliers they will ever need. They are prepared to consider a second wafer if some of their diode circuits have problems. At $90K, the price of an additional wafer run is far less intimidating than the InP amplifier HRL wafer. This ?relatively' inexpensive price is something we would need to consider in our worst case scenario should our MMIC diode designs run into trouble.

Then there is the cost of assembling the units. For the Q-Band post-amps, a conservative guess for the connectors, miniature bias card, w/g probes, etc. would be about $200/unit. For the Ka and Q-Band LO chains, which would have the post-amp, mixer, and LO multiplier in a single integrated package, the cost might go as high as $400/unit (it has SMA extra connectors and such). The brass blocks would also have to be gold-plated. These price estimates should be generous enough to cover that as well. Thus over Phase I and II of the EVLA we might incur the following component costs:

| | | | |
|---|---|---|---|
| Phase I : | Q-Band post-amp (60) | $12K | |
| | Ka-Band post-amp/mixer/multiplier (60) | $24K | |
| | Sub-total | | $36K |
| Phase II : | Q-Band post-amp/mixer/multiplier (40) | $16K | |
| | Ka-Band post-amp/mixer/multiplier (40) | $16K | |
| | Sub-total | | $32K |
| | | | ---- |
| Total | | | $68K |

The blocks can be machined on a CNC mill so it should be relatively straight forward to have them mass-produced. Eric estimates it would take about 4 hours of a machinist's time to do each block. If done by our NRAO shops, the costs might essentially be hidden. If we went to an outside shop which charged $100 an hour, we would have to budget for about $400 per block. The Phase I machining costs for the Q-Band post-amps would come to $24K and a similar amount for the Ka-Band LO chains. For Phase II, we're looking at another $32K.

The question of who does the assembly needs to be fleshed out further. The signals to and from the MMIC chips will have to be wire-bonded. This can be done at the CDL where they have a number of wire-bonding machines but they could easily be swamped by ALMA production at the same time we would need the EVLA units. Skip recommends we send one of our technicians to CDL to be trained. Once he/she learned the ropes (and it is a skill that is quite demanding), our tech could help CDL with the bonding of our MMIC's. It might also make sense to buy our own bonder for the AOC. These cost about $25K. (Note that this memo does not address how MMIC designs might reduce costs for the rest of the EVLA down-converter modules but one can assume that we could make significant savings and simplify the module layouts using commercially available MMIC's below 20 GHz. Even if we didn't go the MMIC route for Ka & Q-Band, a wire-bonder would probably come in handy for the LO/IF Group as well as the ALMA folks here in Socorro.)

Eric estimates it would take about 4 hours to assemble a post-amp and double that for one of the integrated post-amp/mixer/multiplier units. Not all of this assembly need be done by the ?bonder tech' - about half of it could be done by a tech with less specialized skills. It's not obvious to me that we have all the bodies we need at the AOC to fully accommodate the MMIC solution. However, assuming the EVLA will need to hire some additional general purpose techs to do an assortment of assembly tasks for the various groups (ie: for the DCS, LO/IF and the Front End groups), the share of a technician's time to work on MMIC's would come to about 60 x 4 hr x $20/hr = $4800 for the Q-Band post-amps and double that for the Ka-Band post-amp/mixer/tripler. Add $14K for Phase II.

Projected Best/Worst Case Costs for the MMIC Solution:
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So what do all the costs come to? Here are the ones I can think of, but don't hold me to any kind of accuracy at this point. It's presented in a best and worst case scenario format. The latter assumes we have to contract out for each of the 6 MMIC designs plus pay a 50% share of the 2nd HRL wafer and buy our own UMS diode wafer. It also assumes we do all our machining done outside and pay for a tech to do most of the assembly work.

Table 3 : Estimated Best/Worst Case Costs of the MMIC Solution

| | Best Case | Worst Case |
|---|---|---|
| Phase I: | | |
| Q Post-amp MMIC Design | $0K (CDL) | $25K (JPL) |
| Ka Post-amp MMIC Design | $6K (COTS) | $25K (JPL) |
| Ka Mixer MMIC Design | $6K (COTS) | $25K (JPL) |
| Ka Tripler MMIC Design | $6K (COTS) | $25K (JPL) |
| Microstrip Designs | $0K (CDL) | $0K (CDL) |
| Block Designs | $0K (NRAO) | $0K (NRAO) |
| 1st HRL Wafer (post-amps) | $0K (ALMA) | $0K (ALMA) |
| 1st UMS Wafer (mixers & triplers) | $0K (ALMA) | $0K (ALMA) |
| 2nd HRL Wafer (more post-amps) | $63K (25%) | $125K (50%) |
| 2nd UMS Wafer (more mixer/triplers) | $0K (N/A) | $90K (100%) |
| Q Post-amp Block Fabrication | $0K (NRAO) | $24K (Ext) |
| Q Post-amp Components | $12K (COTS) | $12K (COTS) |
| Q Post-amp Assembly | $0K (NRAO) | $5K (Ext) |
| Ka Post-amp/Mixer/Tripler Block Fab | $0K (NRAO) | $24K (Ext) |
| Ka Post-amp/Mixer/Tripler Cpts | $24K (COTS) | $24K (COTS) |
| Ka Post-amp/Mixer/Tripler Assembly | $0K (NRAO) | $10K (Ext) |
| Wire-Bonder | $25K | $25K |
| Travel - Tech (wire-bonder training) | $15K | $25K |
| Travel - Eng (CDL/JPL liaison) | $15K | $25K |
| Sub-Total | $172K | $489K |
| Phase II: | | |
| Q Mixer MMIC Design | $6K (COTS) | $25K (JPL) |
| Q Tripler | $6K (COTS) | $25K (JPL) |
| Q Post-amp/Mixer/Tripler Block Fab | $0K (NRAO) | $16K (Ext) |
| Q Post-amp Components | $8K (COTS) | $10K (COTS) |
| Q Post-amp Assembly | $0K (NRAO) | $7K (Ext) |
| Ka Post-amp/Mixer/Tripler Block Fab | $0K (NRAO) | $16K (Ext) |
| Ka Post-amp/Mixer/Tripler Cpts | $16K (COTS) | $16K (COTS) |
| Ka Post-amp/Mixer/Tripler Assembly | $0K (NRAO) | $7K (NRAO) |
| Sub-Total | $36K | $122K |
| Phase I & II Total | $208K | $611K |

Key : NRAO = From internal NRAO resources:
- for machining, use GB and/or VLA shops
- for assembly, use currently employed techs

COTS = Commercial Off-The-Shelf components

Ext = From outside resources:
- for machining, out-source to machine shops (4 hrs x $100/hr = $400 per block)
- for assembly, out-source or hire an assembler (post-amp = 4 hrs x $20/hr per block; post-amp/mixer/tripler = 8 hrs x $20/hr per block)

When these costs are compared with those shown in Table 2 for the Commercial solution, we see that in Phase I the use of MMIC's could save us $524K in the ?best case' scenario. This drops to only about $207K in the ?worst case'. This is still a substantial saving. One can look at it as nearly $7K per antenna that some other sub-system could make use of. When applied to Phase II, we could save $728K at best and $642K at worst.

So, in broad terms, for something on the order of a quarter of a million dollars of ?investment' in MMIC's, we could save somewhere between a quarter to half a million in Phase I and close to another 3/4 of a million in Phase II.

## MMIC Project Requirements, Tasks and Schedule:

We will need the Q-Band RF post-amps by early 2004 since, according to the current EVLA schedule, that's when we have to start upgrading the current Q-Band receivers as the antennas begin to be cycled through the barn for their EVLA modifications. This a fairly tight schedule for the MMIC option since the prototypes would only become available by late 2003 at best. This means that the first of the EVLA Q-Band receivers might have to use commercial post-amps. We would have to hope that there would be enough MMIC's on the HRL ?development' wafer to tide us through until the HRL ?production' wafer is available towards the end of 2004. If, heaven forbid, the prototype MMIC design effort is a complete failure, we could still opt out of the ?production' wafer run, bite the bullet and buy our amplifiers of-the-shelf from commercial sources.

On the good news front, we have just heard that John Webber has given his approval for the CDL (ie: mainly Eric) to work on the Q-Band post-amp MMIC design. This will be an important step forward for us. The staff there certainly have more experience than any of us at the AOC in high-frequency circuit design, plus they have the requisite CAD tools. Obviously this will be at a lower priority than the circuits required for ALMA which must take precedence. But on the other hand, the EVLA circuits can be built upon the experience developed doing the ALMA designs.

The Ka-Band post-amp/mixer/tripler schedule might appear to be somewhat less time critical. These don't have to be mass-produced until the middle of 2005. But if we want to use custom MMIC's, their designs have to be complete by fall 2002 in order to make the deadlines for the HRL and UMS wafers. Eric suggests that the post-amp might be done using commercially available MMIC chips. In theory two ALH140C balanced MMIC amplifiers from Velocium could be cascaded together. At less than $100 per chip, we could purchase all the chips we would need for half of what a custom $25K design might cost us (this assumes it would meet our performance specifications). There are some commercial mixers and multipliers MMIC's which, while they don't meet our RF and IF bandwidths, might be used as pre-prototypes. However, the Ka-Band mixers and triplers would likely use devices from the UMS diode wafer. This means the designs would have to be completed within 6 months, presumably by contracting them out to JPL. If we were lucky, Eric might be able to provide redundant designs for us.

The Q-Band mixers & triplers are somewhat more of an open question. Since these are not needed until Phase II, there may be less incentive to try and get these custom designs in time for the UMS wafer run. On the other hand, since they are essentially identical, at least in function, to the Ka-Band mixer/tripler designs, it might just be a small incremental cost to scale the circuit ?up' in frequency. We could also be optimistic and hope that by the time Phase II rolls around, there might be commercial MMIC's out there that could do the job for us off-the-shelf.

The following is a list of the performance specifications, schedule requirements and major tasks [along with my suggestion on which group might be best placed to carry each of them out] for the MMIC solution:

Q-Band post-amp:
* Post-amp spec's = 40-50 GHz, NF < 5 dB, Gain = 25 dB
  - Design of MMIC (required by 2002 Q3 for 1st HRL wafer) [CDL]
  - Design of microstrip circuit [CDL]
  - Design of block [CDL/AOC]
  - Bonding & assembly of prototypes [CDL]
  - Prototype testing (required by 2003 Q4) [CDL/AOC]
  - Bonding & assembly of production units [CDL/AOC]

Ka-Band post-amp/mixer/tripler:
* Post-amp spec's = 26-40 GHz, NF < 5 dB, G = 25 dB
* Mixer spec's = RF=26-40 GHz, LO=36-50 GHz, IF=8-18 GHz
* Tripler spec's = In=12-16.7 GHz @ 0 dBm (?), Out=36-50 GHz
  - Design of post-amp MMIC (buy commercial?) [COTS/JPL]
  - Design of mixer MMIC (by 2002 Q3 for 1st UMS wafer) [JPL]
  - Design of tripler MMIC (by 2002 Q3 for 1st UMS wafer) [JPL]
  - Design of Ka-Band microstrip circuit [CDL]
  - Design of Ka-Band block [CDL/AOC]
  - Bonding & assembly of prototypes [CDL]
  - Prototype testing (required by 2004 Q4) [CDL/AOC]
  - Bonding & assembly of production units [CDL/AOC]

Q-Band post-amp/mixer/multiplier (for Phase II):
* Post-amp spec's = 40-50 GHz, NF < 5 dB, G = 25 dB
* Mixer spec's = RF=40-50 GHz, LO=50-60 GHz, IF=8-18 GHz
* Tripler spec's = In=16.6-20 GHz @ 0 dBm, Out=50-60 GHz
  - Design of post-amp MMIC (uses previous design) [CDL]
  - Design of mixer MMIC (by 2002 Q3 for 1st UMS wafer) [JPL]
  - Design of tripler MMIC (by 2002 Q3 for 1st UMS wafer) [JPL]
  - Design of Q-Band microstrip circuit [CDL]
  - Design of Q-Band block [CDL/AOC]
  - Bonding & assembly of prototypes [CDL]
  - Prototype testing (required by 2005) [CDL/AOC]
  - Bonding & assembly of production units [CDL/AOC]

I have attached a table laying out the who, what, when and where that has to take place for this MMIC option to be useful for the EVLA Phase I. It is in a pdf file and should more or less be self-explanatory. Some of the items with question marks obviously need to be tied down. It only deals with the Q-Band post-amp and the Ka-Band post-amp/mixer/tripler designs. It assumes we can merge our designs on the ALMA wafers and that, hopefully, the ALMA project is free of the funding delays that has plagued it to date. It also assumes a level of additional support from the CDL which has not yet been asked of them formally. This kind of request should come from our senior EVLA management and may require some quid pro quo to massage it through the NRAO hierarchy. Additionally it requires a number of contracts to be placed with JPL to provide the MMIC circuit designs we'll need (ie: at least 4 for Phase I).

Summary:
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>From the facts and cost estimates presented above, I think the MMIC solution is rather compelling. We could save somewhere between a quarter to half a million dollars in Phase I and perhaps as much as another half a million in Phase II.

It would also be good for NRAO on a more general principle - that of keeping us on the leading edge of technology. Other observatories, such as the Australian CSIRO, are already traveling down this road. If the EVLA is going to be left behind, then we should only do so based on a conscious decision and not by default.

Bob Hayward

PS : I'm waiting to hear back from Sandy Weinreb on what MMIC designs we could contract out to JPL. Once I have firmer costs estimates, I intend to turn this manuscript into an official EVLA Memo for wider distribution.

# EVLA Phase I Schedule for Q & Ka-Band MMIC's

*(R. Hayward - 26 March 2002)*

| Task | | Modified Q-Band | New Ka-Band | | |
|---|---|---|---|---|---|
| Prototype Rxeceiver | Time Period | 2003 Q1 → 2003 Q3 | 2004 Q3 → 2005 Q2 | | |
| Production Receivers | Time Period | 2004 Q1 → 2007 Q4 | 2006 Q1 → 2010 Q4 | | |
| | | Post-Amp (25 dB) ① | Tripler | Mixer | Post-Amp (25 dB) |
| Total Needed | @ 2 units per Rx | 60 + Spares | 60 + spares | 60 + spares | 60 + spares |
| MMIC Design | Primary / Backup | CDL / JPL ② (?) | JPL ② / CDL(?) | JPL ② / CDL(?) | COTS / JPL ②(?) |
| | Needed By | 2002 Q3 | 2002 Q3 | 2002 Q3 | - |
| Development Wafers | Type | HRL (InP) # 1 | UMS (Diode) # 1 | | ALH140C (?) |
| | Date Available | 2003 Q1 | 2003 Q1 | | - |
| Package Design | Block | CDL / AOC | CDL / AOC | | |
| | Microstrip Circuit | CDL | CDL | | |
| | Needed By | 2003 Q1 | 2004 Q1 | | |
| Prototype Unit | Machining | CDL / GB / VLA | CDL / GB / AOC | | |
| | Bonding&Assembly | CDL | CDL | | |
| | Testing | CDL / AOC | CDL / AOC | | |
| | Needed By | 2003 Q4 ③ | 2004 Q4 | | |
| ALMA Production Wafer | Type | HRL (InP) # 2 | - | | (?) |
| | Date Available | 2004 Q1 (?) | - | | (?) |
| Production Units | Machining | CDL / GB / VLA | CDL / GB / VLA | | |
| | Bonding&Assembly | CDL ④ | CDL ④ | | |
| | Begin Production | 2004 Q2 | 2005 Q2 | | |

Notes: ① Q-Band only needs a Post-Amp design for Phase I, will need an additional Tripler + Mixer + Post-Amp design for Phase II.
② MMIC design contracted out to JPL (Sandy Weinreb's student) on a consulting basis.
③ Early prototype Q-Band receivers may have to use commercially purchased post-amps.
④ AOC may have to send a technician to CDL for several months to aid in the bonding & assembly of the production units.