MILLIMETER ARRAY
MEMO NO. 65

Some Considerations on the IF and Transmission System of the Millimeter Array.

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This memo outlines some preliminary ideas for the part of the receiving system of the MMA that takes the signals from the front-end outputs and delivers them in digital form to the inputs of the correlator. The IF amplifiers following the SIS mixers used in the highest frequency bands will probably have frequency passbands from 1 to 2 GHz, and the outputs of FET front ends can easily be converted to the same band. It will therefore be assumed that the front end outputs consist of two or four such IF bands carrying signals of two frequency bands and/or polarizations. It will also be assumed that the inputs of the correlator consist of four level (two-bit) digital data covering a total signal bandwidth of 2 GHz, divided into at least eight bands. These figures are consistent with the specifications in the MMA proposal document. They are intended to provide a basis for preliminary discussion of system details, and may well be changed several times as the system evolves. Note that much of the following discussion would also be applicable to an upgrade of the VLA receiving system.

(1) A System with Analog Signal Transmission.

Some insights on possible system arrangements can be obtained by considering how similar problems are handled in the VLA and VLBA. In the VLA the signal is transmitted in analog form in the waveguide. A diagram of a system for the MMA using analog transmission in optical fibers is shown in Fig. 1. A total of 2 GHz is selected from the four IF bands and modulated onto an optical fiber transmission line that runs from the antenna to the central building where the correlator is located. The 2 GHz bandwidth can probably be accommodated on a single fiber, so the IF signals could be combined in a frequency multiplex system, and demultiplexed at the output of the optical receiving system. Sideband separating mixers would be used to convert each 500 MHz-wide IF signal into two baseband channels with maximum upper cutoff frequency of 250 MHz. The samplers would run at a clock speed of 500 MHz. The specifications of the correlator given in the proposal document indicate that the 2 GHz bandwidth would be analyzed into 1024 spectral channels of width 2 MHz. Discussion at the meeting on 4/11/91 in Socorro indicated that the finest spectral resolution likely to be required is about 6 kHz, which corresponds to a velocity resolution of 0.02 km/s at 100 GHz. Thus it would be necessary to reduce the spectral channel bandwidth by a factor of about 340 which could be achieved in a recirculating correlator by a reduction in the input bandwidth by a factor of 18. Switchable filters would thus be required in the baseband amplifiers to cover bandwidths of 250, 125, 62.5, 31.25, 15.62 and possibly 7.81 MHz. With the reduced filter bandwidths the frequencies converted to baseband would be tuned across the IF passbands by varying the local oscillator used in the baseband conversion. The oscillator should be tunable in increments of no more than a few spectral bandwidths, say, 10 kHz. The same oscillator could be used for the corresponding IF band from all antennas (so long as fringe rotation is not introduced at this oscillator: see section 3). In the VLA a set of Fluke synthesizers in the Electronics Room of the Control Building perform the corresponding function.

The scheme outlined in Fig. 1 has the advantage of being about the simplest that one could devise. The serious disadvantage of it is that it involves long paths of analog signal transmission which produce some distortion, including time variation of the signal passbands resulting from temperature effects etc. Experience with the VLA has shown that passband mismatching is a source of closure errors, and that variation of the passbands is a possible limit on the calibration of closure errors (see the paper by Bagri and Thompson in the Proceedings of the VLA 10 th Anniversary Symposium, 1990). It is not easy to make a quantitative estimate of the likely limits on dynamic range imposed by variability in the transmission system, but such a limit must occur, and it can be avoided entirely by transmitting the signals in digital form. Although errors occur in digital systems also, error rates are readily measurable and can be made almost arbitrarily small. Since the signals must be digitized before correlation, there seems to be every reason to digitize them at the antennas and transmit them in digital form. One may therefore ask why analog transmission was chosen in the case of the VLA. Three reasons can be given, as follows. (1) Putting the baseband conversion, filtering, and sampling at the antennas would have increased the complexity of the equipment at the antennas which can be located as far as 21 km away from the central maintenance area, requiring access times of over an hour. (2) Tuning the narrow baseband responses to cover specific frequencies of spectral lines would have required local oscillator tunability in increments of about 1 kHz or less, and generating such LO signals with synchronous phases at each of the antennas is a complicated procedure. Note that the larger tuning increments required for the MMA greatly simplify this problem. (3) At the time that the VLA system was designed the requirements of dynamic range and the effects of closure errors were not understood.

(2) A System with Digital Signal Transmission.

Since the development of the VLA the range of signal processing functions that can be performed digitally has increased greatly, in large part due to the development of large custom design IC's based on gate arrays and of circuits with programmable functions. Also the commercial development of optical fiber components has been aimed largely, but not exclusively, at digital signal transmission. Thus to take maximum advantage of the accuracy and flexibility of state-of-the-art techniques, it would appear to be advantageous to perform essential analog processing and then get the signals into digital form as soon as possible after they are received.

A system based on digital signal transmission from the antennas is shown in Fig. 2. This system is based on that developed for the VLBA. The unit in which conversion to baseband, filtering, and amplification are performed is the Baseband Converter (BBC), which is shown in more detail in Fig. 3. By means of the input switch each BBC can be assigned to any of the four IF signals as required by the particulars of the observation. The digital outputs of the samplers go to a formatter which performs splitting or interleaving of the bit streams that may be required by the optical transmission system. Parity bits for monitoring the transmission error rates may be added at this point. The optical fiber link would have a capacity of 8 Gb/s to accommodate a 2 GHz signal bandwidth with four-level sampling. Four fibers would probably be required for each antenna. At the correlator location the data are reconstituted into eight output streams, corresponding to the baseband signals, for further digital processing. The deformatter could also perform the parity checking mentioned above. This need not be done continuously, but would be useful as a periodic check, especially as the connectors of optical fibers are commonly a source of problems. Alternatively a check of the error rate could be obtained by transmission of a reproducible sequence of pseudo-random code.

In the BBC block diagram in Fig. 3 the local oscillator is tunable in increments of 10 kHz, which corresponds to a velocity increment of 0.03 km/s at 100 GHz, and should be fine enough for any observations with the MMA. If the required LO frequency is N times 10 kHz, a part of the oscillator output is divided by N and then compared with a 10 kHz reference to phase-lock the oscillator. The 10 kHz reference is easily established at all antennas, and for any given frequency the oscillators at the different antennas always maintain the same phase relationships. Note, however, that this scheme will only work successfully if N is not too large since the frequency division results in some generation of phase jitter in the LO. An oscillator with division from 1 GHz to 10 kHz has been satisfactorily used in Alan Rogers' design of the BBC's for the VLBA. (If the 10 kHz intervals are not fine enough other possibilities would include reconstituting the signals in analog form at the central location and then applying further filtering and resampling, as in the Australia telescope, or distributing finely tunable signals to the antennas from the central location.) The baseband filter bandwidths from 250 MHz down to about 15 MHz are too large to be implemented using operational amplifiers and switched resistors as in the VLBA design, so all of the filters would probably be implemented as custom L-C filters. The synchronous detectors in the unit are required to measure the gain by detecting the signal from a switched noise source at the receiver input (these would also be required in the system in Fig. 1). The BBC also contains a monitor and control (M/C) interface for setting of the input selector switch, the LO frequency, and the baseband bandwidths, and for readout of the synchronous detector voltages. For system maintenance there are significant advantages in placing the components of the BBC together in a single module. Each BBC processes a certain fraction of the total bandwidth, and a breakdown of one unit should not affect the others. Spare units would be available for replacement, or, better still, an additional BBC and sampler could be in place at each antenna and could be brought into operation remotely to replace a failed unit. Configuring the components in some other arrangements could save the use of an individual M/C interface for each baseband pair, but very little else. If the signals were transmitted in an analog form from the antennas the only saving would be in the 1-2 GHz LO's, for which separate units would not be required for each antenna. For the full array of 40 antennas a total of 160 BBC's would be required for operation, with perhaps another 40 spares. Although this is a rather complicated module, careful design with attention to minimization of required adjustments should make production of such numbers by NRAO a practical proposition.

(3) Fringe Rotation.

Rotation of the fringe pattern to slow to zero the fringe oscillations at the correlator outputs can be performed by inserting phase shifts at a required rate into one of the local oscillators. For each band that is processed, the fringes are stopped for the frequency that is brought to zero in the conversion to baseband. Fringes at other frequencies within the baseband are then also stopped by the phase shifts introduced by the compensating delays. With receiving bandwidths of 1 GHz or more it is necessary to break the bandwidth down into smaller bands (eight in the schemes considered here for the VLBA) which are processed in parallel. Each of these requires different fringe offsets to stop the fringes precisely. To accomplish fringe stopping by means of LO offsets would necessitate applying a different offset to each of the oscillators used in the conversion to baseband. The full fringe rotation could be applied at these oscillators, or else the major part could be applied at an earlier LO which would be within the front end block in Figs. 1 and 2. If double sideband reception is used in the front end, the fringe stopping would be applied for a signal frequency equal to the first LO. In the system under consideration, signals within the upper or lower receiving bands are all within 2 GHz of this LO frequency. Thus if the maximum distance of an antenna from the phase reference point (taken to be at the center of the array) is 1.5 km, the maximum additional frequency offset for any baseband is 0.73 Hz. These offsets could be applied at the conversion to baseband, or digitally in the correlator, either before or after cross correlation. Stopping the additional fringe frequency after correlation would probably be the simplest. The maximum additional frequency for any antenna pair would be 2x0.73 = 1.46 Hz. The correlator output could be averaged over about (+/-) 5° of phase, i.e. 40 ms of time. Every 40 ms, for each frequency band, it would be necessary to apply a small (and different) phase shift to each of the 40x39/2 = 780 cross correlator outputs. The disadvantage of this method is that it does not accommodate phasing of the array as used in VLBI observations since the full correction is applied only to the cross products of the signals. Digital frequency correction before cross correlation may be the optimum method.

(4) Conversion to Baseband.

In the conversion of signals to baseband a sideband separating mixer (sometimes called a single-sideband mixer) is generally used. In such an arrangement the outputs corresponding to the signal and image channels of the input are separated by applying precise phase shifts, and the best isolation that is achievable is a little more than 30 dB. John Archer obtained about 32 dB consistently for the baseband mixers of the VLA, using carefully selected diodes, and hybrids and baseband quadrature networks designed and made at NRAO. After about ten years, some of these mixers have been remeasured and typically show isolation in the range 26-30 dB, presumably as a result of ageing of the components. In the sideband separating mixers of the VLBA BBC's an isolation of 26 dB can just be achieved with some difficulty, and we have no experience of how this may degrade with time. In the VLBA system, commercial mixers and hybrids are used with an IF phasing network designed by Alan Rogers. The lower isolation relative to the VLA is due, at least in part, to the wider bandwidth over which the input is tuned: 500 to 1000 MHz for the VLBA and only 100 to 150 MHz or 200 to 250 MHz in the case of the VLA. These examples illustrate a general problem: sideband separating mixers require careful design, and a great deal of time and effort to adjust, and then are little more than marginally acceptable.

An alternative to the sideband separating mixer would be the use of a regular mixer with very careful filtering to allow only one sideband in the baseband output. Two frequency conversions would be necessary as in the scheme in Fig. 4. A band of width 250 MHz is selected from the input band of 1000 to 2000 MHz, and can be tuned over this band by conversion with a 750 to 1500 MHz oscillator. The resulting signal is passed through a sharp-sided filter covering 2500 to 2750 MHz (9.5% bandwidth). This could be converted to baseband with an LO at 2500 MHz, but it will ease the specifications of the 2500-2750 MHz filter if instead it is converted to 250-500 MHz using an LO at 2250 MHz. In this latter case bandpass sampling would be used, but the sampling frequency would be the same since it depends upon the bandwidth to be sampled. In this type of system each converter unit produces only one output band rather than two as in the case of the sideband separating mixer. However, since the two bands of the sideband separating case are not independently tunable, one can equally well process the same signal band by using the scheme of Fig. 4 with a bandwidth twice that of the lowpass filters used with a sideband separating mixer.

For a given total signal bandwidth and a given number of baseband converters, a design using sideband separating mixers uses twice as many samplers as a design based on Fig. 4, but the latter requires a sampling frequency higher by a factor of two. In the first of these schemes the critical parameters are the matching of the phase and amplitude responses of the mixers and phasing networks, and in the second the selectivity of the filters. The scheme in Fig. 4 would cost more in commercially obtainable components but should require much less adjustment during assembly. Further investigation is required to clarify the choice between these schemes.

(5) Conclusions.

(1) Digital transmission offers minimum distortion of the signals and no serious problems in its implementation have been identified.

(2) Large bandwidths require correspondingly large numbers of IF conversions to baseband (or to a low frequency passband) for sampling, and the hardware involved will comprise a fairly large part of the signal processing equipment. Adequate time should be allowed for investigating and testing the approaches discussed in section (4), in order to obtain a well engineered design before the main construction phase of the MMA is started. Configuration of the required components in a form similar to the BBC in Fig. 3 offers some practical advantages.

(3) Fringe rotation (stopping) could be performed in an analog manner in the LO's, digitally in the correlators, or by a combination of both methods. A different rotation is required for each signal band that is sampled, and further study of the system design is required before a specific scheme can be recommended. The feasibility of fringe rotation in the correlator will depend upon whether an FX or a lag design is chosen.

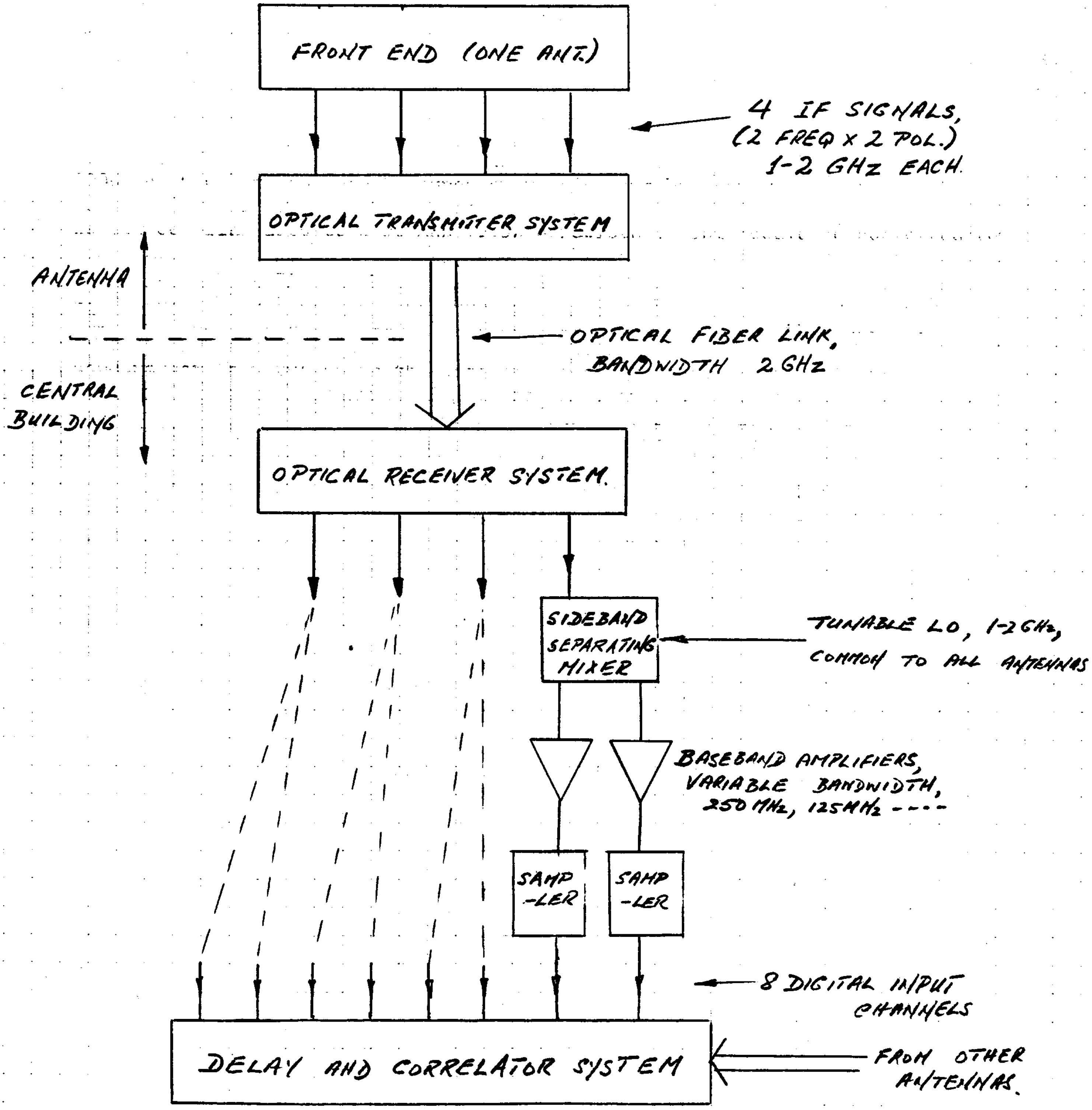

Fig. 1. System with analog signal transmission.

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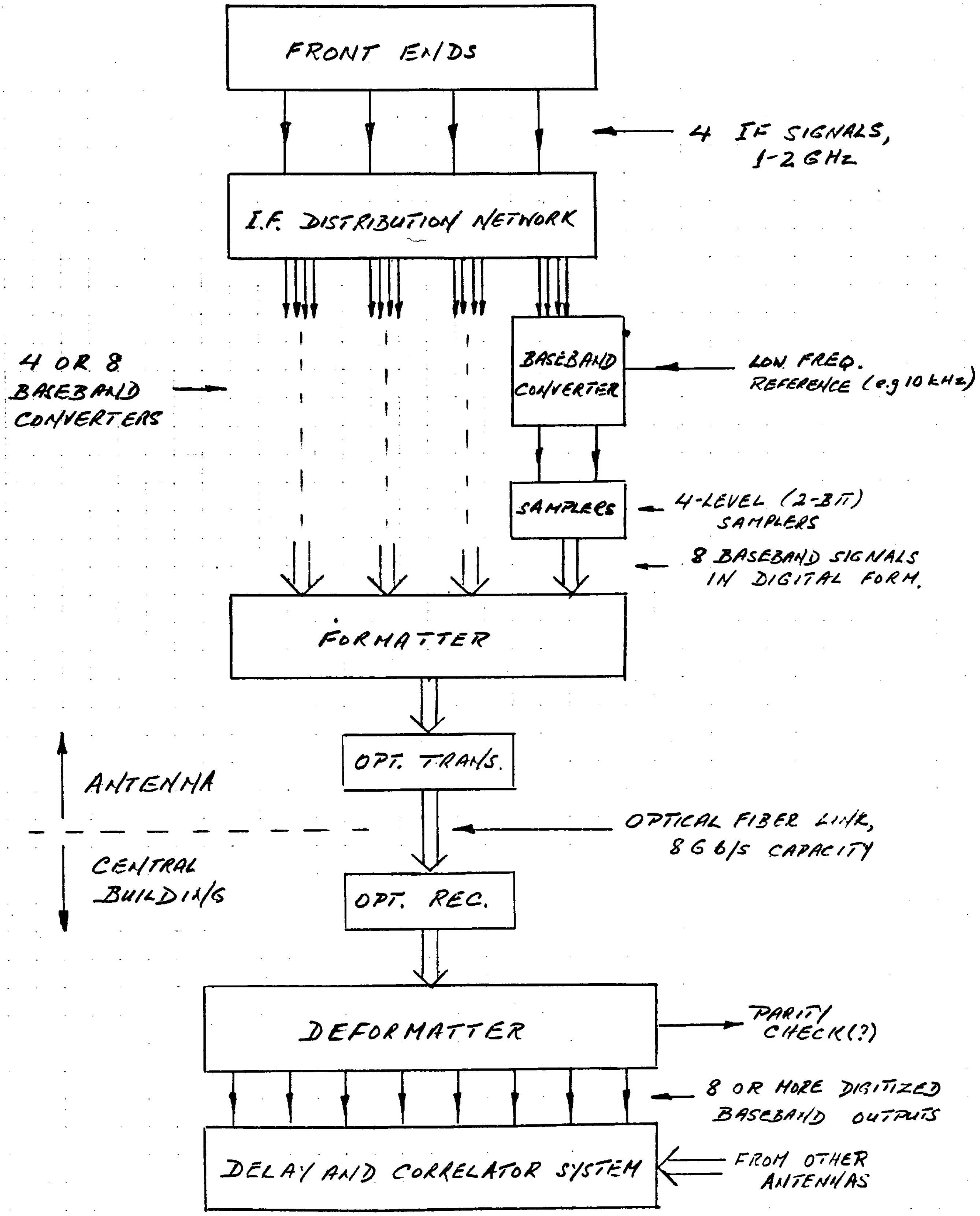

Fig. 2. System with digital signal transmission configured to include a Baseband Converter unit as in the VLBA.

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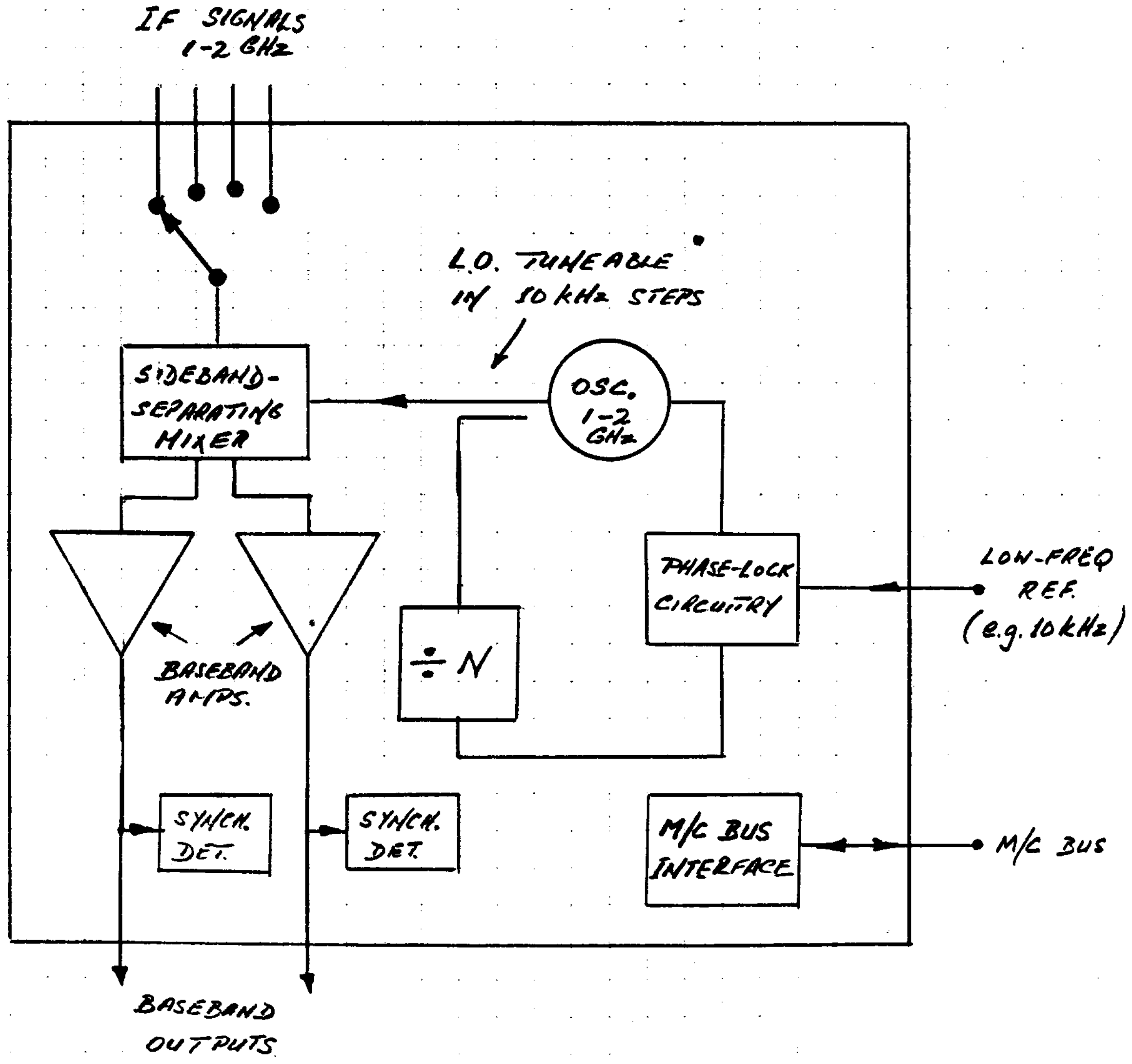

Fig. 3. Details of Baseband Converter unit in Fig. 2. The baseband amplifiers have selectable bandwidths of 250 MHz, 125 MHz, 62.5 MHz, etc.

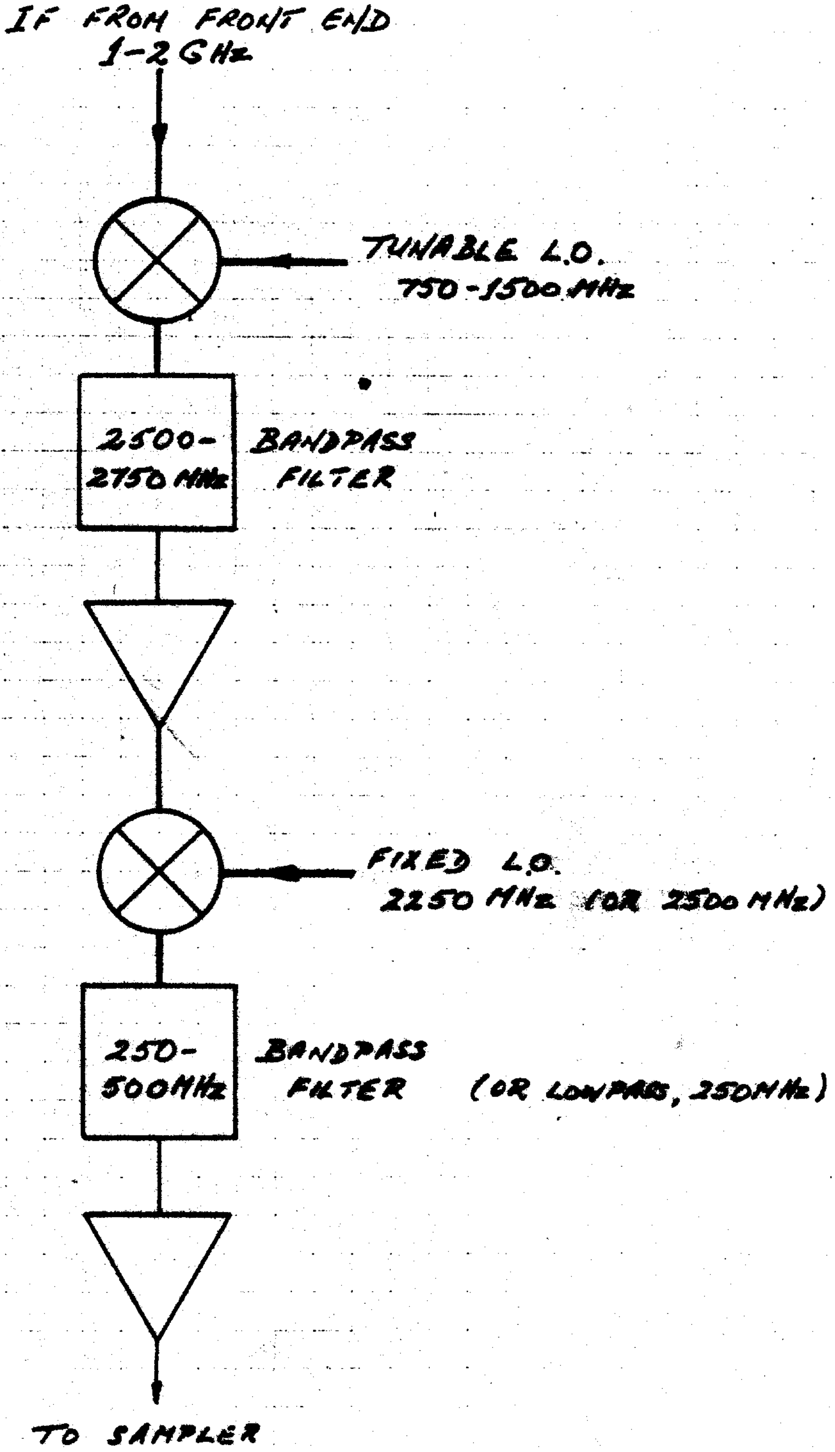

Fig. 4. Possible scheme for conversion to a baseband or bandpass spectrum for sampling, without the use of a sideband-separating mixer.