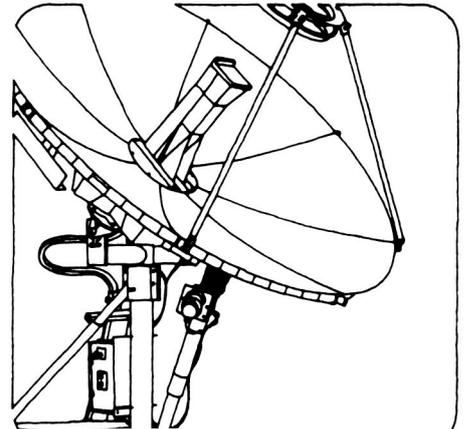
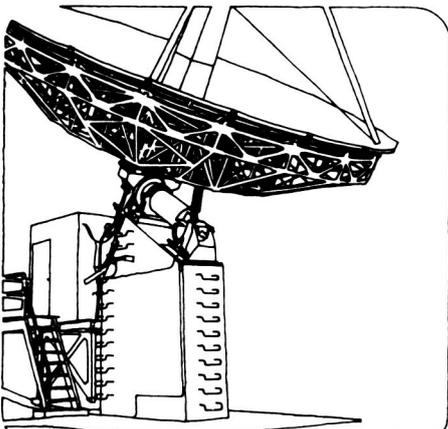
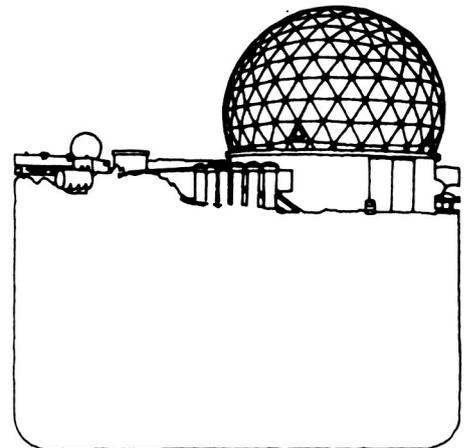
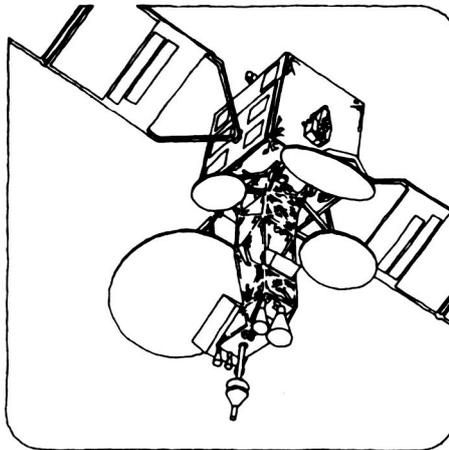


THE POTENTIAL IMPACT OF MMICs ON FUTURE SATELLITE COMMUNICATIONS - TECHNOLOGY ASSESSMENT (EXECUTIVE SUMMARY)

Contract No. NAS3-25077

Prepared for:
NASA-Lewis Research Center
Cleveland, Ohio 44135



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The Potential Impact of MMICs On Future
Satellite Communications - Technology Assessment

EXECUTIVE SUMMARY

September 1988

Prepared for NASA-Lewis Research Center
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1.0 EXECUTIVE SUMMARY

1.1 INTRODUCTION

During the past ten years dramatic strides have been made in the technology of Gallium Arsenide Monolithic Microwave Integrated Circuits (GaAs MMICs). These developments have demonstrated the potential of this technology for opening up new systems opportunities by making it possible to accomplish microwave circuit functions in a physical size or at a cost which would be unattainable using conventional microwave circuit technology. This technology has obvious potential benefit for space-based equipment because of its ability to radically reduce the size and weight of microwave circuitry and its capability for realizing functions which would be impractical with conventional techniques.

The purpose of this study is to identify the potential space communication applications of MMICs, assess the potential impact of MMICs on the classes of systems identified, determine the present status and probable ten-year growth in capability of required MMIC and competing technologies, identify the applications most likely to benefit from further MMIC development, and present recommendations for NASA development activities to address the needs of these applications.

The relationship among these tasks is illustrated graphically in Figure 1-1. The survey of upcoming satellite communication requirements results in the identification of potential MMIC applications, based on criteria such as the number of identical circuits required by the application, their complexity, the potential benefit from size reduction, performance, cost, frequency, and the importance of uniformity.

For each of these identified applications, an attempt is made to define the circuit requirements as explicitly as possible. At the same time an assessment of MMIC technology and competing technologies is made.

All of the above results are then used to assess the potential of MMICs for the identified applications. Applications most likely to benefit from focused development are identified based on such rationale as improvement in system economic performance, enabling technology for the mission, or improved technical performance. Cost benefits are quantified where possible.

Finally recommendations are made for NASA development activities based on such criteria as time scale, priority among recommended programs, estimate of economic benefit versus development cost, and relationship to other known development activities.

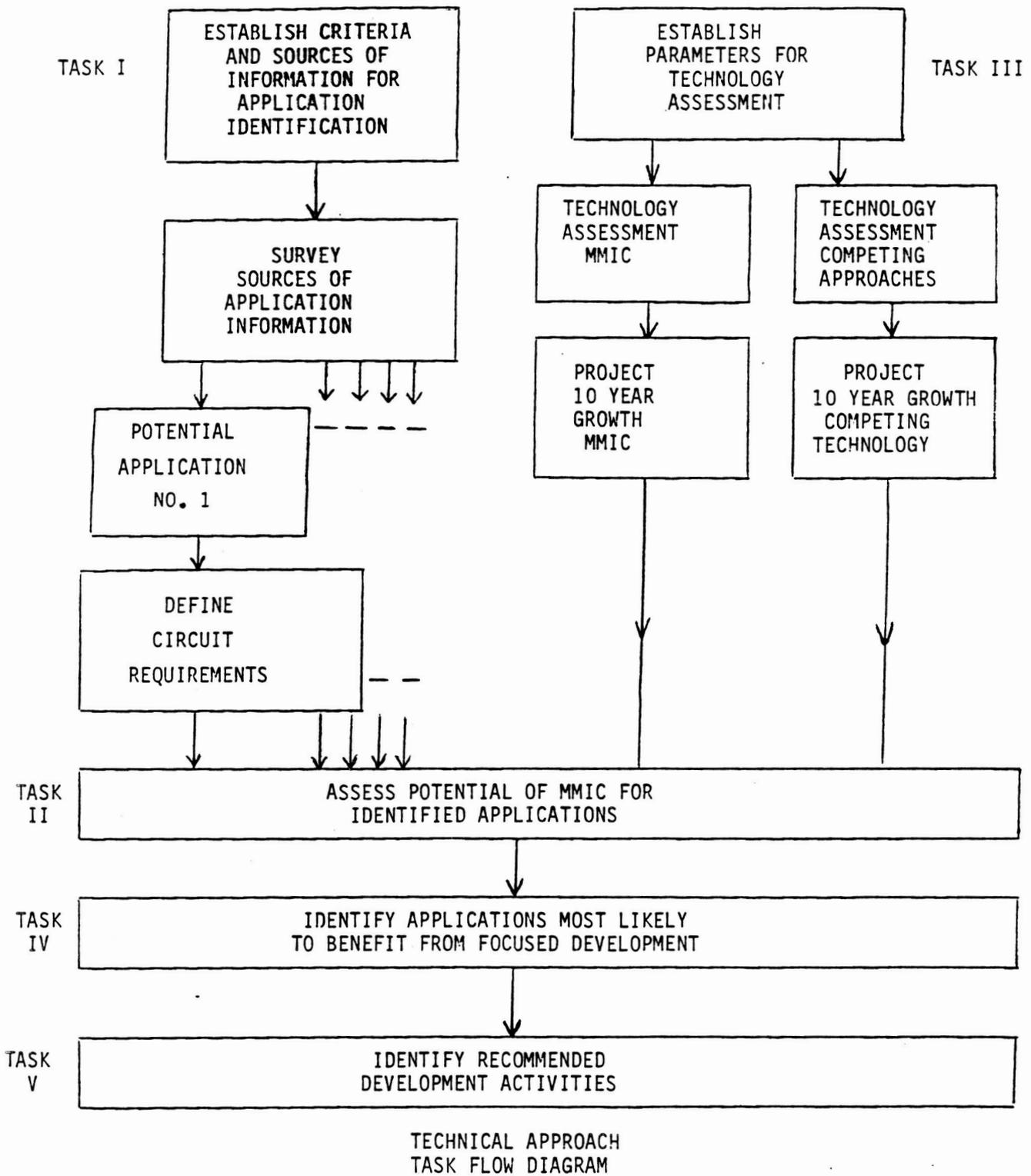


FIGURE 1-1 Technical Approach - Task Flow Diagram

1.2 DESCRIPTION OF THE MMIC APPROACH

Monolithic microwave integrated circuits are defined here, in what has become the conventional way, as circuits in which all active elements and their associated passive elements and interconnections are formed into the bulk, or onto the surface, of a semi-insulating substrate by semiconductor processing techniques such as epitaxy, ion implantation, sputtering, evaporation, etc.(1)

Many of the advantages of the monolithic approach can be appreciated by considering a microwave amplifier constructed using hybrid microwave integrated circuit (MIC) techniques, the more conventional approach which the MMIC technique attempts to replace. Figure 1-2 is a photograph of a state-of-the-art hybrid MIC amplifier, using the most advanced techniques of hybrid MIC construction. The active devices, dual-gate FETs in the case of this variable-gain amplifier, are unpackaged GaAs chips brazed to the metal housing and connected to the associated circuitry by means of wire bonds. The matching circuitry is etched in thin-film metalization on alumina substrates which are also brazed to the housing. The required capacitors are chip components soldered to the housing or to the substrates. The resistors in this case are etched in tantalum nitride metalization on the substrate, but in many hybrid MIC circuits the resistors are also chip components bonded to the substrate. Tuning adjustments can be made to the amplifier by bonding or not bonding to extra tabs etched in the metalization. As a final step, the amplifier is hermetically sealed to protect the active devices by welding a lid on to the package.

As a simple comparison an MMIC amplifier is shown in Figure 1-3. Like Figure 1-2, this is a two-stage amplifier using two FETs, but in this case both FETs and all of their associated circuitry are on the same GaAs chip. Capacitors are MIM capacitors fabricated on the substrate. Air bridges are used for cross-overs when needed and ground connections are brought to the circuitry on top of the substrate by means of plated vias. This amplifier chip was fabricated along with many other circuits on a three-inch diameter Gallium Arsenide substrate like the one shown in Figure 1-4. There would have been room for over one-thousand of these 3.0 by 1.3 millimeter amplifier chips on the GaAs wafer if it had been entirely dedicated to this particular circuit. Figure 1-5 is a photograph showing the MMIC and hybrid amplifiers side by side for comparison.

A comparison of these two realizations of a two-stage amplifier reveals many of the advantages and disadvantages of the MMIC approach. The MMIC version is, of course, much smaller. Even after taking into account that the MMIC amplifier is for 20 GHz while the hybrid amplifier operates at 12.5 GHz, the MMIC unit is substantially smaller. This is partly because of the high dielectric constant of Gallium Arsenide, but it is also due to the elimination of unnecessary interconnections and the ability to fabricate circuit elements such as the capacitors and their interconnections in a much smaller size using semiconductor processing techniques. A very significant difference is

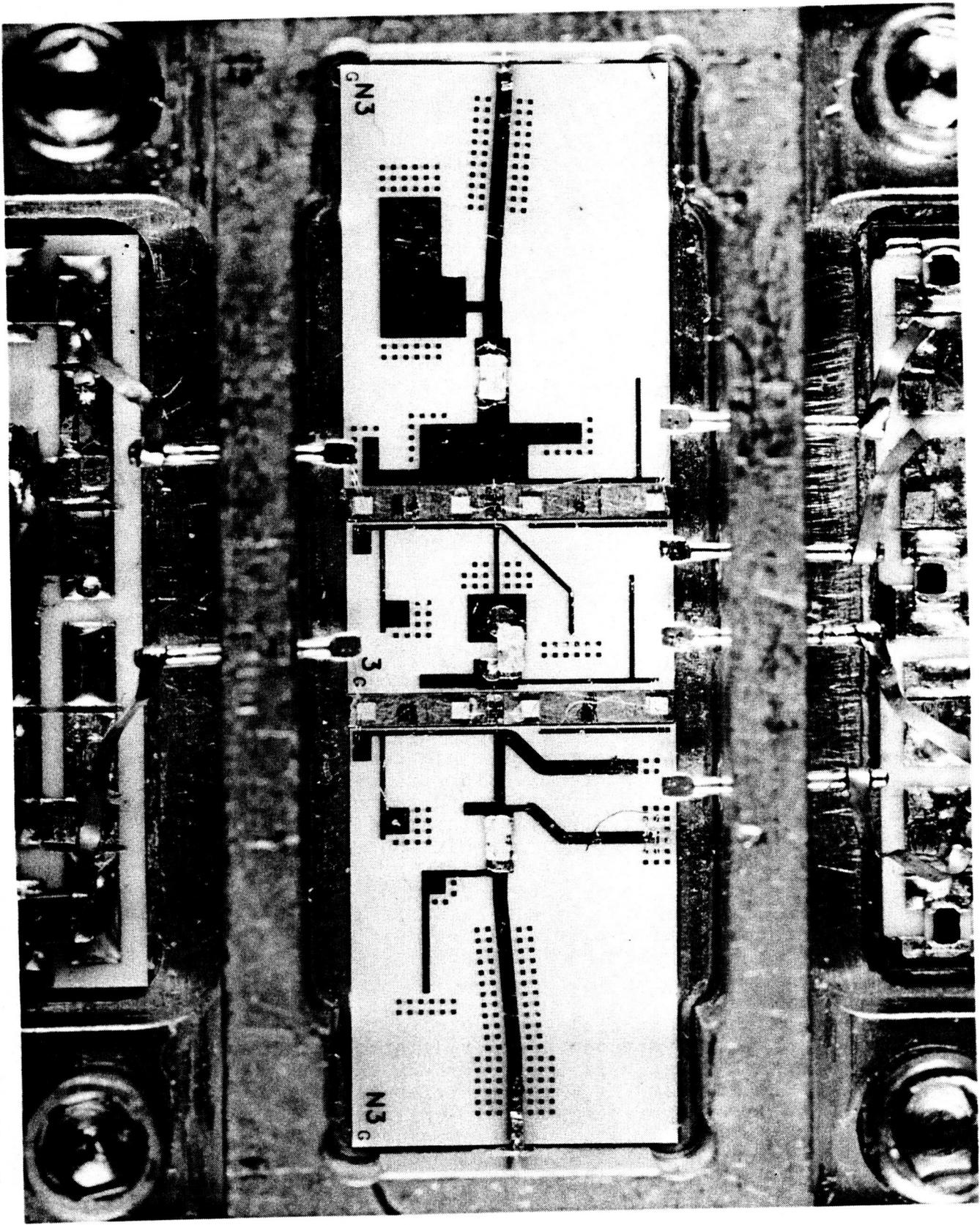


FIGURE 1-2 State-of-the-art
Hybrid MIC Amplifier

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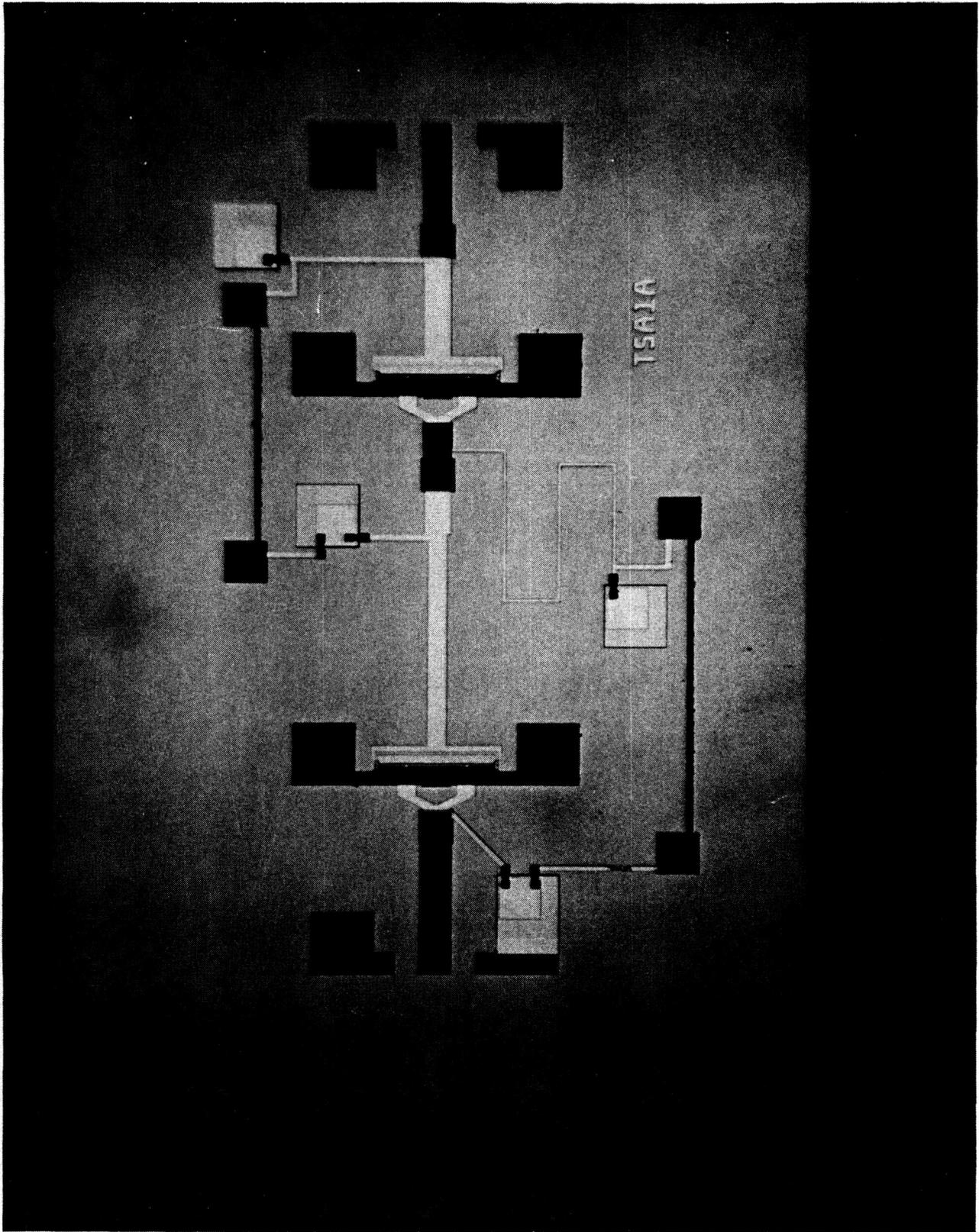


FIGURE 1-3 A Two-Stage MMIC Amplifier

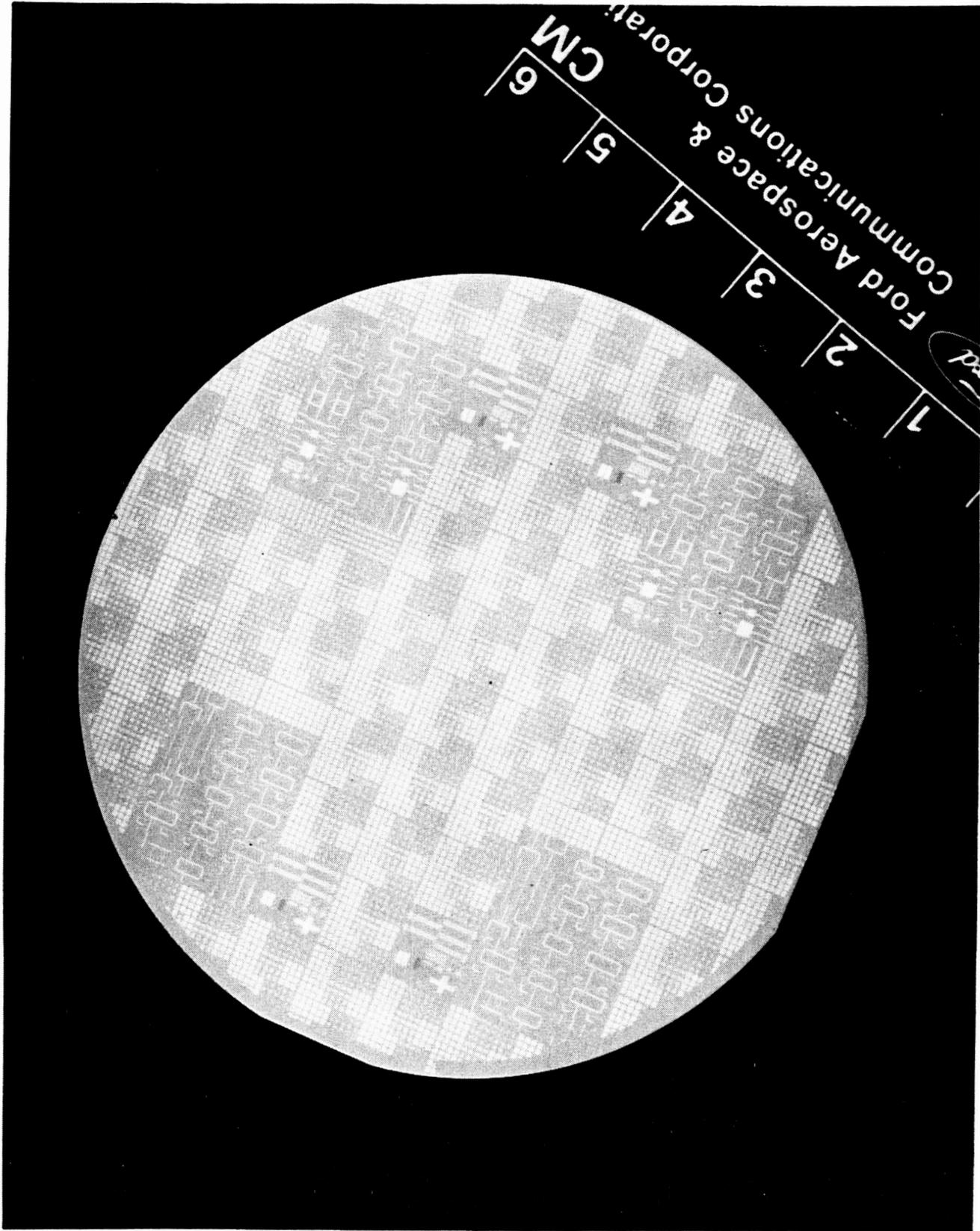


FIGURE 1-4 A Three-inch Diameter GaAs Wafer Containing A Variety of Monolithic Circuits and Devices

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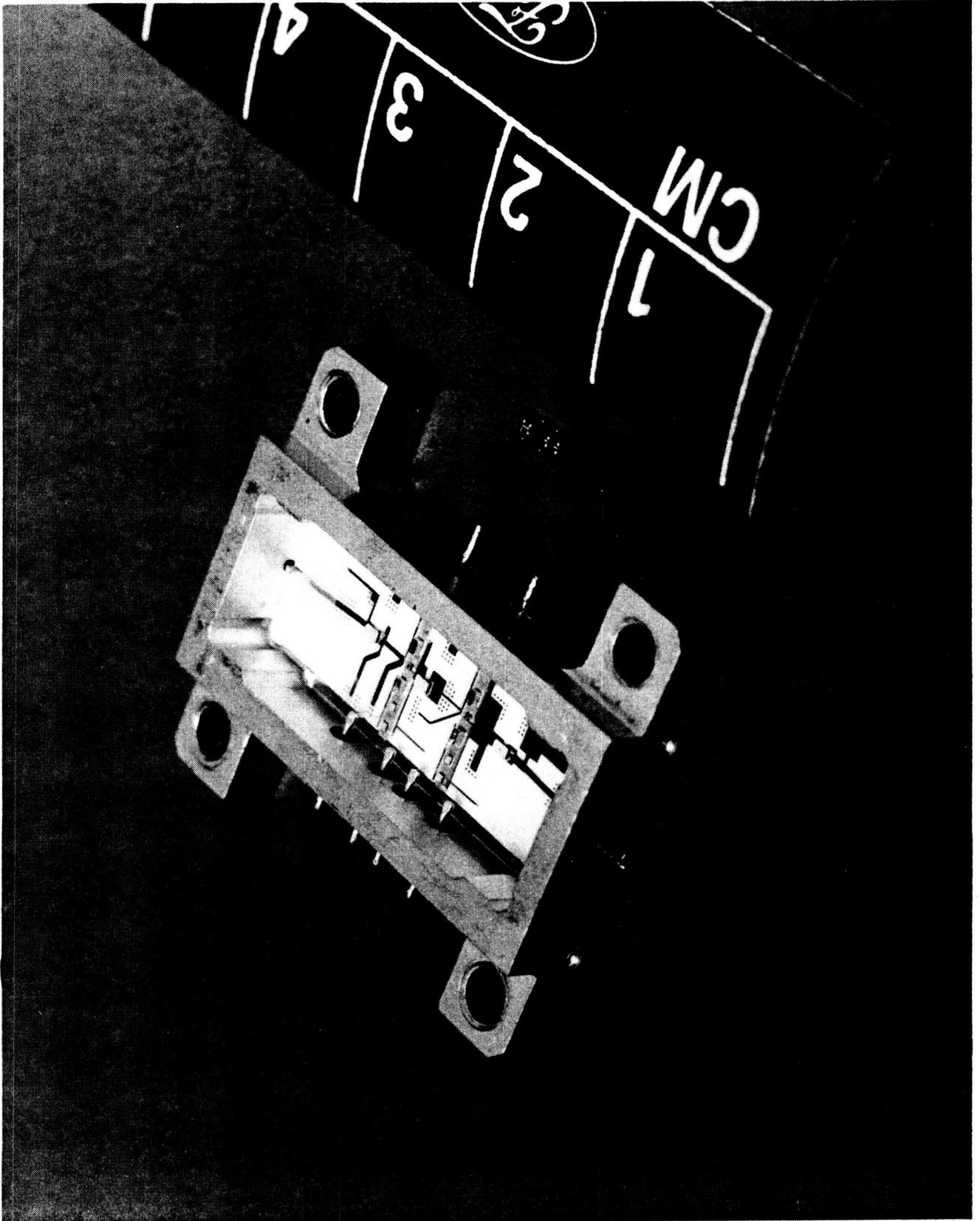


FIGURE 1-5 Hybrid MIC And MMIC Two-Stage Amplifiers

that the active device is fabricated in intimate association with the circuitry in a way that is precisely repeatable in the case of the MMIC, whereas in the hybrid approach wire bonds must be used to connect the gate, drain, and source of the devices to the circuit. These are very critical connections and at frequencies such as X-band and above the reactance of these wires form a significant portion of the circuit. In addition, the connection to the ground of the microstrip is through the brazed connection of the substrate to the housing. The inability to make these connections sufficiently repeatably is one of the major reasons that the hybrid amplifier must be tuned, consuming expensive skilled manpower as well as making it necessary to make the circuit large enough to permit tuning. Thus, the assembly of the hybrid unit is expensive and time consuming because of the many critical connections that must be made, and the inevitable variations in assembly necessitate expensive and time consuming tuning adjustments.

Aside from the variability the interconnections introduce, their very presence in many cases is a serious limitation on the performance which can be achieved, particularly in terms of bandwidth. These problems rapidly become more severe as frequency is increased. Whereas they can be an important cost factor at X-band, they can make the circuit completely unproduceable at millimeter wavelengths.

The elimination of the many wire bonds and interconnects lead to another important advantage of the MMIC approach: reliability. The wire bonds of the hybrid approach seriously degrade the reliability of the circuit.

Advantages in circuit design and functionality accrue from the fact that the MMIC approach makes the use of active devices much less expensive. The incremental cost of adding an additional FET to an MMIC is small, mainly the cost attributable to whatever decrease in yield results from the additional active device and the cost of the additional GaAs area. As a result circuit designs which are extravagant in the use of active devices, such as broadband distributed amplifiers, become more practical with the MMIC technology.

Thus, the major advantages of the MMIC approach are:

- * Low production cost through batch fabrication
- * Small size
- * Reliability
- * Permits the use of large numbers of active devices

Some other attributes of MMICs are important in particular applications. For example, active arrays require that all of the large number of active modules have nearly identical performance which tracks well from unit to unit over temperature. This is more readily accomplished with MMICs where a large number of identical circuits can be made from one GaAs wafer.

There are disadvantages, also, to the MMIC approach. First, and in many cases most important, the development of an MMIC circuit is costly and time consuming. Although these factors can vary widely depending on the circuit and its similarity to previous designs, the development of a new relatively sophisticated circuit can typically consume several hundred thousand dollars and a year or two of time. This may not be justified unless the development cost can be spread over a large number of production units, or unless there are substantial size, weight, or performance benefits from the MMIC approach. Also, while the MMIC approach can sometimes produce better performance by eliminating parasitics, for instance in broadband amplifiers, in some cases the performance is inferior. A hybrid circuit can be tuned to maximize the performance, while an MMIC may have an economical yield only if a significant margin is allowed between the specification and optimized performance, or if design techniques such as feedback are used which sacrifice some performance for insensitivity to process variations. In addition, the losses of the MMIC matching circuits don't allow MMICs to achieve the lowest possible noise figures or highest power outputs.

Table 1-1 summarizes some important advantages and disadvantages of the MMIC approach.

1.3 OVERVIEW OF MICROWAVE CIRCUITS FOR SPACE APPLICATION

Several general observations can be made about the microwave circuit requirements for space applications. First and foremost, of course, is that an extremely high premium is put on reliability. Second, minimizing size and weight is an important objective. These considerations are strong arguments in favor of the MMIC approach. On the other side of the ledger, microwave assemblies for space applications are usually required only in very small quantities, so the development costs for custom designs cannot be spread over a large quantity. The benefit of the MMIC must be sufficient to justify the development for only a small quantity of units. The argument that the batch fabrication of MMICs leads to low large quantity cost is not generally a reason to use MMICs in space. Finally, microwave components for space are often performance driven with the best possible performance required, even if this means large amounts of expensive tuning and optimization.

Thus, considering the nature of the requirements only in these general terms, there are arguments both for and against the MMIC approach. Whether or not the approach is beneficial depends on the requirements of the specific application.

TABLE 1-1

SUMMARY OF THE ADVANTAGES AND DISADVANTAGES
OF THE MMIC APPROACH

ADVANTAGES
OF MMIC APPROACH

- * Small size
- * Light weight
- * Low quantity cost through batch fabrication
- * Reliability
- * Makes it practical to use large number of active devices
- * Capability for large bandwidth
- * Good tracking from unit to unit

DISADVANTAGES
OF MMIC APPROACH

- * Expensive in small quantity if custom design required
- * Does not achieve as low noise figure as best hybrid circuits
- * Does not achieve as high power or efficiency as best hybrid circuit

1.4 SURVEY OF SPACE APPLICATIONS

The first task of this project was to identify potential space communications applications of MMIC technology in the areas of commercial, military, and government non-military satellite communications. The areas to be considered in the assessment were to include all foreseeable commercial, military, and government non-military applications of space communications; and the technology areas to be considered were to include, but not be limited to, all microwave, optical, intermediate frequency, and baseband technologies judged to be, or likely to become, relevant to space communication systems. When the study was approximately half-way completed, the contractor was requested by the Program Manager to deemphasize military requirements in order to concentrate attention on NASA requirements.

1.4.1 EVALUATION CRITERIA

In order to focus the survey of space applications, it was important to first establish some criteria reflecting the particular characteristics and attributes of MMIC technology. It was decided that in the survey of possible MMIC applications, the applications should be considered in the light of the following characteristics of MMICs:

- * Potential benefit from size and weight reduction. One of the clearest benefits of the MMIC approach is the dramatic size and weight reduction it leads to in the microwave circuitry. An application where the size and weight have high leverage either on the cost or on the technical capability will be a clear candidate for MMIC application.

- * Number of identical circuits required.
The MMIC approach is particularly attractive in applications where a large number of identical circuits are needed, because of the batch fabrication nature of the process. On the other hand, the development costs of a new MMIC design are greater than for a hybrid MIC design so that if the number of circuits required is small, the cost of the MMIC version can be high.
- * Circuit complexity.
The MMIC approach has its greatest advantage in fairly complex circuits having a large number of active and passive elements. It can be an enabling technology in the sense that it can make it possible to place circuit complexity on board the spacecraft which would be impractical with conventional technology.
- * Performance.
The electrical performance requirements of the application are important parameters in determining the applicability of MMICs, with some "high performance" specifications (e.g., low noise or high power) being arguments against MMICs while some (e.g., wide bandwidth) favor MMICs.
- * Frequency.
This is an important consideration in determining MMIC applicability. Millimeter wavelengths present some of the strongest motivations for MMICs because reproducibility is so difficult to achieve with conventional techniques, but MMIC techniques are considerably more well established at microwave frequencies.
- * Importance of Uniformity.
The monolithic approach is particularly attractive for applications where uniformity from unit to unit is important.
- * Cost.
Generally cost will be an argument in favor of the monolithic approach if quantities are large, and against if quantities are small.
- * Radiation Hardening.
GaAs MMICs are inherently less susceptible to radiation effects than other types of microwave circuitry, and in addition their small size reduces the weight penalty of shielding.

These MMIC considerations, then, imply system characteristics which must be considered in the survey as determinators of the applicability of MMICs. These systems characteristics which are particularly significant as indicators in the survey are:

- * Frequency and Bandwidth of the system
- * Type of Antenna (Scanning spot beam? Multibeam? Fixed beam?)

- * Performance Parameters (e.g., Transmitter Power Output, Receiver Noise Figure)
- * On-board Signal Processing Requirements
- * Efficiency and Power Consumption Constraints
- * Size and Weight Constraints
- * Requirements for Radiation Hardening

The nature of the antenna system required for the satellite is important because of the applicability of MMICs to active arrays. Active arrays, either phased arrays or arrays of elements for a multibeam antenna, require large numbers of receive or transmit modules. They must meet tight size constraints determined by the physics of the array. They must be highly repeatable so that the elements will exhibit good tracking from unit to unit over frequency and temperature. They must be inexpensive if the system is to be cost effective. These requirements become more difficult to meet as frequency is increased since the required size of the circuit decreases and the effect of circuit parasitics and wire bonds become more severe making conventional techniques labor intensive and expensive. Therefore, systems which use scanning spot beams for frequency reuse or multibeam antennas for antijam capability are likely to be benefited significantly by MMICs.

Satellites with much on-board complexity, for instance for switching or signal processing, are likely to benefit from monolithic technology or even be impractical without it. Unusual size and weight constraints, or unusually high premiums on weight reduction, call for MMICs. As mentioned before, MMICs have low susceptibility to radiation and, in addition, because of their small size can be easily shielded. Therefore, they may be required to satisfy needs for radiation hardening.

1.4.2 SOURCES OF INFORMATION FOR SURVEY

In order to identify potential space communication applications of MMICs, an extensive study was made of anticipated NASA space missions, military needs for space-based communications, and projections for commercial applications of space. This was accomplished by reviewing many published reports, studies, and projections, and by personal contacts and interviews.

1.4.3 MILITARY REQUIREMENTS

A valuable source of information on military space requirements is the Advanced Space Communications Technology Assessment (3). Prepared by the Aerospace Corporation, it provides a comprehensive and up-to-date overview of perceived technology requirements for military space communications. The report considers all relevant technologies, so of necessity does not generally penetrate to the level of detail of indicating MMIC requirements explicitly. However, the general issues addressed by the report together with an understanding of the available techniques for implementing space communication hardware can identify areas where MMICs can play an important role.

According to that report (3) and interviews with individuals intimately involved with military space communications, the important technical issues in military space communications are:

- * The need for greater bandwidth for antijamming and greater throughput.
- * Improved survivability.
- * Autonomy.
- * Affordability
- * The increased use of higher frequencies (44/20 GHz and eventually 94/100 GHz) to reduce congestion.
- * The use of modular components (standard data buses and standard spacecraft modules) for lower cost.
- * Maintaining long term utility of UHF networks.
- * On-board processing.
- * The use of superconducting materials.

On the basis of the Aerospace report (3), numerous other surveys and projections, and interviews, it was clear that many of these upcoming military satellites will utilize 20 and 44 GHz uplinks and downlinks and 60 GHz crosslinks, with a need for electronic beam steering and antijam nulling. Therefore, they will have a critical need for MMIC transmit and receive active array modules. In addition, our studies indicate that monolithic technology can have an important application in the DSCS III X-Band antijam antenna.

A detailed study of specific applications of MMICs in military satellite programs was not completed because of the decision to concentrate this program on applications for NASA missions. However, it was clear from the survey that MMICs must play a critical role in future military satellites. In particular, the following are clearly possible applications MMICs to address the perceived technology drivers:

- * Active array modules for receiver arrays at 44 GHz to implement scanning multibeam and antijam systems.
- * Active array modules for transmitter arrays at around 20 GHz.
- * Active array modules for both receivers and transmitters at 60 GHz.

- * Low weight frequency synthesizers.
- * Components for on-board signal processing such as bulk demodulators and switch matrices.
- * Reduction of size and weight of conventional transponder components to reduce cost and improve radiation hardening

1.4.4 COMMUNICATION SATELLITE REQUIREMENTS

Communication satellites represent the largest market for space applications. This area has experienced rapid growth since the early 1970's. But because of a number of factors, this market is changing rapidly and all forecasts are subject to a great deal of uncertainty.

In particular the communication satellite business is changing under the influence of several factors such as:

- * The rapid development of fiber optic cable as a long distance communication medium.
- * The introduction of the Integrated Services Digital Network (ISDN).
- * The use of Very Small Aperture Terminals (VSATs) to provide long distance service directly to the user, bypassing the terrestrial network.
- * The recent launch problems which have increased the costs and uncertainties of satellite communications.
- * The deregulation of the communication industry. All of these factors have a major influence on requirements for communication satellites, and in many cases their influence is in opposite directions.

The rapid implementation of fiber optic cables has drastically lowered the present and projected use of satellites for long distance point-to-point trunking. However, the long haul portion is only a small part of the cost to the user of user-to-user service. The cost of the local network can be the major part of the overall cost to the user. This is the major incentive for the use of VSATs to provide service directly to the user, avoiding the cost of the local network. This service has grown rapidly and has become a significant user of communication satellites. However, to date this service has been restricted primarily to data transmission, since the systems presently utilize a double hop through a master station. The resulting time delay is not acceptable for voice traffic.

Satellites are very attractive for broadcasting large amounts of information from a central source to many destinations, as in the distribution of television programs. This is reflected in the fact

that approximately one-third of the transponders currently available for domestic U.S. communications are presently being used for video transmission. This use of satellites is expected to continue, but in the U. S. probably does not represent a growth market.

Satellites may provide the means of introducing ISDN service to many parts of the world. The wideband access will greatly increase the bandwidth per user.

Therefore, projections of future demand for communication satellites are very uncertain due to the many conflicting influences. The growth of the use of VSATs for customer premises service tends to offset the loss of satellite business to fiber optics. It is possible that the increase in use of VSATs will approximately offset the decline in satellite usage for long distance trunking, so that projections made in the early 1980's of saturation of the geostationary arc for North America occurring in the early 1990's may be correct. This would be particularly likely if the use of VSATs to provide terrestrial bypass for voice communication becomes widespread. In this case normal growth would lead to demand significantly exceeding arc capacity in the early 2000's unless developments such as greater frequency reuse are implemented.

The use of VSATs for voice traffic seems to hinge on the elimination of the second hop and its attendant delay. This can be done if the satellite can be made to accomplish the function now served by the master ground station. This requires adding considerable complexity to the satellite with a resulting increase in size and weight which is probably prohibitive unless the maximum use is made of monolithic circuits. In particular, several studies (2,5) have identified bulk demodulators as a key technology for this application, as well as switch matrices.

The use of VSATs for voice communication and the development of satellites to accommodate them could be seen as the first step toward truly personal communication as an extension of cellular land mobile technology. Such concepts have been proposed(2) and their implementation would require advanced bulk demodulator capability, extensive frequency reuse through the use of large numbers of spot beams, and very large switch matrices. Monolithic technology would be the key to all of these needs.

Therefore, it is concluded that in the commercial satellite area, the candidate applications of MMICs, to be studied in more detail in the subsequent sections of this report, are the following:

- * Modules for active transmitter and receiver arrays to implement scanning spot beams for frequency reuse in order to increase the capacity of the geostationary arc.
- * Modules for active arrays at Ka-Band to open up additional spectrum.
- * Bulk Demodulators to facilitate the use of satellites for two-way voice communication between VSATs.

- * Switch matrices to enable frequency reuse and single hop voice communications.
- * Use of MMICs to reduce the size and weight of conventional transponders, thus making them more economical.

1.4.5 APPLICATIONS IN NASA SPACE MISSIONS

NASA requirements tend to be mission driven and cover an extremely wide variety of applications. A broad overview of possible future NASA missions can be obtained from the "Ride Report" (4). The report describes four candidate initiatives, proposed as a basis for discussion in defining goals and objectives for the space program. Although it is not anticipated that all four initiatives will be pursued in their entirety or in the form proposed in the report, the proposed initiatives illustrate the range of possibilities for future NASA missions and give some idea of the technologies which will be required.

The four initiatives described by the report are: (1) Mission to Planet Earth, (2) Exploration of the Solar System, (3) Outpost on the Moon, and (4) Humans to Mars.

To identify areas where MMIC technology can contribute to future NASA missions, discussions were held with NASA technical personnel involved in studies for projects related to these four initiatives. In addition, discussions were also held with individuals familiar with the requirements for systems, such as TDRSS and the Space Station, which will provide necessary support for these initiatives as well as other possible space missions.

In particular discussions were held with the following individuals at the Jet Propulsion Laboratory of the California Institute of Technology:

- * Dr. Lance Riley (Deep Space Missions)
- * Arthur Kermode (Spacecraft Transponders)
- * Ed Caro (Synthetic Aperture Radar, Mission to Planet Earth)
- * Dr. Fuk Li (Radar)

JPL reports provided by these individuals were helpful in identifying requirements. D. Arndt of the Johnson Space Flight Center provided useful information regarding the Space Station. Barney Roberts of Johnson was interviewed regarding Lunar Bases. At Ford Aerospace many individuals contributed information regarding the Space Station and TDRSS.

The general requirements of these missions and projects as they possibly relate to MMICs are described in the following paragraphs.

1.4.5.1 DEEP SPACE MISSIONS

A major factor in determining the technology required to support future deep space missions is the planned move from X-Band to Ka-Band (32 GHz). The decision to use Ka-Band was made after extensive study demonstrated its advantages, at least until some future time when optical links may become a superior approach. (6,7)

The advantage of Ka-Band is basically the higher antenna gain which can be achieved for the same antenna dimensions. The potential improvement in going from 8.4 GHz to 32 GHz is 11.6 dB due to the increased antenna gain. This is offset somewhat by atmospheric effects and actual antenna performance, but an improvement of at least 8 dB has been established. This 8 dB advantage can be exploited in various ways depending on the mission needs. (8) For example, for the same antenna size and data rate, the power can be reduced for missions where power is at a premium. Since DC power is typically obtained from a radio isotope thermonuclear generator (RTG), at a cost of \$200,000 per Watt, this can be an important driver. On the other hand, in some situations it may be more desirable to use the 8 dB advantage to reduce antenna size, or to increase the data rate with the same antenna size and power consumption. (8)

Some planned planetary missions which will use the new Ka-Band capability are the Comet Rendezvous Asteroid Flyby (CRAF), Cassini (Saturn Orbiter/ Titan Probe), Mars Sample Rover (MSR), and Neptune Orbiter Probe. In addition, as part of the development path to this capability a Ka-Band link experiment is planned for the Mars Observer. The deep space programs are summarized in Table 1-2, and described in more detail later in this report.

1.4.5.2 TRANSPONDERS

As in conventional communication satellites, transponders for use in space missions consist of a receiver, frequency converter, and transmitter. For example, an uplink X-Band signal is received, amplified, and downconverted to baseband, then upconverted to drive the transmitter at a K-Band downlink frequency. Also as in the case of communication satellite transponders, it would be possible to make very substantial reductions in the size and weight of the transponder through the use of MMICs. However, since the quantities involved are very small, use of MMICs will probably be limited to generic, "off-the-shelf" chips unless techniques are perfected to make custom MMICs affordable for small quantity applications.

TABLE 1-2

Ka-Band Requirements for JPL Deep Space Missions

| Mission | Year(approx) | Description |
|--|--------------|---|
| Mars Observer (MOS) | 1990 | Transmission experiment. Ka/X-Band antenna using sub and primary reflector dish antenna. |
| Comet Rendezvous Asteroid Flyby (CRAF) | 1991-2 | Ka-Band amplifier. One candidate is to use a MMIC power amplifier. |
| Cassini (Saturn Orbiter) | 1996 | Ka-Band phase shifter/power amplifier antenna feed array modules with dish antenna. |
| Mars Sample Return (MSR) | 2000 | Ka-Band amplifier array with more elements and a plane antenna of patch radiation elements. |

1.4.5.3 RADAR SYSTEMS (MISSION TO PLANET EARTH)

Radar development is taking place at JPL for synthetic aperture radar (SAR) which was first demonstrated by JPL in 1978 in SEASAT. The next JPL SAR was demonstrated as Shuttle Imaging Radar A, (SIRA), in 1981 and as SIRB in 1984. The next SAR will probably be on the Venus radar mapping mission, Magellan, scheduled for a shuttle launch. The Earth Orbiting Satellite (EOS) series, as part of Mission to Planet Earth, will map the earth surface using SAR. SAR missions and systems are summarized in Table 1-3.

TABLE 1-3

SAR MISSIONS AND SYSTEMS

SAR Missions and Systems

SEASAT - 1978

SIRA - 1981

SIRB - 1984

MAGELLAN

SIRC - 1992

NASA SCATTERMETIC (NSCAT) - 1993

EOS1 - 1994

EOS2 - 1995

SPACE STATION (Altimeters)

TITAN (Saturn Moon Mapper) - 2000

MMICs appear to have the potential for benefitting at least some of these future radars quite significantly. As phased array radars they require a large number of active elements; and as space systems, size, weight, and reliability are crucial considerations.

The potential synthetic aperture radar application of MMICs will be considered in detail later in this report.

1.4.5.4 TRACKING AND DATA RELAY SATELLITE SYSTEM

The experimental and scientific satellites launched and operated by NASA generate large amounts of data which must be returned to earth. The transmission of this data has long been dependent on NASA's world wide network of Satellite Tracking and Data Stations. Data is stored on board the satellite until it is in view of one of the stations, at which time it is dumped to the earth. This network is expensive to maintain, and depends on stations in foreign countries where political considerations may cause complications.

For some time it has been NASA's goal to replace this network with the Tracking and Data Relay Satellite System (TDRSS). By means of this system, the scientific and experimental satellites will transmit their data to the TDRS which will relay the data to a single ground station at White Sands. This will alleviate many of the problems with the present system, reduce the requirements for storing data on board the spacecraft, and increase the amount of data which can be returned.

Problems such as the shuttle disaster which destroyed the second TDRS have plagued the program and delayed its operation, but the need for it continues to exist and will grow more acute as space activities increase. Hence, NASA is considering improvements to TDRS. In addition, planned and projected missions in the 2000-2015 time frame, such as an expanded Space Station, polar and co-orbiting platforms, orbiting transfer vehicles and low-earth orbiting missions will require an Advanced Tracking and Data Relay Satellite System (ATDRSS) to meet NASA's mission requirements. The Advanced TDRSS will maintain existing TDRSS services at S- and Ku-Bands and will add new 60 GHz and laser space-to-space links. Multiple space-to-ground links at Ku- and/or Ka-Bands will also be added.

Improved versions of TDRS and the longer range ATDRS appear to have several possible applications of MMICs. ATDRS has a tentative requirement for multiple beam communications antennas with five fixed and one movable beam covering CONUS, and one world-wide mobile movable beam operating in the Ku- and Ka-Bands. These requirements are summarized in Table 1-4.

TABLE 1-4

Summary of Tentative ATDRS Antenna Requirements

| Communication Use | Transmit | Receive | Transmit | Receive |
|---------------------|--|---------|----------|---------|
| Frequencies (GHz) | 13.80 | 14.98 | 19.45 | 29.25 |
| Bandwidth (GHz) | 0.80 | 0.75 | 4.0 | 4.0 |
| Diameter (meters) | -----2.0----- | | | |
| Gain (dB) | 46.2 | 46.9 | 49.2 | 52.7 |
| Beamwidth (degrees) | 0.69 | 0.65 | 0.50 | 0.33 |
| Fixed Beams * | -----6 for CONUS----- | | | |
| Movable Beams * | ---1 for CONUS-----1 for World Wide--- | | | |

* Some beams may use only one of the frequency bands while others may use both. Beam frequency allotments are open at this time. An MMIC based active array can be considered for this requirement.

Another possible TDRS application was also identified. This application is in the S-Band space-to-space links in an improved implementation which would provide on-board beam forming to replace the ground based processing required by the present TDRS. On-board beam forming has the advantage of eliminating the need for transmitting the signals picked up by the thirty antenna elements to ground for processing. This would free up spectrum space for other uses, facilitate future upgrades to more beams or antenna elements, and eliminate problems caused in the present approach by differential phase shifts in the space-to-ground link.

1.4.5.5 SPACE STATION

The Space Station has specialized communications requirements which will likely require MMICs for their realization. The requirements can be divided into two categories: communication services to nearby (within 37 km) vehicles and activities (the so-called control zone), and the far range communication to satellites in the 37 km to 2000 km range. The services to spacecraft in the control zone include the capability to distribute audio, video, telemetry, command and head-up display data to/from free flyers, National Space Transportation (NSTS), Orbiting Maneuvering Vehicle (OMV), Extravehicular Activity (EVA) terminal, Mobile Service Center (MSC), and the Mobile Transporter (MT). A basic system would support four simultaneous users. A proposed baseline design for Ku-Band provides seven 40 MHz wide

channels in both the forward and reverse directions with one high data rate carrier (44 Mb/sec) or two low data rate carriers in each channel. It would use omni antennas for users in the proximate zone, and two 2 ft. parabolas for communication to 37 km.

Several frequency bands are under consideration for these cluster communication operations. In January, 1987, NASA requested the NTIA for the use of the 14.0-14.3 and 14.5-14.89 GHz Bands for this service. NTIA recommended against this and recommending, instead, the consideration of the following bands in order of desirability:

- a. 32-33 GHz (primary)
- b. 21.4-22 GHz (possible primary)
- c. 22.5-23.56 and 25.26-27.0 GHz (possible overflow bands)

Trade-off studies have been performed by GE Aerospace on the use of these bands. (9) As would be expected, the suitability of the higher frequency bands is highly dependent on the projected capability of solid state devices at these frequencies in terms of power output, efficiency, and noise figure. In particular, the attainable range in the EVA to space station return link is restricted by available DC power and RF power device efficiency. Some of the important assumptions used in the trade study were:

- a. EVA transmitter power of 0.8 W @ 21 GHz, limited by projected 20% efficiency and available DC power.
- b. EVA Transmitter power of 0.6 W @ 32 GHz, limited by projected 15% efficiency and available DC power.
- c. Space Station transmitter power of 8 W for six devices at 21 GHz.
- d. Space Station transmitter power of 5 W from eight to sixteen devices at 32 GHz.
- e. Noise figures of 3 dB at 21 GHz and 3.3 dB at 32 GHz. In the longer term, this baseline system using omni antennas for nearby users and dishes for more distant users will be inadequate. As the number of users increase, the number of dishes must increase at the expense of size and weight. An electronically steered multibeam antenna using MMIC active elements has many advantages in terms of size, weight, reliability, and flexibility.

1.4.5.6 SUMMARY OF POSSIBLE NASA APPLICATIONS

As a result of the information gathered on this survey, the possible NASA applications for MMICs to be considered are:

- * Transmitter modules at 32 GHz for interplanetary missions.
- * C-Band modules for synthetic aperture radar.
- * Active array modules for multibeam antennas and on-board beam forming for ATDRS.
- * Modules for electronically steered multibeam antenna for the Space Station.

1.5 ASSESSMENT OF POTENTIAL MMIC APPLICATIONS

As a result of a careful review of the specific requirements of the potential applications described briefly in Section 1.3, this study identified the following important MMIC applications:

- a. 32 GHz transmit modules for feed arrays and phased arrays on JPL probes.
- b. C-band modules for use in JPL synthetic aperture radar for Mission to Planet Earth.
- c. Modules for electronically steerable multibeam antenna for control zone communication for space station.
- d. Phase shifters for on-board beam forming for TDRSS.
- e. Bulk demodulators for numerous communication satellite applications including Data Distribution Satellite.
- f. Transmit modules for active arrays at 20 and 60 GHz and modules for 30, 44, and 60 GHz.
- g. IF and baseband switch matrices. Interface between MMIC and optic control or signal distribution.
- i. Use in conventional transponders to reduce size and weight to improve reliability.

The key performance requirements for these applications are indicated in Table 1-5.

To assess the benefits of possible development programs focused on these applications requires the consideration of a number of factors including the following:

- a. Benefits resulting from successful development program.
The can take several forms:
 - May make a mission possible which otherwise would not be possible
 - An economic benefit, ie the development is cost effective in the sense that the development cost can be recovered through cost savings resulting from the development
 - Improvement in system performance
- b. Possible commonality- the development would impact several applications
- c. Cost and difficulty of the proposed development
- d. Likelihood of success, degree of risk
- e. Likelihood that the technology would be developed without NASA support: would it be developed by the military or by private industry?
- f. Timing of the requirement

It must be recognized that the assessment of benefits is not a straight- forward, objective task when the benefits are as disparate as those which would result from the developments of Table 1-5. Some are readily quantifiable in economic terms. Some are not.

For instance, the study of the channel amplifier showed that an MMIC version in an advanced modern communication satellite transponder could save 11.3 kg of mass. Using the well established factor of \$50,000 per kilogram to translate mass savings in geostationary orbit to cost savings, leads to the conclusion that a savings of \$560,000 per flight would result from weight savings alone. In addition, the recurring costs of the MMIC version should be less than that of the hybrid MIC version, so that it is estimated that the nonrecurring development cost could be recovered on the first satellite using the MMIC channel driver, with substantial savings on further flights.

A similar analysis was made of the benefits of on board beamforming using MMIC phase shifters versus hybrid MIC phase shifters. There it was shown that the mass savings of the MMIC approach would make it \$1.2 M less expensive to implement per flight than the MIC version. This is in addition to the savings resulting from expected lower recurring costs for producing the MMIC phase shifters in the quantities assumed. In the case of the X-Band beam forming network, this study showed that a proposed MMIC realization would weigh only 24 pounds compared with the 125 pounds of a waveguide beam forming network using ferrite phase shifters and variable power dividers. Using the \$50,000 per kilogram factor this implies a savings of \$2.3 M per flight as a result of the weight reduction.

A Ford Aerospace study performed for NASA-Lewis concluded that a bulk demodulator using digital GaAs technology would have substantial mass and power advantages over a CMOS VLSI approach. For the advanced satellite studied, a satellite which would be a candidate for a NASA Data Distribution Satellite, the study predicts a mass saving of about 64 kg and a power savings of over 1000 Watts using the projected 1995 GaAs technology.

For the interplanetary mission applications, JPL has made thorough analyses of the advantages of using 32 GHz rather than X-Band. They have made extensive studies of how the 8 dB advantage of 32 GHz over X-Band could be translated in to benefits for missions such as the Cassini Probe and Mars Sample Return. JPL studies project, for instance, that a 25 Watt RTG could be eliminated from the Cassini probe at a savings of \$5M, overcoming a projected \$3.4M increase in the recurring cost of the 32 GHz array. They estimate a non- recurring development cost of \$7M.

Benefits for the Mars mission are substantial but not so easily quantifiable. The JPL study considered both the use of flat planar arrays and TWTA fed parabolas at both X-Band and 32 GHz, using both 70 and 34 meter receiving systems. In all cases 32 GHz demonstrated a clear mass advantage over X-Band, on the order of a factor of two. Between the two 32 GHz approaches, the flat planar array has substantial size advantages over the parabola and TWTA approach.

TABLE 1-5

KEY PERFORMANCE REQUIREMENTS OF MMIC APPLICATIONS

| APPLICATION | SOURCE OF REQUIREMENT | KEY PERFORMANCE REQUIREMENTS |
|---|-----------------------|--|
| Interplanetary Probes (eg Cassini and Mars Sample Return) | JPL | 32 GHz power amplifiers (100 mW, > 30% efficiency), phase shifters and variable gain amplifiers for active arrays |
| Synthetic Aperture Radar (Mission to Planet Earth) | JPL | 5.3 GHz four-bit phase shifter and small signal amplifier (Long term: power amplifier with 12 W peak, 1 W avg; low noise amplifier with 1.5 dB noise figure) |

TABLE 1-5

KEY PERFORMANCE REQUIREMENTS OF MMIC APPLICATIONS
(continued)

| APPLICATION | SOURCE OF REQUIREMENT | KEY PERFORMANCE REQUIREMENTS |
|---|--|--|
| Space Station (Control Zone Comm.) | Johnson Space Center | 21-23 GHz power amplifiers, 2 W, 15 dB gain, 30 % efficiency |
| TDRSS (On board beam forming) | Ford Aerospace and Goddard Space Flight Center | 2.29 GHz narrowband five-bit phase shifter |
| Future Commercial, Military and NASA Communication Satellites (eg NASA Data Distribution Satellite) | Ford Aerospace | Bulk demodulator, eg 400 channels, 72 kbit/sec IF switch matrices (100 X 100) |
| Downlink Multi-scanning beam antenna | NASA-Lewis | Transmitter modules, 17.7-20.2 GHz, 200 mW, 15 % efficiency, 16 dB gain. Phase shifter, 5 bits Variable power, 0 to 0.5 W, 6 to 15 % efficiency, 4-bit control |
| Uplink Multi-scanning-beam antenna | NASA-Lewis | Receiver modules, 27.5-30 GHz, 5 dB noise figure, 30 dB RF/IF gain, 5-bit phase control, 4-bit gain control |
| Intersatellite link active array | Military | 60 GHz power amplifiers, low noise amplifiers, digital phase shifters, variable gain amplifiers |

TABLE 1-5

KEY PERFORMANCE REQUIREMENTS OF MMIC APPLICATIONS
(continued)

| APPLICATION | SOURCE OF REQUIREMENT | KEY PERFORMANCE REQUIREMENTS |
|-------------------------------|-----------------------|---|
| Anti-jam antenna | Military | 7.9-8.4 GHz amplifier, 2.5 dB noise figure, 20 dB gain, 5-bit phase shifter and variable gain amplifier |
| Transponder Channel Amplifier | Ford Aerospace | 12.25-12.75 GHz, 45 dB max gain, 21 dB gain variation commandable in 3 dB steps, 7 dB noise figure |

Thus, to a limited extent and in some applications it is possible to express MMIC benefits and costs in terms of dollars, and in this way to reach a conclusion about the advisability of pursuing the monolithic approach. This tends to be the case in the more immediate, more straightforward applications where the benefits can be calculated easily in monetary terms. The channel amplifier is an example of this class. The decision of whether to proceed with the MMIC approach can be based on whether the savings exceed the development costs. No new capabilities or intangible benefits would appear to be promised by the development.

The benefits in applications such as the space station and interplanetary probes are not so easily summarized in monetary terms. An initial space control zone communication capability can be established using omni antennas for close in communication and one, or more, steerable directional antennas for more distant users. But an approach using multibeam active arrays not only will consume less space and not be dependent on mechanical steering mechanisms, but more importantly will have far greater potential for expanding to handle more users and activity, as would be demanded, for example, if the space station is to be used as an assembly station or a fueling depot, as for the Humans to Mars Initiative of the Ride Report.

Similarly, TDRSS can operate with beam forming accomplished on the ground as it is currently designed to do. This approach limits the capacity of the system, however, and is subject to possible performance limitations. On board beam forming appears to have far greater potential for future expansion. Although it is possible to quantify the advantage of an MMIC approach to on board beam forming over a hybrid approach, as was done on this contract, the benefit of on board versus off board beam forming is more difficult to quantify.

Several of the applications of Table 1-5 are for future communication satellite systems, to accommodate VSATs and to serve as stepping stones to the capability for personal access to the

communication satellite system. The technologies for on board signal processing, such as bulk demodulators and switch matrices, and for scanning multi-beam arrays fall into this category. Such a capability to provide convenient, low cost access from small, personal terminals to a world wide digital communication network can have clear economic and social benefits. However, it is difficult to weigh this benefit rationally against the also clear benefits of technologies devoted to space exploration and to taking man into space.

Fortunately, the difficulty of weighing different categories of benefits against one another may not be as serious as it might seem. When the applications of Table 1-5 are studied from the point of view of common technologies rather than competing applications, it is seen that there is a great deal of commonality which suggests some clear technical directions. Clearly a "cutting edge" technology is efficient power amplifiers for frequencies from 20 to 60 GHz. Developing power amplifier technology with this capability is the key to transmitters for interplanetary probes, to power amplifiers for active arrays on the space station, to scanning multi-beam downlinks for advanced communication satellites, and to transmitter arrays for intersatellite links.

Together with the efficient power amplifier capability, this set of applications requires the monolithic phase shifters and variable gain amplifiers needed for active arrays. Fiber optic control circuitry may be required in some applications for signal distribution and control. This same technology development with the addition of low noise amplifiers at 30, 44 and 60 GHz would support also the need for uplink receive arrays and intersatellite link receive arrays.

Thus a broad category of applications can be supported by the development of this 20-60 GHz MMIC based active array technology. A good foundation has already been laid in this technology through development sponsored by NASA and the Air Force. As a result of this work much of the required development can be regarded as low risk. Recent laboratory results from GE and Texas Instruments on power HEMTs show efficiencies in the desired range in the 30 GHz region. For example, GE has reported 132 milliwatts at 35 GHz with 30% power added efficiency.

To date the power device performance closest to that required has been obtained from power HEMTs. An important element of risk is that the reliability of this approach has not been established. Heterojunction Bipolar Transistors (HBTs) have shown significant promise for efficient high power devices. However, to date these results have been only at lower frequencies, for example Rockwell's reported 400 milliwatts at 48% efficiency at 10 GHz and TI's 160 milliwatts at 35% efficiency also at 10 GHz. The HBT approach would seem to have great promise for efficient power devices in the 20-60 GHz range. Thus, to reduce risk, power HBT technology should be developed as a backup to the power HEMT approach.

Although much work has been done on MMICs for millimeter-wavelength active arrays, additional work is required to support the many applications for such arrays. In particular the digital phase shifters reported to date show large variation in insertion loss as the phase setting is changed, and the magnitude of this problem varies from unit to unit. This is a serious problem in an array application. In principle it is possible to compensate by changing the associated variable gain element when the phase is changed. This places a large additional burden on the control circuitry, however, and in some applications the control circuitry is already becoming a important contributor to the weight and power consumption of the system. In principle this insertion loss variation can be reduced to a very small value by more sophisticated design. This development would have important benefit.

The backplate technology, the technology for integrating the MMIC modules to the radiating elements and distributing the control and RF signals to the elements, is an important technology area which needs more development to support all of these array applications. This millimeter-wavelength active array development is clearly beneficial because it serves so many of the identified applications of Table 1-5. By the same token it benefits many possible users such as NASA, the military, and commercial satellite communications. Thus the development should be coordinated and supported by all the potential beneficiaries. This requires close coordination of NASA, the Air Force, and private industry to avoid needless duplication of effort while maintaining the advantages of pursuing competing approaches.

Some important applications of Table 1-5, however, are not encompassed by the development of millimeter-wavelength active array development. In particular, the phase shifter for on board beam forming seems to be a very important and beneficial application. The requirement seems to be within the capability of the state-of-the-art and, hence, entails only low risk. It requires a custom MMIC chip which will not be developed as a generic part by an MMIC vendor, nor will it be developed for some other application. The successful development of the phase shifter would help establish the credibility of MMICs as a useful component for space circuitry. Therefore, this appears to be a very attractive component for NASA funded focused development.

The MMIC module for the C-Band synthetic aperture radar for the Mission to Planet Earth is another beneficial MMIC circuit which is not encompassed by the millimeter-wavelength array efforts. The development of the digital phase shifter and the low power gain stages would make a major contribution to the solution of the problem of reducing the weight of the radar. Yet the development of these circuits should be within the capability of present technology. The development of this chip would serve the important function of establishing MMIC technology as a credible contributor to the needs of space based synthetic aperture radars. A more ambitious program would tackle the power output stages and the low noise preamplifier where the requirements are a greater challenge to the technology and hence would entail greater cost and risk.

Of the remaining applications identified in Table 1-5, the MMIC channel amplifier, according to the analysis on this program, has cost benefits in comparison with the present hybrid approach. But since it does not promise benefits beyond this cost savings, it seems to be an application best left to industry to develop or not depending on its perception of the cost tradeoffs. The X-Band anti-jam antenna would be of benefit to the military, and the analysis on this program illustrates the benefits of MMICs to active arrays in general. However, the development of MMICs for this application should be done by the military.

Finally, the on board signal processing application is a difficult one for this program to evaluate. In the first place, as a digital circuit technology, it does not accurately fit into the category of MMICs, although as was pointed out, the use of GaAs integrated circuitry promises significant benefits. In addition, although GaAs bulk demodulators promise impressive weight and power consumption advantages in comparison to silicon VLSI, except for a possible Data Distribution Satellite, the benefits are mainly applicable to future communication satellite systems to serve mobile and very small aperture terminals. Thus, although the benefits promise to be significant enough to justify development, whether the development is in the province of NASA or private industry must be answered by considerations beyond the scope of this project.

1.6 RECOMMENDATIONS FOR NASA DEVELOPMENT

On the basis of the considerations summarized in Section 1.4, a development program has been outlined to support the requirements identified by this study. This recommended program is summarized in Table 1-6 and described in more detail in the following paragraphs.

1.6.1 MMICS FOR MILLIMETER-WAVELENGTH ACTIVE ARRAYS

Section 1.4 discussed the fact that the commonality of several important applications makes it clear that the development of efficient power amplifier MMICs in the 20 to 60 GHz range is a high priority goal. Specifically, 32 GHz power amplifiers with at least 100 milliwatts output and an efficiency greater than 30% are needed for interplanetary probe applications such as the Cassini mission (Saturn Orbiter/Titan Probe) and the Mars Sample Return. The efficiency is extremely important in this application particularly for the Cassini probe since power savings in comparison to an X-Band approach is a major driver for the 32 GHz system. The power amplifiers will be used in arrays for electronic beam steering. A possible implementation of the Cassini probe would use 21 elements, spaced by about 1.7 cm, each producing 100 milliwatts with a power added efficiency of at least 30%. The Mars Sample Return would also use an array but with many more elements. For the Space Station a steerable multibeam antenna for communication with users in the control zone would require large numbers (several hundred) of power amplifiers for a transmitter array. Frequency would be 21-23 GHz. 2 Watts of output power with 15 dB gain at a power added efficiency of greater than 30% is

required. The technology for such MMICs would also be capable of providing power amplifiers for communication satellite arrays for scanning spot beam downlinks.

This development program will also advance the capability for 60 GHz power amplifiers. Such devices are needed both as elements for active arrays for intersatellite links and as elements which can be combined in a passive combiner to produce 5 to 10 Watts to feed a dish antenna in an intersatellite link.

Power HEMT devices now seem to be the most promising approach for these power amplifiers. However, a risk of this approach is the unproven reliability of these devices. A promising backup approach is the Heterojunction Bipolar Transistor (HBT). Since the development of efficient power amplifier MMICs for these frequencies is the key to the success of important systems for both NASA and the military, both power HEMT and HBT approaches, at a minimum, should be supported to reduce risk. Although the power amplifier is the critical development, and other important elements of the active arrays have already received attention, some important issues remain. Phase shifter technology is not yet adequate. Improvement needs to be made in the designs to make the insertion loss less sensitive to the phase setting. A development program should develop 21-23 GHz or 32 GHz phase shifters with loss variation less than 0.5 dB, as is theoretically possible.

Another important unsolved problem in millimeter-wave active arrays is that of packaging the chips, providing a low loss path from the chip to the antenna element, providing heat sinking to the active devices and distributing the RF and control signals to the MMIC elements. The use of optical fibers for distribution of the RF and control signals may be an important part of the solution to this problem. NASA-Lewis recognized the importance of this technology and has already taken the lead in developing optical electronic integrated circuits. It is also possible that the new high temperature superconductors will play an important role in solving this antenna array control problem. This problem area will be studied, for 20 and 44 GHz arrays, under a planned RADC program. This work should be followed closely and supplemented if it seems desirable to support alternative approaches to those studied under the Air Force program.

TABLE 1-6

RECOMMENDED MMIC DEVELOPMENT PROGRAM

| APPLICATION | DEVELOPMENT | COMMENTS |
|---|---|--|
| <p>Millimeter-wavelength Active Arrays (Space Station, Interplanetary Probes, Communication Satellites with Scanning Spot Beams, Anti-jam Antennas)</p> | <ol style="list-style-type: none"> 1. Efficient Power Amplifiers (22, 32 GHz, > 30% efficiency) 2. 5-bit Phase Shifters with Minimum Insertion Loss Variation 3. Array Backplate Technology | <p>Overlapping military and NASA needs require coordination and cooperative development Recommend HBT as backup to prime HEMT approach for efficient power amplifiers</p> |
| <p>Tracking and Data Relay Satellite System (TDRSS)</p> | <p>2.29 GHz Phase Shifter</p> | <p>Low risk development, important benefit to program, helps to establish MMIC as viable technique</p> |
| <p>Synthetic Aperture Radar (Mission to Planet Earth)</p> | <p>5.3 GHz Five-bit Phase Shifter and Small Signal Amplifier</p> | <p>Also a low risk development, important for reducing weight of array. More ambitious program would develop power and low noise amplifiers as well</p> |
| <p>General-To Reduce Development Costs for Low Quantity Applications</p> | <p>Application Specific MMICs Advanced CAD tools</p> | |

1.6.2 PHASE SHIFTERS FOR TDRSS ON BOARD BEAMFORMING

The development of a 2.29 GHz phase shifter would be a valuable contribution to future improved versions of TDRSS. On board beam forming would facilitate handling a greater number of users and antenna elements, and would eliminate possible problems resulting from differential phase shifts between the signals transmitted to the ground for processing in the present approach. However, on board beam forming adds considerable complexity aboard the satellite. This study has shown that, based on a typical scenario requiring 762 phase shifters on the satellite, hybrid MIC phase shifters would add over 28 kg to the weight of the satellite, whereas MMIC phase shifters would add only 3.7 kg. Thus, the MMIC approach could be crucial to making on board beam forming practical. It is considered a low risk development based on present MMIC technology, and its development would be helpful in demonstrating that MMIC is a viable technology.

1.6.3 PHASE SHIFTER AND AMPLIFIER FOR SYNTHETIC APERTURE RADAR

An important need exists to reduce the weight of a space based synthetic aperture radar such as would be used for Mission to Planet Earth. MMICs could make a major contribution to this objective, but need to prove their capability by demonstrating the ability to produce a significant number of repeatable, reliable, full-spec devices. The recommended program would develop digital phase shifters and small signal amplifiers for the C-Band radar (5.3 GHz) and would produce enough units to demonstrate the reproduceability of the process. A more ambitious program would develop also the power amplifiers (12 Watt peak, 1 Watt average) and low noise amplifiers (< 2 dB noise figure) for 5.3 GHz.

1.6.4 DEVELOPMENT OF SUPPORTING TECHNOLOGY

A typical characteristic of microwave circuit requirements for space applications is that a high premium is placed on reliability and minimizing weight, characteristics which argue for the use of MMIC technology. On the other hand it is also characteristic of most space applications that the quantity required of any particular circuit is very small and tight electrical performance specifications must be met. These latter characteristics generally are incompatible with the MMIC approach because the high development costs of custom MMICs cannot be spread over a large number of units. Therefore, a valuable contribution to making MMICs available for space applications is design tools which would greatly reduce the cost of MMICs for high performance, very small quantity applications. The Application Specific MMIC approach described in Section 4 is a promising approach to this need. Development of this approach may be supported to some extent by the military, for whom this approach also has potential value. Developments along these lines should be followed carefully to see how adequately the program funded by the military supports NASA needs with serious consideration given to supplementing the military program as needed, for instance by developing an ASMMIC "footprint" usable for NASA programs.

1.6.5 CONCLUSION

This study has surveyed future potential applications of MMICs in military communication satellites, commercial communication satellites, and in NASA space missions. It has showed that the benefits of this new technology translate into significant system benefits which can take the form, in some instances, of substantial cost savings, and, in other instances, of important improvements in system capability. The study has identified considerable commonality among several of the important applications. It has also identified some specific device developments which would have important near term application, thereby demonstrating the viability of MMIC technology.

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