LOW COST MICROWAVE GROUND TERMINALS FOR SPACE COMMUNICATIONS

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ABSTRACT

Large arrays of small antennas are under development to greatly increase the sensitivity for both deep space communications and radio astronomy. An important spin-off of this technology is the development of single small antenna systems for near-earth space communications. This paper first reviews the figure of merit of antenna gain divided by system noise, G/Tsys, required for a given data rate. The large array projects that are developing applicable new technologies are then summarized and the status of the new technology is reported.

1. INTRODUCTION

The data rate for a given distance, transmitter and receiver parameters can be calculated using the common equation for link path loss and the Shannon channel capacity theorem [1] given by,

$$C = B \log_2(1 + S/N)$$

where C is the data rate in bits/sec, B is the channel bandwidth in Hz, and S and N are the average signal and noise powers. It is important to note that N is proportional to B and refers to additive noise due to the receiver and background sources. The data rate for a typical set of parameters relevant to communication with low-earth orbit (LEO), geostationary (GEO), and science instruments at the Lagrangian point, L2, are shown in Figure 1. The curves are for examples of (from highest to lowest data rates), 6m antenna with cooled receiver, 6m antenna with an ambient temperature receiver, and 2m antenna with an ambient temperature receiver. Transmitter power of 10 W, transmit antenna gain of 6 dB, bandwidth of 10 MHz, and margin of 6 dB are assumed.

The data rate for Deep Space Communications is summarized in Figure 2 for the current DSN (70m antenna at X band), optical communications projected by 2010, and arrays of 100 and 3600 x 12m antennas. These curves are for 50W of DC power at the spacecraft (nuclear power of 5KW could increase the data rate by 100), 1.5m radio and 0.3m optical spacecraft transmit antennas, 50 MHz bandwidth at X band and 500 MHz bandwidth at Ka band, and 9db of link margin including coding efficiency.

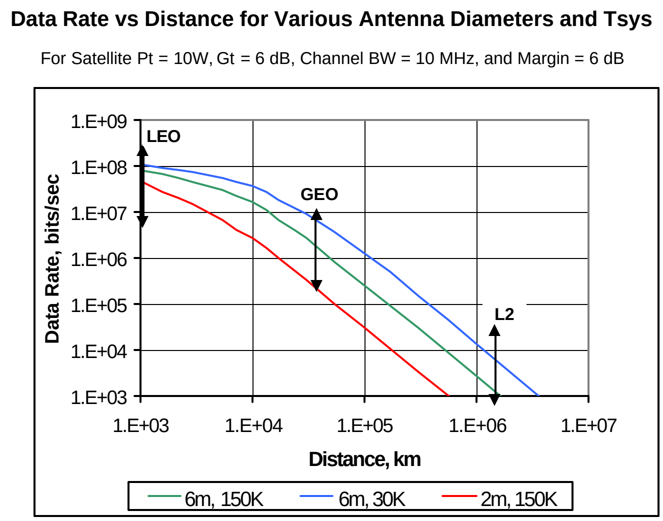


Figure 1. Data rate for spacecraft in earth orbits.

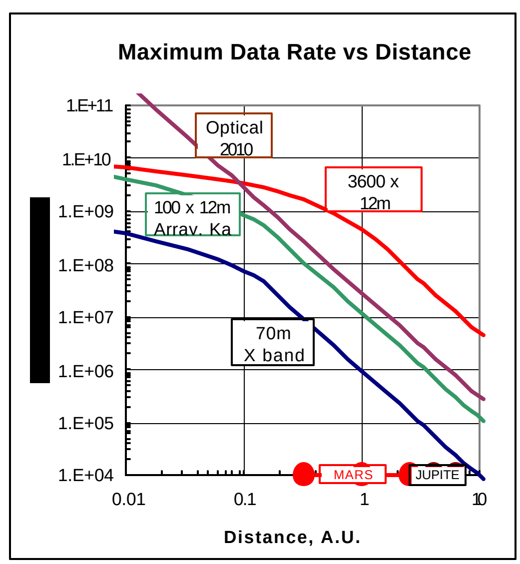


Figure 2. Data rate for deep space communications.

2. LARGE ARRAYS WITH TECHNOLOGY APPLICABLE TO GROUND SYSTEMS

There are three large microwave array projects that are developing technology applicable to NASA ground systems and these are summarized in Table 1 below:

Table 1

Project	Institution	Array Elements	Time Scale
Allen Telescope Array (ATA)	SETI Institute and UC Berkeley	350 x 6m 0.5 to 11 GHz	2001-2007
Deep Space Network Array (DSNA)	NASA JPL	100 x 12m 8/32 GHz	2002-2008
Square Km Array (SKA)	International Consortium	Many concepts 0.15 - 22 GHz	2003-2016

A. Allen Telescope Array (ATA)

The spearhead project in this group is the ATA under construction and summarized in Figures 3 and 4.

Allen Telecope Array - ATA

- 350 x 6m array for SETI and radio astronomy under construction in Hat Creek, CA
- Instantaneous receiver frequency range of 0.5 to 11 GHz

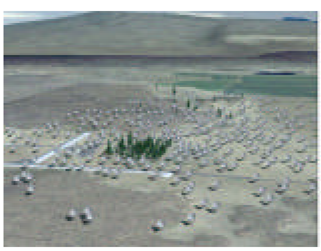
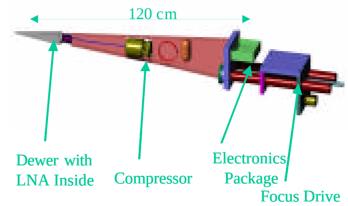


Figure 3 - Artist concept of array and photograph of first 6m offset paraboloid antenna

The ATA utilizes new technologies in both the antenna construction and receiver electronics to reduce cost. The antennas are hydroformed, a metal stamping technique that provides precise, low cost reflectors. The innovations in the electronic system are summarized in Figure 4.

New Technology in Allen Telescope Array

- Single wideband 0.5 to 11 GHz feed and LNA
- Miniature pulse-tube long life cryogenic 70K refrigerator
- No frequency conversion or local oscillator at antenna.
- Entire 0.5 to 11 GHz band is transmitted to a central processing building by fiber optics



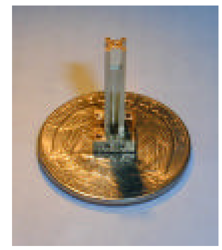


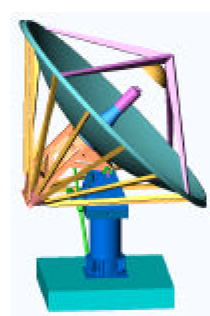
Figure 4. The ATA receiver front-end, shown in the top portion of the figure, fits within the 0.5 to 11 GHz feed shown in the lower left of the figure. MMIC low noise receivers mount on the small chassis shown in lower right of the figure.

B. Deep Space Network Array (DSNA)

At JPL an array is being developed for deep space communications and is summarized in Figure 5 and Table 2.

Deep Space Network Array (DSNA)

Breadboard 6m antenna for array of 100 x 12m antennas



New Technologies

- Precise, low cost hydroformed antennas with simple backup structure
- Cryogenic InP HEMT low noise amplifiers; with 4K noise at X band and 14K at Ka band.
- Monolithic Microwave Integrated Circuits (MMIC) implementation of RF functions.
- New technology, long life cryogenic refrigerators
- Field-programmable gate arrays (FPGA) for signal processing.

Figure 5. Antenna drawing and new technology applied to the JPL DSN array.

Table 2 - Cost Reduction Factors for the DSNA

- •Capital cost for a given antenna area is greatly reduced because smaller antenna have a lower cost per unit area.
- •Receiver cost is greatly reduced by using modern analog and digital integrated circuits - MMIC's and FPGA.
- •No single point failure. Array elements can fail with little consequence. Maintenance can be on a routine 40 hr week schedule
- •"Just enough" array element assignments allow many missions to be accommodated.
- •Multibeaming of the array allows simultaneous communication to many spacecraft within one small antenna beam; applicable to communication with many missions to Mars.
- •Flexible growth. Antennas can be added as required for future missions.

C. Square Km Array (SKA)

The SKA is an international radio astronomy project with the goal of extending receiving system sensitivity by factors of 10 to 100 over existing instruments. Seven concepts are under study in the US, Australia (2) , Canada, Netherlands, China, and India [3,4]. A common goal is effective area divide by system temperature, Ae/Tsys, of 20,000 over the 0.15 to 22 GHz frequency range. The present US approach is 4550 x 12m antennas providing Ae of 360,000 m^2 with Tsys of 18K to meet the Ae/Tsys goal. This US approach utilizes technology being validated by the ATA and DSNA arrays. Two innovative approaches from Australia and the Netherlands are described in Figures 6, 7, and 8.

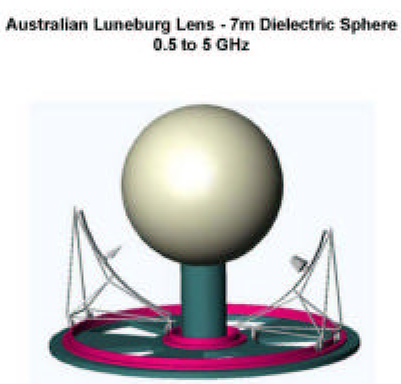


Figure 6. Luneberg lens approach to SKA under study in Australia. A dielectric sphere focuses an incoming beam to a feed on the opposite side of the sphere. Many beams can be produced by having many feeds or a beam can be steered by moving a feed. Issues are the cost, loss, and water absorption of the dielectric sphere.

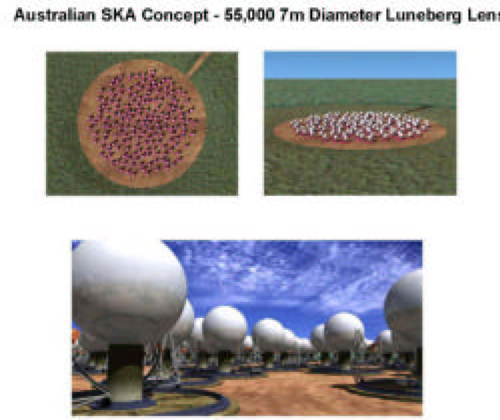


Figure 7 - Australian SKA concept of 55,000 7m diameter Luneberg lenses.

A phased-array approach to the SKA is under study in the Netherlands [5]. The concept is small antenna elements which have very broad beams covering most of a hemisphere of sky. These elements are arrayed and combined digitally to form beams covering the entire hemisphere. A prototype 1000 element array for the 0.6 to 1.8 GHz band is shown in Figure 8.

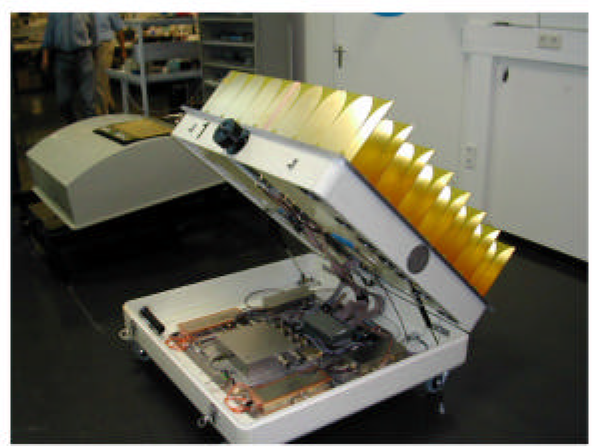


Figure 8 - Phased array approach to SKA. A close-spaced array of Vivaldi antenna elements are coupled to receivers which are combined and processed in the lower portion of the box. Many such boxes of arrays are required.

The phased array approach has advantages of simultaneous all-sky coverage with no moving parts. However, the number of elements is fundamentally very large if a large effective area is required and the frequency is high. For antenna elements with hemispheric beam the gain is 2 and the effective area is $?^2 /2 ?$. To obtain the effective area of a D=2m antenna = D^2 ? /4 the required number of elements N = $?^2 D^2 /2 ?^2$. For D = 2m and ? = 3.6 cm (8.4 GHz) N = 15, 230. At $100 per antenna including receiver the cost would be approximately $1.5M which is much more than a 2m antenna including mount.

3. NEW LOW COST MICROWAVE TECHNOLOGY

The new technologies which enable the cost reduction of microwave ground terminals are: 1) aluminum hydroforming for manufacture of precision microwave reflectors with up to 12m diameter, 2) microwave integrated circuits (MMIC's) to reduce the cost of the RF electronics , 3) lower noise GaAs and InP high-electron mobility transistors (HEMT's) which have extremely low noise at ambient and higher cryogenic temperatures, 4) new long-life, small cryocoolers for reducing the receiver noise, 5) fiber optic transmission lines for interconnection of a number of antennas, and 6) extremely powerful digital integrated circuits for signal processing.

Hydroforming is a process for forcing aluminum sheet to conform to a mold. The parabolic shape required for microwave focusing is consistent with the dome shape that gives high mechanical stiffness. Once the mold has been made, the reflectors can be manufactured at low cost [6]. Reflectors of 6m diameter with costs under $10K and complete antennas with pedestal and drives under $50K appear feasible in quantities of > 100.

Hydroformed Aluminum Antennas

Hydroforming is a process of using a fluid or gas at very high pressure to force aluminum sheet to conform to a mold. The result is a stiff, accurate, and low cost reflector.

JPL has performed a structural analysis of 5m and 8m hydroformed reflectors manufactured by www.andersoninc.com and has found that the wind and gravitational distortions would allow operation at frequencies as high as 100 GHz.

Example	Antenna Diameter	Cost per Antenna	Cost per m^2	Cost per km^2
New 70m DSN antenna	70m	$100M	$40.8K	$40.8B
25m VLBA antenna	25m	$3M	$9.6K	$9.6B
6m ATA antenna	6m	$30K	$1.7K	$1.7B
Target SKA cost	10m	$30K	$600	$0.6B
Hydroformed DBSTV antenna	4m	$2.8K	$350	$0.35B
Aluminum, 3mm thick sheet	Any	NA	$30	$.03B

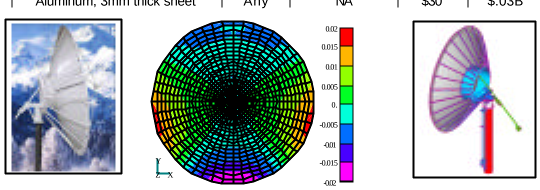


Figure 9 - Cost comparison per unit area of conventional large antennas and small hydroformed antennas.

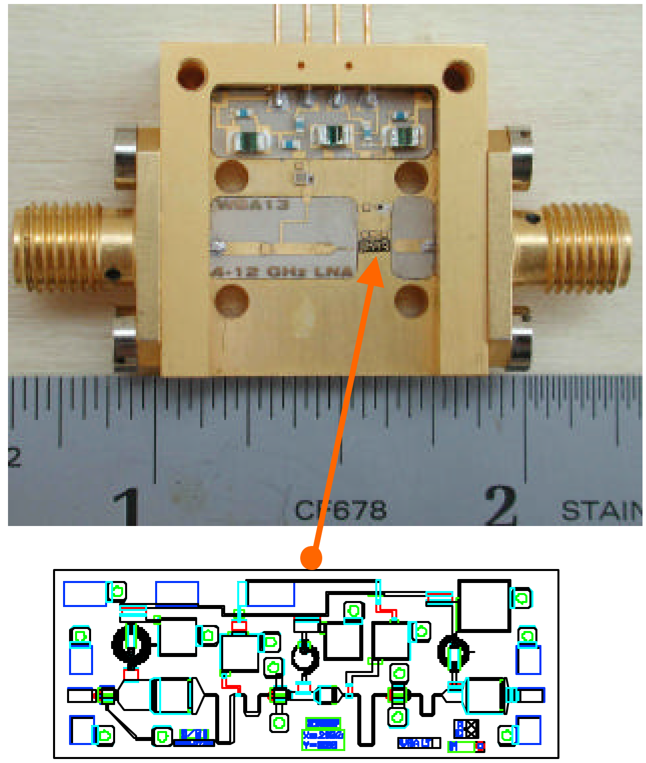


Figure 10 - Wideband very-low noise amplifier using monolithic-integrated circuit (MMIC) technology. The heart of the packaged amplifier is the 3 stage Indium Phosphide MMIC chip of dimension 2mm x 0.7mm shown in the lower portion of the figure.

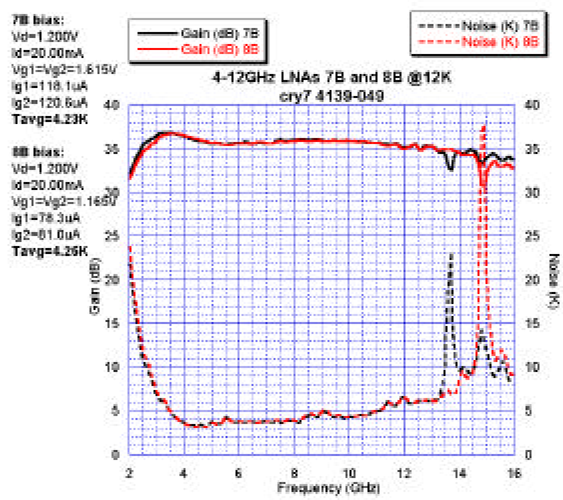


Figure 11. Gain and noise temperature of the MMIC amplifier shown in Figure 10 at a temperature of 12K. The noise is under 5K over a 4-12 GHz frequency band. The MMIC was designed at Caltech and fabricated by the Northrop Grumman Space Technology foundry (formerly TRW).

An important advantage of MMIC technology is the low manufacturing cost which results when MMICs are wire bonded together in a multi-chip module [7] as shown in Figure 12.

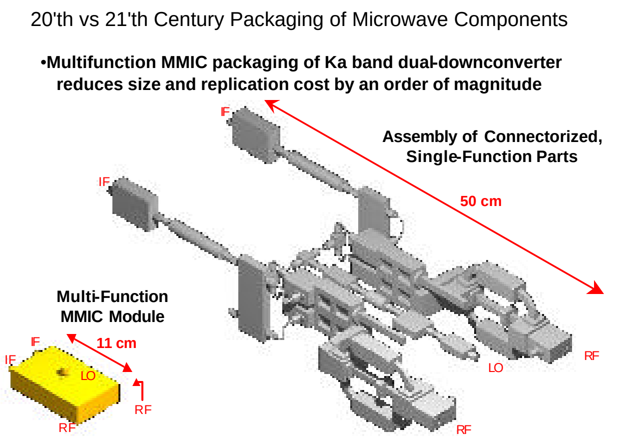


Figure 12. The reduction in volume and manufacturing cost realized by realizing a microwave subsystem, in this case a Ka band downconverter, is illustrated above. The MMIC module performs functions of amplification, frequency conversion, switch filtering, and switched attenuation for two channels all in one compact module which would require an assembly of single-function connectorized components without this technology.

As shown in Figure 1, cryogenic cooling of the low noise amplifier results in a factor of 5 or more reduction in the system noise temperature and is economically justified when large Ae/Tsys is required. For the past 25 years the most common type of cryocooler has been the Gifford-McMann type which cools to 15K, cost of the order of $12K, and should be serviced about once per year. Newer, pulse-tube cryocoolers with no moving parts at cryogenic temperatures and no rubbing parts at room temperature have been developed for space applications and are now becoming available at much lower cost for ground-based applications. An example is the unit manufactured by Sunpower [8] shown in Figure 13 which cools 2W to 40K, has an advertised life of 6 years, and has similar capital cost to the Gifford-McMann coolers but consumes an order of magnitude less power.

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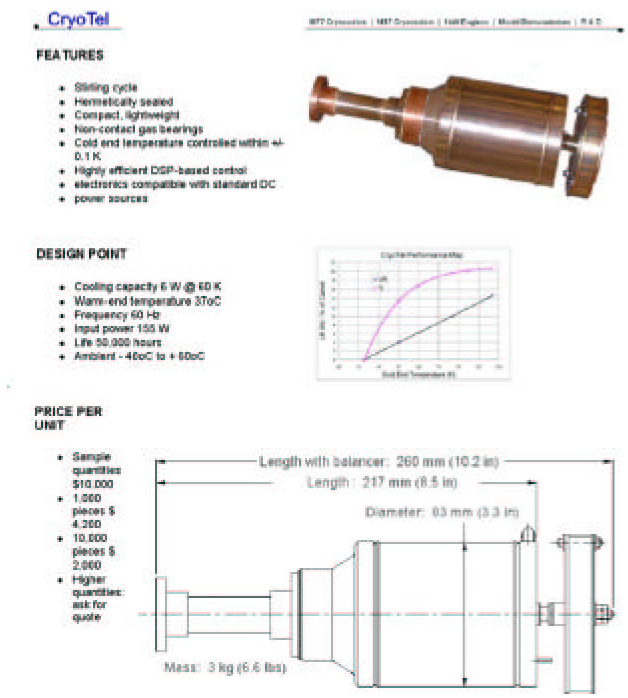

Figure 13 - Example of low maintenance, low power consumption cryocooler. This unit by Sunpower offers 2W at 40K, 50,000 hour life, and cost of $4.2 K per unit in quantity of 1000.

4. REFERENCES

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