Final Report - Year Three

AAH CAGE OUT-LINK AND IN-LINK ANTENNA CHARACTERIZATION

NASA Ames/Marquette University Joint Research
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Introduction. This final report encapsulates the accomplishments of the third year of work on an Advanced Biotelemetry System (ABTS). Overall MU/ABTS project objectives are to provide a biotelemetry system that can collect data from and send commands to an implanted biotransceiver. This system will provide for studies of rodent development in space. The system must be capable of operating in a metal animal cage environment. An important goal is the development of a small, "smart", micropower, implantable biotransceiver with eight-channel data output and single channel command input capabilities with the flexibility for easy customization for a variety of physiologic investigations. The NASA Ames/Marquette University Joint Research work has been devoted to the system design of such a new state of the art biotelemetry system, having multiple physiologic inputs, and bi-directional data transfer capabilities. This work has provided a successful prototype system that connects, by two-way radio links, an addressable biotelemetry system that provides communication between an animal biotelemeter prototype and a personal computer. The operational features of the prototype system are listed below:

- Two-Way PCM Communication with Implanted Biotelemeter
- Microcontroller Based Biotelemeter
- Out-Link: Wideband FSK (60 kBaud)
- In-Link: OOK (2.4 kBaud)
- Septum Antenna Arrays (In/Out-Links)
- Personal Computer Data Interface

The important requirement of this third year's work, to demonstrate two-way communication with transmit and receive antennas inside the metal animal cage, has been successfully accomplished.

The advances discussed in this report demonstrate that the AAH cage antenna system can provide Out-link and In-link capability for the ABTS bi-directional telemetry system, and can serve as a benchmark for project status. Additions and enhancements to the most recent (April 1997) prototype cage and antenna have been implemented. The implementation, testing, and documentation was accomplished at the Biotelemetry Laboratory at Marquette University with Out-Link (slot) antenna design assistance provided by Dr. Philip Carter, Jr, Jefferson Laboratories, Palo Alto, CA. In-Link loop antennas and the associated RF amplifier circuitry and septum antenna board were designed and characterized. Finally, the Out-link/In-link cage antenna array was tested with the existing ABTS bi-directional telemetry system.

Progress and Accomplishments - Year Three. The following is a tabulation of the accomplishments of year three of the ABTS project:

- Completed Septum Antenna Arrays
  - Out-Link Slot Array
  - In-Link Loop Array
  - In-Link Transmitter placed on Antenna Septum
- Characterized Signal Strengths vs. Location in Cage
  - Out-Link at 184 MHz.
  - In-Link at 434 MHz.

- Demonstrated the 2-way Biotransceiver Communication Link Inside the Metal Animal Cage

- Benchmarked the System for Future Work

SAA System Description

The Septum Antenna Array (SAA) is a self-contained antenna system incorporating both In-Link and Out-Link antennas and associated matching and power supply circuits. The block diagram (**figure 1**) and circuit schematic diagram (**figure 2**) describe the configuration and operation of the array. The Out-Link antenna array is a system of vertical and horizontal tuned slot antennas fabricated onto printed circuit board material. The In-Link antenna array consists of two squared loop antennas that are situated just above the ground plane of the printed circuit board septum. Both In-Link and Out-Link antennas have associated MMIC amplifier devices and matching networks. Further the In-Link 434 MHz RF source and OOK switch circuits are now located on the board. The features of the SAA are listed below:

- Drop-Out Free 2-Way Radio Links
- Fabricated on a Cage Septum Printed Circuit Board
- Includes In-Link TX
- Includes In-Link & Out-Link Combiners, Amplifiers, Antennas

Out-Link Slot Antenna Array Circuits

The Out-Link slot antenna array consists of 3 vertical and 3 horizontal slots etched into the SAA printed circuit board (see **figures 3 and 4**). Each slot measures 7.5 cm by 1.2 cm. as recommended by Jefferson Labs. Slots are arranged so that they minimally couple/interact. Each slot is fed at the longitudinal center point and tuned by parallel-

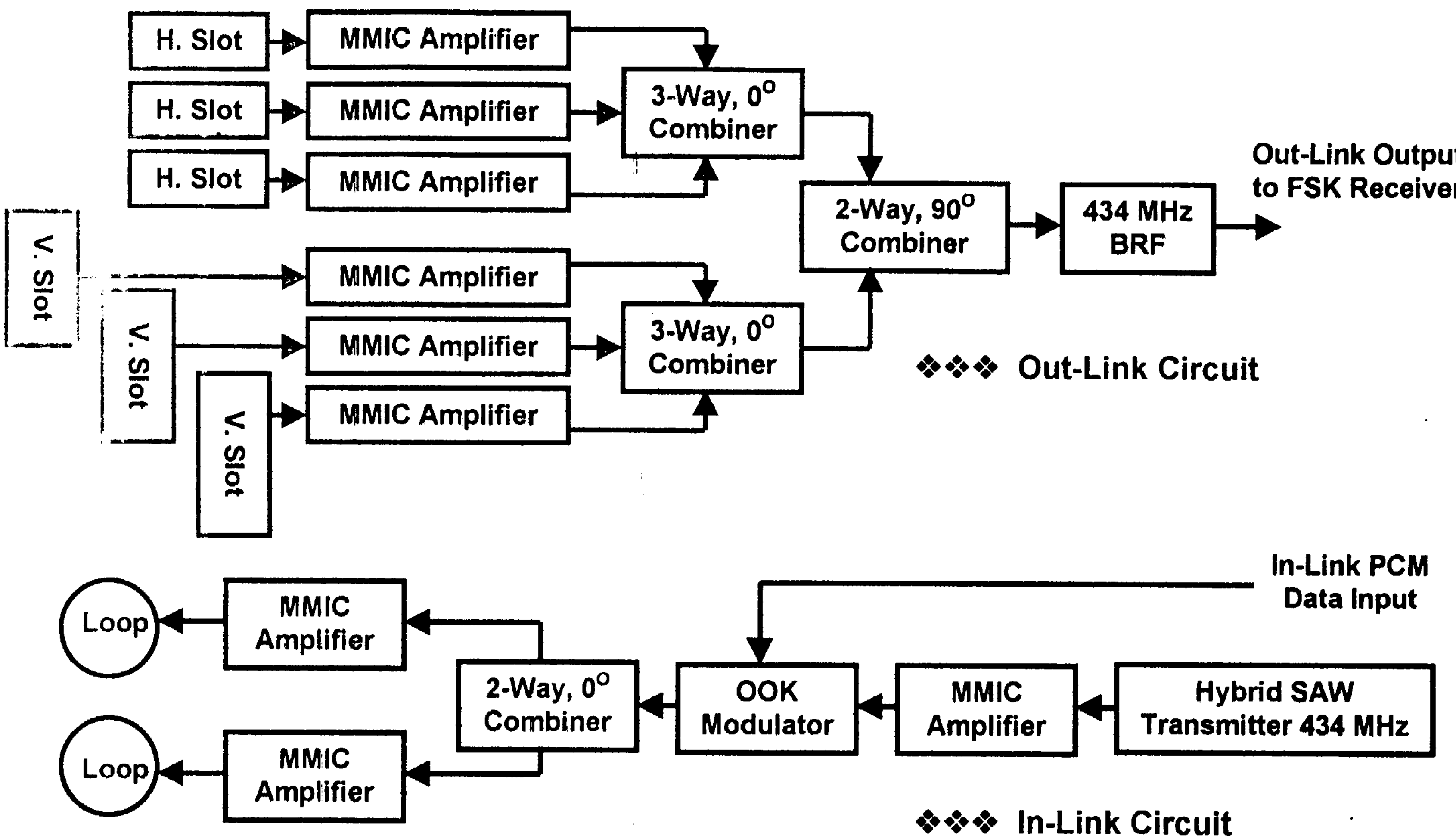
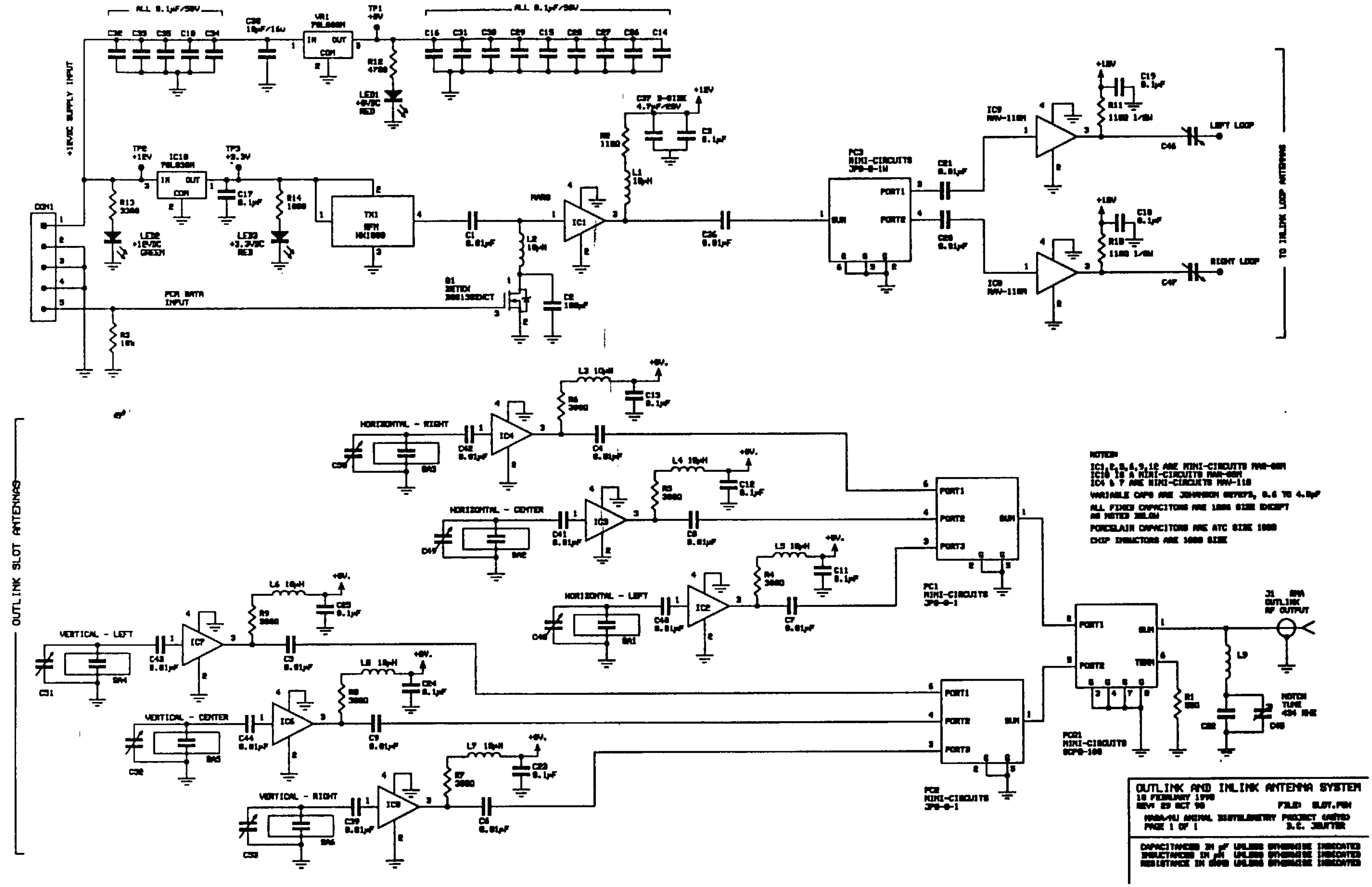


Figure 1: Septum Antenna Array (SAA) System Block Diagram


OUTLINK AND INLINK ANTENNA SYSTEM
PAGE 1 OF 1
+12VDC SUPPLY INPUT
CON1
PCR DATA INPUT
TX1
IC1
PC3
MINI-CIRCUITS
PORT1
PORT2
SUM
IC9
IC8
LEFT LOOP
RIGHT LOOP
TO INLINK LOOP ANTENNAS
OUTLINK SLOT ANTENNAS
HORIZONTAL - RIGHT
HORIZONTAL - CENTER
HORIZONTAL - LEFT
VERTICAL - LEFT
VERTICAL - CENTER
VERTICAL - RIGHT
PC1
PC2
PORT3
TERM
OUTLINK
RF OUTPUT
NOTCH
TUNE
NOTES:
PORCELAIN CAPACITORS ARE ATC SIZE 100
CHIP INDUCTORS ARE 1008 SIZE

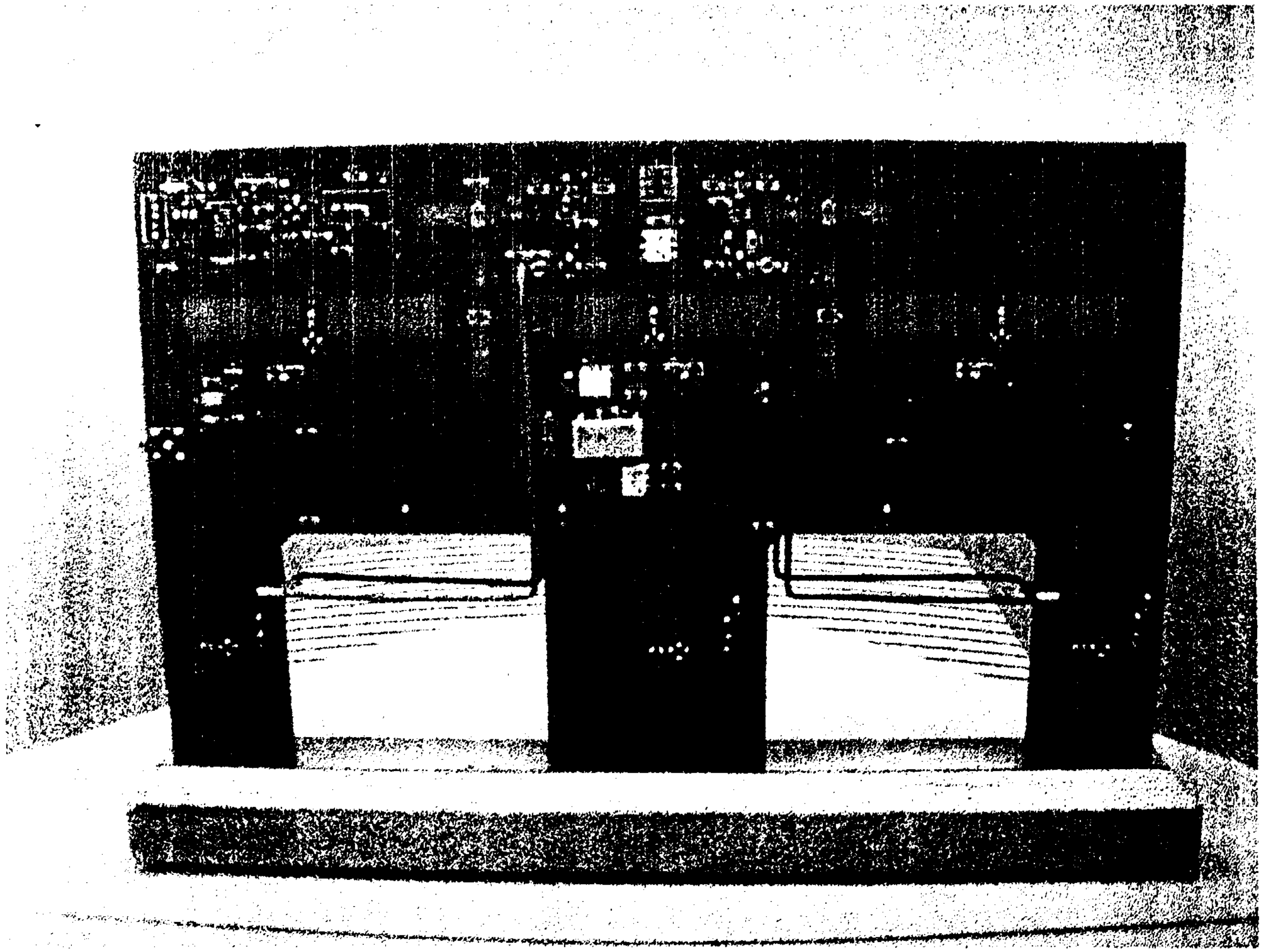


Figure 3: The Septum Antenna Array (SAA) – Front View

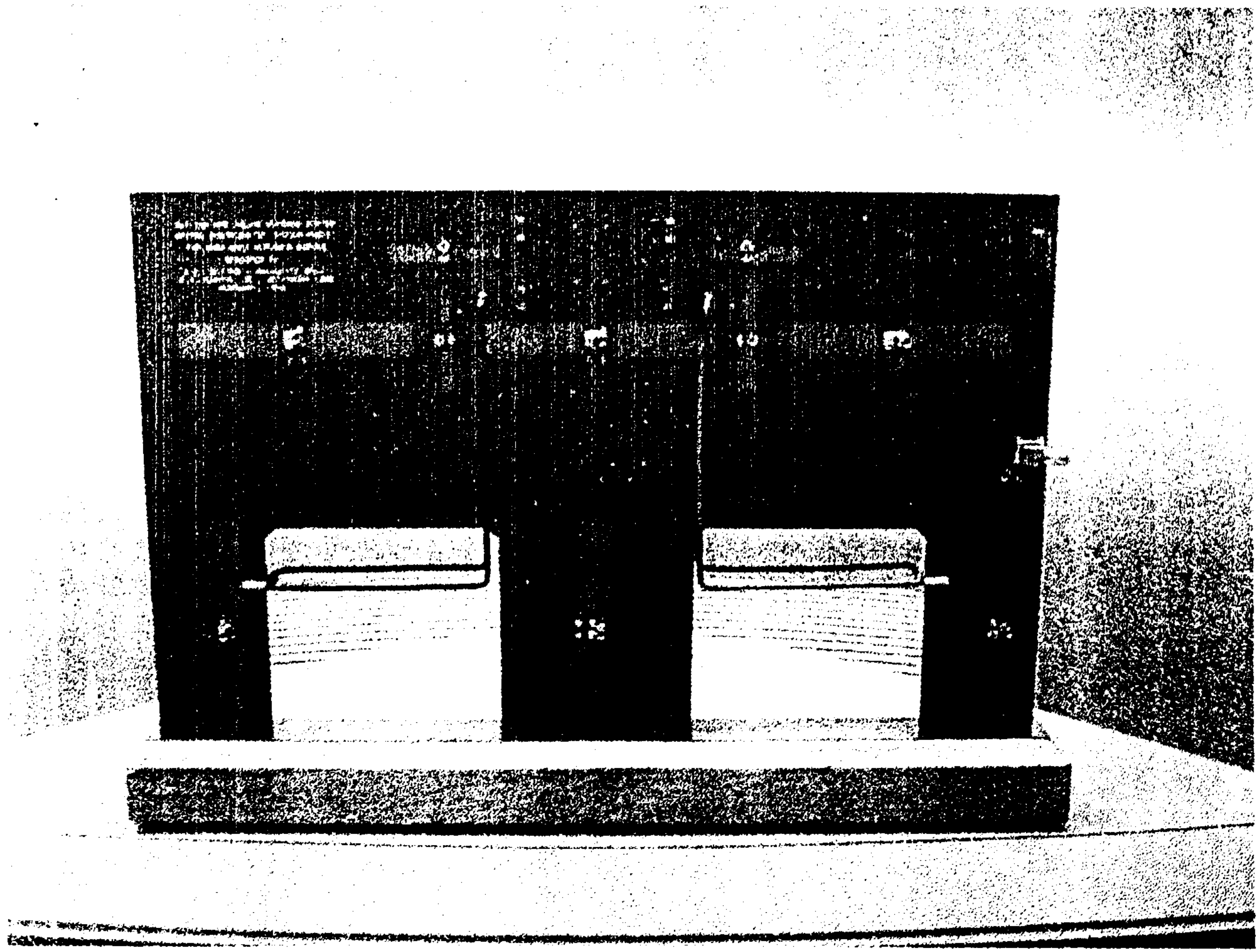


Figure 4: The Septum Antenna Array (SAA) – Rear View

connected fixed and variable capacitors at that center point. Individual slot antennas are resonated at a center frequency of 194 MHz. The bandwidth of the relatively low Q slots is approximately 20 MHz. that provides coverage of telemetered signals from 174 to 216 MHz. Signals from the slots' feed points are capacitively coupled to the inputs of MMIC amplifiers (6 total). The amplifiers are low noise devices with gain of about 18 dB. The devices (Mini Circuits, MAR-6SM) have 50 Ω input and output impedances for easy interfacing.

The outputs of the 3 vertical slot antenna amplifiers are connected to the inputs of a 3-way, 0° combiner (Mini-Circuits, JPS-3-1) and the outputs of the 3 horizontal slot antenna amplifiers are connected to the inputs of another 3-way, 0° combiner. The single outputs from the vertical and horizontal combiners are fed to a 2-way, 0° combiner to provide the 50Ω impedance final RF output from the slot antenna array. This signal is subsequently sent to the 174 to 216 MHz FSK Out-Link receiver via coaxial cable.

The Out-Link slot antennas are arranged on the printed circuit board in a manner that provides best telemetry coverage of the interior of the animal cage (**figure 3**). The printed circuit board resembles the letter "E" rotated 90° with openings provided for animal movement between the two chambers of the cage created by the SAA. Three horizontal slot antennas are arranged end-to-end along the spine of the E pattern and the three vertical slot antennas are situated in the legs of the E pattern. These slot arrangements minimize the coupling among the horizontal slots and among the vertical slots. Horizontal and vertical slot groupings are separated as much as practical on the SAA in order to minimize coupling.

In-Link Loop Antenna Array Circuits

The In-Link loop antenna array was designed to couple OOK telemetry commands to the implanted biotransceiver's receiver. The two finalized In-Link antennas are open L shaped loops that provide dropout free communication with the 434 MHz In-Link receiver (**figure 3**). Each loop is tuned to the In-Link frequency and has a bandwidth of about 1 MHz. that accommodates the In-Link data bandwidth. Each loop is fed, from a signal generated on the SAA, at its center point via a series tuning capacitor.

The onboard 434 MHz. signal source is a RF Monolithics, Inc hybrid transmitter model HX1000 (upper left-hand corner in **figure 3**). This transmitter runs continuously. The 50Ω output from the transmitter is directed to a MMIC (Mini-Circuits, MAR-8SM) which offers a matching 50Ω input impedance and provides about 10 dBm power output. On Off Keying (OOK) modulation of this In-Link command signal is accomplished by the MOSFET switch inserted in shunt with the transmitter output and between the transmitter and the MMIC. With PCM data applied to the gate of the n-channel MOSFET the transmitter output is shunted to ground (off keyed) with a data logic 1 or not shunted to ground (on-keyed) with a data logic 0. (Baud rates to 100 kBaud are available). Next the ON/OFF keyed 434 MHz signal from the MMIC amplifier 50Ω output is connected to the 50Ω input port of a 2-way, 0° splitter. Each of the splitter outputs is connected to a power amplifier MMIC (Mini-Circuits, MAV-11SM) and hence to a series tuned loop antenna. The power amplifiers exhibit 12 dB gain each and the power applied to each loop antenna is about 17 dBm (50 mW).

It should be noted that the final loop antenna configuration was arrived at empirically. An accurate analysis of loop operation in and interaction with the metal animal cage would be complicated and time consuming. Therefore the loop antenna array was optimized by cut and try. A large number of hairpin and other loop configurations were tried with significantly inferior performance. Performance is assessed by positioning the In-Link receiver antenna at various locations within the animal cage and observing the reliability of the received In-Link data. The finalized loop antennas provide dropout free performance at any location or orientation of the receiver antenna in the animal cage.

Specifically, each loop antenna is ½ wavelength long (34.6 cm.) and tuned to resonance with a 0-10 pF. tubular trimmer capacitor (Johanson, #27273). The wire therefore is 34.5 cm long and fashioned with PVC insulated AWG #18 solid copper wire. The arms of the loop antennas are spaced 1 cm. above the ground plane (printed circuit board) so that the width of the open area is 2 cm.

Figure 3 shows the finished SAA printed circuit board and **figure 5** shows the SAA installed as a septum in the animal cage. The implementation of the loops as low profile structures ensures that the SAA can be completely enclosed in the future to prevent destruction by caged animals.

SAA Performance Testing Methods

The important performance parameters of the SAA include measurements that reflect dropout free operation regardless of biotransceiver position in the animal cage. First, the *Out-Link Antenna Array Performance vs. Telemeter Position in the Animal Cage* was assessed by measuring the received strength of the Out-Link signal vs. position of the signal source (i.e.: a loop antenna driven at 190 MHz) in the animal cage. These performance evaluations were made for characterization and for comparison with baseline measurements made by Dr. Phil Carter on an early Out-Link slot antenna prototype. Second, *In-Link Loop Antenna Impedance Measurements* were made to determine the driving point impedance of the newly designed In-Link loop antenna array. Finally, *Overall SAA Performance* assessment of the complete In-Link and Out-Link with both the biotransceiver and the SAA in the animal cage environment was made. The latter assessment successfully demonstrated reliable two-way communication between the SAA and a biotransceiver located anywhere within the cage.

Out-Link Antenna Array Performance vs. Telemeter Position in Animal Cage

The first of the tests was made by positioning a balanced loop test antenna at a variety of sites within the animal cage. The 2.54 cm. diameter balanced loop was fashioned from

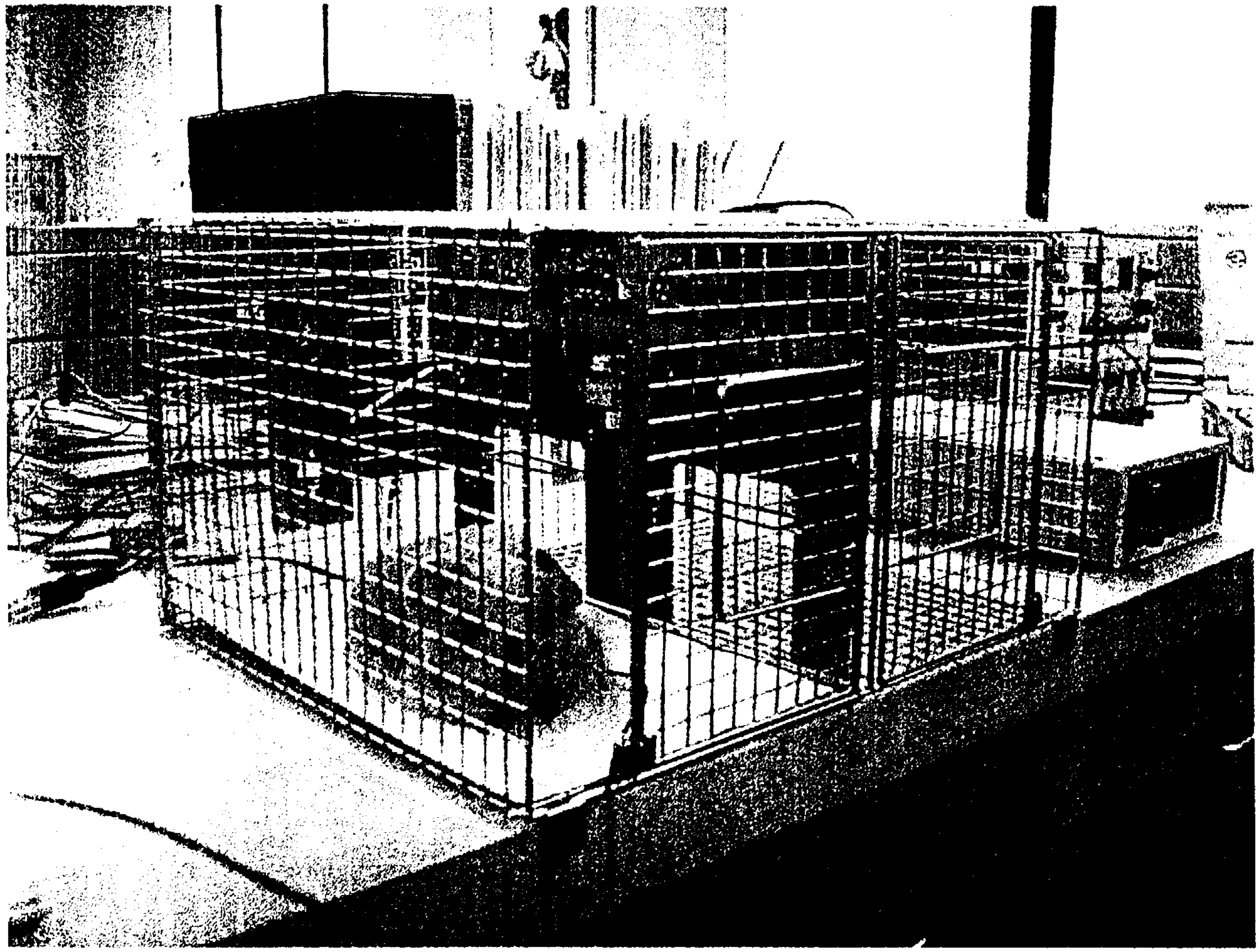


Figure 5: The SAA Installed as a Septum Inside the ABTS Metal Animal Cage

small 50Ω coaxial cable (Cooner Wire, #AS450-2650SR) and identical to the test loop used by Dr. Carter in his preliminary tests. The balanced loop is preferred over an unbalanced loop in order to eliminate RF currents on the shield of the feedline coaxial cable that could introduce measurement errors. All of the sites tested within the animal cage were the same as those previously tested by Dr. Carter and his coordinate system for placement was adopted. Several other sites were monitored in order to document additional coverage within the cage.

The results of these tests are summarized in **Table 1**. The measurements were made by driving the test loop antenna with a RF signal generator (Marconi 2018) set to an output power of 0 dBm (1 mW) at a frequency of 190 MHz. Received signal strength readings were made with a spectrum analyzer (Tektronix 495P) connected to the Out-link port of the SAA. The SAA was installed in the slots provided in the middle of the animal cage and powered by a 12 VDC supply.

The test loop antenna was located at 8 different positions within the cage. Dr. Carter's cage coordinates conventions for locating the test antenna loop were adopted in order to maintain consistency with his preliminary measurements.

At each position 3 measurements were made with the **axis** of the test loop antenna adjusted with respect to the axes of the Vertical and Horizontal Out-link antenna slots on the SAA printed circuit board. Each position is identified by X, Y, and Z coordinates with the center of the cage referenced at X,Y,Z = 0,0,0. Thus 24 measurements were made to characterize the received signal strength vs. test loop location using the Out-link antenna array.

The coordinate convention is described as follows, where Loop Axis Orientation definitions refer to the relationship of the test coil's axis to the planes of the Horizontal (H) and Vertical (V) slot antenna axes on the SAA printed circuit board:

|| H = Loop axis parallel to "H" slot axes
|| V = Loop axis parallel to "V" slot axes
⊥ V&H = Loop axis perpendicular to "H" and "V" slot axes

The position of the cage's center is at X,Y,Z = 0,0,0.

The results presented in **Table 1** show that the weakest received Out-Link signal is –49.2 dBm, in the || V transmitting loop orientation, at the coordinates X,Y,Z = -3, -6, -5 inches (i.e.: the cage's lower rear corner). The strongest received Out-Llink signal is –26.8 dBm, in the || H transmitting loop orientation, at the coordinates X,Y,Z = -3/4, 2, 0 inches. The column of normalized readings in the table show the relative signal strengths at other locations within the cage compared to the location of the strongest signal.

TABLE 1: OUT-LINK ANTENNA: SIGNAL STRENGTH VS. POSITION IN CAGE

F = 190 MHz
Pin = 0 dBm
Cage Center X,Y,Z = 0,0,0

Out-Link Loop Antenna Position, Inches			Loop Axis Orientation	Spectrum Analyzer Reading, dBm	Normalized Reading, dBm
X	Y	Z			
-1 1/4	3	0	‖ H	-35.6	-8.8
-1 1/4	3	0	‖ V	-33.2	-6.4
-1 1/4	3	0	⊥ V&H	-46.4	-19.6
3/4	2	0	‖ H	-26.8	0
3/4	2	0	‖ V	-38.4	-11.6
3/4	2	0	⊥ V&H	-33.2	-6.4
3/4	4 1/2	0	‖ H	-35.2	-8.4
3/4	4 1/2	0	‖ V	-48	-21.2
3/4	4 1/2	0	⊥ V&H	-48.8	-22
3/4	4 1/2	2 3/4	‖ H	-36.4	-9.6
3/4	4 1/2	2 3/4	‖ V	-46.4	-19.6
3/4	4 1/2	2 3/4	⊥ V&H	-42.4	-15.6
3/4	2	-2 3/4	‖ H	-33.2	-6.4
3/4	2	-2 3/4	‖ V	-43.2	-16.4
3/4	2	-2 3/4	⊥ V&H	-38.4	-11.6
3/4	2	2 3/4	‖ H	-31.6	-4.8
3/4	2	2 3/4	‖ V	-41.2	-14.4
3/4	2	2 3/4	⊥ V&H	-35.6	-8.8
-3	-6	5	‖ H	-48.8	-22
-3	-6	5	‖ V	-49.2	-22.4
-3	-6	5	⊥ V&H	-47.6	-20.8
3/4	-4 1/2	0	‖ H	-32.8	-6
3/4	-4 1/2	0	‖ V	-44.8	-18
3/4	-4 1/2	0	⊥ V&H	-45.6	-18.8

In-Link Loop Antenna Impedance Measurements

The feed point impedance of each loop was measured from the SAA located inside the animal cage. This was done as follows: With the 2-way, 0° splitter in the circuit each loop was separately tested. First the port 1 tuned loop antenna contribution to the array impedance was measured, with port 2 of the splitter terminated at 50Ω, using a HP8753A Vector Network Analyzer connected to the splitter's input port. At 434 MHz. the measurements are $Z_{in} = 125 + j18.5\ \Omega$, VSWR = 2.5:1, and $S_{11} = 440\ \underline{/7.6^\circ}$.

Next the procedure was reversed with port 2 tuned loop connected, port 1 terminated in 50Ω, and the splitter's input port impedance measured with the VNA. The results at 434 MHz show that $Z_{in} = 141 - j47.2\ \Omega$, VSWR = 3:1, and $S_{11} = 520\ \underline{/-14.5^\circ}$.

The indicated mismatches of 125Ω and 141Ω, corresponding to VSWR's of 2.5:1 and 3:1, respectively were not considered unsatisfactory enough to warrant addition of impedance matching circuits.

In-link tests were made using a receiver antenna implemented as a hairpin shaped antenna, ¼ wavelength long at 434 MHz. This test antenna was mounted 1.5 cm. above a 7 cm. by 2.54 cm. printed circuit board with ground plane. This receiver antenna was connected to a spectrum analyzer (Tektronix 495P) via coaxial cable for the measurements presented in **Table 2**. This test antenna was placed at different positions within the animal cage.

The position of the cage's center is at X,Y,Z = 0,0,0.

The results represented in **Table 2** show that the weakest received In-Link signal is –39.6 dBm, in the || V hairpin orientation, at the coordinates X,Y,Z = -3/4, 4 1/2, 2 3/4 inches. The strongest received In-Link signal is –8 dBm, in the ⊥ V&H hairpin antenna orientation, at the coordinates X,Y,Z = -3/4, 2, -2 3/4 inches. The column of normalized readings in the table show the relative signal strengths at other locations within the cage compared to the location of the strongest signal.

Comparisons with Dr. Carter's In-link data are not meaningful in this case since different antennas were used to obtain the data presented in **Table 2**.

TABLE 2: IN-LINK ANTENNA:
SIGNAL STRENGTH VS. POSITION IN CAGE

F = 434 MHz
Cage Center X,Y,Z = 0,0,0

In-Link Loop Antenna Position, Inches			Loop Axis Orientation	Spectrum Analyzer Reading, dBm	Normalized Reading, dBm
X	Y	Z			
-1 1/4	3	0	‖ H	-31.2	-23.2
-1 1/4	3	0	‖ V	-29.2	-21.2
-1 1/4	3	0	⊥ V&H	-24.8	-16.8
3/4	3	0	‖ H	-17.2	-9.2
3/4	3	0	‖ V	-31.6	-23.6
3/4	3	0	⊥ V&H	-29.6	-21.6
3/4	4 1/2	0	‖ H	-16	-8
3/4	4 1/2	0	‖ V	-33.2	-25.2
3/4	4 1/2	0	⊥ V&H	-27.6	-19.6
3/4	4 1/2	2 3/4	‖ H	-20	-12
3/4	4 1/2	2 3/4	‖ V	-39.6	-31.6
3/4	4 1/2	2 3/4	⊥ V&H	-19.2	-11.2
3/4	2	-2 3/4	‖ H	-16.8	-8.8
3/4	2	-2 3/4	‖ V	-18	-10
3/4	2	-2 3/4	⊥ V&H	-8	0
3/4	2	0	‖ H	-15.2	-7.2
3/4	2	0	‖ V	-22.4	-14.4
3/4	2	0	⊥ V&H	-21.2	-13.2
3/4	2	2 3/4	‖ H	-17.2	-9.2
3/4	2	2 3/4	‖ V	-23.2	-15.2
3/4	2	2 3/4	⊥ V&H	-8.8	-0.8
-3	-6	5	‖ H	-31.6	-23.6
-3	-6	5	‖ V	-32.4	-24.4
-3	-6	5	⊥ V&H	-31.2	-23.2
3/4	-4 1/2	0	‖ H	-19.2	-11.2
3/4	-4 1/2	0	‖ V	-31.2	-23.2
3/4	-4 1/2	0	⊥ V&H	-32.4	-24.4

Overall SAA Performance

The final test was made by placing the RF portions of the biotelemeter inside the animal cage with the PCM encoder located outside the cage (fig. 5). The RF and encoder circuits were electrically connected by a three conductor shielded cable (PCM Out-Link signal, PCM In-Link signal, 5VDC supply, and ground). The RF portion includes the 190 MHz Out-Link FSK transmitter circuit with its toroidal antenna (inductor wound on a 4 mm diameter core) and the 434 MHz In-Link receiver circuit with its hairpin antenna. The 434 MHz hairpin antenna is a ¼ wavelength AWG 24 wire in a hairpin shape placed 1 cm. above and in a plane parallel to the printed circuit board. For the purposes of this test, these circuits were fashioned on a printed circuit board 8 cm. by 2 cm. that could be easily positioned within the animal cage.

These SAA tests were performed to determine the efficacy of the overall 2-way ABTS biotransceiver communication links inside the metal animal cage. The resulting successful demonstration of reliable communication has benchmarked the system for future work.

The efficacy of a bi-directional telemetry linked biotelemetry system has been demonstrated. The Present Status of the System Prototype is described in the listing below:

- Implant Transceiver Completed
- PCM/FSK Out-Link Receiver Completed
- PCM/OOK In-Link Transmitter Completed
- 2-Way Communication Software Completed
- 4-Channel Data Display Software Completed
- Cage Septum Antenna Arrays Completed
- Reliable 2-Way Communication within Animal Cage Demonstrated

As a final demonstration of the success of the ABTS Project to date, actual transmitted data from the bio-transceiver and acquired by the SAA and receiver system is presented in **figure 6**. Data input to Channels 1, 2, and 4 are DC and the ECG waveform on Channel 3 was generated by an ECG simulator. This data can be acquired from any position within the cage without dropouts. Further, In-Link data can be transmitted from the SAA and acquired by the biotransceiver without dropouts.

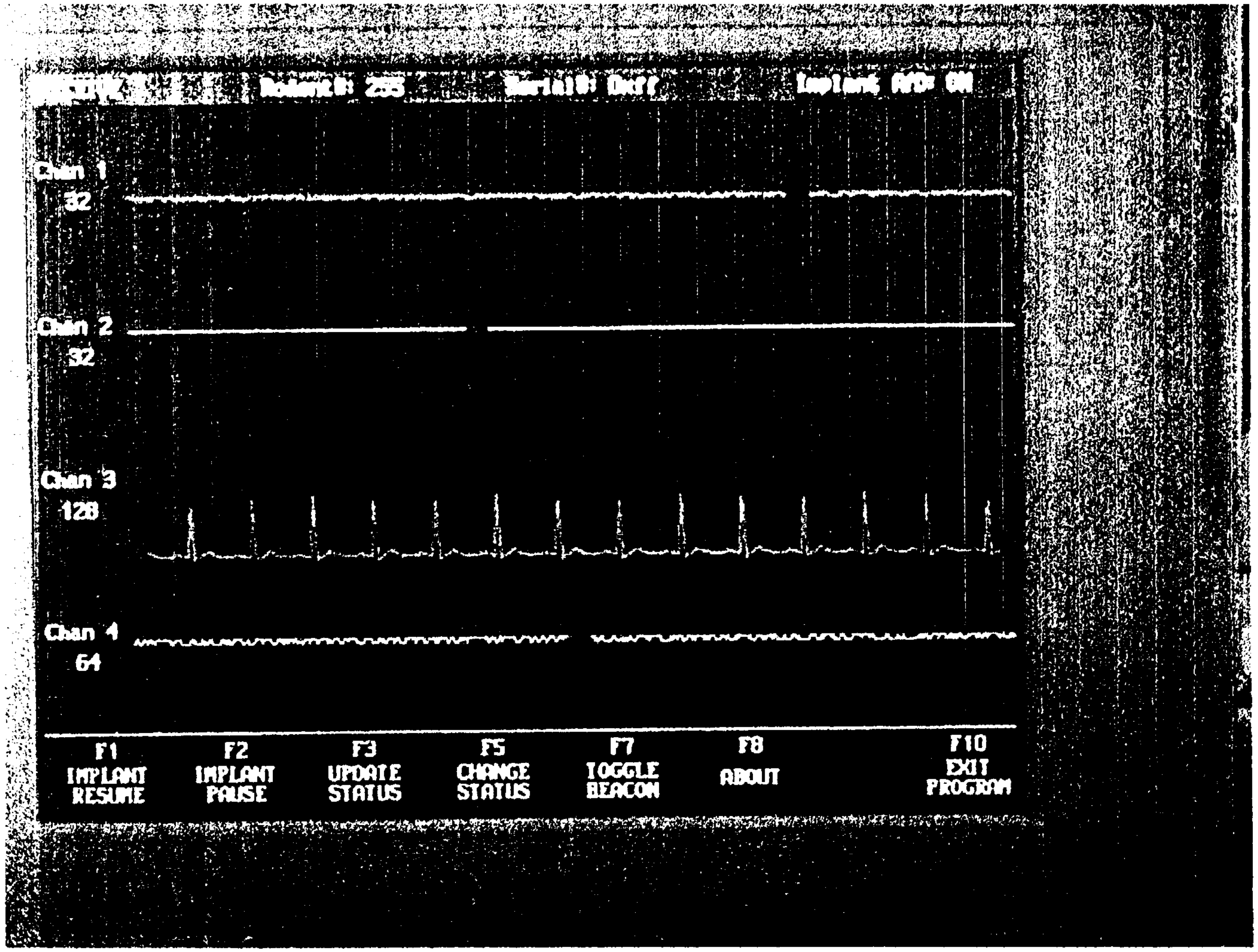


Figure 6: Actual Data transmitted and Acquired Inside the ABTS Metal Animal Cage

Summary

The completion of this phase of the ABTS project demonstrates a successful NASA/University Collaboration. The work has realized a working Biotransceiver system prototype that is a benchmark for future ABTS / AAH project work. The next steps in the development of the biotransceiver system include work in the three system areas of biotransceiver, out-link receiver system (including the septum antenna array system), and integration of the system into the Advanced Animal Habitat.

Biotransceiver future work includes:

- Design an improved Stable, Tunable, FSK Transmitter
- Upgrade Telemeter Microcontroller and Software
- Miniaturization and Packaging
- Design Implant Antenna System
- Decrease Power Consumption

Out-link receiver system future work includes:

- Multiplex multiple Out-link FSK receivers for multiple animal experiments
- Packaging and "Rat-Proofing" the Septum Antenna Array

Integration into the AAH includes:

- Migration of the computer controller interface to a PC-104 Platform
- Packaging
- Electrical interfacing that is compatible with the RF noisy environment of the AAH

A preliminary Timetable for the tasks that need to be done next is presented in **Table 3** that follows this page.

Table 3: Timetable – Next Tasks

Today ↓ (Year 4)

Task	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7
Implant R.F. Transmitter				N			
Update Implant Microcontroller				N			
Design Customizable Implant Signal Conditioners				N			
Migrate User Interface Platform					N		
Miniaturize Implant Circuits					N		
Package Implant Circuits					N		
Incorporate System into ABTS Habitat						N	
Test and Evaluate with Animals						N	
System Verification and Documentation						N	
Project Completion							★