

Antarctic Impulsive Transient Antenna (ANITA) Instrumentation

S. Barwick^a, J. Beatty^b, D. Besson^c, J. Clem^d, S. Coutu^c, M. DuVernois^e,
P. Evenson^f, P. Gorham^{f,g,*}, F. Halzen^h, D. Kiedaⁱ, J. Learned^f, K. Liewer^g,
S. Matsuno^f, C. Naudet^{g,**}, D. Saltzberg^j, D. Seckel^d, and G. Varner^f

^aDepartment of Physics, University of California at Irvine; ^bDepartment of Physics, Pennsylvania State University;
^cDepartment of Physics, University of Kansas; ^dUniversity of Delaware, Bartol Research Institute; ^eDepartment of
Physics, University of Minnesota; ^f Department of Physics & Astronomy, University of Hawaii at Monoa; ^gJet
Propulsion Laboratory, California Institute of Technology; ^hDepartment of Physics, University of Wisconsin, Madison; ⁱ
Department of Physics, University of Utah; ^j Department of Physics & Astronomy, University of California at Los
Angles

ABSTRACT

We will report on the details of the ANITA instrument. This instrument is fundamentally a broadband antenna, which is arrayed and constructed in such a way as to be optimized for the detection and characterization of high-energy neutrino cascades [1]. The requirement to maximize the detector view of the Antarctic ice fields implies low gain antennas yet the need for maximum sensitivity dictates using the highest gain possible. Since the Cherenkov signal increases quadratically at higher frequencies suggesting that the optimal selection is an antenna with constant gain as a function of frequency. The baseline design will be a linearly polarized log-periodic zigzag (LPZZ) antenna.

Keywords: ANITA, neutrino, balloon, Antarctic, Cherenkov

1. INTRODUCTION

The Antarctic Impulsive Transient Antenna (ANITA) mission involves a proposed balloon-borne radio-frequency (RF) instrument designed to detect and characterize radio events arising from GZK neutrino interactions within the 1M km³ volume of Antarctic ice that is synoptically observed from an altitude of 37 km. ANITA will achieve unprecedented sensitivity to the GZK neutrino flux for a relatively modest investment of resources, and will provide an early, low-resolution view of the ultra-high energy neutrino universe.

ANITA measurements will be directly sensitive to established but untested models for many different kinds of high-energy particle astrophysics phenomena. Due to ANITA's ability to achieve extreme sensitivity in a relatively short time frame the mission will act as a pathfinder for high-energy neutrino astronomy.

2. INSTRUMENTATION

Presently, the ANITA instrument is envisioned as a broadband antenna cluster, which is optimized for pulse detection and characterization. The requirement for synoptic observation of all of the ice visible from the balloon prescribes a nearly 2π field of view, implying relatively low-gain antennas. Balancing the needs of maximum sensitivity, wide RF bandpass requirements, and uniform angular coverage demands the use of a unique antenna. ANITA has chosen to use a dual-linearly-polarized log-periodic zig-zag (LPZZ) antenna as the baseline design. These antennas, known since the 1960's [2] are now also being baselined for use as the primary feed antennas for the Allen Telescope Array (ATA). They have remarkably wide bandwidth (up to 20:1, or 0.5-10 GHz in the case of the ATA), and constant directivity gain across these ultra-wide bands.

* Principal Investigator, gorham@phys.hawaii.edu, Univ. of Hawaii at Manoa, 2505 Correa Rd, Honolulu, HI, 96822

** Author, Charles.J.Naudet@jpl.nasa.gov, Jet Propulsion Laboratory, 4800 Oak Grove Drive, CA, 91011, USA

The beamwidth of the antenna chosen is about 60-70 degrees with a gain of approximately 10 dBi. By arranging a cylindrical array of 16 of these antennas, with a downward cant of about 10 degrees, we achieve complete coverage of the horizon, down to within 40 degrees of the nadir, covering most of the observable area. The antenna beams in this configuration overlap well within their 3dB points, giving redundant coverage in the horizontal plane. A second ring of 16 antennas provide a vertical baseline for establishing pulse direction in elevation angle, and additional nadir-pointing antennas complete the array.

The frequency range for the antennas is 0.3 to 1.2 GHz. The lower limit of the range is primarily dictated by limitations of the gondola size and the requirement to have overlapping beams, and the upper end of the frequency range is set to allow for measurement of the spectral rolloff due to increasing attenuation of the ice, which will provide a first-order measure of the depth of the cascade.

Figure 1 shows that basic layout of the gondola and the antennas. There are three separate LPZZ antenna clusters. The two horizon-view clusters consist of two azimuthally offset rings of 8 antennas each. A stack of the two rings is shown as a detail to the left of the gondola in Fig. 1. The two ring clusters view to within 40 degrees of the nadir. A cluster of 4 antennas at the bottom of the instrument then complete the coverage at the nadir. For the two sets of ring clusters at the upper and lower portions of the gondola, the vertical offset is just under 4 m, and provides a baseline for triangulation of the received pulse.

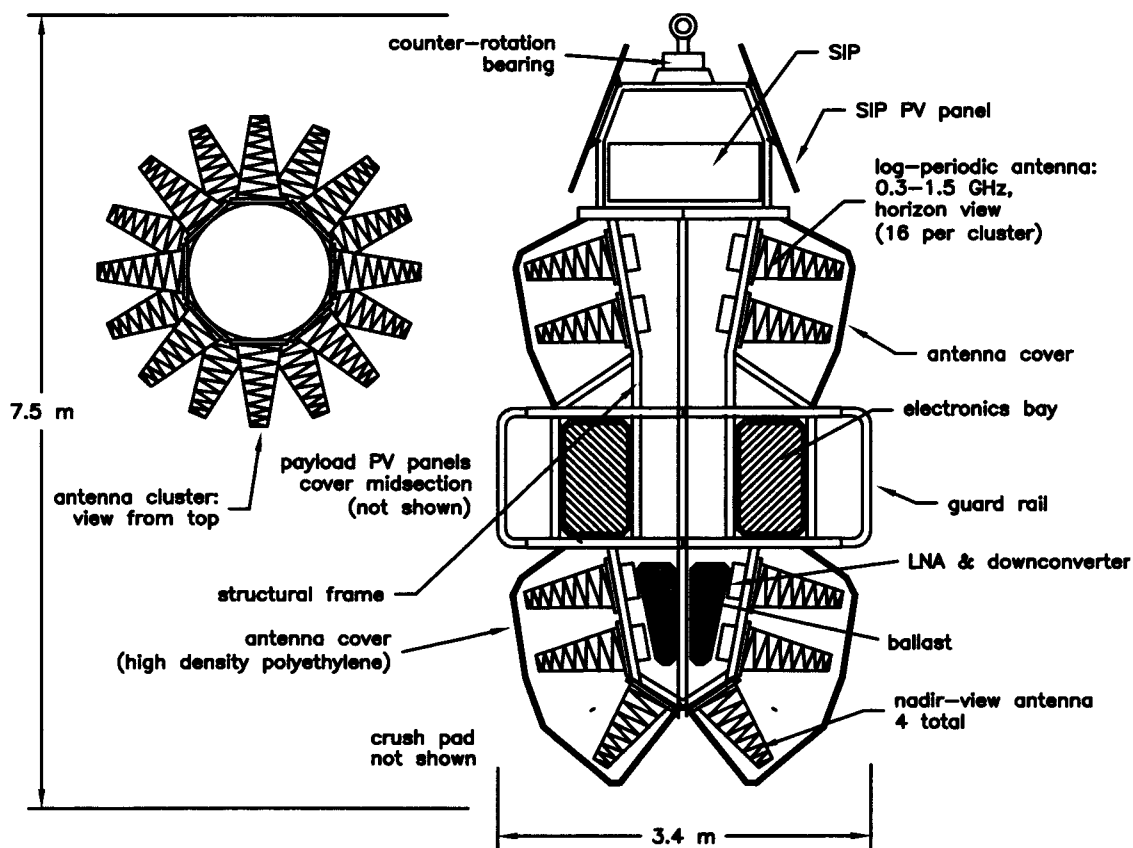


Figure 1. Layout of the ANITA payload showing the antenna geometry. The antenna covers are shown partly cut away for clarity.

Geolocation of the pulse direction is accomplished by different methods in elevation and azimuth. Elevation angle is the most important parameter for determination of the energy of a neutrino cascade, since it is directly related to range. The elevation angle resolution that can be achieved for a pair of antennas separated by baseline B is of order $\Delta\theta = \lambda_{\min}/(2B\sin\alpha)$, where λ_{\min} is the shortest wavelength detected in the pulse, and α the angle of the arrival direction.

of the pulse with respect to the baseline. For $\lambda_{\min} = 0.3$ m and a 3.7m baseline, $\Delta\theta = 2$ degrees near the horizon, which corresponds to a fractional range resolution $\Delta R/R = 50\%$ improving rapidly to about 10% near the edge of the nadir field of view. For the Askaryan process the cascade energy resolution $\Delta E/E \sim \Delta R/R$ because the detected field strength falls off as R^{-1} .

Azimuth angle will be determined to a coarser resolution by amplitude measurements of adjacent antennas which both detect the pulse. The beam amplitude pattern of the antennas will be calibrated before launch to 3-5% accuracy, and this should provide resolution of about 1/5 of a beam (~ 12 degrees) by looking at the amplitude ratio in antenna pairs.

Figure 2 shows the basic layout of the detection and digitization system for ANITA. The dual linear polarization signals from the antenna are converted to dual circular polarization by an internal hybrid (not shown) and these signals are then fed into a first stage low-noise amplifier (LNA). The LNA is not aggressively cooled, since the system noise temperature is several hundred K due to the ice in the field of view. An amplifier noise temperature of < 80 K is assumed. Additional amplifier stages then bring the signals up to a level appropriate for digital sampling.

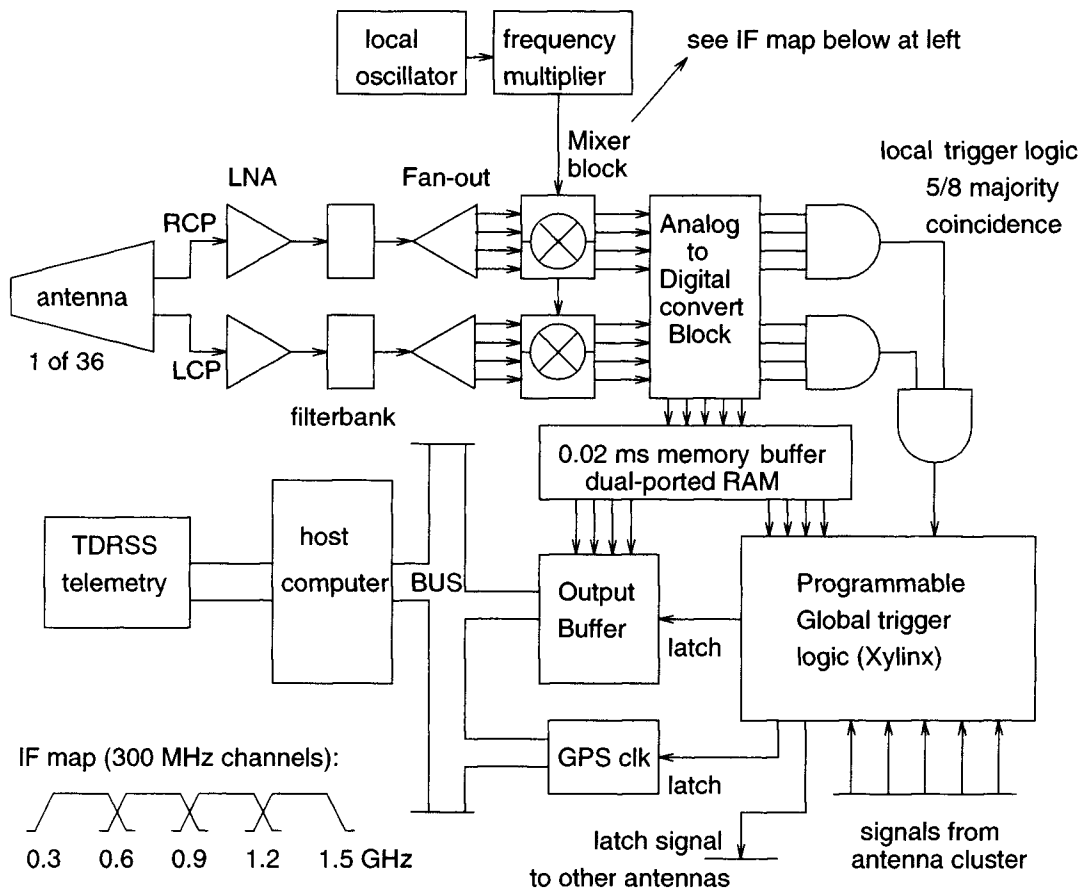


Figure 2. Block diagram of the ANITA detector system. One antenna sub-block is included.

The antenna signals require front-end amplification with a gain of order 35 dB, and a noise temperature of less than 50 K. Such amplifiers are commercially available at a high technology readiness level, and the costs are relatively low. Much of the technology for the RF conditioning has been pushed by the wireless telecommunication industry. Thus we do not anticipate any significant technology development to produce the fully conditioned IF bands for the antenna array.

Because the EMP from a cascade is expected to be highly linearly polarized, we convert the two linear polarizations of the antenna into dual circular polarizations using standard 90 degrees hybrid techniques. This is important since a linearly polarized pulse will produce equal amplitudes in both circular polarizations, and thus some background rejection is gained by accepting only linearly polarized signals.

We have assessed preliminary design issues for the digitizer, and we find again that the approach we have adopted should be straightforward to implement with commercial parts that should not present any significant problems for use at balloon altitudes or in the balloon thermal environment. We have baselined the Analog Devices AD9283 8-bit 100 Msample/second analog-to-digital converter as the basic unit of the digitizer, primarily because it has (unlike other CMOS digitizers) a high analog bandwidth (of order 450 MHz) which will enable us to use several of the parts in parallel to synthesize an 800 Msample/second low-power ADC. This synthesized ADC block will become the IF digitizer block for each of the 300 MHz IF channels per antenna. We intend to implement the trigger logic in Xilinx field-programmable gate arrays. Again the technology readiness for this application is high and the logic requirements for the FPGAs are relatively straightforward and the number of channels being implemented here (288) is not large.

Signals from the antennas recorded by a bank of monolithic 32-channel waveform recorder ICs with triggering, now under preliminary design development. Triggering is provided on-chip by two complimentary means. A high-level threshold allows triggering based on a large signal in a single channel. In addition, multiplicity logic allows for a coincidence based upon a number of channels exceeding a smaller threshold. A 12-bit on-chip ADC, capable of 2M conversions/sec, provides a digital data stream out. Waveform record length is 256 samples per channel, which corresponds to between 128ns to 256ns depending upon sampling frequency, adjustable between 1-2 GSa/s.

As readout can take up to 10ms, deadtime is avoided by the use of multiple chips in parallel, thus providing multi-hit capability. Taking advantage of the low-power and compact size of these chips, in addition to multi-buffering, interleaved sampling at higher effective sampling frequencies or simultaneous logging of multiple Intermediate Frequencies may be accomplished. An external Field-programmable gate array (FPGA) sequences the accepted triggers. This FPGA, perhaps in combination with a downstream digital signal processor (DSP), may be used to zero-suppress noise triggers and channels containing only noise, if required.

We estimate that a trigger based on majority logic over several antennas (as in Fig. 2 above) can achieve a threshold of order 2σ above the thermal noise level for each antenna. At this level the rate of accidental triggers is of order 1 every 3-4 minutes. This basic trigger rate provides a quasi-continuous monitor of instrument health with no risk of data contamination. In fact, thermal noise triggers will not have the required characteristics to emulate the true cascade signals, for several reasons:

- (1) Thermal triggers will not obey spatial and temporal closure relationships among antennas.
- (2) Thermal triggers will not have coherence across the IFs in each antenna. Since the IF signals are coherently recorded, the original broadband pulse can be synthesized from the IF signals. Thermal noise will not be correlated between IF channels.
- (3) The antenna pattern of the trigger will be random for a thermal noise trigger, and the individual antenna response functions will be uncorrelated.
- (4) Thermal triggers will not be able to reproduce the Cherenkov spectrum, which has a distinct phase and amplitude across the band.

Measurement of the plane of polarization of the pulse is also an important part of the available information, since for a cascade, the plane of polarization is defined by the track of the initial particle and the Poynting vector of the radiation. Thus any measurement of the polarization vector of the pulse gives direct information on the projected track direction of the incident particle. The precision in radians of this measurement is of order $1/\text{SNR}$ per antenna. Combining signals from several antennas we expect to achieve precision of < 10 degrees for this measurement on each event. Combining this with the constraints on the track geometry from the other range and angle measurements should give comparable overall resolution on the absolute particle direction. Once the trigger logic has generated a coincidence, the digitizer is

enabled and all of the IF channels are digitized and written out to the host computer which then stores the data and submits it to the telemetry, which is discussed further in the mission implementation section below.

We conclude this section by describing several strategies we plan to employ to minimize RF interference problems. The most effective mitigation strategy in our system will be the requirement for extremely broadband coincidence of a trigger event across multiple antennas, multiple IF frequency bands, and dual polarizations. These requirements effectively force any interfering signal that can trigger to appear very similar to the signal of interest, a subnanosecond, highly polarized pulse. Such pulses are quite difficult to produce in pure form in practice. Although there are high-frequency radar systems that employ such pulses, these are primarily used in microwave systems above 5 GHz. High-power switching transients can produce pulses but they are never completely isolated or band-limited, and tend to produce spectra that fall off at higher frequencies.

Another source of potential interference triggers for ANITA will occur when a narrow or moderately broadband persistent signal appears within one or more of the IF bands and the additional power effectively raises the thermal noise of the band to a higher level. Our response to this is to enforce a so-called *noise-riding threshold* similar to that of the highly successful FORTE satellite [3,4] for our digital comparators. This will allow that particular channel to ride up with the increasing noise level and thus not increase its rate of threshold crossing events. The threshold level will be recorded at a slower rate to ensure that the sensitivity and energy threshold of the instrument can be established as a function of time in post-analysis. Our most fundamental strategy in dealing with interference that passes beyond our hardware front-end filters is to develop frequency agile methods for digital filtering of the signals on each of the downconverted IF bands. Such techniques are mature in many areas of RF and microwave development.

3. MASS AND POWER BUDGETS

Engineering estimates of the mass requirements are shown as an allocation, based on the preliminary instrument and gondola model, in Table 1. The current best estimates (CBE) are based on no particular effort at lightweighting the gondola frame or electronics systems, and we anticipate that we will gain back some margin as the design proceeds and addresses some specific lightweighting opportunities.

ANITA power requirements (Table 2) are relatively high for a balloon mission because of the large number of channels that must be amplified and digitized. We propose to use a solar array of high efficiency (triple-junction) cells in conjunction with a 2x concentrator. The concentrator is not required but reduces the cost by reducing the total number of cells required. The concentrator has a relatively flat response in one dimension out to +/- 10 degrees and then drops rapidly. This axis would be along the direction that is stabilized. The solar array would have a cosine response in the other dimension. The variations in the solar height during a flight will introduce variations in the power by less than 2%.

The battery system is intended to fulfill several functions. The batteries will provide power from the time ground power is disconnected until the solar panels are operational. The batteries will also provide power for the attitude control system to enable return to Sun point for the solar panel and they will allow some data to be taken if the solar panels fail. The battery system is currently planned as a bank of Li/Thionyl Chloride primary batteries with 29 kw-hrs of capacity. This is sufficient power to run the instrument for 24 hours.

A second solar array and a second set of batteries are flown on the gondola as part of the SIP. This hardware powers the balloon control system, and the telemetry system. The designs for this hardware exist and have been flown many times. This solar array and power system for the SIP will be provided as part of the support costs paid to the NSBF.

In Table 2 we show the summary of the mass and power budget values, including a 20% reserve on the science instrument and gondola. No reserves are held on the NSBF supplied equipment (ballooncraft in the table) since these are measured values. The present margins on the totals are also shown.

System -- Subsystem -- item	Mass Estimate (Kg)
Science Payload	1078
Gondola	381
Ring antenna mounts	103
Nadir antenna mounts	11
Photovoltaics	18
Batteries	58
Crush Pads	6
Structure/strongback	186
Instrument	556
Antennas	95
Digital electronics	241
RF/IF electronics	200
Power electronics	20
Science Reserves (15%)	141
Balloncraft	604
SIP	172
LDB Batteries	27
Ballast system	237
LDB photovoltaics	59
LDB antenna system	18
Rotator	91
TOTALS	1684

Table 1. The ANITA Mass Distribution

Instrument Subsystem	Current Best Estimate (W)
RF receivers	140
LO + RF distribution	26
Digital Electronics	616
Sun sensors	15
TLM & HK	50
Rotator	15
Conversion electronics	88
TOTAL	950

Table 2. ANITA power estimates.

We do not anticipate any stringent control or knowledge requirements on the balloon attitude and pointing during the mission. We have specifically designed ANITA to be insensitive to orientation to first order, since the antennas themselves have a wide angular response. Since the highest precision we can attain at present in angular knowledge is of order 2-3 degrees, we require knowledge of order 1-degree tilt angle with respect to the local gravity vector. This allocation thus adds no more than 10% uncertainty to our overall elevation angle determinations. Since balloon gondolas do experience pendulations, we will require an update in this knowledge at a rate of order 10 times the highest pendulum frequency to avoid any possibility of aliasing the tilt measurement. We anticipate an update rate of order several Hz will be required. Control of the tilt direction is not necessary as long as the tilt amplitude does not exceed 10 degree, and we

do not anticipate tilt amplitudes of this magnitude. Control of the azimuth is also not required at any level more stringent than 10 degrees, and this should be easily accommodated by a standard sun-pointing anti-rotation device.

SUMMARY

The technology employed by ANITA is largely mature and we do not anticipate any significant technology development issues. Even within a single 10-day Antarctic flight ANITA is capable of providing the first detection of cosmogenic high-energy neutrinos. ANITA represents a novel approach to neutrino astronomy which is itself a relative newcomer to the astrophysics discipline.

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