Proposal for a Rapid Test Array (RTA)

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1. Motivation

Current LWA scientific requirements (Memo 49 & 70) call for ~52 stations comprised of $N_a = 256$ stands each. This is consistent with the estimated collecting area per station (A_e) required for calibration (Memo 52) of N_a ~176, roughly independent of frequency. Estimates of mutual coupling effects (Memos 73 & 75) applicable for the sparse, pseudo-random array geometry proposed for LWA-1 (Memo 35) suggested this criteria might not be achievable except relatively close to the zenith. A pending memo (aka Memo 52 Redux) that accounts for impedance mismatch efficiency with respect to both system temperature (T_{sys}) and A_e appears to allay that concern. It suggests N_a ~ [252,99] stands at [80,20] MHz, respectively, at $z \sim 74^{o}$, consist with the current design for LWA-1 being viable from a calibration standpoint.

However Memos 73 &74 also predict that mutual coupling from a sparse, pseudo-random array will impose deterministic, correlated perturbations on the phase response of individual antennas (see Figures 3 & 4, Memo 75) in LWA-1. The expected consequences on the primary beam, owing in part to its nonlinear response to the expected geometric phases, may pose a significant risk to astronomical calibration and related measurements including direction of arrival determination and spatial nulling. In that case, a significant re-design of LWA-1 to increase the number of stands and employ mutual coupling to stabilize the station primary beam response might be desirable (see again Figures 3 & 4, Memo 75). The consequences of such a redesign could be major, e.g. requiring analog beam-forming to mitigate the explosive cost of additional digital receiver chains. Moreover, with CDR for LWA-1 scheduled for late 2008, it is unlikely that the 256 element array envisaged in LWA-1 (Memo 35) will emerge soon enough to evaluate its performance and make the *in situ* measurements required to determine whether a significant re-design is warranted.

Alternatively, the situation can be viewed as follows, in which either of the following hypotheses holds true:

Hypothesis A:

The LWA stations will work as expected if built using broad band dipoles (e.g. Big Blades or Forks) over small (3m x 3m) ground screens using the NRL pseudorandom array pattern with 4-m spacing. Working "as expected" entails:

- Having an effective area at zenith ($z=0^{o}$) reasonably close to 256 times the theoretical expectation for a single dipole: $A_e = G*\lambda^2/(4*\pi)$, where G is the gain as obtained from electromagnetic (e.g. using NEC) simulations

- The effective A_e/T_{sys} should degrade no faster than geometric projection and primary beam expectations (i.e. COS (z) times the individual dipole pattern response).

- Having impedance characteristics similar to those of an individual dipole. If the simulated and measured impedances of an individual dipole are found to differ significantly, we need to determine to what extent these impedances change when the dipole is placed in the environment of the other dipoles in a station.

- Having a main and sidelobe station primary beam pattern that is predictable out to some acceptable level. It is difficult to determine an astronomical requirement on sidelobe levels. It depends upon how well CLEAN or other algorithms can be made to operate on real data from the system, and those depend on factors beyond the characteristics of any individual station, e.g. on the u-v coverage of the entire array. We successfully CLEAN 74 MHz VLA maps that have 10 to 30% sidelobe levels.

Hypothesis B:

Mutual coupling effects among the large number of elements, particularly at frequencies below 40 MHz where the effective apertures of the elements approach overlap, cause a breakdown in one of the assumptions listed in Hypothesis A. Cleverly taking these collective effects into account in the design of the stands and station (e.g. by significantly increasing the number of stands and/or changing their distribution) may yield a significant improvement in the collecting area, frequency dependence, and/or stability and predictability of the station primary beam response.

If Hypothesis A is correct, we should build LWA-1 as outlined in the Memo 35 plan. If Hypothesis B is correct, we need to do more simulations and measurements in order to come up with the optimal element and station designs.

To address this challenge, we propose a Rapid Test Array (RTA) field able in advance of LWA-1 PDR (early 2008) to provide experimental evidence to prove one of the hypotheses. The RTA would consist of ~300 moveable stands that could be deployed in either pseudo-random sparse or condensed geometries. The key goal is to obtain the empirical measurements required to either validate or repudiate the hypothesis that mutual coupling effects will drive a serious redesign of LWA-1. The RTA must be designed and deployed as cheaply and quickly as possible, with no intent for long-term maintenance or operation. All hardware through the back-end, except the antennas, will be developed with the minimum requirement to obtain results pertinent to addressing the mutual coupling question. If possible, the antennas will be designed so that a modest upgrade can provide the stands required to field LWA-1 after CDR (i.e. to realize antennas comparable to one of our leading prototypes, e.g. the Forks in LWA Memo 88.)

We propose to deploy the RTA at the LWDA site (or at an alternate site for LWA-1 if available) utilizing UNM labor available during Summer 2007, and to bring it on line as an engineering test instrument that can address the mutual coupling uncertainties by the end of Fall 2008. If serendipitous technical or science opportunities emerge naturally they can be pursued, but only if they do not significantly deter from the main technical goal of obtaining field measurements of mutual coupling effects from an array large enough to be comparable to subsequent LWA stations.

2. RTA Conceptual Design

Two types of measurements are planned, first, impedance and mutual coupling measurements on dipoles in the station while immersed in the environment of the other resistively-loaded dipoles of the station and, second, phase and amplitude measurements of the response of selected dipoles to radio sources, again with the dipole immersed in the environment of the station. In order to examine the response of a single dipole it is necessary to reduce the effects of large angular scale Galactic emission. It is proposed to do this by operating the selected dipole as an interferometer with a grating array that will respond only to bright, small diameter sources such as Cas-A and Cyg-A. However, the interferometric response will also be perturbed by ionospheric effects. Therefore, we propose to monitor these ionospheric effects by simultaneously operating interferometers between the grating array and three dipoles arranged in a triangle short distances outside the main station (far enough outside to assure immunity from mutual coupling effects).

A schematic overview of the RTA required to obtain these two types of measurements is shown in Figure 1. It will consist of two stations of stands, hereafter RTA-1 and RTA-2. All stands in both arrays, initially, will be modeled after 4-wire ASTRON dipoles. This design provides structures that can be modeled with errors low enough to make comparison of field measurements with EM predictions reliable. Later, extra wires may be added to all stands to make them into the FORK design of LWA Memo #88.

RTA-1 will consist of 259 stands, 256 of which will initially be deployed in the "main station" according to the pseudo-random geometry anticipated for LWA-1, but moveable so that alternative geometries can explored. 255 of these 256 elements, hereafter the "passive elements" of RTA-1, will be passively loaded with resistors and hence require no baluns, cables, or power. 4 stands of RTA-1, hereafter the "active stands", will employ active baluns. Three stands (elements 257-259), with active baluns, will be placed outside of the station to monitor ionospheric refractive effects that might otherwise compromise the measurement of mutual coupling effects. A 4th front-end (balun & cable), effectively the 256th stand of the main station, will be slowly cycled through successive elements of RTA-1, leaving them "active" for a sufficient period to obtain the required field measurements.

The three ionospheric monitoring dipoles would be placed in fixed locations just outside the array, far enough outside (≥ 15 m) that mutual coupling would be negligible. The deviations in the phases of the fringes from these dipoles (when multiplied against the signal from RTA-2) would be used to determine the magnitude and direction of an ionospheric refractive wedge, or to determine when the ionosphere is too disturbed for a simple wedge to be a reasonable approximation. Knowing the wedge one could then determine what the phase of the test dipole should be in the absence of ionospheric refraction, leaving any residual deviations to be attributable to coupling effects.

In its initial configuration, RTA-1 will be fully carpeted by ground screen, simplifying the ability to compare measured results with predictions of theory and numerical simulations. The four cables from the active elements will bring signals back to the LWDA trailer for further processing, including analog filtering, additional gain, and digital sampling. Figure 2 provides a schematic of the receive chain for both RTA-1 and RTA-2.

RTA-2 will be a linear EW grating array offset ~300 m south of RTA-1. It will consist of 32 “active” stands (identical to those in RTA-1) that will each require baluns, power, and cabling. The signals from all 32 stands in RTA-2 will be combined via a set of successive 4:1 power combiners to produce a single EW grating response that will be brought back by a single longer cable to the LWDA trailer for further processing, including analog filtering, amplification, digital sampling, and cross correlation with the signals from RTA-1.

Passive Impedance Measurements: These will require a network analyzer to sample the self and mutual impedances of sample elements within RTA-1. In principle, using a network analyzer we could measure the mutual impedance between each of the 256 array elements and its 255 companions. This would be tedious in the extreme but, in fact, only the nearby elements need to be measured. The more distant ones are at essentially random separations and their effects can be estimated stochastically. Once the nearby elements have been measured for a number cases (in particular, for interior and edge elements) it should be possible to develop an algorithm that could be applied to any element to estimate the coupled impedances. If we consider transmitting a signal into the array and applying a phase gradient across the aperture we can use these measured self plus coupled impedances to estimate the dipole currents and the radiation pattern of the whole array. Possibly one may wish to iterate this process but, since the coupled signals are 20 to 30 dB below the impressed signal even for nearby dipoles, any iteration should converge quickly.

Interferometer measurements: RTA-2 will be operated as a linear EW grating array whose single output can be successively multiplied against the 4 active elements in RTA-1. This will require a digitally controlled 4x1 analog RF switch, into which the signals from the 4 active elements of RTA-1 are fed. After the switch the single signals from RTA-1 and RTA-2 each follow identical paths through 2 analog filters, 2 amplifiers, 2 samplers, and then are cross-correlated via a two element software correlator. The individual stands in RTA-2 will be separated enough to generate sufficient grating lobes (main beam plus 2 grating lobes within $z = 45^\circ$) such that the interferometer response from the multiplication of the signal from RTA-2 with the signal from any single active element in RTA-1 will provide fringes on bright sources at a variety of azimuths and elevations. For grating lobes at 45° from the meridian plane, one would need a dipole spacing of $2^{0.5}\lambda$. We therefore adopt a stand spacing of $s = 5.3$ m * [$80/\nu$ (MHz)] for the antennas of RTA-2. The receive chain will be designed so that the system will be front-end noise dominated. The phases, after ionospheric correction, will be compared to theoretical predictions and the results of numerical simulations, with the aim of quantifying our knowledge of the degree and character of the mutual coupling effects. If field measurements confirm predictions, then the degree to which the effects of mutual coupling may place successful wide-field astronomical calibration at risk for the full LWA can be determined, and corrective action (i.e. redesign) taken if warranted.

3. Parts

3.1 Antennas

- Parts: 300 antenna assemblies, each consisting of
    - 1.5 m PVC mast
    - Cap consisting of a PC board with antenna mounting studs (or and active balun and studs)
    - Wire dipoles with eye lugs
    - Bungee cords and stakes to attach to ground
    - Assorted mounting hardware
    - 4 tent stakes
- Labor
    - Protoyping at NRL: Erickson, Hicks, Schmitt, Polisensky
    - Manufacturing at UNM: Gerstle et al.
- Cost: ~$30/antenna x 300 = $9K

3.2 Baluns

- Parts: 50 active baluns (36+14 spares) for RTA-2 + 4 active antennas of RTA-1
    - Develop at NRL
        - Labor ~1 week of NRL in house development (Hicks) before it can be shipped to Teletech for a production run
            - R&D will benefit run to PDR/CDR for final LWA-1 balun, independent of RTA exercise
        - Cost:~$15K
- Parts: 300 passive baluns for RTA-1
    - Develop at NRL and farm out to Galaxy electronics
        - $7 each in quantities of 300: $2.1K

3.3 Ground Screen (GS)

- Parts: 1 full station GS for RTA-1, 32 postage stamp GS for RTA-2
    - RTA-1: Need 170 500’x5’ rolls ($80/roll) to pave station footprint
        - ~$14K for one, ~$28K to criss-cross two layers
    - RTA-2: 32 3’x3’ postage stamps
        - ~$1K
- Labor: UNM – Gerstle et al.
- Cost: ~29K

3.4 Cables & power combiners

- Parts

    - 4x100m cables for RTA-1
    - 32x125 m cables & 1x500 m cable for RTA-2
    - Power combiners (mini-circuits)
        - 4 ea – 8 way - ZCSC-8-1 @ $120 = $480
        - 1 ea – 4 way - ZB4PD1-500 @ $ 80 = $80
    - Comments - all cables will be deployed above ground
- Labor: none – order cables from Beltsville Applied Specialties, power combiners from MCL
- Cost:
    - Cable: LMR-400: 500 feet = $590.00 ($424.21 wholesale = 85 cents/ft
        - 3281 feet = 1 km ~ $2.8K
        - ~$14K for ~5 km of cables
    - 21 4 way power combiners: $1.7K
    - Total: ~$16 K

3.5 Backend Electronics

- Parts
    - 4x1 digitally controlled RF switch – MCL ZSWA-4-30DR $120
    - One 2-element software correlator & desktop computer – $5K
    - 2 samplers: GaGe CompuScope 14200: 200 MHz, 14 bits, $6K each
        - An in house GaGe board will be used to verify coherent sampling of the two channels
    - 2 sets of analog filters ahead of amplifiers and samplers: ~$1500/each
        - 5BT-30/76-5-N/N: $1375.00
        - 5BT-24/48-5-N/N: $1775.00
        - 5BT-15/30-5-N/N: $3500.00
    - 2 amps – MCL ZFL-500HLN, NF=3.8 dB, IP3=30 dB, G=19 dB, $100
    - 2nd Desktop computer (post correlation processing) - $5K
    - Power supplies as needed - $1K
- Labor: design by NRL (Ray & Erickson) and VT (Ellingson)
- Cost: ~$29K

3.6 Cost Summary

- Antennas: $9K
- Baluns: $17K
- Ground Screens: $29K
- Cables & Power Combiners: $16K
- Backend electronics: $29K
- **Total costs: ~$100K**

4 Siting

Deployment of RTA-1 following the current 100-m footprint design of the pseudo-random distribution anticipated for LWA-1 is problematic at the current site because of the obstruction by the LWDA. Either accommodation has to be made to expand the current (requiring permission, additional fencing, and associate site preparation labor and costs), or another site has to be adequately developed in advance of RTA deployment. The latter is probably impractical to execute within Summer 2007. The simplest option might be to deploy RTA-1 within the formal (fenced) confines of the LWDA site, and to simply exclude deployment of the 16 passive elements that would otherwise be installed at the site of the current 16 LWDA antennas. (In this scenario, the current LWDA antennas would be left in place as is.)

A suitable location for RTA-2 is also required. At 80 MHz $2^{0.5}\lambda$ stand separation implies a ~170 m EW array, but exceeds 0.5 km at 20 MHz. If the latter is impractical, at lower frequencies we may need to use fewer than 32 stands – this decrease is offset by the increased collecting area per stand at lower frequencies.

5 Deployment

A prototype antenna will be developed at NRL and shipped to UNM. Gerstle et al. can implement suggested modifications and thereafter proceed to manufacture 300. Deployment of the array, including baluns, ground screens, and cabling will be done by UNM. In late Summer 2007 a team from NRL and VT will visit the site and initiate the engineering measurements, that can thereafter be completed by UNM.

6 Schedule

Start date: June 25, 2007. Complete RTA construction and initiate measurements in early August (to coincide with NRL/VT site visit), complete measurements by end of Fall 2007. UNM to modify schedule based on available resources & in house estimates.

General remarks: We estimate in the following order the time required to execute needed activities, in decreasing order:

1) Surveying the positions of the antennas will probably take the most time. Our guesstimate that it will take ~3 weeks can certainly be improved upon by Walter Gerstle. We emphasize that the antenna positions need to be correct only to ~1" accuracy. We do need an overall reference frame for the RTA (i.e. an accurate North-South reference) accurate to ~1 arc-minute.
2) Laying the ground screen – again, Walter will probably have a better estimate of the time required.
3) Deployment – the realistic pace will likely only be known after it is started, but once the positions are known and the ground screen laid, we think this could proceed rather quickly.
4) Fabrication of the antennas, since they are so trivial in design, should be very quick.

- Antennas
    - NRL: Fabricate Mark I prototype antenna

        - 0.5 days (June 25)
    - NRL: Document with photographs & sketch – send to UNM (Gerstle)
        - 0.5 days (June 28)
    - UNM: Design Mark II based on Mark I design
        - Field worthy, e.g. possible use of UV resilient PVC, other suggested improvements
            - 4 days (excl. July 4) – (July 2-6)
    - UNM Concurrent Tasks
        - Task I: Build 300 Mark II field-worthy stands
            - Assume 2 workers build 30 stands per day => 15 stands/person/day
                - 300 stands/5 = 20 worker days
            - Assume 6 workers available => ~7 days
            - 50% overhead – complete ~July 15
        - Task II: Survey Antenna Positions & Lay Ground Screen
            - Start consecutively with Task I, complete ~July 20
- Antenna & Cable Deployment
    - Complete by Jul 28
- Backend Development – NRL & VT
    - NRL and UNM to coordinate acquisition of required hardware
    - NRL to coordinate with VT on design, assemble and test at NRL
    - Completed system to be shipped from NRL to LWDA site in time for ~July 28 field visit
        - Allows ~ 4 weeks for development
- Field measurements
    - Initiate field measurement during July 28 – Aug 4 site trip by NRL & VT.
        - Demonstrate passive impedance measurements
        - Demonstrate interferometer measurements
        - Initiate ionospheric calibration measurements
        - Make effective collecting area measurements of both imbedded and isolated stands
    - Measurements to be completed by UNM by end of Fall 2007.

7 Postscript

We briefly update this proposal based on feedback from the System Engineer (SE) and Executive Program Director, and our own internal discussions.

7.1 We have received approval to move forward with the RTA. A notable criticism is that while useful, there is general doubt that the interferometer measurements will lead to any clear cut discrimination between hypothesis A or B. However, a benefit of the RTA not emphasized in the proposal is for gaining more experience in methodology for testing the bona fide LWA-1. Thus, the main value of the RTA exercise might lie in developing test infrastructure and methodologies, e.g. suggesting that RTA-2 be left in place for LWA-1 testing. Also, the benefits of an ionospheric model generated by the "3 ionospheric stands" (together with RTA-2) might offer significant technical and programmatic benefits beyond the narrower goal of removing refraction from the mutual coupling measurements. These points suggest that development of RTA-2 and the active elements of RTA-1 take precedence, with the decision to populate the full 256 elements of RTA-1 subject to revision based on the formal pace of LWA-1 PDR & CDR activities.

7.2 The SE notes the hypotheses discussed in the beginning of proposal address the per-element vs. per-station ground screen issue, however the proposal mentions only per-station ground screen measurements. It might be advisable to include measurements of isolated stands, otherwise is should be made plain that the proposed work, as currently described, will not answer the per-station vs. per-stand question(s).

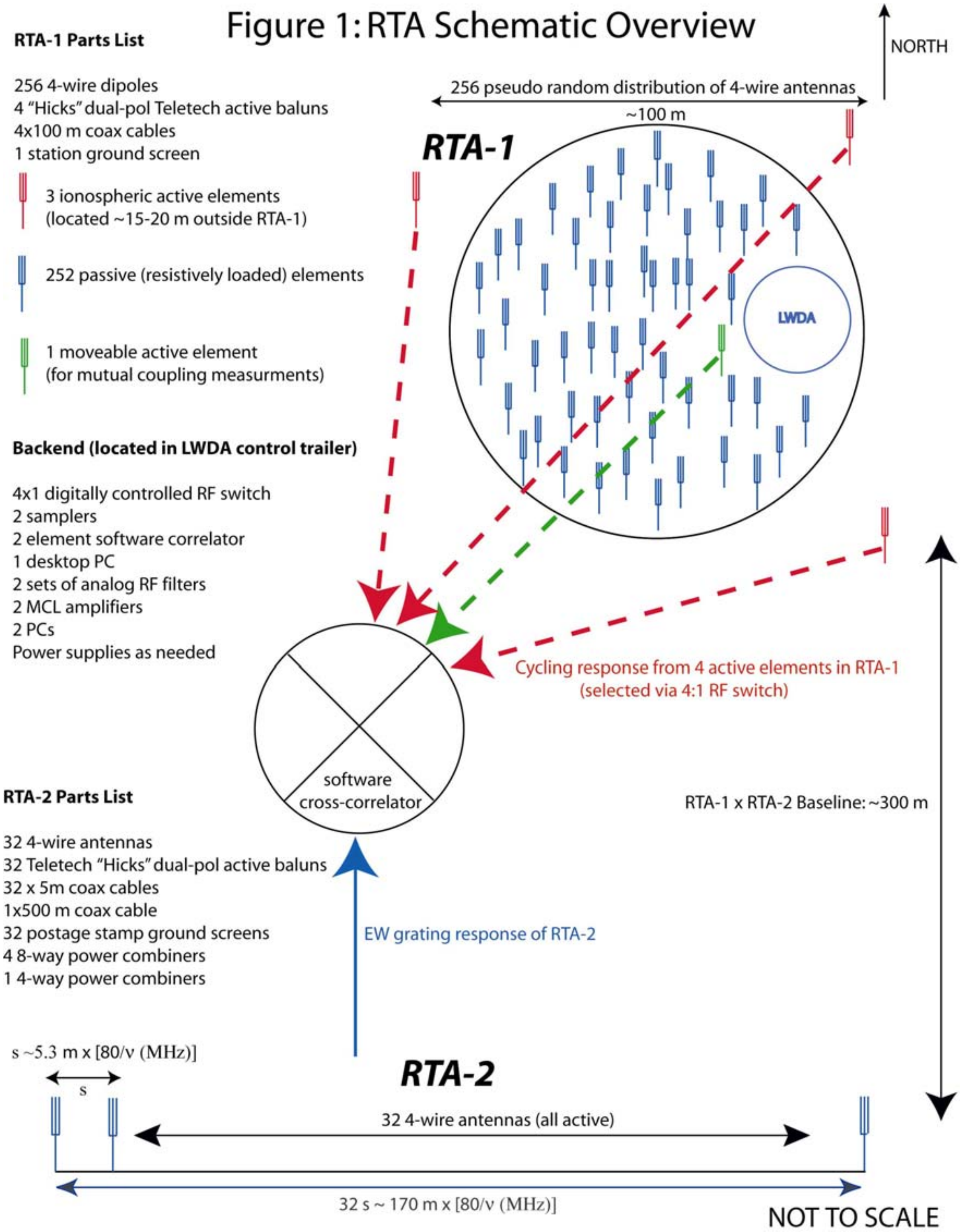
7.3 The SE felt that 19 dB gain for the receivers will be too low unless the A/D ENOB is really 12 bits and the SFDR is outstanding, and suggests planning for 30-55 dB to be sure.

7.4 The SE had concerns about the risks of implementing the digitizer stage of the backend in a timely manner. We share his concerns, but note that our need to employ a nominal observing bandwidth of only a few MHz may relax some of the time synchronization burden relative to operating at an instantaneous bandwidth equivalent to the fully sampled RF.

7.5 We recognize now that the maximum EW dimension of RTA-2 might become unmanageable at the lowest frequencies. Hence we are considering deploying RTA-2 as a 2-dimensional array of 8x4 stands, or in another more condensed geometry.

7.6 An additional useful task is to constrain the effective collecting area of both isolated and imbedded dipoles from measurements of Cas A and Cyg A whose absolute flux densities are known.

Figure 1: RTA Schematic Overview



RTA-1 Parts List

256 4-wire dipoles
4 "Hicks" dual-pol Teletech active baluns
4x100 m coax cables
1 station ground screen

3 ionospheric active elements
(located ~15-20 m outside RTA-1)

252 passive (resistively loaded) elements

1 moveable active element
(for mutual coupling measurments)

Backend (located in LWDA control trailer)

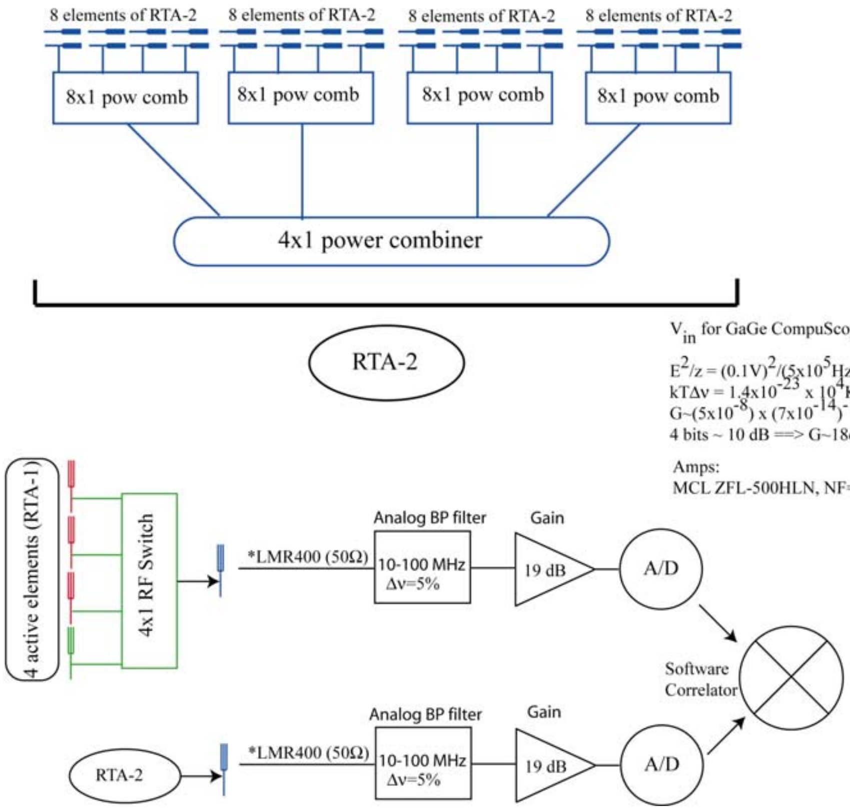
4x1 digitally controlled RF switch
2 samplers
2 element software correlator
1 desktop PC
2 sets of analog RF filters
2 MCL amplifiers
2 PCs
Power supplies as needed

RTA-2 Parts List

32 4-wire antennas
32 Teletech "Hicks" dual-pol active baluns
32 x 5m coax cables
1x500 m coax cable
32 postage stamp ground screens
4 8-way power combiners
1 4-way power combiners

* All cabling LMR400uF

Figure. 2: RTA Receive Chain



V_{in} for GaGe CompuScope 14200 sampler: 100 mV@0.5 MHz

$E^2/z = (0.1V)^2/(5x10^5 Hz) = 10^{-2}$ x $0.5x10^{-5} = 5x10^{-8}W = 500mW$
$kT\Delta v = 1.4x10^{-23}$ x $10^4 K$ x $5x10^5 Hz = 1.4$ x $5x10^{-14} = 7x10^{-14}W$
$G \sim (5x10^{-8})$ x $(7x10^{-14})^{-1} \sim 10^6 \sim$ 60dB - 32dB = 28dB
4 bits ~ 10 dB ==> G~18dB - assume 19 dB gain needed

Amps:
MCL ZFL-500HLN, NF=3.8, IP3=+30, G= 19 dB $100