<u>Vertically Scanning Doppler Radar for NOAA's G-IV Aircraft - A Concept Paper</u>

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Background

NOAA's Aircraft Operations Center (AOC) owns and operates a Gulfstream G-IVSP high altitude jet aircraft, primarily used to collect atmospheric data in support of National Weather Service (NWS) forecasting. As configured currently, the aircraft is instrumented for in-situ measurements and expendable atmospheric profiling probes (GPS Dropwindsondes). One of the G-IV's primary missions is to collect data in the environment of Tropical Cyclones and send that information to be assimilated into hurricane track forecast computer models. The next generation of computer model, the Hurricane Weather and Research Forecast (HWRF) model, is currently under development. HWRF requires detailed wind and precipitation structure data to initialize its model runs. AOC has been funded to instrument the G-IV to provide these wind and precipitation data to HWRF. A project plan was developed and approved, calling for (among other instruments) a vertically scanning Doppler radar to provide wind measurements in regions of detectable hydrometeors.

Measurement Requirements

The HWRF model requires wind and precipitation data to initialize its forecast computation. Since HWRF is still in the developmental stages, specific resolution and accuracy requirements have not been determined, but are expected to be similar to dropwindsonde accuracies of ~2 m/s. Initially, HWRF will be working with data on a 10-15 km horizontal grid, with future versions requiring grid resolutions of 4 km or less. Vertical resolution requirements are 5 km, with 1 km vertical grids expected in future enhancements. As can be seen in Figure 1, a typical strong hurricane (this is Hugo in 1989 as a Category 5 storm) can have eye diameters (including the eyewall) of about 40 km. If the G-IV can not penetrate the storm, it should at least have the capability to map the inner core wind field from just outside of the core region.

Radars can only measure wind data when there is a detectable reflectivity return from a sampled volume. The determining factors are the reflectivity characteristics of the particles, the power and frequency of the radar transmitter and the sensitivity and 'noise floor' of the receiver. Particles in a hurricane environment range from large rain drops and graupel particles shafts in the eyewall and rainbands to thin cirrus layers composed of small ice crystals in the outflow layer.

The following table summarizes some of the basic desirable characteristics required for this radar:

Parameter	Desired Characteristic
Reflectivity	Accuracy ~1dBz
Radial Velocity	Accuracy ~1 m/s
Maximum Unambiguous Range	> 50 km
Maximum Rotational Rate	at least 10 rpm (60°/sec) (to provide target horizontal data spacing of 1.5 km)
Maximum Sample Gate Length	150 m

Horizontal winds will be calculated from the intersecting forward and aft looking beams in a traditional pseudo-dual-Doppler technique. Accuracy of the calculated horizontal winds is a function of beam geometry. The target is <2 m/s at a 0° (horizontal) elevation angle. Accuracy degrades as elevation angle increases, due to vertical wind and particle fall rate velocity contamination.

Measuring winds near the surface are problematic because any sea surface return contaminates the velocity measurement of particles just above the surface that are in the same sampled bin. One way to measure surface winds is by using the strength of the surface reflectivity return as an indicator of surface roughness, and to deduce surface winds from that. This is the technique used by the stand-alone scatterometer instruments installed on the P-3's, and should be a target feature on the G-IV system.

Conceptual Model of the G-IV Radar System

The G-IV radar system is envisioned to be similar to other tail-mounted meteorological research radar systems. Two examples are the systems installed on the NOAA P-3 Orion aircraft and the National Center for Atmospheric Research's (NCAR's) Eldora system, currently installed on a Naval Research Lab (NRL) P-3. For this discussion 'P-3 Radar' will refer to the NOAA system. AOC has the most experience with the NOAA system, so it will be used as the primary reference. The NOAA P-3 system consists of an X-band (9.3 Ghz) magnetron-based transmitter with a peak power of about 60 kW, an antenna system, a receiver system which mixes the returned signal to an Intermediate Frequency (IF), digitizes the IF, derives In-phase (I) and Quadrature (Q), and calculates reflectivity (Z), velocity (V), and spectral width (W) for each sampled range bin. The computed values are sent to a minicomputer for recording, display and transmission to other computers over a Local Area Network (LAN).

There are two interchangeable antenna options, a parabolic dish with selectable tilt (tilt defined as fore or aft of the plane perpendicular to the aircraft track) and a dual back-to-back flat plate antenna, where only one plate is active at any time. The beam pattern for the flat plates are oriented so one has an elevation (angle referenced to a plane perpendicular to the aircraft heading) of about +20° and the other about -20° (see Figure 2). Alternately selecting each flat plate produces a fore-aft scan pattern to provide two dimensional Doppler data as depicted in Figure 3. The parabolic antenna can perform a similar scan pattern by alternating the tilt angle, a function built into the antenna control unit firmware.

The G-IV aircraft flies at about twice the true airspeed of the P-3's. To achieve horizontal data spacing similar to the P-3 system (1.5 km - see Figure 3), the concept proposes to simultaneously transmit forward and aft looking beams. The G-IV system would have two pulsed transmitters feeding back-to-back flat plate antennas mounted in a tail cone. The same antennas would receive signals and feed two receivers, which would digitize the signals and pass them to one or two processor units to derive one dimensional (along the radar beam) particle velocities, along with reflectivity and spectral width. Figure 4 shows a conceptual block diagram of the radar system electronics and Figure 5 shows the conceptual tail antenna and beam pattern. Since the G-IV flies about twice the speed of a P-3, the dual R/T scheme gives the same spatial resolution, assuming that the antenna rotation rate is the same as the P-3 system (10 rpm).

System Characteristics

As with the P-3 and Eldora systems, it is expected that the system will operate in the X-band aeronautical radar band (9.3 Ghz, 3.22 cm). This is a compromise between the greater penetrating capability of lower frequencies and the smaller antenna size requirements of higher frequencies. Reflectivity returns in an intense rain shaft or hurricane eyewall can exceed 50 dBz, and higher frequencies (e.g. Ku-band) would have unacceptable signal loss from all targets beyond the first feature.

The beam size, rotational rate, pulse duration, pulse rate, sampling rate and averaging scheme are all factors in determining the size of a discrete sample volume. As a reference, the P-3 system has a 1.9° antenna beam, rotates the antenna at 10 rpm, operates with either a ¼ µsec pulse at a rate of 3200 pulses/sec or a ½ µsec width at 1600 pulses/sec. With the new RVP-7 processor, it will sample at 50 meter intervals along each ray, can average two or more samples into a combined bin, and typically will average 32 pulse returns into a single ray. This averaging results in a basic measurement accuracy of ~1 dBZ for reflectivity and ~1 m/s for radial velocity, which is the desired accuracy for the G-IV system. The P-3 system can stagger the pulse rate at ratios of 2:3, 3:4 and 4:5 to extend the Nyquist velocity folding interval. It will be able to use the random phase characteristic of the magnetron transmitter to detect and subtract 2^{nd} trip echo contamination. All of these characteristics provide a research quality radar system. The operational requirements of HWRF are less demanding, but to make the G-IV system useful for other applications, meeting or exceeding the P-3 system specifications should be a goal.

Antenna, Beam Pattern and Radome

The concept is for two flat plate antennas mounted back-to-back on a single pedestal, fed by individual waveguides. The assembly rotates vertically through 360° at a nominal rate of 10 rpm. The flat plates are either physically canted at off of the perpendicular axis, or designed so that the beam pattern points off axis, in either case at about 20-25°. Figure 5 shows a conceptual view of the antenna assembly, along with possible beam angles.

The beam pattern is dependent on antenna size and transmit frequency. At X-band, a 30" flat plate will produce a 3° beam, a 48" diameter plate will give a 2° beam width. The primary trade-off in this decision is beam size (smaller is better) vs aerodynamic drag from the radome (less is better). A graph of these two parameters will be required to decide what the best antenna size is. This study, along with the actual radome design and fabrication, modifications to the aircraft, and certification of the installation should be done by a vendor with access to the mold line drawings, tail structure information and airflow analysis of an unmodified Gulfstream IVSP aircraft. The antenna shape can either be circular or elongated. There is almost no drag penalty for an elongated antenna, so the decision is primarily cost (a circular flat plate may be commercially available vs an expensive custom design).

One of the important considerations in the antenna design is pressurization (or lack thereof) along the transmitter pulse path. Waveguide power capacity at G-IV's operating altitudes (40,000-45,000 feet) is about 10% of the rated capability. As an example, WG-90 (a typical X-band) waveguide has to be derated from 200 kW to about 20kW peak power. An antenna may be even more limited. Options include pressurizing some or all of the antenna subsystem, or accepting a transmit power limitation.

Transmit Power and Transmitter Technology

The P-3 and Eldora systems use a very high power pulse to maximize the return from very weak targets and to provide for some return through heavy attenuation. Although a 60 kW system has worked very well for the P-3 and Eldora systems, lower transmit power may be acceptable. A 20 kW system (see the antenna discussion) would have about 5 dB less transmit (and therefore received) power. Lower transmit power will affect system performance primarily in two areas: shadowing due to intervening attenuation, and reduced coverage in very low reflectivity regions. Shadowing will not occur very often, even in high reflectivity rainbands and eyewalls, but may affect some of the most critical data (hurricane inner core measurements). Reduced coverage in areas of cirrus and other low-density ice crystal regions may significantly reduce the volume with reportable wind measurements. Very low power systems (like commercially available solid state systems) provide acceptable information for weather avoidance of significant (>30 dBz) targets, but would be unacceptable for surveying large areas of weak return.

There are four transmitter technologies considered: Solid State, Klystron, Traveling Wave Tube (TWT) and Magnetron. As stated, commercially available solid state transmitters do not have enough power. Custom solid state systems are being designed for military applications, but may be prohibitively expensive. Klystron systems have the power capability, but are very large, expensive, and somewhat inefficient compared to other options. Klystrons (and TWT's) are RF amplifiers, taking a known signal and boosting the power while maintaining phase and frequency stability. Multiple pulses at slightly different frequencies ('chirps') can be transmitted without decreasing the unambiguous range of the system, a technique used in the Klystron-based Eldora system. TWT's are lower power (and cost) cousins to Klystrons, with a maximum power output of about 20 kW. If the system is power limited due to antenna and waveguide characteristics, TWT's are an alternative to consider. If there are no power limitations, TWT's do not provide enough advantages to outweigh their inherent power limits. Magnetrons are high power free-running RF oscillators. The transmit frequency is determined by the design of the RF cavity, and can change with air pressure and temperature. To keep a stable frequency, a magnetron transmitter should be mounted in the pressurized cabin. For a dual transmitter system, magnetron tubes will have to be selected so that they do not interfere with each other. Magnetron systems cannot do multi-frequency chirps, but the pulse-to-pulse phase variation can be used to detect 2nd trip echo signals.

Receiver Subsystem

There are several commercial receiver systems available; a custom processor solution is also an option. While one of the most critical subsystems, the receiver section will most likely be an off-the-shelf unit. Using the P-3 system as a reference, one option is to mix the RF signal with the output of a Stable Local Oscillator (Stalo) down to IF, then sample the IF with a high speed digitizer. A digitized sample of the transmit pulse is used by processing software to separate the received IF samples into I and Q components. These are then fed into a pulse pair algorithm to derive reflectivity, velocity and spectral width for each bin along the ray. The division of work between the dedicated processor subsystem and the host computer (typically PC based) varies, but the trend is to simplify the unique components in the system. Filtering, averaging, and processing algorithms have migrated to software, so required and desired features can be customized.

Processor and Control

A host processor unit is required for the concept receiver system. Ideally, one host system will handle the dual R/T outputs. The receiver system, combined with a host processor, produces data for each bin along a ray. Those data must be recorded on the host computer for post-flight processing and archive. Although AOC currently uses Digital Audio Tape (DAT) as the primary recording media, technology advances in optical media (DVD) and reliability of hard disk drives may make these storage methods acceptable alternatives. AOC is also working on wireless LAN technology to stream archive data to a ground-based system as the aircraft is parked near the hangar after a flight.

During the flight, the data must streamed over a LAN to other computers on the aircraft for compositing and combination with other data types before being transmitted to ground systems for assimilation into forecast models. Real time display of the data in Range-Height Indicator (RHI) format is required for qualitative monitoring by on-board personnel. Ideally, this would be available as a LAN-based product. Dual display panels (one for each R/T) would be easier to interpret than the interleaved display currently available on the P-3's. Real time removal of aircraft velocity from the displayed image is also desired.

System control consists of starting and stopping the transmitters, setting transmit pulse parameters (width, pulse rate, dual PRF mode), setting receiver parameters (bin size, averaging, filters) and setting the antenna rotational speed. Ideally, this would be accomplished with a LAN-based window available at any networked computer on the aircraft.

Airborne Considerations

There are many issues related to an airborne system which are not applicable to the design and operation of a ground-based radar. The nature of the environment (altitude, shock, vibration, pitch, roll) must be considered in the construction of all components. The installation must be FAA certified, either with a field approval (8110-3 and 337) or more likely, a Supplemental Type Certificate (STC). The radome and any other external structure must be designed to minimize flutter, drag, and airflow distortions. It is likely that these structures must undergo a lifetime fatigue analysis. Other information and procedures, including maintenance, inspection, repair techniques and flight limitations, must be generated.

The operation of an airborne radar system poses another set of challenges. One of the most important aspects is defining the position and velocity of particles in each bin of a ray. The aircraft position and attitude must be combined with the antenna's position relative to the aircraft to define each bin's location with respect to the earth. Similarly, the velocity of the antenna must be determined and subtracted from the Doppler measurement to derive true particle velocity. Navigation data from the aircraft consists of a high speed (25 Hz) feed from the inertial system and a low speed (1 Hz) feed from a Global Positioning System (GPS) unit, both available on ARINC-429 avionics busses. The inertial data provides better velocity measurements and is the only source of aircraft attitude. The GPS provides more accurate absolute positional data, albeit only once per second. There are several methods of blending these two data types, but the required end result is a way of tagging the radar data with antenna position and velocity.

Maintenance and Support

The system will be used in support of operational requirements. AOC's reliability model is to minimize down-time, provide for in-flight repair where practical, and use commercially available parts and subsystems when possible. Fully redundant or fail-operational systems are generally not required, but systems should be designed to minimize mean time to repair. The G-IV can operate from several locations while chasing a storm, and usually must carry spares on board, rather than set up a fixed maintenance and storage facility. For a system as critical as the tail radar, AOC would plan to carry spares for all major components that could be replaced in flight. If the R/T subsystem is packaged into a single box, a third unit could be carried in a dummy mount. There is a common computer type used for most systems on the aircraft, so that by changing a removable hard disk and some interface connections, a secondary display system can take over for a failed primary data collection computer. If the tail radar system is able to use this same computer type (a ruggedized, rack-mount PC running either Windows or Linux), only the specialized interface cards would need a spare set on board. Most remote operating locations have 1-2 day delivery service for parts not carried in a fly-away spares kit.

In the field, maintenance facilities can be very limited. There is usually a ladder available, but not a forklift or crane. Again, using the P-3 as reference, normally there would be facilities in the field to open a radome and replace a motor, but not to remove the radome and/or antenna. The system should be designed with ease of replacement in mind, especially for high failure rate items like motors.

AOC has some capability for RF testing and calibration. Current P-3 radar systems are designed to be maintained by AOC, with little or no support required from the manufacturer. AOC would anticipate setting up a ground mockup system (single R/T) at the Tampa facility for repair, calibration and future development.

Summary

To support NWS and other NOAA users, AOC needs to add remote wind measurement capability to the G-IV aircraft. A proposed concept is to install a vertically scanning Doppler radar system similar to the tail radar systems that have been used successfully for many years by NOAA and NCAR. The system would be the primary wind measurement instrument for the G-IV's support of the HWRF computer model requirements. It would also be able to provide data for research scientists and for weather projects other than hurricanes. The system may serve as the prototype for the next generation of airborne weather radar, both as a retrofit to aging systems on existing aircraft and to add capability to new research aircraft.

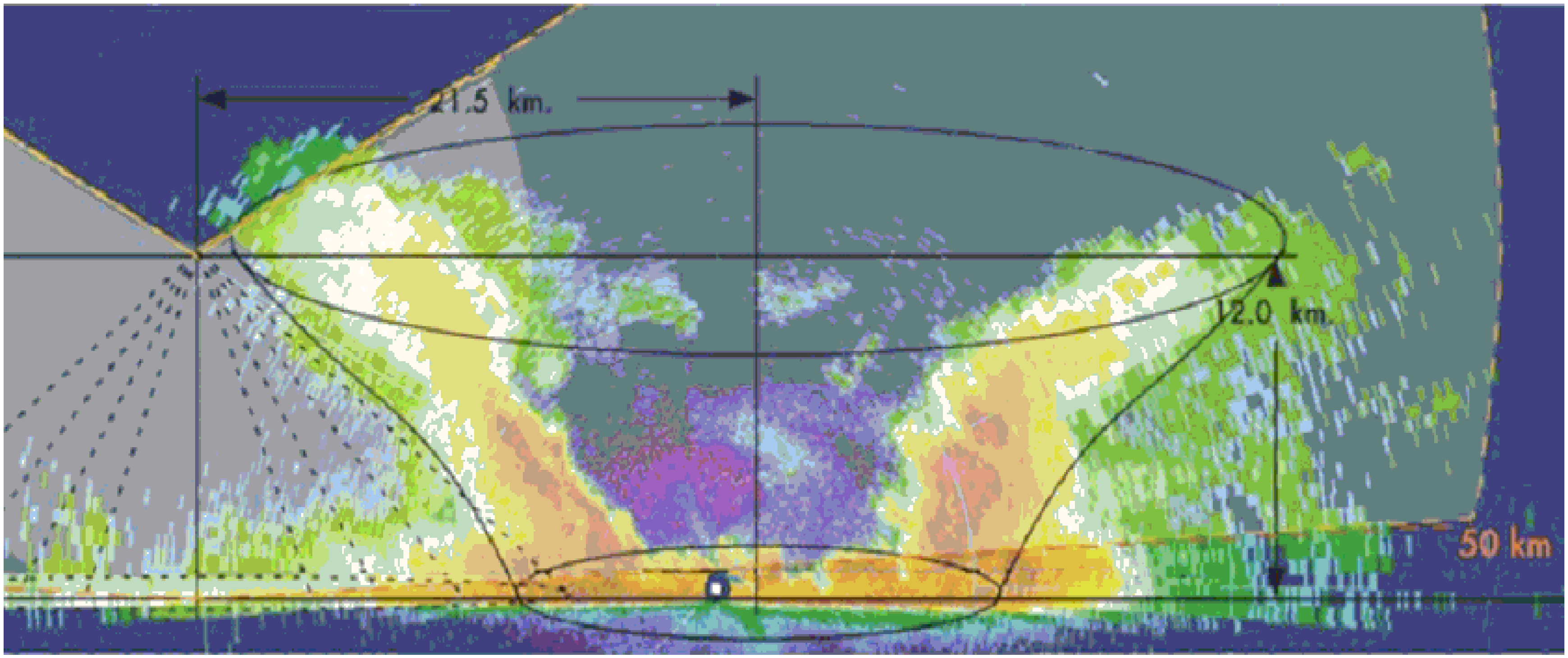

Figure 1

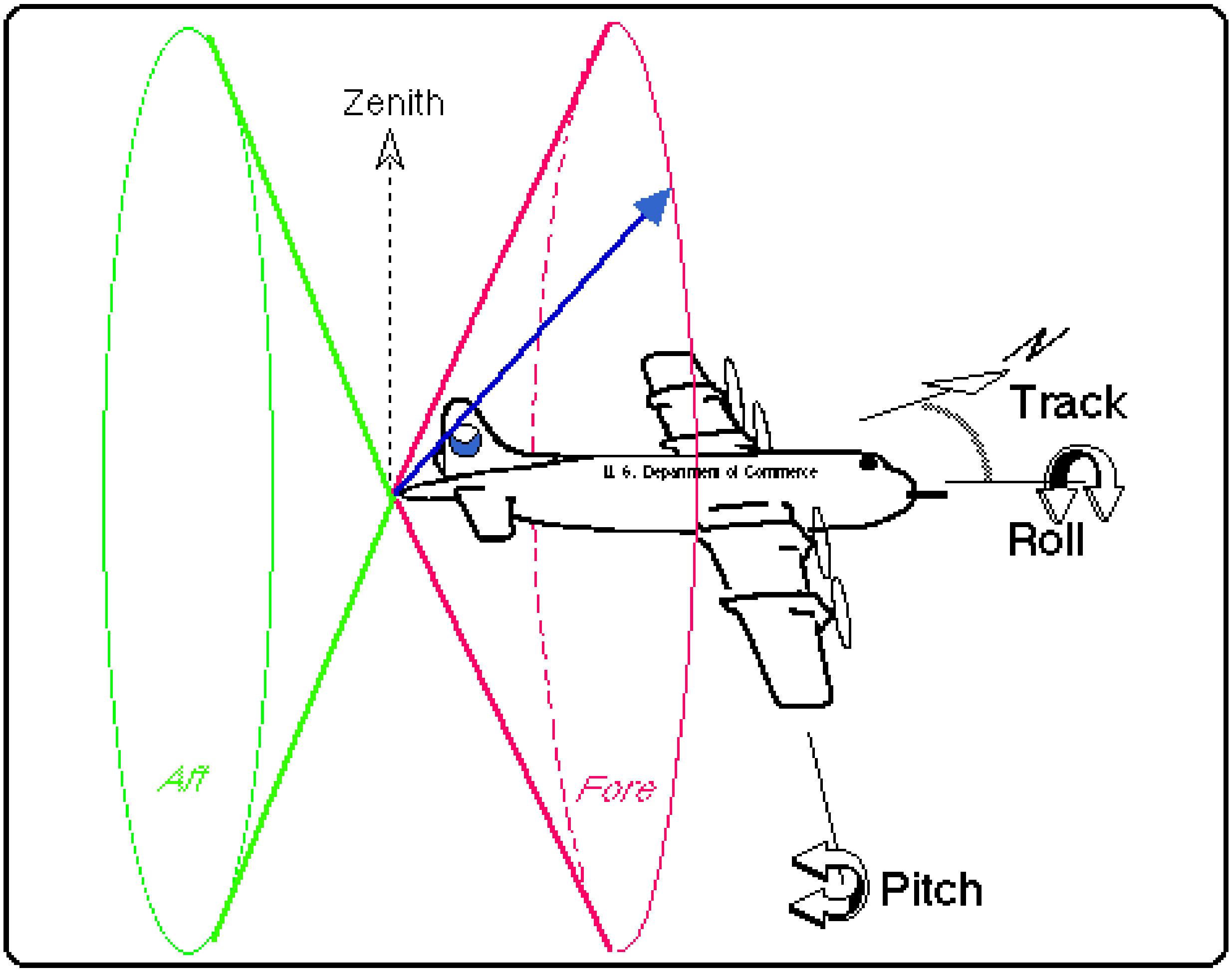

Figure 2

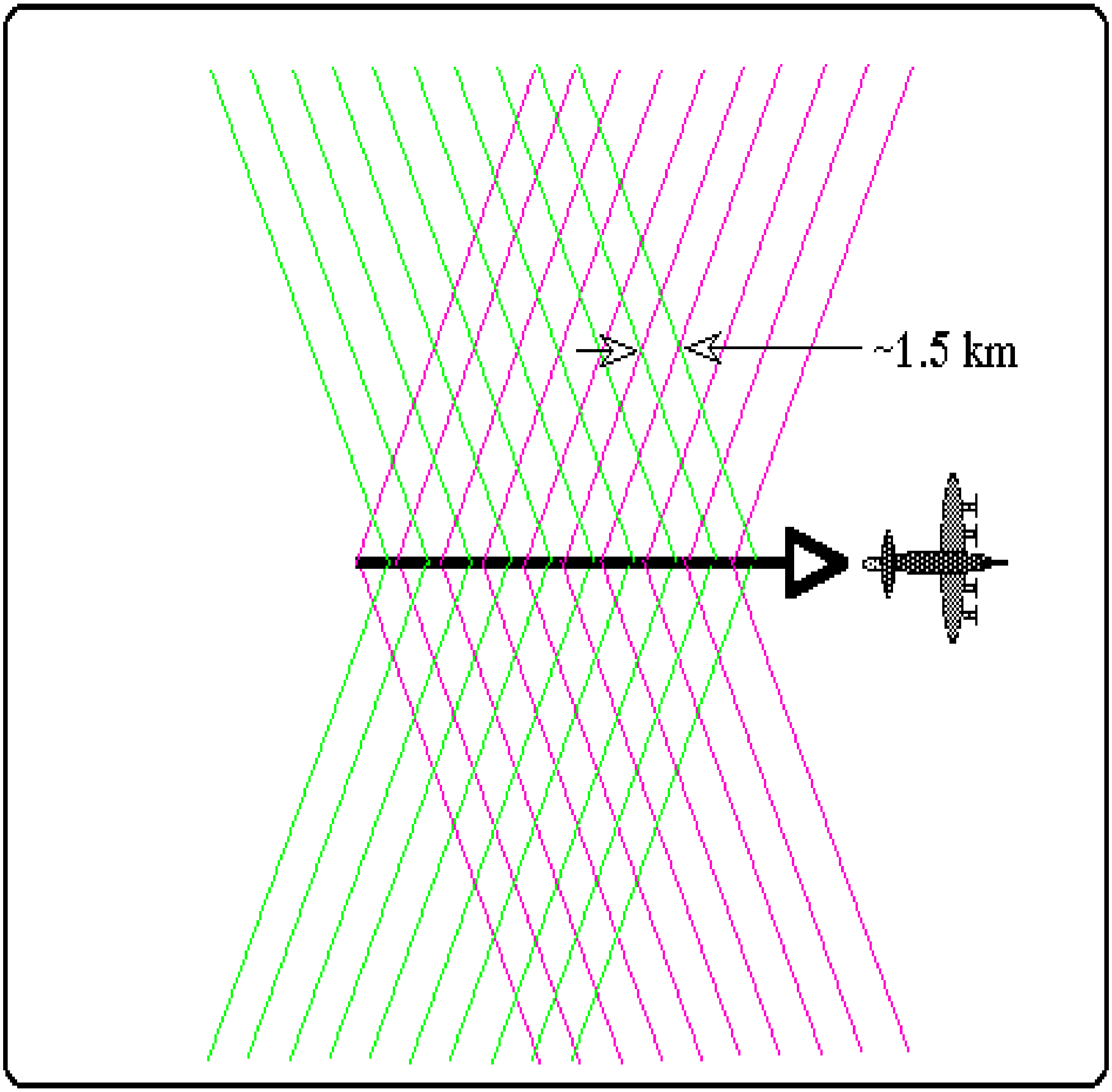

Figure 3

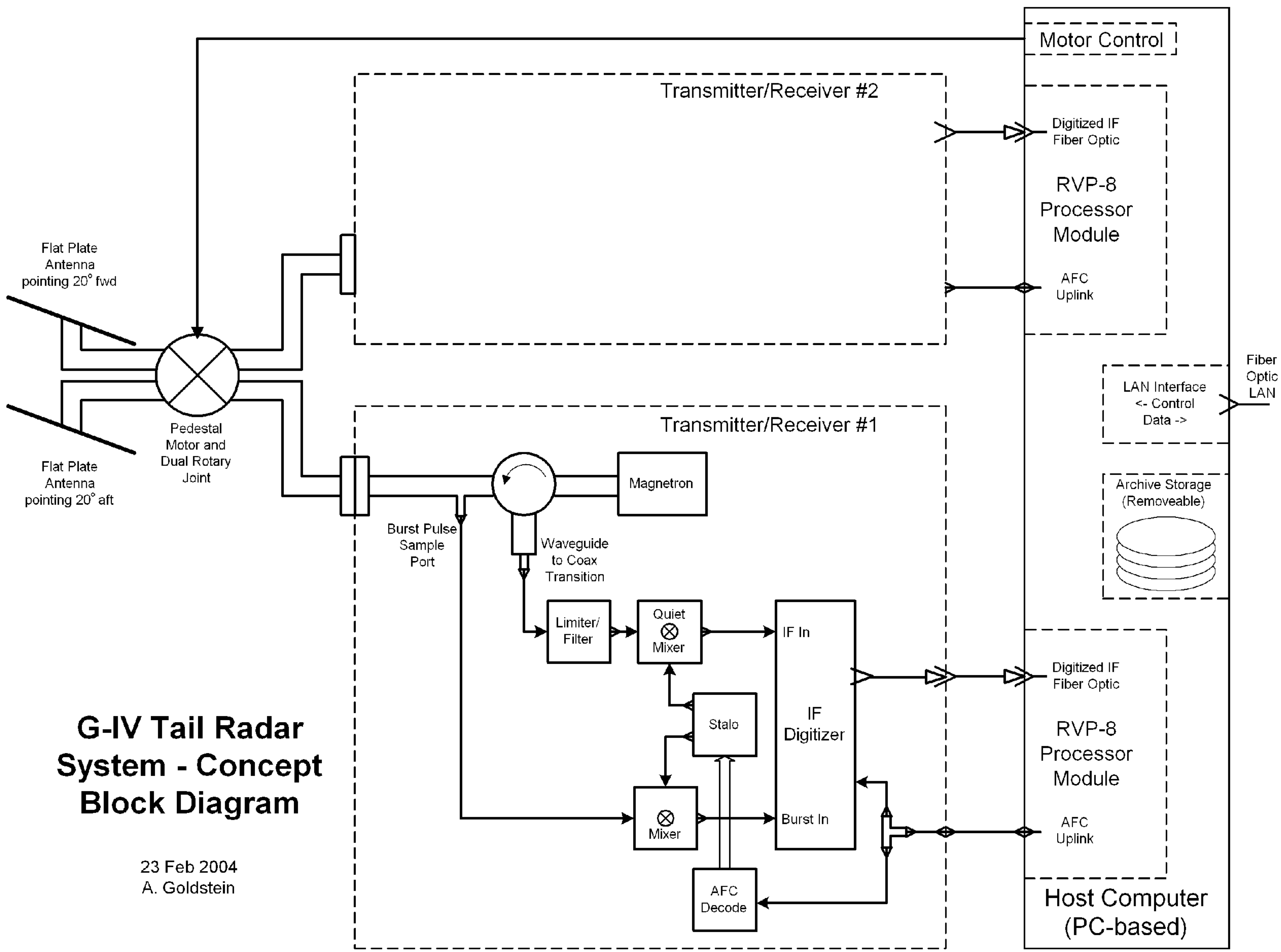
Motor Control
Transmitter/Receiver #2
Digitized IF Fiber Optic
RVP-8 Processor Module
AFC Uplink
Flat Plate Antenna pointing 20° fwd
Flat Plate Antenna pointing 20° aft
Pedestal Motor and Dual Rotary Joint
Fiber Optic LAN
LAN Interface <- Control Data ->
Archive Storage (Removeable)
Transmitter/Receiver #1
Magnetron
Burst Pulse Sample Port
Waveguide to Coax Transition
Limiter/ Filter
Quiet Mixer
IF In
IF Digitizer
Burst In
Stalo
Mixer
AFC Decode
Digitized IF Fiber Optic
RVP-8 Processor Module
AFC Uplink
Host Computer (PC-based)
G-IV Tail Radar System - Concept Block Diagram
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Figure 4

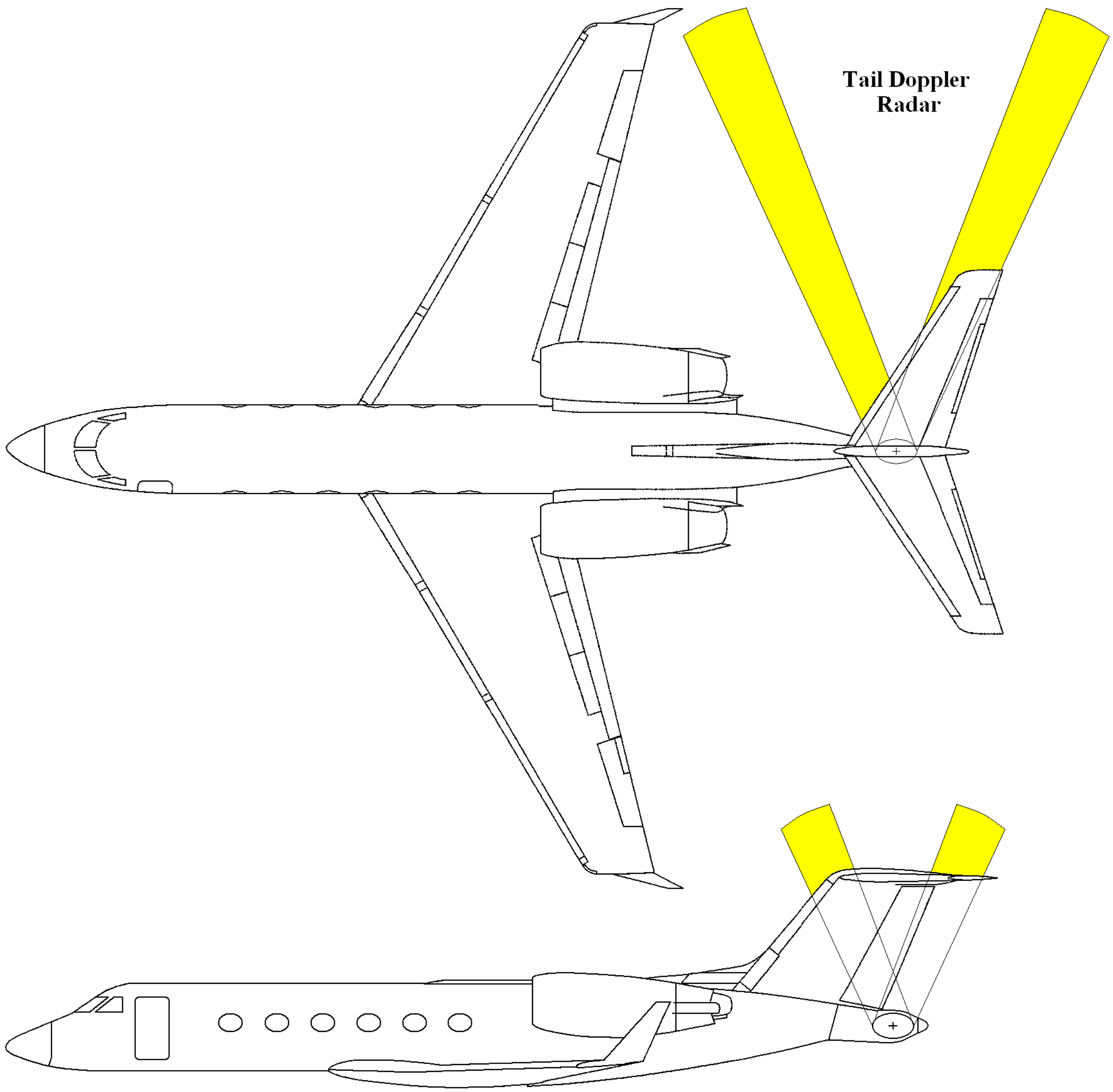

Figure 5