ernet link, the other one processes a subset of radar data in real time and sends the processed data products to ground through a satellite downlink. A multi-function I/O card is used for radar control and house keeping data communication. The digital receiver hardware is very similar to that of CRS (see Section 1.1.3). HIWRAP also uses a dedicated high-speed navigation system that provides precise platform position/altitude information on the local network. Radar status information, scanner position, navigation data, and radar data are collected and saved on a solid state disk array by the host computer.

*1.1.5 **ER**-2 **X**-band **R**adar (EXRAD)*

Following the successful development of a compact, light weight successor to EDOP was initiated in 2004 for studies of tropical storm formation using the Global Hawk Unmanned Aerial System (UAS); this radar would become ER-2 X-band Radar (EXRAD). EXRAD operation has combined precipitation radar and scatterometer objectives for measuring both the 3D cloud/precipitation structure and surface winds with fixed nadir and conical/cross-track scanning beams (Fig. 1.9). Although the cross-track scanning capability is useful for coordinating with cross-track radiometers on the ER-2 payload, the cross-track scanning configuration has only seen limited use. The first version of EXRAD was flown between 2014 and 2022 with a 9 kW peak power TWT transmitter that was more compact and lighter than its predecessor. EXRAD shares a number of key subsystem technologies with HIWRAP and CRS, including the power distribution unit, digital receiver, and data system.

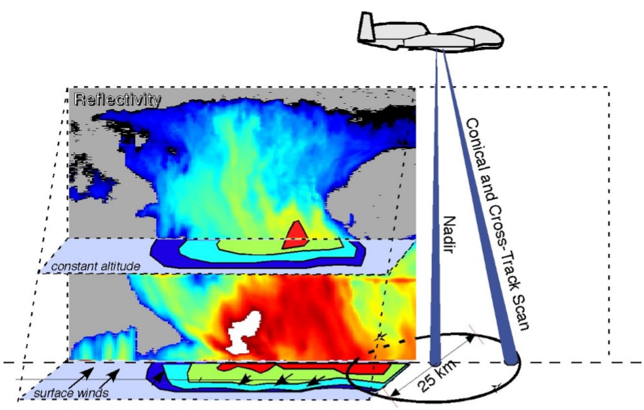

Figure 1.9 EXRAD measurement concept showing two beam geometry. The white shades in the image are reflectivities exceeding 50 dBZ.

In contrast to the pair of differently-polarized conical scanning beams of HIWRAP, EXRAD uses a 0.66 m diameter slotted waveguide antenna with a single linear polarization for a conical/cross-track scanning beam plus a second 0.66 m linear polarized slotted waveguide antenna for a nadir beam. Despite this difference, the wind retrieval algorithms (Section 1.5) are similar between EXRAD and HIWRAP, although the presence of a nadir beam on EXRAD enables direct measurement of vertical Doppler motions. The EXRAD antenna setup is also an improvement over the pair of fixed-angle beams employed by EDOP, which were only capable of providing the vertical Doppler motion and the along-track horizontal wind component (Section 1.1.2).

The development of EDOP, CRS, and HIWRAP provided considerable experience with autonomously-operated high-altitude radars. The design approach for EXRAD focused on maximizing the use of off-the-shelf components and shared technologies, developed through the other NASA high-altitude radars, to reduce development and maintenance costs without compromising the performance of the system. This was aided by advances in the commercial availability of a number of the subsystems that had previously been custom built for previous high-altitude radars. Furthermore, EXRAD was designed to use the same ER-2 nose section that had been used by EDOP. Figure 1.10 shows the configuration for the EXRAD antennas in the ER-2 nose.

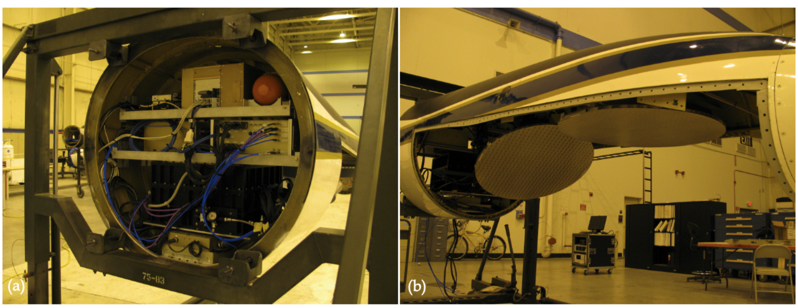

Figure 1.10 EXRAD configuration in ER-2 SLR nose. Two flat plate slotted waveguide antennas are used for a fixed nadir pointing and a scanning beams.From [12]. Published 1996 by the American Meteorological Society.

Since its completion, EXRAD has been successfully flown for a number of field campaigns on ER-2 and Global Hawk (Figure 1.3). During the 2022 Investigation of Microphysics and Precipitation for Atlantic Coast Threatening Snowstorms (IMPACTS) field deployment, the EXRAD TWT transmitter started to show issues with its aging high voltage power supply and the TWT tube. An upgrade was initiated to replace the TWT transmitter with a 900 W compact and light weight SSPA, which enables higher transmit-duty-cycle operation for pulse compression and versatile waveforms. A new digital unit with a high speed digital waveform generator and a digital receiver modules has also been adapted to replace the previous Virtex-5 FPGA-based digital receiver.

than the standard ER-2 nose. Being the first weather Doppler radar built for use on a high-altitude aircraft created a number of additional design challenges. The use of a 25-kW-peak-power Traveling Wave Tube (TWT)-based high-voltage transmitter and a high-speed digital receiver/processor introduced potential concerns with high voltage/RF arching, thermal dissipation, high data storage requirements, weight limitations, and unattended operation.

Table 1.1 Specifications for high-altitude radars

	EDOP	EXRAD	HIWRAP	CRS
Frequency (GHz)	9.60 (X-band)	9.596 (Scan) (X-band) 9.624 (Nadir)	13.47, 13.91 (Ku-band) 33.72, 35.56 (Ka-band)	94.00 (W-band)
Transmitter	TWT	TWT	SSPA	SSPA
RF Peak Power (W)	25,000	9,000	80 (Ku)/40 (Ka)	30
Antenna Size (m)	0.76 (Reflector)	0.66 (Slotted Waveguide Flat Plate)	0.51 (Reflector)	0.51 (Reflectarray)
Antenna Beam Width (degree)	2.9	3.4	3.0 (Ku)/1.2 (Ka)	0.46
Antenna Gain (dB)	36.0	34.5	35.4 (Ku)/42.2 (Ka)	52.0
PRF (Hz)	4,400	5,000/4,000	5,000/4,000	5,000/4,000
Range Resolution (m)	37.5-150	75-150	37.5-150	37.5-150
Footprint at Surface (m)	1,010	1,190	1,050 (Ku), 420 (Ka)	160
Beam Pointing	Nadir and Forward	Nadir & Conical Scan	Conical Scan (GH, WB57) Nadir (ER-2)	Nadir
Measurement Products	Reflectivity, Doppler, LDR	Reflectivity, Doppler	Reflectivity, Doppler, LDR	Reflectivity, Doppler, LDR
Minimum Detectable Reflectivity (dBZe @10 km range)	-5	-15 (Nadir)/ -8 (Scan)	-10 (Ku)/ -12 (Ka)	-28
Doppler Nyquist Range (m/s)	34.4	156.2	107.8 (Ku)/42.2 (Ka)	15.9
Aircraft has Flown	ER-2	ER-2, Global Hawk	ER-2, Global Hawk, WB57	ER-2, WB57

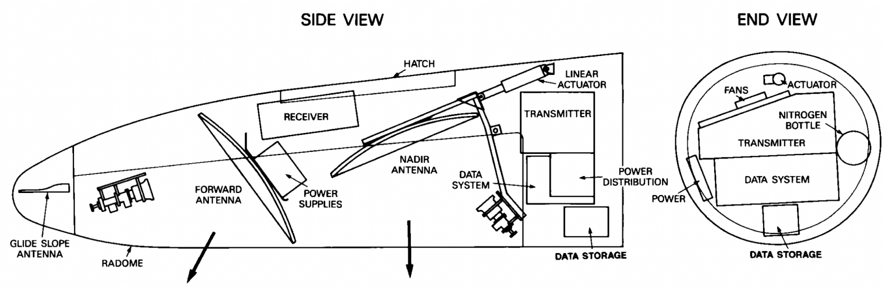

Figure 1.4 EDOP two fixed antenna configuration in ER-2 nose.

The first EDOP flights occurred in 1993 and the instrument continued to fly until 2007, when it was retired due to reliability issues resulting from aging components. During its 14 years of operation, EDOP primarily took part in field experiments studying tropical convection and hurricanes (e.g., [13, 14], Fig. 1.1). In addition to the successful collection of science data during numerous field campaigns, the instrument provided valuable experience that was leveraged during the development of CRS, HIWRAP, and EXRAD.

An example of EDOP data is shown in Fig. 1.5. This curtain of radar data was collected from Hurricane Georges (1998) as the eyewall was passing over the