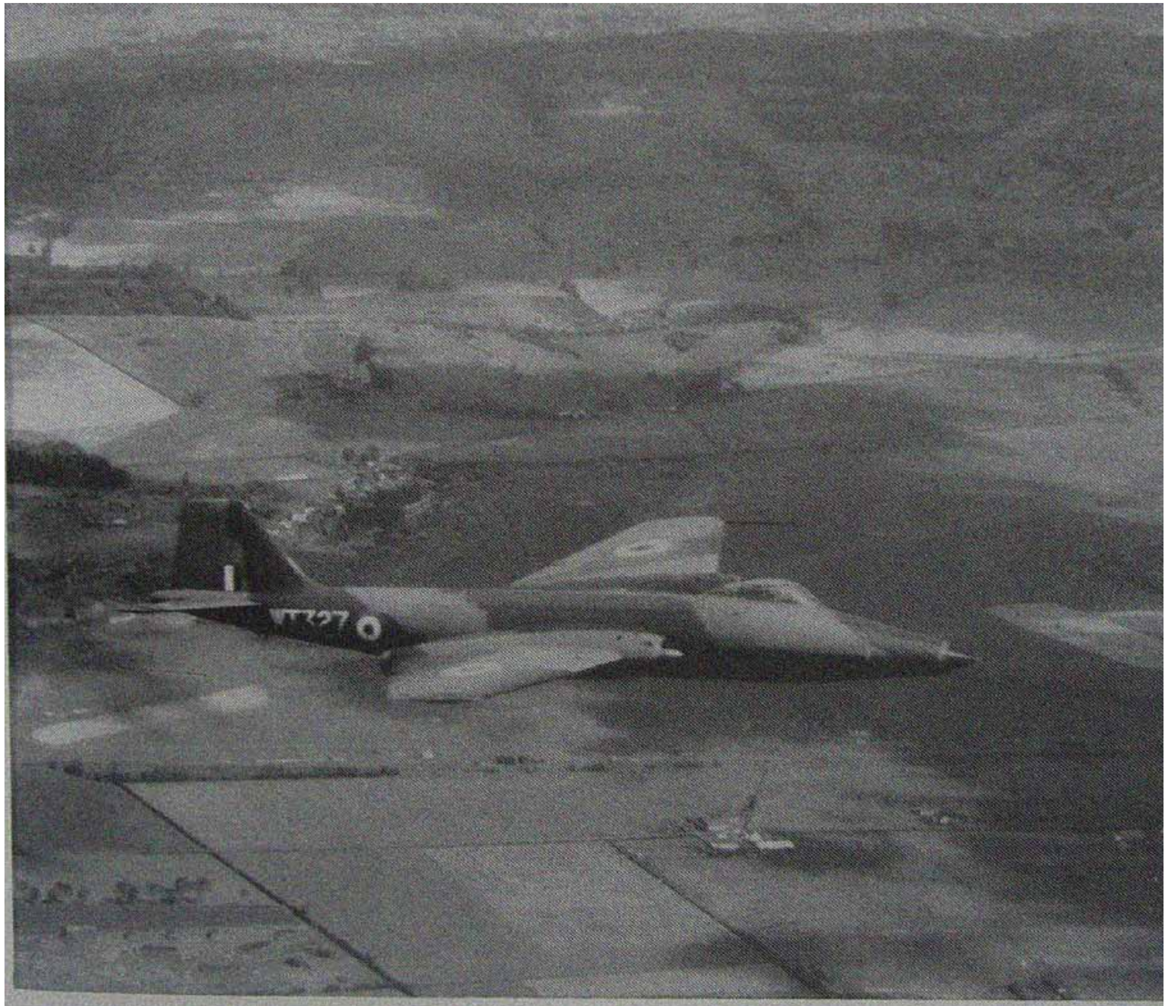
TSR.2 terrain following radar development at Ferranti in Edinburgh

photos supplied by Bill Blain.

These pictures, some taken as scans from a contemporary Ferranti brochure, illustrate the development of the terrain following radar, one of several avionic equipments being developed by Ferranti, at the time a giant in the UK electronics industry, for TSR.2. The Dakota and Canberra were flown as part of the famous “Ferranti Ar Force” from Edinburgh’s Turnhouse airport.



Canberra WT 327 fitted with Forward Looking Radar for the TSR–2 flying near Turnhous

TSR2 Terrain Following Radar Development - 1959 to 1964.

Recollections of Bill Blain
Ferranti Defence Systems Ltd.
Edinburgh

Background

I joined Ferranti Radar Systems Department, at Crewe Toll, Edinburgh, in 1955 as an honours graduate in Electrical Engineering from the Royal College of Science and Technology, Glasgow (later the University of Strathclyde).

When of school age, I had been most interested in mechanical engineering, particularly aircraft and boats - I made many working models powered by the recently-introduced miniature diesel engines. However, during my last school year my elder brother, David, with wider scientific and particularly electrical interests, had bought an ex-RAF Type 62 Radar Display Unit and I learned about electronics by doing much of the work of converting it to an oscilloscope.

I had previously intended to go into aviation but, on starting college, I opted for Electrical Engineering as being a rapidly developing and expanding area. In the event, the courses I took were very fairly evenly divided between electrical and mechanical matters.

At Ferranti, after a 6 weeks ‘Cook’s Tour’ of the company in Edinburgh, I made the fortunate choice to go into Alan Wesley’s laboratory, within John Stewart’s Radar Department, to work under Don Miller on the Ranging Unit for the AI23 radar for the English Electric Lightning Interceptor. This ranging unit “captured” and then tracked the pilot selected radar target within a range gate, thus allowing the antenna servos to track it in angle. It also fed range and range rate to the approach path computer. The ranging unit used a double integrator feed back loop to derive range rate and filter the output data.

It also had a fairly complex logic system, implemented by 27 relays (in these pre-electronic switching or digital computer days) to assist selection of the correct target and to guard against enemy countermeasures.

During my two years on this project and on the subsequent AI23B radar, I displayed some talent for invention and in making things work. I managed to cut the number of relays from 27 to 14, with essentially the same performance, and made many radical changes and simplifications to the electronics. I also tried to persuade, without success, other analogue computing workers to switch from using servoed potentiometer systems, for multiplication, division and function generation, to an all electronic method related to the architecture of the ranging unit.

The Ferranti TSR2 Radar Project

In 1957-58 Ferranti sent me on a ten month Post Graduate Diploma course in Communication and Control to Edinburgh University. Whilst I was away, Ferranti, under an MOD contract, started a study for the Terrain Following system for the TSR2. This was required to allow the aircraft to fly, in good or bad weathers, day or night, to distant targets at high speed and at heights down to 200 ft to avoid radar detection.

In 1959 Gus Scott, the leader of the then small TSR2 radar project, left to join Hughes Microcircuits at Glenrothes. Greg Stewart (an electrical engineering friend from Strathclyde) and Dick Starling (an aerodynamics and systems engineer from Cambridge) were appointed as joint project leaders of the rapidly growing TSR2 radar team, who were now contracted to produce development models of the TSR2 multi mode radar. The modes covered terrain following, ground mapping and air-to-surface ranging. I was given the task of leading an ancillary project to finalise development of the terrain following radar system, to be implemented in the final radar, and to demonstrate its successful operation, using a converted AI23B Lightning Interceptor radar, in a Canberra aircraft.

The proposed TF Radar system was based on a study and some experimental work carried out by Cornell University for the US Department of Defence. The profile of the ground ahead of the aircraft was determined by ground echoes from a vertically scanning radar mounted in the nose of the aircraft. The required flight vector, to maintain a safe low clearance height, was determined by sliding an electronic ski-toe, extending from 1,500 ft to 20,000 ft in front of the aircraft, over the radar derived ground profile. The electronic ski-toe was effectively pivoted at the nose of the aircraft with the flat part of the ski set at the required clearance height below the aircraft. The aircraft flight vector was controlled by the pilot following symbols on a head-up display, or by the aircraft auto-pilot, to be parallel to the flat part of the ski. The clearance height could be set to between 200 and 1200 feet above the flat part of the ski-toe. This caused a smoothed flight path at this minimum height above the highest ground. For close ground hugging, at the expense of a rougher ride, the ski-toe could be bent upwards more abruptly. To avoid 'ballooning' over high hills, an "early climb high" term was added to the flight path calculation. This caused the flight path to be close to horizontal over the peak of the hill.

To avoid problems of not seeing hills close behind other hills, the flight path was limited to a 0.5g down bunt. In addition, for flying over calm water, with very poor radar returns, the required flight path was controlled using height from a radio altimeter. Cornell had not demonstrated the system fully. (My impression, possibly wrong, was that the USA Department of Defence had abandoned interest in the system as it was deemed unlikely to be satisfactory.)

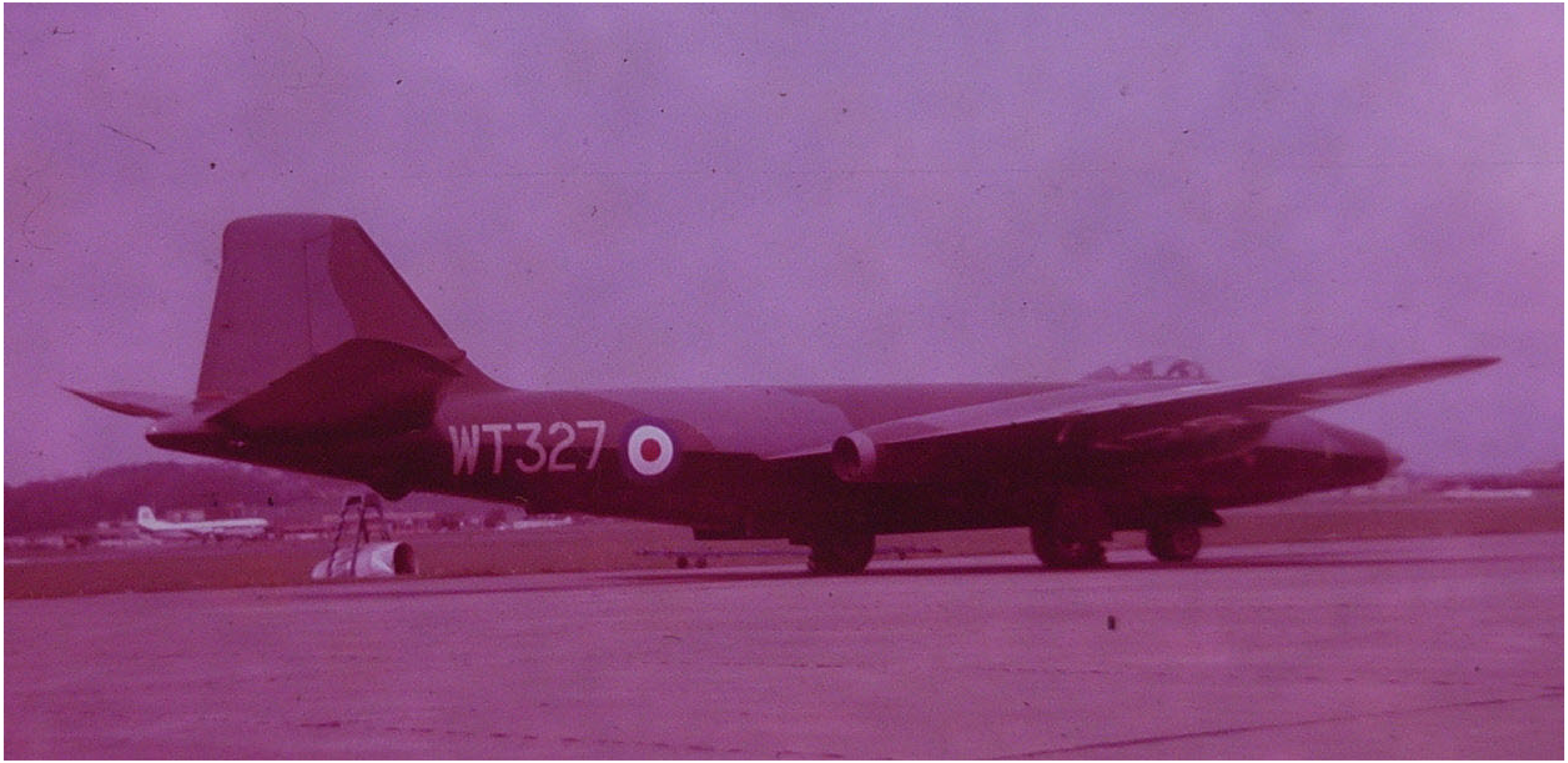
RAE Terrain Following Radar

Simulator

A simulator of the Cornell TF system had been constructed at RAE, Farnborough, in building Y20 at the west end of the airfield. This was run by Peter Byshe. I visited this facility a few times.

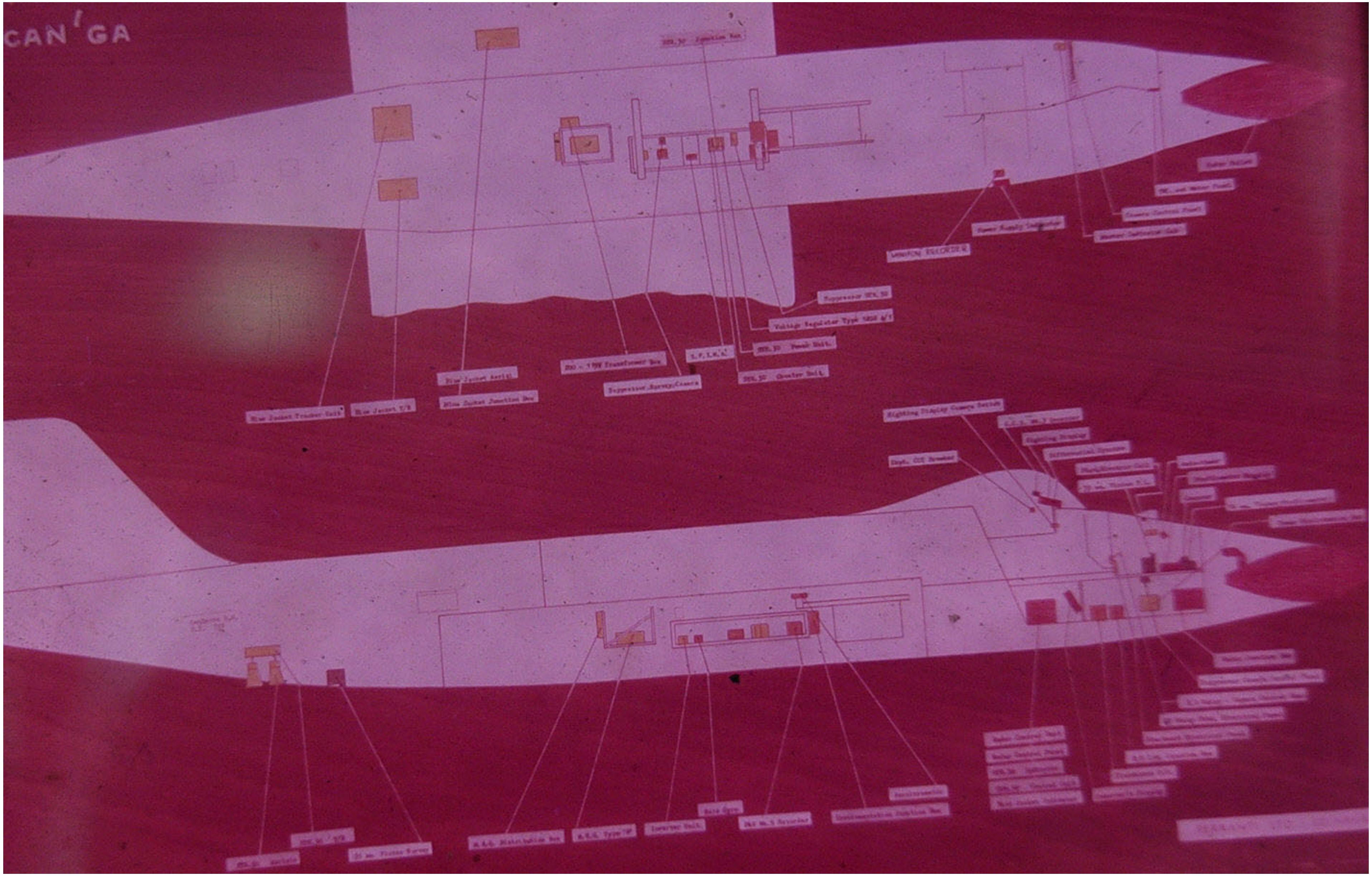
Now, almost 50 years later, I am not sure that my recollection is accurate or is the product of some confused Kafkaesque dream triggered by my initial visit. The simulator appeared to occupy several rooms. There were racks of operational amplifiers with old style telephone exchange cables and jacks for configuring them to adders, integrators, differentiators. etc. The racks included calibrated and servo driven potentiometers for multiplication and division, non-linear function generators and various odd things. A 20-channel pen recorder was fed with a very wide roll of paper, which it gobbled up high speed. It appeared to be vey difficult to get this system to faction fully and to ensure that it was functioning correctly. When the rest of he system appeared to work, one of the spidery pens on the recorder often failed to pass ink onto the paper.

Adding to the general clutter, the floors and shelves, close to windows



Above, The Ferranti Terrain Foliowing Radar mounted in the Canberra trials aircraft, seen at Turnhouse airport.

Right, schematic of the instrumentation associated with the Canberra TFR trials fit.


CAN'GA
Blue Jacket Aerial
Blue Jacket Junction Box
Blue Jacket Tracker Unit
Blue Jacket T/R
Voltage Regulator Type
Sighting Display Camera Switch
Sighting Display
Differential Synchro
Inverter Unit
Rate Gyro
Instrumentation Junction Box
Accelerometer

and doors of the building, were packed with trays of miniature cacti - Peter, a breezy likeable character, about three years older than myself and with a somewhat staccato manner, was the President of the RAE Cactus Society! (In the later 1960's Peter was seconded, for two years, to the British Embassy in Washington as a technical liaison officer. When the time to transfer back to the UK arrived, he had grown to prefer the US life. He left MOD and became a US resident. I lost track of him after that. I sometimes muse that he now has a large cactus farm in Arizona.)

Whatever its problems, this simulator had been successful in refining the Cornell terrain following system main parameters and adapt them to the TSR2 chrematistics. It had apparently shown that this TF system should operate well - provided the radar system could provide an acceptably accurate profile of the ground ahead of the aircraft and could also convert this profile into satisfactory steering demands for the pilot or auto-pilot.

Trials and Development of Demonstrator TF Radar

I started my role, of making the radar system work adequately, by reading all the relevant reports and by talking to the existing demonstrator model trials staff - Jim Hay (leader), George Anderson, Terry Evett and Merlin Edwards. The team included the very useful Andy Toshak, our Land Rover driver and general handyman.

An AI23B Lightning radar had been converted to directly implement the experimental Cornell system. This was being test flown, from Turnhouse, Edinburgh, in a Dakota and also in a Canberra aircraft.

Both aircraft had extensive instrumentation for recording and photographing data on aircraft position and attitude, flight path, radar data, including ground profile, and radio altimeter height over ground. For ground trials of the system, a sizeable cabin, on elevated ground overlooked a wide range of hilly ground and the small town of Linlithgow to the north, provided a good range of test terrain. The radar could also be mounted in a trailer, with an aircraft radome at one end, that could be towed by our Land Rover.

The trials team were specialists in aircraft installation, trials instrumentation and in flight trials procedure rather than in radar design. However they were incredibly enthusiastic and capable energetic workers. We designed and implemented most of the further modifications to the AI23 ourselves with only occasional recourse to the main design team. Since the AI23B was the last of our valve based radars and the TSR2 radar was the first of the solid state (transistor) range there was, in any case, little direct circuitry read across between the experimental model and the final radar circuitry. The system developed in the AI23B was, however, implemented fully in the final TSR2 radar.

Initial Trials Performance - Flying Cancelled

At that time the trials radar performance was totally unsatisfactory. Several flight trials had been carried out, mainly in the Dakota, as it allowed several observers. These showed little other than that the noise on the radar profile of the ground ahead, indicated by the monopulse radar, was so excessive as to render the system useless. Neither existing reports nor the trials staff could offer satisfactory explanations for the excessive noise and large errors. With no positive relationship of success to flying - and the vast overhead of time required to inspect the system as safe for flight, following tests and modifications and then to install it and inspect the installation - I banned further flying until the radar could provide satisfactory ground profiles of the Linlithgow trials site.

This decision, to cancel flying, was initially met with considerable opposition from senior company management. They, together with MOD, appeared to judge progress on the number of hours flown. However I convinced Harry Holmes and Ian Gray, two senior managers in the Ferranti Flying Unit, that flying was, at present, a waste of precious time. Testing, analysis, modification and proving on ground trials was the sensible route. Harry, in particular, was a master of persuasion. With his backing we were permitted to proceed sensibly using ground trials only.

I recall, in that period, an MOD progress meeting being imminent and we had two months of no flying. John Toothill, the Ferranti Edinburgh MD, barged into Alan Wesley's lab at Crewe Toll and demanded "Where's that young chap (I was aged 28 at the time but looked even younger) who seems to know what's going on? Get him to talk to the MOD next week.." This was my first major meeting. Solly Zuckerman, the government Chief Scientist was present.

In response to questioning, I remarked that I now found it impossible to see a hill without assessing the possibility of pulling our radar trailer to the top. He half smiled and nodded his head - I got the impression he had been there. The meeting, with Harry Holmes adroitly tying up any loose ends, went sufficiently well to justify the lack of flying for the time being. (At that time Harry, part owner of a Dragon, was a noted racing yachtsman. He was later commodore of the Royal Forth Yacht Club. A good man with loose-ends!)

Curing Radar Ground Profile Errors and Noise

Our major systems work was resolving the problem of excessive elevation errors and noise. Early conical scan radars derived the position of a target by moving the centre of the conical scan until the signal, from the shoulder of the beam, did not vary during the scan. These radars had to perform a complete circular scan, with many transmitted pulses to determine the direction of a target. The modern AI23B monopulse radar derived sum and difference elevation and azimuth signals, for returns from each transmitted radar pulse.
It suitably combined the signals received by the four waveguide feeds facing the parabolic antenna. In the AI23B Lightning radar, these difference signals fed the elevation and azimuth antenna servos to track the aerial boresight onto the target selected by the ranging unit range gate. In the TSR2 TF radar, the elevation difference signal was used to determine if any ground was

Right and left, the Ferranti AI23B Terrain Following Radar mounted in a Dakota trials aircraft at Turnhouse.

above the Antenna boresight (positive signal) - or below (negative signal). As the aerial performed a vertical scan ahead of the aircraft, any positive signal return above the electronic ski-toe, drove the ski-toe upwards until no positive returns were received. Thus the electronic ski-toe rested on top of the highest point of the radar derived profile of the ground ahead. With the aircraft flight vector controlled to be parallel to the ski-toe flat bottom the aircraft flew a smoothed path close to the ground.

Sources of Radar Angular Errors

On the AI23B ground trials, we traced the very excessive angular errors and noise to two main sources. Firstly a point target, within the centre of the main antenna beam, does give the correct negative equals below boresight difference signal. However in the side beams, and even in the skirts of the main beam , this relationship need not hold. At the time I took over, the aerial was scanned, once per second round a two bar squared-off ‘0’ scan covering 20 degrees in elevation and about 3 degrees left and right of the aircraft flight vector - up the left side, across the top, down the right side and across the bottom. In turns the vertical scan was tilted to look round the bend. A continuous automatic gain control (AGC) system wound the receiver gain up and down such that the maximum signals within the ski-toe range gate, were slightly below the receiver saturation limit. With this system, when the aerial main beam was pointing well above the ground, the

gain was wound up and ground could be "seen" in the side beams. Here, the difference signal could have the wrong polarity and the radar ground profile appear ludicrously high.

"U" Scan and Ratchet AGC

The side beam problem was obviated by changing to a 'U' scan with a ratchet AGC reset at the bottom of the scan. As the antenna scanned upwards the gain could only be reduced. Thus, when the beam was above a target, the gain had been set with it in the main beam. Side lobe returns were eliminated by suitably limiting the dynamic range of signals that were allowed to move the ski-toe up.

Reduction of Angular Glint from Radar Pulse Packet

The U scan, ratchet AGC and limited dynamic range removed the very radar errors but the angular noise of the monopulse system, but it was still somewhat excessive. This was determined to be due to the radar, at any instant after the 1/3 microsecond transmitted pulse, receiving a return from a "pulse packet" of ground approximately 170 feet long by the aerial azimuth beamwidth (4 deg) wide. In general a radar pulse package will not be uniform - there will be many major radar reflectors within it - small undulations in the ground, large stones, shrubs, trees, a configuration of objects giving a corner reflector effect, a tin can, etc.. All these separate main reflectors return radio frequency signals at differing and changing phases to the aerial which are summed and differenced to form the overall sum and difference signals. This causes the signals from a pulse packet of ground to be quite noisy in both amplitude (scintillation) and in indicated angle (glint). Analysis and measurements, however, showed that the difference signal is only likely to be of the wrong polarity when the sum signal is low compared with its average.

With no digital computers available to simulate this scintillation and glint phenomena, it was sorted out firstly by drawing vector diagrams of the radio frequency sum and difference signals by adding and differencing signals from several targets within a pulse packet with the phase of each changing. (I did the first of these diagrams on a bus from Edinburgh to Stirling after a perplexing but illuminating day at Linlithgow when understanding of the problem dawned.) After this initial work a mathematician was tasked with determining the statistics of the phenomenon. This angular noise was reduced sufficiently to make the TF system workable by further restricting the dynamic range of the radar returns that could cause the ski-toe to move up.

Terrain Following Computer Design

The analogue computing method, that I had previously derived from the A23 Ranging Unit, proved ideal for generating the required ski-toe range gate as function of scanner elevation angle and also for the subsequent feedback loop filtering to derive the smoothed required flight vector. I designed the changes to this thermionic valve based unit on the trials AI23B radar to implement this system. Brian Pitches and John Morrison designed the transistor version for the final TSR2 radar and also did a lecture tour round Ferranti on this novel analogue computing system.

During this TF computer design phase I attended several systems meetings at Vickers, Weybridge. These were run by an old Cambridge University friend of Dick Starling. He was about five years older than myself and a somewhat Jeremy Paxton type - incisive, abrupt, dismissive. I kept my head down and survived.

George Edwards, of Vickers Viscount fame (the main aircraft on the then Edinburgh to Heathrow run) appeared at one meeting to be introduced to the systems group. An older attendee, meeting-hardened Peter Tombs, I think from Marconi and involved in the auto pilot, became a useful ally. He arranged to ferry me to and from Heathrow in his Mini-Cooper. He also took me to the small company, north of Heathrow, who provided the radio altimeter, to allow me to check its peculiar current feed interface to my TF computer.

Recreation at Linlithgow

Most of the work in establishing these problems and their solutions was carried out at the Linlithgow trials site over an intensive eight month period. To get some relaxation from the hectic pace and frequent puzzlement, we often had a short game of football after lunch in the field surrounding our cabin.

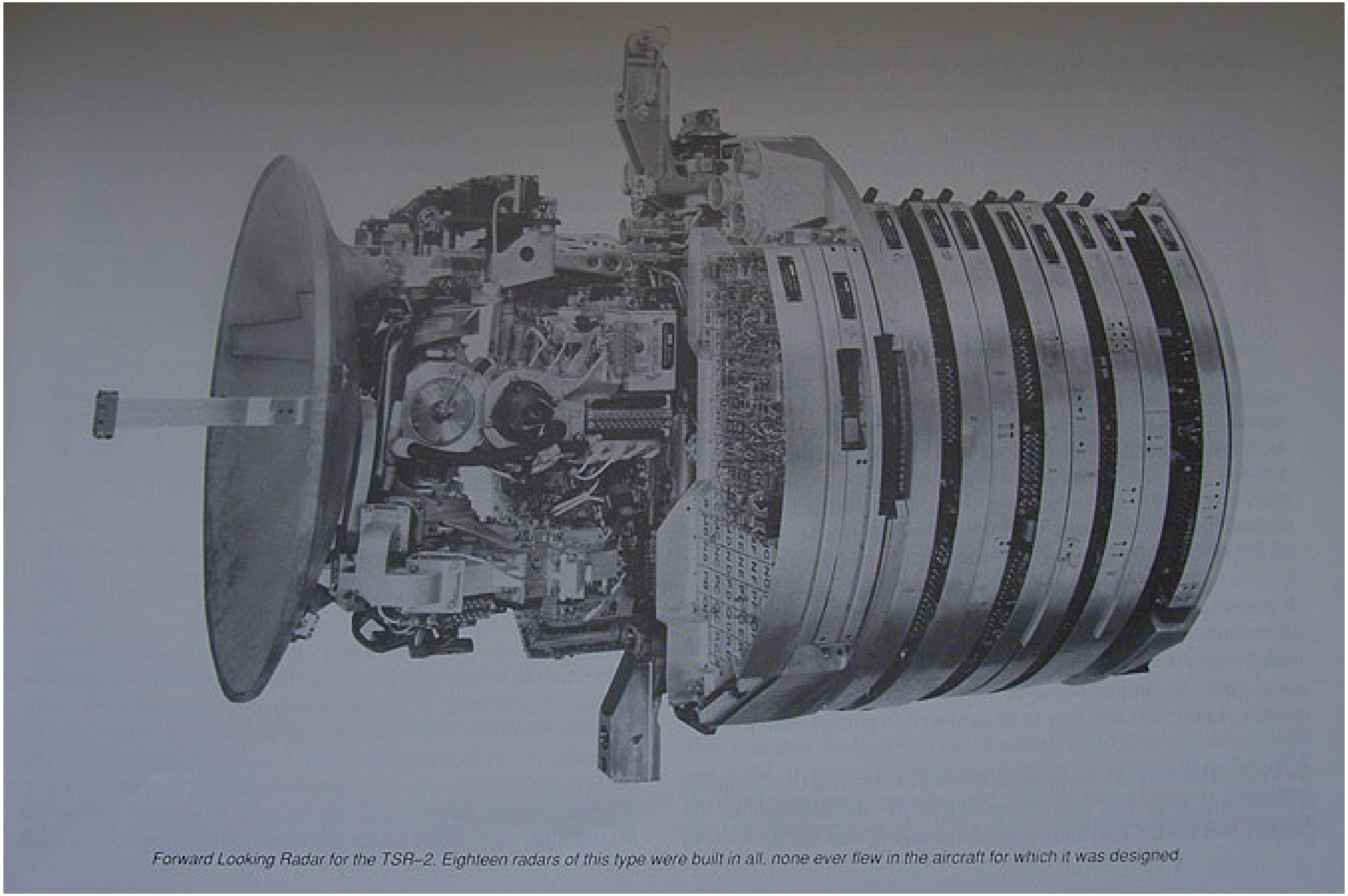
As summer approached we laid out a 4 ‘hole’ pitch and putt course. All was rough - balls within 2 feet of the ‘flags’ were deemed holed Lunch was made by a local retired miner, John, who was also caretaker for our facility. I feel that these periods of relaxation helped us to revert to systematic exploration and logical thought in the afternoons. We certainly behaved as an enthusiastic team and made reasonably swift progress through puzzling problems.

Installation of Demonstrator TF Radar in Canberra WT327

Once the system had been trialled extensively and successfully at the Linlithgow site it was installed in Canberra WT327 at Turnhouse during the very cold winter of 1961-62. First thing every morning I had the vast paraffin fan heater started up. Even then it was very cold work with the hanger door open sufficiently to use the radar. The latter was aimed at the Turnhouse golf course, to the north east of the airfield, A radar corner reflector was sited on the course to check radar alignment to the Head Up Display (HUD). Polarities and correct scaling of the signals to the Head Up display, showing the actual and required flight vectors, were checked by azimuth movement of the aircraft and by jacking it in pitch and roll. The complete fitting and subsequent checking of the system took about four months

Ferranti Simulators

During this installation period I became concerned that the pilot might tend to over steer when striving to fly the actual flight vector (AFV) onto the required flight vector (RFV). The response of the AFV has a considerable phase lag behind the joy sick. I checked this with Peter Byshe at Farnborough. I think, however, that his complex simulator fed the radar demand directly into the auto-pilot, so he had no data on this. Consequently, we made a simple analogue simulator of the link between the joy stick and the AFV and checked the pilots ability to fly the AFV onto the RFV on a HUD. Typical radar noise motion was included on the RFV symbol. We found it desirable to add phase



Above, first development TSR.2 multi-mode radar:
right, the AI23B TFR destined for TSR.2


DANGER

Seen a few years after the TSR.2's cancellation, our contributor Bill Blain is pictured with the Ferranti Laser Ranger and Marked Target Seeker (LRMTS) head, which went on to equip Jaguar, Harrier, and, later, Tornado ADV aircraft of the RAF.

advance between the AFV and the indicated flight vector (IFV) displayed on the HUD. This considerably eased the pilots task in tracking the symbols..

A few weeks after this simple trial, Alan Wesley offered me two naval engineering officers who had been seconded to Ferranti for six weeks. Could they assist me in any way? After a few moments thought I said yes - I would like them to build a more complete TF simulator.
I had thought about this before constructing the above very simple one. I found that Brian English, an at times brilliant engineer (like many of us) with useful experience in servo systems, could spare time to supervise the naval officers and show them the ropes of getting things made in Ferranti.

I drew out the system on a single sheet of paper. A ground profile of our preferred trials route over the Scottish highlands was cut out of 1/8 inch aluminium sheet. This, about 6 feet long, was rolled horizontally, by an electric drive, at a speed representing the aircraft horizontal velocity, The aircraft was represented by a potentiometer with a solid ski-toe, for 200 feet clearance height, appropriately mounted on its shaft. The body of he potentiometer was mounted on a servo driven vertical screw thread The output of the potentiometer, with the Ski-Toe sliding along the ground profile, gave the RFV with respect to horizontal.

Joy stick inputs were converted through simulation of the aircraft response, to vertical and horizontal velocity which determined the rate of the height screw servo and the rate of the horizontal drive of the ground profile under the aircraft. The potentiometer position up the screw represented, aircraft height above sea level. The HUD was arranged to show the AFV ,as a cross +, relative to the aircraft, using calculated aircraft elevation and angle of incidence. The Displayed RFV, a circle O, relative to aircraft, was derived from the potentiometer output less the aircraft elevation angle. Radar noise was added using a sampled noise source.

This system worked very well. Again, it was found desirable to add a phase advance to the AFV (Actual Flight Vector), making it the IFV (Indicated Flight Vector), to ease pilot’s work load.

This simulator became very popular. At a “lab open day”, when all the Ferranti Crewe Toll labs exhibited their projects to other Ferranti employees, it was probably the most popular exhibit. For weeks afterwards there would be queue at lunch time for people to fly over the Scottish highlands.

Flight Trials of TF Radar

The first effective real TF flight was in Canberra WT327 in Spring 1962. An easterly route was selected over flattish terrain east of Edinburgh, between Aberlady and Dunbar. (This passed close to the East Fortune airfield where the Scottish Museum of Flight is Located. The converted AI23B and the a subsequent final TSR2 radar are on display in this museum, together with a film covering the full flight trials.)

I instructed the Canberra Pilot, John Pascoe-Watson, to set the clearance height to 1000 feet, commence the run over the route at 1200 feet straight and level, check, on the Head Up Display, that the indicated flight vector (IFV +) was about 1 deg above the distant sea-sky horizon and the required flight vector (RFV O) about 3 deg below the IFV. If OK commence a shallow dive,. Check that the RFV rose and, at 1000 ft altitude, was about 1deg above the horizon. Meanwhile, George Anderson, the observer, was to check that the radar E-scan (range versus elevation angle) and the radio height appeared OK throughout. If successful, commence flying the aircraft to track the IFV onto the RFV.

This first real flight was completely successful. Following analysis of the recorded flight details we moved on to test the system over a very demanding 45 mile flight path over Ben Vorlich, Ben Lawers (both Munros well over 3000 feet high) and up north to Carn Dearg., near Newtonmore Within a few months the set clearance height was reduced to 350 feet and later to 200 feet. The system was also proved over water and transitions from land to water and back to land. On several occasions the higher parts of the route were obscured by cloud when flown over. The pilots, assured by the observer's monitoring of the radar E-scope, rapidly came to trust the system and continued following the system in these blind conditions.

George Anderson, Merlin Edwards and Andy Toshak climbed Ben Vorlich in mid-winter to erect a marker to allow the clearance height to be determined accurately by the vertical Recce camera in the aircraft. They also filmed the Canberra's approach, crewed by Pascoe Watson and Terry Evett, on several runs.

In order to test the bandwidth of the Radio Altimeter and its subsequent instrumentation, one flight was routed back over the very steep cliffs of the Bass Rock, just off the coast east of North Berwick. This was mainly to allow assessment of the ground profiles of the flight paths that we derived from this system. When radio height was subtracted from Barometric height this gave a very useful ground profile.

Flyers and Flights - Barmaids and Glasgow Zoo

Pascoe Watson and John Field shared the flying of the converted AI23B radar. Pascoe kept close to the project throughout. He wanted to know how it all worked and visited the Linlithgow site several times. Consequently Pascoe flew the Canberra with some delicacy.

Johnny Field just wanted to know what he had to do. "On the HUD, fly the IFV + onto the RFV O ? Right! OK!" And he did - like a high bandwidth servo. Some people may remember an early 1950's film 'The Sound Barrier'. The opening sequence was of a Spitfire, flown by Johnny Field, performing spectacular and beautiful aerobatics.

One morning, Pascoe flew the 100 miles long trials route, from Ben Vorlich, north of Callander, to Carn Dearg, near Newtonmore six times. In the afternoon he drove up north, in his Triumph TR2 sports car, for the weekend. Passing a small hotel, near Delphinine (I think), that he had "buzzed" six times that morning, he stopped off for a coffee. In the course of conversation he asked the girl at the bar if they ever had any aircraft in the area. She had a think but then declared she could not recall ever seeing or hearing any aircraft in the area!

A later sortie had a more noticeable reaction. A main remaining system concern was whether the noise limited dynamic range of signals, allowed to cause up demands, was sufficient to avoid a strongly reflecting target from preventing detection of a dangerous low reflectivity one. I had managed to collect a substantial number of reports covering the likely range of ground reflectivity and concluded that our system should cope in real circumstances. During the trials we had calibrated the receiver gain voltage against antenna received power and had analysed the range of signals received during trials. We had also automated a photographic process of displaying the ranges over which the radar obtained ground data verses the ranges over which ground ahead was visible from the aircraft. We had never found serious masking, but I wanted to check the system in a major built up area, with high radar reflectivity, and determine if any masking was encountered at the transition to and from more open country.

The trials group managed to obtain sanction, from MOD and from the Civil Authority at Refrew Airport, to fly the Canberra over a selected Glasgow route at 1200 feet altitude., This route happened to pass over the Zoo on the suburban east side of Glasgow. Unknown to ourselves, on the previous day this zoo had been declared a no-go area to aircraft - the zoo officials had been complaining of low flying aircraft causing distress to the animals for some time.

Events then added to the mischief. Pascoe Watson was the unfortunate pilot. Approaching Glasgow, Pascoe checked flight clearance with Refrew Control Tower. The route finally passed through the airport approach path. Because of poor visibility on that day, Renfrew instructed Pascoe to fly at 200 feet instead of 1200 feet. An official from the local authority happened to be at the zoo, informing them that their aircraft problems were over, when he Canberra roared past - fast and low. This was repeated a further five times at ten minute intervals. Phones rang, voices were raised and there was a threat of serious legal proceedings. There must have been some contrite talking from our important people to resolve the situation. At least the flight showed no technical problems with the radar system.

TV Masts

I was concerned, also, about the ability of the system to provide safe clearance over a TV mast. These masts, generally between 700 and 1000 feet tall, and supported by guy wires, might appear, on radar, to be of lower height and prove a severe hazard. Using the radar in the trailer, parked on the verge of the A8 road between Edinburgh and Glasgow, we checked he radar returns from the 1000 foot Kirk-O-Shots BBC TV mast. (A main finding was a noticeable slowing of the traffic on this main road - this was about the time radar speed traps were first mooted.)

The mast radar returns exhibited fairly static angular glint which could prove a problem. However, there was little wind on that day and the mast was fairly stationary, with little sway, relative to the radar. Analysis showed, however, that an approaching radar, in an aircraft, should cause fluctuating scintillation and glint from the mast due to changes in the relative phases of signals from different parts of the mast. This should allow the AGC to operate sensibly and sufficient up demands to be obtained to provide a safe mast clearance.

We also inspected the Kirk-o-Shotts mast and the guy wires. An Air Vice-Marshall had asked me, at a progress meeting, how many masts he TSR2 might be able to fly thorough before being disabled. I had suggested zero and I think I was right. The aircraft might cut through a guy wire and survive, but not the mast. I had read reports of wartime trials at RAE Farnborough on the effect of flying a Fairey Battle into barrage balloon cables. This showed that a fast flying aircraft could cut the cable, due to the high impact shock, particularly if the wing leading edge was steel reinforced.

RAE also designed a cable cutting system. This comprised steel reinforcing of the wing leading edge and a slot far out the wing into which the cable would slide due to the aircraft slewing. Here, the cable triggered a 12 bore shotgun cartridge which fired a steel blade through the cable. The RAE test pilot, a famed pre-war long distance record breaker, vividly describes how, on the first test, the cartridge failed and the Battle spiralled round the mast until it hit the ground 1000 feet lower down. The pilot walked away! (In the 1990's an American A6 aircraft cut a - probably thicker - mountain railway cable in Italy with its tail fin and survived. The gondola and its passengers were less lucky.

The TV mast is another matter. It is a lattice of substantial galvanised steel struts and ties. Both aircraft and mast were likely to be destroyed in any collision)

I decided personally to check how the radar would "see" a mast when approaching at appropriate heights. We obtained permission to fly the radar, in the Dakota, at heights, down to 200 feet, towards the BBC Cairn-0-Mount mast, north of Aberdeen. Johnny Field was the pilot. It took about an hour to fly from Turnhouse (Edinburgh) to the mast. The already noisy Dakota was made many times worse by a large 200V 400Hz generator being fitted in the starboard side of the fuselage. My impression was that this generator generated more noise and heat than electricity. We had to use head-sets to communicate. Also, it had been decreed that, since we would be at low level, we would have to wear harnesses at all times so that we could rapidly clip on our parachutes on the way to the rear door. I was instructed on how to jettison this door, which involved removing door hinge pins! It was a somewhat most uncomfortable flight.

We carried out 6 runs towards the mast starting at 20,000 feet range and 1000 feet above ground and banked steeply away fairly close to the guy wires. On successive runs we reduced the height down to a final 200 feet. I was satisfied that the radar would obtain adequate signals to provided a safe clearance height. The velocity of the aircraft towards the mast caused a considerable cycling of the angular glint.

Returning to Edinburgh, Johnny Field declared that he could not understand the need for a radar to fly low. He backed this up by flying at tree top height most of the 90 miles to Dundee. It was a very rough ride. I did not point out, to Johnny, that the radar system could perform at night and through fog - I feared that he would seek some fog to demonstrate this also!

Aerial Survey of Linlithgow Trials Site

As a finale to this flight, I wanted to over fly and survey our Linlithgow trials site. Our ground mounted radar has shown substantial differences in the ground contours and in the position of key ground features - buildings, roads, fences, trees, hedgerows - from the Ordinance Survey map. Our aerial survey used the aircraft mounted Recce camera, the radio altimeter and the barometric height.

George Anderson went up front to direct Johnny to fly over our trials cabin and the Hope Monument north of Linlithgow. George was late in identifying our cabin. “Oh s**t!” exclaimed Johnny as he put the plane into a vertical bank about 300 feet up. I remember the details of the wing rivets as I looked vertically down at the ground. That was the finale for me - have never felt so sick before or since that flight! That evening, for our wedding anniversary, I was to take my wife out to a posh Edinburgh restaurant for our third anniversary dinner!

The flight over the trials site proved worth while. The ordinance Survey map was wrong in placement of many landmarks and contours. We later learnt that many objects and contours were merely hand drawn in by the map maker rather than measured. Our radar measurements of the site, using the converted AI23B, were more accurate than the maps.

This was my only flight during the trials programme. To qualify for flying in the Canberra, or the later Buccaneer, I was informed that I would have had to do a sea survival course. This involved, they told me, of jumping into freezing water 5 miles off Portland Bill, inflating a dingy with one arm only and remaining in it until ‘rescued’, possibly about an hour later. It was winter. I considered that, if I did survive the survival course, I would possibly be incapacitated for some time. Besides it was doubtful if my observing ‘live’ would further assist the programme. I think the trials crew did intend to put me off.

Frequency Diversity Magnetron - Reduction of Angular Glint

It remained desirable to increase the safety margin by increasing the dynamic range of signals detected without increase to the elevation noise. New “frequency diversity” tuneable magnetrons, which allowed the transmitted frequency to be shifted between pulses, had been developed recently. This was principally used to cause fast cycling of sea clutter and allow ships and aircraft to be identified more readily against this background. In the TF system it would cause fast cycling of the amplitude scintillation and the angular glint of the radar returns This would allow improved setting of the AGC and better filtering of the angular noise.

We proved this improvement on ground trials at Linlithgow, using a manually pulled string round a pulley on the tuning shaft of an early tuneable magnetron - it would have taken several days to design, build and fit an electric drive to vary the tuning appropriately. This frequency and amplitude of the manual string pulling was timed to give an approximately saw-tooth transmitted frequency modulation, over a sequence of radar pulses, that could be tracked by the klystron local oscillator automatic frequency control.

Later Greg Stewart, project leader of the final TSR2 radar, established that Phillips, in Stockholm, were producing a spinner-tuned “frequency diversity” magnetron possibly suitable for the final radar. We visited Stockholm together to assess its suitability and to arrange its procurement for the TSR2 radar.

First Development TSR2 Radar - Flight Trials in Buccaneer

The terrain following system, developed on the trials AI23B, was incorporated in the TSR2 radar. The first development model, of the later, became available for trials in 1963.It was installed in a Buccaneer aircraft. Pascoe Watson, with Terry Evett or George Anderson, flew the early flights. Len Houston, well known in BAe Warton, took over as the main pilot shortly after the initial flights. Flight trials proved successful. These culminated in flights at 100 feet over the Scottish Highlands and Islands. Greg Stewart, an inveterate showman, underwent the sea survival course (in Summer) and flew a long 100 foot clearance flight with Len. The Buccaneer landings, at Turnhouse, were always noticeable. For safety reasons, the road just beyond the north west end of the main runway had to be closed to traffic and a special net barrier erected, by electric motors, to catch the aircraft if it overran.

I phased out early in the Buccaneer programme, the system and he trials methodology having become fairly standard. I finished - writing reports, specifying parts of the system - in early 1964, before the TSR2 cancellation, and moved on to head a new Future Radar Systems Group in Edinburgh.

Later Business Resulting from TSR2 TF Radar Experience.

Through the TSR2 experience we were one of the world leaders in air-to-surface non- coherent pulse radar. The first proposal, of the new group, was for miniature air-to-surface radar for the P1154, a forerunner to the Harrier. This was followed by studies on air-to-air and air-to-surface radars for the Anglo French Variable Geometry Aircraft. This study included the first British air-to-air pulse-Doppler radar. The AFVG aircraft mutated into the Multi Role Combat Aircraft with Germany, and Italy. During further MRCA radar studies I proposed an air-to-surface laser ranger as being superior to a radar.

At that time I founded a small Electro-Optics Group to pursue business in this area. Our remarkable success in this new area, particularly the projects involving lasers, proved to be dependent on our TSR2 radar experience as described below. Our first experimental E-O contract, however, was for an airborne stabilised laser ranger and TV sight for RSRE, Malvern. George Crossly, with Terry Snowball, were the RSRE staff on this successful project. RSRE provided the calcium tungstate laser transmitter.

This system, our first to incorporate a gyro controlled stabilisation mirror mechanism, was flown experimentally, by RSRE, in a

Varsity aircraft based at Pershore. This equipment proved to be the forerunner of a still (2007) continuing range EO equipments using stabilisation mirror mechanisms.

The first production descendant was the TIALD (Thermal Imaging Airborne Laser Designator) pod. Our rejected proposal for the EFA IRST (Infra Red Search and Track) was based partly on this technology. The current DIRCM (Directed Infra Red Counter Measures) turret, part of the Northrop/Finmeccanica system for protecting aircraft from missile attack, is a later derivative.

TIALD was first used, as early demonstrator models, Tracy and Sandra, on Tornados to steer Laser Guided Bombs, very successfully, in the first Gulf War. Later, following full development, production models were fitted to the Tornado. (We had expected to receive a development contracts for TIALD in about 1978. The RAF however decided to base their air-to-surface future on cluster bombs. Fortunately RAE had the foresight to fund, in 1976, the two demonstrator TIALDs used in the first Gulf war.).

Exchange of TSR2 TF Radar Data for Westinghouse Laser Transmitter Data

Our second Electro Optics contract, the key-stone of our success in this area, was vitally enabled by our TSR2 Terrain Following System experience. This first Major EO contract, in 1968, leading to full development and production, was for a demonstrator for a Laser Ranger and Marked Target Seeker (LRMTS) that could fit into the nose of the Harrier and Jaguar. We won the precursor to this contract against 15 other bidders.

We had expected to be able to buy a laser for EO equipments as one would buy a magnetron for radar. However, Barr and Stroud, the only UK company then with a militarised (Hughes-derived) laser, refused to join us as sub-contractor for this contract. They wished us to supply them with a stabilised platform on which to mount their laser rangefinder. (Not a viable solution for the noses of these aircraft.) Fortuitously, at that time the Ferranti Edinburgh Support Department had a team in Westinghouse, Baltimore, learning how to support their AUG10 radar in the Phantoms being bought by the RAF. Westinghouse had several military laser programmes and offered to provide us with full data, on one of them in, exchange for the data we had produced on the Terrain Following System for the TSR2. The US had renewed interests in the latter area.

I took a team of six engineers, covering optics, electrical and mechanical engineering, across to Westinghouse for two weeks. We had sent our TF system data to Westinghouse previously. I spent most of my time, at Baltimore, on the laser but was also involved in explaining our TF system data to their radar people - I had written most of the reports that had been supplied to them.

On the way home, in the plane, we started the redesign of the Westinghouse laser for use in our proposed equipment. We also had several meetings with BAe at Warton and Hawkers at Kingston to ensure that our proposed equipment would fit both aircraft. We only used the Westinghouse based laser on the LRMTS. All of our following projects used our own patented higher efficiency and self-aligning laser.

Ferranti lasers were eventually sold into US military programmes.

Our proposed LRMTS was also dependent on two new experimental silicon detectors being developed to a satisfactory standard and produced for the production models. I had a meeting with Morris Deller of RAE Farnborough and Ron Redstone of Fort Baldock, the MOD facility specialising is solid state devices. Deller and Redstone took responsibility for these developments being successful thus allowed LRMTS to go ahead. (Morris Deller was particularly farsighted in his approach to this and to other later EO projects. He deserves a major share in responsibility for their success.)

We subsequently won the RAE demonstrator contract. This led to the LRMTS (Laser Ranger and Marked target Seeker) that, after demonstration and full development , was installed on the Jaguar, Harrier and Tornado aircraft. In the mid 1970's. When the LRMTS in full production, several Westinghouse directors were shown over our Edinburgh facilities. When they were appraised of the direct linkage between our large production area devoted to LRMTS and the exchange of our TSR2 Terrain Following Radar data for their laser project information they were astounded. They had generated nothing from our radar data. Interestingly, Ron Redstone, responsible for development of the crucial LRMTS detectors, had commented -probably correctly - of the data exchange, "radar will always be more important than Electro- Optics".