FINAL TECHNICAL REPORT

NRRD Programme: Livestock Production

Project Number: R5457

NRI Project Number: Q0009 and C0438

Title: Adaption of harmonic radar for tracking tsetse flies.

Project Leader: J.R. Riley.

Institution: Natural Resources Institute.

Start Date: October 1992

End Date: August 1995

Introduction and developmental context

Background

1. Radar has been used to observe the flight of insects for over 25 years, and the technique has provided unique insights into the high altitude windborne, migratory movements of several pest species. Low altitude "vegetative" flight activities such as feeding, mate- and host-finding, are also of great interest to entomologists concerned with pest control, and this is particularly the case in studies of tsetse flies. Unfortunately, insect flight at low level is inaccessible to normal entomological radars because of the obscuring effect of back-scatter from ground features (clutter).

2. One way to overcome the problem of radar clutter is to "tag" intended targets with electrically non-linear conductors which will absorb radiation at the radar transmitting frequency, and re-radiate it at a harmonic frequency. The radar receiver is tuned to this new frequency, and so responds only to signals from the tag, rejecting echoes from ground features. Systems of this type are called *harmonic* radars. An important potential advantage of using the harmonic technique for insect tracking is that extreme miniaturisation of the tag is possible, because the power to operate it comes from the illuminating radar, and no battery is needed.

Previous work

3. The initial stimulus to investigate the practicality of using harmonic radar to track insects came from Dr. Glyn Vale of the EEC Regional Tsetse and Trypanosomiasis Control Programme (RTTCP) in Zimbabwe. Dr. Vale considered that the lack of a means of observing tsetse flight over distances of more than a few metres was a serious impediment to optimising the tsetse control techniques currently in use, and he believed that harmonic radar might remedy this problem. As a result of Dr. Vale's representations, the NRI Radar Unit undertook a feasibility study of the technique supported by a short speculative research project (NRI I0048 and I0071).

I0048 began with a literature search and was followed by theoretical calculations which indicated that a harmonic radar, based on the 25 kW peak power, 3.2 cm wavelength NRI entomological radar transmitters, should have a maximum range of about 900 metres. It was, of course, clear from the outset that the feasibility of using harmonic radar for entomological studies depended on the practicality of developing a tag small enough to be carried by insects without perturbing their behaviour, but of comparable efficiency to that known to be achievable in conventional macroscopic microwave harmonic generating circuits.

4. The theoretical study was followed by a brief laboratory investigation in which low-barrier, high frequency, Schottky detector diodes were selected as suitable non-linear conductors Some of these were procured, and were fitted with wire antennas designed to act as half-wave dipoles at a wavelength of 3.2 cm. Illuminated with a 3.2 cm, continuous wave source in an anechoic enclosure, the diode/dipole assemblies gave (radiated) conversion efficiencies to the second harmonic of about 0.04%, with an incident power density equal to that deliverable by the NRI transmitters at 900 m (5 Wm^{-2}). The harmonic power was measured with a calibrated horn and a high frequency spectrum analyser lent to us by the Defence Research Agency, Malvern (DRA). These results implied that the conversion efficiency of the devices was about 100 times less than had been expected from the theoretical studies. It seemed likely at this stage that recovery of the expected efficiency might be achieved by adoption of circuit tuning elements into the diode/antenna configuration, and the conclusion of the initial feasibility study was that the development of a miniature tag of higher efficiency should be pursued (Riley 1992).

5. The follow-up project (I0071) had the specific objective of investigating the low conversion efficiency of the diode/antenna tags. The first step was to test whether the power *absorbed* by the diode/dipole configurations was as predicted by theory, by measuring the tag back-scattering cross-sections at 3.2 cm wavelength, and comparing them with control dipoles fitted centrally with an (optimal) 50 Ω resistive load. The results showed that the tags had scattering cross-sections equivalent to shorted dipoles, i.e. the dipoles were badly matched to the diodes which were therefore absorbing very little power. Observations of illuminated diodes using a thermal imaging device confirmed this conclusion, and it became clear that the diode impedance specified by their manufacturer did not adequately describe their performance in "free space" configurations.

6. Improvement of the diode antenna match at both fundamental and harmonic frequencies could be achieved in principle by the use of a appropriate tuning circuits, but the very exacting size requirements meant that an innovative solution was required, perhaps using highly miniaturised lumped circuit elements. Project Q0009 was set up to allow pursuit of this solution (Riley 1993).

Objectives

The objectives of the project were as follows

To produce a diode/antenna tag small enough to be carried by a flying insect, and capable of generating harmonic signals of a 3.2 cm radar signal at a high enough efficiency to allow detection at a range of 900 m.

To build a complete, prototype, dual-frequency harmonic radar to assess the performance of the prototype tags in an intense clutter environment.

Results

8. We began the current project by describing the performance of our diode/antenna tags to experts in the field of microwave diode interactions - notably Mr. Doug Yell of Hybrid Electronics, Research Engineering Electronics Sector, Defence Research Agency (DRA), Malvern. He considered that our analysis of tags' electrical characteristics was appropriate, and that the circuit simulations we had produced using the proprietary antenna software AWAS were correct. A consensus emerged that a possible cause for the low conversion efficiency found in practice was that diode/dipole structures irradiated in free space might generate self-biasing charges that would tend to turn the diode off.

9. We had anticipated in our earlier designs that there was a possibility that this might happen, but earlier attempts to check this hypothesis using a loop antenna had proved inconclusive. An alternative method of shorting out self-bias charges was therefore tried using a newly available, high frequency, 4.7 nH chip inductor (1 mm x 2 mm) wired in parallel across the diode. Circuit simulation of the diode-inductor combination showed that it presented an impedance of 44 Ω at the irradiator frequency (9.4 GHz), and so presented a reasonable (reactive) match to a resonant dipole antenna.

10. Laboratory experiments on this component incorporated into dipole/diode configurations, and carried out using a 25 kW, 9.45 GHz pulsed radar transmitter fitted with an appropriate waveguide assembly and attenuators, showed a very large gain in harmonic conversion efficiency (approximately x 40) above that achieved previously. It therefore seemed clear that diode self-biasing was indeed a critical limiting factor in the earlier designs, and largely explained why conversion efficiency was much less than was indicated from theoretical calculations.

11. Having achieved a diode tag conversion efficiency high enough to give a theoretical maximum range of 700 m with a 16 mm antenna, the next step was to test the tag in a field trial. A balanced mixer receiver, working at a centre frequency of 18.8 GHz and with a bandwidth of 7 MHz, was therefore designed, components were commissioned and the receiver was constructed. It was tested, and found to have a noise figure of 11 dB, close to the design figure. One of the Radar Unit's 25 kW, 9.4 GHz transceivers was re-configured to act as a stand-alone transmitter. The transmitter and receiver were fitted with horn antennas, both of 20 dB gain, and the equipment was aligned to produce static transmit/receive beams with overlapping coverage over a range of 50 to 180 m.

12. A diode tag attached to a fine line fastened to a wooden pole was then carried into the overlapping beam area, and it was found to be detectable (on an "A" 'scope display) out to 150 m. This range was very close to that predicted for the horn antennas. The experiment demonstrated that the tag could indeed be detected in the presence of the huge amount of "clutter" returned by typical ground features. As we had anticipated, this result was achieved only with the use of a higher mode suppression filter in the transmitter output: without this filter the residual harmonics in the magnetron output produced clutter returns which obscured the tag. The success of this field trial prompted the construction of a complete, dual-frequency, azimuthially scanning radar.

13. The illuminator for the radar was based on one of our Decca marine 9.4 GHz, 25 kW, peak power transmitters. This was mounted on a modified X-band rotational antenna platform, and it fed a 1.3 m diameter parabolic reflector equipped with a double dipole feed, oriented to produce vertical polarisation. A 0.7 m paraboloid with a Ka-band horn feed was fitted above the illuminator, and formed the reception antenna for the harmonic receiver. Signals from this antenna were fed through the X-band waveguide of the antenna platform on low-loss semi-rigid microwave cable, to a coaxial rotating joint, and thence to the 18.8 GHz receiver. A Plan Position Indicator (PPI) display from a conventional entomological radar was modified for use with the harmonic receiver. A control system to allow remote tuning of the harmonic receiver and an interface between the receiver and the PPI display, were designed, tested and incorporated into the new system.

14. The completed radar was tested at DRA's test range at Pershore, Worcestershire, using the NRI prototype tags, and also some tags made by Hybrid Electronics of DRA with ultra miniature diodes (see par. 16, below). The system worked exceptionally well, providing *complete* rejection of ground clutter, including that from nearby aircraft hangers. Individual diode tags registered as clear, single, dot targets on the otherwise blank radar screen out to a maximum range of approximately 700 m. The interference phenomenon known as the "Lloyd's mirror" effect tended to reduce the detectability of the tags very close to the ground, and again at a height of 2 m. The phenomenon is determined by the smoothness and electrical conductivity of the ground, and will therefore depend on the nature of the terrain in which the radar is used. The tag was not detectable when placed behind a gorse bush at a range of about 600 m. Since vegetation absorbs or reflects radiation at both incident and re-radiated wavelengths, it would be expected to obscure the tag, except possibly when it was close to the transmitter/receiver.

15. The field trial identified the need for a number of modifications to the radar antenna, principally to facilitate alignment of the transmit and receive beams, and these modifications were duly carried out.

16. Discussions with Hybrid Electronics of DRA, Malvern had been initiated in the spring of 1994 to explore methods of mounting ultra-miniature diodes in tags. DRA kindly fabricated some tags for us, incorporating miniature diodes, but when they were used in the field trial described above, the tags gave rather disappointing results. The reasons for this poor performance are not yet understood. In the interim, refinement of conventional construction methods by the NRI Unit, led to a reduction in the overall weight of the tags by approximately 50% (*i.e.* to about 2 mg).

17. Laboratory measurements were made to assess any loss of tag conversion efficiency when they were attached to insects. We used freshly killed locusts (*Locusta migratoria).* It was found that an efficiency loss of approximately 10 dB occurred, apparently due to field distortion caused by the proximity of the insect body. Mounting the tag in a small dielectric tube, so that it was separated by about 2.5 mm from the insect body, restored the conversion efficiency to its "free space" value.

18. The final stage in the current project was to carry out a short field trial of tags mounted on flying insects. This was undertaken in collaboration with staff of the Bee Research Unit at Rothamsted Experimental Station, who are themselves very interested in applying harmonic radar to studies of the flight paths of bumble bees. These insects are robust and powerful, and seemed likely to act as ideal flying test-beds for our prototype tags.

19. The Rothamsted field trials were successful, and provided the first demonstration that prototype tags could be detected when carried by flying insects, apparently behaving normally. Much more extensive trials are needed however to confirm this point, and to allow evaluation of ultra-miniature tags which would be needed to track smaller insects like tsetse. The trials also highlighted how some limitations of the prototype system might be addresssed.

Discussion

20. The gain in harmonic conversion efficiency achieved with the incorporation of a miniature inductor into the diode/dipole tag configuration resulted in the achievement of the planned detection range of about 700 m for a diode tag with a half-wavelength dipole (18 mm). Detection distances of this order represent a dramatic improvement over any other means of observing low altitude insect flight, and would make viable the investigation of the host-finding and pheromone-following flight by a wide variety of pest species.

21. We have discussed with entomologist colleagues the question of whether a tag of this size could be carried by insects without impeding their flight performance, and the consensus was that large moths or medium-to large grasshoppers would probably be able to perform normally, but that a reduction in tag dimensions was nevertheless very desirable, even if this entailed a reduction in detectable range. This conclusion is supported by the results of the trials with bumble bees at Rothamsted. The research project has thus demonstrated for the first time that the harmonic radar technique is a viable means of tracking insects in low altitude flight. It remains to further refine the diode design to optimise conversion efficiency and reduce size, and to undertake full scale tracking experiments on appropriate pest species.

References

Riley, J.R. (1992) NRI Innovative R&D: Project I0048. Harmonic radar diode tag development end-of-project report. 27 April 1992. NRI Internal report, 30 pp.

Riley, J.R. (1993) NRI Innovative R&D: Project I0071. Harmonic radar diode tag development end-of-project report. 1 April 1993. NRI Internal report, 15 pp.

Publications

Conference papers

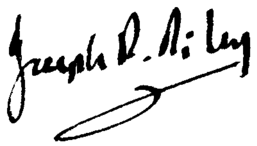
None (see below).

Journal articles

None. Project policy has been to keep dissemination to a minimum. Firstly because it seemed unwise to publicise the method until it has actually been proved in practice, and secondly because of the possible commercial potential of a the system. As far as we can establish, the mass of our harmonic transponder tag, at approximately 2 mg is less than 0.002 times the smallest conventional radio tag currently available commercially, and it seems clear that there would be numerous applications for such a device.

Internal Reports

Internal progress reports were produced quarterly, and summary reports annually throughout the duration of the project. Progress has also been reported to RTTCP through correspondence with Dr. Glyn Vale.



Dr. Joe Riley
17 August 1995