
NUCLEAR QUADRUPOLE RESONANCE (PAPER I)

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INTRODUCTION

Nuclear quadrupole resonance (NQR) combines the spatial localization capability and convenience of metal detection or ground-penetrating radar (GPR) with the compound specific detection capability offered by chemical detection techniques. Starting in the mid-1990s, groups at Quantum Magnetics Inc. and the Naval Research Laboratory made considerable improvements in the basic scientific and instrumentation techniques for performing an NQR measurement over the ground. These advances have led to programs to build a vehicle-mounted NQR system to work in conjunction with the Army Ground Standoff Mine Detection System (GSTAMIDS) mine clearance system, and a man-portable system to meet Marine Corps requirements for a man-carried mine detector. Overall, NQR is the only new technology in the past 10 years to progress to the stage at which practical deployment has become a possibility.

NQR is an electromagnetic technique-based operating system in the frequency range of 0.5–5.0 MHz. Its current limitations for landmine detection are

- Insufficient signal for rapid detection of small deeply buried TNT mines
- Radio frequency interference; in particular, commercial AM radio stations within 20 kHz of the frequencies for detection of TNT, and electromagnetic noise sources in the immediate vicinity of the system.

To develop the full potential for NQR landmine detection, a number of ancillary issues must be addressed:

- Development of techniques to enable an NQR system to operate while in motion. In its present form, an NQR detection coil can operate only while stationary.
- Development of array techniques in order to operate multiple NQR detection coils in close proximity of each other.
- Reduction of the overall system size, weight, and power to enable integration of an NQR with other mine detection sensors on a single platform.
- Engineering modifications to improve reliability and reduce system cost.

There are two general approaches to deploying NQR technology for landmine detection. The first is to work to solve the basic limitations (e.g., the first items of the lists above) in order to build a stand-alone NQR system operating in a conventional sweeping mode detecting all types of mines. The principal risk is that some problems, item 1 in particular, may be difficult to solve completely. The second approach is to focus on using NQR where it is presently strong, such as in the detection of RDX and CompB mines, or operating in a stationary mode as a confirmation sensor to augment other mine detection technologies. This appendix will address the results that can be expected in taking each of these approaches.

MAGNITUDE OF THE NQR SIGNAL FOR THE EXPLOSIVES USED IN LANDMINES

In contrast to GPR, metal detection, and many other technologies that are primarily limited by ground clutter, NQR technology is usually limited by its own internal system noise. This noise is thermal, which means that extending the interrogation time, t , increases the overall signal-to-noise ratio (SNR) of the measurement by \sqrt{t} (for example, doubling the measurement time increases the SNR by a factor of 41 percent). Cancellation of radio frequency interference (RFI) appears to scale as \sqrt{t} also, and so its effect can be included by a fixed decrease in the system SNR. Given that the NQR signal is proportional to the mass of explosive, the most suitable way to describe

the performance of an NQR system is the SNR per unit time per unit mass of explosive. The present SNR for the present man-portable NQR system on 100 g of the three types of explosive used in antipersonnel mines deployed at tactical depths with zero RFI for a 1-second measurement is listed in Table J.1.¹

Because the statistics of the NQR system noise are well defined, the relationship between the probability of detection (PD) and probability of false alarm (PFA) for a given measurement SNR can be accurately calculated. PD/PFA pairs at operating points relevant to mine detection are shown in Table J.2.

For example, these results show that an NQR measurement on a small RDX mine in an RFI environment that results in a 20-percent loss in SNR (the present target for the antitank detection systems) provides an SNR of 4.7, which is easily large enough to meet present performance goals. The worst case at the present time is the TNT antipersonnel mine, for which a 1-second measurement is inadequate even under conditions of zero RFI. To combat this, four individual measurements are necessary to detect such mines. Unfortunately, a property of NQR for TNT (not shared by RDX and only in a

Table J.1
Present Signal-to-Noise Ratio for a 1-Second NQR Measurement of 100 g of Explosive

	100 g RDX	100 g TNT	100 g Tetryl
SNR in 1 second	13.1	1.2	10.7

Table J.2
Example PD and PFA Operating Points 2 to 7 for NQR SNR

	Operating Point/SNR					
	2	3	4	5	6	7
Probability of detection (%)	88.00	91.00	95.00	99.60	99.80	99.99
Probability of false alarm (%)	20.0	5.0	1.0	1.0	0.1	0.1

¹The NQR signal is also temperature dependent and varies a little with ground conductivity. The data are at 20°C and are for typical ground conditions.

minor form by tetryl) is that immediate repeat measurements are not possible. Instead, a dead time on the order of 5–10 seconds is required between TNT measurements (e.g., the optimum time for four measurements at 20°C is 20 seconds). The need for this dead time considerably complicates the use of NQR to detect antipersonnel mines that contain only TNT.

PERFORMANCE PROJECTIONS FOR NQR AS A STAND-ALONE MINE DETECTOR

To date, two separate mine detection configurations have been pursued: large vehicle-mounted coils for road clearance applications and minimal weight systems for man-portable use. The size and weight of NQR technology is comparable to GPR and metal detection systems, and so these two categories naturally apply to NQR systems as well. It should be noted that NQR per se cannot be used to detect metal-cased mines because of shielding of the applied RF field. However, a metal-cased mine is easily detected by a low-grade metal detector and tests have shown that such mines can also be detected by their electrical loading effect on the QR coil. Furthermore, it is believed that a stand-alone NQR system could be easily modified to detect metal-cased mines at a level greater than 99-percent PD, and so such mines are excluded from this study. To include such mines in the analysis below, the projected PDs should be increased by a weighting factor based on the respective ratio of mine types.

Performance of Current NQR Technology as a Stand-Alone Sensor

As indicated, NQR is adequate to detect RDX and tetryl-based antipersonnel mines at present tactical depths and for present mine sizes—but not for small TNT mines. However, not all mines are small and contain TNT, and it is of practical interest to consider a spectrum of explosive types, explosive masses, and mine burial depths. Computer simulations using outdoor experimental results as calibration have been written to calculate the average PD for the type of mines contained in the Army test lanes at Yuma (Ariz.) and Aberdeen (Md.) proving grounds, over the full range of expected temperature

and mine depths.² The results are listed in Table J.3 for the man-portable NQR system presently under development. Also included, for reference, is the PD on antitank mines for the man-portable system and also for the vehicle-mounted NQR system currently under development. The present hardware for these two systems is shown for reference in Figure J.1. Each system detects mines roughly within the footprint defined by the diameter of the detection coil. The vehicle-mounted system is designed to detect antitank mines only. However, antitank mines are a potential threat in humanitarian demining, and, in addition, the larger NQR detection coil for the vehicle-mounted system could be split into a number of smaller coils to detect antipersonnel mines with a larger area per measurement, thereby increasing clearance rate.

The projections shown in Table J.3 are fully supported by previous tests³ and show that NQR has adequate sensitivity in its present form to provide a threshold level of sensitivity. However, these results should be viewed with the following caveats, all of which affect the system SNR and highlight the need for continuing development efforts in NQR:

1. All NQR systems to date have been operated with a stationary detection coil. Thus the present systems must be moved from

Table J.3

Projected Results for Detection of Low-Metal Landmines at Aberdeen and Yuma Proving Grounds (Net PD at 5-Percent PFA Over All Mine Types, Burial Depth and Temperatures)

	Low-Metal AP Mines (%)	Low-Metal AT Mines (%)
Man portable	96.7	94.9
Vehicle mounted	N/A	99.5

²The variation of SNR with mine depth is very similar to that for metal detectors. Based on experimental data, ground conductivity is taken to be 50 mS per meter for the man-portable system and 20 mS per meter for the vehicle mounted.

³The vehicle-mounted NQR system was formally tested at Yuma Proving Ground in April 2002. The final test results have not yet been made available for release. In a dry run, in February 2002, the system recorded 100-percent PD (63/63).



Figure J.1—Present Configuration of the Man-Portable (left) and Vehicle-Mounted NQR Systems (right)

point to point, stopping to carry out the measurement. Preliminary experiments show that the NQR signal for a moving system is about a factor of 2 lower than that for a stationary system and that this signal decreases by about 10 percent going from velocities of 1 to 3 m per second.

2. The projections for the present performance are for a coil-to-ground standoff of 2.0 cm and antipersonnel mines at depths of up to 7.5 cm. This is comparable to the present use of the Handheld Standoff Mine Detection System (HSTAMIDS) currently being developed by the Army, but the NQR signal decreases more with increased standoff than GPR. Increasing the separation from the mine to the NQR by 1 cm reduces the SNR by a factor of approximately 30 percent.
3. The analysis assumes that the background RFI level is mitigated to within 1 decibel of the coil noise floor. There is an insufficient amount of field data at this time to know to what extent the 1-decibel target can be met, but the RFI level is generally low in regions where humanitarian demining is needed. Note that the question of RFI for NQR is analogous to the problem of clutter due to metal fragments and rocks for metal detection and GPR, respectively. It is difficult to develop a test protocol that adequately assesses general performance against clutter.

The total system interrogation time is dominated by the need to detect TNT and is essentially 20 seconds for the cases in Table J.3 (RDX and tetryl can be probed during the dead time between TNT measurements). The coil for the man-portable NQR system covers approximately a 100-sq-cm region, and therefore the area scan rate for that system is approximately 30 minutes per square meter. However, *a critical advantage of NQR, particularly for humanitarian demining, is that because the SNR increases with measurement time, an NQR system can be used to reexamine its own alarms.* For example, 5-percent PFA translates to 5 false alarms per square meter for the man-portable system. These alarms could be reinterrogated in an additional 100 seconds, resulting in a notional system false alarm rate (FAR) of 0.25 per square meter with a small reduction in overall system PD (e.g., down to 93.5 percent for low-metal antipersonnel mines). This property means that best- and worst-case field conditions can generally be accommodated by varying the NQR measurement time.

One possible scenario with present technology would be to increase the basic NQR measurement time by a factor of 2, which would increase the PD for the man-portable case shown in Table J.3 to 99.9 percent and 99.6 percent for antipersonnel and antitank mines, respectively, in a time on the order of 1 hour per square meter. The 5 false alarms per square meter would be remeasured in an additional 200 seconds for a total scan time of 63 minutes per square meter with a PD of greater than 99 percent. Alternatively, to reduce scan time, the NQR system could be operated as a confirmation sensor for essentially any other mine detection technology. One example of operation in this mode is discussed in the Combination of NQR with Other Mine Detection Technologies section below.

Performance Projections for Future Stand-Alone NQR Landmine Detection Systems

To develop a general-purpose NQR landmine detector to replace present metal detectors, two elements are needed: an increase in SNR of about a factor of 2 for stationary and 4 for in-motion detection of TNT and the development of hardware to use NQR while in motion. Given the need for improved TNT sensitivity, there has been essentially no work on the motion problem.

The majority of progress in improving the TNT signal in the past five years has come from increasing the power used and careful optimization of the measurement parameters. Further improvements in these specific areas are unlikely. Recently, a method has been developed to reduce the dead time needed between TNT measurements by a factor of 2. For the 20-second composite TNT measurement described above, this improvement increases the SNR by $\sqrt{2}$, but it does not increase the SNR per individual measurement and thus has no impact on the issue of using NQR in motion. A factor of $\sqrt{2}$ increase in SNR for the present man-portable configuration would increase the PD for antipersonnel and antitank mines to 99.9 percent and 99.6 percent, respectively (i.e., the same improvement as for doubling the measurement time). It is straightforward to predict the system performance for any given improvement in TNT sensitivity.

COMBINATION OF NQR WITH OTHER MINE DETECTION TECHNOLOGIES

At present, NQR is being developed for use as a confirmation sensor to be used in conjunction with the Army HSTAMIDS and GSTAMIDS systems to reduce the overall system FAR. As such, it is already being designed for use in combination with other technologies, and a confirmation sensor role is ideal to NQR at its current state of development. However, a more intriguing possibility is to develop a truly integrated measurement approach in which the capabilities of NQR are used to relax the requirements on the initial radar and metal detection sensors and increase the PD of the initial primary scan.

Approaches That Use Current NQR Technology

One possibility for a high-speed mine detector with high PD is to modify the detection algorithm for the HSTAMIDS system to increase PD and use NQR to cope with the associated increase in FAR. Specifically, GPR systems tend to have difficulty distinguishing shallow mines from ground surface effects but distinguish much better with deeper mines, while metal detectors detect shallow targets better but lose signal with depth. The present HSTAMIDS system takes the logical AND function of the GPR and metal readings to reduce FAR. However, if the logical OR is taken of the two HSTAMIDS sensors, then the PD increases to over 99 percent. Table J.4 compares

AND and OR HSTAMIDS modes when used in conjunction with an NQR confirmation sensor for the most difficult combination of low-metal mines in off-road conditions. If metallic mines and less demanding test conditions are included, the average PD for a combined NQR HSTAMIDS system is predicted to be in excess of 99.5 percent. Note that for this application it is not essential that the NQR system be physically integrated with the other sensors, but it could be used as a separate detection system.

In addition to sensor combinations that increase performance, one innovative approach would be to build a low-cost NQR system that could be placed over a suspect region and left to interrogate the ground for up to several minutes. Such a system could have extremely high PD and very low PFA (that could be set by the user) and could essentially replace the act of ground probing and excavation, thereby increasing area coverage rate and greatly improving safety.

Projections for Future Multisensor Landmine Detection Systems That Include NQR

Future improvements in the NQR signal from TNT can be translated to improved detection performance along the lines illustrated above in Performance Projections for Future Stand-Alone NQR Landmine Detection Systems. However, a more significant advance would be to use NQR in an integral role as part of the primary mine detection function. One possibility is to use NQR to detect only RDX-based mines for a sweeping sensor and develop a combined system in

Table J.4
Comparison of Two Possible Combinations of NQR with HSTAMIDS for Low-Metal Mines Measured in Off-Road Conditions

	PD (%)	FAR	Sweep Rate (s/m ²)
HSTAMIDS alone	92.3	0.25	60
HSTAMIDS (conventional mode) + NQR confirming	97.0	0.09	74
HSTAMIDS (logical OR mode) + NQR confirming	99.3	0.28	105

which other sensors detect TNT mines. This has the obvious benefit of overcoming the present limited detection capability for TNT. One approach is to note that RDX-based mines are smaller and tend to have more complex shapes than TNT mines. As a result, present GPR systems have lower PD on such RDX antipersonnel mines than the less sophisticated TNT-based targets. Thus, one potential combination of sensors is to use an NQR system that detects only RDX in conjunction with a GPR system with an increased detection threshold. By raising its threshold the FAR of the GPR system could be reduced, possibly quite significantly. An NQR confirmation sensor could also be used to optimize the overall system PD, FAR, and scan time.

SUMMARY

NQR provides a compound specific detection capability and combined with rescanning offers the opportunity for essentially zero false alarms. Present NQR technology has adequate PD/FAR to be used alone provided sufficient scan time is available. The required time could be reduced significantly if the TNT signal could be improved. In addition, a number of such practical issues as RFI have not yet been fully evaluated, and continued research and testing is needed in these areas.

An NQR confirmation sensor based on present technology can provide significant benefit when used to reinterrogate areas flagged by the existing mine detection systems. In this mode, NQR would replace the dangerous and time-consuming activity of ground probing and excavation. In addition, present NQR performance is adequate to consider integrating NQR more fully with present sensors, for example, by modifying the detection protocol used in combined radar and metal detection systems.

Finally, use of NQR as a primary sensor requires development of technology to enable an NQR system to operate while in motion. A system that detects only RDX is probably feasible with a moderate engineering effort, while a complete NQR primary sensor requires a significant increase in TNT sensitivity. While challenging, these problems have received little attention in the relatively brief time spent on NQR to date and may be solvable at moderate research and development costs.