(B)

PROPOSAL SUMMARY

Feasibility Study of Microwave Thrusters for Satellite Propulsion

Microwave thrusters are an innovative concept of electrical propulsion for spacecraft. Whilst chemical propulsion is unrivalled for achieving Earth orbit, the use of electric propulsion for spacecraft attitude control, orbit changing and high energy missions is growing. Conventional electric propulsion is based on accelerating inert gas propellant to high exhaust velocities. The microwave thruster is the first electrical propulsion technique to demonstrate thrust without the use of a propellant.

It has always been recognised that if a propulsion technique should be developed that does not require reaction mass (propellant) it would have a profound effect on the space industry. The NASA Glenn Research Centre has an ongoing programme in Breakthrough Propulsion Physics with this as one of its objectives. For this programme future deep space missions are the application. However, microwave thrusters can be employed in a much shorter time frame with substantial commercial benefits. As an example the launch mass of a conventional 3 tonne geostationary communications satellite can be reduced to 1.3 tonnes. Over a 10 year period this offers an estimated saving of £36 Billion to the satellite industry.

The theoretical principles of the microwave thruster are based on the well known phenomenon of radiation pressure but utilised within a resonant waveguide assembly. They have been developed in conjunction with considerable experimental work over a number of years. A patent has recently been granted. The work has been the subject of a number of discussions and reviews with physicists and engineers within the space industry. The prevailing view is well summarised in a recent report by a firm of Patent Attorneys, attached in ANNEX A This cautiously acknowledges that the theory presented to date is "reasonable" and that the experimental work provides "indication" that the theory works in practice.

It is clear however that the engineering and space qualification of the technology requires prior confirmation of the theoretical and experimental work by an established independent laboratory. To this end a company has been set up "Satellite Propulsion Research Limited" with four initial objectives:

1. Development of the existing experimental thruster and measuring equipment for independent testing.
2. Organisation and management of an independent test programme.
3. Preparation of theoretical paper for peer review.
4. Market and cost assessment for engineering and qualification stages of the thruster development.

This proposal covers funding to assist the successful attainment of these objectives over the next twelve months, and therefore to establish the feasibility of this innovative technology.

Discussions with potential venture capital sources have indicated that once feasibility is proven, funding for the next stage would become available. This would involve the design and manufacture of an engineering model to prove performance by test in a simulated space environment. (Thermal vacuum tests). The final stage would involve selection of a flight opportunity, qualification of a flight unit, and successful demonstration of in-orbit operation.

Proposal for the Feasibility Study of Microwave Thrusters for Satellite Propulsion

1. The Project

This project is a study covering both the experimental and theoretical work necessary to establish the feasibility of an innovative propulsion technology for satellites. The technology would have a profound effect on the space industry as it offers for the first time, a method of direct conversion of electrical energy into thrust without the use of a propellant.

The technique involves a major change in approach to propulsion, namely the replacement of Newtonian Rocket Propulsion Principles, with those based on radiation pressure and the special theory of relativity. The acceptance of this approach is not intuitive to many physicists and engineers working in propulsion. There is a need for independent evaluation and review of the work carried out to date. It is anticipated that a prominent UK laboratory, e.g. AEA Technology Abingdon, ERA Technology Leatherhead, or DERA Farnborough would be interested in a small sub contract for the test and evaluation work.

The project is an opportunity for the UK to support the early demonstration of a technology with significant implications for a global industry. It will enable UK industry to follow up the commercial exploitation of satellite equipment with potential sales value of £330 million per annum.

2. Objectives

2.1 Thruster upgrade

The first objective is to upgrade the existing experimental thruster and measurement apparatus to obtain more accurate test data. The upgrade will enable results to be obtained free of thermal offsets and balance inertia effects. It will also be possible to correlate power and thrust data throughout a test run to identify effects of power source instability. This data will confirm measurements made on the existing apparatus.

2.2 Theoretical Paper

In addition to the equipment upgrade,it is proposed to complete a theoretical paper, deriving the design equation from first principles and showing compliance of test data with theoretical calculations.

2.3 Independent Evaluation

The third objective is to carry out an independent test of the upgraded thruster at a recognised UK laboratory with relevant experience of space microwave hardware. Government, private and academic organisations would be invited to tender for a sub contract to carry out the work. In addition it is expected that the selected laboratory would review the theoretical paper.

2.4 Market Assessment

The final objective is to carry out a limited market assessment to establish which UK companies would be interested in pursuing the engineering and qualification stages of the thruster development. A cost and schedule estimate would be prepared for these stages and would be included in the assessment report.

2.5 Milestones

These objectives would be met in a series of milestones as follows:

	Milestone	Week No.
1	Development of power monitoring within thruster completed	10
2	Design and manufacture of hermetically sealed thruster module completed	24
3	Procurement of direct electronic balance and data logging equipment	24
4	Completion of performance testing	32
5	Completion of theoretical paper	32
6	Invitations to tender prepared and distributed	34
7	Proposals evaluated and contractor selected	36
8	Completion of independent test	38
9	Receipt of evaluation report	42
10	Completion of market assessment report	52

3. Technical Description

3.1 Principles of Operation

The concept of the microwave thruster offers a significant advance in electric propulsion performance as it is a method of providing direct conversion of electrical energy into thrust by employing the well known phenomenon of radiation pressure. The laws of conservation of momentum and conservation of energy are preserved. The principle of operation is based on microwave energy propagated through a resonant waveguide structure at relativisitic velocities. The Newtonian concept of a closed system has to be replaced by an open system which obeys the principles of relativity.

The operation of the microwave thruster is based on a simple result of relativity theory. Once an electromagnetic wave (EM) has been launched within a waveguide, the velocity of that wave is independent of the velocity of the waveguide. Thus if the waveguide is accelerated towards an observer, the EM wave within it is not accelerated. (If this were not correct, velocities above *c* would be achievable).

This principle remains valid if both ends of the waveguide are closed by reflective end walls. The velocity of the EM wave is determined only by the geometry of the side walls and the permittivity and permeability of the material, if any, filling the waveguide. The EM wave can therefore be regarded as being in an external reference frame rather than being within the reference frame of the waveguide itself. Thus the system comprising waveguide plus EM wave is an open system. This allows any force produced by radiation pressure on the end walls to act on the waveguide as if it were acting from the external reference frame.

Note that in a similar manner the laser gyroscope may be regarded as an open system. Thus whereas the instrument itself is in the reference frame, the laser beam is in an external reference frame (the so-called "inertial" frame), enabling changes of attitude to be measured.

A full description of the thruster is given in the patent specification in ANNEX B

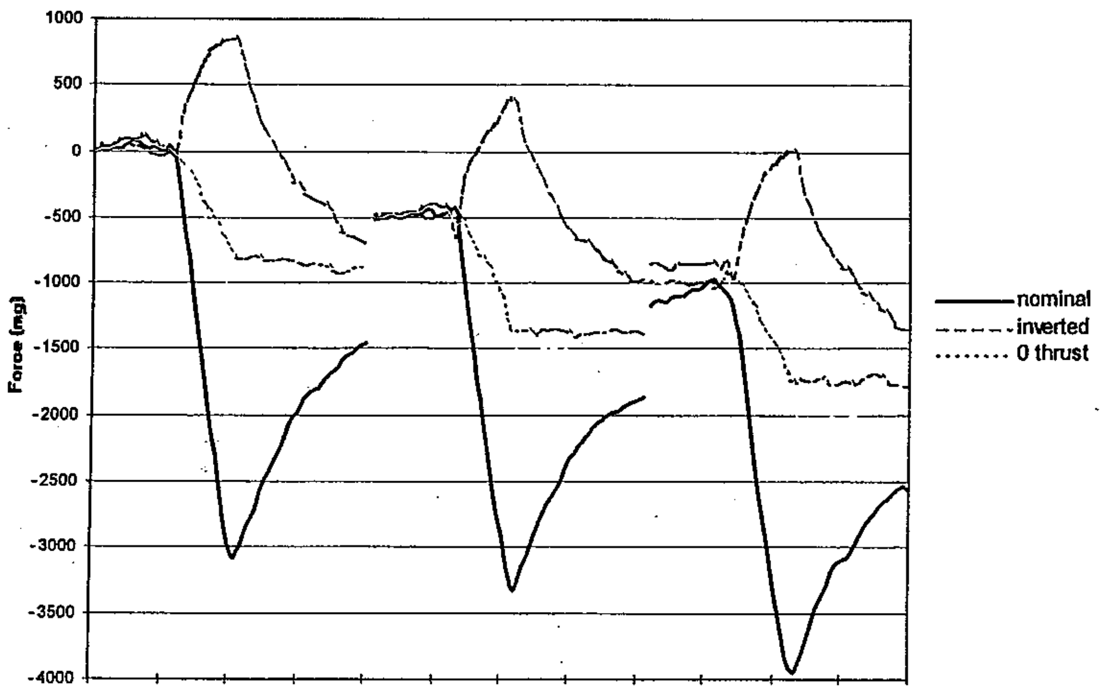
3.2 Experimental Work carried out to date

An experimental thruster with an unshaped dielectric section has been built and balance tested. The thruster was designed around a Siemens dielectric resonator type LN89/52B with a dielectric constant (e_r) of 38. An operating frequency of 2450 MHz was selected to allow a commercial 850 W magnetron to be used as a power source. A tapered circular waveguide was designed with TM01 as the dominant mode of propagation. A rectangular feed structure was used with a resonant slot selected for the input launcher. Input matching was achieved by feed length adjustment and a tuning screw. Thruster resonance tuning was carried out by variation of the position of the end wall, using screw adjusters. Optimum impedance matching at the dielectric boundary was achieved by fine adjustment of the axial position of the dielectric section.

Low power testing using a crystal controlled source enabled initial tuning to be carried out and final input feed tuning using the magnetron source enabled high Q operation to be established.

The complete thruster module comprising the thruster, input feed, magnetron and enclosure (total mass 9.4 kg) was tested on a counterbalanced load cell. The balance measurements were made in air, with a draught shield in place.
High voltage d.c. power was fed to the magnetron via flexible links at the centre of the balance beam. Considerable care was taken to carry out a test programme that would clearly discriminate between the thrust produced and other effects which would cause a change in load cell reading during powered operation.

The primary test was to invert the thruster and show that the thrust direction changed accordingly. The thruster module was inverted 'front to back' so that symmetry was maintained along the centre line of thrust. This ensured that spurious torques due to thermal expansion would be common to both nominal and inverted operation. The major thermal effect was the increase in buoyancy following heating of the air within the module enclosure. The enclosure provided sufficient cooling air volume to enable the magnetron to be run for 50 second periods without overheating. A series of three 'on' periods were carried out for each configuration with monitored 'off' periods.



The results of three groups of three test runs are given above. Each test run consists of 50 secs 'off', 50 secs 'on', 100 secs 'off'. Both the nominal and inverted configuration results shown are with optimum resonance and input tuning settings, and record the highest thrust levels achieved to date. In the zero thrust results, both resonance and input settings are off tune to give effectively zero thrust, but enabling the thermal effects alone to be measured. Peak thrust levels up to 1.8 grms were recorded, which is consistent with predicted design performance when powered at 850 W.

The test programme included a total of 48 test runs with different settings for resonance and input tuning. These tests were also repeated with a different magnetron. All tests showed the thrust peaked with optimum tuning and could be reduced to zero by detuning. This clearly discriminates against spurious test results and demonstrates thruster operation according to theory.

A further series of tests were carried out that confirmed that the test data could not be attributed to thermal, mechanical, electromagnetic or outgassing effects.

3.3 Upgrade of Experimental Thruster

The upgrade of the existing experimental thruster module is designed to overcome three factors affecting the accuracy and repeatability of test data.

Thermal Offset. - Air within the module enclosure produces a complex buoyancy offset as heat is dissipated during a test run. It is proposed to overcome this effect by enclosing the thruster module inside a hermetically sealed container. This will ensure that no mass decrease takes place due to leakage of heated air. The input and resonance tuning mechanisms will need modification, together with adaption of all electrical connections to ensure effective sealing. A capability for pressurisation and measuring the internal pressure will also be added.

Balance Inertia. - The counterbalance technique, currently used to measure thrust, results in a large inertia which together with electronic damping of the load cell results in long time constants being applied to the measurements. These distort the data taken during a test run. It is proposed to purchase an electronic balance capable of direct measurement of thruster module mass with a resolution of at least 0.1 grm. The balance would be calibrated to ISO 9002 requirements, have a data logging interface and be battery powered to provide EMC isolation from the magnetron power supply. A possible instrument would be the Avery Berkel model FC161.

Magnetron Stability. - The magnetron used in the experimental thruster is a standard 850 w microwave oven source. Its low cost commercial specification results in a wide band performance and variation in output power with temperature. Whilst adequate for oven use it introduces significant stability effects during typical test runs that degrade the repeatability of results. It is proposed to design and develop an internal power monitoring system to measure input and reflected power. This will enable data to be recorded during a test run and allow correlation with thrust data.

3.4 Assessment of technical risk

The work proposed will have low levels of technical risk in the following areas:

Hermetic sealing. - The temperatures and pressure differences are low and will allow effective sealing to be achieved by use of tank sealant coatings. Electrical connections will be sealed with epoxy potting techniques.

Power monitoring. - Power measurements will use voltage probe or current loop sensors with diode detection circuits. Suppression of spurious arcs due to the high field strengths encountered within the thruster and feed system will need careful design.

Resonance and input tuning mechanisms. - These mechanisms must be modified to operate within the sealed enclosure, whilst maintaining the necessary resolution and tuning range together with easy access. A number of design solutions will be evaluated before manufacture.

4. Level of Innovation

4.1 Impact on Space Industry.

The ability of microwave thrusters to provide propulsion by direct conversion of electrical energy from solar arrays without the need to expel propellant will enable all future Earth orbit and deep space missions to be undertaken for a fraction of existing launch mass and costs. Two examples of near term applications are given in the following sections to illustrate the significance of this technology. The use of microwave thrusters will lead to a major global expansion of both commercial and science missions, with the opportunity for UK industry to supply the propulsion systems.

4.2 Communication Satellites

A typical geostationary communications satellite with a launch mass of 3000 kg would have a dry mass of around 1300 kg. Thus 1700 kg of propellant is necessary for transfer from a geostationary transfer orbit (GTO) to the operational position in geostationary orbit (GEO) and to maintain that position throughout the operational life of 15 years.

The mass of the chemical propulsion system itself, including tanks, apogee engine and attitude control thrusters would be around 110 kg. Thus, the basic satellite mass, less propellants and propulsion system, is 1,190 kg.

Complete dependency on microwave thruster technology would result in a propulsion system comprising one S band thruster and six C band thrusters. The S band thruster would be used to accomplish GTO to GEO transfer and station keeping whilst the C band units would be used for attitude control. Note that momentum wheel and solar sailing techniques (employing solar radiation pressure) are conventionally employed alongside thruster operation to achieve complete attitude control. The total mass of the microwave propulsion system is 122 kg.

Total launch mass then becomes 1,312 kg , which is 44% of the original 3000 kg launch mass.

A typical GTO to GEO transfer requires a velocity change of 1500 m/sec. For an output thrust of 339 mN from a C band thruster and a mass of 1,312 kg the transfer would therefore take 67 days.

For a 15 year operational lifetime a total stationkeeping velocity change of 670 m/sec would be required. This would include both North/South and East/West stationkeeping. For an output thrust of 14 mN from a C band thruster the total operating time of the C band thruster system would be 725 days. This represents a duty cycle of 13%, which can be accommodated within the battery charging cycle of the satellite.

It should be noted that the usual limit to operational lifetime is the propellant necessary for stationkeeping and the final "graveyard burn". With a spacecraft totally dependent on microwave thruster technology, the limit on operational life becomes the reliability of the electronic systems, the lifetime of mechanical units such as momentum wheels or the end of life performance of the power subsystem. A significant enhancement of operational life may therefore be expected.

4.3 Primary propulsion for deep space missions

The following table compares the electrical propulsion system proposed for the SMART 1 mission currently being designed by ESA with the performance of a C band microwave thruster.

	ESA ion propulsion system	Microwave propulsion system
D.C. Power	700 w	700 w
Output thrust	23mN	19.6 mN
Thruster operating life	1.6 years max	15 years min
System mass	94 Kg	9.4 Kg

Thus for a slightly reduced thrust/power ratio a mass reduction of one order of magnitude is achieved together with a total impulse (thrust x time) increase by a factor of eight.

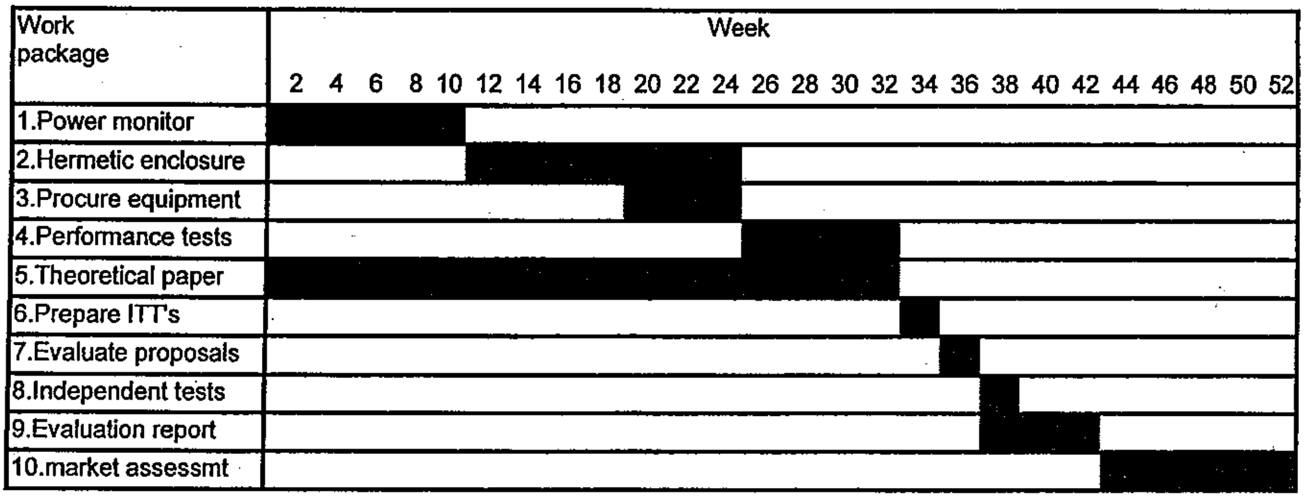
The use of microwave thrusters will clearly revolutionise the planning of science missions.

4.4. Patent Protection

The significance of this concept led to an initial patent application which was granted 5 May 1993, specification number GB2229865. Further theoretical and experimental work led to an improved understanding of the concept which resulted in a second patent being granted 19 April 2000, specification number GB2334761, a copy of this patent is given in Annex B.

5. Project Timetable

The project is scheduled to be completed in a 12 month period and will consist of 10 work packages carried out according to the following progress chart. Each work package results in a milestone as given in section 2.5.



6. Commercial Exploitation

The opportunity for commercial exploitation is illustrated by the following estimates.

6.1 Microwave Propulsion System (MPS) Cost Estimate

Costs are based on a 12GHz, 100 W power amplifier (TWTA), a power supply (EPC) and an output filter network currently used on commercial telecommunications satellites (July 2000 costs).

TWTA plus EPC	£ 115 K
Output filter	£ 25 K
	£ 140 K

S band thruster (2 GHz, 6kW) cost scaled for frequency and power

$$= £140\text{ K} \times \frac{6000}{100} \times \frac{2}{12}$$

$$= £1400\text{ K}$$

C band thruster (7 GHz, 500W) cost scaled for frequency and power

$$= £140\text{ K} \times \frac{500}{100} \times \frac{7}{12}$$

$$= £408\text{ K}$$

Total propulsion system cost (1 S band plus 6 C band thrusters)
= £3.85 million

Cost Saving per satellite

For a typical 3 tonne geostationary communications satellite, July 2000 costs are:

Chemical propulsion system (CPS) £3,100 K
Spacecraft structure £4,500 K

Replacement of CPS with MPS will result in a mass reduction to 44% of original.

Assuming this will result in a halving of spacecraft structure mass and cost, cost saving per satellite is:

MPS cost	£3848 K
less CPS cost	- £3100 K
less 0.5 structure cost	- £2250 K
	- £1502 K

Thus cost saving per satellite = £1.5 million

A mass reduction to 44% will enable a single launcher to deploy two satellites to geostationary transfer orbit (GTO) rather than one.

Current minimum cost of GTO launch for a 3 tonne satellite is £80 M (Proton launcher)

i.e. launch cost saving per satellite = £40 M

then total cost saving per satellite in orbit = £41.5 million

6.3 Business Forecast

A market analysis by the Teal Group (a well respected US aerospace consulting firm) predicts a total of 2147 satellites will be launched during the next 10 years. Of these, approximately 40% are expected to be above 1 tonne and in geostationary orbit.

Thus total geostationary satellite MPS business over the next 10 years would be

2147 x 0.4 x £3.85M
= £3.3 billion (i.e £330 M p.a.)

The total saving to the geostationary satellite users would be

2147 x 0.4 x £41.5 M
= £35.6 billion (i.e. £3.56 B p.a.)

It can be seen that once the technology is established, this huge potential saving will encourage rapid utilisation, with the creation of a high turnover MPS business.

7. Business Background and Project Management

Satellite Propulsion Research Ltd was formed in October 2000 to further the research and development of microwave thrusters. The company's initial objectives are to raise funding and provide technical and project management functions during the feasibilty study.

Once the preliminary findings are confirmed, the engineering development phase of the project will be sub-contracted under licence in exchange for equity, to commercial partners in the space procurement industry. The research company would not realistically be capable of funding from its own resources the intensive engineering work required to bring the apparatus to flight status. Instead, the approach is to collaborate with suitable partners at an early stage and work with them to bring the proven concept to fruition.

Interested parties may come from any of the following organisation that would have a vested interest in reducing launch costs and/or prolonging the life cycle of satellites: space propulsion systems; satellite construction; telecommunications; data management e.g Reuters and the insurance industry.

Remuneration will be derived in due course from a combination of licences, royalties and launch fees on the use of technology; on production of flight modules and per launch.

The founding shareholders are:

R J Shawyer C.Eng MIEE Director.
A consultant Engineer with extensive senior technical and managerial experience including 20 years in the space industry. The majority of technical and managerial work on the study will be carried out by Mr Shawyer working full time over 12 months. Mr Shawyer is the Inventor of the microwave thruster.

[redacted] Company Secretary.
A Chartered Accountant with many years' experience in providing support for small and medium sized businesses. In the last ten years assignments have included finance directorship in a consulting engineering practice employing up to 725 people; and working with one of the UK's leading private equity advisors.

Primary role is to lead the fund-raising activity; control the company finances and seek out commercial partners for the second stage.

[redacted] Marketing Manager.
[redacted] and has 20 years experience of managing the transition from invention to commercial success for many products. Provides marketing and venture capital search expertise for Satellite Propulsion Research Ltd.

[redacted] Technical Advisor.
[redacted] with many years experience of engineering and management of high technology developments. Acts in a technical advisory role for Satellite Propulsion Research Ltd

CV's are given in ANNEX C.

8. Use of Available Funds

The business has no other activity requiring funds other than the central aim of furthering the microwave thruster technology.

The total funding requirement for the feasibilty study is £60,386 over a twelve-month period.

Approximately half of the funds will be used to support Mr Shawyer in his role as technical and project manager for the duration of the assignment - there are no other salaried positions envisaged in the feasibilty study.

Third party test and evaluation fees of £15,000 are allowed in the schedule, and equipment with an initial cost of £4,500 is required. Finally, a budget of £8,000 has been set to allow for a market assessment.

The gap between a full SMART award of £45,000 and the £60,386 requirement would be covered by: share capital £1,000; refund of professional fees of £4,000 and shareholder loans where appropriate.

9. Need for SMART Support

Mr Shawyer, the inventor and principal shareholder has committed hundreds of hours in bringing the project to its present state. He has stated his willingness to concentrate full-time on the technical and managerial role that this feasibilty study demands.

The award would allow Mr Shawyer to devote himself full-time to this project and thereby accelerate the process significantly. On the other hand, failure to win the award would mean that the project would continue to be worked upon in a piecemeal fashion, but only as personal time and funds allowed.

Critically, the failure to attract a SMART award would severely reduce the chances of attracting a commercial partner to carry out third party tests and evaluation of the project.

All of the shareholders are fully committed themselves, and have agreed to provide funding loans to support the company through the first stage if the award is granted.

10. Project Costs

A cost summary and cashflow projections are given in ANNEX D.