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The Importance of Co-ordination in National Technology Policy: Evidence from the Galileo Project[1]

VASILIS ZERVOS & DONALD S. SIEGEL

ABSTRACT *We assess the benefits from transatlantic collaboration in technology policy for publicly-funded R&D space projects such as Galileo, a proposed European radio-navigation space project. An industrial organisation methodology is employed to model negative security spillovers of 'unilateral' space projects such as Galileo, or space-based anti-ballistic missile defence, on the public sector of the other region (the US vs. the European Union). The findings imply that transatlantic co-ordination in technology policy is required to allow the respective space industries (in the US and the European Union) to exploit the benefits of cross-border strategic research partnerships (SRPs). This coordination not only reduces the costs of the respective programmes, but also addresses security concerns.*

Keywords: Galileo; navigation; space; technology policy; transatlantic.

Introduction

The recent rise of public–private research partnerships in OECD nations has underscored the need for an institutional framework that facilitates the commercialisation of publicly funded R&D. This paper describes an initiative that attempts to achieve this objective: the Galileo space-based navigation system.

Galileo is a proposed European non-military, space-based, radio-navigation programme that relies on ground-controlled satellites to provide users with accurate positioning information. This project is expected to have broad commercial applications, such as radio-navigation based automatic landing systems and navigation and positioning systems in autos. Galileo is a classic example of a public–private partnership (PPP), as its development (the 'D' of R&D) was publicly funded, while its deployment and implementation will be largely financed and managed by firms, who will assume equity in the enterprise. Policymakers hypothesise that this PPP will result in the further development and commercialisation of high accuracy, space-based navigation assets. The projected cost of developing and implementing Galileo is approximately 3.3 billion.

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This programme is quite unusual because it constitutes the first time the European Commission (EC) and the European Space Agency (ESA) have agreed to share equity/ownership with European space firms, service providers, and financial institutions. The unprecedented nature of this joint venture, coupled with the large risks associated with large-scale investment in the space industry, raise concerns about the nature of the social returns to this project. These concerns are heightened by the fact that the revenue resulting from Galileo will result from its value-added products, which utilise the precision signal, since its basic, less accurate navigation signal will be un-coded and provided free of charge.[2] This is the same approach used in the American Global Positioning System (henceforth, GPS) and the Russian Glonass. Several consulting firms project a high return to Galileo.[3] They also predict a substantial increase in space-based navigation services worldwide. However, the time horizon for the realisation of these returns is quite long. Private funds will not be required until its deployment stage, which is expected to run from 2006 to 2007. The EC expects not to provide further public subsidies after 2007, when the operational phase begins. It is important to note that there are substantial risks associated with this endeavour, including delays and dramatic changes in market conditions.[4] Furthermore, firms may be reluctant to do what is necessary to successfully implement the project, once substantial public funds have been incurred. This is especially likely to occur when indirect public subsidies end in 2007.

Security concerns regarding Galileo have risen substantially in the aftermath of the September 11 terrorist attack. To deal with such cases, the provisions of the Galileo proposal provide for an independent management team. This team is under European political control, and is authorised to assume stricter security measures in the event of another terrorist attack. US involvement in Galileo has not yet been finalised at either institutional, or industry level, although it is possible that there will be participation at the sub-contracting level. Note that Galileo is quite different from the well-known US GPS, which is owned and controlled by the US Department of Defense (DoD). In contrast to GPS, Galileo will be managed by a commercial entity, and a potential concern among the military establishment in several nations (especially after September 11) is that profitability might take precedence over security.

These areas of concern, which have traditionally been treated separately, are shown to be interrelated in our analysis. Specifically, we outline a model that accounts for the structure of the European–US industries and public sectors, market conditions and industrial/procurement policies. This allows the examination of an alternative scenario where the US and European public sectors promote transatlantic industrial links in undertaking such projects.

A unique aspect of the paper is that we model negative security spillovers of 'unilateral' space projects such as Galileo, or space-based anti-ballistic missile defence, on the public sector of the other region (the US vs. the European Union). Our findings imply that transatlantic co-ordination in technology policy is required to allow the respective space industries (in the US and EU) to exploit the benefits of cross-border strategic research partnerships (SRPs). This coordination not only reduces the costs of the respective programmes, but also addresses security concerns.

The remainder of the paper is organised as follows. The next section presents background information on the Galileo project, followed by a description of the nature of space markets, with an emphasis on the characteristics of industry structure and firm conduct. We outline the model in the next section and then present our findings, based on calibrated values of the parameters of this model, in the following section. The final section consists of conclusions and suggestions for additional research.

Background Information on Galileo

As noted earlier, the two existing global satellite-based positioning and navigation systems are the Russian Glonass and the US Global Positioning System (GPS). These systems were designed during the Cold War era. Thus, they were developed primarily for military operations, such as navigation and targeting on a global scale.[5] For instance, the US military uses GPS for navigation and targeting. It was used quite effectively during the Gulf War to guide tanks through the desert in Iraq and Saudi Arabia. Although both systems are operational, GPS is much more widely known, due to its widespread commercialisation. GPS is managed by the US Department of Defense (DoD), which provides a non-military-coded signal (based on GPS) that can be used by commercial enterprises free of charge. By design, for national security reasons, the commercial signal is less accurate than the signal used for military purposes. Over time, however, DoD has allowed a much more accurate signal to be used in the commercial domain.[6] The purpose of this change is to enhance the social return to public investment in R&D, as the signal has broad commercial applications and can significantly increase productivity in downstream sectors. In fact, the commercial potential of GPS is probably the greatest of any space-based, military spin-off since the Internet. Uses of these systems range from auto-navigation to GPS-based automated aircraft landing systems.[7]

Thus, the decision of EU ministers to launch a new, fully commercial positioning and navigation system in early 2002 is a landmark one. It is significant for two reasons: it represents a strong commitment to full commercialisation of space-based navigation and positioning services and it constitutes the first public–private partnership involving numerous countries in the space sector.

Table 1 presents a schedule for the implementation of Galileo, which involves three stages. The first stage, which is expected to run through 2005, involves development and in-orbit testing of the system (satellites and ground stations). This phase is expected to cost approximately 1.1 billion, shared equally by the two partners, the European Space Agency (henceforth, ESA) and the European Commission (henceforth, EC). Next is the deployment stage, which is expected to transpire from 2006 to 2007. This stage involves the assembly and launch of the satellites constellation (30 satellites required) as well as the completion of the satellite signal receivers. The second stage is expected to cost about 2.1 billion, out of which just 0.6 billion is expected to be publicly funded. The third and final stage is the operational phase, starting in 2008, when no public subsidies are expected and the annual costs of running the system are estimated at 0.2 billion, borne fully by the public–private partnership that will manage Galileo.[8]

In essence, the system will be built with European public funds, facilitated through a public–public partnership between ESA and EC. The second (lower risk) stage will be financed with private funds, which will enlarge accordingly the partnership into a public–private partnership. This organisational structure is novel and the resulting joint venture is a public–private partnership, where not only the ‘private’ part of the partnership is comprised of more than one entity, but also the ‘public’ part.

Table 1. Implementation plan for the Galileo project

	Phase	Period	Funding € (2000) billions/*amount of subsidy*	Galileo partnership
Stage 1	Development	2001–2005	*1.1*	Joint undertaking between ESA and EC, private funding and partners possible, but not necessary
Stage 2	Deployment	2006–2007	2.1 *(0.6)*	Operating company. Equity provided by EC, ESA (controlled by a single public management scheme) and private shareholders. There are debt providers. Public regulation with regards to security issues
Stage 3	Operations	2008 onwards	0.2	

Sources: EC (2000), EC (2002), PriceWaterhouseCoopers (2001).

Firms have two concerns when embarking on such a partnership: standard concerns about profitability, technology and market risk, and concerns regarding undue interference from the public sector, since public institutions are subsidising the endeavour and will be regulating the firm. On the other hand, Galileo's key prime contractors will be European space firm(s) which is likely to hold equity in the resulting enterprise.

The development and operation of the system would have benefit greatly from avoidance of duplication and the technical expertise of the US and Russian space industries, which have a long established experience in radio-navigation. Although there are some ongoing technical discussions taking place between European and Russian space officials, there has been limited contact with the US. This is partly due to the lingering effects of Cold War animosity, which seem to be slowly drifting away, but also due to concerns about additional competition and industrial policies in the US and Europe that prohibit certain types of interaction with the Russians. The access to markets and marketing of the system would also have much to benefit from collaboration, primarily with the US, and finally collaboration would result in reduced pressure for further costly commercialisation of the US GPS. There are clear benefits for both the US and European public sectors from such collaboration at industry level, as well as for the space industries involved. However, there are also greater complications associated with such collaborations, as compared to the European–Russian endeavour. This is due to the fact that a US–European collaboration would not simply exist on a technical level, but would also require the formation of partnerships for developing the system, managing it, and marketing the resulting commercial services in the US (see below).

Space Markets and Industry Structure

From an economic standpoint, space systems, industries and public sectors are interdependent. That is, there are strategic interactions between space industries and public sectors in Europe and the US. The decision by Europe to build such a system has implications for the competitiveness of the commercial markets of European and US space firms, their size and performance, as well as the strategies of the US public sector.

Both industries have undergone substantial consolidation, assisted by respective public policies. This has left just one major space integrator in Europe, the European Aerospace and Defence Systems (EADS), and two in the US, Lockheed Martin and Boeing. The two industries virtually control the commercial market for expendable launch services and major telecommunications satellites, the two major commercial space markets. This is achieved by the fact that the substantial Russian and Ukrainian launching services, which carry a high level of reliability and low cost, are marketed by Arianespace (directly controlled by EADS) and the respective US firms.[9] In major US projects, both major space integrators are expected to participate, as, given the size of government business, if there is a consistent single 'winner' of projects, this inevitably leads the other firm to exit the market (see for example, the united space alliance, a 50–50 joint venture maintaining the Space Shuttle). This results in encouraging collusion involving the respective firms.

European and American firms encounter almost no domestic competition in their respective domestic space industries. However, they do encounter competition in commercial space markets, such as launching services, telecommunication satellites, and remote sensing products. As a result, each firm is assumed to behave as a monopolist in the domestic public space market it is faced with, and as a duopolist, in competition with the other firm in the commercial space market.[10]

This setting, though quite simple, adequately describes the preferential treatment the domestic space industries of the US and Europe enjoy in their respective public sectors. Policymakers in the US and Europe also use procurement and industrial policies (although the Americans would reluctantly refer to this as an industrial policy!) to enhance the competitiveness of their domestic space industries in commercial markets. Some of the actions they take to achieve these goals include:

- promoting consolidation, which has resulted in a domestic monopoly or duopoly;
- raising entry barriers for foreign firms (e.g. the 'Buy American Act' in the US and 'juste retour' in Europe[11]);
- inhibiting free trade in commercial space products and controlling the supply and pricing policies of the Russians and the Chinese. Such restrictions are diminishing as US and European firms utilise the capabilities of the countries of the former USSR.

In sum, public agencies in the US and Europe demonstrate a clear preference in the procurement of space products for domestic manufacturers. When possible, national governments also implement policies to enhance the competitive position of their domestic space industries in commercial markets. In light of these facts, the European space industry is producing space goods for two space markets,[12] one for the commercial marketplace, and another for the European public sector, i.e. ESA or the Western European Union (WEU). Equivalently, the US space industry is assumed to be producing commercial space goods and space goods for public space markets, where the relevant US agencies are the National Aeronautics and Space Administration (NASA) and the Department of Defense (DoD).

This paper uses a model to capture the structure and conduct of space firms and analyses the impact of collaboration and competition in public space markets (e.g. European Galileo, US reusable launch system—RLV) on firm performance, costs incurred by public agencies, and the resulting market price and size of commercial markets.

Modelling Markets and Cost Characteristics

Following the above, the space industries of the US and Europe can be approximated with the use of a simplifying model of two space firms, representing the US and European space industries. There are three markets to be considered, two of them are the public space markets of Europe and the US, respectively, which are closed to foreign competition. The third is an international commercial market where the two industries compete as duopolists at contractors' level.[13]

The demand functions of the respective markets facing the space integrators (EADS, Boeing and Lockheed Martin) in public space markets are assumed to be a function of the price the public sector has to pay for civil and military space systems. Demand is also assumed to be related to the other region's level of public space programmes, which reflect security concerns. This results in the price the public sector pays being determined not just by space programmes undertaken domestically, but also by the military and civil public space programmes supplied by the integrator in the other region to their respective public sector. The inclusion of this additional argument is justified on two grounds.

The first justification is the power of the space industry lobby on the domestic public choice. This results in the incorporation of 'reaction factors' in the demand for national space products. A reaction factor would result in increases in demand for national space products, in response to increases in the rival's demand for public space goods, which, if left un-answered can result in the rival obtaining a competitive advantage in commercial space markets. In the case of radio-navigation systems, we expect that the US space manufacturers will advance the argument that if Europe is developing its own commercial-oriented system of radio-navigation, then the modernisation programme of GPS must be further developed and accelerated. The US firms will advocate this because they do not wish to see US industry lag behind their European counterparts with respect to technical capabilities. Such a scenario would have profound implications for US competitiveness in commercial markets.

A second justification for considering the role of the other region's public sector is that for radio-navigation systems, extreme reliance on the other region's capabilities result in loss of control of strategic assets. The reaction to such loss of control for Europe, for example, has contributed much to its decision to build its own system (Galileo). Thus, investment by European governments and firms in Galileo is expected to result in further development of GPS by the US (more than if Galileo was not built), in order to maintain US leadership in the space industry.

Note that this scenario does not constitute a 'space race', like the one experienced during the Cold War between the US and the Soviet Union. Under this scenario, rivals determined the extent of their space programmes based on strategic considerations with the aim to obtain an advantage in case of armed conflict.[14] However, it is a form of 'space competition' based on security and commercial considerations[15] and has a very similar impact on the form of the government demand for space programmes, with increases in an areas' public space funding being met by respective increases by the other areas' public sector. This means that the market structure of the public space markets, though a monopoly for the domestic suppliers, includes non-price security considerations and a 'competing public sector reaction' element.

If European and US space integrators encounter overseas competition in public markets, it is possible that US integrators will be major participants/contractors in Galileo, or that European integrators will be major contractors on the US re-usable launch vehicle or the US space-based missile defence system (an updated version of the controversial 'Strategic Defence Initiative'). This could result in a US–European (and even Russian) space industrial base, with major restructuring at firm-level leading to multinational space integrators.

For the case of radio-navigation service providers, the incorporation of US space firms as major contractors in Galileo, followed by European firms becoming contractors of US civil space systems (RLV), would result in the phasing out of the 'public sector reaction' factor of the demand for public space systems. This would require stronger participation by US firms in Galileo than currently planned. Under the current scenario, the two candidate consortia to run Galileo (see Stage 2 in Table 1) are Eurely (led by Alcatel-France, Finmeccanica-Italy, Aena and Hispasat-Spain), which is predominately French and Italian based and iNavSat (led by Inmarsat Ventures, EADS Space and Thales), which is predominately German and UK based.[16] The involvement of US firms in the above consortia is minimal, since the US is not a candidate to join Galileo. Specifically, Boeing has made an agreement with each candidate consortium and Lockheed Martin has linked with iNavSat. The US involvement is aiming at ensuring interoperability with GPS and promoting commercialisation of Galileo primarily in the US market.[17]

In terms of costs, the total cost functions of the US and the European space integrators are assumed to be symmetric for the two industries.[18] The respective functions also exhibit the cost characteristics of a multi-product space integrator described (i.e. economies of scale and economies of joint production for civil, military and commercial products) for the relevant output range.[19] That is, an expansion of output results in a decline in average cost, which is commonly observed in heavy manufacturing industries, which are highly capital intensive. There are also certain desired theoretical properties for such a cost function, such as being non-negative and non-decreasing (see the Appendix).

To compare the two scenarios of open and closed foreign competition in publicly funded space projects, we outline and calibrate a model under closed to overseas competition public space markets (**Scenario 1**) and open to overseas competition public space markets (**Scenario 2**). The results are compared in terms of prices in commercial and public space markets (costs faced by ESA–Galileo partnership, or NASA for RLV), profitability of the space industries and the respective quantities supplied. The key assumptions of the modelling of markets and costs under Scenarios 1 and 2 are summarised in Table 2.

Results

Having outlined the characteristics of the cost functions of space firms, their market structure, and the nature of their conduct, it is necessary to determine the behaviour of the firms with respect to their objectives.

Following the convention in this literature, we assume that space integrators aim to maximise profits and the respective firms compete in terms of quantity supplied to the commercial space markets as duopolists (Cournot quantity-based competition; see Appendix and relevant literature[20]). In this model, it is assumed that firms

Table 2. Key assumptions regarding the type of markets for alternative scenarios

Type of market	Scenario 1	Scenario 2
US Public Market (mainly NASA, DoD)	Monopoly facing the US space industry because of: exclusion of non-US major integrators from public procurement ('Buy American Act'—FAR, 2002) and consolidation-encouraging policies result in nationally confined concentrated integrators.	Both public markets 'merge' into a duopoly transatlantic public space market. This results in a wide spectrum of space programs/ projects facing the US and European space corporate entities multinational integrators/joint ventures). This allows the formation of trans-Atlantic public- private commercial partnerships in space (Galileo).
EU Public Market (ESA, European national space agencies)	Monopoly facing the EU space industry because of: Preferential treatment in public procurement ('juste retour') of European national space firms and consolidation-encouraging policies at EU level result in Europe-confined multinational Integrators.	
Commercial Markets	Duopoly in the manufacturing of space projects/ programs by major space integrators between the US and European space industries. Russian and Ukrainian space industries, though technically highly competent, are best seen as partnering subcontractors/major suppliers to US and European space firms.	

compete by setting quantities, in a manner that maximises their profit. Given the complicated nature of the theoretical solution to this model, the equilibrium solutions to the two calibrations for Scenarios 1 and 2 are examined and compared in Table 3.

As Table 3 indicates, the most economically efficient structure, in terms of low prices and high output, is Scenario 2. The profits of the two firms are lower under Scenario 2, as they have to compete in domestic and international markets and they loose their domestic monopoly status. This means that for a project such as Galileo, competitive pressures from overseas participation would diminish the possibility of 'lock-in' and the ability of the domestic firm to extract high rent from budgetary appropriations for the development phase. Benefits from collaboration at firm level in programmes such as Galileo and RLV, or space-based missile defence, will also lead to avoidance of duplication at R&D level and exploitation of complementary tasks through programme-specific strategic research partnerships. This is expected to lead to reductions in fixed costs, with the most prominent example being R&D appropriations [F in Equation (1) of the Appendix]. The only quantitative implication of such reductions for the equilibrium results of this model is that for each Euro saving in fixed costs there is a one Euro increase in profits. Thus, for the space industry, pressures on its profitability due to increased competition would be somewhat offset by lower R&D costs under Scenario 2 due to the absence of duplication.

Table 3. Equilibrium outcomes under alternative scenarios

Scenarios	Variable	Firm 1 (US)		Firm 2 (EU)
Scenario 1	q_i	12.21		12.21
	p		51.15	
	q_{di}	4.86		4.86
	p_{dj}	32.97		32.97
	Profits	410.91		410.91
Scenario 2	q_i	12.30		12.30
	p		50.81	
	q_{di}	5.88		5.88
	p_{dj}	26.45		26.45
	Profits	389.74		389.74

This analysis illustrates how the introduction of non-protective market-considerations in European and US public policies can reduce uncertainties and costs of space programmes, such as Galileo. Specifically, the model results and comparison indicate how the introduction of the US technical expertise, industrial capabilities and facilitation of market access (primarily to the US public radio-navigation market) could benefit the Galileo project in terms of size of markets (public and commercial) and costs of the system.

The losses at the political level from Scenario 2 refer mostly to shared control of strategic radio-navigation and other assets which must be weighted against economic losses. The political issues that need to be addressed refer to political, security and military issues. For example, the introduction of US firms into the Galileo partnership, coupled by corresponding partnerships between the US and European industry on US projects, would result in economic benefits in the form of know-how and risk sharing, but such know-how would be subject to export restrictions of the US, which could prove complicated, given that GPS is a DoD project.

This highlights the requirement of improved co-ordination and formation of links at industry and public office levels between Europe and the US to improve economic efficiency, lower costs of space projects and facilitate in the expansion of space-based commercial markets.

Conclusions

In this paper, we examined the design of Galileo, a proposed European radio-navigation space project. We attempted to illustrate the impact that US–European policy collaboration on publicly-funded R&D can have on the cost, market size and prices of space programmes. Galileo faces the problem of high risk, given the absence of European experience at integrators level on space-based radio-navigation, which could result in duplication of technologies developed in Russia (Glonass) and the US (GPS) which increase cost. In addition, Galileo faces the problem of the possibility of further upgrades and commercialisation of the US GPS, as well as security concerns by the US regarding potential misuse of Galileo's commercial services by terrorists and other enemies of the free world. These areas of concern, which have traditionally being treated as separate issues, were shown to be interrelated in our analysis.

The paper models two scenarios for the European and the US space industries, that take into consideration economic factors (such as fixed costs—R&D) and policy factors (procurement policies and national security considerations). The first scenario is based on the assumption that all markets are closed to foreign competition, reflecting the current procurement policies of the respective areas. This results in the exclusion of the US space industry from being a major competitor/contractor and also the European space integrators being excluded from US public space markets. The second scenario is based on the assumption that there is open competition in public space markets in Europe and the US. In the case of Galileo, this would result in the formation of transatlantic collaboration at industry level which could well extend into US programmes.[21]

The comparison demonstrates the importance of transatlantic cooperation at the public policy level to achieve an optimal result in space projects like Galileo. We show this by illustrating how such policy coordination results in reduction in operating costs and prices of public procurement and commercial application services, as well as an increase in the respective production levels. In addition, coordination in national technology and procurement policies under Scenario 2 enables the respective industries to exploit the benefits of cross-border strategic research partnerships (SRPs), reducing duplication and maintaining profit levels for the respective industries. Such policy coordination might also yield benefits for other public goods.[22]

Notes and References

1. Paper presented at the May 2002 Ehud Zuscovitch Memorial Conference, BETA, Strasbourg, France. The authors thank the organisers and participants for useful comments. The usual disclaimer applies.
2. For example, value added services include the incorporation of positioning functions for emergency services in mobile telephones, high-precision navigation support for aircraft and in-vehicle navigation services to drivers; see European Commission, *The Galileo Program*, report of the European Commission, Brussels, Belgium, 2002, online at http://www.europa.eu.int/comm/energy_transport/en/gal_how_en.html.
3. *Ibid.*
4. For example, the status of the US GPS can change, or problems with global security can arise, due to the non-maturing of sustained commercial applications of high-accuracy navigation. The bankruptcy of the space-based mobile telephony service provider Iridium, which by the time it was built was too expensive to compete against the rival terrestrial networks, highlights how market studies often neglect the 'reaction', or development of competing systems.
5. The same can be said of the Internet, which was developed primarily by the US DoD, as noted in D. C. Mowery and T. Simcoe, 'Is the Internet a US invention? An economic and technological history of computer networking', *Research Policy*, 31, 8–9, 2002, pp. 1369–87.
6. The accuracy has gone down to a few meters by 2000, see Peter E. Dana, *The Global Positioning System*, 1999, online at http://www.colorado.edu/geography/gcraft/notes/gps/gps_f.html.
7. European Commission, *Commission Communication to the European Parliament and the Council On Galileo*, European Commission, Brussels, 2000.
8. *Ibid.*
9. See V. Zervos, 'The markets for launching services and industrial space policies in Europe and the US', conference paper, 51st International Astronautical Congress, Rio de Janeiro,

Brasil, October 2000, American Institute of Aeronautics and Astronautics paper no.: IAA-00-IAA.4.1.04. Reprints available from AIAA, Washington, DC.

10. See V. Zervos, 'The economics of the European space industry: the impact of the government space market on structure, conduct and performance', in G. Haskell and M. Rycroft (eds), *New Space Markets*, Kluwer Academic Publishers, the Netherlands, 1998; V. Zervos, *The Economics of the European Space Industry*, D.Phil. thesis (Economics), University of York, UK, 2001.
11. For the 'Buy American Act', see Federal Acquisition Regulations–FAR, 2002, online at http://www.arnet.gov/far/current/html/Subpart_25_1.html. ESA applies the principle of 'juste retour' in its industrial policy, meaning that it aims to equalise member-state contributions to space programmes with value of appropriations directed to the respective national space industry.
12. There is an extensive literature analysing the impact of monopoly markets on competition in a single product case. Refer to the relevant literature by J. A. Brander and P. R. Krugman, 'A reciprocal dumping model of international trade', *Journal of International Economics*, 15, 1983, pp. 313–23; A. R. Cooper and K. Hartley, *Export Performance and the Pressure of Demand*, University of York Studies in Economics, T&A Constable, Edinburgh, 1970; as well as the examining of a numerical example of a similar model with one monopoly market. See I. J. Bulow, D. J. Geanakoplos and D. Klemperer, 'Multimarket oligopoly: strategic substitutes and complements', *Journal of Political Economy*, 93, 1985, pp. 489–511.
13. Zervos, 2001, *op. cit.*
14. See T. Sandler and K. Hartley, *The Economics of Defense*, Cambridge University Press, New York, 1995; V. Zervos, 'The impact of the strategic defence initiative on the space race', *Journal of Defense and Peace Economics*, 15, 4, August 2004, pp. 365–77.
15. Zervos, 2001, *op. cit.*
16. See A. M. Taverna, 'U.S., China, eye Galileo', *Aviation Week and Space Technology*, 31 January 2005, p. 26.
17. *Ibid.*
18. Several reports on the European space industry (see Zervos, 2001, *op. cit.*,) indicate that there is no substantial cost differences between the US and European space industries, and this result seems plausible for the commercial products, given the commercial orientation of the European space industry. For the military space products however, due to their generic and custom made nature, this is hard to establish. This lack of substantial cost differences can also be attributed to the subsidisation of the EU space industry by the EU public sector, in the form of contributions to ESA and subsidisation of publicly owned or controlled aerospace firms.
19. It would be reasonable to expect that beyond some production level, the production of any good would be subject to diseconomies of scale.
20. There are a number of relevant studies for the commercial airliner manufacturers, such as G. Klepper, 'Entry into the market for large transport aircraft', *European Economic Review*, 34, 4, June 1990, pp. 775–803; G. Klepper, 'Industrial policy in the transport aircraft industry', in P. Krugman and A. Smith (eds), *Empirical Studies of Strategic Trade Policy*, NBER, University of Chicago Press, 1994; D. Neven and P. Seabright, 'European industrial policy: the airbus case', *Journal of Economic Policy*, 21, October 1995, pp. 313–58.
21. See V. Zervos, 'A view to the future: trans-Atlantic space firms and US–European industrial policy co-ordination', conference paper, 50th International Astronautical Congress, Amsterdam, the Netherlands, 1999, American Institute of Aeronautics and Astronautics, paper No. IAA-99-IAA.3.1.09. Reprints available from AIAA, Washington, DC.
22. *Ibid.*, p. 449.

Appendix

From Table 2, for Scenarios 1 and 2, the inverse demand function of the commercial markets is assumed to be of the following form:

$$p = a - b(q_1 + q_2), \tag{1}$$

where

p = price of the commercial space good;
q_1 = the quantity of the commercial space good supplied by the US firm;
q_2 = the respective quantity supplied by the European firm;
a = the vertical intercept;
b = the slope of the demand line
(a and b are assumed greater than zero).

In Scenario 1 the inverse demand functions for the US and European firms are assumed to be of the following form:

$$p_{\mathrm{d}i} = c - d(q_{\mathrm{d}i}) + s(q_{\mathrm{d}j}) \quad \text{for } `i, j\text{'} = \text{US, EU}, \tag{2}$$

where

$p_{\mathrm{d}i}$ = the price of the domestic public space good in the US and the European markets, respectively;
$q_{\mathrm{d}j}$ = the quantity of the government purchased space good by the US and the European public sectors, and c, $d > 0$;
s = the reaction coefficient, whose value depends on the perceived 'threat' by the public sector on security issues and the competitiveness of the domestic space industry, as well as the lobby power of the domestic space industry. Both of these factors are positively related to s.

While in Scenario 2, there is a joint US/European duopoly market, as the respective public sectors are open to overseas competition. Space integrators are assumed to compete 'a la Cournot', meaning that they make an output choice, assuming that their rivals will produce exactly what they made in the previous period. This results in the value of 's' diminishing (normalised to zero), as domestic industries can participate in the other area's public civil and military space projects:

$$p_{\mathrm{d}} = e - f(q_{\mathrm{d}i} + q_{\mathrm{d}j}) \qquad \text{for } `i, j\text{'} = \text{US, EU}, \tag{3}$$

where $e, f > 0$.

The cost frontier is assumed to be a function only of output quantities and not input prices. This method of formulating cost functions makes the analysis less complicated, without much loss in generality when the main concern is to examine the impact of output changes (see W. J. Baumol, C. J. Panzar and D. R. Willig, *Contestable Markets and the Theory of Industry Structure*, Harcourt Brace Jovanovich, Inc., New York, 1982, p. 453). In addition, the TC function should be meaningful in the case of the production of a subset of the products set and should 'not in itself prejudge the presence or absence of any of the cost properties that play an important role in the analysis of the industry' (p. 449). Based on the above, the TC function is of the following form:

$$C_i = F + M(q_i + q_{\mathrm{d}i}) + \alpha_i(q_i^2 + q_{\mathrm{d}i}^2) + \alpha_{ii}(q_i q_{\mathrm{d}i}) \quad (4)$$

where

$i = 1, 2$;
F = fixed costs (including R&D);
α_{ii} = coefficient denoting economies of scope;
α_i = coefficient denoting economies of scale.

None of the coefficients needs to be constrained to be non-negative, provided that for the output range considered, a negative coefficient will not result in a decreasing cost function, or negative average or marginal costs.

The calibration of the two scenarios faces a major quantitative challenge as no quantification of the cost characteristics of multi-product space firms has been undertaken. A main reason for a lack of empirical evidence demonstrating economies of scope and scale in this industry is that most space firms are divisions of multi-product aerospace firms. Many of them have a military and commercial range of aerospace and space products, some of which are produced in production lines, while others are developed as prototypes. On the other hand, cost data on certain top-secret military space and aerospace projects cannot be obtained. Such differences in the information of the production of space goods makes the quantification of a general cost function very complicated and with doubtful validity for output range outside the current production levels.

As a result, the calibration of the cost function was done for illustration purposes, with the only requirement being that for the relevant output range the cost function is well behaved and exhibits economies of joint production and economies of scale. The values for F, M, α_{aij} and α_{ai} were thus chosen arbitrarily in terms of their absolute magnitudes, but in order to support the assumptions of the presence of economies of scale and scope between public and commercial space goods and are presented in Table A1.

Table A1. Calibrated values of the parameters of Equations (1) –(4) under alternative scenarios

Parameter	Scenario 1	Scenario 2
c	100	100
b	2	2
c	50	–
d	14	–
e	–	50
f	–	2
F	50	50
M	15	15
α_i	0.6	0.6
α_{ij}	–0.6	–0.6

As Table A1 indicates, the assumption of symmetry in cost characteristics is also employed in the case of public space markets in the US and Europe. Given the substantial size differences between these two markets, this is not a realistic assumption; it is employed however, since it simplifies this analysis, without having an impact on its results.